U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**

NHTSA

DOT HS 812 717

May 2019

Safety Performance of Rechargeable Energy Storage Systems

Disclaimer

Suggested APA Format Citation:

National Highway Traffic Safety Administration. (2019, May). *Safety performance of rechargeable energy storage systems* (Report No. DOT HS 812 717). Washington, DC: Author.

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EXECUTIVE SUMMARY

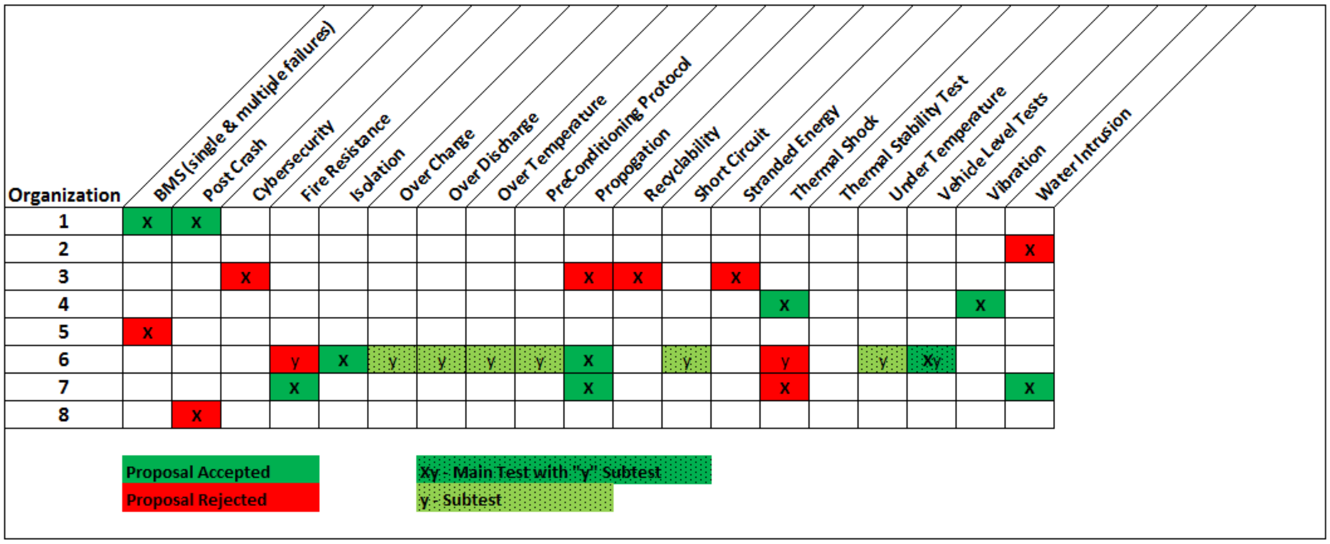
Safety Performance of Rechargeable Energy Storage Systems

The purpose of this project is to develop objective test procedures for meaningful, comparable, and quantitative evaluations of Li-ion based Rechargeable Energy Storage Systems (RESSs) in hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV) and electric vehicle (EV) platforms. The test procedures are applicable to all components of the RESS and ancillary vehicle systems associated with electric propulsion; these standards can also serve as a guide for future designs. RESS safety performance is assessed with both single and dual point failure modes during all normal and abnormal operating conditions including charging, vehicle storage, operation, crash event, and post-crash state. Test data are used to quantitatively determine the response of the RESS at both the cell and system level.

The test procedures provided herein were developed based on a Failure Mode and Effect Analysis (FMEA) through a Cooperative Research Partnership (CRP) with five OEMs. A thorough analysis was conducted to identify gaps in current global battery standards and it was determined that they do not address RESS-based vehicle applications. Rather, existing test standards are derived from the consumer electronics industry, shipping and transportation requirements, and internal combustion engine (ICE) vehicle platforms. Additionally, wide variations in boundary conditions and performance metrics were found for similar types of tests.

Thus, as part of the FMEA process, a technical review team was formed to develop test procedures for the identified high risk areas in RESS-based vehicle applications. The technical review team consisted of a Principal Investigator (PI), two SAE Project Managers, and the Contracting Officer's Technical Representative (COTR). Various organizations and consultants with automotive Li-ion battery expertise were solicited as Subject Matter Experts (SMEs) to participate in the development of these procedures. The interested SMEs submitted proposals within their respective area(s) of expertise (e.g., vibration, thermal shock, overcharge, etc.). The approved projects were structured such that the SMEs could work independently under the direction of a technical review team; the PI was responsible for providing oversight and leading technical interactions with the SMEs.

A total of 18 unique proposals encompassing 26 test procedure development ideas were received from eight companies (see Figure 1). The technical review team reviewed the proposals and initially approved 10 test development projects from four companies (see Figure 2). After further analysis and review, however, the technical review team decided to cancel the post-crash test procedure development due to resource constraints. It was also decided to combine the thermal shock and vibration tests into a single procedure development. Following are summaries of the final eight test procedures that were selected for full development. Note, however, that the fire resistance test procedures included as part of this effort were found to be impractical and potentially unsafe if followed independently. This includes both the internal fire (i.e., thermal runaway propagation) and external fire tests. Therefore, they were omitted from the final report.

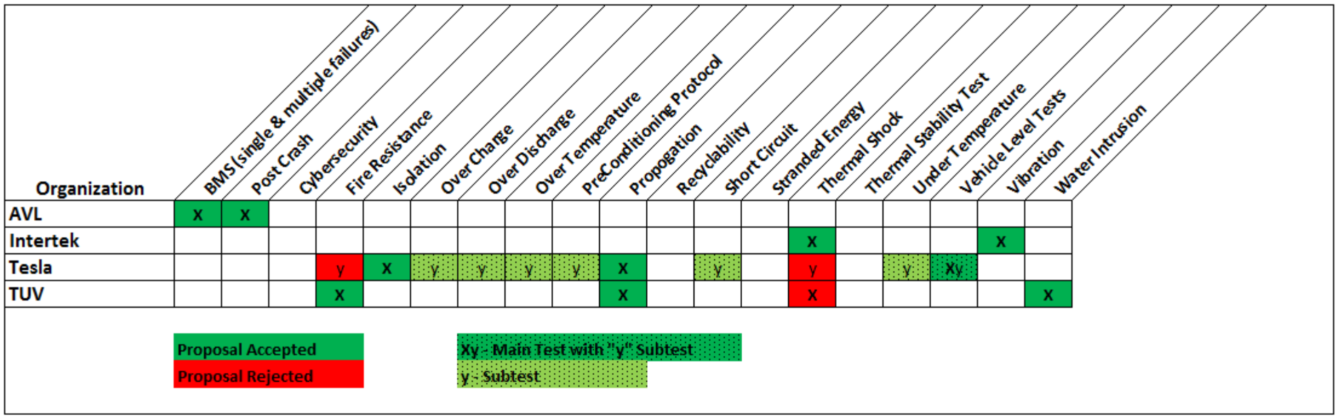


Organization	BMS (single & multiple failures)	Post Crash	Cybersecurity	Fire Resistance	Isolation	Over Charge	Over Discharge	Over Temperature	PreConditioning Protocol	Propogation	Recyclability	Short Circuit	Stranded Energy	Thermal Shock	Thermal Stability Test	Under Temperature	Vehicle Level Tests	Vibration	Water Intrusion
1	🟩 X	🟩 X																	
2																			🟥 X
3			🟥 X							🟥 X	🟥 X		🟥 X						
4														🟩 X				🟩 X	
5	🟥 X																		
6				🟥 y	🟩 X	y	y	y	y	🟩 X		y		🟥 y		y	Xy		
7				🟩 X						🟩 X				🟥 X					🟩 X
8		🟥 X																	

🟩 Proposal Accepted
🟥 Proposal Rejected

Xy - Main Test with "y" Subtest
y - Subtest

Figure 1 - Test procedure proposals.



Organization	BMS (single & multiple failures)	Post Crash	Cybersecurity	Fire Resistance	Isolation	Over Charge	Over Discharge	Over Temperature	PreConditioning Protocol	Propogation	Recyclability	Short Circuit	Stranded Energy	Thermal Shock	Thermal Stability Test	Under Temperature	Vehicle Level Tests	Vibration	Water Intrusion
AVL	🟩 X	🟩 X																	
Intertek														🟩 X				🟩 X	
Tesla				🟥 y	🟩 X	y	y	y	y	🟩 X		y		🟥 y		y	Xy		
TUV				🟩 X						🟩 X				🟥 X					🟩 X

🟩 Proposal Accepted
🟥 Proposal Rejected

Xy - Main Test with "y" Subtest
y - Subtest

Figure 2 - Selected test procedure proposals.

BMS Failure Mode Test: DC Charging Interface

Goal

- Introduce failure modes between the battery management system (BMS) and DC charging system.

Safety Metric

- Evaluate the BMS safety response to various charging system failures.

Approach

Various fault conditions can occur before, during and after DC charging. This test procedure consists of 16 discrete tests that evaluate the following failure modes:

1. Ground faults
2. Chassis ground offsets
3. DC bus shorts
4. DC bus held high
5. 12V system overvoltage
6. 12V system under voltage
7. 12V system disturbance
8. 12V system electromagnetic interference
9. Vehicle movement
10. Vehicle crash or bump
11. Charge operation disturbance
12. Charge connector control signal disturbance
13. Charge connector high voltage connection disturbance
14. Cooling/Heating system
15. BMS internal fault detection
16. Overcharge test

Several of these tests can be conducted with a breakout box, which is a device that interfaces between the vehicle charge coupler and the DC charger (see Figure 3). It allows the test technician to safely introduce various failure modes during testing by flipping appropriate switches. The procedure clearly identifies the switch setting sequence for each relevant failure mode test.

Note that an additional goal of this project was to develop a procedure for battery health assessment in a vehicle post-crash event, but the technical review team determined that alternative research efforts should be used to address this issue.

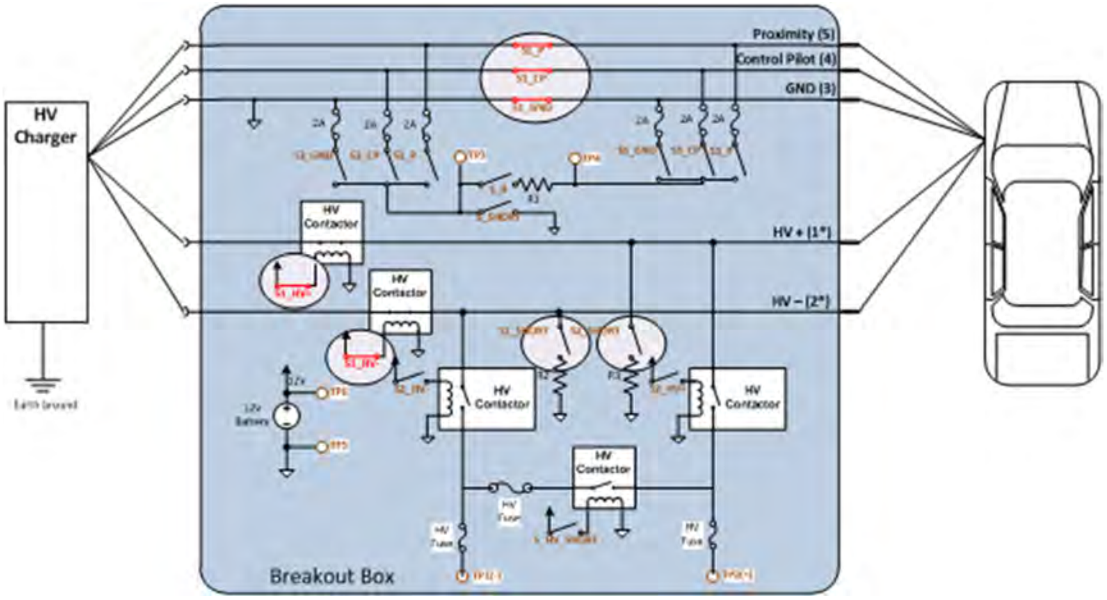


Figure 3 - Breakout box.

Test Verification

Eleven of the 16 test procedures were evaluated using a representative RESS-equipped vehicle and charging station. The vehicle manufacturer provided technical assistance to ensure appropriate communication protocols were used. The test report includes all of the relevant observations, faults, and diagnostic trouble codes. Graphs of the RESS performance (e.g., voltage, current, state of charge, etc.) are also provided.

RESS Isolation Stress Test

Goal

- Induce high voltage isolation stress on a RESS such that its safety mechanism is not triggered.

Safety Metric

- Assess the potential hazards to the vehicle occupant or surrounding environment from a reasonably foreseeable pollutant introduced inside the battery assembly that may cause degradation or loss of isolation.

Approach

Electrical isolation is achieved through the use of various types of insulators, including air, between high voltage components and ground. Loss of isolation failures associated with Li-ion based RESSs are of particular concern because they have been known to occasionally cause thermal runaway conditions, which is very hazardous for vehicle occupants and the surrounding environment.

The RESS Isolation Stress (RIS) test, unlike many standards available at the time of this writing, is intended to create a high voltage isolation stress condition and observe the system response. The ideal method meets the following characteristics:

- It would have a high probability of degrading electrical isolation
- It would be relevant to RESSs of many designs
- It would provide stress throughout the RESS (multi-point)
- It would be somewhat architecture independent
- It would not directly force high current flows (i.e., internal fuses and switches are not activated)
- It would provide poor warning properties of a potential problem

To meet the above criteria, two methods of pollutant introduction are described in this test procedure:

- Application of the Single Cell Thermal Runaway Initiation (SCTRI) method.
- Remote introduction of vent gases from a thermal runaway initiation vessel into a RESS.

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

The test sequence consists of the following steps:

1. Conduct pre-test loss of isolation measurements using both the insulation resistance test and the dielectric withstand test. Each test shall be performed twice, once between the negative battery terminal and vehicle ground and once between the positive terminal and vehicle ground.
2. Initiate loss of isolation with the identified pollutant introduction (i.e., SCTRI or vent gases through an initiation vessel).
3. Conduct post-test loss of isolation measurements using both the insulation resistance test and the dielectric withstand test. Each test shall be performed twice, once between the negative battery terminal and vehicle ground and once between the positive terminal and vehicle ground.
4. Conduct the transient overvoltage stress test. This involves connecting a DC power supply with a current limit set to 200 mA between the vehicle ground and the negative terminal (i.e., positive terminal of power supply to negative terminal of battery). The voltage is increased over 5 minutes to 353 V_{DC} and maintained for 1 hour. The voltage is then reduced back to 0 V over 5 minutes.
5. Conduct final loss of isolation measurements using both the insulation resistance test and the dielectric withstand test. Each test shall be performed twice, once between the negative battery terminal and vehicle ground and once between the positive terminal and vehicle ground.

From the acceptance criteria requirements, the vehicle or RESS shall not report an isolation value greater than 500 Ω/V if the previous insulation resistance test measured less than 500 Ω/V.

Test Verification

Full-scale RIS tests were conducted in conjunction with SCTRI testing using two EV models. The batteries consisted of small cylindrical cells (Manufacturer A) and hard case prismatic cells (Manufacturer B). In both cases, the vehicles had previously been subjected to NHTSA New Car Assessment Program (NCAP) crash testing; the RESSs, however, were not damaged and could be used to verify this test procedure. Insulation resistance and dielectric withstand measurements were conducted on the RESS after all signs of thermal runaway propagation (if any) had ceased. This was followed by the transient overvoltage stress test and a final insulation resistance and dielectric withstand measurement.

This test procedure was only verified with EVs. Although the approach is applicable, it has not been verified with HEVs and PHEVs.

Single Cell Thermal Runaway Initiation (SCTRI) Test

Goal

- Induce single cell thermal runaway within a full-scale RESS that is installed in a vehicle and observe any propagation effects.

Safety Metric

- Assess the potential hazards to the vehicle occupant or a surrounding environment from full-scale, in-vehicle single cell thermal runaway initiation.

Approach

Although rare, thermal runaway reactions do occur in the field, even with batteries produced by the most experienced and conscientious cell and battery manufacturers, and even with batteries that meet applicable standards and routinely pass a variety of abuse tests. Thermal runaway reactions with Li-ion cells are of particular concern since the cells have higher energy density, usually contain a flammable electrolyte, and are used to make high capacity battery packs.

The purpose of a Single Cell Thermal Runaway Initiation (SCTRI) testing standard is not to determine the likelihood that a single cell will undergo a thermal runaway reaction due to any particular cause. Rather, the purpose is to assume that a single cell within a RESS will undergo a thermal runaway reaction due to an unspecified cause, and to then determine whether that reaction will pose a significant hazard in two categories of risk: hazard to the occupant, and hazard to the surrounding environment. The first category maintains that the cabin must remain tenable for sufficient time to allow safe egress. The second category maintains that the vehicle must not pose an unreasonable ignition or mechanical hazard to the surrounding environment. The test procedure is composed of three parts:

1. Selecting an appropriate single cell thermal runaway initiating methodology.
2. Verifying the initiation methodology in coupon or module level tests.
3. Full scale, in-vehicle testing.

The selected SCTRI methodology shall force only one cell into thermal runaway and be representative of field failures. Any subsequent cell thermal runaway reactions shall be the result of propagation from the initiating cell, not caused directly by the initiation method. Although various initiation methods could be used, studies included with this test procedure indicate that overheating is the most reliable and relevant method to trigger thermal runaway in a single cell. The heater must be sized appropriately (e.g., a 30 W nichrome wrapped wire heater for small cells, or a 240 W heater pad for larger, 20+ Ah, cells) with the goal of thermal runaway initiation after ~10-30 minutes of heating.

The intent of coupon or module level initiation trials is to ensure that the selected methodology will be effective in full-scale RESS testing. Furthermore, the effect of interactions with neighboring cells and other battery module components can be observed. It is also intended to allow refinement of the initiation method (e.g., the location of the trigger cell and triggering methods).

For full-scale in-vehicle SCTRI testing, the following information is required:

- Details and justification of the selected initiation method
- Location of the initiation method, including justification for the selected location
- Locations of all installed sensors
- Evidence that instrumentation has not significantly affected RESS internal isolation
- Voltage of the pack prior to test beginning
- Video of the test from several angles, at least three
- Time that the first thermal runaway occurred
- Evidence that the first runaway occurred, visually, audibly, and/or thermally
- Times of any subsequent runaways, vehicle events, ignition, smoke alarm activation. Use t=0 as the time when the initiating device was activated
- Temperature data and gas sensor data if measured
- Photographs of the battery pack after testing has completed

Test Verification

Full-scale SCTRI testing was conducted with three EV models. The batteries consisted of small cylindrical cells (Manufacturer A), hard case prismatic cells (Manufacturer B), and large pouch cells (Manufacturer C). In all cases, the vehicles had previously been subjected to NHTSA New Car Assessment Program (NCAP) crash testing; the RESSs, however, were not damaged and could be used to verify this test procedure. During propagation testing, high voltage electrical isolation was lost on all vehicles. This often occurs when a cell vents within a battery pack due to the electrical conductivity of electrolyte.

This test procedure was only verified with EVs. Although the approach is applicable, it has not been verified with HEVs and PHEVs.

Vehicle External Fire Test

NOTE: This procedure is not included in the final report due to potential safety concerns. If independently conducted, testing could lead to dangerous outcomes or consequences.

Goal

- Introduce an external fuel fire underneath a full-scale RESS that is installed in a vehicle and observe any failure propagation effects.

Safety Metric

- Assess the potential hazards to the vehicle occupant or a surrounding environment from an external fire source.

Approach

An external fire at or near a RESS-based vehicle can be influenced by a number of factors such as fuel type, distance of flames from vehicle, distance of flames from battery pack, ambient conditions (e.g., wind and weather), duration of the fire, flammability of the vehicle under body, flammability of components under the body, and secondary fuels. The traction battery can potentially also influence the fire dependent on its location, extent of exposed surfaces, type and flammability of surfaces, and state of charge.

This test procedure evaluates the effects of an external fire using a fuel fire fixture that is geometrically centered under the test vehicle (see Figure 4). An array of propane burners are positioned in a predetermined pattern to regulate the flame and heat. Structural perimeter screens of height >2.4 m are placed around the test vehicle to catch any projectiles that may be expelled. The inner perimeter can be wire mesh and the outer perimeter should be solid wall.

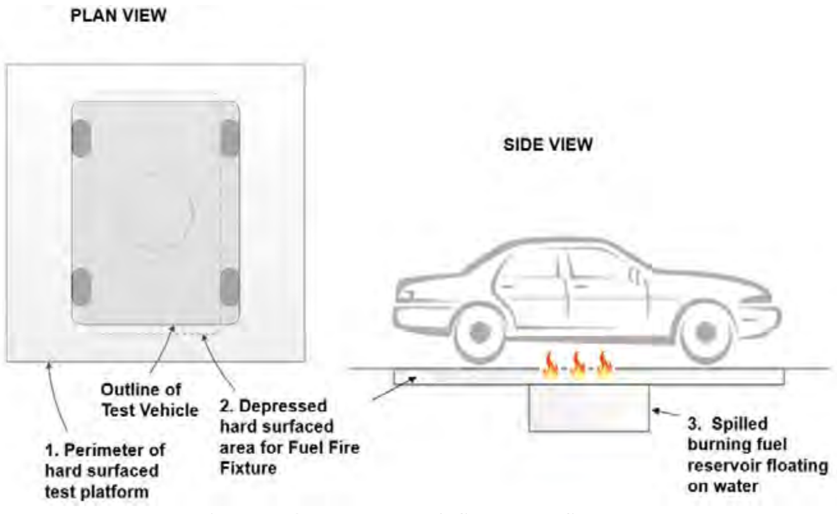


Figure 4 - External fire test fixture.

The test procedure requires a maximum flame temperature of 1,000°C within 5 minutes of test initiation. The fire is continued for 60 minutes or until all instrumentation has stopped functioning. Proposed data requirements include:

- Voltage measurements (HV and LV systems both internal and external to the RESS)
- Temperature measurements (fuel fire fixture, RESS, vehicle, etc.)
- Gas detection (sensors for carbon monoxide and for methane in the vehicle cabin)
- Smoke detection (vehicle cabin)
- Video capture (interior of trunk, interior of cabin from driver and passenger sides, interior of engine bay, and ground level view of fuel fire under vehicle)
- Thermal imaging video capture (driver's side of the cabin interior)
- Digital photographs (before, during, and after testing)

Test Verification

NHTSA is collaborating with Transport Canada in a research and development project to develop an external fire exposure test procedure. Therefore, to avoid duplicity, the project review team decided not to pursue vehicle testing using this procedure.

Vehicle Pack Internal Fire Test

NOTE: The intent of this test procedure was to evaluate propagation effects after a thermal runaway initiation. Although the need to assess thermal runaway propagation is critical for RESS safety assessment, this test procedure is insufficient and could lead to hazardous outcomes or consequences if conducted independently. Validation testing demonstrated characteristics that were not intended and potentially dangerous. Thus, this procedure is not included in the final report.

Goal

- Introduce a fire from within a full-scale RESS that is installed in a vehicle and observe any failure propagation effects.

Safety Metric

- Assess the potential hazards to the vehicle occupant or a surrounding environment from an internal fire source. Assess the potential hazards to the vehicle occupant or a surrounding environment from an internal fire source.

Approach

The purpose of this procedure is to evaluate the consequences to the RESS and vehicle when a cell undergoes thermal runaway. The test sequence consists of a provocation step that attempts to initiate a thermal runaway in one or more cells. This is followed by a propagation step which monitors the chain reaction (if any) in the battery pack. Placement and activation of the trigger cell(s) is important for both provocation and propagation evaluation. To optimize the type of provocation method (e.g., heater plates) and installation location, this standard requires individual assessment of each RESS that will be subjected to testing.

The provocation step requires that a significant amount of heat energy be released from one or more trigger cells within the RESS over a short period of time (i.e., a high-power provocation step). Although various methods could be used (e.g., overcharge, over discharge, external short circuit, crush, nail penetration, etc.), this procedure recommends using heater plates that are preferentially positioned inside a module between two or more cells. The heater plates are used to initiate a thermal runaway reaction that can lead to propagating failure modes up to an unrestricted RESS fire.

Prior to provocation, the vehicle is preheated to 40±3°C. This represents a hot weather environment (i.e., worst case) for test and evaluation. The trigger cell(s) is then provoked using a heating rate that corresponds to the SAE J2464 requirement of achieving 400°C within 5 minutes (i.e., ~70°C/minute). Unlike SAE J2464, heating is continued beyond 400°C if needed to ensure thermal runaway and the onset of an internal fire. However, the temperature shall not exceed the melting point of the heating plates or maximum allowable temperature of the heating elements. A simple thermal calculation procedure was developed to estimate the electrical power requirements for the heater plate to initiate cell thermal runaway and fire.

Testing should be performed on the same fuel fire fixture developed for the external fire test. Structural perimeter screens of height >2.4 m are placed around the test vehicle to catch any projectiles that may be expelled. The inner perimeter can be wire mesh and the outer perimeter should be solid wall.

Test Verification

Full-scale vehicle testing was conducted with six different vehicles, including two EVs, three PHEVs, and one HEV. Cell types included prismatic hard cases, prismatic soft cases, and 18650 cylindrical cases. In most cases, the vehicle was used and damaged, but the RESS was still intact. Extensive photographic documentation was captured during the test setup, including the vehicle damage and any required RESS modifications (e.g., installing the heater blocks). During testing, time and temperature data were captured with data loggers and video cameras (including IR cameras). Data observations included the first indication of flames, smoke/gases/vapor, and the first bang, explosion, or pressure wave. Cabin tenability (temperature, hazardous gases, etc.) was extensively monitored to evaluate hazards to the occupant and available escape times.

Six vehicles were selected for the Internal Fire Test:

• EV	42 kWh	Under Body
• EV	24 kWh	Under Body
• PHEV	7.6 kWh	In Body
• PHEV	7.6 kWh	In Trunk
• PHEV	4.4 kWh	Rear Cargo Area
• HEV	0. 68 kWh	Rear Seat Back

A range of vehicle responses were observed. One of the six vehicles took significantly longer to indicate the onset of cell abuse (i.e., smoke and vapors likely to have come from cell venting). Another vehicle showed rapid cell venting, but no visible flames.

Vehicle Sequential Testing after 5000 Mile Preconditioning

Goal

- Evaluate the robustness of a RESS safety architecture after aggressive aging.

Safety Metric

- Assess the potential hazards to the vehicle occupant or a surrounding environment from full-scale, in-vehicle sequential testing after preconditioning for 5000 or more miles.

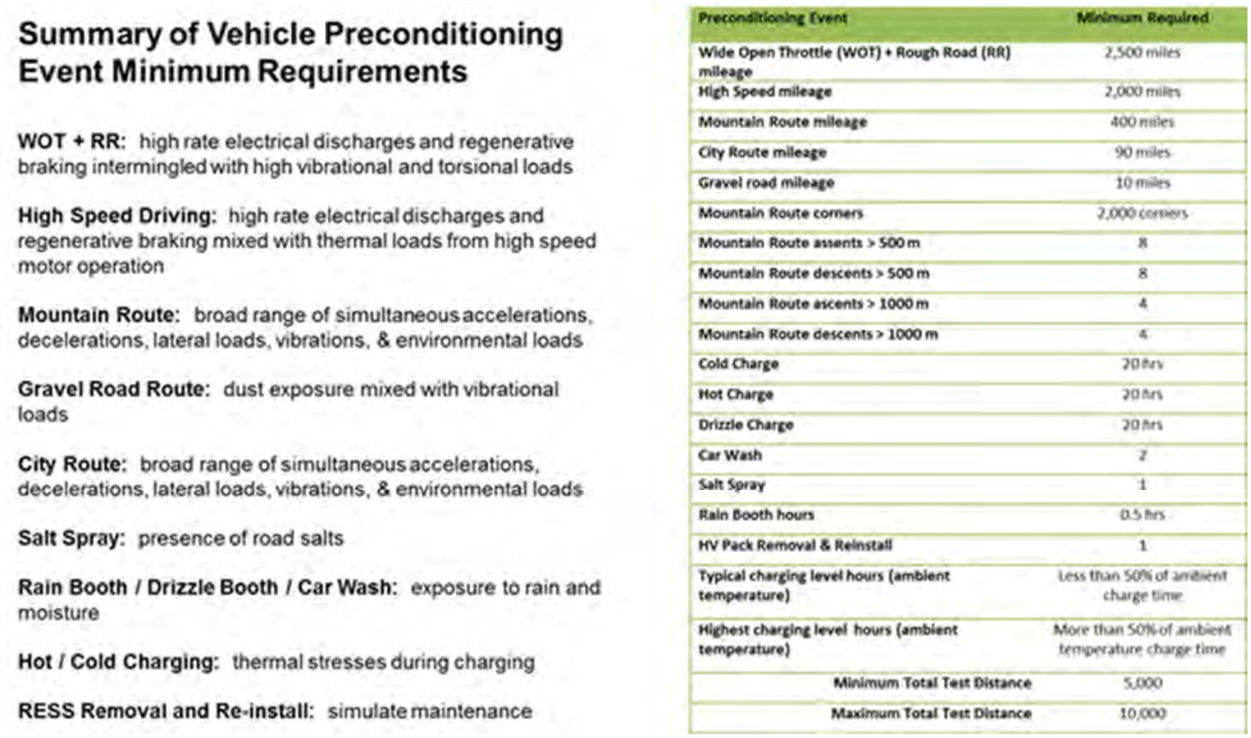
Approach

RESS cells and associated components are subject to aging mechanisms that can affect their performance, including safety. The intent of this test procedure is to ensure that the RESS components, particularly the battery cells, are robust enough to meet typical safety performance requirements after an aggressive aging sequence. The 5000 mile preconditioning sequence is intended to age the RESS with real-world electrical, mechanical, thermal, and environmental loads. Sequential testing is intended to validate RESS safety robustness after preconditioning.

Preconditioning. Although electrical cycling remains an important aging mechanism, a vehicle RESS is subject to a number of additional mechanical, thermal, and environmental aging mechanisms that affect safety. The simultaneous or intermingled application of these aging mechanisms are, therefore, importance for safety evaluation. For example, electrically charging a RESS with 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.

The preconditioning sequence is summarized in Figure 5. It mixes a large number of high acceleration driving patterns with some low acceleration factor driving patterns. Various charging conditions and environmental loads are applied throughout the sequence. The procedure was not rigidly defined because it is more important that representative preconditioning be applied to a RESS rather than a specific sequence. Thus, preconditioning was developed to be relatively non-burdensome to a testing agency and allows for variability between test facilities. Preconditioning events include:

- Route driving on rough, mountain, gravel, and city roads using proving ground tracks or public roads
- Charging events at different rates under various conditions (i.e., hot, cold, drizzle)
- Car washes, salt spray application, rain booth, and RESS removal/reinstallation



Summary of Vehicle Preconditioning Event Minimum Requirements

WOT + RR: high rate electrical discharges and regenerative braking intermingled with high vibrational and torsional loads

High Speed Driving: high rate electrical discharges and regenerative braking mixed with thermal loads from high speed motor operation

Mountain Route: broad range of simultaneous accelerations, decelerations, lateral loads, vibrations, & environmental loads

Gravel Road Route: dust exposure mixed with vibrational loads

City Route: broad range of simultaneous accelerations, decelerations, lateral loads, vibrations, & environmental loads

Salt Spray: presence of road salts

Rain Booth / Drizzle Booth / Car Wash: exposure to rain and moisture

Hot / Cold Charging: thermal stresses during charging

RESS Removal and Re-install: simulate maintenance

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

Figure 5 - Vehicle preconditioning requirements.

Sequential testing. The vehicle sequential tests are designed to evaluate the robustness of a RESS by applying normal and expected stresses after accelerated aging. The tests were selected based on widely accepted standards that represent commonly experienced single point failure modes. They were placed in a sequence that not only reduces the number of required test articles, but also reveals and exacerbates a range of failure modes. The RESS should be able to withstand the applied abuse and failure conditions without posing a hazard to the vehicle occupant or the surrounding environment. The specific test sequence is as follows:

1. Vehicle charge and discharge during low temperature conditions: failed heating system
2. Vehicle charge and discharge during high temperature conditions: failed cooling system
3. Over-discharge
4. Overcurrent overcharge
5. Overvoltage overcharge
6. External short circuit
7. Destructive discharge

A DC link is required for the RESS over-discharge, overcurrent overcharge, overvoltage overcharge, and external short circuit tests. A variety of devices can be connected to the DC link to achieve the required electrical conditions. Appropriate connections between the RESS and DC link is based on the vehicle and may require assistance from the manufacturer.

The destructive discharge requirement of sequential testing is intended to ensure that a method exists to remove "stranded energy" from a RESS; it is not a stress test. If electrical discharge at the system or component level is not sufficient to fully discharge a RESS, a destructive discharge method that can be effective for Li-ion battery packs is the salt bath method, where the system is submerged in a salt water solution.

Test Verification

DC link connections were demonstrated for three EV models. The batteries consisted of small cylindrical cells (Manufacturer A), hard case prismatic cells (Manufacturer B), and large pouch cells (Manufacturer C). Additionally, the Manufacturer A vehicle was used to verify and demonstrate the preconditioning and sequential test procedures. Total preconditioning distance was 8,416 miles. For sequential testing, there was no evidence of smoke or fire and cabin tenability remained uncompromised. The RESS was then subjected to a salt water bath; it was demonstrated that destructive discharge should be conducted at an individual module level.

This test procedure was only verified with an EV. Although the approach is applicable, it has not been verified with HEVs and PHEVs.

Vehicle Water Immersion Test

Goal

- Submerge a test vehicle in a conductive liquid (i.e., seawater) and observe the system reaction both during immersion and for an extended period after immersion.

Safety Metric

- Assess the potential hazards to the vehicle occupant and bystanders from full-scale vehicle immersion.

Approach

Seawater immersion is a reasonably foreseeable hazard due to accidents or natural disasters. The purpose of this procedure is to evaluate the potentially hazardous reactions of low voltage (LV) and high voltage (HV) components of a RESS-based vehicle while a) submerged in a conductive seawater solution and b) during the storage period afterwards. The procedure is composed of four parts:

- Pre-immersion: equipment and sensor setup
- Immersion: submerging the test vehicle in seawater within 10 minutes
- Extraction: pumping out the seawater within 10 minutes after 2 hours of immersion
- Post-extraction: observing the RESS behavior for a specified storage period

Vehicle immersion is a potentially abusive test that determines if the RESS and fundamental safety systems continue to function and not pose a significant hazard to the vehicle's occupants or bystanders.

The test vehicle is first instrumented to detect loss of isolation and closure of contactors. Other sensors include voltage and temperature monitors on both the LV and HV batteries. The vehicle cabin as also instrumented with gas sensors to detect the presence of hydrogen, methane, and chlorine. Sensors record data at specified rates for the duration of the test, including the 2-hour immersion period and the post-extraction observation period. Samples of the seawater are taken before and after the 2-hour immersion period to analyze the pH, density and conductivity; samples are also used to test for the presence of lower molecular weight volatile organic compounds as well as the total oil and grease content.

Seawater immersion is performed in a watertight container large enough to accept a test vehicle with its doors open. High capacity water pumps are used to transfer the conductive liquid (salt water) from the storage tank to the specified fill level in approximately 10 minutes. The same high capacity water pumps are used to remove the conductive liquid from the container at the end of the 2-hour immersion period.

The post-extraction period is conducted with the vehicle remaining in the immersion container. The duration of this step is at least 28 days (or sooner if a hazardous electrical or fire event occurs) since the longest known rest period after vehicle impact testing leading to fire is 3 weeks from the Chevrolet Volt battery incident (i.e., DOT HS 811 573).

Test Verification

Immersion testing was conducted with 12 vehicle models consisting of HEVs, PHEVs, and EVs. Six of the vehicles were tested in winter conditions (i.e., an average ambient temperature of approximately -8°C). However, a wide range of vehicle responses were observed. One vehicle suffered short circuits internal to the pack and loss of isolation leading to a thermal event. Thus, a second round of testing was performed in late summer conditions (i.e., an average ambient temperature of approximately 19°C). This group of vehicles resulted in minimal loss of voltage and isolation.

Vibration with Thermal Cycling Test

Goal

- Evaluate robustness of RESS safety architecture to multi-axis vibration profiles and shock tests with thermal variations.

Safety Metric

- Ranked safety performance metric based on a set of acceptance criteria and evaluation tolerances.

Approach

The RESS is subject to both vibration and temperature excursions over the lifetime of the vehicle. The purpose of this testing is to assess RESS safety and robustness from an electrical and mechanical standpoint based on various multi-axis vibration profiles with thermal variations and shock tests. Vibration, shock, and thermal cycling are generally non-destructive tests that subject a RESS to stresses that are typical of real world environmental conditions. The RESS is rated for safety based on isolation resistance, temperature rise, voltage drift, structural damage, and capacity loss. The test sequence is as follows:

- Step 1: Sine Sweep Test
- Step 2: Mechanical Shock Test
- Step 3: Sine Sweep Test (repeated)
- Step 4: Random Vibration Test
- Step 5: Sine Sweep Test (repeated)

Vibration and mechanical shock profiles are conducted in three orthogonal axes, referred to as X, Y, Z. The RESS mounting and support structure (fixture) shall be as similar as possible to the manufacturer's recommended installation requirements for all vibration and mechanical shock tests. The fixture shall keep the RESS from direct contact with any point of the vibration exciter. At a minimum, the fixture shall hold the RESS with the same level of rigidity as the vehicle. The fixture shall not have any resonances below 50 Hz. It shall be designed and built to allow removal from the vibration exciter for repositioning the RESS in each of the three orthogonal axes without having to remove the RESS from the fixture itself.

The purpose of the sine sweep test is to find any resonances in the RESS which could lead to potential mechanical failure under normal operating vibration conditions. It consists of a 1 gn constant acceleration value applied over a frequency range of 10 to 1000 Hz with a sweep rate of 1 octave/min. This test is repeated after the mechanical shock and random vibration tests to ensure that identified resonances from the initial sine sweep have not changed. Resonance changes after mechanical shock and random vibration may indicate a potential mechanical change or damage within the RESS.

The purpose of the mechanical shock test is to ensure proper isolation between the energy cells, enclosure, and any other devices placed within RESS. A half-sine pulse is applied at a 25 gn acceleration for 15 ms. The shock test is performed three times per axis (X, Y, Z) on both the positive and negative directions for a total of 18 tests.

The purpose of the random vibration test is to ensure that the DUT can be considered safe for use in a typical light vehicle transportation scenario. It is performed in conjunction with a temperature profile that varies between -40 and 85°C with relative humidites or 45 and 85%. The total test duration is dependent on the stabilization time of the RESS, which is determined from a thermal cycle profile development test that is performed prior to the start of the vibration test sequence.

RESSs subjected to this test procedures are compared based on a safety star rating system, which is an improvement over the existing pass/fail criteria in existing standards. The performance is categorized based on a color coding and star system. It is assigned a certain color code for each measurable data point. The color code sequence is as follows:

- Red: evaluation tolerance was not met (any red evaluation means that the RESS does not meet the acceptance criteria and is deemed unsafe).
- Yellow: evaluation tolerance was within acceptance criteria but deviation was recorded.
- Green: evaluation tolerance was within acceptance criteria.

Acceptance criteria include the following metrics:

- Isolation resistance
- Temnperature
- Voltage drift (change in SOC)
- Structural damage

A peer review of the draft test procedure was conducted by the authors of a Millbrook Electric Vehicle Battery Vibration Research Study, who are now affiliated with University of Warwick in UK.

Verification

While there were safety elements that might have been observed during vibration testing, such as loss of isolation, they were only indirectly related to battery safety. As a result, battery pack vibration and thermal cycling verification testing was not pursued.

BMS FAILURE MODE TEST: DC CHARGING INTERFACE

Test Procedure and Report

1. PURPOSE

Electric propulsion in a Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV) and Electric Vehicle (EV) platform relies on Rechargeable Energy Storage Systems (RESSs), commonly referred to as batteries. However, 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 that are different than those associated with an internal combustion engine. The purpose of this test procedure is to evaluate the potential failure modes associated with the battery management system (BMS) interfaces to a DC charging system for a variety of configurations. The tests simulate real world fault conditions that can occur before, during, and after DC charging. The BMS reaction to those fault conditions is used to assess the risk of harm to the operator and the vehicle system. Ideally, the BMS will rapidly identify the fault condition and transition the RESS to a safe state.

2. SCOPE

This test procedure is applicable to all RESS-equipped vehicles that require a plug-in connection (i.e., PHEV and EV platforms). The scope includes a description of various potential failure modes, the required steps to create or simulate each failure condition, and how to observe and measure the system response. Each failure mode test specifies the required limits (e.g., temperatures, battery SOC levels, etc.) and boundary conditions. Pass/fail criteria for the system response, system limit conditions, measurement criteria and metrics are also identified for each test.

Several tests in this procedure require the use of a breakout box that interfaces between the DC charger and the vehicle (see Section 5.4.1.3). The breakout box shall be located at a sufficient distance from the vehicle and charger to enable a test technician to safely introduce fault conditions both before and during an active charge session. The fault conditions are introduced through a specific sequence of switches that are defined in each relevant test procedure. The breakout box also includes test points (**TP1** through **TP6**) to measure voltages during active testing.

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 the Society of Automotive Engineeres (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 J1113 Electromagnetic Compatibility Measurement Procedures and Limits
- SAE J1715 Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) Terminology
- SAE J1739 Potential Failure Mode and Effects Analysis in Design (Design FMEA), Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA)
- SAE J1766 Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing
- SAE J1772 Recommended Practice for SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler
- SAE J1797 Recommended Practice for Packaging of Electric Vehicle Battery Modules
- SAE J1908 Electrical Grounding Practice
- SAE J2293 Energy Transfer System for Electric Vehicles—Part 2: Communication Requirements and Network Architecture
- SAE J2464 Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing
- SAE J2847 Communication Between Plug-in Vehicles and Off-Board DC Chargers
- SAE J2929 Electric and Hybrid Vehicle Propulsion Battery System Safety Standard - Lithium-based Rechargeable Cells
- SAE J2931/3 PLC Communication for Plug-in Electric Vehicles
- SAE J2950 Recommended Practices (RP) for Transportation and Handling of Automotive-type Rechargeable Energy Storage Systems (RESS)
- SAE J2953 Plug-In Electric Vehicle (PEV) Interoperability with Electric Vehicle Supply Equipment (EVSE)

3.1.2 IEC Publications

Available from the International Electrotechnical Commission (IEC): 446 Main Street 16th Floor, Worcester, MA 01608, Tel: 508-755-5663, www.iec.ch.

- IEC 62660-2 Reliability and abuse testing for lithium-ion cells
- IEC 61010 Safety requirements for electrical equipment for measurement, control and laboratory use

3.1.3 ISO Publications

Available from International Standards Organization (ISO) Central Secretariat: 1, ch. de la Voie-Creuse CP 56, CH-1211 Geneva 20 Switzerland, Tel.: +41-22-749-01-11, www.iso.org.

- ISO 6469-1 Electrically propelled road vehicles – Safety specifications – Part 1: On-board rechargeable energy storage system (RESS)

- ISO 6469-3 Electrically propelled road vehicles – Safety specifications – Part 3: Electrical safety

- ISO 12405-1 Electrically propelled road vehicles – Test specification for lithium-ion traction battery packs and systems – Part 1: High-power applications

- ISO 12405-2 Electrically propelled road vehicles – Test specification for lithium-ion traction battery packs and systems – Part 2: High-energy applications

- ISO 16750-2 Road vehicles – Environmental conditions and testing for electrical and electronic equipment

3.1.4 UL Publications

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

- UL 2580 Batteries for Use in Electric Vehicles

3.1.5 US DOT Publications

Available from the United States Department of Transportation (US DOT) National Highway Traffic Safety Administration (NHTSA): 1200 New Jersey Avenue, SE West Building Washington, DC 20590, Tel: 202-366-4000, www.nhtsa.gov.

- Federal Motor Vehicle Safety Standards (FMVSS) 305 Electric Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection

- DOT HS 811 574 Interim Guidance for Electric and Hybrid-Electric Vehicles Equipped With High Voltage Batteries

- NHTSA Test Procedure TP-581-01 – Bumper Standard

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 NFPA Publications

Retrieved from the National Fire Protection Association (NFPA): http://www.evsafetytraining.org/resources.aspx.

- Alternative Fuel Vehicles Safety Training

3.2.2 ANSI Publications

Retrieved from the American National Standards Institute (ANSI): http://publicaa.ansi.org/sites/apdl/evsp/ANSI_EVSP_Roadmap_May_2013.pdf.

- Standardization Roadmap for Electric Vehicles, Version 2.0

4. DEFINITIONS

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

Active Protection Device

Safety device consisting of a sensor and actuator that protects or mitigates abusive, out-of range conditions experienced by the RESS.

Ambient Temperature

The air temperature surrounding the RESS. Unless otherwise specified, the ambient temperature shall be 25±5°C.

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 Management System / Unit (BMS / BMU)

Electronic components that monitor and/or control battery functions such as charge and discharge operations. It calculates and communicates battery status and state of function to the vehicle system for energy flow management. In the event of a system failure, the BMS can also open contactors and isolate the battery from the rest of the hybrid system.

Breakout Box

An interface between the vehicle charge coupler and the DC charger that allows the test technician to introduce various failure modes that can occur before, during and after DC charging.

Diagnostic Trouble Code (DTC)

An alpha-numeric code that is issued by the vehicle onboard diagnostic system to indicate a specific fault condition. A DTC is activated when the system detects behavior outside the specified limits of operation.

EV: Electric Vehicle

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

Ground Fault

A condition where one pole of the DC bus has continuity with ground. This type of fault represents a dangerous condition that can be hazardous if not detected.

Personal Protective Equipment (PPE)

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

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.

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.

Safe State of the System

A condition of the vehicle and charger system that contains high voltage within the designated boundaries and protects the operator from getting harmed under any system condition (i.e., fault or no fault).

State of Charge (SOC)

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

5. GENERAL TEST REQUIREMENTS

5.1 General Precautions

5.1.1 When working on or around high voltage (HV) systems, always follow the appropriate safety precautions. For the vehicle/system under test, read and follow the recommended service procedures on high voltage systems and parts.

5.1.2 Be sure to wear the appropriate personal protective equipment (PPE), which includes Class 0 insulated rubber gloves with leather outer gloves. Always inspect the insulated gloves for any defects that might prevent the insulating properties and do not wear them if they are damaged.

5.1.3 Always observe HV warning labels (see Figure 1 for examples).

Figure 1 - Example high voltage warning labels (source: GM First Responder Guide).

5.2 Test-Specific Precautions

5.2.1 While working on a vehicle system, always ensure that the emergency parking brake is actuated. Additionally, block the drive wheels to prevent unintended vehicle movement.

5.3 Safety Requirements

5.3.1 Portions of this test procedure involve the manipulation of HV connections and the introduction of ground faults that can be dangerous to the test technician. Appropriate PPE to isolate the test operator from HV contact is required at all times when interacting with high voltage components. Use high voltage insulated tools and always wear eye protection (e.g., face shield) while setting up and performing these tests. Wear appropriate isolation gloves while working on high voltage systems or the breakout box.

5.3.2 The work shall be performed in a well-ventilated area to allow the safe removal of any smoke or toxic gases. Appropriate fire extinguishing equipment shall be available and easily accessible at all times during the test execution.

5.4 Test Facility/ Equipment Requirements

5.4.1 The following equipment is required to conduct the tests defined in this procedure. The test equipment shall fulfill the general requirements outlined below.

5.4.1.1 The facility must have a thermal chamber or temperature-controlled area for thermal soaking of the vehicle to a temperature of 25±5°C (see Section 5.8).

5.4.1.2 The facility must have a DC fast charger with a voltage range of 0-600 V_{DC} and a power range of ≤100 kW or a battery test system that can be used for DC charging (e.g., a BTS-320). See Figure 2, left side.

5.4.1.3 The facility must have a breakout box that interfaces between the DC fast charger and the test vehicle (see Figure 2, middle). The breakout box consists of toggle switches to initiate faults and internal fuse protection (see Figure 3). Note that test resistance R1, which is between **TP3** and **TP4**, should be easily accessible since its value changes during some test sequences (e.g., see Section 6.2.5).

5.4.1.4 The facility must have an HV meter to measure DC voltage from 0-600 V with a minimum safety classification of CAT III according to IEC 61010 (e.g., a Fluke 189).

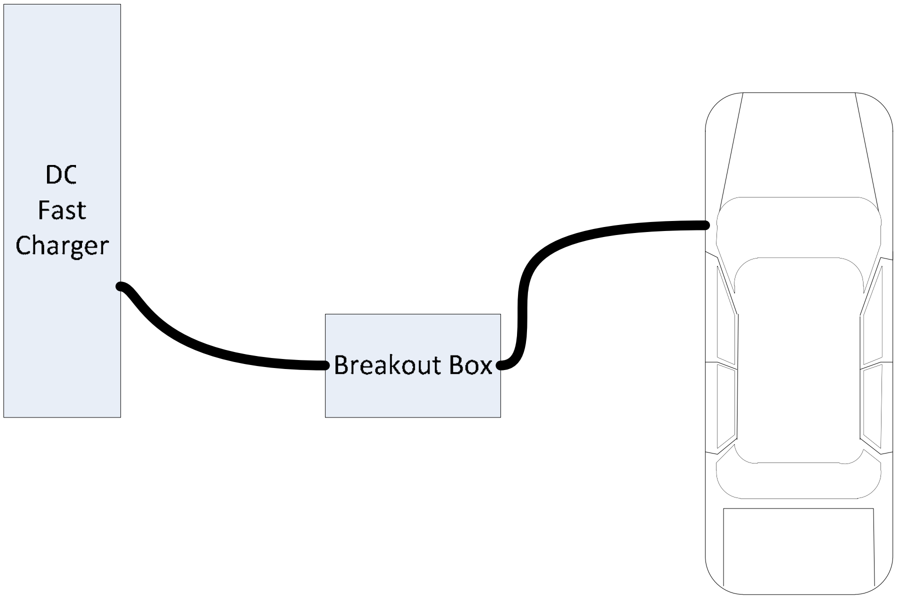


Figure 2 - DC fast charge configuration with breakout box connection.

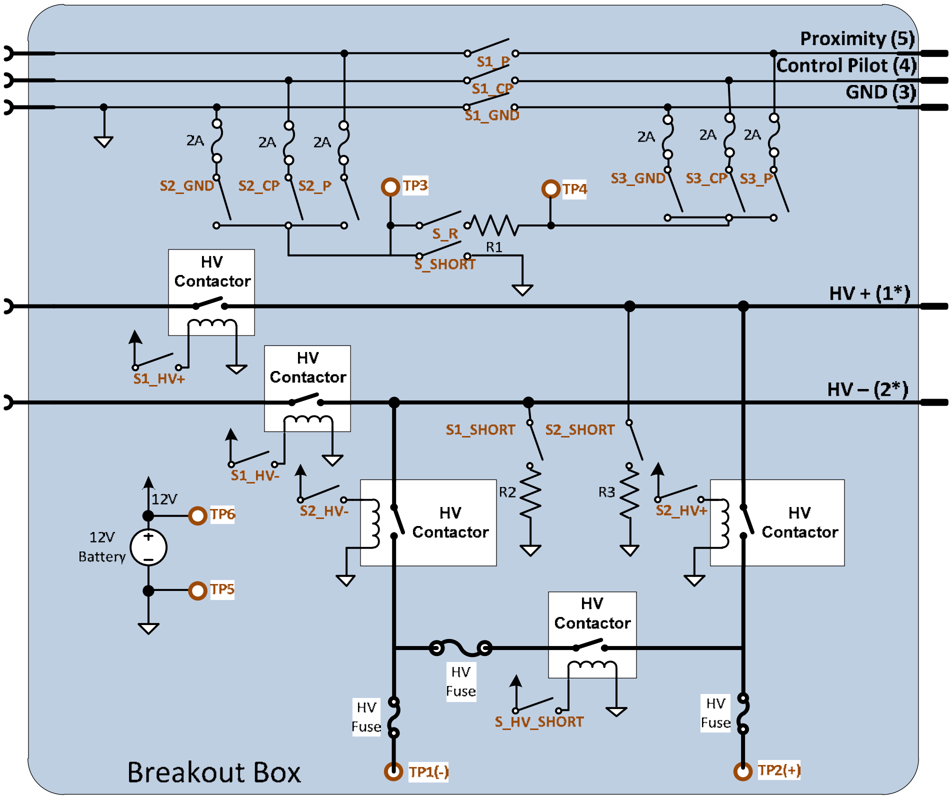


Figure 3 - DC fast charge breakout box schematic.

5.4.1.5 The facility must have an HV insulation tester with a minimum safety classification of CAT III according to IEC 61010 to measure the insulation between HV circuits and chassis/earth ground (e.g., a Fluke 1503).

5.4.1.6 The facility must have a vehicle-specific scan tool to read and clear diagnostic trouble codes (DTC).

5.4.1.7 The facility must have a short circuit protected HV power supply that is diode protected against backfeeding (e.g., a Magna-Power SL600-2.5).

5.4.1.8 The facility must have a short circuit protected low voltage power supply with voltage regulation from 24 V down to 0 V with a minimum power of 1200 W (e.g., a Sorensen XFR 33-85).

5.4.1.9 The facility must have a 12 V switchable load with a minimum current draw of 20 A at 12 V, (e.g., an automotive fan or pump).

5.4.1.10 The facility must have a CAN communication tester/monitor with the ability to generate error frames at a defined rate (e.g., a Vector CANalyzer).

5.5 Test Equipment Calibration

5.5.1 A written calibration procedure shall be provided that includes, at a minimum, the following information for all measurement and test equipment:

- Type of equipment, manufacturer, model number, etc.
- Measurement range
- Accuracy
- Calibration interval
- Type of standard used (calibration traceability of the standard must be evident)

5.6 Device Under Test

5.6.1 The device under test (DUT) is a complete RESS-based vehicle and DC charger system.

5.7 Test Guidelines

5.7.1 Testing shall be conducted on representative RESSs from vehicles that are capable of interfacing with a DC charger. Test samples should represent vehicle fleets having identical fit, form, function, and similar usage profiles. The RESS shall remain installed in the vehicle and not require any special modifications or alterations for this test procedure. All vehicle modifications for measurement access shall not alter the overall system configuration (e.g., access to the CAN bus shall be with a wire connection that is as short as possible to prevent the electrical alteration of the CAN bus configuration).

5.8 Test Parameters

5.8.1 Test parameters are as follows:

- Beginning Test Temperature: 25±5°C unless otherwise specified
- Beginning SOC: 45% to 50% SOC unless otherwise specified; if the SOC exceeds 80% SOC during testing, the RESS shall be reset to approximately 50% SOC using the procedure specifed in Section 5.9.3.
- 12 V System Voltage (Beginning of Test): 12.8±0.5 V
- Observation Period (End of Each Test): At least 1 hour at 25±5°C

5.9 DUT Preconditioning

5.9.1 The RESS shall be inspected using the manufacturer recommend service tool to retrieve any stored fault codes. No fault codes shall be present prior to testing.

5.9.2 The vehicle shall be soaked at ambient temperature for a sufficient time to ensure internal battery cell temperature has achieved ambient temperature conditions (±5°C). Depending on the vehicle installation and setup, the soak time can be up to 48 hours under constant ambient conditions without exposure to sun load or other heat sources.

5.9.3 A battery discharge to the specified minimum SOC, followed by a complete charge to the specified maximum SOC, shall be conducted to verify proper system operation prior to testing. The RESS shall then be discharged to approximately 50% SOC using the manufacturer recommended procedure prior to failure mode testing, as specified in Section 5.8.1.

5.9.4 The charge plug and the vehicle receptacle shall be visually inspected to determine if there are any incompatibilities; resolve incompatibility issues as necessary prior to testing. Look for any debris, mechanical damage, abrasions, distortions and/or discolorations.

6. TEST PROCEDURES

6.1 Ground Fault Tests

6.1.1 Purpose

6.1.1.1 The purpose of this test is to introduce a ground fault or a loss of ground connection between the vehicle charge port and the charger.

6.1.2 Rationale and Description

6.1.2.1 A ground fault can happen due to contamination (moisture, dust, etc.), an internal failure of insulation, or cable insulation breakdown due to excess temperature or abrasion.

6.1.2.2 Failure to detect a ground isolation fault can be from the BMS or charger being in the wrong operating mode, an impaired or lost connection of the BMS to reference ground, or an internal malfunction of the BMS.

6.1.2.3 The ground connection should be established through a 30 kΩ resistor or higher to prevent system harm should the BMS protection mechanisms fail. The 30 kΩ value was chosen so that all possible HV systems down to 60 V are able to detect the fault without drawing excessive current and causing damage (note that the fault threshold for a 60 V system would be 30 kΩ / 60 V = 500Ω/V). Resistor values lower than 30 kΩ are not advisable given the high heat generation of an HV system (e.g., 600 V), especially with the potential power loss of a dual fault condition (i.e., when the system already has an undetected fault on one HV line to ground prior to testing). At 600 V, the power loss is 600 V * 600 V / 30 kΩ = 12 W.

6.1.2.4 This test will determine the reaction of the BMS to the following conditions: a) a loss of ground connection, b) a fault on the ground connection between the vehicle charge port and the charger, and c) a loss of isolation to ground during a DC charge. The test conditions shall be applied both before a charge session is initiated and during an active charge session to determine the effects of different charging modes.

6.1.2.5 The ground connection is established through switches **S1_SHORT** and **S2_SHORT** on the breakout box (see Figure 4). When activated, the switches introduce a ground fault through R2 and R3, respectively. The resistance values should be 30 kΩ or higher to prevent system harm should the BMS protection mechanisms fail (see Section 6.1.2.3).

6.1.3 Sample Preparation

6.1.3.1 This test requires a DC charger and a breakout box.

6.1.3.2 Appropriate resistance values for R2 and R3 should be integrated into the breakout box (see Figure 4).

6.1.3.3 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with ground fault testing if an isolation fault is detected.

6.1.4 Equipment Setup

6.1.4.1 Connect the DC charger to the vehicle charge port through the breakout box as shown in Figure 4.

6.1.4.2 Configure the breakout box to perform the ground fault test with the initial switch setting defined in Table 1.

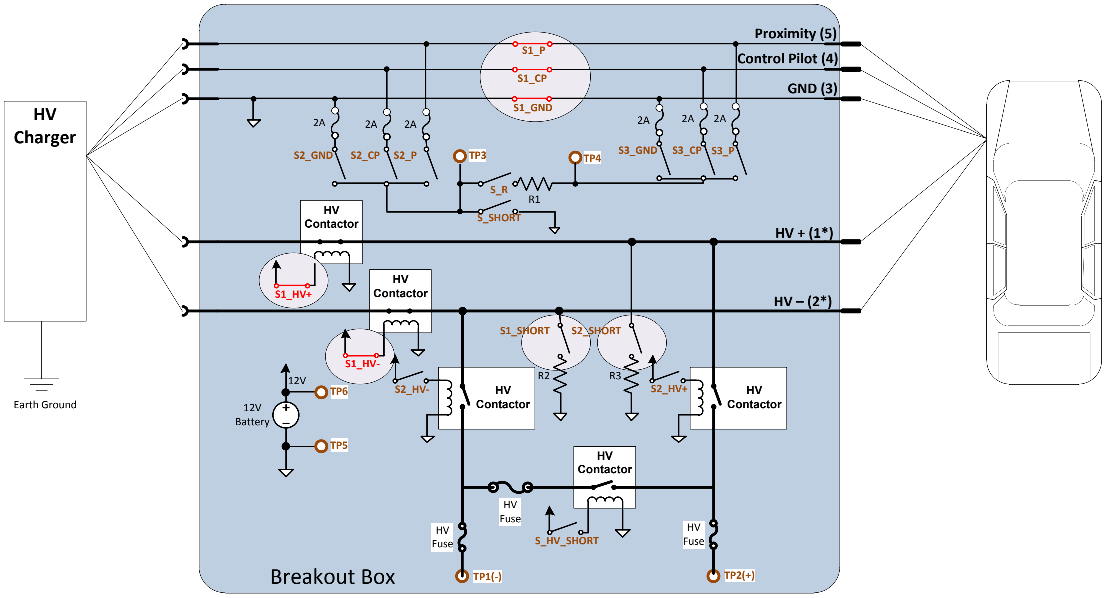


Figure 4 - Initial breakout box configuration for ground fault tests.

Table 1 - Initial Switch Configuration for Ground Fault Tests

Switch	Setting	Switch	Setting	Switch	Setting
S1_P	Closed	**S3_P**		**S2_SHORT**	
S1_CP	Closed	**S3_CP**		**S1_HV+**	Closed
S1_GND	Closed	**S3_GND**		**S1_HV-**	Closed
S2_P		**S_R**		**S2_HV+**	
S2_CP		**S_SHORT**		**S2_HV-**	
S2_GND		**S1_SHORT**		**S_HV_SHORT**	
Green:	Closed as part of the initial configuration				
Yellow:	Switches manipulated during the test				

6.1.5 Test Method and Procedure

6.1.5.1 Faults introduced before a charge session is initiated:

Fault to Ground – DC Positive

1. Introduce a short between the DC positive and the ground connection at the breakout box by **closing** switch **S2_SHORT**.
2. Attempt to start a charge session.
3. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
4. If necessary, stop the charge session.
5. Remove the short between the DC positive and the ground connection by **opening** switch **S2_SHORT**.
6. If necessary, clear all vehicle faults and do a key cycle.
7. Reset the faults on the charge station as needed.

Fault to Ground – DC Negative

1. Introduce a short between the DC negative and the ground connection at the breakout box by **closing** switch **S1_SHORT**.
2. Attempt to start a charge session.
3. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
4. If necessary, stop the charge session.
5. Remove the short between the DC negative and the ground connection by **opening** switch **S1_SHORT**.
6. If necessary, clear all vehicle faults and do a key cycle.
7. Reset the faults on the charge station as needed.

Fault – Ground Connection Between Station and Vehicle Removed

1. Remove the ground connection between the DC fast charge station and the vehicle at the breakout box by **opening** switch **S1_GND**.
2. Attempt to start a charge session.
3. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.

4. If necessary, stop the charge session.
5. Restore the ground connection by **closing** switch **S1_GND**.
6. If necessary, clear all vehicle faults and do a key cycle.
7. Reset the faults on the charge station as needed.

6.1.5.2 Faults introduced during a fast charge session:

Fault to Ground – DC Positive

1. Start a charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Introduce a short between the DC positive and the ground connection at the breakout box by **closing** switch **S2_SHORT**.
4. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
5. If necessary, stop the charge session.
6. Remove the short between the DC positive and the ground connection by **opening** switch **S2_SHORT**.
7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.

Fault to Ground – DC Negative

1. Start a charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Introduce a short between the DC negative and the ground connection at the breakout box by **closing** switch **S1_SHORT**.
4. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
5. If necessary, stop the charge session.
6. Remove the short between the DC negative and the ground connection by **opening** switch **S1_SHORT**.
7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.

Fault – Ground Connection Between Station and Vehicle Removed

1. Start a charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Remove the ground connection between the DC fast charge station and the vehicle at the breakout box by **opening** switch **S1_GND**.
4. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
5. If necessary, stop the charge session.
6. Restore the ground connection by **closing** switch **S1_GND**.

7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.

6.1.6 End of Test Procedure

6.1.6.1 Disconnect the vehicle from the breakout box.

6.1.6.2 Disconnect the charger from the breakout box.

6.1.7 Data Acquisition and Documentation

6.1.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage. Measurements from the charging station can include target voltage, output voltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.1.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.1.7.3 For all test conditions (Section 6.1.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger.
- Document any faults and/or DTCs on the vehicle/BMS.
- Document any faults and/or DTCs on the DC fast charge station.

6.1.8 Pass/Fail Evaluation Criteria

6.1.8.1 For faults introduced before a charge session is initiated, the pass/fail evaluation criteria are as follows:

- The system shall not start the charge session and the system shall remain in a safe state.
- As appropriate, the system shall set a fault code to identify the problem.

6.1.8.2 For faults introduced during a fast charge session, the pass/fail evaluation criteria are as follows:

- The system shall stop or abort the charge session and bring the system to a safe state.
- As appropriate, the system shall set a fault code to identify the problem.

6.2 Chassis Ground Offset Tests

6.2.1 Purpose

6.2.1.1 The purpose of this test is to introduce an offset on the ground connection between the vehicle charge port and the charger.

6.2.2 Rationale and Description

6.2.2.1 The ground between the charge station and the vehicle can become degraded from increased resistance due to poor connections or conductor failure. This condition can result in communication stress (signal offset), causing partial or complete loss of communication. The pilot and proximity signals and/or CAN communication signals can also be impaired.

6.2.2.2 This test will determine the reaction of the vehicle and charger to an offset in the ground connection. The test conditions shall be applied both before a charge session is initiated and during an active charge session to determine the effects of different charging modes.

6.2.2.3 The offset in the ground connection is established through switch **S_R** on the breakout box (see Figure 5). When activated, this switch introduces an offset through R1. Multiple values of R1 are used to evaluate the system behavior at various ground offset levels.

6.2.3 Sample Preparation

6.2.3.1 This test requires a vehicle charger and a breakout box.

6.2.3.2 R1 resistor values of 1 kΩ, 100Ω, 47Ω, and 24Ω shall be available to insert into the breakout box during testing (see Figure 5).

6.2.3.3 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with chassis ground offset testing if an isolation fault is detected.

6.2.4 Equipment Setup

6.2.4.1 Connect the DC charger to the vehicle charge port through the breakout box as shown in Figure 5.

6.2.4.2 Configure the breakout box to perform the chassis ground offset test with the initial switch setting defined in Table 2.

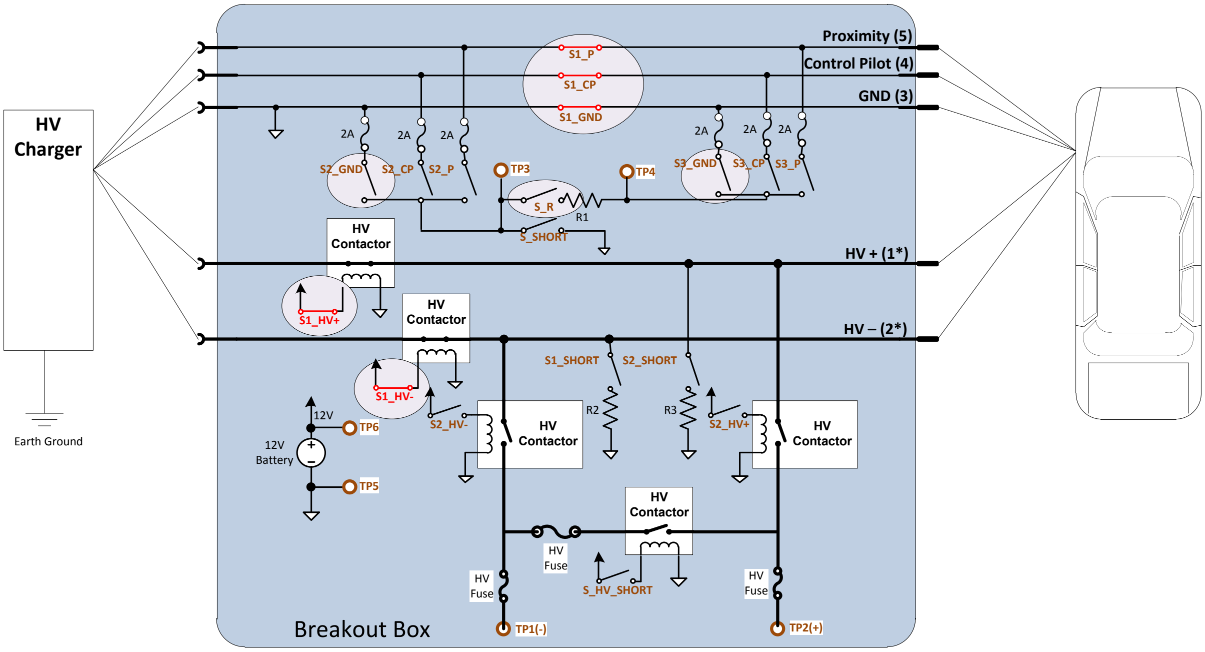


Figure 5 - Initial breakout box configuration for chassis ground offset tests.

Table 2 - Initial Switch Configuration for Chassis Ground Offset Tests

Switch	Setting	Switch	Setting	Switch	Setting
S1_P	Closed	**S3_P**		**S2_SHORT**	
S1_CP	Closed	**S3_CP**		**S1_HV+**	Closed
S1_GND	Closed	**S3_GND**		**S1_HV-**	Closed
S2_P		**S_R**		**S2_HV+**	
S2_CP		**S_SHORT**		**S2_HV-**	
S2_GND		**S1_SHORT**		**S_HV_SHORT**	

Green: Closed as part of the initial configuration

Yellow: Switches manipulated during the test

6.2.5 Test Method and Procedure

6.2.5.1 Faults introduced before a charge session is initiated:

Chassis Ground Offset

1. Set the value of R1 to 1 kΩ on the breakout box.
2. Introduce R1 between the vehicle and charger ground connections by **closing** switches **S2_GND**, **S3_GND** and **S_R**.
3. Open the shorting bar connection between the vehicle ground and the charger ground by **opening** switch **S1_GND**, leaving only the connected resistance.
4. Measure the voltage between chassis ground and earth (station) ground (**TP4-TP5**). Record this as a pre-test value.
5. Attempt to start a charge session.
6. Measure the voltage between chassis ground and earth (station) ground (**TP4-TP5**). Record this value.

7. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
8. If necessary, stop the charge session.
9. Remove R1 by **opening** switches **S2_GND**, **S3_GND** and **S_R**.
10. Restore the shorting bar connection to ground by **closing** switch **S1_GND**.
11. If necessary, clear all vehicle faults and do a key cycle.
12. Reset the faults on the charge station as needed.
13. Repeat Steps 2 through 12 using R1 values of 100Ω, 47Ω, and 24Ω.

6.2.5.2 Faults introduced during a fast charge session:

Chassis Ground Offset

1. Set the value of R1 to 1 kΩ on the breakout box.
2. Start a normal charge session.
3. Wait for approximately 1 minute for the charge to initialize and stabilize.
4. Introduce R1 between the vehicle and charger ground connections at the breakout box by **closing** switches **S2_GND**, **S3_GND** and **S_R**.
5. Open the shorting bar connection between the vehicle ground and the charger ground by **opening** switch **S1_GND**, leaving only the connected resistance.
6. Measure the voltage between chassis ground and earth (station) ground (**TP4-TP5**). Record this value.
7. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
8. If necessary, stop the charge session.
9. Remove R1 by **opening** switches **S2_GND**, **S3_GND** and **S_R**.
10. Restore the shorting bar connection to ground by **closing** switch **S1_GND**.
11. If necessary, clear all vehicle faults and do a key cycle.
12. Reset the faults on the charge station as needed.
13. Repeat Steps 2 through 13 using R1 values of 100Ω, 47Ω, and 24Ω.

6.2.6 End of Test Procedure

6.2.6.1 Disconnect the vehicle from the breakout box.

6.2.6.2 Disconnect the charger from the breakout box.

6.2.7 Data Acquisition and Documentation

6.2.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage. Measurements from the charging station can include target voltage, output

voltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.2.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.2.7.3 For all test conditions (Section 6.2.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger.
- Document any faults and/or DTCs on the vehicle/BMS.
- Document any faults and/or DTCs on the DC fast charge station.
- Record all voltage measurements between the chassis ground and earth (station) ground (**TP4-TP5**).

6.2.8 Pass/Fail Evaluation Criteria

6.2.8.1 For faults introduced before a charge session is initiated, the pass/fail evaluation criteria are as follows:

- The system shall not start the charge session and the system shall remain in a safe state.
- As appropriate, the system shall also set a fault code to identify the problem.
- The voltage measured between the vehicle ground and the earth ground (**TP4-TP5**) shall be no more than 0.7 V per J1772-2012-10 for proper function of the pilot signal.

6.2.8.2 For faults introduced during a fast charge session, the pass/fail evaluation criteria are as follows:

- The system shall stop or abort the charge and bring the system to a safe state.
- As appropriate, the system shall also set a fault code to identify the problem.
- The voltage measured between the vehicle ground and the earth ground (**TP4-TP5**) shall be no more than 0.7 V per J1772-2012-10 for proper function of the pilot signal.

6.3 DC Bus Short Test

6.3.1 Purpose

6.3.1.1 The purpose of this test is to introduce a DC bus short in the vehicle charge coupler.

6.3.2 Rationale and Description

6.3.2.1 The vehicle charge coupler could have a short circuit due to tampering, frayed insulation, etc.

6.3.2.2 This test will determine the reaction of the BMS to a short circuit on the charge coupler prior to a charge session initiation. The BMS should safely detect the short on the coupler before the main charge session is initiated.

6.3.2.3 The DC bus short is established through switches **S2_HV-** and **S2_HV+** on the breakout box (see Figure 6). When activated, a fuse-protected short is introduced between the high voltage DC bus connector pins (HV+ and HV-). It is important to ensure that an appropriately-rated fuse is installed in the breakout box during this test.

6.3.3 Sample Preparation

6.3.3.1 This test requires a vehicle charger and a breakout box.

6.3.3.2 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with DC bus short testing if an isolation fault is detected.

6.3.4 Equipment Setup

6.3.4.1 Connect the DC charger to the vehicle charge port through the breakout box as shown in Figure 6.

6.3.4.2 Configure the breakout box to perform the DC bus short test with the initial switch setting defined in Table 3.

6.3.4.3 Test the fuse with an ohmmeter before testing to ensure it is not blown (**TP1-TP2**). Replace as necessary.

6.3.4.4 Record the resistance value of the intact fuse.

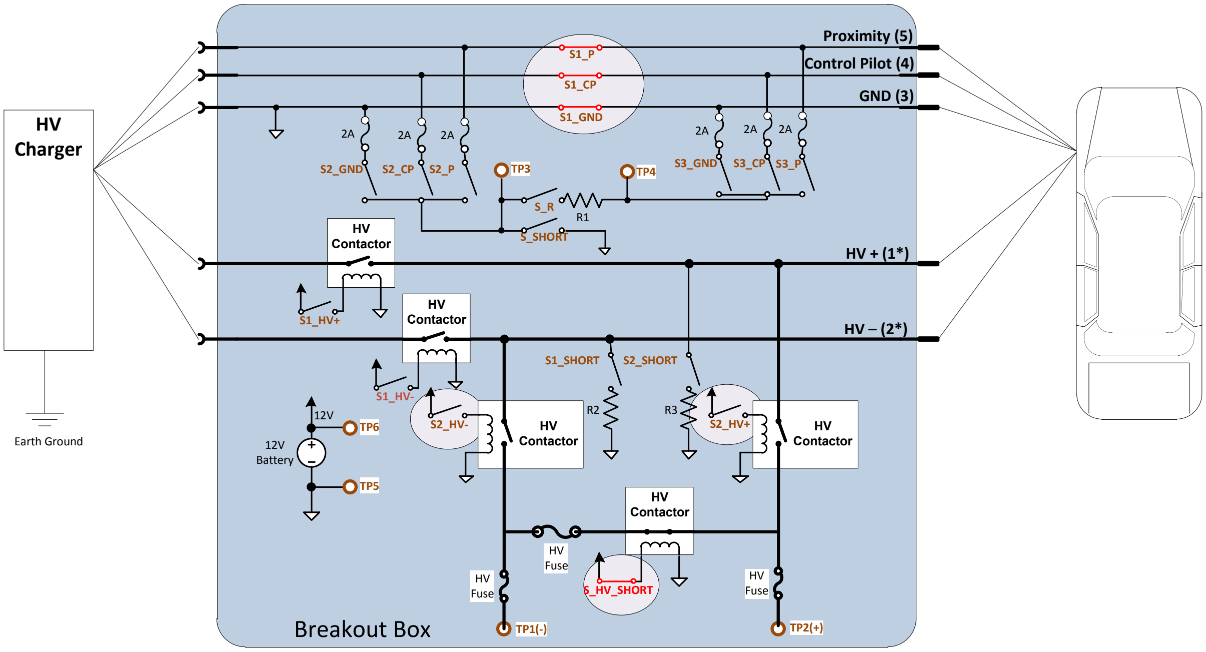


Figure 6 - Initial breakout box configuration for DC bus short test.

Table 3 - Initial Switch Configuration for DC Bus Short Test

Switch	Setting	Switch	Setting	Switch	Setting
S1_P	Closed	S3_P		S2_SHORT	
S1_CP	Closed	S3_CP		S1_HV+	
S1_GND	Closed	S3_GND		S1_HV-	
S2_P		S_R		S2_HV+	
S2_CP		S_SHORT		S2_HV-	
S2_GND		S1_SHORT		S_HV_SHORT	Closed

Green: Closed as part of the initial configuration

Yellow: Switches manipulated during the test

6.3.5 Test Method and Procedure

6.3.5.1 Faults introduced before a charge session is initiated:

DC Bus Short in the Charge Coupler

1. Introduce a fused short between the DC positive and DC negative at the breakout box by **closing** switch **S2_HV-** and **S2_HV+**.
2. Attempt to start a normal charge session.
3. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
4. If necessary, stop the charge session.
5. Remove the short by **opening** switch **S2_HV-** and **S2_HV+**.
6. Measure the resistance of the fuse with an ohmmeter to determine if it is blown (**TP1-TP2**).
7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.
9. If the fuse is blown, replace it and repeat Steps 1 through 8. If the fuse is not blown, record the resistance value.

6.3.6 End of Test Procedure

6.3.6.1 Disconnect the vehicle from the breakout box.

6.3.6.2 Disconnect the charger from the breakout box.

6.3.7 Data Acquisition and Documentation

6.3.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage. Measurements from the charging station can include target voltage, output voltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.3.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.3.7.3 For this test condition (Section 6.3.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger.
- Document any faults and/or DTCs on the vehicle/BMS.
- Document any faults and/or DTCs on the DC fast charge station.
- Record the resistance value of the fuse (**TP1-TP2**), both pre-test and post-test.

6.3.8 Pass/Fail Evaluation Criteria

6.3.8.1 For faults introduced before a charge session is initiated, the pass/fail evaluation criteria are as follows:

- The system shall not start the charge session and the system shall remain in a safe state.

- The fuse shall not be damaged.

6.4 DC Bus Held High Tests

6.4.1 Purpose

6.4.1.1 The purpose of this test is to simulate a vehicle DC bus being held high, which means that a potential high voltage is still present at the two charge connector pins.

6.4.2 Rationale and Description

6.4.2.1 A DC bus being held high can occur if the charger bus voltage decay after it disconnects from the vehicle is interrupted or if the bus voltage measurement does not match the actual bus voltage during the initial connection. DC bus voltage can also be held high if a faulty DC/DC converter is back feeding to the high voltage DC bus.

6.4.2.2 This test will determine the reaction of the vehicle and DC charging system to a DC bus being held high. The test conditions shall be applied both before a charge session is applied and after a charge session has ended.

6.4.2.3 The DC bus is held high with a high voltage power supply that is connected between test points **TP1(-)** and **TP2(+)** on the breakout box (see Figure 7). The power supply is diode protected to prevent negative current flow.

6.4.3 Sample Preparation

6.4.3.1 This test requires a vehicle charger, a breakout box, and an HV power supply with diode protection.

6.4.3.2 For safety reasons, the DC bus should not be kept high after a charge session is ended. Thus, this test also requires a capacitor with a parallel bleed down resistor to gradually reduce the voltage once the charge session is ended.

6.4.3.3 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with DC bus held high testing if an isolation fault is detected.

6.4.4 Equipment Setup

6.4.4.1 Connect the DC charger to the vehicle charge port through the breakout box as shown in Figure 7.

6.4.4.2 Attach the power supply's leads to the breakout box test points; the negative is connected to **TP1(-)** and the positive is connected to **TP2(+)**, see Figure 7.

6.4.4.3 Configure the breakout box to perform the DC bus held high test with the initial switch setting defined in Table 4.

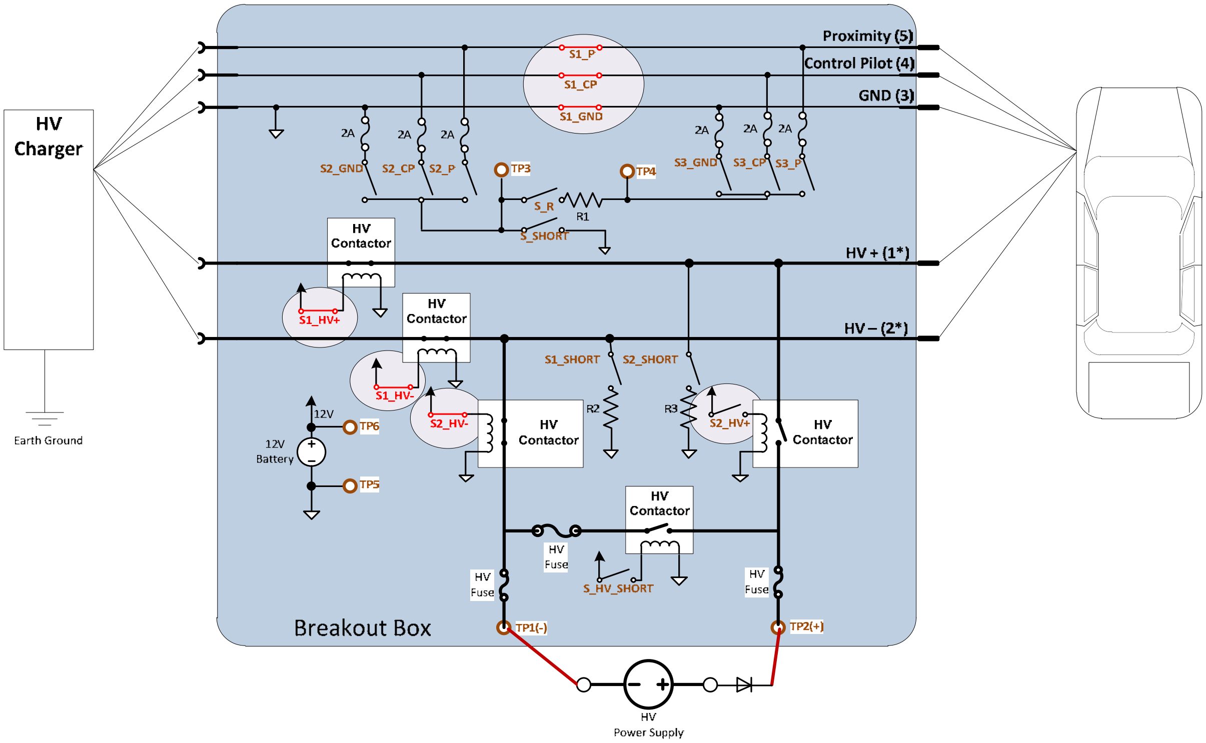


Figure 7 - Initial breakout box configuration for DC bus held high tests.

Table 4 - Initial Switch Configuration for DC Bus Held High Tests

Switch	Setting	Switch	Setting	Switch	Setting
S1_P	Closed	S3_P		S2_SHORT	
S1_CP	Closed	S3_CP		S1_HV+	Closed
S1_GND	Closed	S3_GND		S1_HV-	Closed
S2_P		S_R		S2_HV+	
S2_CP		S_SHORT		S2_HV-	Closed
S2_GND		S1_SHORT		S_HV_SHORT	
Green:	Closed as part of the initial configuration				
Yellow:	Switches manipulated during the test				

6.4.5 Test Method and Procedure

6.4.5.1 Faults introduced before a charge session is initiated:

DC Bus Held High

1. Set the power supply to voltage control mode with a current limit.
2. Set the voltage to 60 V_{DC} (+5/-0) and the maximum current to 1 A.
3. Connect the DC bus of the charge coupler to the HV power supply (diode protected to prevent negative current flow) at the breakout box by **closing** the switch **S2_HV+**.
4. Start a charge session.
5. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
6. If necessary, stop the charge session.
7. Remove the connection to the power supply by **opening** the switch **S2_HV+**.
8. Disconnect the HV power supply from the breakout box.
9. If necessary, clear all vehicle faults and do a key cycle.
10. Reset the faults on the charge station as needed.

6.4.5.2 Faults introduced after a charge session is ended:

DC Bus Held High

1. Start a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Enable a RESS voltage measurement at the breakout box by **closing** the switch **S2_HV+**.
4. Measure the RESS voltage (at **TP1-TP2**) and record.
5. Disable the RESS voltage measurement at the breakout box by **opening** the switch **S2_HV+**.
6. Connect an HV power supply at the breakout box (**TP1-TP2**). Set the power supply to voltage control mode with a current limit. Connect the power supply to a capacitor with a parallel bleed down resistor to gradually reduce the voltage once the charge session is ended.
7. Set the voltage to the RESS voltage measured in Step 4 (+5/-0 V_{DC}) and the maximum current to 1 A.
8. Connect the DC bus of the charge coupler to the HV power supply (diode protected to prevent negative current flow) by **closing** the switch **S2_HV+**.
9. If necessary, stop the charge session.
10. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
11. Remove the connection to the power supply by **opening** the switch **S2_HV+**.

12. If necessary, clear all vehicle faults and do a key cycle.
13. Reset the faults on the charge station as needed.

6.4.6 End of Test Procedure

6.4.6.1 Disconnect the vehicle from the breakout box.

6.4.6.2 Disconnect the charger from the breakout box.

6.4.6.3 Disconnect high voltage power supply from the breakout box.

6.4.7 Data Acquisition and Documentation

6.4.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage. Measurements from the charging station can include target voltage, output voltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.4.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.4.7.3 For all test conditions (Section 6.4.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger.
- Document any faults and/or DTCs on the vehicle/BMS.
- Document any faults and/or DTCs on the DC fast charge station.
- Document if the charge connector can be disconnected from the vehicle.

6.4.8 Pass/Fail Evaluation Criteria

6.4.8.1 For faults introduced before a charge session is initiated, the pass/fail evaluation criteria are as follows:

- The charge session shall not start if the fault is present at the beginning of the charge session. The vehicle shall remain in a safe state.
- The vehicle and charger system shall not allow the charge connector to be removed from the vehicle coupler if the voltage is held high.
- As appropriate, the system shall set a fault code to identify the problem.

6.4.8.2 For faults introduced after a charge session is ended, the pass/fail evaluation criteria are as follows:

- The vehicle and charger system shall not allow the charge connector to be removed from the vehicle coupler if the voltage is held high at the end of a charge session. The vehicle shall remain in a safe state.

- As appropriate, the system shall set a fault code to identify the problem.

6.5 System Overvoltage Tests (12 V Board Net)

6.5.1 Purpose

6.5.1.1 The purpose of this test is to simulate an overvoltage on the 12 V net during a DC charge session.

6.5.2 Rationale and Description

6.5.2.1 The 12 V system on the vehicle can experience an overvoltage due to a faulty DC/DC converter, an external jump start, or an external charge of the 12 V battery during a DC fast charge.

6.5.2.2 This test will determine the reaction of the vehicle and charger to the initiation of a charging session during 12 V overvoltage conditions.

6.5.2.3 The specified overvoltage conditions are based on ISO 16750-2 test procedures. They are achieved through a DC power supply that temporarily replaces the 12 V lead acid battery in the vehicle (see Figure 8).

6.5.3 Sample Preparation

6.5.3.1 This test requires a vehicle charger and a high power DC power supply in place of the 12 V lead acid battery in the vehicle.

6.5.3.2 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with system overvoltage testing if an isolation fault is detected.

6.5.4 Equipment Setup

6.5.4.1 Connect the DC charger directly to the vehicle charge port without the breakout box as shown in Figure 8.

6.5.4.2 Connect the DC power supply to the vehicle and configure it to provide 12 V power. Set the initial DC power supply voltage to 13.2 V. Ensure that the 12 V power to the vehicle is never interrupted during the installation.

6.5.4.3 In vehicle systems where there is a DC/DC converter connected to the 12 V battery that is activated during charging, it must not interfere with the overvoltage test condition. It is therefore necessary to disconnect the DC/DC converter 12 V output from the vehicle system.

Figure 8 - 12 V power supply connection for system overvoltage test.

6.5.5 Test Method and Procedure

6.5.5.1 Faults introduced before a charge session is initiated:

12 V System Overvoltage

1. Conduct an overvoltage test according to ISO 16750-2, "Test at a temperature of T_{max}-20°C", but thermalize the RESS to 25±5°C instead.
2. Attempt to start a charge session while applying the conditions outlined in ISO 16750-2 for overvoltage (**18 V** for a maximum of **60 minutes**).
3. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
4. If necessary, stop the charge session.
5. Return the vehicle 12 V system to normal (set the DC power supply back to 13.2 V).
6. If necessary, clear all vehicle faults and do a key cycle.
7. Reset the faults on the charge station as needed.

12 V System Overvoltage due to Jump Start Condition

1. Conduct an overvoltage test for jump start conditions according to ISO 16750-2, "Test at room temperature". Thermalize the RESS to 25±5°C.
2. Attempt to start a charge session while applying the conditions outlined in ISO 16750-2 for jump start (**24 V** for a maximum of **60 seconds**).
3. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.

4. If necessary, stop the charge session.
5. Return the vehicle 12 V system to normal (set the DC power supply back to 13.2 V).
6. If necessary, clear all vehicle faults and do a key cycle.
7. Reset the faults on the charge station as needed.

6.5.6 End of Test Procedure

6.5.6.1 Disconnect the vehicle from the charger.

6.5.6.2 Return the vehicle 12 V system to its original configuration by disconnecting the power supply and reinstalling the 12 V lead acid battery.

6.5.7 Data Acquisition and Documentation

6.5.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage. Measurements from the charging station can include target voltage, output voltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.5.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.5.7.3 For all test conditions (Section 6.5.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger.
- Document any faults and/or DTCs on the vehicle/BMS.
- Document any faults and/or DTCs on the DC fast charge station.

6.5.8 Pass/Fail Evaluation Criteria

6.5.8.1 For faults introduced before a charge session is initiated, the pass/fail evaluation criteria are as follows:

- The system shall complete a successful charge session or the system shall disconnect and bring itself to a safe state.

6.6 12 V System Under Voltage Test

6.6.1 Purpose

6.6.1.1 The purpose of this test is to simulate the gradual discharge of the 12 V battery during a fast charge.

6.6.2 Rationale and Description

6.6.2.1 The vehicle's 12 V system can experience an under voltage condition during a DC fast charge due to a faulty DC/DC converter, a loss of connection between the DC/DC and the 12 V battery, a faulty 12 V battery, or the operator leaving on a high current draw accessory.

6.6.2.2 This test will determine the reaction of the vehicle and charger to the initiation of a charging session during a 12 V under voltage condition.

6.6.2.3 The specified under voltage conditions are based on the ISO 16750-2 test procedure. They are achieved through a DC power supply that temporarily replaces the 12 V lead acid battery in the vehicle (see Figure 9). Alternatively, a fully charged low capacity lead acid battery (4-8 Ah) could be used in combination with a low power supply to provide a slowly dropping 12 V system voltage.

6.6.3 Sample Preparation

6.6.3.1 This test requires a vehicle charger and a high power DC power supply in place of the 12 V lead acid battery in the vehicle. A low capacity lead acid battery in combination with a low power supply could be used instead of a high power DC power supply.

6.6.3.2 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with 12 V system under voltage testing if an isolation fault is detected.

6.6.4 Equipment Setup

6.6.4.1 Connect the DC charger directly to the vehicle charge port without the breakout box as shown in Figure 9.

6.6.4.2 Connect the DC power supply to the vehicle and configure it to provide 12 V power. Set the initial DC power supply voltage to 13.2 V. Ensure that the 12 V power to the vehicle is never interrupted during the installation.

6.6.4.3 In vehicle systems where there is a DC/DC converter connected to the 12 V battery that is activated during charging, it must not interfere with the reduction of the 12 V system voltage. It is therefore necessary to disconnect the DC/DC converter 12 V output from the vehicle system (if it is determined that it will not interfere with the charging operation). Alternatively, it is possible to install a 150Ω (100 W) resistor at the output of the DC/DC inline to the 12 V board net. This resistor will limit the current the DC/DC converter can provide to the 12 V board net and allow the test to be conducted.

Figure 9 - 12 V Power Supply Connection.

6.6.5 Test Method and Procedure

6.6.5.1 Faults introduced during a fast charge session:

12 V System Under Voltage due to Battery Discharge

1. Set the DC power supply to **13.2 V**.
2. Start a normal charge session.
3. Wait for approximately 1 minute for the charge to initialize and stabilize.
4. Apply the conditions outlined in ISO 16750-2 for "Slow decrease and increase of supply voltage" but only use the slow discharge test. Simulate a gradual discharge from a **starting value** of **13.2 V** at the beginning of the DC fast charge, **down to** **0 V** **at a rate** of **0.5 V/min**. If possible, maintain the DC fast charge rate during the entire duration of the gradual discharge test (approximately 26 minutes).
5. Observe the system behavior during the entire charge cycle until 0 V is reached or the charger/vehicle systems enters a permanent fault state.
6. If necessary, stop the charge session.
7. Record any faults on the BMS and the DC fast charge station.
8. Return the vehicle 12 V system to normal (set DC power supply back to 13.2 V).
9. If necessary, clear all vehicle faults and do a key cycle.
10. Reset the faults on the charge station as needed.

6.6.6 End of Test Procedure

6.6.6.1 Disconnect the vehicle from the charger.

6.6.6.2 Return the vehicle 12 V system to its original configuration by disconnecting the power supply and reinstalling the 12 V lead acid battery.

6.6.7 Data Acquisition and Documentation

6.6.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage. Measurements from the charging station can include target voltage, output voltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.6.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.6.7.3 For the test condition (Section 6.6.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger (this includes any contactors disconnecting, chattering relays, etc.).
- Document any faults and/or DTCs on the vehicle/BMS.
- Document any faults and/or DTCs on the DC fast charge station.
- Document when the charge stopped (time and power supply voltage level).

6.6.8 Pass/Fail Evaluation Criteria

6.6.8.1 For faults introduced during a fast charge session, the pass/fail evaluation criteria are as follows:

- The system shall stop the charge session during the test and the vehicle and charger system shall be brought to a safe state.

6.7 12 V System Disturbance Test

6.7.1 Purpose

6.7.1.1 The purpose of this test is to simulate a switching load application that can disturb the stability of the 12 V battery.

6.7.2 Rationale and Description

6.7.2.1 It is possible that a large 12 V load turning on and off, such as a pump, fan, aftermarket system, or jump starting a second car, can cause disturbances in the 12 V system of the vehicle. These fluctuations, if severe enough, may cause different modules on the vehicle to malfunction during a DC fast charge.

6.7.2.2 This test will determine the reaction of the vehicle and charger to the initiation of a charging session during a 12 V load disturbance.

6.7.2.3 A system disturbance is introduced by toggling a 20 A load on and off as a charge session is being initiated. The load is connected to the 12 V lead acid battery in series with as controllable switch (see Figure 10).

6.7.3 Sample Preparation

6.7.3.1 This test requires a vehicle charger and a 12 V switchable load with a minimum current draw of 20A (e.g., an automotive fan, pump, heater, etc.).

6.7.3.2 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with 12 V system disturbance testing if an isolation fault is detected.

6.7.4 Equipment Setup

6.7.4.1 Connect the DC charger directly to the vehicle charge port without the breakout box as shown in Figure 10.

6.7.4.2 Connect the switchable load to the 12 V lead acid battery in the vehicle (Figure 10).

Figure 10 - 12 V Load Connection.

6.7.5 Test Method and Procedure

6.7.5.1 Faults introduced before a charge session is initiated:

<u>Alternating Current Pulse Applied to Low Voltage System</u>

1. Start a charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Initiate a 20 A load to the low voltage system of the BMS supply (e.g., a pump, fan, heater, etc.)
4. Toggle the 20 A load at an on/off rate of **1 Hz**.
5. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
6. If necessary, stop the charge session.

7. Turn off the 20 A load to the low voltage system of the BMS supply.
8. If necessary, clear all vehicle faults and do a key cycle.
9. Reset the faults on the charge station as needed.

6.7.6 End of Test Procedure

6.7.6.1 Disconnect the vehicle from the charger.

6.7.6.2 Return the vehicle 12 V system to its original configuration by disconnecting the switchable load from the 12 V lead acid battery.

6.7.7 Data Acquisition and Documentation

6.7.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage. Measurements from the charging station can include target voltage, output voltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.7.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.7.7.3 For the test condition (Section 6.7.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger.

- Document any faults and/or DTCs on the vehicle/BMS.

- Document any faults and/or DTCs on the DC fast charge station.

6.7.8 Pass/Fail Evaluation Criteria

6.7.8.1 For faults introduced before a charge session is initiated, the pass/fail evaluation criteria are as follows:

- The vehicle or charger does not react to the load switching and the DC charge session is not interrupted. The vehicle shall remain in a safe state.

6.8 12 V System EMI/EMC Test

6.8.1 Purpose

6.8.1.1 The purpose of this test is to simulate electromagnetic interference / electromagnetic compatibility (EMI/EMC) disturbances during a DC charge session.

6.8.2 Rationale and Description

6.8.2.1 Large electromagnetic disturbances during a DC fast charge can affect the low voltage power system and disturb communication between vehicle components.

6.8.2.2 This test will determine the reaction of the vehicle and charger to the initiation of a charging session during electromagnetic interference.

6.8.2.3 The EMI/EMC conditions applied to the vehicle for this test are based on SAE J1113-3, -4, -21, -24 test procedures.

6.8.3 Sample Preparation

6.8.3.1 This test requires a vehicle charger and EMI/EMC equipment.

6.8.3.2 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with 12 V system EMI/EMC testing if an isolation fault is detected.

6.8.4 Equipment Setup

6.8.4.1 Connect the DC charger directly to the vehicle charge port without the breakout box.

6.8.4.2 Prepare the EMI/EMC equipment per SAE test procedures J1113-3, -4, -21, and -24.

6.8.5 Test Method and Procedure

6.8.5.1 Faults introduced before a charge session is initiated:

Electromagnetic Disturbance

1. Conduct the EMI/EMC vehicle level SAE test procedures according to SAE J1113-3, -4, -21, -24 to the extent to which it is feasible.
2. Start a charge session.
3. Observe the behavior of the system.
4. If necessary, stop the charge session.
5. Record any faults on the BMS and the DC fast charge station.
6. If necessary, clear all vehicle faults and do a key cycle.
7. Reset the faults on the charge station as needed.

6.8.6 End of Test Procedure

6.8.6.1 Disconnect the vehicle from the charger.

6.8.6.2 Remove the EMI/EMC test equipment.

6.8.7 Data Acquisition and Documentation

6.8.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage. Measurements from the charging station can include target voltage, output voltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.8.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.8.7.3 For all test conditions (Section 6.8.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger.
- Document any faults and/or DTCs on the vehicle/BMS.
- Document any faults and/or DTCs on the DC fast charge station.

6.8.8 Pass/Fail Evaluation Criteria

6.8.8.1 For faults introduced before a charge session is initiated, the pass/fail evaluation criteria are as follows:

- The system shall not set any DTCs.
- The DC charge session ends normally and does not stop prematurely. The vehicle shall remain in a safe state.

6.9 Vehicle Movement Tests

6.9.1 Purpose

6.9.1.1 The purpose of this test is to determine if the drive away interlocks of the vehicle system are effective during a DC fast charge.

6.9.2 Rationale and Description

6.9.2.1 The operator of the vehicle may inadvertently try to drive off while the charger is still connected. The vehicle could also roll away during a DC fast charge due to faulty park pawl or park brake mechanism.

6.9.2.2 This test will determine the reaction of the vehicle and DC charging system to vehicle movement during a charging session.

6.9.2.3 The vehicle movement tests include manipulating PRND gear shift lever and rotating one or more wheels when the vehicle is jacked up.

6.9.3 Sample Preparation

6.9.3.1 This test requires a vehicle charger and a floor jack.

6.9.3.2 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with vehicle movement testing if an isolation fault is detected.

6.9.4 Equipment Setup

6.9.4.1 Connect the DC charger directly to the vehicle charge port without the breakout box.

6.9.4.2 Position the vehicle so that it can be easily jacked up using a floor jack.

6.9.5 Test Method and Procedure

6.9.5.1 Faults introduced during a fast charge session:

<u>Vehicle Drive Away Attempt</u>

1. Start a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. **Release** the parking brake.
4. Observe the system behavior. Record any faults from the BMS and the DC charge station.
5. Get inside the vehicle and attempt to **turn on** the vehicle.
6. Observe the system behavior. Record any faults from the BMS and the DC charge station.
7. Attempt to **move the PRND** gear shift lever to the Drive position. If successful, do not attempt to accelerate forward.
8. Observe the system behavior. Record any faults from the BMS and the DC charge station.
9. Attempt to **move the PRND** gear shift lever to the Neutral position.
10. Observe the system behavior. Record any faults from the BMS and the DC charge station.
11. Attempt to **move the PRND** gear shift lever to the Reverse position. If successful, do not attempt to accelerate backward.
12. Observe the system behavior. Record any faults from the BMS and the DC charge station.
13. If necessary, stop the charge session.
14. If necessary, clear all vehicle faults and do a key cycle.
15. Reset the faults on the charge station as needed.

Simulated Vehicle Movement

1. Elevate one or more wheels on the vehicle using the floor jack.
2. Start a normal charge session.
3. Wait for approximately 1 minute for the charge to initialize and stabilize
4. Attempt to **rotate** the wheels at a rate of **1 rev/s** (approximately 5 mph) during the charge.
5. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
6. If necessary, stop the charge session.
7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.

6.9.6 End of Test Procedure

6.9.6.1 Disconnect the vehicle from the charger.

6.9.6.2 Lower the vehicle from the jack.

6.9.7 Data Acquisition and Documentation

6.9.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage. Measurements from the charging station can include target voltage, output voltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.9.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.9.7.3 For all test conditions (Section 6.9.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger.
- Document any faults and/or DTCs on the vehicle/BMS.
- Document any faults and/or DTCs on the DC fast charge station.

6.9.8 Pass/Fail Evaluation Criteria

6.9.8.1 For faults introduced during a fast charge session, the pass/fail evaluation criteria are as follows:

- The vehicle shall remain in a safe state. It should prevent any movement despite inadvertent operator interference.

- The test has failed if any unintended vehicle movement is allowed during a fast charge. If there is vehicle movement, the BMS should detect it and stop the charge with a vehicle initiated shutdown.

6.10 Vehicle Crash or Bump Tests

6.10.1 Purpose

6.10.1.1 The purpose of this test is to simulate a low energy collision during a DC fast charge.

6.10.2 Rationale and Description

6.10.2.1 The typical DC fast charger is located in a public parking lot. It is inevitable that a slow speed collision will occur to an actively charging vehicle during a DC fast charge, possibly even causing it to move.

6.10.2.2 This test will determine the reaction of the BMS to a front and rear impact during a DC charge session.

6.10.2.3 The crash or bump tests are based on FMVSS Test Procedure TP-581. A pendulum test device is used to impact the vehicle.

6.10.3 Sample Preparation

6.10.3.1 This test requires a vehicle charger and a pendulum test device.

6.10.3.2 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with vehicle crash or bump testing if an isolation fault is detected.

6.10.3.3 Prepare the vehicle for an impact equivalent to the FMVSS Test Procedure TP-581, pendulum impact test. The vehicle is subjected to an equivalent impact during the charge session, but it is not necessary to duplicate the full TP-581 instrumentation and data recording requirements.

6.10.3.4 The vehicle shall be parked normally with the parking brake engaged. Do not place the vehicle in neutral as specified in TP-581; this is not the typical condition during a fast charge session.

6.10.4 Equipment Setup

6.10.4.1 Connect the DC charger directly to the vehicle charge port without the breakout box.

6.10.4.2 Setup the pendulum test device according to FMVSS Test Procedure TP-581.

6.10.5 Test Method and Procedure

6.10.5.1 Faults introduced during a fast charge session:

Simulated Vehicle Crash or Bump (Front Impact)

1. Start a charge session.
2. Wait for 1 minute for the charger and vehicle to connect and stabilize.
3. Impact the vehicle in the front with the pendulum test device (PTD) at **2.3±0.1 mph** using the Bumper Impact Block Test Device defined in TP-581.
4. Observe the state of the charger and vehicle system.
5. If necessary, stop the charge session.
6. Record any faults on the BMS and the DC fast charge station.
7. Record any damage of the charger coupler or cable.
8. If necessary, clear all vehicle faults and do a key cycle.
9. Reset the faults on the charge station as needed.

Simulated Vehicle Crash or Bump (Rear Impact)

1. Start a charge session.
2. Wait for 1 minute for the charger and vehicle to connect and stabilize.
3. Impact the vehicle in the rear with the PTD at **2.3±0.1 mph** using the Bumper Impact Block Test Device defined in TP-581.
4. Observe the state of the charger and vehicle system.
5. If necessary, stop the charge session.
6. Record any faults on the BMS and the DC fast charge station.
7. Record any damage of the charger coupler or cable.
8. If necessary, clear all vehicle faults and do a key cycle.
9. Reset the faults on the charge station as needed.

6.10.6 End of Test Procedure

6.10.6.1 Disconnect the vehicle from the charger.

6.10.6.2 Remove the pendulum test device.

6.10.6.3 Perform a post-test safety inspection to ensure that no high voltage safety violation is present (e.g., disconnected or damaged HV connectors/wires, debris or sharp edges).

6.10.6.4 Inspect all cables and connectors between fast charger and vehicle.

6.10.7 Data Acquisition and Documentation

6.10.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage. Measurements from the charging station can include target voltage, output

voltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.10.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.10.7.3 For all test conditions (Section 6.10.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger.
- Document any faults and/or DTCs on the vehicle/BMS.
- Document any faults and/or DTCs on the DC fast charge station.

6.10.8 Pass/Fail Evaluation Criteria

6.10.8.1 For faults introduced during a fast charge session, the pass/fail evaluation criteria are as follows:

- The charge session shall terminate as soon as impact is detected.
- The vehicle and charger system shall remain in a safe state with no exposed energized components due to damaged components or subsystems.

6.11 Charge Operation Disturbance Tests

6.11.1 Purpose

6.11.1.1 The purpose of this test is to determine if abnormal actions by the operator can cause an unsafe condition during a DC fast charge.

6.11.2 Rationale and Description

6.11.2.1 Unintended conditions can be realized by unexpected inputs to either the vehicle or charger during a DC fast charge.

6.11.2.2 This test will determine the reaction of the vehicle and charger to a sequence of operator interferences during an active charge session.

6.11.2.3 The charge disturbance tests include various operator interferences with the charger, connector, and vehicle.

6.11.3 Sample Preparation

6.11.3.1 This test only requires a vehicle charger.

6.11.3.2 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel.

Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with charge operation disturbance testing if an isolation fault is detected.

6.11.4 Equipment Setup

6.11.4.1 Connect the DC charger directly to the vehicle charge port without the breakout box.

6.11.5 Test Method and Procedure

6.11.5.1 Faults introduced during a fast charge session:

Premature Disconnect Attempt

1. Begin a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Attempt to disconnect the charge coupler from the vehicle without pressing the stop button on the charger.
4. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
5. If necessary, stop the charge session.
6. If necessary, clear all vehicle faults and do a key cycle.
7. Reset the faults on the charge station as needed.

Operator Interference at the Charger

1. Begin a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Press all the available operator accessible buttons on the DC fast charger.
4. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
5. If necessary, stop the charge session.
6. If necessary, clear all vehicle faults and do a key cycle.
7. Reset the faults on the charge station as needed.

Wiggle the Connector

1. Begin a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Wiggle the charger connector while it is plugged in to the vehicle.
4. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
5. If necessary, stop the charge session.

6. If necessary, clear all vehicle faults and do a key cycle.
7. Reset the faults on the charge station as needed.

Operator Interference on the Vehicle

1. Begin a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Turn on the vehicle ignition.
4. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
5. If necessary, stop the charge session.
6. If necessary, clear all vehicle faults and do a key cycle.
7. Reset the faults on the charge station as needed.

Operator Interference with the Vehicle Key Fob

1. Begin a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Press all key fob functions on the vehicle transmitter/key.
4. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
5. If necessary, stop the charge session.
6. If necessary, clear all vehicle faults and do a key cycle.
7. Reset the faults on the charge station as needed.

Operator Interference with a Remote Telematics Command

1. Begin a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Exercise all telematics functions (e.g., unlock doors, turn on HVAC remotely during a charge, etc.).
4. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
5. If necessary, stop the charge session.
6. If necessary, clear all vehicle faults and do a key cycle.
7. Reset the faults on the charge station as needed.

6.11.6 End of Test Procedure

6.11.6.1 Disconnect the vehicle from the charger.

6.11.7 Data Acquisition and Documentation

6.11.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage.

Measurements from the charging station can include target voltage, output voltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.11.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.11.7.3 For the test condition (Section 6.11.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger.
- Document any faults and/or DTCs on the vehicle/BMS.
- Document any faults and/or DTCs on the DC fast charge station.

6.11.8 Pass/Fail Evaluation Criteria

6.11.8.1 For faults introduced during a fast charge session, the pass/fail evaluation criteria are as follows:

- The vehicle and charger shall result in either no reaction, a vehicle initiated shutdown, or a charger initiated shutdown.
- The vehicle/charger system shall remain in a safe state.

6.12 Charge Connector Control Signal Disturbance Tests

6.12.1 Purpose

6.12.1.1 The purpose of this test is to introduce control signal disturbances between the vehicle and the DC fast charger.

6.12.2 Rationale and Description

6.12.2.1 Control signal disturbances in the charge coupler connector can cause loss of control of the charge session and potentially hazardous situations. These control signals can include field ground, CAN communication, pilot (including Power Line Communication over pilot), and proximity signals. Power Line Communication signals can degrade due to disturbances induced from the grid (e.g., arc welder, compressor, etc.) or incompatible devices on the network. CAN signals can degrade due to increased resistance, too many error frames, a "bus-off" condition, duplicate messages with the identical charger ID, excess bus loading, etc. The physical connection can degrade or break due to contamination in the charge coupler or connector terminals. The connector can even forcefully "break-away" during a charge session if any vehicle movement or a minor collision is experienced.

6.12.2.2 This test will determine the reaction of the vehicle and DC charging system to various control signal disturbances both before a charge session is initiated and during an active charge session.

6.12.2.3 A disturbance on the control pilot can include both signal loss and a short to ground. The loss of the control pilot signal is established with switch **S1_CP** on the breakout box (see Figure 11). The short to ground is established with switches **S2_CP** and **S_SHORT**. High resistance through R1 can be introduced to the control pilot signal with switches **S2_CP**, **S_R**, and **S3_CP**. Multiple values of R1 are used to evaluate the system behavior at various disturbance levels.

6.12.2.4 A disturbance on the proximity can also include both signal loss and a short to ground. The loss of the proximity signal is established with switch **S1_P** on the breakout box (see Figure 11). The short to ground is established with switches **S2_P** and **S_SHORT**. High resistance through R1 can be introduced to the proximity signal with switches **S2_P**, **S_R**, and **S3_P**. Multiple values of R1 are used to evaluate the system behavior at various disturbance levels.

6.12.2.5 System disturbances can also be present in the CAN bus signal through increasing error frames, increasing bus load with non-colliding messages, or a short to ground. The short to ground is established on both the high and low side of the CAN bus.

6.12.3 Sample Preparation

6.12.3.1 This test requires a vehicle charger, a breakout box, and a CAN communication tester/monitor.

6.12.3.2 R1 resistor values of 1 kΩ, 100Ω, 47Ω, and 24Ω shall be available to insert into the breakout box during testing (see Figure 11).

6.12.3.3 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with charge connector control signal disturbance testing if an isolation fault is detected.

6.12.4 Equipment Setup

6.12.4.1 Connect the DC charger to the vehicle charge port through the breakout box as shown in Figure 11.

6.12.4.2 Configure the CAN communication tester/monitor to generate error frames as defined in Section 6.12.5.3. The tester/monitor must be connected such that either the high and low side can be shorted to ground.

6.12.4.3 Configure the breakout box to perform the charge connector control signal disturbance test with the initial switch setting shown in Table 5.

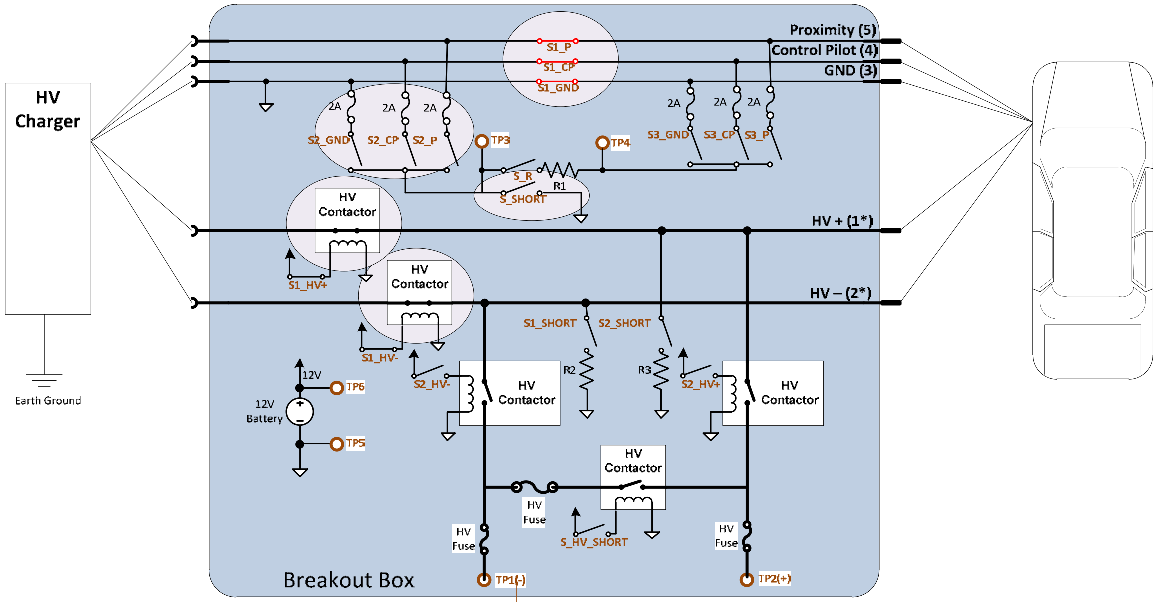


Figure 11 - Initial breakout box configuration for control signal disturbance tests.

Table 5 - Initial Switch Configuration for Control Signal Disturbance Tests

Switch	Setting	Switch	Setting	Switch	Setting
S1_P	Closed	**S3_P**		**S2_SHORT**	
S1_CP	Closed	**S3_CP**		**S1_HV+**	Closed
S1_GND	Closed	**S3_GND**		**S1_HV-**	Closed
S2_P		**S_R**		**S2_HV+**	
S2_CP		**S_SHORT**		**S2_HV-**	
S2_GND		**S1_SHORT**		**S_HV_SHORT**	

Green: Closed as part of the initial configuration

Yellow: Switches manipulated during the test

6.12.5 Test Method and Procedure

6.12.5.1 Communication connection interrupted during charge session:

Control Pilot Interruption

1. Start a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Interrupt the control pilot connection at the breakout box by **opening** switch **S1_CP**.
4. Observe the system behavior. Record any faults from the BMS and the DC charge station.
5. If necessary, stop the charge session.
6. Remove the control pilot signal interruption by **closing** switch **S1_CP**.
7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.

Control Pilot Short to Ground

1. Start a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Introduce a short to ground in the control pilot connection at the breakout box by **closing** switches **S2_CP** and **S_SHORT**.
4. Observe the system behavior. Record any faults from the BMS and the DC charge station.
5. If necessary, stop the charge session.
6. Remove the short to ground in the control pilot signal connection by **opening** switches **S2_CP** and **S_SHORT**.
7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.

Proximity Interruption

1. Start a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Interrupt the proximity signal connection at the breakout box by **opening** switch **S1_P**.
4. Observe the system behavior. Record any faults from the BMS and the DC charge station.
5. If necessary, stop the charge session.
6. Remove the proximity signal interruption by **closing** switch **S1_P**.
7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.

Proximity Short to Ground

1. Start a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Introduce a short to ground in the proximity signal connection at the breakout box by **closing** switches **S2_P** and **S_SHORT**.
4. Observe the system behavior. Record any faults from the BMS and the DC charge station.
5. If necessary, stop the charge session.
6. Remove the short to ground in the proximity signal connection by **opening** switches **S2_P** and **S_SHORT**.
7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.

6.12.5.2 High resistance on communication connections:

High Resistance on the Control Pilot *Before* a Charge Session

1. Set the value of R1 to 1 kΩ on the breakout box.

2. Introduce R1 on the control pilot signal by **closing** switches **S2_CP**, **S_R**, and **S3_CP**.
3. Open the primary control pilot signal connection by **opening** switch **S1_CP**, leaving only the connected resistance.
4. Measure the voltage across R1 (**TP3-TP4**). Record this as a pre-test value.
5. Start a normal charge session.
6. Measure the voltage across R1 (**TP3-TP4**). Record this value.
7. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
8. If necessary, stop the charge session.
9. Remove R1 by **opening** switches **S2_CP**, **S_R**, and **S3_CP**.
10. Restore the primary control pilot signal by **closing** switch **S1_CP**.
11. If necessary, clear all vehicle faults and do a key cycle.
12. Reset the faults on the charge station as needed.
13. Repeat Steps 2 through 12 using R1 values of 100Ω, 47Ω, and 24Ω.

High Resistance on the Control Pilot *During* a Charge Session

1. Set the value of R1 to 1 kΩ on the breakout box.
2. Start a normal charge session.
3. Wait for approximately 1 minute for the charge to initialize and stabilize.
4. Introduce R1 on the control pilot signal by **closing** switches **S2_CP**, **S_R**, and **S3_CP**.
5. Open the primary control pilot signal connection by **opening** switch **S1_CP**, leaving only the connected resistance.
6. Measure the voltage across R1 (**TP3-TP4**). Record this value.
7. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
8. If necessary, stop the charge session.
9. Remove R1 by **opening** switches **S2_CP**, **S_R**, and **S3_CP**.
10. Restore the primary control pilot signal by **closing** switch **S1_CP**.
11. If necessary, clear all vehicle faults and do a key cycle.
12. Reset the faults on the charge station as needed.
13. Repeat Steps 2 through 12 using R1 values of 100Ω, 47Ω, and 24Ω.

High Resistance on the Proximity Signal *Before* a Charge Session

1. Set the value of R1 to 1 kΩ on the breakout box.
2. Introduce R1 on the proximity signal by **closing** switches **S2_P**, **S_R**, and **S3_P**.
3. Open the primary proximity signal connection by **opening** switch **S1_P**, leaving only the connected resistance.
4. Measure the voltage across R1 (**TP3-TP4**). Record this as a pre-test value.
5. Start a normal charge session.

6. Measure the voltage across R1 (**TP3-TP4**). Record this value.
7. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
8. If necessary, stop the charge session.
9. Remove R1 by **opening** switches **S2_P**, **S_R**, and **S3_P**.
10. Restore the primary proximity signal by **closing** switch **S1_P**.
11. If necessary, clear all vehicle faults and do a key cycle.
12. Reset the faults on the charge station as needed.
13. Repeat Steps 2 through 12 using R1 values of 100Ω, 47Ω, and 24Ω.

High Resistance on the Proximity Signal *During* a Charge Session

1. Set the value of R1 to 1 kΩ on the breakout box.
2. Start a normal charge session.
3. Wait for approximately 1 minute for the charge to initialize and stabilize.
4. Introduce R1 on the proximity signal by **closing** switches **S2_P**, **S_R**, and **S3_P**.
5. Open the primary proximity signal connection by **opening** switch **S1_P**, leaving only the connected resistance.
6. Measure the voltage across R1 (**TP3-TP4**). Record this value.
7. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
8. If necessary, stop the charge session.
9. Remove R1 by **opening** switches **S2_P**, **S_R**, and **S3_P**.
10. Restore the primary proximity signal by **closing** switch **S1_P**.
11. If necessary, clear all vehicle faults and do a key cycle.
12. Reset the faults on the charge station as needed.
13. Repeat Steps 2 through 12 using R1 values of 100Ω, 47Ω, and 24Ω.

6.12.5.3 CAN errors during a charge session:

CAN Error Frames

1. Start a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Using the CAN tester, introduce CAN error frames at the rate of **1/sec**.
4. Increase the CAN error frames to a rate of **500/sec** over a time of **5 minutes**.
5. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
6. If necessary, stop the charge session.
7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.

CAN Bus Load Increase

1. Start a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Using the CAN tester, introduce non-colliding CAN messages to increase the bus load to **80%** over a period of **5 minutes**. The non-colliding CAN messages shall have IDs lower than the lowest observed CAN ID on the network.
4. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
5. If necessary, stop the charge session.
6. If necessary, clear all vehicle faults and do a key cycle.
7. Reset the faults on the charge station as needed.

CAN Bus High Shorted to Ground

1. Start a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Short the CAN bus high signal to ground.
4. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
5. If necessary, stop the charge session.
6. If necessary, clear all vehicle faults and do a key cycle.
7. Reset the faults on the charge station as needed.

CAN Bus Low Shorted to Ground

1. Start a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Short the CAN bus low signal to ground.
4. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
5. If necessary, stop the charge session.
6. If necessary, clear all vehicle faults and do a key cycle.
7. Reset the faults on the charge station as needed.

6.12.6 End of Test Procedure

6.12.6.1 Disconnect the vehicle from the breakout box.

6.12.6.2 Disconnect the charger from the breakout box.

6.12.6.3 Disconnect the CAN communication test/monitor.

6.12.7 Data Acquisition and Documentation

6.12.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage. Measurements from the charging station can include target voltage, output vsoltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.12.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.12.7.3 For all test conditions (Section 6.12.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger.
- Document any faults and/or DTCs on the vehicle/BMS.
- Document any faults and/or DTCs on the DC fast charge station.
- Record all voltage measurements across R1 (**TP3-TP4**).

6.12.8 Pass/Fail Evaluation Criteria

6.12.8.1 For communication connections interrupted during a charge session, the pass/fail evaluation criteria are as follows:

- The charge session stops during the test and the vehicle and charger system is brought to a safe state.

6.12.8.2 For the introduction of high resistance on the communication connections, the pass/fail evaluation criteria are as follows:

- The charge session stops during the test and the vehicle and charger system is brought to a safe state.

6.12.8.3 For the introduction of CAN error during a charge session, the pass/fail evaluation criteria are as follows:

- The charge session shall continue without interruption during the test and the vehicle and charger system shall remain in a safe state.

6.13 Charge Connector High Voltage Connection Disturbance Test

6.13.1 Purpose

6.13.1.1 The purpose of this test is to introduce a poor HV connection between the vehicle and the DC fast charger.

6.13.2 Rationale and Description

6.13.2.1 The HV connection between the vehicle and the charger can become degraded or interrupted during a charge due to contamination of the terminals. This can result in increased resistance of the receptacle/plug interface, worn high voltage contacts, over-temperature of the cable or terminals, or a degraded cable due to inadequate strain relief.

6.13.2.2 This test will determine the reaction of the vehicle and DC charging system to a charge connector HV connection disturbance during an active charge session.

6.13.2.3 The high voltage connection disturbance is established through switch **S1_HV+** or **S1_HV-** on the breakout box (see Figure 12). When either switch is opened, the charging current to the vehicle is interrupted.

6.13.3 Sample Preparation

6.13.3.1 This test requires a vehicle charger and a breakout box.

6.13.3.2 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with charge connector high voltage connection disturbance testing if an isolation fault is detected.

6.13.4 Equipment Setup

6.13.4.1 Connect the DC charger to the vehicle charge port through the breakout box as shown in Figure 12.

6.13.4.2 Configure the breakout box to perform the charge connector high voltage connection disturbance test with the initial switch setting shown in Table 6.

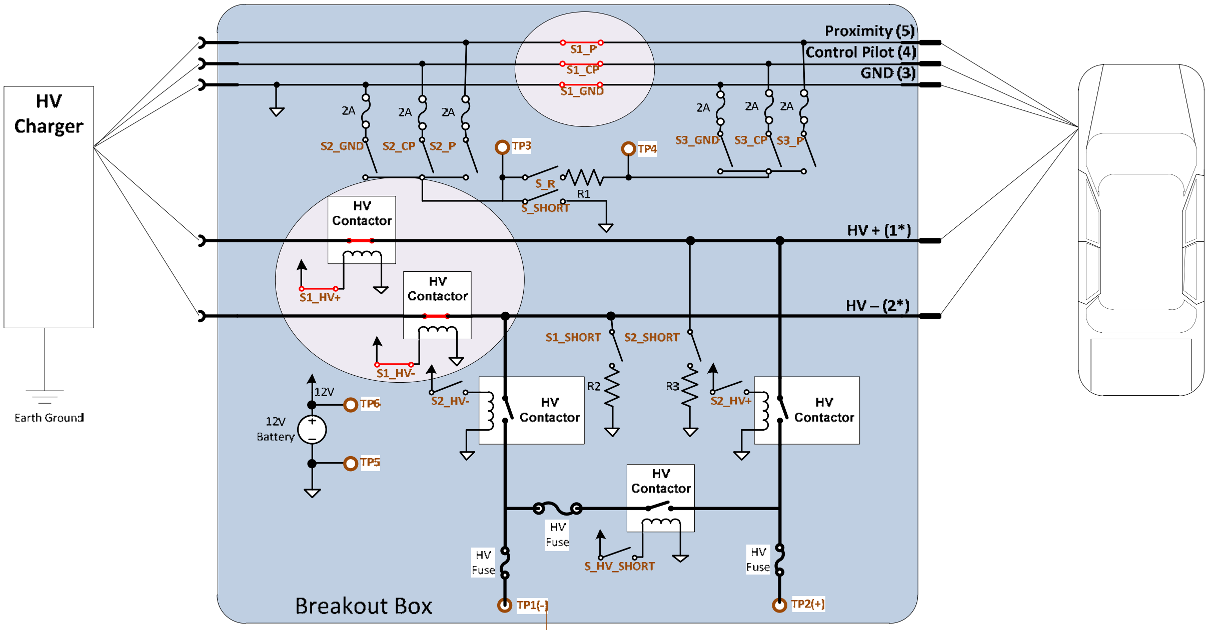


Figure 12 - Initial breakout box switch configuration for the charge connector high voltage connection disturbance test.

Table 6 - Initial Switch Configuration for the Charge Connector High Voltage Connection Disturbance Test

Switch	Setting	Switch	Setting	Switch	Setting
S1_P	Closed	**S3_P**		**S2_SHORT**	
S1_CP	Closed	**S3_CP**		**S1_HV+**	Closed
S1_GND	Closed	**S3_GND**		**S1_HV-**	Closed
S2_P		**S_R**		**S2_HV+**	
S2_CP		**S_SHORT**		**S2_HV-**	
S2_GND		**S1_SHORT**		**S_HV_SHORT**	
Green:	Closed as part of the initial configuration				
Yellow:	Switches manipulated during the test				

6.13.5 Test Method and Procedure

6.13.5.1 Faults introduced during a fast charge session:

Interrupt DC Connection During Fast Charge

1. Start a normal charge session.
2. Wait for approximately 1 minute for the charge to initialize and stabilize.
3. Disconnect one of the DC bus connections (by **opening** either **S1_HV+** or **S1_HV-**) at the breakout box.
4. Observe the system behavior. Record any faults from the BMS and the DC charge station.
5. If necessary, stop the charge session.
6. Restore DC bus connection by **closing** **S1_HV+** or **S1_HV-**.

7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.

6.13.6 End of Test Procedure

6.13.6.1 Disconnect the vehicle from the breakout box.

6.13.6.2 Disconnect the charger from the breakout box.

6.13.7 Data Acquisition and Documentation

6.13.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage. Measurements from the charging station can include target voltage, output voltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.13.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.13.7.3 For this test condition (Section 6.13.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger.

- Document any faults and/or DTCs on the vehicle/BMS.

- Document any faults and/or DTCs on the DC fast charge station.

6.13.8 Pass/Fail Evaluation Criteria

6.13.8.1 For faults introduced during a fast charge session, the pass/fail evaluation criteria are as follows:

- The charge session stops during the test and the vehicle and charger system shall be brought to a safe state.

6.14 Cooling/Heating System Tests

6.14.1 Purpose

6.14.1.1 The purpose of this test is to simulate a degraded or failed thermal management system.

6.14.2 Rationale and Description

6.14.2.1 High powered off-board DC fast charging can be up to 200 A continuous. This would typically require cooling in the RESS being charged. The cooling system can be degraded due to loss of refrigerant, failed actuator (pump, fan, etc.), or other condition which causes the RESS to overheat during a fast charge.

6.14.2.2 This test will determine the reaction of the vehicle and DC charging system to a cooling/heating malfunction during an active charge session.

6.14.2.3 With support from the vehicle manufacturer, the RESS heating and cooling capabilities can be disabled to simulate a failed thermal management system. Once disabled, the battery is soaked at both high and low temperatures for at least 24 hours prior to initiating a charging session.

6.14.3 Sample Preparation

6.14.3.1 This test requires a vehicle charger and a thermal chamber capable of heating/cooling the vehicle and RESS to the specified temperatures.

6.14.3.2 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with cooling/heating system testing if an isolation fault is detected.

6.14.3.3 Methods for restricting RESS thermal management systems may differ significantly from vehicle to vehicle. Therefore, this test requires specific knowledge of the cooling and heating system design details for each RESS under test. The BMS must be modified to meet the test conditions described below.

6.14.3.4 High Ambient Temperature Test Preparation:

For the high ambient temperature test, the vehicle must be placed in an environmental chamber capable of increasing the RESS temperature to 40±5°C. Allow the sample to soak at this temperature for at least 24 hours prior to the test.

6.14.3.5 Low Ambient Temperature Test Preparation:

For the low ambient temperature test, the vehicle must be placed in an environmental chamber capable of decreasing the RESS temperature to -20±5°C. Allow the sample to soak at this temperature for at least 24 hours prior to the test.

6.14.4 Equipment Setup

6.14.4.1 There is no equipment setup for this test.

6.14.5 Test Method and Procedure

6.14.5.1 Faults introduced before a charge session is initiated:

Restricted RESS Cooling at High Ambient Temperature

1. Place the vehicle in the environmental chamber for at least 24 hours at 40±5°C while restricting the cooling capability.
2. Connect the DC charger directly to the vehicle charge port without the breakout box.
3. Start a normal charge session.
4. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
5. If necessary, stop the charge session.
6. Disconnect the vehicle from the charger.
7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.

Restricted RESS Heating at Low Ambient Temperature

1. Place the vehicle in the environmental chamber for 24 hours at -20±5°C while restricting the heating capability.
2. Connect the DC charger directly to the vehicle charge port without the breakout box.
3. Start a normal charge session.
4. Observe the system behavior. Record any faults on the BMS and the DC fast charge station.
5. If necessary, stop the charge session.
6. Disconnect the vehicle from the charger.
7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.

6.14.6 End of Test Procedure

6.14.6.1 Remove the thermal management system restrictions and restore the RESS cooling and heating components back to normal.

6.14.7 Data Acquisition and Documentation

6.14.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage. Measurements from the charging station can include target voltage, output voltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.14.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.14.7.3 For all test conditions (Section 6.14.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger.

- Document any faults and/or DTCs on the vehicle/BMS.
- Document any faults and/or DTCs on the DC fast charge station.

6.14.8 Pass/Fail Evaluation Criteria

6.14.8.1 For faults introduced before a charge session is initiated, the pass/fail evaluation criteria are as follows:

- The BMS may record an over-temperature or under-temperature fault, limit the charge current, or stop the charge session prematurely. The vehicle shall remain in a safe state.
- The charge current limiting behavior of the BMS may vary significantly for each vehicle's RESS.
- The BMS shall not allow the RESS to enter into thermal runaway conditions due to excessive charge current at high or low ambient temperatures.

6.15 BMS Internal Fault Detection Tests

6.15.1 Purpose

6.15.1.1 The purpose of this test is to determine if a BMS is able to detect internal faults which, if not detected and handled adequately, may lead to hazardous conditions.

6.15.2 Rationale and Description

6.15.2.1 There are a number of internal BMS faults which may cause hazardous conditions. These faults are application specific and require specific knowledge of each BMS architecture and design. Therefore, the following tests shall be described in general terms due to the specific nature of internal BMS designs. The tests provided are the minimum requirements for this procedure, but they are only a small subset of the overall tests that should be completed for a given RESS. It is anticipated that in future revisions of this procedure (or in a separate document), additional test steps will be identified.

6.15.2.2 This test will determine the reaction of the vehicle and DC charging system to internal BMS faults. The test conditions shall be applied before a charge session is applied.

6.15.2.3 At a minimum, testing should include cell overvoltage, cell under-voltage, and temperature faults.

6.15.3 Sample Preparation

6.15.3.1 This test only requires a vehicle charger.

6.15.3.2 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with BMS internal fault detection testing if an isolation fault is detected.

6.15.3.3 For each test vehicle, specific knowledge is required to modify the internal subsystems and subject the BMS to the conditions described below. It is therefore necessary to obtain a detailed wiring schematic and layout information from the manufacturer to determine appropriate access points and implant the required signal modifications. It would also be desirable to obtain RESS specific break out harnesses to allow safe access to the BMS signals under test.

6.15.4 Equipment Setup

6.15.4.1 Connect the DC charger directly to the vehicle charge port without the breakout box.

6.15.4.2 The equipment requirements for this test are highly RESS dependent and need the active support of the manufacturer. Sensor signals should be modified based on RESS manufacturer recommendations to prevent any damage or unsafe conditions while the test is being conducted.

Example equipment for cell voltage fault simulations could be a variable resistor mounted inline and/or in parallel to a cell voltage sensor signal that is used to simulate an overvoltage and under-voltage condition.

Example equipment for temperature fault simulation could be a variable resistor mounted inline and/or in parallel to the actual temperature sensor for a single cell or a number of cells.

6.15.5 Test Method and Procedure

6.15.5.1 Faults introduced before a charge session is initiated:

Cell Overvoltage Fault Test

1. Set the simulated cell voltage signal to match the actual cell voltage.
2. Start a normal charge session.
3. Wait for approximately 1 minute for the charge to initialize and stabilize.
4. Alter the simulated cell voltage to reach the defined cell overvoltage threshold (RESS-specific) and hold it there.
5. Observe the system behavior. Record any faults from the BMS and the DC charge station.
6. If necessary, stop the charge session.
7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.

Cell Undervoltage Fault Test

1. Set the simulated cell voltage signal to match the actual cell voltage.
2. Start a normal charge session.
3. Wait for approximately 1 minute for the charge to initialize and stabilize.
4. Alter the simulated cell voltage to reach the defined cell under-voltage threshold (RESS-specific) and hold it there.
5. Observe the system behavior. Record any faults from the BMS and the DC charge station.
6. If necessary, stop the charge session.
7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.

Cell Temperature Fault Test

1. Set the simulated cell temperature signal to match the actual cell temperature.
2. Start a normal charge session.
3. Wait for approximately 1 minute for the charge to initialize and stabilize.
4. Alter the simulated cell temperature to reach the defined cell over temperature threshold (RESS-specific) and hold it there.
5. Observe the system behavior. Record any faults from the BMS and the DC charge station.
6. If necessary, stop the charge session.
7. If necessary, clear all vehicle faults and do a key cycle.
8. Reset the faults on the charge station as needed.

Other Fault Tests

1. Perform additional tests to cover all BMS related internal fault detections (e.g., high voltage interlock circuit, cooling system actuator disconnection, cooling system sensor disconnection, etc.).

6.15.6 End of Test Procedure

6.15.6.1 Disconnect the vehicle from the charger.

6.15.6.2 Remove all implanted BMS system faults and restore the RESS harness and components back to normal.

6.15.7 Data Acquisition and Documentation

6.15.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage. Measurements from the charging station can include target voltage, output

voltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.15.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.15.7.3 For all test conditions (Section 6.15.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger.
- Document any faults and/or DTCs on the vehicle/BMS.
- Document any faults and/or DTCs on the DC fast charge station.

6.15.8 Pass/Fail Evaluation Criteria

6.15.8.1 For faults introduced before a charge session is initiated, the pass/fail evaluation criteria are as follows:

- The BMS shall detect all implanted faults within a time frame that prevents an unsafe RESS condition. The vehicle shall remain in a safe state.

6.16 Overcharge Test

6.16.1 Purpose

6.16.1.1 The purpose of this test is to simulate an overcharge condition.

6.16.2 Rationale and Description

6.16.2.1 The DC charger could apply more current than is requested by the vehicle BMS due to a failure in communication between the vehicle and the charger or a defective DC power supply in the charger.

6.16.2.2 This test should be conducted by connecting to an equivalent battery tester with hardware/software to simulate the charge station operation. Alternately, if engineering access to the charge station software debugging interface is available, the test conditions can be achieved by modifying the signals using overrides that may be available in the charger software debugging interface.

6.16.2.3 This test will determine the reaction of the vehicle and DC charging system to an overcharge condition during an active charge session.

6.16.2.1 The overcharge test is established with controllable currents through the battery test equipment or modified charge station. The charge station software controls should be modified to report a current that is 15-20% less than the delivered current (e.g., charge at 55 A while only reporting 45 A).

6.16.3 Sample Preparation

6.16.3.1 This test requires a modified DC charger or battery tester with hardware/software to simulate the charge station operation.

6.16.3.2 Prepare the vehicle and RESS as defined in Section 5.8. Ensure that the vehicle high voltage system has no isolation fault that will endanger test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector. Do not proceed with overcharge testing if an isolation fault is detected.

6.16.4 Equipment Setup

6.16.4.1 Connect the modified DC charger or battery tester to the vehicle charge port without the breakout box.

6.16.4.2 Configure the modified DC charger or battery tester to allow the override of the current request signal coming from the vehicle.

6.16.5 Test Method and Procedure

6.16.5.1 Faults introduced during a fast charge session:

<u>Override of Current Request</u>

1. Start a charge session using the modified DC charger or battery tester. Ensure that the reported current level is 15-20% less than the delivered current.
2. Observe the system behavior. Record any faults from the BMS and the DC charge station.
3. If necessary, stop the charge session.
4. If necessary, clear all vehicle faults and do a key cycle.
5. Reset the faults on the charge station as needed.

6.16.6 End of Test Procedure

6.16.6.1 Disconnect the vehicle from the charger.

6.16.6.2 Store the vehicle in an open space area and monitor any heat generation (e.g., using a thermal imaging camera) for at least 72 hours.

6.16.6.3 Reduce the battery charge to 50% SOC and continue monitoring the thermal signature for 48 hours.

6.16.6.4 Perform a battery system check according to the manufacturer recommended practice to ensure that no long-term failure is present.

6.16.7 Data Acquisition and Documentation

6.16.7.1 Record information from the RESS and charger system as appropriate during testing using a sampling rate of at least 1 Hz. RESS measurements from the BMS can include voltage, current, SOC, temperature, and maximum cell voltage. Measurements from the charging station can include target voltage, output voltage, output current, and sensor levels (e.g., power supply enable, contactor status, ready for charging, etc.).

6.16.7.2 The time when events occurred during the test sequence should also be recorded (e.g., when charging started, when a fault was introduced, test termination, etc.).

6.16.7.3 For all test conditions (Section 6.16.5), record the following information:

- Document the system behavior and note any abnormal behavior from the vehicle or the charger.
- Document any faults and/or DTCs on the vehicle/BMS.
- Document any faults and/or DTCs on the DC fast charge station.

6.16.8 Pass/Fail Evaluation Criteria

6.16.8.1 For faults introduced during a fast charge session, the pass/fail evaluation criteria are as follows:

- The system shall stop or abort the charge session and bring the system to a safe state.
- The system shall also set a fault code to identify the problem.

7. APPENDIX A

This appendix provides example full-scale EV test results for various real world fault conditions that can occur before, during, and after DC charging. The purpose of this test report is to illustrate the BMS failure mode test methods and application; it is not intended to be a performance and safety evaluation for a manufacturer. Thus, evaluating the RESS relative to the primary acceptance criteria (i.e., risk of harm to the operator and the vehicle system) is not within the scope of this report. This appendix provides results for all test procedures defined in Section 6.0 except the following:

- System Overvoltage Test (12 V Board Net) (Section 6.5)
- 12 V System Disturbance Test (Section 6.7)
- 12 V System EMI/EMC Test (Section 6.8)
- Vehicle Crash or Bump Test (Section 6.10)
- BMS Internal Fault Detection (Section 6.15)

7.1 Test Facility/ Equipment

Testing was conducted with a 2014 Chevrolet Spark Electric Vehicle (see Figure 13) using the following equipment:

- A public charging station with an SAE fast charge port in Irvine, CA (Figure 14). The maximum available charge current for this station was 50 A.
- An engineering fast charging station with an SAE fast charge port in Santa Ana, CA. The maximum available charge current for this station was 70 A. It allowed the required software modifications to simulate some of the test conditions.
- A prototype breakout box (Figures 15 and 16).
- A Fluke DVM 289 (Figure 17a).
- A Fluke ScopeMeter 199C (Figure 17b).
- A Tektronix current probe A622 (Figure 18).
- A 12 V Everstart ES5LBS (4 Ah) lead acid battery (Figure 19).
- A CANalyzer (V8.0).
- A vehicle Scan Tool, "Global Diagnostic System 2".

Figure 13 - GM Spark test vehicle.

Figure 14 - Public charging station in Irvine, CA.

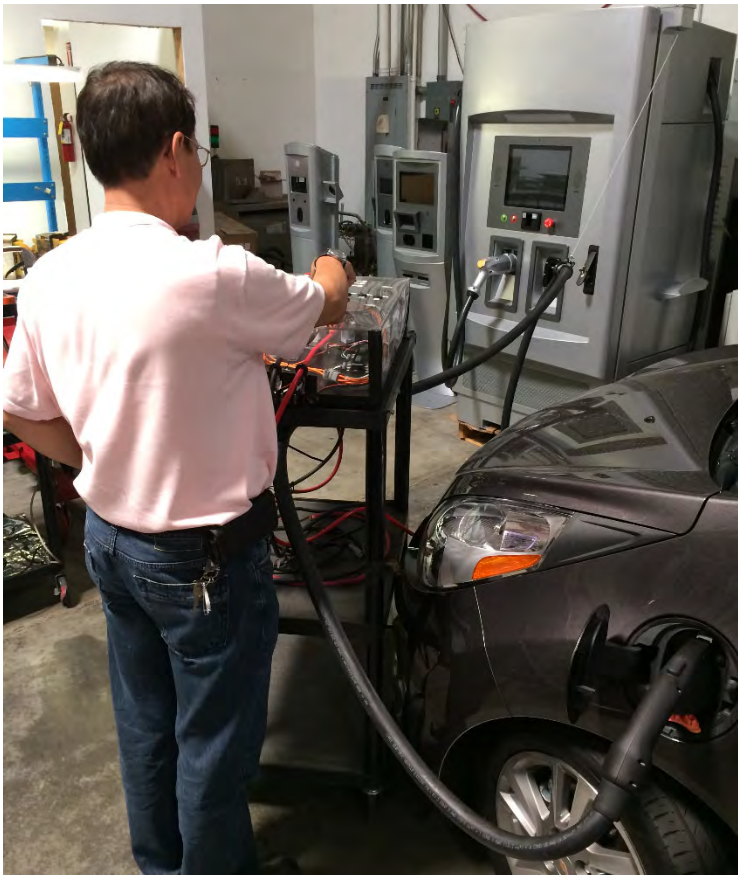


Figure 15 - Engineering charging station with breakout box installed.

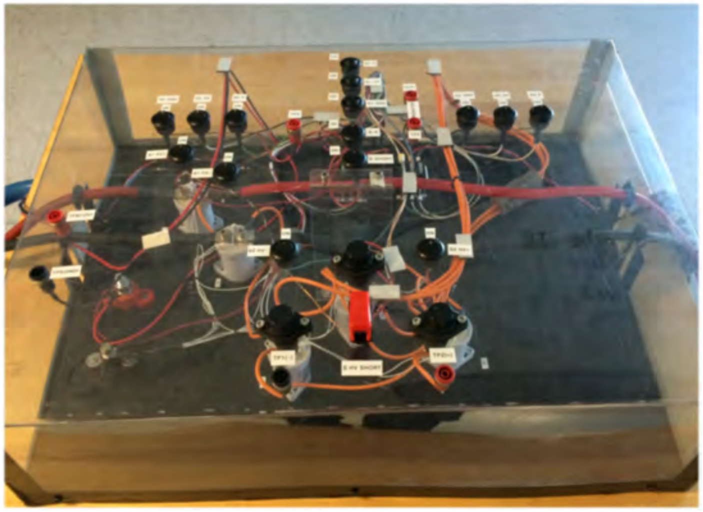
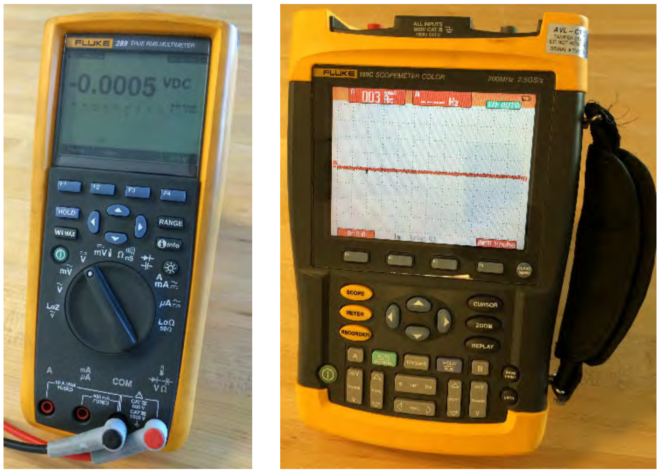


Figure 16 - Prototype breakout box.



(a) (b)

Figure 17 - (a) Fluke DVM and (b) Fluke hand held scope.

Figure 18 - Tektronix current probe.

Figure 19 - 12 V lead acid battery.

7.2 Visual Inspection of Charge Port

7.2.1.1 As specified in Section 5.9.4, the charge port and vehicle receptacle were visually inspected for any debris, mechanical damage, abrasions, distortions and/or discolorations.

7.2.1.2 No problems were detected on the vehicle side of the charge receptacle or the charger coupler side (see Figure 20).

Note: Extensive testing with the charger revealed an inadequate mechanical switch on the charge coupler connection. This led to repeated random charge start failures that required wiggling of the charge coupler. The mechanical interlock connection for this coupler was not optimal.

(a) (b)

(c) (d)

Figure 20 - Visual inspection of a) the vehicle charge receptacle, b) the vehicle charge receptacle (close-up), c) the charger coupler, and d) the charger coupler (close-up).

7.3 Test Results

7.3.1 Ground Fault Tests (Section 6.1)

7.3.1.1 Fault to ground – DC positive (before a charge session is initiated):

<u>System behavior:</u> A charging session was initiated after connecting a **24 kΩ** resistor between the HV positive and chassis ground at the breakout box. The vehicle control opened the contactors to interrupt charging after approximately 2 seconds with a fault. Figure 21 shows the attempted charging cycle and the shutdown at 88 seconds.

<u>Vehicle/BMS faults and/or DTCs:</u> The vehicle display showed "Not able to Fast Charge" and "Use Standard Cord". The following DTCs were set:

- P1E00: Hybrid Powertrain Control Module 2 Requested MIL illumination
- P300B: Hybrid/EV Battery DC Charging Output Current Performance

- P302F: Hybrid/EV Battery DC Charging System Isolation Lost

Charge station faults and/or DTCs: The charging station reported a fault and also shut down due to vehicle request for shutdown.

Pass/fail evaluation: **PASS** - the charge session was not fully initiated and the vehicle remained in a safe condition. Fault codes were set to identify the problem.

7.3.1.2 Fault to ground – DC negative (before a charge session is initiated):

System behavior: A charging session was initiated after connecting a **24 kΩ** resistor between the HV negative and chassis ground at the breakout box. The vehicle control opened contactors to interrupt charging after approximately 2 seconds with a fault. Figure 22 shows the attempted charging cycle and the shutdown at 139 seconds.

Vehicle/BMS faults and/or DTCs: The vehicle display showed "Not able to Fast Charge" and "Use Standard Cord". The following DTCs were set:

- P302F: Hybrid/EV Battery DC Charging System Isolation Lost

Charge station faults and/or DTCs: The charging station reported a fault and also shut down.

Pass/fail evaluation: **PASS** - the charge session was not fully initiated and the vehicle remained in a safe condition. Fault codes were set to identify the problem.

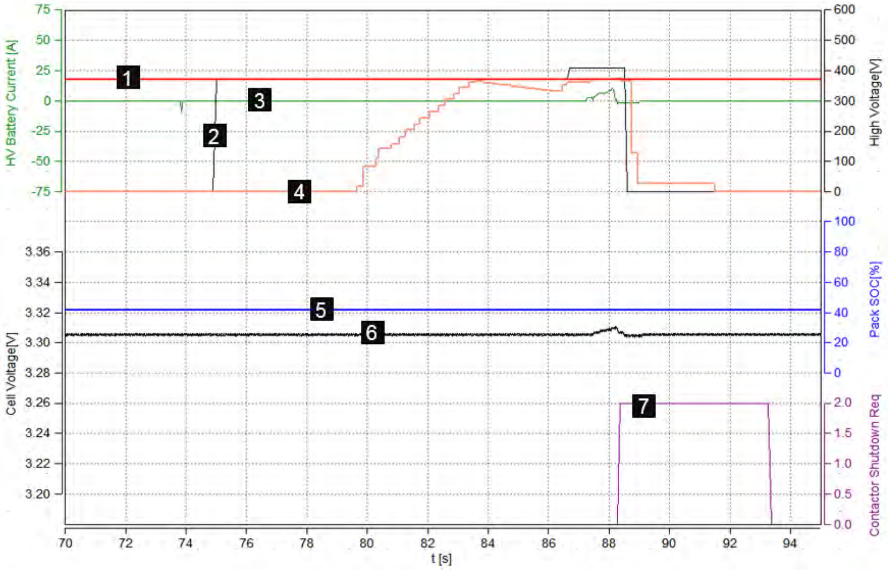


Figure 21 - Charging cycle and shutdown at 88 seconds for a fault introduced on the DC positive before a charge session is initiated.

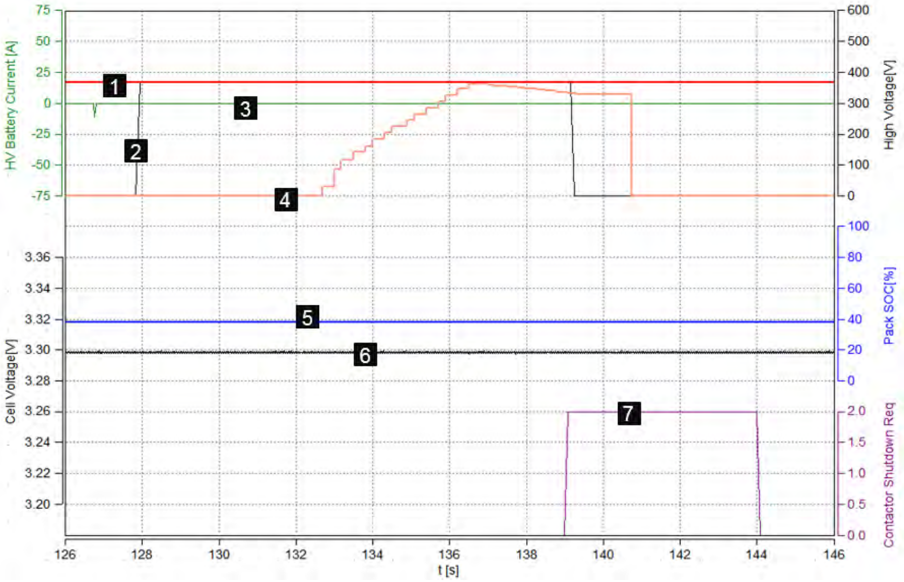


Figure 22 - Charging cycle and shutdown at 139 seconds for a fault introduced on the DC negative before a charge session is initiated.

<u>Legend</u>:

1 HV Battery Voltage [V] sensed by BMS
2 Off Board HV Charging Station Target Voltage [V]
3 HV Battery Current [A] sensed by BMS
4 Off Board HV Charging Station Voltage Output [V]
5 Customer Usable State of Charge [%]
6 HV Battery Cell Voltage (single) [V]
7 HV Contactor Shutdown Req. (1=Emergency; 2=Controlled; 3=Emergency Crash)

7.3.1.3 Fault – ground connection between station and vehicle removed (before a charge session is initiated):

System behavior: A charging session was initiated after removing the chassis ground connection between the charging station and vehicle at the breakout box. There was no reaction on vehicle side; the charge station timed out after several communication attempts and shut down. Figure 23 shows the attempted charging cycle.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the charge session was not started and the vehicle remained in a safe condition. No fault codes were set to identify the problem.

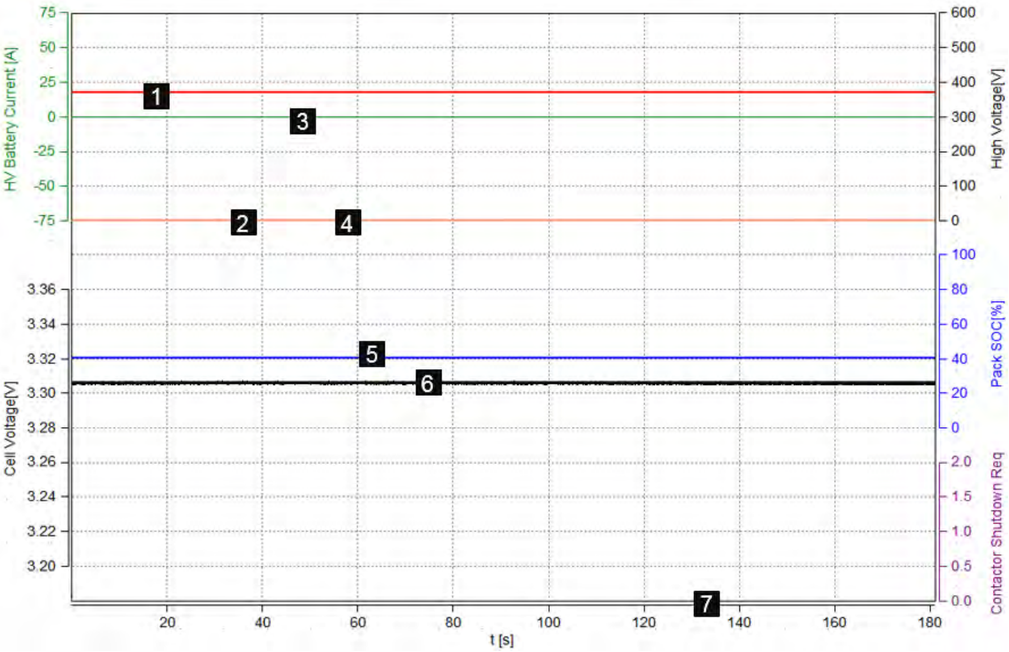


Figure 23 - Attempted charging cycle when the ground connection between station and vehicle is removed before a charge session is initiated.

Legend:
1 HV Battery Voltage [V] sensed by BMS
2 Off Board HV Charging Station Target Voltage [V]
3 HV Battery Current [A] sensed by BMS
4 Off Board HV Charging Station Voltage Output [V]
5 Customer Usable State of Charge [%]
6 HV Battery Cell Voltage (single) [V]
7 HV Contactor Shutdown Req. (1=Emergency; 2=Controlled; 3=Emergency Crash)

7.3.1.4 Fault to ground – DC positive (during a fast charge session):

System behavior: Approximately 60 seconds after a charging session was started, a **24 kΩ** resistor was connected between the HV positive and chassis ground at the breakout box. The vehicle control opened contactors to interrupt charging after approximately 30 seconds with a fault. Figure 24 shows the charging cycle and the shutdown at 193 seconds.

Vehicle/BMS faults and/or DTCs: The vehicle display showed "Not able to Fast Charge" and "Use Standard Cord". The following DTCs were set:

- P302F: Hybrid/EV Battery DC Charging System Isolation Lost

Charge station faults and/or DTCs: The charging station reported a fault and also shut down.

Pass/fail evaluation: **PASS** - the system stopped the charge session and the vehicle remained in a safe condition. Fault codes were set to identify the problem.

7.3.1.5 Fault to ground – DC negative (during a fast charge session):

System behavior: Approximately 60 seconds after a charging session was started, a **24 kΩ** resistor was connected between the HV negative and chassis ground at the breakout box. The vehicle control opened contactors to interrupt charging after approximately 3 seconds with a fault. Figure 25 shows the charging cycle and the shutdown at 117 seconds.

Vehicle/BMS faults and/or DTCs: The vehicle display showed "Not able to Fast Charge" and "Use Standard Cord". The following DTCs were set:

- P302F – Hybrid/EV Battery DC Charging System Isolation Lost

Charge station faults and/or DTCs: The charging station reported a fault and also shut down.

Pass/fail evaluation: **PASS** - the system stopped the charge session and the vehicle remained in a safe condition. Fault codes were set to identify the problem.

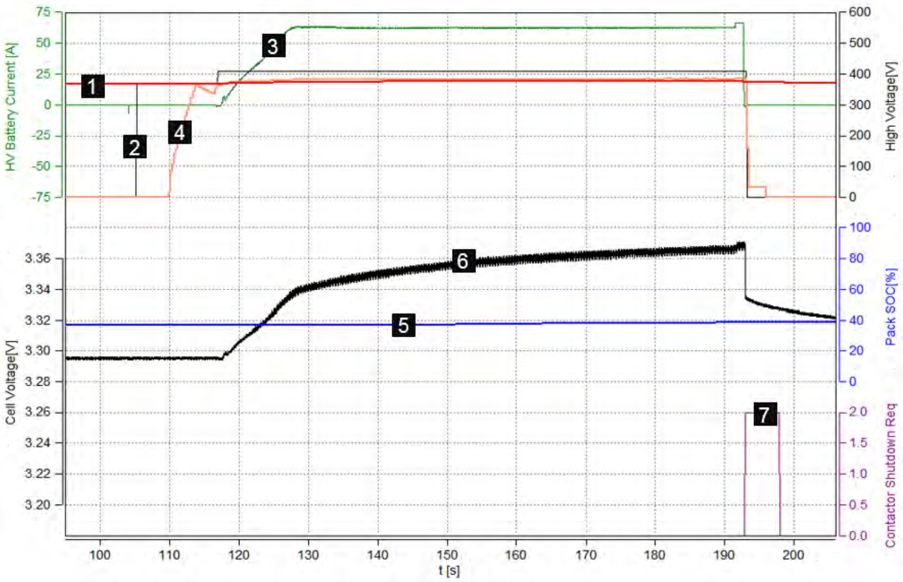


Figure 24 - Charging cycle and shutdown at 193 seconds for a fault introduced on the DC positive during a charge session.

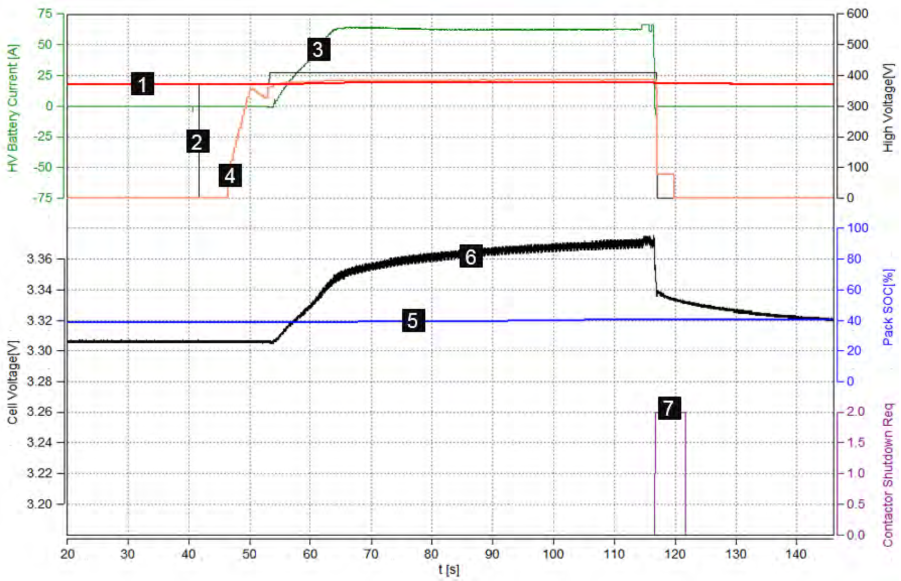


Figure 25 - Charging cycle and shutdown at 117 seconds for a fault introduced on the DC negative during a charge session.

Legend:

1 HV Battery Voltage [V] sensed by BMS
2 Off Board HV Charging Station Target Voltage [V]
3 HV Battery Current [A] sensed by BMS
4 Off Board HV Charging Station Voltage Output [V]
5 Customer Usable State of Charge [%]
6 HV Battery Cell Voltage (single) [V]
7 HV Contactor Shutdown Req. (1=Emergency; 2=Controlled; 3=Emergency Crash)

7.3.1.6 Fault – ground connection between station and vehicle removed (during a fast charge session):

System behavior: Approximately 79 seconds after a charging session was started, the chassis ground connection between the charging station and vehicle was removed at the breakout box. Charging was interrupted and the charge station shut down. The vehicle sounded its horn after approximately 30 seconds. Figure 26 shows the attempted charging cycle.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the system stopped the charge session and the vehicle remained in a safe condition. No fault codes were set to identify the problem.

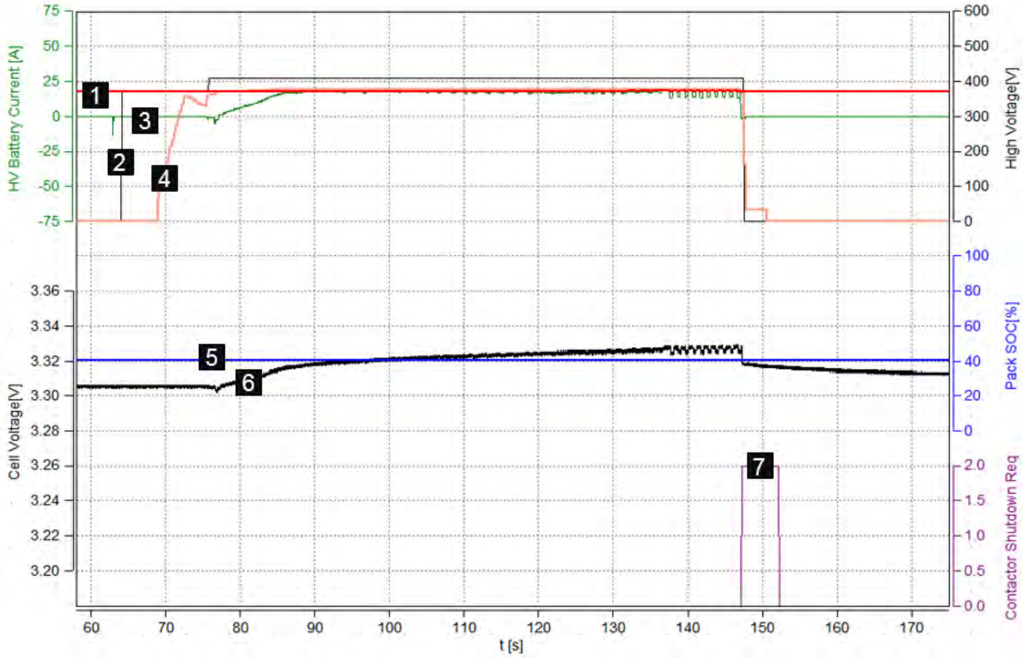


Figure 26 - Attempted charging cycle when the ground connection between station and vehicle is removed during a charge session.

<u>Legend</u>:

1 HV Battery Voltage [V] sensed by BMS
2 Off Board HV Charging Station Target Voltage [V]
3 HV Battery Current [A] sensed by BMS
4 Off Board HV Charging Station Voltage Output [V]
5 Customer Usable State of Charge [%]
6 HV Battery Cell Voltage (single) [V]
7 HV Contactor Shutdown Req. (1=Emergency; 2=Controlled; 3=Emergency Crash)

7.3.2 Chassis Ground Offset Tests (Section 6.2)

These are example test results; not all of resistance values specified in the procedure are included herein. Missing test results would be conducted in a similar fashion.

7.3.2.1 Chassis ground offset fault at 100Ω (before a charge session is initiated):

System behavior: A charging session was initiated after connecting a **100Ω** resistor between the vehicle and charger ground connection at the breakout box. The charge station was unable to establish communication. The measured voltage between chassis ground and earth (station) ground (**TP4** - **TP5**) toggled (0 V / 0.3 V) across the 100Ω resistor. Figure 27 shows the charging cycle.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: The charge station shut down with a fault of “Unexpected Proximity Signal Fault”.

Pass/fail evaluation: **PASS** - the charge session was not started and the vehicle remained in a safe condition. A fault code was issued and the voltage (TP4 - TP5) was less than 0.7 V.

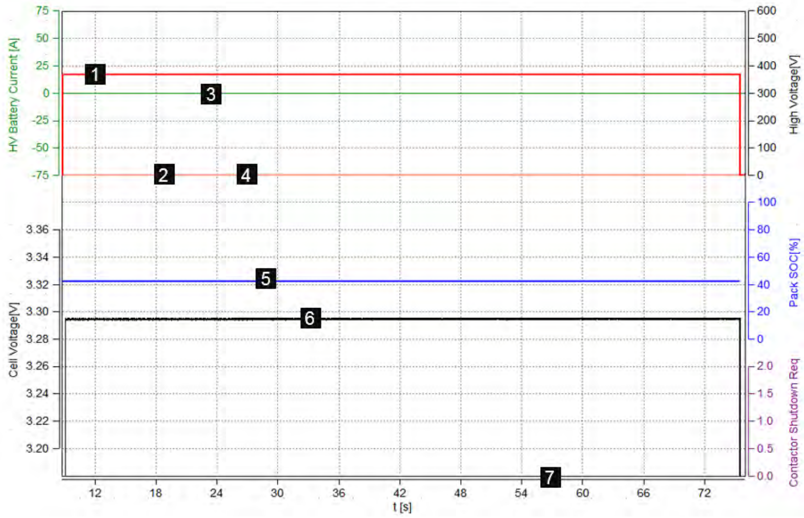


Figure 27 - Chassis ground offset with a 100Ω resistor before a fast charge is initiated.

Legend:

1 HV Battery Voltage [V] sensed by BMS
2 Off Board HV Charging Station Target Voltage [V]
3 HV Battery Current [A] sensed by BMS
4 Off Board HV Charging Station Voltage Output [V]
5 Customer Usable State of Charge [%]
6 HV Battery Cell Voltage (single) [V]
7 HV Contactor Shutdown Req. (1=Emergency; 2=Controlled; 3=Emergency Crash)

7.3.2.2 Chassis ground offset fault at 47Ω (before a charge session is initiated):

System behavior: A charging session was initiated after connecting a **47Ω** resistor between the vehicle and charger ground connections at the breakout box. The measured voltage between chassis ground and earth (station) ground (**TP4 - TP5**) before charging started was 0.138 V across the 47Ω resistor. Once charging communication was established, the voltage across **TP4 - TP5** measured 0.012 V. The charging current ramped up to 65A; after approximately 20 seconds, charging was interrupted and the charging station shut down. Figure 28 shows the charging cycle.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **FAIL** - although the vehicle remained in a safe state, a charge session was started and terminated after 20 seconds. The voltage (TP4 - TP5) remained lower than 0.7 V. No fault codes were set.

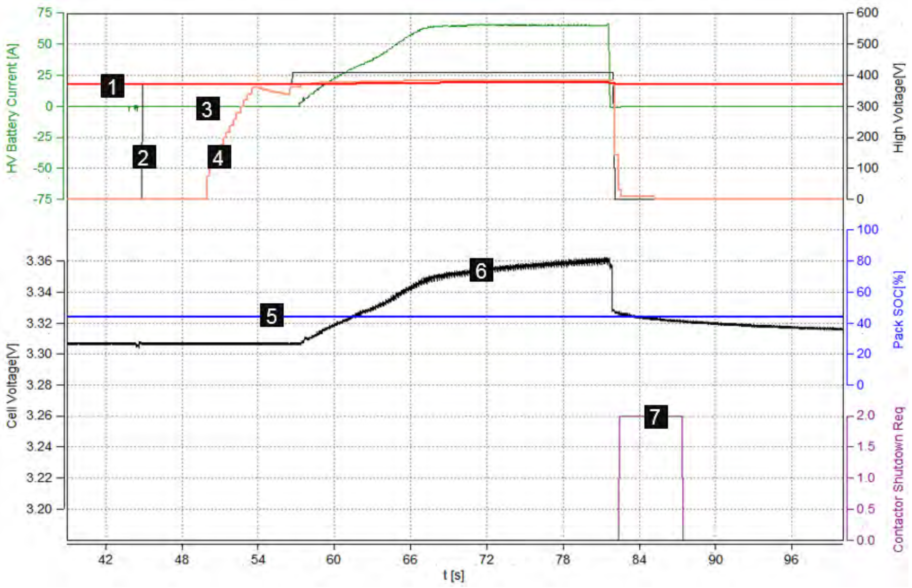


Figure 28 - Chassis ground offset with a 47Ω resistor before a fast charge is initiated.

Legend:

1 HV Battery Voltage [V] sensed by BMS
2 Off Board HV Charging Station Target Voltage [V]
3 HV Battery Current [A] sensed by BMS
4 Off Board HV Charging Station Voltage Output [V]
5 Customer Usable State of Charge [%]
6 HV Battery Cell Voltage (single) [V]
7 HV Contactor Shutdown Req. (1=Emergency; 2=Controlled; 3=Emergency Crash)

7.3.2.3 Chassis ground offset fault at 24Ω (before a charge session is initiated):

System behavior: A charging session was initiated after connecting a **24Ω** resistor between the vehicle and charger ground connections at the breakout box. Once charging communication was established, the measured between chassis ground and earth (station) ground (**TP4** - **TP5**) was 0.07 V across the 24Ω resistor. The charging current ramped up to 65 A and continued without interruption until it was stopped manually by the operator. Figure 29 shows the charging cycle.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No issues on charging station observed.

Pass/fail evaluation: **FAIL** - although the vehicle remained in a safe state, the charge session was terminated manually by the operator. The voltage (TP4 - TP5) remained lower than 0.7 V. No fault codes were set to identify the problem.

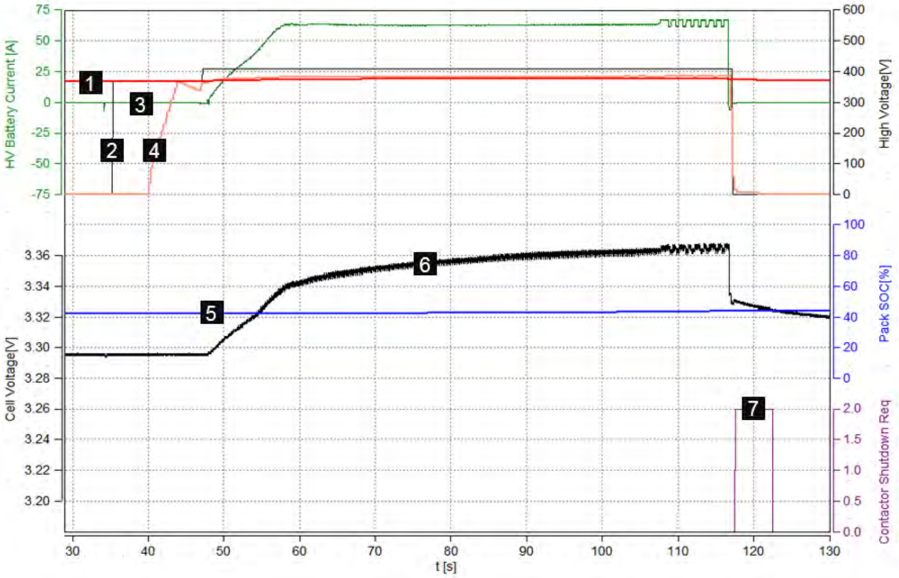


Figure 29 - Chassis ground offset with a 24Ω resistor before a fast charge is initiated.

Legend:

1	HV Battery Voltage [V] sensed by BMS
2	Off Board HV Charging Station Target Voltage [V]
3	HV Battery Current [A] sensed by BMS
4	Off Board HV Charging Station Voltage Output [V]
5	Customer Usable State of Charge [%]
6	HV Battery Cell Voltage (single) [V]
7	HV Contactor Shutdown Req. (1=Emergency; 2=Controlled; 3=Emergency Crash)

7.3.2.4 Chassis ground offset fault at 1 kΩ (during a fast charge session):

System behavior: After a charging session was started, a **1 kΩ** resistor was connected between the vehicle and charger ground connections at the breakout box. Upon insertion of the resistance, the charging interrupted and the charge station shut down. The measured voltage between chassis ground and earth (station) ground (**TP4 - TP5**) was 2.9 V. Figure 30 shows the charging cycle.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **FAIL** - although the system stopped the charge session and the vehicle remained in a safe condition, the voltage (TP4 - TP5) was greater than 0.7 V. No fault codes were set to identify the problem.

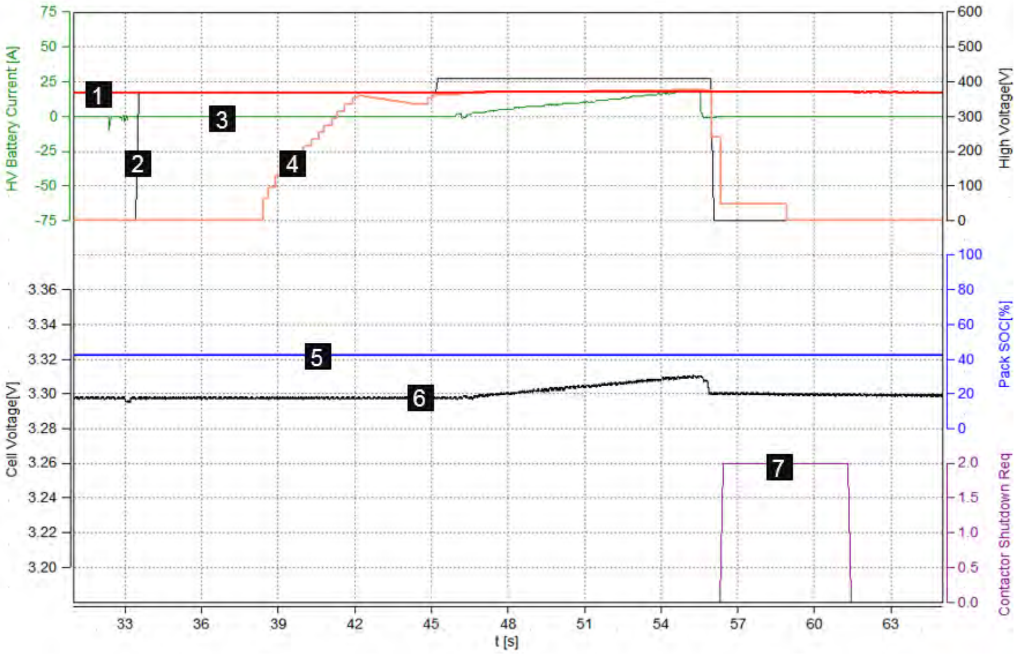


Figure 30 - Chassis ground offset with a 1 kΩ resistor during a charge session.

Legend:

1 HV Battery Voltage [V] sensed by BMS
2 Off Board HV Charging Station Target Voltage [V]
3 HV Battery Current [A] sensed by BMS
4 Off Board HV Charging Station Voltage Output [V]
5 Customer Usable State of Charge [%]
6 HV Battery Cell Voltage (single) [V]
7 HV Contactor Shutdown Req. (1=Emergency; 2=Controlled; 3=Emergency Crash)

7.3.3 DC Bus Short Test (Section 6.3)

7.3.3.1 DC bus short in the charge coupler (before a charge session is initiated):

System behavior: A fused short was installed on the charge coupler side by activating switches **S1_HV-** and **S1_HV+** at the breakout box. A charge session was attempted, but it did not succeed and the station timed out after several attempts. The vehicle did not attempt to activate the contactors due to 0 V at the input. Figure 31 shows the charging cycle (note that the values shown correspond to the red vertical line).

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the charge session was not started and the vehicle remained in a safe condition. Note that this example test report does not convey the condition of the fuse as required.

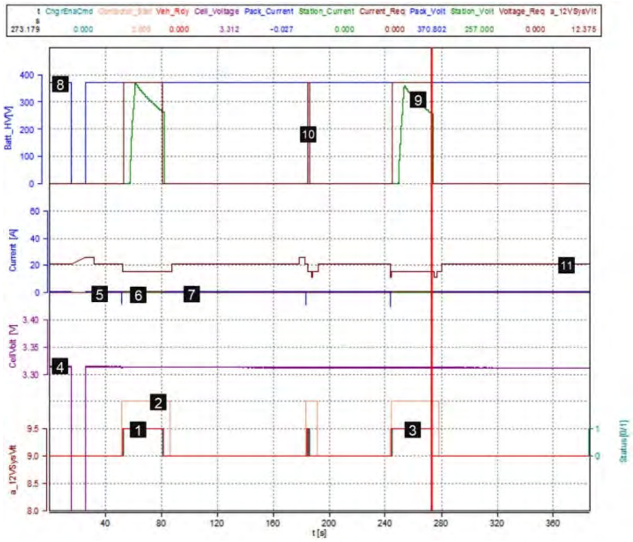


Figure 31 - DC bus short in the charge couple before a fast charge is initiated.

Legend:

1	Charger HV Power Supply Enable [0/1]	{light green}
2	HV Contactor Status [0/1] (0=Open; 1=Pre-charge; 2=Close)	{tan}
3	Vehicle Ready for Charging [0/1] (0=False; 1=True)	{red}
4	HV Battery Cell Voltage (single) [V]	{purple}
5	HV Battery Current [A] sensed by BMS	{blue}
6	Off Board HV Charging Station Current Output [A]	{green}
7	Off Board HV Charging Station Current Request [A]	{brown}
8	HV Battery Voltage [V] sensed by BMS	{blue}
9	Off Board HV Charging Station Voltage Output [V]	{green}
10	Off Board HV Charging Station Target Voltage [V]	{brown}
11	12 V System Voltage [V]	{brown}

7.3.4 DC Bus Held High Tests (Section 6.4)

7.3.4.1 DC bus held high (before a charge session is initiated):

System behavior: A charging session was initiated after applying 62 V to the HV lines using a power supply and the breakout box. The charging operation started without any issues and with no fault indication. After stopping the charging operation manually, the system shut down normally. The 62 V were still present at the HV lines. The mechanical lock was released by the vehicle and the charge coupler could be removed without any issues. There was no indication from the charge station that 62 V were still at the coupler. Figure 32 shows the charging cycle (note that the values shown correspond to the red vertical line).

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **FAIL** - a charge session started with 62 V on the HV lines and the connector could be removed once the charging was manually terminated. The system was not in a safe state and no fault codes were set to identify the problem. The charger station did not indicate the presence of high voltage at the charge coupling contacts.

7.3.4.2 DC bus held high (after a charge session is ended):

System behavior: Using a 3300μF capacitor (with a 5 kΩ parallel bleed down resistor), the HV at the charge coupler was kept high after a normal charging session was stopped. The voltage started bleeding down and the vehicle released the mechanical lock of the charge coupler at approximately 240 V. It was then possible to disconnect the charge coupler (with 240 V still on the contacts).

Vehicle/BMS faults and/or DTCs: An indication on the vehicle display provided a charging problem alert: "Problem Detected with charging station". The following DTCs were set:

- U18A4: Lost Communication with Hybrid/EV Battery DC Charging Communication Gateway

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **FAIL** - the charge connector could be removed from the vehicle coupler with a high voltage (240 V) present at the end of a charge session. A DTC was set and the system was not in a safe state. The charger station did not indicate the presence of high voltage at the charge coupling contacts.

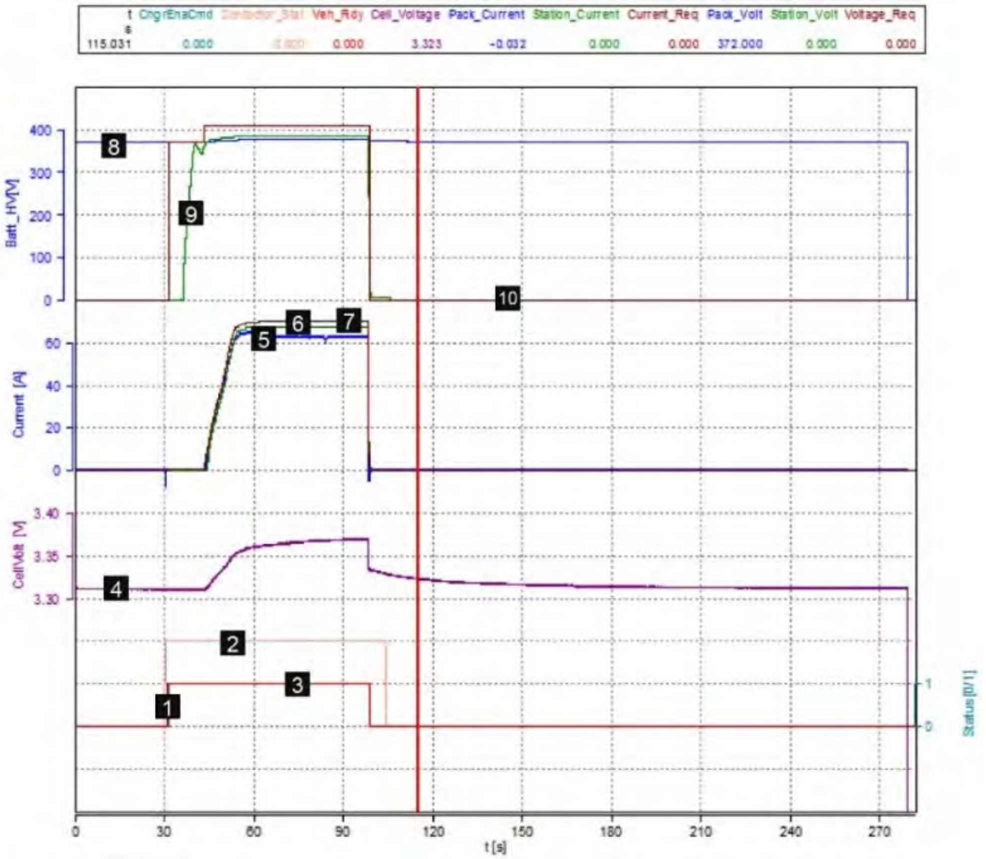


Figure 32 - DC bus held high before a fast charge is initiated.

Legend:

1	Charger HV Power Supply Enable [0/1]	{light green}
2	HV Contactor Status [0/1] (0=Open; 1=Pre-charge; 2=Close)	{tan}
3	Vehicle Ready for Charging [0/1] (0=False; 1=True)	{red}
4	HV Battery Cell Voltage (single) [V]	{purple}
5	HV Battery Current [A] sensed by BMS	{blue}
6	Off Board HV Charging Station Current Output [A]	{green}
7	Off Board HV Charging Station Current Request [A]	{brown}
8	HV Battery Voltage [V] sensed by BMS	{blue}
9	Off Board HV Charging Station Voltage Output [V]	{green}
10	Off Board HV Charging Station Target Voltage [V]	{brown}

7.3.5 System Overvoltage Tests (12 V Board Net) (Section 6.5)

7.3.5.1 This test procedure was not performed.

7.3.6 12 V System Under Voltage Test (Section 6.6)

7.3.6.1 Under voltage due to battery discharge (during a charge session):

System behavior: A small (4Ah) 12 V battery and power supply was installed and used to slowly drop the battery voltage (0.5 V/min) during a charge session. The vehicle aborted charging at around 10 V. Figure 33 shows the charging cycle (note that the values shown correspond to the red vertical line).

Vehicle/BMS faults and/or DTCs: The following DTCs were set:

- P0562 – System Voltage Low Voltage

Charge station faults and/or DTCs: No faults or DTCs were reported.

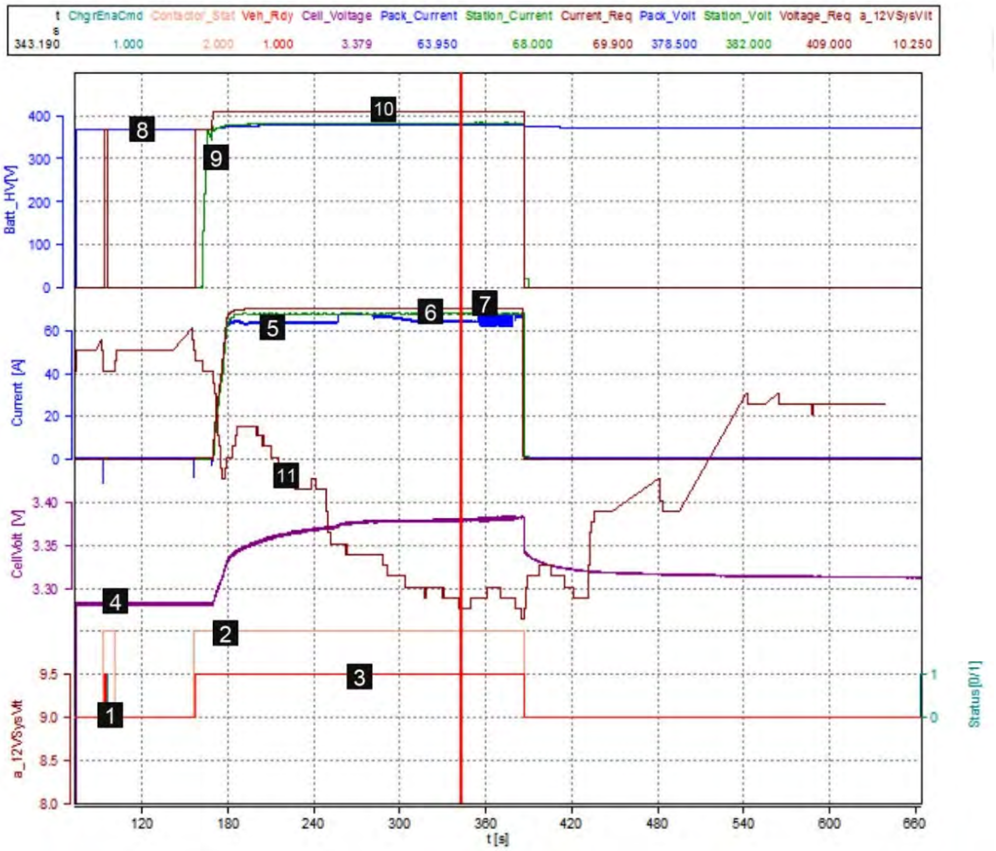
Pass/fail evaluation: **PASS** - the system stopped the charge session and the vehicle was brought to a safe condition.

7.3.7 12 V System Disturbance Test (Section 6.7)

7.3.7.1 This test procedure was not performed.

7.3.8 12 V System EMI/EMC Test (Section 6.8)

7.3.8.1 This test procedure was not performed.



t s	ChgrEnaCmd	Contactor_Stat	Veh_Rdy	Cell_Voltage	Pack_Current	Station_Current	Current_Req	Pack_Volt	Station_Volt	Voltage_Req	a_12VSysVlt
343.190	1.000	2.000	1.000	3.379	63.950	68.000	69.900	378.500	382.000	409.000	10.250

Figure 33 - Slow reduction of 12 V during a charge session.

Legend:

1	Charger HV Power Supply Enable [0/1]	{light green}
2	HV Contactor Status [0/1] (0=Open; 1=Pre-charge; 2=Close)	{tan}
3	Vehicle Ready for Charging [0/1] (0=False; 1=True)	{red}
4	HV Battery Cell Voltage (single) [V]	{purple}
5	HV Battery Current [A] sensed by BMS	{blue}
6	Off Board HV Charging Station Current Output [A]	{green}
7	Off Board HV Charging Station Current Request [A]	{brown}
8	HV Battery Voltage [V] sensed by BMS	{blue}
9	Off Board HV Charging Station Voltage Output [V]	{green}
10	Off Board HV Charging Station Target Voltage [V]	{brown}
11	12 V System Voltage [V]	{brown}

7.3.9 Vehicle Movement Tests (Section 6.9)

7.3.9.1 Drive away attempt - parking brake release (during a charge session):

System behavior: After a charging session was started, pressing the electronic parking brake release did not release the parking brake. The parking brake was electronically controlled and actuated at the time the charger established communication with the vehicle and the bus pre-charge was performed.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the vehicle prevented movement despite operator interference. The vehicle remained in a safe state.

7.3.9.2 Drive away attempt - turn on vehicle (during a charge session):

System behavior: The vehicle ignition could be turned on during a fast charge operation. All comfort functions were operational (including AC); the dash indicator showed “Charge Cord Connected”; power steering was operational. There was no impact on charging behavior.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the vehicle prevented movement despite operator interference. The vehicle remained in a safe state.

7.3.9.3 Drive away attempt – PRND to Drive (during a charge session):

System behavior: The shift lever was locked, so it was not possible to move out of park. This attempted action did not interrupt charging; there was no impact on charging behavior.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the vehicle prevented movement despite operator interference. The vehicle remained in a safe state.

7.3.9.4 Drive away attempt – PRND to Neutral (during a charge session):

System behavior: The shift lever was locked, so it was not possible to move out of park. This attempted action did not interrupt charging; there was no impact on charging behavior.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the vehicle prevented movement despite operator interference. The vehicle remained in a safe state.

7.3.9.5 Drive away attempt – PRND to Reverse (during a charge session):

System behavior: The shift lever was locked, so it was not possible to move out of park. This attempted action did not interrupt charging; there was no impact on charging behavior.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the vehicle prevented movement despite operator interference. The vehicle remained in a safe state.

7.3.9.6 Simulated vehicle movement – rotate wheels (during a charge session):

System behavior: The parking brake was electronically controlled and actuated at the time the charger established communication with the vehicle and the bus pre-charge was performed. Thus, rotating the wheels was not possible.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the vehicle prevented movement despite operator interference. The vehicle remained in a safe state.

7.3.10 Vehicle Crash or Bump Tests (Section 6.10)

7.3.10.1 This test procedure was not performed.

7.3.11 Charge Operation Disturbance Tests (Section 6.11)

7.3.11.1 Premature disconnect attempt (during a charge session):

System behavior: After a charging session was started, an attempt was made to disconnect the charge coupler from the vehicle without pressing the stop button on the charger. Pushing the release button stopped the charging and the charger handle could be released after several seconds. The vehicle switched to normal operation mode (with the parking brake on); it was fully operational without requirement to key cycle.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the vehicle initiated a shutdown and remained in a safe condition.

7.3.11.2 Operator interference at the charger (during a charge session):

System behavior: All of the touch screen buttons were pressed. None (except "Stop") changed the charging behavior. The "Stop" button discontinued charging and the vehicle switched out of charging mode. Several "Stop" button presses after charging discontinued caused the charger to issue a fault (see below). After removing and reinserting the charge coupler into the vehicle and reactivating the charge, the vehicle resulted in a "Fast Charging Stopped" mode on the operator display and the station was stuck in "Preparing to charge; Communicating to vehicle" mode.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: A fault was issued after several "Stop" button presses once charging discontinued: "No CAN communication, Terminal out of service".

Pass/fail evaluation: **PASS** - the vehicle initiated a shutdown and remained in a safe condition.

7.3.11.3 Wiggle the connector (during a charge session):

System behavior: Wiggling the connector was unable to disturb the charge operation. There was no impact on charging behavior.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the vehicle had no reaction and remained in a safe condition.

7.3.11.4 Operator interference on the vehicle (during a charge session):

System behavior: The vehicle ignition could be turned on during a fast charge operation. All comfort functions were operational (including AC); the dash indicator showed "Charge Cord Connected"; power steering is operational. There was no impact on charging behavior.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the vehicle had no reaction and remained in a safe condition.

7.3.11.5 Operator interference with the vehicle key fob (during a charge session):

System behavior: After a charging session was started, all key fob functions were actuated by pressing buttons (e.g., unlock doors, turn on HVAC remotely during a charge, etc.). None of key fob functions disturbed the charge operation; there was no impact on charging behavior.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the vehicle had no reaction and remained in a safe condition.

7.3.11.6 Operator interference with remote telematics (during a charge session):

System behavior: N/A - telematics functions were not available for this vehicle.

7.3.12 Charge Connector Control Signal Disturbance Tests (Section 6.12)

These are example test results; not all of disturbance tests specified in the procedure are included herein. Missing test results would be conducted in a similar fashion.

7.3.12.1 Control pilot interruption (during a charge session):

System behavior: After approximately 10 seconds at full current during a charging session, the control pilot signal was interrupted using the breakout box. Charging continued for approximately 3 seconds and then interrupted; the charger returned to its initial state. Figure 34 shows the charging cycle (the values shown in Figure 34 correspond to the red vertical line at 53 seconds where the control pilot signal was interrupted).

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the system stopped the charge session and the vehicle was brought to a safe state.

7.3.12.2 Control pilot short to ground (during a charge session):

System behavior: After approximately 20 seconds at full current during a charging session, a short to ground on the control pilot signal was generated using the breakout box. Charging was interrupted immediately; the charger returned to its initial state. Figure 35 shows the charging cycle (note that 20 seconds at full current corresponds to 83 seconds of test measurement time; the values shown correspond to the red vertical line at 83 seconds where a short to ground was introduced on the control pilot signal).

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the system stopped the charge session and the vehicle was brought to a safe state.

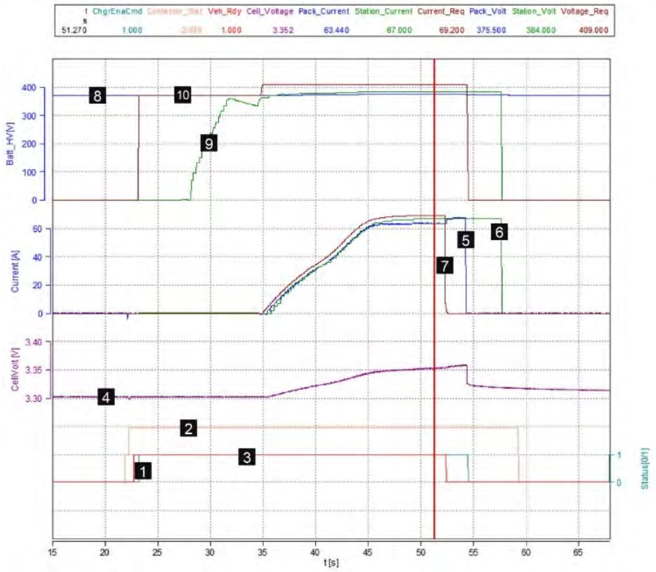


Figure 34 - Control pilot interruption during a charge session.

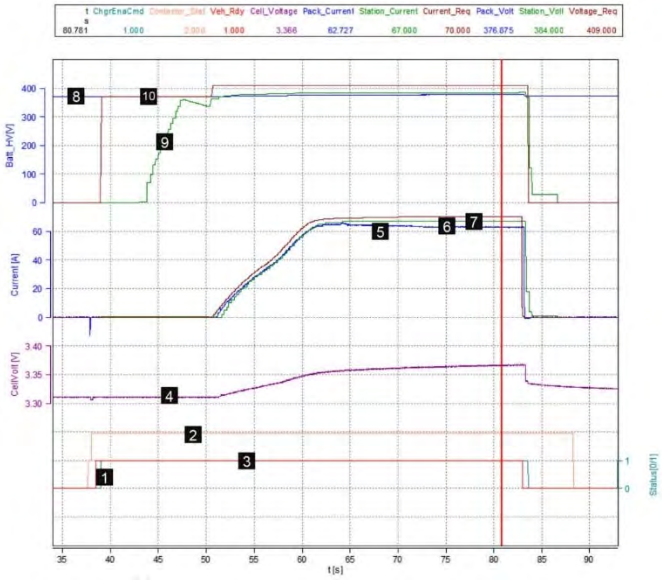


Figure 35 - Control pilot short to ground during a charge session.

<u>Legend</u>:

1	Charger HV Power Supply Enable [0/1]	{light green}
2	HV Contactor Status [0/1] (0=Open; 1=Pre-charge; 2=Close)	{tan}
3	Vehicle Ready for Charging [0/1] (0=False; 1=True)	{red}
4	HV Battery Cell Voltage (single) [V]	{purple}
5	HV Battery Current [A] sensed by BMS	{blue}
6	Off Board HV Charging Station Current Output [A]	{green}
7	Off Board HV Charging Station Current Request [A]	{brown}
8	HV Battery Voltage [V] sensed by BMS	{blue}
9	Off Board HV Charging Station Voltage Output [V]	{green}
10	Off Board HV Charging Station Target Voltage [V]	{brown}

7.3.12.3 Proximity interruption (during a charge session):

System behavior: After approximately 20 seconds at full current during a charging session, the proximity signal was interrupted using the breakout box. Charging continued without any interruption until manually stopped by the operator. Figure 36 shows the charging cycle (note that 20 seconds at full current corresponds to 30 seconds of test measurement time; the values shown correspond to the red vertical line at 30 seconds where the proximity signal was interrupted).

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **FAIL (inability to verify)** - although the vehicle remained in a safe condition, the charge session had to be stopped manually. It was determined that the station did not monitor the proximity signal, so it did not perform any action or provide any feedback; the vehicle still had a valid proximity signal available. The ability to interrupt the proximity signal is required to successfully pass this test.

7.3.12.4 Proximity short to ground (during a charge session):

System behavior: After a charging session was started, a short to ground on the proximity signal was generated using the breakout box. Charging was interrupted immediately. The charger detected an overvoltage at its output and the vehicle forced the contactors open. Figure 37 shows the charging cycle (note that the values shown correspond to the red vertical line at approximately 90 seconds where a short to ground was introduced on the proximity signal).

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **FAIL (inability to verify)** - the system stopped the charge session and the vehicle was brought to a safe state. The station did not monitor the proximity signal and did not perform any action at the time the signal was shorted. This led to the overvoltage condition and subsequent shutdown on the station side. It also meant that the vehicle interrupted the charging cycle by opening the contactors during full current operation, which can lead to major degradation and potential welding of the contactors. It would therefore be a good practice on the station side to monitor the proximity signal during high current charge operation and drastically reduce the charge current as soon as a proximity signal short to ground condition is detected.

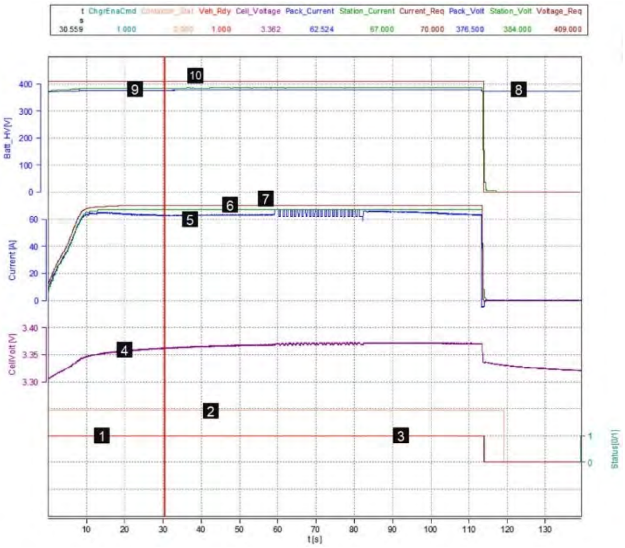


Figure 36 - Proximity interruption during a charge session.

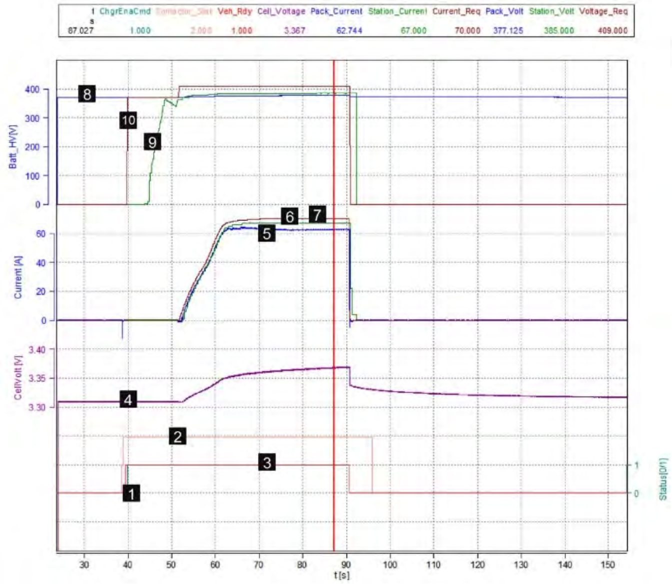


Figure 37 - Proximity short to ground during a charge session.

Legend:

1	Charger HV Power Supply Enable [0/1]	{light green}
2	HV Contactor Status [0/1] (0=Open; 1=Pre-charge; 2=Close)	{tan}
3	Vehicle Ready for Charging [0/1] (0=False; 1=True)	{red}
4	HV Battery Cell Voltage (single) [V]	{purple}
5	HV Battery Current [A] sensed by BMS	{blue}
6	Off Board HV Charging Station Current Output [A]	{green}
7	Off Board HV Charging Station Current Request [A]	{brown}
8	HV Battery Voltage [V] sensed by BMS	{blue}
9	Off Board HV Charging Station Voltage Output [V]	{green}
10	Off Board HV Charging Station Target Voltage [V]	{brown}

7.3.12.5 Control pilot resistance at 24Ω (before a charge session is initiated):

System behavior: A charging session was initiated after connecting a **24Ω** resistor inline the control pilot signal using the breakout box. During charging, the measured voltage across the control pilot signal (**TP3** – **TP4**) measured -0.007 V. Charging continued without any impact and was stopped manually. Data are not available for this test.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **FAIL** - although the vehicle remained in a safe state, the charge session was terminated manually by the operator.

7.3.12.6 Control pilot resistance at 47Ω (before a charge session is initiated):

System behavior: A charging session was initiated after connecting a **47Ω** resistor inline the control pilot signal using the breakout box. During charging, the measured voltage across the control pilot signal (**TP3** – **TP4**) measured -0.012 V. Charging continued without any impact and was stopped manually. Figure 38 shows the charging cycle (note that the values shown correspond to the red vertical line).

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **FAIL** - although the vehicle remained in a safe state, the charge session was terminated manually by the operator.

7.3.12.7 Control pilot resistance at 100Ω (before a charge session is initiated):

System behavior: A charging session was initiated after connecting a **100Ω** resistor inline the control pilot signal using the breakout box. The measured voltage across the 100Ω resistor (**TP3** – **TP4**) before charging started was -0.293 V. During charging, it measured -0.024 V. Charging continued without any impact and was stopped manually. Figure 39 shows the charging cycle (note that the values shown correspond to the red vertical line).

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **FAIL** - although the vehicle remained in a safe state, the charge session was terminated manually by the operator.

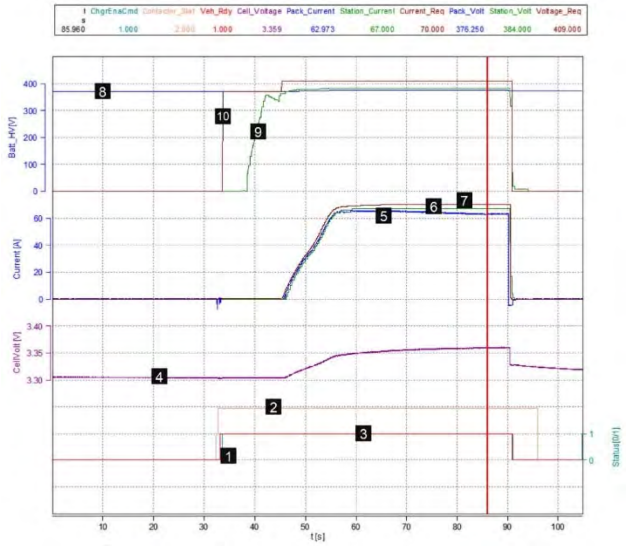


Figure 38 - Control pilot signal with a 47Ω resistor before a fast charge is initiated.

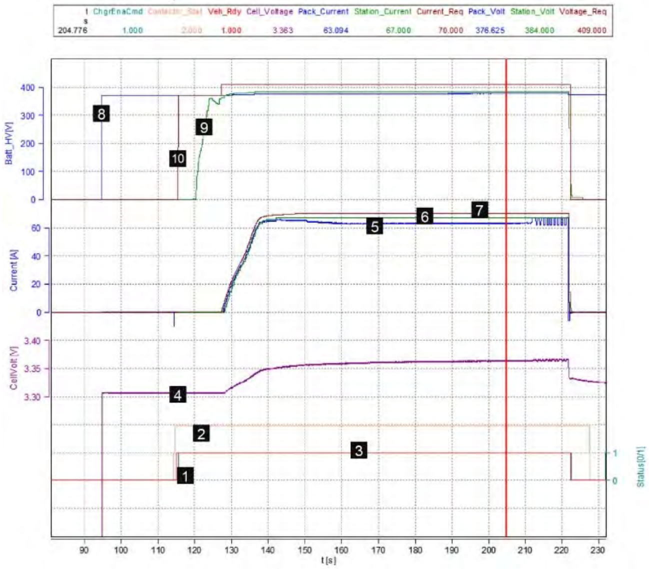


Figure 39 - Control pilot signal with a 100Ω resistor before a fast charge is initiated.

Legend:

1	Charger HV Power Supply Enable [0/1]	{light green}
2	HV Contactor Status [0/1] (0=Open; 1=Pre-charge; 2=Close)	{tan}
3	Vehicle Ready for Charging [0/1] (0=False; 1=True)	{red}
4	HV Battery Cell Voltage (single) [V]	{purple}
5	HV Battery Current [A] sensed by BMS	{blue}
6	Off Board HV Charging Station Current Output [A]	{green}
7	Off Board HV Charging Station Current Request [A]	{brown}
8	HV Battery Voltage [V] sensed by BMS	{blue}
9	Off Board HV Charging Station Voltage Output [V]	{green}
10	Off Board HV Charging Station Target Voltage [V]	{brown}

7.3.12.8 Control pilot resistance at 1 kΩ (before a charge session is initiated):

System behavior: A charging session was initiated after connecting a **1 kΩ** resistor inline the control pilot signal using the breakout box. The measured voltage across the 1 kΩ resistor (**TP3 – TP4**) before charging started was -2.344 V. The system could not start charging and the vehicle shut down automatically after 2 minutes. Figure 40 shows that there was no charging activity (note that the values shown correspond to the red vertical line).

Vehicle/BMS faults and/or DTCs: The vehicle set an internal fault on the CANalyzer data "Failed_ChargerSystemIncompatibility".

Charge station faults and/or DTCs: A charger fault occurred.

Pass/fail evaluation: **PASS** - the charge session did not start and the vehicle remained in a safe state.

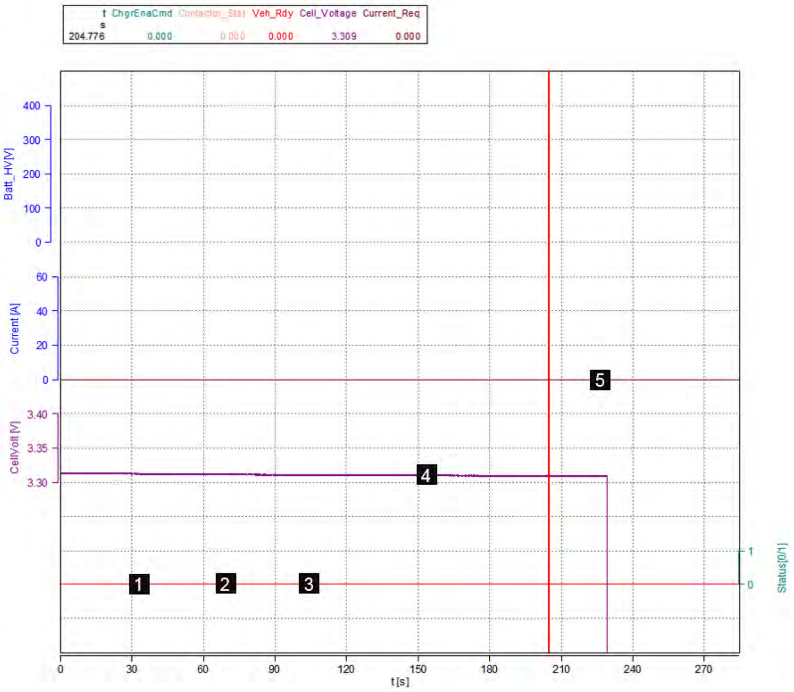


Figure 40 - Control pilot signal with a 1 kΩ resistor before a fast charge is initiated.

Legend:

1	Charger HV Power Supply Enable [0/1]	{light green}
2	HV Contactor Status [0/1] (0=Open; 1=Pre-charge; 2=Close)	{tan}
3	Vehicle Ready for Charging [0/1] (0=False; 1=True)	{red}
4	HV Battery Cell Voltage (single) [V]	{purple}
5	Off Board HV Charging Station Current Request [A]	{brown}

7.3.12.9 Control pilot resistance (during a charge session):

System behavior: After a normal charging session was started, the following resistors were installed inline the control pilot signal using the breakout box (the corresponding measured voltages across the resistors between **TP3** – **TP4** are also shown):

- **24Ω** at 60s: -0.006 V (no impact)
- **47Ω** at 105s: -0.012 V (no impact)
- **100Ω** at 150s: -0.024 V (no impact)
- **1 kΩ** at 195s: -0.090 V (charging stopped; voltage switched to -2.344 V)

After charging shut down, the vehicle display showed the message “Fast Charging Stopped” and the vehicle shut down automatically after 3 minutes. Figure 41 shows the charging cycle (note that the values shown correspond to the red vertical line).

Vehicle/BMS faults and/or DTCs: The vehicle set an internal fault that showed up on the CANalyzer data as “Failed_ChargerSystem Incompatibility”.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS (only at 1 kΩ)** - the system stopped the charge session and the vehicle was brought to a safe state. The test failed for lower resistance values since the charge session continued uninterrupted once the resistance was introduced.

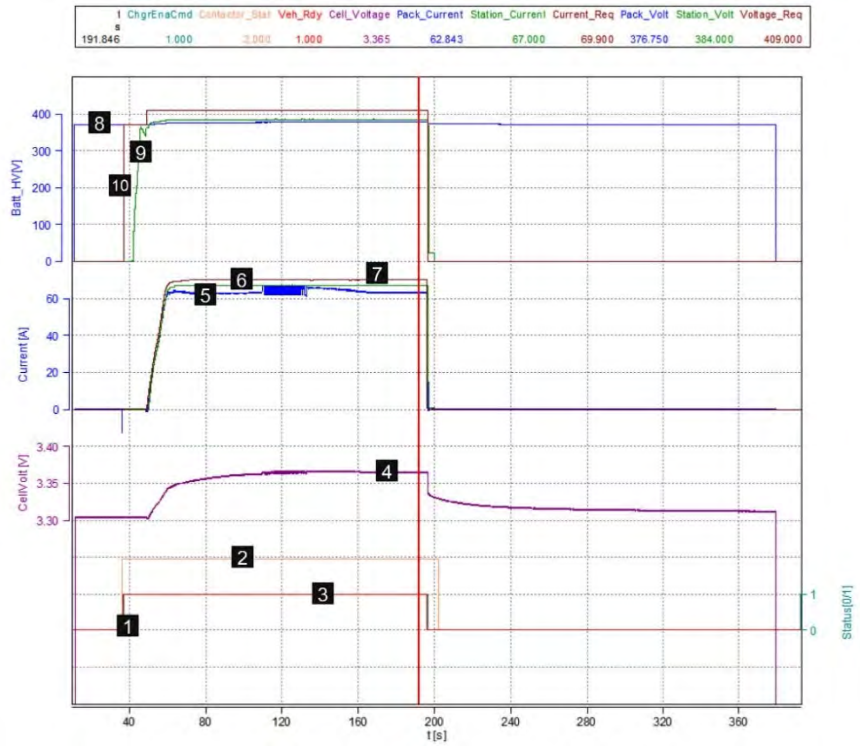


Figure 41 - Control pilot signal with inline resistance during a charge session.

Legend:

1	Charger HV Power Supply Enable [0/1]	{light green}
2	HV Contactor Status [0/1] (0=Open; 1=Pre-charge; 2=Close)	{tan}
3	Vehicle Ready for Charging [0/1] (0=False; 1=True)	{red}
4	HV Battery Cell Voltage (single) [V]	{purple}
5	HV Battery Current [A] sensed by BMS	{blue}
6	Off Board HV Charging Station Current Output [A]	{green}
7	Off Board HV Charging Station Current Request [A]	{brown}
8	HV Battery Voltage [V] sensed by BMS	{blue}
9	Off Board HV Charging Station Voltage Output [V]	{green}
10	Off Board HV Charging Station Target Voltage [V]	{brown}

7.3.12.10 Proximity signal resistance at 24Ω (before a charge session is initiated):

System behavior: A charging session was initiated after connecting a **24Ω** resistor inline the proximity signal using the breakout box. During charging, the measured voltage across the proximity signal (**TP3** – **TP4**) measured 0 V. Charging continued without any impact and was stopped manually. Figure 42 shows the charging cycle (note that the values shown correspond to the red vertical line).

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **FAIL (inability to verify)** - although the vehicle remained in a safe condition, the charge session had to be stopped manually. The station did not monitor the proximity signal and therefore there was no voltage drop across inline resistance; the vehicle still had a valid proximity signal available. The ability to introduce proximity signal resistance is required to successfully pass this test.

7.3.12.11 Proximity signal resistance at 47Ω (before a charge session is initiated):

System behavior: A charging session was initiated after connecting a **47Ω** resistor inline the proximity signal using the breakout box. During charging, the measured voltage across the proximity signal (**TP3** – **TP4**) measured 0 V. Charging continued without any impact and was stopped manually. Figure 43 shows the charging cycle (note that the values shown correspond to the red vertical line).

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **FAIL (inability to verify)** - although the vehicle remained in a safe condition, the charge session had to be stopped manually. The station did not monitor the proximity signal and therefore there was no voltage drop across inline resistance; the vehicle still had a valid proximity signal available. The ability to introduce proximity signal resistance is required to successfully pass this test.

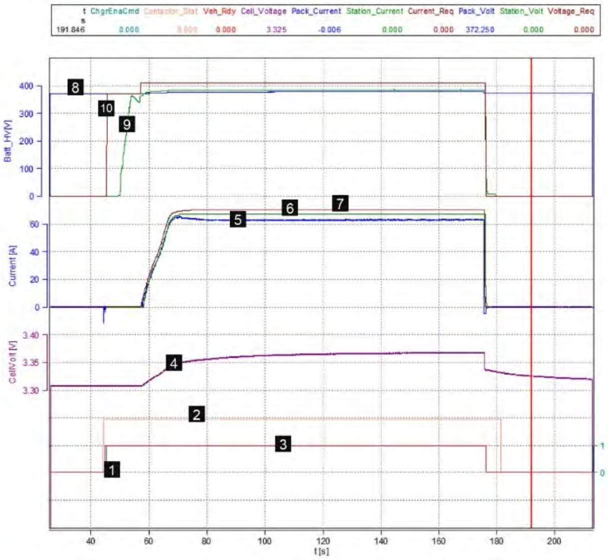


Figure 42 - Proximity signal with a 24Ω resistor before a fast charge is initiated.

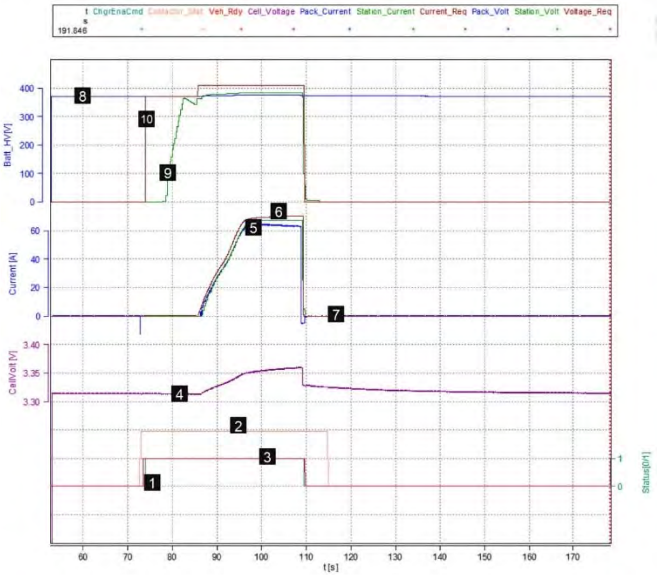


Figure 43 - Proximity signal with a 47Ω resistor before a fast charge is initiated.

Legend:

1	Charger HV Power Supply Enable [0/1]	{light green}
2	HV Contactor Status [0/1] (0=Open; 1=Pre-charge; 2=Close)	{tan}
3	Vehicle Ready for Charging [0/1] (0=False; 1=True)	{red}
4	HV Battery Cell Voltage (single) [V]	{purple}
5	HV Battery Current [A] sensed by BMS	{blue}
6	Off Board HV Charging Station Current Output [A]	{green}
7	Off Board HV Charging Station Current Request [A]	{brown}
8	HV Battery Voltage [V] sensed by BMS	{blue}
9	Off Board HV Charging Station Voltage Output [V]	{green}
10	Off Board HV Charging Station Target Voltage [V]	{brown}

7.3.12.12 Proximity signal resistance at 100Ω (before a charge session is initiated):

System behavior: A charging session was initiated after connecting a **100Ω** resistor inline the proximity signal using the breakout box. During charging, the measured voltage across the proximity signal (**TP3 – TP4**) measured 0 V. Charging continued without any impact and was stopped manually. Figure 44 shows the charging cycle.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **FAIL (inability to verify)** - although the vehicle remained in a safe condition, the charge session had to be stopped manually. The station did not monitor the proximity signal and therefore there was no voltage drop across inline resistance; the vehicle still had a valid proximity signal available. The ability to introduce proximity signal resistance is required to successfully pass this test.

7.3.12.13 Proximity signal resistance at 1 kΩ (before a charge session is initiated):

System behavior: A charging session was initiated after connecting a **1 kΩ** resistor inline the proximity signal using the breakout box. During charging, the measured voltage across the proximity signal (**TP3 – TP4**) measured 0 V. Charging continued without any impact and was stopped manually. Figure 45 shows the charging cycle.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **FAIL (inability to verify)** - although the vehicle remained in a safe condition, the charge session had to be stopped manually. The station did not monitor the proximity signal and therefore there was no voltage drop across inline resistance; the vehicle still had a valid proximity signal available. The ability to introduce proximity signal resistance is required to successfully pass this test.

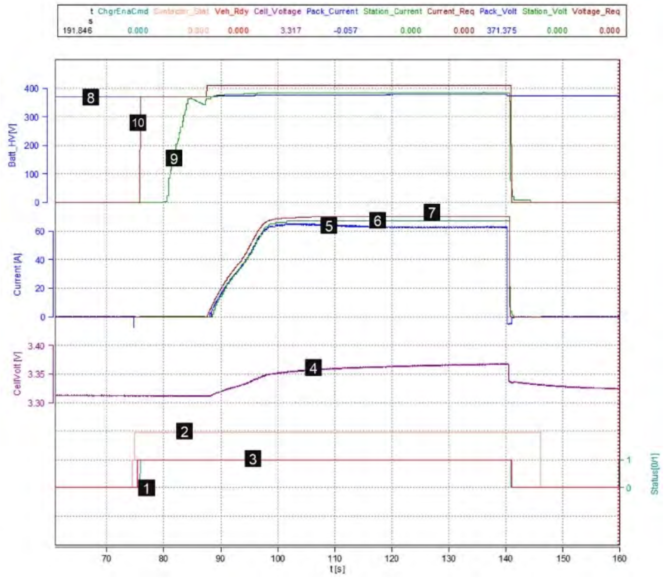


Figure 44 - Proximity signal with a 100Ω resistor before a fast charge is initiated.

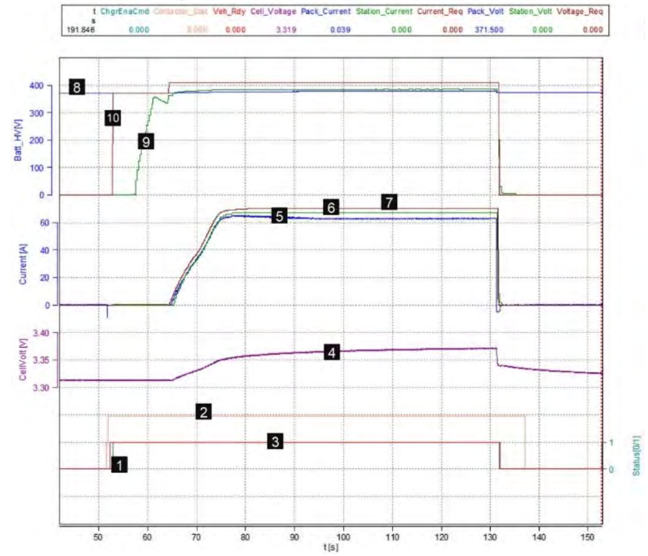


Figure 45 - Proximity signal with a 1 kΩ resistor before a fast charge is initiated.

<u>Legend</u>:

1	Charger HV Power Supply Enable [0/1]	{light green}
2	HV Contactor Status [0/1] (0=Open; 1=Pre-charge; 2=Close)	{tan}
3	Vehicle Ready for Charging [0/1] (0=False; 1=True)	{red}
4	HV Battery Cell Voltage (single) [V]	{purple}
5	HV Battery Current [A] sensed by BMS	{blue}
6	Off Board HV Charging Station Current Output [A]	{green}
7	Off Board HV Charging Station Current Request [A]	{brown}
8	HV Battery Voltage [V] sensed by BMS	{blue}
9	Off Board HV Charging Station Voltage Output [V]	{green}
10	Off Board HV Charging Station Target Voltage [V]	{brown}

7.3.12.14 Proximity signal resistance (during a charge session):

System behavior: After a normal charging session was started, the following resistors were installed inline the proximity signal using the breakout box (the corresponding measured voltages across the resistors between **TP3** – **TP4** are also shown):

- **24Ω** at 60 s: 0 V (no impact)
- **47Ω** at 75 s: 0 V (no impact)
- **100Ω** at 95 s: 0 V (no impact)
- **1 kΩ** at 135 s: 0 V (no impact)

The inline resistance did not affect the charging operation in any way. Figure 46 shows the charging cycle (note that the values shown correspond to the red vertical line).

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **FAIL (inability to verify)** - although the vehicle remained in a safe condition, the charge session had to be stopped manually. The station did not monitor the proximity signal and therefore there was no voltage drop across inline resistance; the vehicle still had a valid proximity signal available. The ability to introduce proximity signal resistance is required to successfully pass this test.

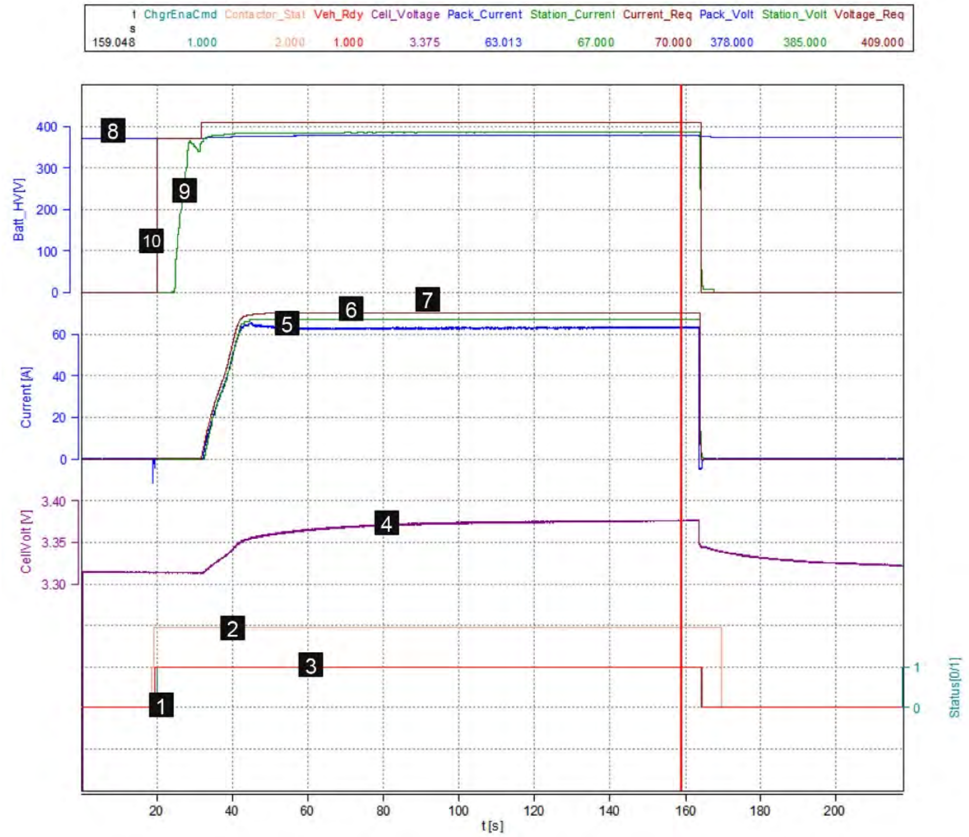


Figure 46 - Proximity signal with inline resistance during a charge session.

Legend:

1	Charger HV Power Supply Enable [0/1]	{light green}
2	HV Contactor Status [0/1] (0=Open; 1=Pre-charge; 2=Close)	{tan}
3	Vehicle Ready for Charging [0/1] (0=False; 1=True)	{red}
4	HV Battery Cell Voltage (single) [V]	{purple}
5	HV Battery Current [A] sensed by BMS	{blue}
6	Off Board HV Charging Station Current Output [A]	{green}
7	Off Board HV Charging Station Current Request [A]	{brown}
8	HV Battery Voltage [V] sensed by BMS	{blue}
9	Off Board HV Charging Station Voltage Output [V]	{green}
10	Off Board HV Charging Station Target Voltage [V]	{brown}

7.3.12.15 CAN error frames (during a charge session):

System behavior: After a normal charging session was started, CANalyzer recording was initiated for both the vehicle main CAN network and the HV battery/charger CAN network. CAN error frames were introduced at the following rates:

- Error frames every 100 ms (no problem)
- Error frames every 50 ms (no problem)
- Error frames every 25 ms (no problem)
- Error frames every 12 ms (no problem)
- Error frames every 6 ms (no problem)
- Error frames every 3 ms (no problem)
- Error frames every 2 ms (no problem)
- Error frames every 1 ms (no problem)

There was no noticeable degradation in the CAN data rate. All communication between battery BMS and charging hardware performed without issues. Figure 47 shows the charging and induced error frames.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the charge session was not interrupted and the vehicle remained in a safe state.

7.3.12.16 CAN bus load increase (during a charge session):

System behavior: After a normal charging session was started, CANalyzer recording was initiated for both the vehicle main CAN network and the HV battery/charger CAN network. Dummy CAN message frames were introduced to increase the bus load up to >80%; there was no noticeable degradation in the CAN data rate. All communication between battery BMS and charging hardware performed without issues. The charge operation was manually stopped by the operator. Figure 48 shows the charging and induced bus load.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the charge session was not interrupted and the vehicle remained in a safe state.

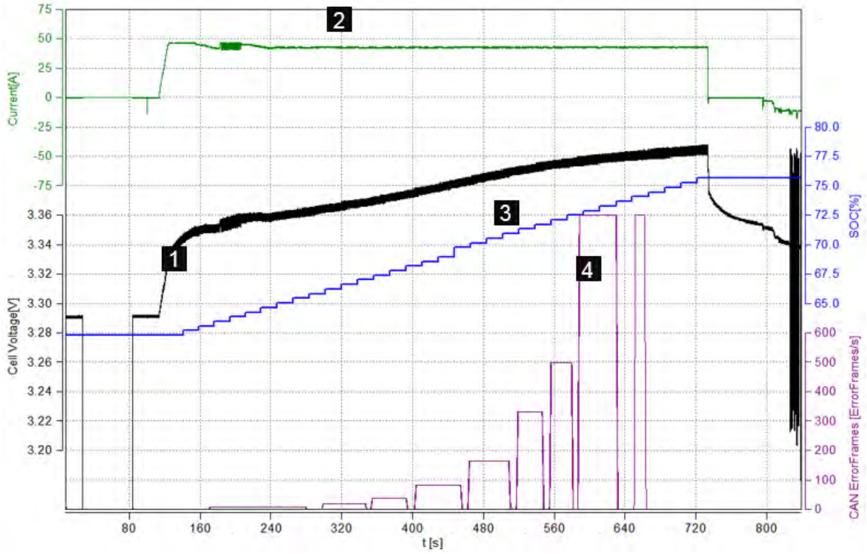


Figure 47 - CAN error frames introduced during a charge session.

Legend:

1	HV Battery Cell Voltages (all) [V]	{black}
2	HV Battery Current [A] sensed by BMS	{green}
3	Customer Usable State of Charge [%]	{blue}
4	CAN error frames [#/s]	{purple}

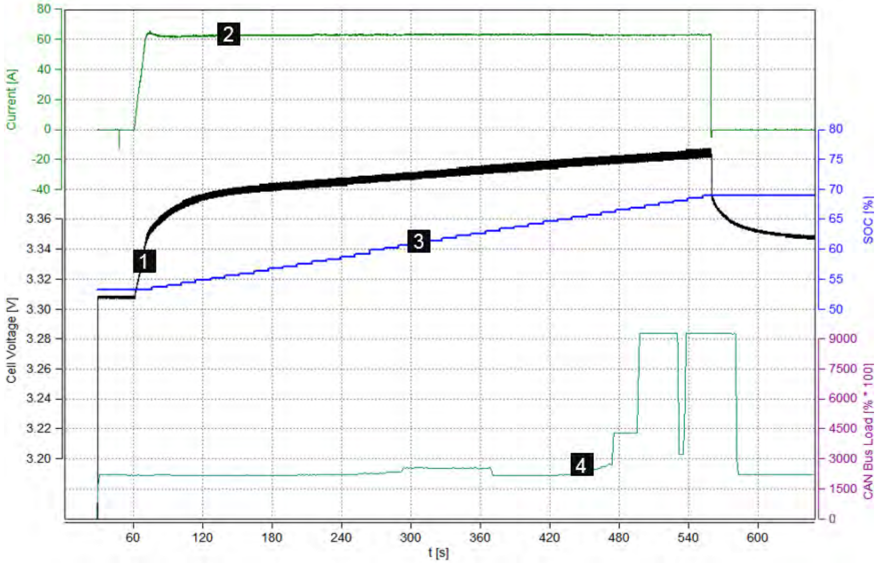


Figure 48 - CAN bus load increase during a charge session.

Legend:

1	HV Battery Cell Voltages (some) [V]	{black}
2	HV Battery Current [A] sensed by BMS	{green}
3	Customer Usable State of Charge [%]	{blue}
4	CAN Bus Load [%]	{light blue}

7.3.13 Charge Connector High Voltage Connection Disturbance Test (Section 6.13)

7.3.13.1 Interrupt DC positive connection (during a charge session):

System behavior: After a normal charging session was started, the HV positive connection was interrupted using the breakout box. The charger station detected a loss of current and shut down immediately. Figure 49 shows the charging cycle (note that the values shown correspond to the red vertical line).

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the system stopped the charge session and the vehicle was brought to a safe state.

7.3.13.1 Interrupt DC negative connection (during a charge session):

System behavior: After a normal charging session was started, the HV negative connection was interrupted using the breakout box. The charger station detected a loss of current and shut down immediately.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the system stopped the charge session and the vehicle was brought to a safe state.

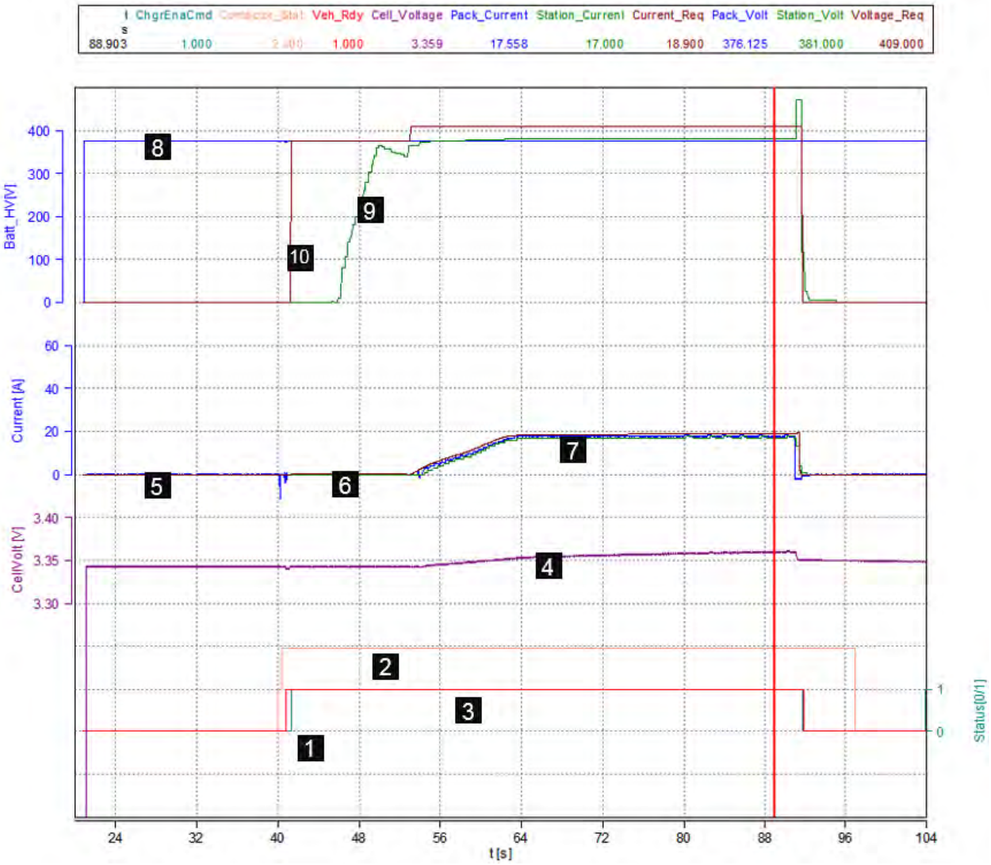


Figure 49 - Interrupt the DC high voltage positive during a charge session.

<u>Legend</u>:

1	Charger HV Power Supply Enable [0/1]	{light green}
2	HV Contactor Status [0/1] (0=Open; 1=Pre-charge; 2=Close)	{tan}
3	Vehicle Ready for Charging [0/1] (0=False; 1=True)	{red}
4	HV Battery Cell Voltage (single) [V]	{purple}
5	HV Battery Current [A] sensed by BMS	{blue}
6	Off Board HV Charging Station Current Output [A]	{green}
7	Off Board HV Charging Station Current Request [A]	{brown}
8	HV Battery Voltage [V] sensed by BMS	{blue}
9	Off Board HV Charging Station Voltage Output [V]	{green}
10	Off Board HV Charging Station Target Voltage [V]	{brown}

7.3.14 Cooling/Heating System Tests (Section 6.14)

These are example test results; not all of thermal tests specified in the procedure are included herein. Missing test results would be conducted in a similar fashion.

7.3.14.1 Restricted RESS cooling at high ambient temperature (before a charge session is initiated):

System behavior: A restriction in the battery cooling circuit was installed to drastically reduce its performance (Figure 50). Constant acceleration/ deceleration driving maneuvers were performed to deplete the HV battery SOC and increase the internal temperature from 25°C to 40°C. Figure 51 shows the driving cycle.

A normal fast charging session was then started at 45 A up to 80% SOC with the cooling restriction still installed. The internal temperature from changed from 39.5°C to 42.5°C. The charging rate was not high enough to cause any over temperature issues for the vehicle system. Figure 52 shows the charging cycle.

Vehicle/BMS faults and/or DTCs: No faults or DTCs were reported.

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - charging continued uninterrupted and the vehicle remained in a safe state. The charge current was too low to determine the BMS response to extreme thermal conditions.

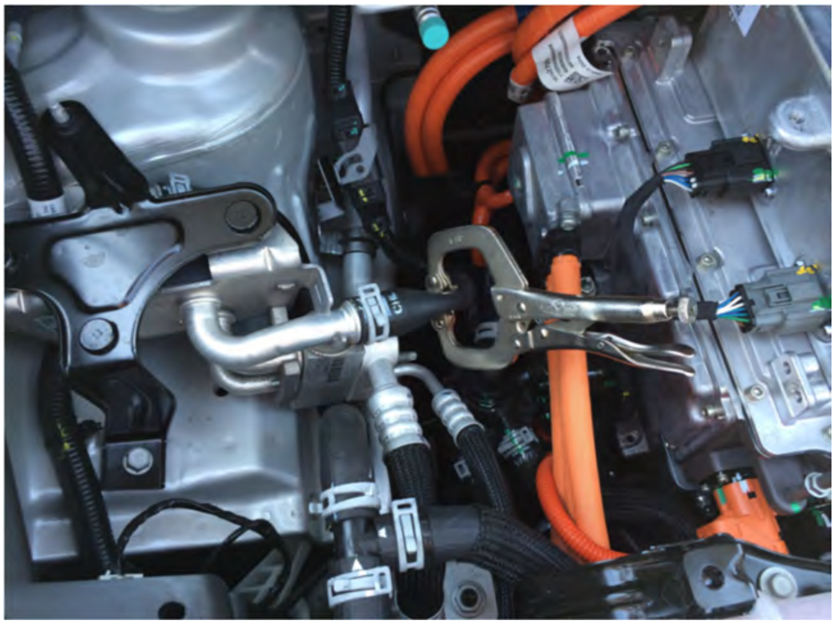


Figure 50 - Restriction in battery cooling circuit.

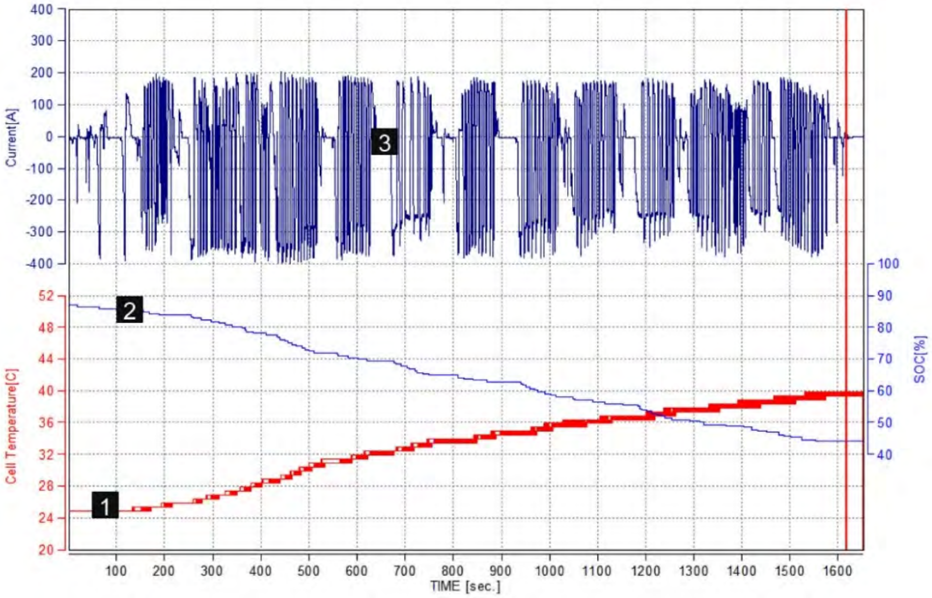


Figure 51 - Driving cycle with restricted cooling system.

Legend:

1	Cell Temperatures [°C] sensed by BMS	{red}
2	Customer Usable State of Charge [%]	{blue}
3	High Voltage Battery Current [A] sensed by BMS	{blue}

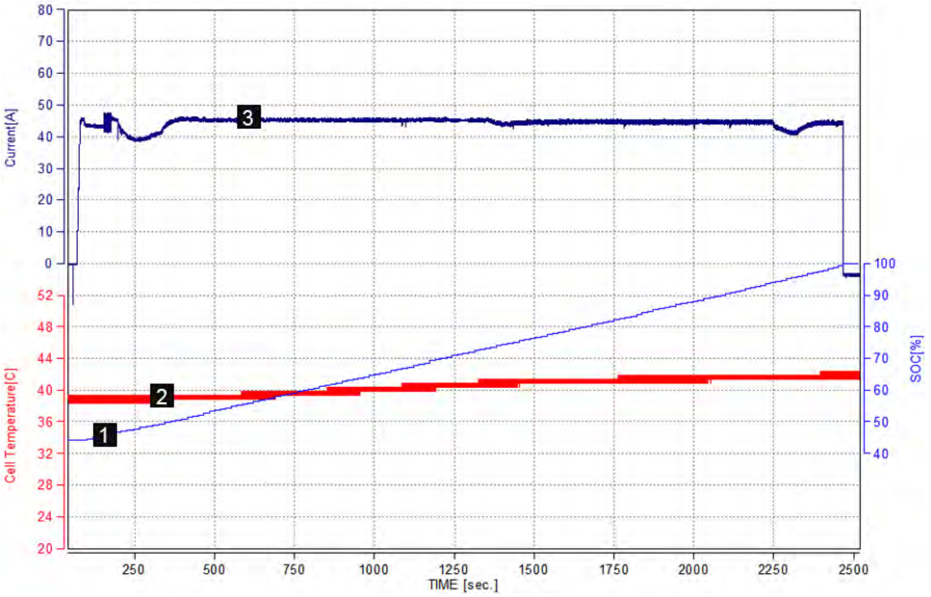


Figure 52 - Charging cycle with restricted cooling system.

Legend:

1	Customer Usable State of Charge [%]	{blue}
2	Cell Temperatures [°C] sensed by BMS	{red}
3	High Voltage Battery Current [A] sensed by BMS	{blue}

7.3.15 BMS Internal Fault Detection Tests (Section 6.15)

7.3.15.1 This test procedure was not performed.

7.3.16 Overcharge Test (Section 6.16)

7.3.16.1 Override of current request (during a charge session):

System behavior: The engineering charge station software controls were modified to deliver a 55 A charge current while only reporting 45 A to the vehicle. A normal charging session was started from 50% SOC. The vehicle allowed charging until it reached 97.3% SOC and then forced a shutdown. Figure 53 shows the charging cycle (note that the values shown correspond to the red vertical line).

Vehicle/BMS faults and/or DTCs: The vehicle set an internal fault which showed up on CANalyzer data as “FAILED_PEVRESSMalfunction”. The following DTCs were set:

- U18A4: Lost Communication with Hybrid/EV Battery DC Charging Communication Gateway

Charge station faults and/or DTCs: No faults or DTCs were reported.

Pass/fail evaluation: **PASS** - the system stopped the charge session and the vehicle was brought to a safe state. Fault codes were set to identify the problem.

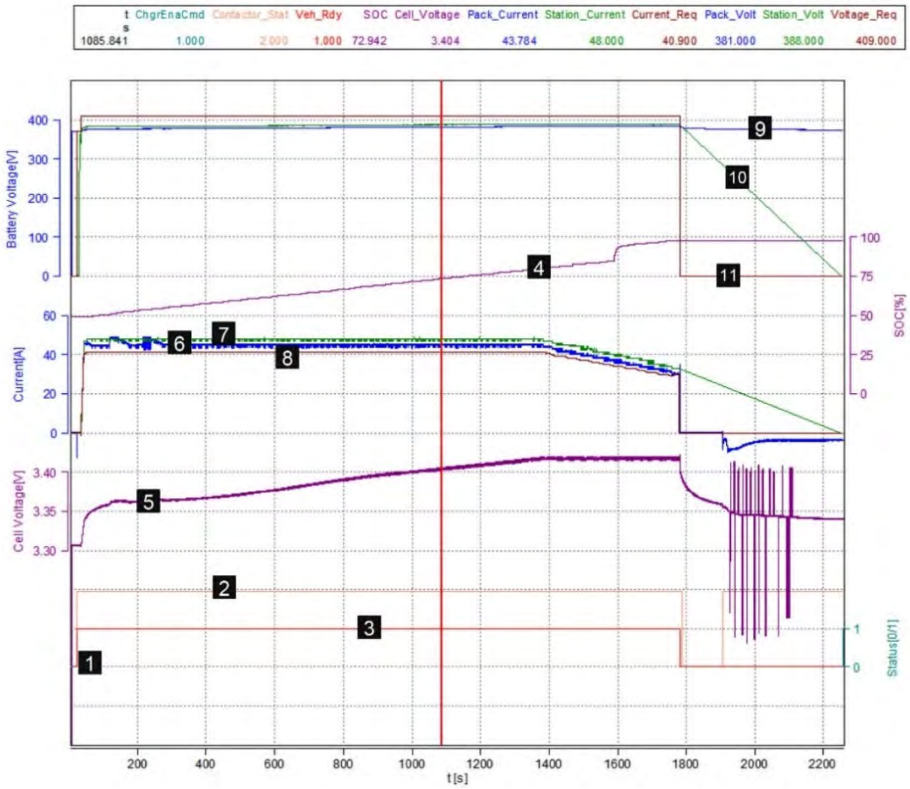


Figure 53 - Overcharge test with an increase in charge current that is 10% above the requested charge current.

Legend:

1	Charger HV Power Supply Enable [0/1]	{light green}
2	HV Contactor Status [0/1] (0=Open; 1=Pre-charge; 2=Close)	{tan}
3	Vehicle Ready for Charging [0/1] (0=False; 1=True)	{red}
4	Customer Usable State of Charge [%]	{purple}
5	HV Battery Cell Voltage (single) [V]	{purple}
6	HV Battery Current [A] sensed by BMS	{blue}
7	Off Board HV Charging Station Current Output [A]	{green}
8	Off Board HV Charging Station Current Request [A]	{brown}
9	HV Battery Voltage [V] sensed by BMS	{blue}
10	Off Board HV Charging Station Voltage Output [V]	{green}
11	Off Board HV Charging Station Target Voltage [V]	{brown}

RESS ISOLATION STRESS TEST

Test Procedure and Report

1. PURPOSE

Electric propulsion in a Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV) and Electric Vehicle (EV) platform relies on Rechargeable Energy Storage Systems (RESSs), commonly referred to as batteries. However, 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 that are different than those associated with an internal combustion engine. Among the potential risks is the loss or reduction of isolation (i.e., loss of isolation) failures, which can lead to thermal runaway reactions. Isolation failures can occur for battery packs using cells of any chemistry, but failures associated with Li-ion chemistries are of particular concern because, at the time of this writing, Li-ion cells are being used to make widely adopted high voltage and high capacity RESSs.

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

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

High voltage isolation loss is an area of active concern when there has been damage to the RESS, when there is a failure of a device external to the RESS, or after significant RESS aging. Many standards at the time of this writing incorporate a method for assessing a low impedance short circuit external to the RESS (see Section 7.1.1). However, a fast discharge through a hard short circuit in most RESS architectures would be terminated by fuses or switches. An uncontrolled low current discharge can also cause an overheating hazard. Protection devices such as fuses and switches are not typically designed to activate due to these low currents or may not be installed in the current pathway of the uncontrolled discharge.

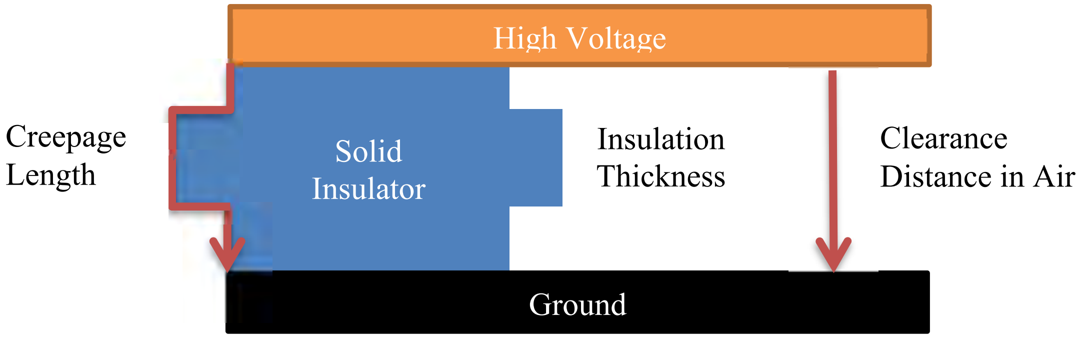


Figure 1 - High voltage insulation.

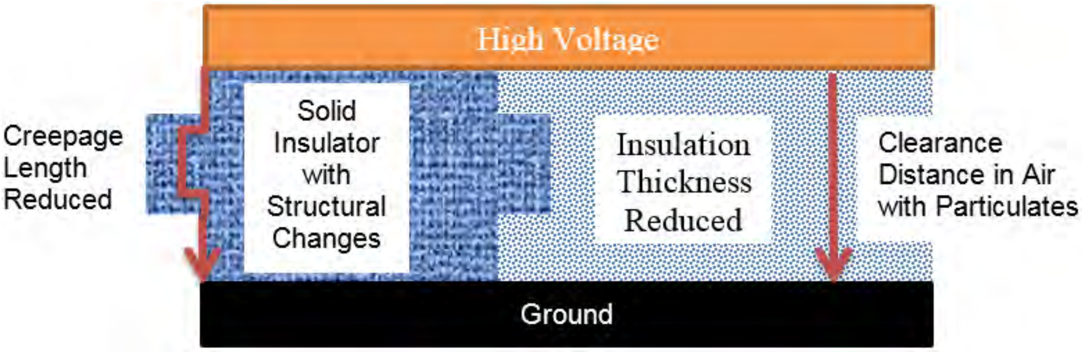


Figure 2 - Examples of deteriorated high voltage insulation: pollution of creepage length, degradation of bulk insulation, reduction of clearance by particulates.

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

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

2. SCOPE

This test procedure is applicable to all Li-ion RESS-equipped HEV, PHEV and EV platforms. The scope includes a description of how a reasonably foreseeable pollutant can be introduced into a RESS and how the effects of that pollutant on internal isolation can be assessed. The pollutant selected for this testing is the product of a single cell thermal runaway reaction (i.e., electrolyte vapor and possible cell degradation products such as smoke and fine debris). This comprises a complex pollutant that can cause the reduction of isolation at different voltage potentials through a variety of mechanisms (e.g., pollution of insulator surfaces). Two methods of pollutant introduction are described:

- Application of the Single Cell Thermal Runaway Initiation (SCTRI) method; or
- Remote introduction of vent gases from a thermal runaway initiation vessel into a RESS.

Two methods for measuring isolation are described:

- Insulation resistance measurements.
- Dielectric withstand test measurements.

In addition to these measurements, this procedure includes a stress test that rapidly assesses the the effect of reduced internal isolation on the vehicle occupant or the surrounding environment. It is a transient overvoltage test that applies a high voltage potential between the battery enclosure and the negative terminal to stimulate latent failure modes such as resistive heating within a RESS.

3. REFERENCES

3.1 Applicable Publications

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

3.1.1 SAE Publications

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

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

- “Single Cell Thermal Runaway Initiation (SCTRI) Test”, see page 176 (herein referred to as the “SCTRI Procedure”).

3.2 Related Publications

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

3.2.1 ASTM Publications

Available from the American Society for Testing and Materials (ASTM) International: 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 19428-2959, Tel: 1-877-909-2786, www.astm.org.

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

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

- ASTM E2187 Standard Test Method for Measuring the Ignition Strength of Cigarettes”

3.2.2 CRC Press Publications

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

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

3.2.3 IEC Publications

Available from the International Electrotechnical Commission (IEC): 446 Main Street, 16th Floor, Worcester, MA 01608, Tel: 508-755-5663, www.iec.ch.

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

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

3.2.4 IEEE Publications

Retrieved from the Institute of Electrical and Electronic Engineers (IEEE) Standards Activities: 445 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-562-5527, www.standards.ieee.org.

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

3.2.5 SAE Publications

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

- SAE J2464 Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing
- SAE J2929 Electric and Hybrid Vehicle Propulsion Battery System Safety Standard – Lithium-based Rechargeable Cells

3.2.6 UN Publications

Available from United Nations (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 UL Publications

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

- UL 840 Standard for Insulation Coordination Including Clearances and Creepage Distances for Electrical Equipment
- UL 1642 Standard for Lithium Batteries
- UL 1973 Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications
- UL 2054 Household and Commercial Batteries
- UL 2271 Batteries for Use in Light Electric Vehicle (LEV) Applications
- UL 2580 Batteries for Use in Electric Vehicles

4. DEFINITIONS

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

Ah

Ampere-hour: a measure of battery capacity.

Battery

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

Battery Cell (Cell)

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

Battery Management System / Unit (BMS / BMU)

Electronic components that monitor and/or control battery functions such as charge and discharge operations. It calculates and communicates battery status and state of function to the vehicle system for energy flow management. In the event of a system failure, the BMS can also open contactors and isolate the battery from the rest of the hybrid system.

Battery Module

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

Brick or Block

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

Dielectric Withstand Test

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

Electrical Isolation

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

Emergency Response Guide (ERG)

A document describing the hazards that may be encountered during an emergency response operation involving an “article”. The Occupational Safety and Health Administration (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 on its shape or design during end use; and (iii) which under normal conditions of use does not release more than very small quantities (e.g., minute or trace amounts) of a hazardous chemical, and does not pose a physical hazard or health risk to employees.

EV: Electric Vehicle

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

Explosion

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

Fire

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

HEV: Hybrid Electric Vehicle (HEV)

An automobile type vehicle, powered by an internal combustion engine and an electric motor that draws stored energy from a rechargeable energy storage device for power assist.

Initiating Cell

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

Insulation Resistance Measurement

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

Loss of Isolation

A reduction of electrical isolation from nominal values. Nominal values are typically greater than 500Ω/V.

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

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

Lithium-Ion (Li-ion)

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

Material Safety Data Sheet (MSDS)

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

PHEV: Plug-in Hybrid Electric Vehicle

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

Personal Protective Equipment (PPE)

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

Pollutant

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

Rechargeable Energy Storage System (RESS)

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

State of Charge (SOC)

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

Thermal Runaway

Thermal runaway refers to rapid self-heating of a battery cell derived from the exothermic chemical reaction of the highly oxidizing positive electrode and the highly reducing negative electrode. It can occur with batteries of almost any chemistry. In a thermal runaway reaction, a cell rapidly releases its stored energy. At the end of a thermal runaway reaction, no electrical energy will be stored within the cell. Note that a measurement of 0 V 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.

Thermal runaway initiating device

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

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.

5. GENERAL TEST REQUIREMENTS

5.1 General Precautions

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5.2 Test Specific Precautions

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

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

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

5.3 Safety Requirements

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

5.4 Test Facility/ Equipment Requirements

5.4.1 Facility requirements for full-scale in-vehicle testing:

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

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

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

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

5.4.1.5 The facility must have the ability to safely open the battery pack before and after testing for both examination and charging or discharging individual cells within the pack.

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

5.4.1.7 The facility must be capable of proper disposal or recycling of damaged/burned RESSs or other byproducts of testing in compliance with environmental regulations.

5.4.2 Equipment requirements for full-scale vehicle testing:

5.4.2.1 Personal protective equipment such as respirators, safety glasses, and high voltage gloves. See discussion in Section 5.3 above.

5.4.2.2 Thermal runaway initiation equipment such as a film heater and an appropriate power supply for the cell thermal runaway initiation heating method, as well as appropriate pass-throughs for electrical leads.

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

5.4.2.4 Sensors and Data Acquisition Equipment:

- Thermocouple DAQ (recommend channel-to-channel isolation) capable of a data collection rate of at least 1 Hz
- Thermocouple wire (recommend K-type with fiberglass insulation)
- Thermocouple bead welder (optional – pre-made K-type thermocouples can be purchased)
- Stopwatch with accuracy of ±1 second
- Smoke detector with a photoelectric sensor (opacity based detection)
- Gas sensor (optional)

- Handheld voltage and insulation resistance meter
- Hipot tester
- Power supply capable of providing approximately 1000 V and 0.2 A (maximum pack voltage plus 353 V_{DC})
- Video cameras (minimum of three)

5.4.3 Should single cell testing be required to select a cell thermal runaway initiation methodology prior to full-scale in-vehicle testing, the facility requirements for conducting single cell testing are:

5.4.3.1 The facility must have a thermal chamber for pre-test thermal soaking of cells to a temperature of 25±2°C prior to burn testing.

5.4.3.2 The facility must be capable of burning individual cells. This may require a flame-resistant fume or vent hood and the capability of handling and exhausting flammable gases.

5.4.3.3 The facility must be capable of safely discharging damaged cells and disposing of or recycling burned cells in compliance with environmental regulations.

5.4.4 Should single cell testing be required to select a cell thermal runaway initiation methodology prior to full-scale in-vehicle testing, the equipment requirements for conducting single cell testing are:

5.4.4.1 Personal protective equipment such as respirators, safety glasses, and chemical resistant gloves. See discussion in Section 5.3 above.

5.4.4.2 The thermal runaway initiation device.

5.4.4.3 A voltage measurement and data logging system with an accuracy of at least 0.5% of cell maximum voltage and a data collection rate of at least 10 Hz. For example, a National Instruments NI 9205 ±10V data acquisition module was used for Li-ion single cell testing. This has an accuracy of ±6.22 mV (i.e., 0.15% of 4.2V).

5.4.4.4 A temperature measurement and data logging system capable of reading Type K thermocouples with a data collection rate of at least 1 Hz. For example, a National Instruments NI 9213 data acquisition module was used for Li-ion cell testing.

5.4.4.5 Type K thermocouples (minimum of two).

5.4.4.6 A stopwatch or similar timekeeping instrument with an accuracy of ±1 second.

5.5 Test Equipment Calibration

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

- Type of equipment, manufacturer, model number, etc.
- Measurement range
- Accuracy
- Calibration interval
- Type of standard used (calibration traceability of the standard must be evident)

6. TEST PROCEDURE

6.1 Test Type

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

6.1.2 In preparation for full-scale-vehicle testing, destructive testing of an individual cell may be required to define and validate an appropriate device that induces a thermal runway reaction. If single cell thermal runaway initiation will be conducted remotely, considerations related to the RESS architecture such as neighbor cell heating and venting direction accuracy may be relaxed.

6.2 Device Under Test

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

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

6.3 Test Guidelines

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

- Application of the Single Cell Thermal Runaway Initiation (SCTRI) method; or
- Remote introduction of thermal runaway vent gases into a RESS.

6.3.2 Testing will require one vehicle with its RESS. The vehicle and RESS should be new (i.e., less than one year old, and with less than five charge discharge cycles applied to the RESS). The RESS may be provided by the manufacturer or vehicle OEM with the necessary modifications for conducting RIS testing. If the testing agency must modify the RESS for testing, then additional RESS components may be required (e.g., replacement enclosure components to reseal the RESS after modifications).

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

6.4 Test Parameters

- RESS cell beginning test temperature: 25±5°C
- Beginning pack state: Cells less than one year old and accumulated <5 electrical cycles
- Beginning SOC of the RESS: 99% to 100% of the maximum operating SOC
- Beginning energy of vehicle: Fully charged RESS; full fuel tank (HEV, PHEV)[1]

6.5 DUT Preconditioning

6.5.1 All RESSs and cells used for testing should be as new and uncycled as practical (i.e., they should be less than one year old and have accumulated less than five charge/discharge cycles prior to testing).

6.5.2 Full vehicle and RESS conditioning occurs during test preparation. The temperature preconditioning requirements are described in Section 6.6.

6.6 Test Methodology

6.6.1 If RIS testing is conducted with thermal runaway initiation from within the RESS, follow the SCTRI Procedure with the following additions:

6.6.1.1 An insulation resistance measurement (Section 6.8.1) and a dielectric withstand test (Section 6.8.2) shall be conducted on the RESS before experimental equipment is added (see Section 6.6.3.7 in the SCTRI Procedure). See Section 7.4.2 for a discussion of dielectric withstand testing.

6.6.1.2 A connection shall be installed that allows both positive and negative battery terminals to be electrically accessible from outside the RESS for measuring the voltage and internal electrical isolation and for applying the transient overvoltage stress test. This connection shall have adequate insulation to avoid affecting isolation measurements (see Section 6.6.3.12 in the SCTRI Procedure). See Section 7.5 for additional discussion on installation of loss of isolation testing and monitoring leads.

6.6.1.3 An insulation resistance measurement (Section 6.8.1) and a dielectric withstand test (Section 6.8.2) shall be conducted on the RESS after a pack is closed prior to installation in the vehicle (see Section 6.6.3.14 in in the SCTRI Procedure).

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[1] See Section 4.0

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

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

6.6.1.6 Conduct an insulation resistance test between the negative battery terminal and vehicle ground and between the positive battery terminal and vehicle ground. The vehicle or RESS shall not report an isolation value greater than 500Ω/V if the previous insulation resistance test measured less than 500Ω/V.

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

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

6.6.1.9 Conduct a final insulation resistance test between the negative battery terminal and vehicle ground and between the positive battery terminal and vehicle ground.

6.6.1.10 Conduct a final dielectric withstand test between the negative battery terminal and vehicle ground and between the positive battery terminal and vehicle ground.

6.6.1.11 Testing is complete when 4 hours have elapsed and:

- Either all temperature readings on cells within the RESS are below 60°C and have been decreasing for at least 30 minutes,
- If thermocouple readings are not available, no visible follow-up reaction have occurred after 8 hours or,
- If a fire has occurred, 30 minutes after the RESS and vehicle have been consumed. Suppression equipment may then be used to suppress lingering flames or cool hot spots.

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

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

6.6.2 If RIS testing is conducted with thermal runaway initiation external to the RESS, the following procedure shall be followed:

6.6.2.1 A single cell thermal runaway initiation vessel shall be selected or fabricated (e.g., see Figure 3).

The initiation vessel shall be a pressure vessel sufficiently robust to safely contain vent gases from a single cell thermal runaway. The vessel and connection to the RESS shall be sealed for ducting as much runaway vent gas and particulate as possible into the RESS and minimizing leakage.

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

The vessel shall be connected to the RESS by a tube or duct that has a length to width or diameter ratio of 3:1 or less. The cross sectional area of the duct should be no smaller than 4 cm^2.

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

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

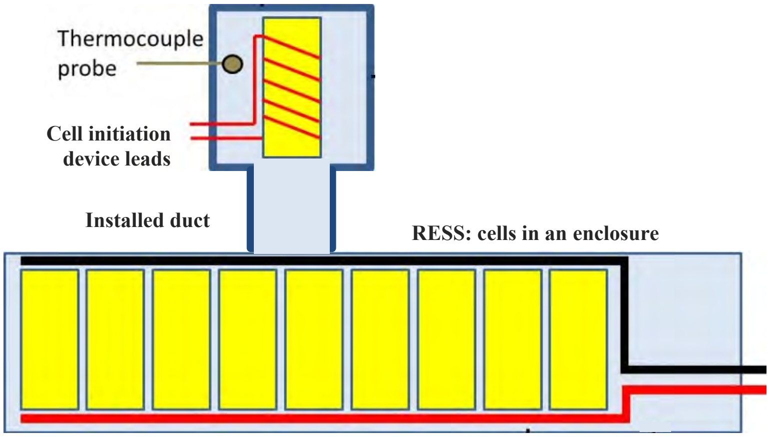

Figure 3 - Schematic of a single cell thermal runaway initiation vessel connected to a RESS.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6.6.2.23 The vehicle as prepared for testing shall be photographed.

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

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

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

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

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

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

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

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

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

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

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

6.6.2.35 Measure the RESS voltage between the positive and negative terminals using the installed loss of isolation testing and monitoring leads.

6.6.2.36 Measure insulation resistance between the negative battery terminal and vehicle ground and between the positive battery terminal and vehicle ground.

6.6.2.37 The vehicle or RESS shall not report[2] an isolation value greater than 500Ω/V if the previous insulation resistance test measured less than 500Ω/V.

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

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

6.6.2.40 Conduct a final insulation resistance test between the negative battery terminal and vehicle ground and between the positive battery terminal and vehicle ground. Attempt to communicate with the RESS. If communication is possible, record the reported internal isolation resistance.

6.6.2.41 Conduct a final dielectric withstand test between the negative battery terminal and vehicle ground and between the positive battery terminal and vehicle ground.

6.6.2.42 Testing is complete when 4 hours have elapsed and:

- Either all temperature readings on cells within the RESS are below 60°C and have been decreasing for at least 30 minutes,
- If thermocouple readings are not available, no visible follow-up reaction has occurred after 4 hours or,
- If a fire has occurred, 30 minutes after the RESS and vehicle have been consumed. Suppression equipment may then be used to suppress lingering flames or cool hot spots.

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

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

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

6.7 Measured Data

6.7.1 Full-scale vehicle RIS test reports shall include the following information:

- Details of the SCTRI method, including justification for its selection.
- Location of the SCTRI method, including justification for its selection. Note if thermal runaway was initiated within the RESS or remotely.
- If thermal runaway is initiated remotely, note the location of vent gas and particulate introduction and provide justification for its selection.
- Locations of all installed sensors.
- Evidence that instrumentation has not significantly affected the RESS internal isolation.
- Results of all voltage, isolation resistance, dielectric withstand, and transient overvoltage stress tests.
- Video of the test from several angles, at least three.
- Time that the first thermal runaway occurred.
- Evidence that the first runaway occurred, visually, audibly, and/or thermally.
- Times of any subsequent runaways, vehicle events, ignition, smoke alarm activation. Use t=0 as the time when the initiating device was activated.
- Temperature data and gas sensor data if measured.
- Photographs of the battery pack after testing has completed.

6.8 Inspection Method

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

6.8.2 Dielectric withstand test method: apply a dielectric withstand test between vehicle ground and at least one terminal of the RESS using a hipot tester. Increase the applied voltage linearly over 3 seconds to the maximum normal RESS voltage (U) plus 1695 V_{DC}, hold for 5 seconds, and then ramp linearly back to 0 V. This is a typical hipot test protocol; see Section 7.4.2 for additional details.

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

6.9 Post-Test Requirements

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

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

6.10 Acceptance Criteria

6.10.1 The purpose of RIS testing is to assess the potential hazards associated with a loss of isolation in two primary areas: hazard to the occupant and hazard to the surrounding environment.

6.10.2 Hazards to the Occupant:

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

6.10.2.2 The vehicle cabin must remain tenable except for the presence of gases directly associated with injection of the pollutant[4] until after completion of testing.

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

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

6.10.3 Hazards to the Surrounding Environment:

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

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

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

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

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

[4] Depending on RESS architecture, injection of a pollutant to the RESS may result in transmission of the pollutant to the vehicle cabin (e.g., with RESS architectures that share cabin air). In those instances, the effect of the initial pollutant should be subtracted from the assessment of cabin tenability.

7. TEST PROCEDURE RATIONALE

7.1 Significance of a Loss of Internal Isolation

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

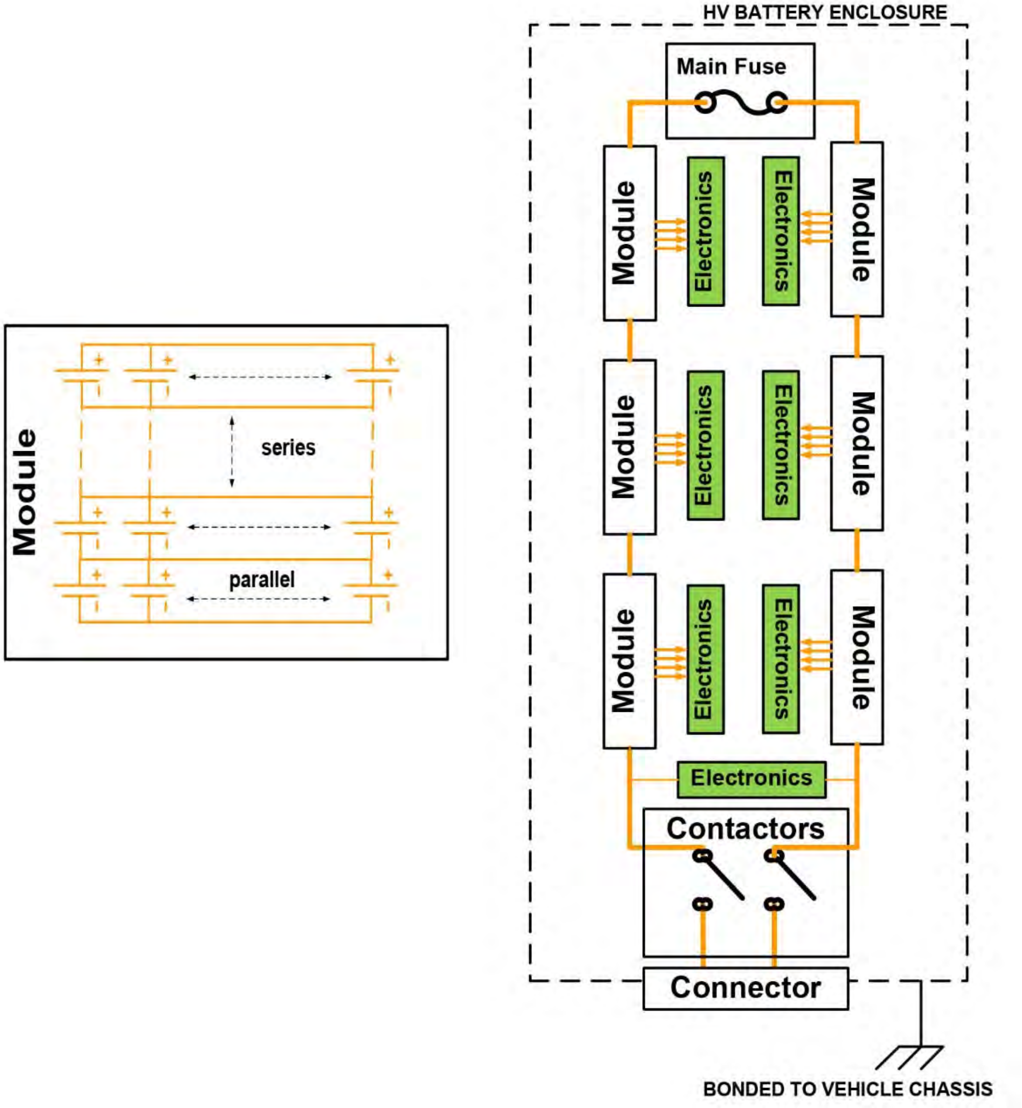

Figure 4 - Schematic of a nominal RESS: cells connected in series and parallel to form modules, modules connected in series with fuses and contactors; electronics connected to modules as well as the overall series string.

7.1.1 External Short Circuit

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

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

$$E=I^2Rt$$

$$E = (1000\text{ A})^2 * 100\text{ m}\Omega * 10\text{ msec} = 1000\text{ J} = 0.0003\text{ kWh}$$

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

A number of standards for batteries and RESSs describe external short-circuit tests, including the following:

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

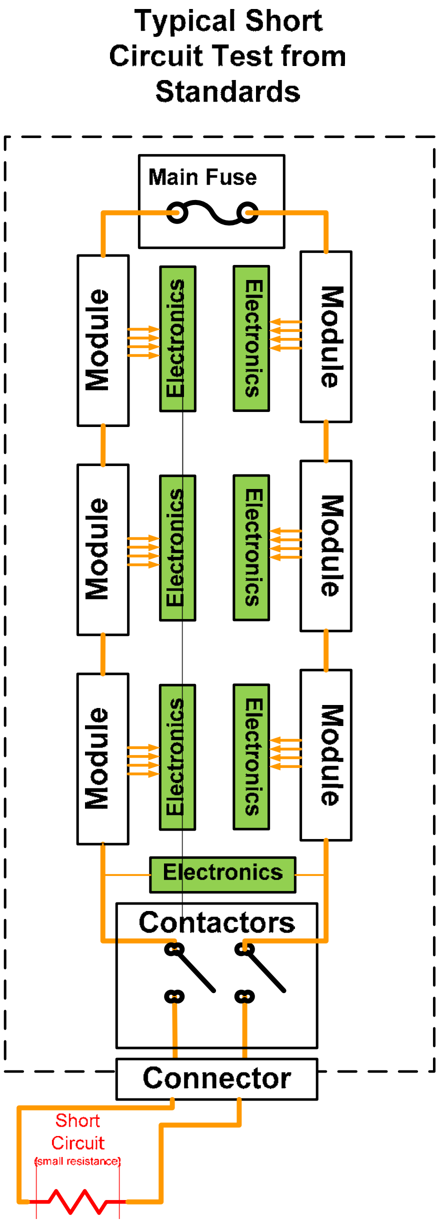

Figure 5 - Schematic of a typical external short circuit test: a short circuit is formed across the external terminals of the RESS.

7.1.2 Single Point Isolation Failure

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

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

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

The resulting power would be:

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

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

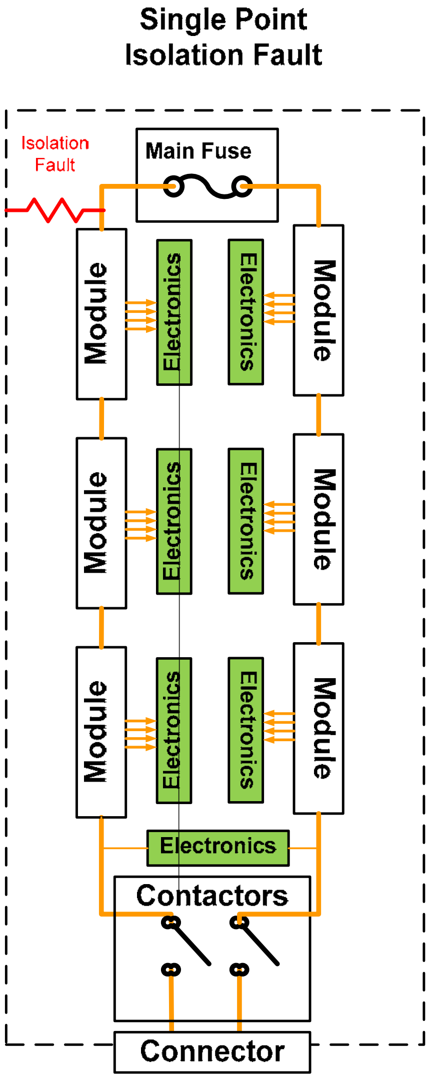

Figure 6 - Schematic of a single point isolation fault; note that a new current pathway has been formed, but current flow will not occur unless the circuit is completed.

7.1.3 Multi-Point Isolation Failure

Applying pollution to a RESS is likely to create multiple points of reduced isolation and a number of different uncontrolled discharge pathways could form (Figure 7). If a circuit pathway with significant current carrying capability is formed, it is possible that installed current interrupt devices will activate. If there are no current interrupt devices within the current path, the affected RESS components will become rapidly drained and significant heating can occur.

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

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

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

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

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

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

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

If a circuit pathway with low current carrying capability is formed, significant localized heating may occur without major bulk heating. Localized heating may be sufficient to destroy the new current path (e.g., by melting a dendrite, boiling away a conductive liquid, or fusing open a fine gage wire that was selected for a low current application but became part of a high current short circuit), or it may cause an expansion of damage (e.g., carbonization of insulation leading to a more serious fault such as thermal runaway of an affected cell or a fire).

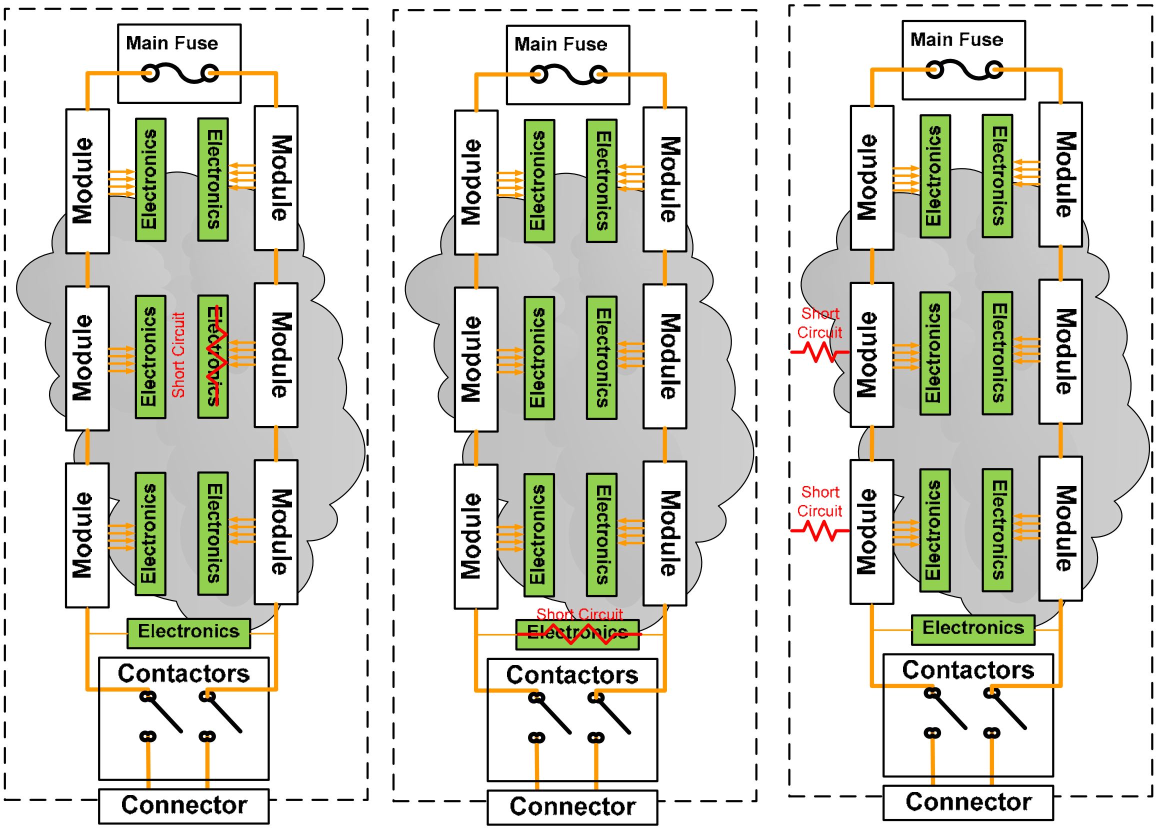

Figure 7 - Schematic of some possible short circuit pathways that could be created due to pollution of a RESS; a short circuit could form (from left to right) on module connected electronics components, on pack level electronics components, or between modules and the RESS enclosure.

7.2 Isolation Stress Testing Background

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

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

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

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

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

7.3 Assessment of Various Methods for Isolation Stress Testing

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

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

A discussion of methods considered follows.

7.3.1 Liquid Ingress

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

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

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

7.3.2 Coolant Leakage

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

7.3.3 Condensation/ Presence of Water Vapor

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

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

Results from the cell coupon testing[5] are shown in Table 1 and Figure 8. The presence of pure water vapor resulted in an average loss of isolation of approximately 60% compared to pre-test values. After 400 minutes, condensation was produced by a rapid drop in chamber temperature. The isolation dropped to approximately 1% of the pre-test value. Once the chamber temperature was re-established and condensation was no longer present, isolation stabilized at approximately

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

9% of the pre-test value. However, the condensation event likely dissolved and re-distributed ions present on the test coupon, affecting subsequent isolation measurements. Applying a voltage bias across two cells in the coupon had no significant effect on isolation values compared to the test without a voltage bias. As water vapor was lost from the chamber, isolation recovered to pre-test values.

The results from the printed circuit board coupons are also shown in Table 1. The presence of water vapor was able to reduce isolation by approximately one order of magnitude. Isolation loss was sporadic, and isolation rebounded to pre-tests levels once the chamber dried out.

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

Table 1 - Summary of Water Vapor and Condensation Tests

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

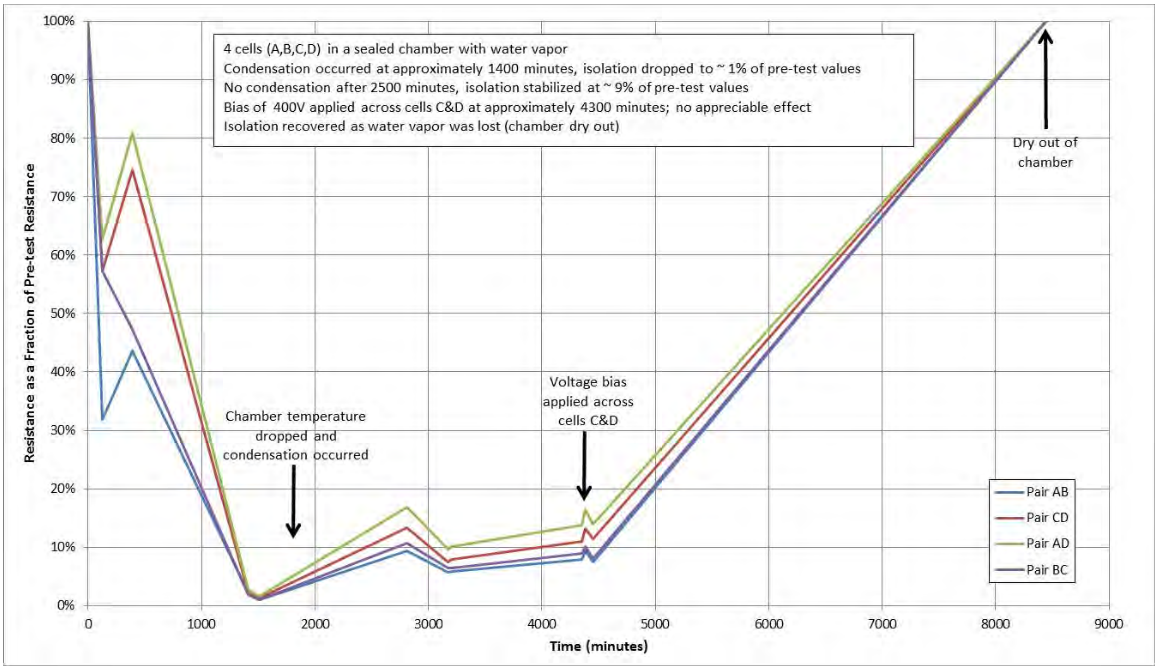

Figure 8 - Results of small cylindrical cell coupon isolation testing with water vapor, condensed water vapor, and water vapor subsequent to condensation.

7.3.4 Solid Debris or Dust Accumulation

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

7.3.5 Smoke

Smoke can be conductive and deposit conductive debris or residue on surfaces. It is straightforward to introduce smoke into a RESS and it will readily spread. Smoke intrusion in the field could occur from overheating of electrical insulation on components within the RESS. At the time of this writing, there are no standards specifying smoke intrusion for a RESS.

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

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

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

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

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[6] See for example: Flammability Handbook for Plastics 5th edition.

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

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

- Smoke Residue: A coupon consisting of multiple cell pairs was held above smoldering or burning material, in its smoke path. Isolation between cells in each pair was evaluated before smoke exposure and after smoke exposure.
- Hot smoke chamber: A coupon consisting of a number of cell pairs was held above smoldering of burning material in its smoke path. Isolation between cell pairs was evaluated before, during, and after smoke exposure.
- Cold circulating smoke: A coupon consisting of multiple cell pairs was held in a sealed chamber. A separate chamber contained smoldering or burning material. The two chambers were connected by a delivery line and a return line, with a circulating fan present in the delivery line. In this experiment one of the cell pairs was subject to a bias voltage during smoke exposure. Figure 11 shows a cold smoke circulation test setup.

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

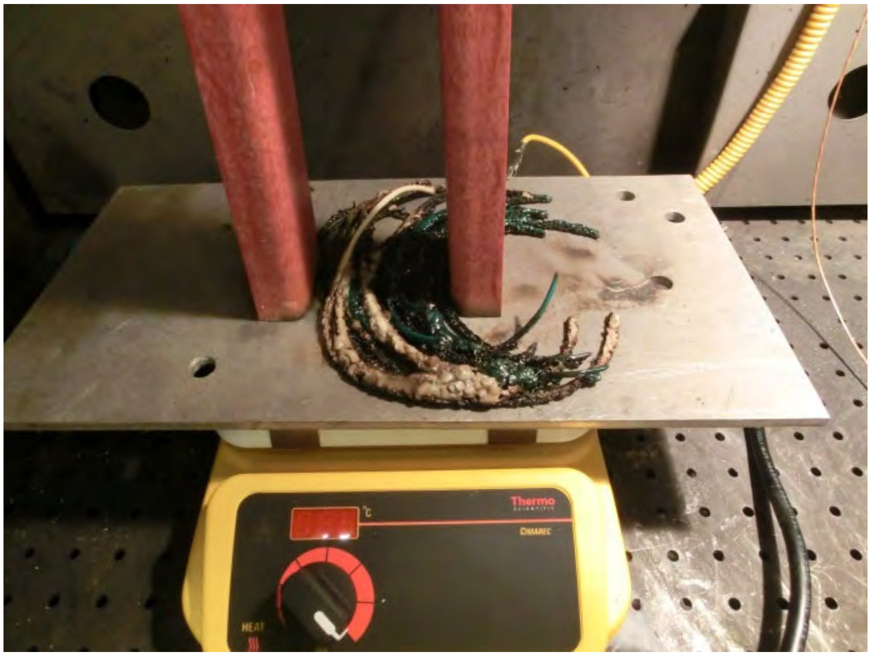

Figure 10 - Electrical wire after it was heated to the point of smoldering to produce smoke for testing.

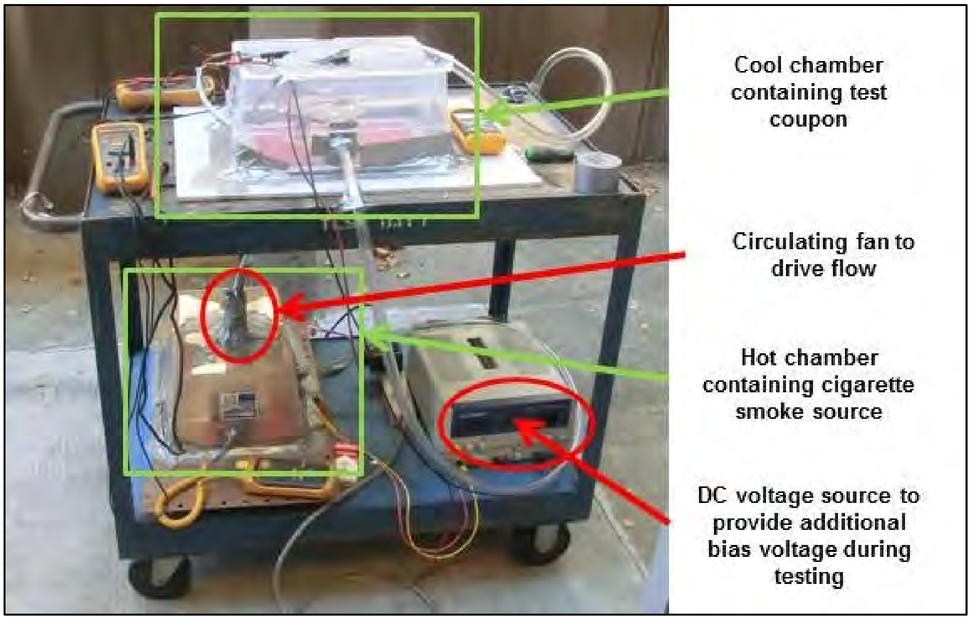

Figure 11 - Cold smoke circulation test: smoke chamber is separated from the coupon chamber so that smoke applied to the coupon is cool.

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

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

Table 2 - Summary of Smoke Exposure Testing

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

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

** 24 hours after smoke exposure.

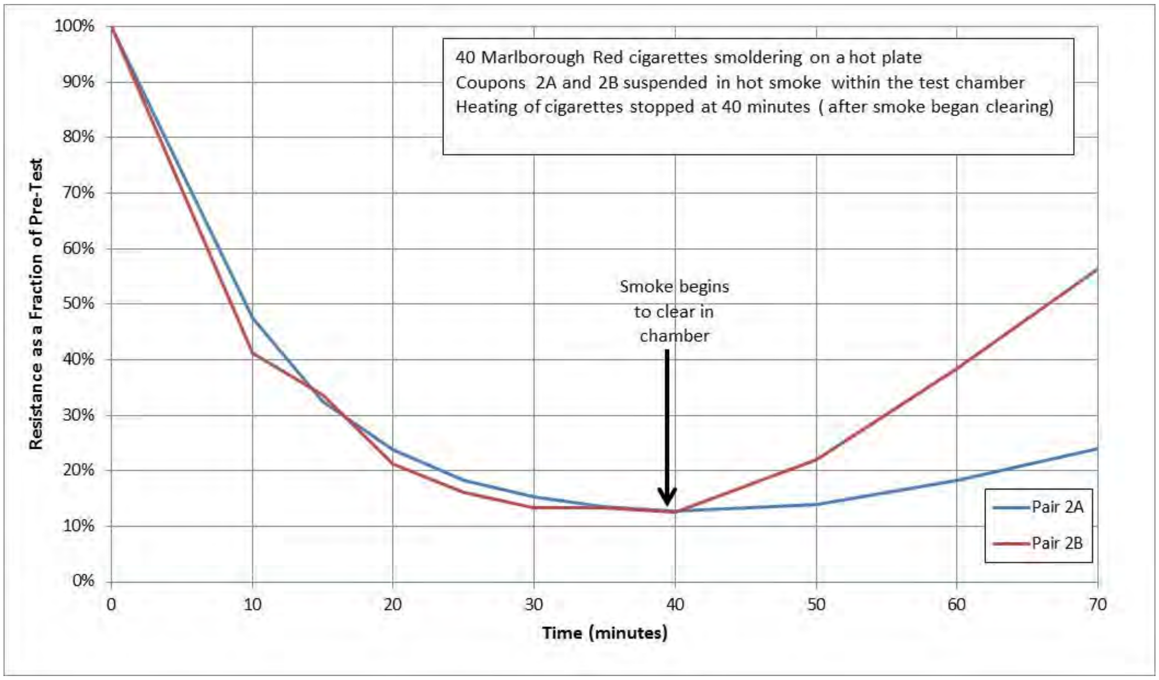

Figure 12 - Insulation resistance between cell pairs 2A and 2B when subjected to hot cigarette smoke: insulation resistance drops to an approximately steady state limit within 40 minutes of smoke application, rebounds after smoke clears.

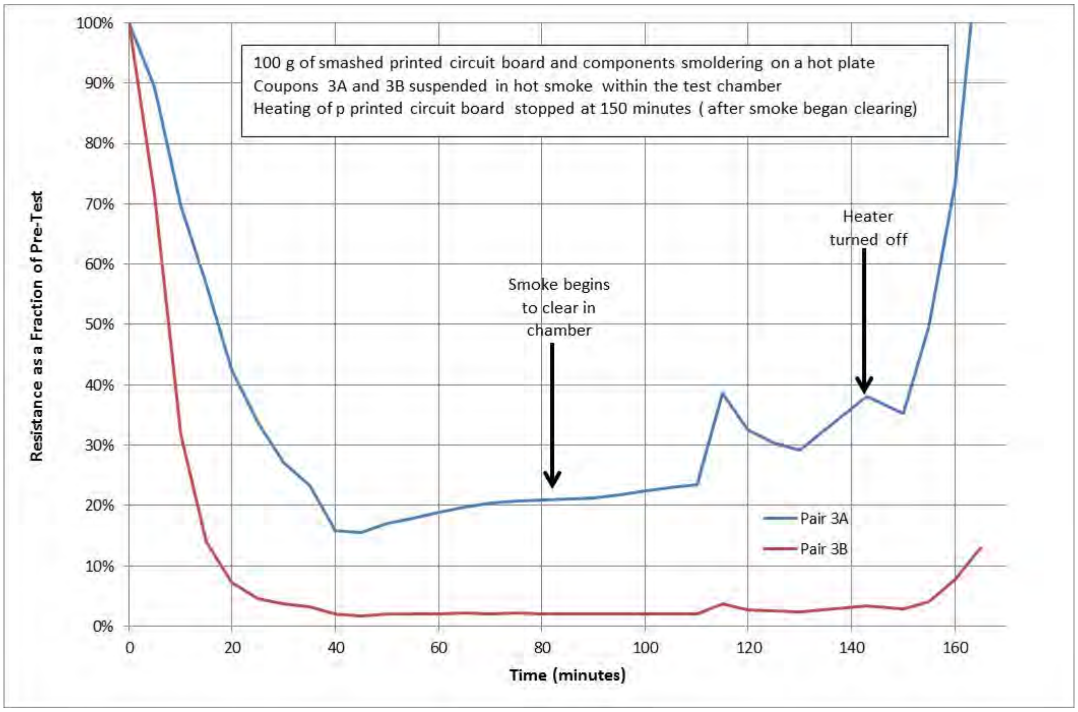

Figure 13 - Insulation resistance between cell pairs 3A and 3B when subjected to hot smoke from smoldering printed circuit board: insulation resistance drops to an approximately steady state limit within 40 minutes of smoke application, rebounds after smoke clears.

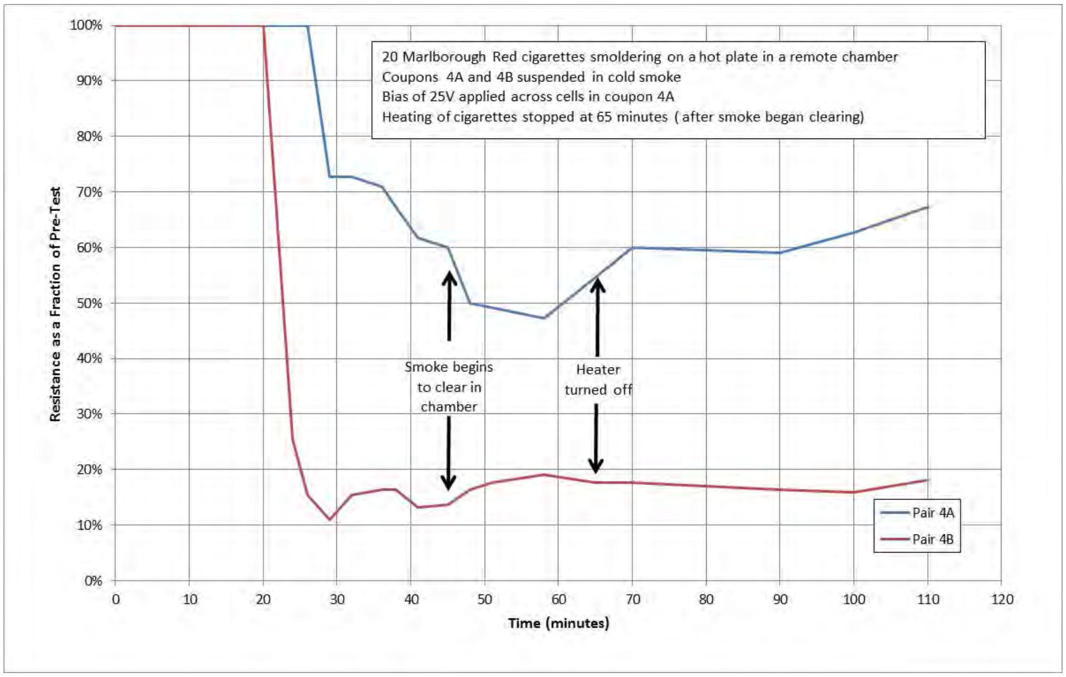

Figure 14 - Insulation resistance between cell pairs 4A and 4B when subjected to cold smoke from smoldering cigarettes: insulation resistance drops to an approximately steady state limit within 40 minutes of smoke application (smoke entered chamber at approximately 20 minutes after start of test), rebounds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

7.3.6 Leakage of Cells (Cell Electrolyte Exposure)

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

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

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

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

A series of tests were conducted with cell coupons and typical printed circuit boards to assess the effect of Li-ion cell electrolyte exposure on loss of isolation. Electrolyte exposure coupons were constructed from small cylindrical cells that were not electrically connected. The cells were placed within millimeters of each other, consistent with the architecture in the Manufacture A RESS. The coupons were placed in a 500 ml chamber heated to 25°C. Li-ion electrolyte was introduced into the chamber in one of two ways: 1) by puncturing a single cell or 2) by adding approximately 1.0 g of Mitsubishi Solrite electrolyte (iMiev) to the base of the chamber (sufficient to saturate the internal air with volatile gases). Figure 15 shows a cylindrical cell test setup.

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

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

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

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

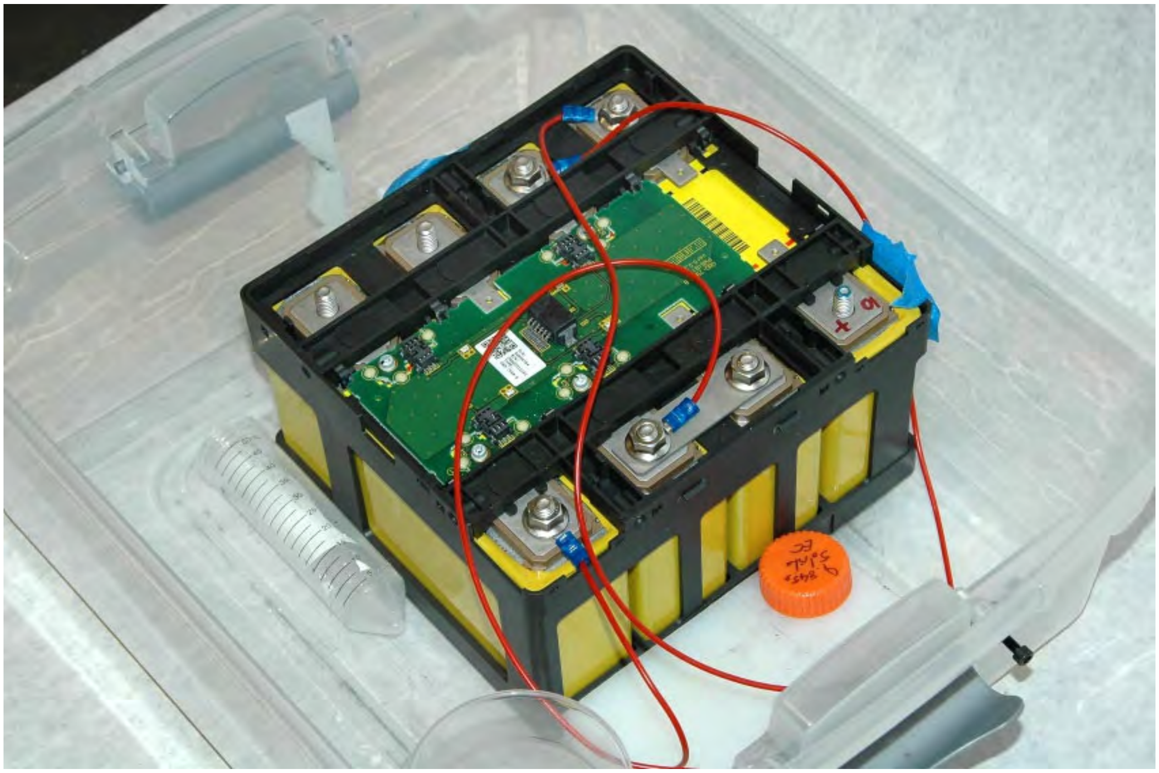

Figure 16 - An electrolyte exposure chamber containing four prismatic cells, their support structure and BMB. The isolation between the circled terminals fell significantly during the test.

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

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

Table 3 - Summary of Electrolyte Exposure Tests

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

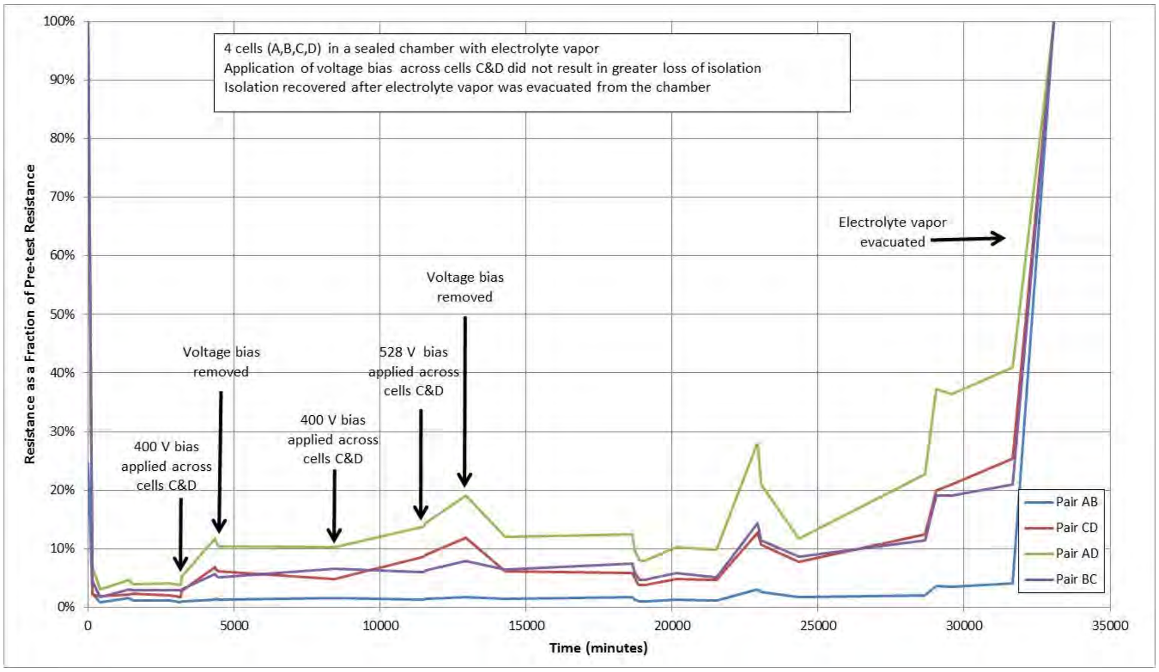

Figure 17 - Graph showing the changing isolation between cells A through D in coupon during exposure to electrolyte vapor.

7.3.7 Cell Thermal Runaway Products

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

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

7.4 Methods for Measuring Loss of Isolation

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

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

7.4.1 Insulation Resistance Measurements

An insulation resistance test is commonly used. It employs a widely available handheld meter (such as a Fluke 1507) to test potentially high resistance connections at specified voltages. It can show how a connection will behave at high voltages (i.e., hundreds of volts) where its resistive properties might be expected to change from what would typically be seen at low voltages (i.e., tens of volts). It will give the testers information about system properties and allow them to predict whether subsequent stress tests are likely to be effective or result in a hazardous condition. An insulation resistance measurement will typically detect contact between conductors; it will not detect other types of damage to insulators (e.g., a hole in insulation between two conductors). It should not result in arcing or appreciable current flows, and thus is unlikely to perturb the system being measured.

7.4.2 Dielectric Withstand Measurements

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

RESS loss of isolation evaluation should be based on IEC 60664-1 Section 5.3.3.2.3, which is a typical dielectric withstand test method. It specifies that the hipot tester linearly increase voltage by 1695 V over 3 seconds. It should maintain that voltage for 5 seconds and then linearly decrease the voltage back to 0 V over 3 seconds.

7.4.3 Transient Overvoltage Stress Testing

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

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

7.4.4 Post-Test Observation

Coupon testing with pollutants such as smoke and electrolyte showed that the effect of these compounds on isolation is strongest shortly after application and the isolation rebounds. Thus, a stress test has been selected to allow a more rapid assessment of the effect of a loss of internal isolation on the vehicle occupant or the surrounding environment. This stress test is the application of a high voltage potential to stimulate latent failure modes such as self-discharge heating within a RESS.

Full vehicle testing involving pollutants generated by cell thermal runaway reactions also showed that isolation rebounded with time. Nevertheless, the RESS should be monitored for at least 28 days after RIS testing to ensure that there are no delayed reactions.

7.5 Installation of Loss of Isolation Testing and Monitoring Leads

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

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

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

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

7.6 Vehicles and RESS Test Temperature

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

- It describes the most likely conditions for a RESS vehicle not in use or with low charge or discharge rates. Many vehicle charge rates are low and produce minimal heating during extended charge periods (i.e., more than 3 hours). Although extreme fast charging techniques produce higher heating rates, it may not be conducted frequently over the life of the vehicle.

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

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

7.7 Electrical Preconditioning of Cells, Modules, and RESS

The test procedure specifies that cells, modules, and RESSs used for testing be as new and uncycled as practical (i.e., being less than one year old and having accumulated less than five charge discharge cycles).

7.8 100% SOC Requirement

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

8. APPENDIX A

This appendix provides example RIS results using two different Li-ion cell formats (i.e., cylindrical and prismatic) that were performed in conjunction with the SCTI Procedure during full-scale vehicle testing. The purpose of this test report is to illustrate the RIS method and application; it is not intended to be a performance and safety evaluation for each manufacturer. Thus, ranking the cells/vehicles relative to the primary acceptance criteria (i.e., hazards to the occupant and the surrounding environment) is not within the scope of this report.

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

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

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

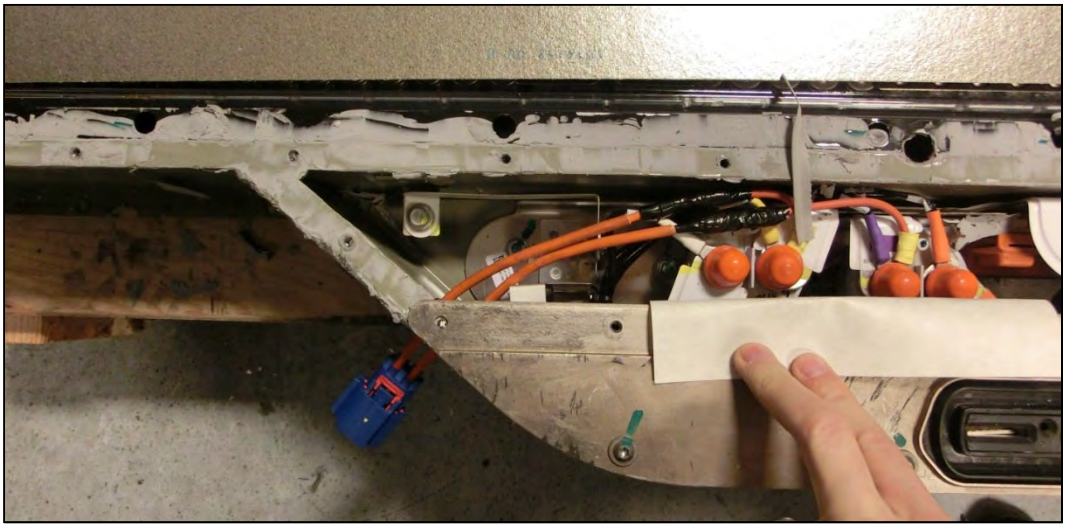

Figure 18 - The connector used for accessing the HV chain for isolation testing.

RIS test results for Manufacturer A are summarized in Table 4. Isolation resistance and dielectric withstand voltage measurements before testing indicated that internal isolation of the RESS had not been significantly compromised by installation of test equipment. Isolation resistance and dielectric withstand voltage were reduced after the initial cell thermal runaway, but exposure to the transient overvoltage stress test did not cause any additional thermal events. After stress testing, dielectric withstand testing indicated that internal isolation was rebounding to pre-test levels.

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

Table 4 - Summary of Manufacturer A RIS Testing Results

Pre-Test	Pack Voltage	350 V
	Isolation – 1000 V handheld insulation resistance meter	5.6 MΩ between the negative battery terminal and enclosure 3.9 MΩ between the positive battery terminal and enclosure
	Dielectric withstand voltage – hipot tester	7.5 mA limit exceeded at 1.67 kV
Post- Test	Pack voltage	350 V
	Isolation – 1000 V handheld insulation resistance meter	0 MΩ between the negative battery terminal and enclosure
	Dielectric withstand voltage – hipot tester	7.5 mA current limit was exceeded at 0.79 kV
	Transient Overvoltage Stress Test – power supply max current at max voltage	0.002 A
	Stress test power supply max voltage if current limited	N/A
Final	Isolation – 1000 V handheld insulation resistance meter	0 MΩ between the negative battery terminal and enclosure
	Dielectric withstand voltage – hipot tester	7.5 mA current limit exceeded at 1.59 kV
	Isolation – 1000 V handheld insulation resistance meter after 6 week dwell	5.8 MΩ between the negative battery terminal and enclosure 4.2 MΩ between the positive battery terminal and enclosure

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

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

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

RIS test results for Manufacturer B are summarized in Table 5. The handheld isolation meter indicated 0.0 MΩ of isolation, and the voltmeter indicated that the service disconnect busbar was approximately 120 V above the vehicle potential. A dielectric withstand test was attempted, but the 7.5 mA maximum current was achieved at 0.0 kV, indicating that no additional potential needed to be applied to allow for 7.5 mA of current flow. The 1-hour power supply test was attempted, but on making the connections, the voltage reading was slightly negative and the current value was at the saturation value. This indicated that too much current was flowing even without the power supply providing additional voltage. The test was aborted to avoid damage to the power supply.

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

Table 5 - Summary of Manufacturer B SCTRI Testing Results

Pre-Test	Pack Voltage	365 V nominal[9]
	Isolation – 1000 V handheld insulation resistance meter	Measurement not possible[9]
	Dielectric withstand voltage – hipot tester	Measurement not possible[9]
Post- Test	Pack voltage	Accurate measurement was not possible due to burned string of cells
	Isolation – 1000 V handheld insulation resistance meter	0.0 MΩ between the negative service disconnect terminal and enclosure
	Dielectric withstand voltage – hipot tester	7.5 mA current limit was exceeded at 0.0 kV
	Transient Overvoltage Stress Test – power supply max current at max voltage	Test aborted
	Stress test power supply max voltage if current limited	N/A
	Time to thermal runaway of additional cells	Test aborted
Final	Isolation – 1000 V handheld insulation resistance meter	Test aborted
	Dielectric withstand voltage – hipot tester	Test aborted
	Isolation – 1000 V handheld insulation resistance meter after 6 week dwell	0.1 MΩ between the service disconnect and enclosure

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

SINGLE CELL THERMAL RUNAWAY INITIATION (SCTRI) TEST

Test Procedure and Report

1. PURPOSE

Electric propulsion in a Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV) and Electric Vehicle (EV) platform relies on Rechargeable Energy Storage Systems (RESSs), commonly referred to as batteries. However, 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 that are different than those associated with an internal combustion engine. Among the potential risks is thermal runaway of the cell(s) or battery pack(s) which, in some cases, may result in a combination of potentially toxic effluent venting, fire, and/or explosion.

Catastrophic failures in cells or batteries of any chemistry, including lead acid and nickel metal hydride, can pose an appreciable hazard (e.g., an aqueous based non-flammable sulfuric acid electrolyte contained in lead acid batteries can emit hydrogen or acid gas upon failure). Although rare, thermal runaway reactions do occur in the field, even with batteries produced by the most experienced and conscientious manufacturers, and even with batteries that meet applicable standards and routinely pass a variety of abuse tests. Some thermal runaway failures in the field can be ascribed to abuse of the batteries, some to identifiable manufacturing failures, and some failures remain unexplained. Thermal runaway reactions with Li-ion cells are of particular concern since cells with this chemistry have a higher energy density than the more familiar automotive battery chemistry types (i.e., lead acid or nickel metal hydride), usually contain a flammable electrolyte, and are used to make higher capacity battery packs than previously achieved with lead acid or nickel metal hydride chemistries.

Previous experience with cells and batteries of a variety of chemistries has shown that many of the thermal runaway reactions which occur in the field begin with a flaw in a single cell. Since these cell flaws are rare, varied, and difficult to detect, it is impossible to prove with testing that any particular cell design is impervious to failure. Thermal runaway of a single cell can pose an appreciable hazard on its own. However, the extent of the resulting hazard is strongly dependent on the likelihood that the thermal runaway reaction propagates to adjacent cells. It may also compromise other systems to create or increase a hazard, such as the emission of toxic or flammable vent gases into the vehicle cabin. Although single cell testing can provide some insight into the potential hazards associated with cell thermal runaway, full-scale testing is required to properly assess the interaction of all RESS components, including RESS architecture and enclosure mitigating features that can limit thermal runaway propagation or control effluent venting.

Going forward, it can be assumed that as battery chemistries and designs evolve, the potential causes of thermal runaway reactions may change, and the resulting hazards may also change. Thus, the purpose of a Single Cell Thermal Runaway Initiation (SCTRI) testing standard is not to determine the likelihood that a single cell will undergo a thermal runaway reaction due to any particular cause. Experience with the consumer electronics, automotive, and aerospace industries have demonstrated that single cell thermal runaway reactions are always possible, even if probabilities are low. Rather, the purpose of SCTRI testing is to assume that a <u>single cell within</u>

a RESS will undergo a thermal runaway reaction due to an unspecified cause, and to then determine whether that reaction will pose a significant hazard to the vehicle's occupant or the surrounding environment. Note that SCTRI testing will not penalize cells with a lower probability of undergoing a thermal runaway reaction. If a cell type is less susceptible to thermal runaway, then the cells surrounding an initiating cell that is forced into thermal runaway will be less susceptible to propagation of thermal runaway.

2. SCOPE

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

The test procedure described is composed of three parts:

- Selecting an appropriate single cell thermal runaway initiating methodology;
- Verifying the thermal runaway initiation methodology in coupon or module level tests; and
- Full-scale, in-vehicle testing to assess whether a single cell thermal runaway within a RESS will pose a significant hazard to the vehicle's occupant or the surrounding environment.

Ultimately, judgment of vehicle safety should be based on full-scale vehicle testing results. Procedures for developing and verifying a single cell thermal runaway initiation method are provided herein to facilitate full-scale testing. Single cell initiation testing and coupon or module verification testing are only required to ensure that an appropriate method is used to initiate single cell runaway at full-scale testing. If the testing agency can provide justification for an initiation method and verify that thermal runaway was successfully initiated in full-scale testing, then single cell and verification testing may be omitted.

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 the Society of Automotive Engineeres (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

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 ECS Publications

Available from the Electrochemical Society (ECS): 65 South Main Street, Building D, Pennington, NJ 08534-2839, Tel: 609-737-1902, http://ma.ecsdl.org/content/MA2010-03/1/762.full.pdf.

- H. Maleki, H. Wang, W. Zhang, and E. Lara-Curzio, "Li-ion Cells Internal Short Circuit Testing," The 15th International Meeting on Lithium Batteries IMLB (2010).

3.2.2 IEC Publications

Available from the International Electrotechnical Commission (IEC): 446 Main Street 16th Floor, Worcester, MA 01608, Tel: 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

3.2.3 IEEE Publications

Retrieved from the Institute of Electrical and Electronic Engineers (IEEE) Standards Activities: 445 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-562-5527, www.standards.ieee.org.

- IEEE 1725 Standard for Rechargeable Batteries for Cellular Telephones

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

3.2.4 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

3.2.5 NFPA Publications

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

- C.J.Mikolajczak et al., “Lithium-Ion Batteries Hazard and Use Assessment,” July 2011.
- D. A. Purser, “Chapter 2-6 Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat,” SFPE Handbook of Fire Protection Engineering, 2008 Edition.

3.2.6 NREL Publications

Retrieved from the National Renewable Energy Laboratory (NREL): 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.
- M. Keyser, G. H. Kim, A. Pesaran, D. Long, J. Ireland, Y. S. Jung, K. J. Lee, K. Smith, S. Santhanagopalan, E. Darcy, “Numerical and Experimental Investigation of Internal Short Circuits in a Li-ion Cell,” NREL/PR-5400-50917.

3.2.7 UN Publications

Available from United Nations (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.

3.2.8 UL Publications

Available from Underwriters Laboratories Inc. (UL): 333 Pfingsten Road, Northbrook, IL 60062-2096, Tel: 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" https://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" http://www.prba.org/wp-content/uploads/UL_Presentation.ppt.

3.2.9 US DOT Publications

Available from the United States Department of Transportation (US DOT): https://www.gpo.gov/fdsys/granule/CFR-2010-title49-vol2/CFR-2010-title49-vol2-sec173-185.

- 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.

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. It calculates and communicates battery status and state of function to the vehicle system for energy flow management. In the event of a system failure, the BMS can also open contactors and isolate the battery from the rest of the hybrid system.

Battery Module

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

Brick or Block

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

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". The Occupational Safety and Health Administration (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 on its shape or design during end use; and (iii) which under normal conditions of use does not release more than very small quantities (e.g., minute or trace amounts) of a hazardous chemical, and does not pose a physical hazard or health risk to employees.

EV: Electric Vehicle

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

Explosion

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

Fire

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

HEV: Hybrid Electric Vehicle (HEV)

An automobile type vehicle, powered by an internal combustion engine and an electric motor that draws stored energy from a rechargeable energy storage device for power assist.

Initiating Cell

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

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

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

Lithium-Ion (Li-ion)

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

Material Safety Data Sheet (MSDS)

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

PHEV: Plug-in Hybrid Electric Vehicle

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

Personal Protective Equipment (PPE)

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

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.

Spontaneous (Unprovoked) Thermal Runaway

When a cell in a battery pack undergoes a thermal runaway reaction in the field and there is no evidence of applied thermal, mechanical, or electrical abuse, it is often described as a "spontaneous" or "unprovoked" thermal runaway reaction. While commonly used (including herein), this terminology is not strictly accurate since the failure occurs due to a flaw within the cell, typically one that has developed over time to a point of inducing failure during normal use.

State of Charge (SOC)

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

Thermal Runaway

Thermal runaway refers to rapid self-heating of a battery cell derived from the exothermic chemical reaction of the highly oxidizing positive electrode and the highly reducing negative electrode. It can occur with batteries of almost any chemistry. In a thermal runaway reaction, a cell rapidly releases its stored energy. At the end of a thermal runaway reaction, no electrical energy will be stored within the cell. Note that a measurement of 0 V 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. Figure 1 provides an example of temperature and voltage traces obtained from a Li-ion cell driven into thermal runaway. The thermal runaway reaction is co-incident with a sharp increase in temperature and drop in cell voltage.

Thermal runaway initiating device

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

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.

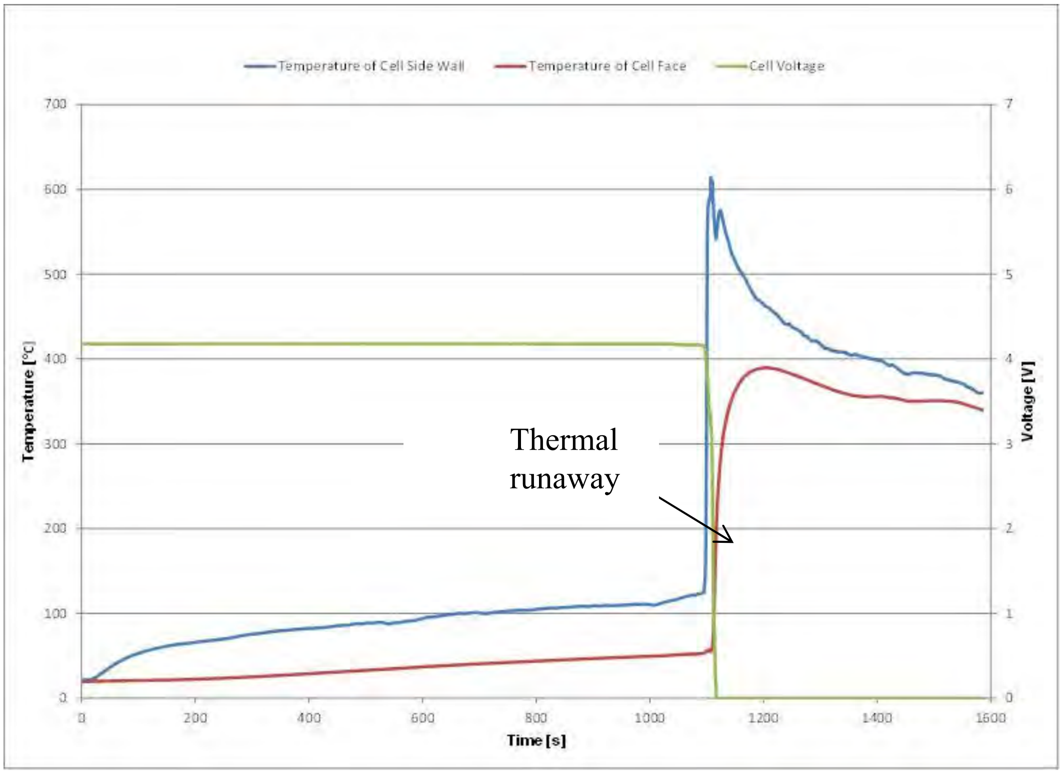

Figure 1 - An example of temperature and voltage traces for a Li-ion cell undergoing a thermal runaway reaction. Note the rapid increase in temperature.

5. GENERAL TEST REQUIREMENTS

5.1 General Precautions

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

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

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

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

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

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

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

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

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

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

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

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

5.1.3 When performing SCTRI testing on a battery pack installed in a vehicle, the testing agency should be prepared for the vehicle to completely burn.

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

5.1.3.2 A vehicle fire can produce a significant quantity of smoke. Should an air scrubbing system be used, the system filters should be selected as appropriate for both the 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 Thermal runaway initiation can fail or be delayed due to test variability. Propagation from cell to cell during a test can also be delayed, and long latency periods are common in SCTRI testing. It is often difficult for test personnel to visually determine whether a test article can be approached safely once a test has begun. Therefore, the testing agency should ensure that there is appropriate monitoring of test articles, or a sufficient delay time requirement, for testing personnel to determine when the test article can be approached after a test has begun. Monitoring can be accomplished with sensors such as thermocouples, thermal imaging cameras, voltage sensors, gas sensors, and flammable gas detectors.

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

5.2 Test Specific Precautions

N/A; see Section 5.1.

5.3 Safety Requirements

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

5.4 Test Facility/ Equipment Requirements

5.4.1 Facility requirements for full-scale in-vehicle testing:

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

5.4.1.2 The facility must have a thermal chamber or temperature-controlled area for pre-test thermal soaking of the vehicle to a temperature of 25±2°C prior to burn testing.

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

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

5.4.1.5 The facility must have the ability to safely open the battery pack before and after testing for both examination and charging/discharging cells or modules within the pack.

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

5.4.1.7 The facility must be capable of proper disposal or recycling of damaged/burned RESSs or other byproducts of testing in compliance with environmental regulations.

5.4.2 Equipment requirements for full-scale vehicle testing:

5.4.2.1 Personal protective equipment such as respirators, safety glasses, and high voltage gloves. See discussion in Section 5.3 above.

5.4.2.2 Thermal runaway initiation equipment such as a film heater and an appropriate power supply for the cell thermal runaway initiation heating method, as well as appropriate pass-throughs for electrical leads.

5.4.2.3 Sensors and data acquisition equipment:

- Thermocouple DAQ (recommend channel-to-channel isolation) capable of a data collection rate of at least 1 Hz

- Thermocouple wire (recommend K-type with fiberglass insulation)

- Thermocouple bead welder (optional – pre-made K-type thermocouples can be purchased)

- Stopwatch with accuracy of ±1 second

- Smoke detector with a photoelectric sensor (opacity-based detection)

- Gas sensor (optional)

- Handheld voltage and insulation resistance meter

- Hipot tester (optional)

- Video cameras (minimum of three)

5.4.3 Should single cell testing be required to select a cell thermal runaway initiation methodology prior to full-scale in-vehicle testing, the facility requirements for conducting single cell testing are:

5.4.3.1 The facility must have a thermal chamber for pre-test thermal soaking of cells to a temperature of 25±2°C prior to burn testing.

5.4.3.2 The facility must be capable of burning individual cells. This may require a flame-resistant fume or vent hood and the capability of handling and exhausting flammable gases.

5.4.3.3 The facility must be capable of safely discharging damaged cells and disposing of or recycling burned cells in compliance with environmental regulations.

5.4.4 Should single cell testing be required to select a cell thermal runaway initiation methodology prior to full-scale in-vehicle testing, the equipment requirements for conducting single cell testing are:

5.4.4.1 Personal protective equipment such as respirators, safety glasses, and chemical resistant gloves. See discussion in Section 5.3 above.

5.4.4.2 The thermal runaway initiation device.

5.4.4.3 A voltage measurement and data logging system with an accuracy of at least 0.5% of cell maximum voltage and a data collection rate of at least 10 Hz. For example, a National Instruments NI 9205 ±10V data acquisition module was used for Li-ion single cell testing. This has an accuracy of ±6.22 mV (i.e., 0.15% of 4.2V).

5.4.4.4 A temperature measurement and data logging system capable of reading Type K thermocouples with a data collection rate of at least 1 Hz. For example, a National Instruments NI 9213 data acquisition module was used for Li-ion cell testing.

5.4.4.5 Type K thermocouples (minimum of two).

5.4.4.6 A stopwatch or similar timekeeping instrument with an accuracy of ±1 second.

5.4.5 Should coupon or module level verification testing be required to verify a cell thermal runaway initiation methodology prior to full-scale in-vehicle testing, the facility requirements for conducting this testing are:

5.4.5.1 The facility must have a thermal chamber or other device for pre-test thermal soaking of coupons or modules to a temperature of 25±2°C prior to burn testing.

5.4.5.2 The facility must be capable of burning multiple cells in coupon or module configurations. This may require a flame-resistant fume or vent hood and the capability of handling and exhausting flammable gases.

5.4.5.3 The facility must be capable of safely discharging damaged cells, coupons, and modules, and disposing of or recycling burned components in compliance with environmental regulations.

5.4.6 Should coupon or module level testing be required to verify a cell thermal runaway initiation methodology prior to full-scale in-vehicle testing, the equipment requirements for conducting this testing are:

5.4.6.1 Personal protective equipment such as respirators, safety glasses, and chemical resistant gloves. See discussion in Section 5.3 above.

5.4.6.2 The thermal runaway initiation device.

5.4.6.3 A temperature measurement and data logging system capable of reading Type K thermocouples with a data collection rate of at least 1 Hz. For example, a National Instruments NI 9213 data acquisition module was used for Li-ion cell testing.

5.4.6.4 Type K thermocouples (minimum of two).

5.4.6.5 A stopwatch or similar timekeeping instrument with an accuracy of ±1 second.

5.5 Test Equipment Calibration

5.5.1 A written calibration procedure shall be provided that includes, at a minimum, the following information for all measurement and test equipment:

- Type of equipment, manufacturer, model number, etc.
- Measurement range
- Accuracy
- Calibration interval
- Type of standard used (calibration traceability of the standard must be evident)

6. TEST PROCEDURE

6.1 Test Type

6.1.1 Single Cell Thermal Runaway Initiation (SCTRI) testing is a destructive full-scale in-vehicle test where a single cell within the RESS is driven into thermal runaway. The resulting effects on surrounding cells, the vehicle cabin, and the vehicle surroundings are monitored to determine whether that reaction will pose a significant hazard to the vehicle's occupant or the surrounding environment.

6.1.2 In preparation for full-scale in-vehicle testing, destructive testing of individual cells and coupons or modules may be required to define and validate an appropriate device to induce a thermal runway reaction of a single cell within the RESS.

6.2 Device Under Test

6.2.1 The device under test (DUT) shall be a full vehicle with a RESS that has been modified to intentionally drive a single cell into thermal runaway and instrumented to measure the result of the thermal runaway reaction.

6.2.2 Prior to full-scale testing, single cell and coupon or module level testing may be required to determine an appropriate methodology for driving a single cell into thermal runaway and selecting an appropriate location within the RESS.

6.2.2.1 Single cells may be harvested from a second RESS unit or may be provided separately by the RESS manufacturer or vehicle OEM.

6.2.2.2 Coupons may be constructed from components harvested from a second RESS unit, or may be provided separately by the RESS manufacturer or vehicle OEM.

6.2.2.3 Modules may be harvested from a RESS unit, or may be provided separately by the RESS manufacturer or vehicle OEM.

6.3 Test Guidelines

6.3.1 Testing will require one vehicle with its RESS. The vehicle and RESS should be new (i.e., less than one year old, and with less than five charge/discharge cycles applied to the RESS). The RESS may be provided by the manufacturer or vehicle OEM with the necessary modifications for conducting SCTRI testing. If the testing agency must modify the RESS for testing, then additional RESS components may be required (e.g., enclosure components, see Section 8.3.3).

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

6.4 Test Parameters

6.4.1 Full-scale vehicle SCTRI test parameters are:

- RESS cell beginning test temperature: 25±5°C (see Section 6.6.5)
- Beginning pack state: Cells less than one year old and accumulated <5 electrical cycles
- Beginning SOC of the RESS: 99% to 100% of the maximum normal operating SOC
- Beginning energy of vehicle: Fully charged RESS; full fuel tank (HEV, PHEV)[1]

6.4.2 Single cell test parameters are:

- Cell Temperature: 25±2°C
- Cell State of Charge (SOC): 99% to 100% of the maximum normal operating SOC

6.4.3 Verification (coupon or module level) test parameters are:

- Cell Temperature: 25±2°C
- Initiating Cell State of Charge (SOC): 99% to 100% of the maximum normal operating SOC
- Neighboring Cell SOC: Various, depending on test configuration

6.5 DUT Preconditioning

6.5.1 All cells, modules, and RESSs used for testing should be as new and uncycled as practical (i.e., they should be less than one year old and have accumulated less than five charge/discharge cycles prior to testing).

6.5.2 Full vehicle and RESS conditioning occurs during test preparation. The temperature preconditioning requirements are described in Section 6.6.5.

6.5.3 For single cell testing, the cell should be at a temperature of 25±2°C prior to test initiation.

6.5.4 For coupon or module level verification testing the device under test should be at a temperature of 25±2°C prior to test initiation.

6.6 Test Methodology

6.6.1 Single Cell Thermal Runaway Initiation Method Selection Process:

6.6.1.1 The test agency shall select a method appropriate to the specific device under test and provide reasoning as to the selection. The test agency shall provide evidence of physical tests at the single cell level to demonstrate efficacy of the selected method (i.e., that it will induce a thermal runaway reaction). See additional discussion in Section 7.1.

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[1] See Section 4.0

6.6.1.2 The selected initiation method shall force only one cell into thermal runaway. Any subsequent cell thermal runaway reactions shall be the result of propagation from the initiating cell, not caused directly by the initiation method. See additional discussion in Sections 6 and 7.

6.6.1.3 The initiation method should best represent the behavior expected from a spontaneous field failure of a single battery cell, such as failure due to an internal short circuit. For example, the selected initiation method should avoid blocking normal exhaust gas flow or adding new and significantly different exhaust paths. It should avoid preheating neighbor cells beyond what would be expected from initiator heating due to a single-cell field failure. It should avoid compromising the electrical isolation of the cell to any surroundings. It should not affect the thermal boundary conditions around the initiator cell due to the addition of conductive or insulating materials that are not typically present in the RESS. Further discussion of relevant test factors can be found in Section 7.2. Examples of analysis of the efficacy of various thermal runaway initiation methods can be found in Section 8.1.

6.6.1.4 Single cell thermal runaway may be initiated with a variety of methods, and no single method is appropriate for all cell chemistries and form factors. The testing agency may need to trial multiple methods to find one method that will reliably induce cell thermal runaway. Section 8.1 provides examples of thermal runaway inducing methods that are effective for some cell designs. Section 7.3 provides discussion of additional thermal runaway inducing methods.

6.6.2 Coupon or Module Thermal Runaway Initiation Method Verification Testing:

6.6.2.1 The testing agency shall determine whether coupon or module level testing is required. The test agency shall provide justification for the decision if coupon or module level testing is not completed.

6.6.2.2 Coupon or module level testing may be required if the testing agency suspects that the method of thermal runaway initiation could have a significant impact on the testing process in the full RESS configuration.

6.6.2.3 Section 8.2 provides examples of coupon and module level verification testing and describes the reasons for testing.

6.6.3 RESS Preparation Procedure:

6.6.3.1 Broadly, preparation of the RESS for full-scale testing will include documentation and characterization of the RESS as-received, installation and documentation of any hardware that is required to initiate thermal runaway in a single cell, installation and documentation of monitoring sensors, charging of the battery pack to the maximum allowable state of charge, and closing of the battery pack.

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

6.6.3.3 It may be most convenient to charge the RESS with an approved charger system prior to removing the battery pack from the vehicle, preparing it for SCTRI testing, and re-installing it in the vehicle. However, in some instances, the testing agency may choose to charge the battery pack after other preparation activities occur.

6.6.3.4 Once charging has occurred, and immediately prior to closing the RESS, record the battery pack voltage, the highest-voltage series element and its location, and the lowest-voltage series element and its location.

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

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

6.6.3.7 If the battery pack must be opened to install 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 be measured between the battery negative terminal and the battery enclosure using an insulation resistance meter. A testing agency may also choose to conduct a dielectric withstand test using a hipot tester.

6.6.3.8 A location shall be selected for thermal runaway initiation. The location should be the most likely to result in thermal runaway propagation per the test agency’s engineering judgment or results of previous testing. For example, the initiation location may be at a cell that is surrounded by neighboring cells, or at a cell that is furthest from active cooling systems. The testing agency shall report the reasons for their selection of initiation location, which can include evidence from physical tests.

6.6.3.9 The single cell thermal runaway initiation device shall be installed at the identified location. Multiple thermal runaway initiation devices may be installed within a single battery pack to allow for more convenient test repetition should the first initiation device fail to operate. Electrical leads connected to the initiating device(s) should use high-temperature insulation to avoid compromising the isolation of the battery pack from the enclosure/vehicle due to the presence of experimental equipment. Similarly, high-temperature pass-throughs should be used to avoid compromising any battery pack seals due to the presence of experimental equipment.

6.6.3.10 Assuming thermal runaway propagation will occur during testing, any electrical leads required to activate the thermal runaway initiation device should be sufficiently long for test personnel to activate and deactivate the device at a safe distance from the vehicle.

6.6.3.11 Instrumentation shall be installed to collected data on the extent or rate of thermal runaway propagation and to determine if a test has been completed. At a minimum, one sensor should be installed in the battery near the initiation location to confirm the first cell thermal runaway and two additional sensors should be installed on adjacent cells to determine if propagation is occurring. High-temperature insulation for any electrical leads to sensors should be used to avoid compromising the isolation of the battery pack from the enclosure/vehicle due to the presence of experimental equipment. Similarly, high-temperature pass-throughs should be used to avoid compromising any battery pack seals due to the presence of experimental equipment. Any connectors to sensors should be sufficiently long for a data acquisition system to be located a safe distance from a vehicle undergoing a complete burn and remain intact.

6.6.3.12 To measure pack voltage and internal electrical isolation, a connection that allows both positive and negative battery terminals to be electrically accessible from outside the pack may be installed. This connection should have adequate insulation to avoid affecting isolation measurements. If the vehicle can provide a measurement of internal isolation and pack voltage or SOC once an instrumented RESS is installed in the vehicle, an additional connection is not required.

6.6.3.13 All modifications to the RESS shall be documented with photographs and appropriate notes; the location of the thermal runaway initiation hardware and all sensors shall be recorded.

6.6.3.14 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. Isolation measurements as per Section 6.6.3.7 should be made after pack closing to ensure that installed instrumentation and any necessary modifications have not significantly degraded the electrical isolation of the RESS. If application of instrumentation has significantly diminished battery pack isolation, the instrumentation setup should be reviewed and the cause of the loss of isolation should be found and, if possible, eliminated.

6.6.4 Vehicle Preparation Procedure:

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

6.6.4.2 The RESS shall be removed from the vehicle and prepared for testing as in Section 6.6.3.

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

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

6.6.4.5 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 (e.g., at locations within the cabin adjacent to the RESS). Location of all sensors shall be documented.

6.6.4.6 The vehicle cabin shall be physically isolated during testing. Doors and windows shall be closed and sealed (with provision for experimental equipment leads to exit the vehicle cabin). The vehicle cabin heating, ventilation and air conditioning (HVAC) system shall not be operational.

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

6.6.4.8 Battery pack voltage and SOC shall be measured and recorded.

6.6.4.9 An internal electrical isolation measurement should be performed. Isolation should be measured between the battery negative terminal and the battery enclosure. Isolation values should be compared to the initial results (see Section 6.6.3.7). If application of instrumentation has significantly diminished battery pack isolation, the instrumentation setup should be reviewed, and the cause of the loss of isolation should be found and if possible, eliminated.

6.6.4.10 The vehicle, as prepared for testing, shall be photographed.

6.6.5 Vehicle Preconditioning Procedure:

6.6.5.1 The vehicle and RESS as instrumented for testing can be brought to test temperatures by placing the vehicle with an installed RESS into a temperature control chamber held at 25±2°C. The vehicle should be held in the chamber for sufficient time to equalize to test temperature, at least 12 hours. Thermal runaway initiation should begin within 30 minutes of removal of the vehicle from thermal conditioning. The RESS temperature at the beginning of thermal runaway initiation shall be 25±5°C as measured by sensors installed within the RESS (Section 6.6.3).

6.6.6 Vehicle SCTRI Test Procedure:

6.6.6.1 The vehicle shall be placed in a location suitable for SCTRI testing (see Section 5.4.1).

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

6.6.6.3 Assuming thermal runaway propagation will occur, cameras should be located at a sufficiently safe distance from the vehicle to allow test personnel to approach them and change recording media (tapes) if necessary during testing.

6.6.6.4 Temperature measurement logging devices should be configured to collect at least one measurement per second.

6.6.6.5 Any connectors to sensors should be sufficiently long for a data acquisition system to be located a safe distance from a vehicle undergoing a complete burn and remain intact. Data acquisition equipment may be protected from heat using shielding or insulation.

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

6.6.6.7 The initiation of temperature logging and video recording should be synchronized (e.g., all systems should be started within 30 seconds of each other). At least five stable temperature measurements should be recorded per temperature logging channel prior to proceeding with thermal runaway initiation.

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

6.6.6.9 The testing agency shall have determined an expected time to thermal runaway during module or coupon testing (Section 8.1). If there is no indication of single cell thermal runaway within twice the expected time, then the testing agency should proceed to energize an alternative thermal runaway initiating device if one has been installed.

6.6.6.10 If thermal runaway initiation fails to occur and no alternative initiating devices have been installed (or have all failed to induce thermal runaway), the testing agency shall abort the test and determine the cause of the experimental failure. This may involve removing the RESS and opening it. Personnel working with the battery pack should be aware that a cell within the RESS may have been damaged and could be susceptible to thermal runaway during system examination. They should conduct the examination in an appropriate location using appropriate tools and PPE.

6.6.6.11 If thermal runaway initiation is not achieved, the testing agency must select an alternative method for initiation and repeat coupon or module level testing to verify its efficacy. Then full-scale testing can be repeated.

6.6.6.12 A stopwatch or other timekeeping device shall be used to measure the time from initial cell thermal runaway to any secondary cell thermal runaway reactions, activation of the in-cabin smoke detector, and the appearance of flames. If flames appear, no effort will be made by test personnel to suppress flaming combustion.

6.6.6.13 Testing is complete when:

- Either all temperature readings on cells within the RESS are below 60°C and have been decreasing for at least 30 minutes,
- If thermocouple readings are not available, then after a confirmed single cell thermal runaway initiation reaction has occurred and there is no visible follow-up reaction after 8 hours or,
- If a fire has occurred, 30 minutes after the RESS and vehicle have been consumed. Suppression equipment may then be used to suppress lingering flames or cool hot spots.

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

6.7 Measured Data

6.7.1 Full-scale vehicle SCTRI test reports should include the following information:

- Details of the initiation method, including justification of the criteria in Section 7.2.
- Location of the initiation method, including justification for its selection.
- Locations of all installed sensors.
- Evidence that instrumentation has not significantly affected RESS internal isolation.
- Voltage of the pack prior to test beginning.
- Video of the test from several angles, at least three.
- Time that the first thermal runaway occurred.
- Evidence that the first runaway occurred, visually, audibly, and/or thermally.
- Times of any subsequent runaways, vehicle events, ignition, smoke alarm activation. Use t=0 as the time when the initiating device was activated.
- Temperature data and gas sensor data if measured.
- Photographs of the battery pack after testing has completed.

6.7.2 Single cell initiation method testing reports should contain the following information:

- A voltage trace of the cell showing drop of voltage at the point of the thermal runaway reaction.
- Two cell surface temperatures up to the point of the thermal runaway reaction.
- Time required from the start of the test to achieve thermal runaway.
- Video recording of the entire test.
- Photograph of the cell after testing.

- An estimate of the amount of energy supplied to the cell by the initiation method, and a comparison to total cell energy.
- An analysis of the test initiation method with regards to suitability for use in full-scale RESS testing.

6.7.3 Initiation method verification (coupon or module level) testing reports should contain the following information:

- A description of the cell thermal runaway initiation method used.
- Time required from the start of the test to achieve thermal runaway and the method used to determine that thermal runaway has occurred.
- Temperature data from which the neighbor cells' average change in temperature and the maximum temperature can be extracted when the initiating cell enters thermal runaway.
- Video recording of the entire test.
- Photograph of the cell after testing.
- An estimate of the amount of energy supplied to the cell by the initiation method and a comparison to total brick energy.
- An analysis of the test initiation method with regards to suitability for use in full-scale RESS testing.

6.8 Inspection Method

6.8.1 If the SCTRI test did not cause propagation to adjacent cells, the vehicle and RESS should be tested for high voltage isolation.

6.8.2 After testing is complete, the RESS should be separated from the vehicle.

6.8.3 The RESS should be opened and visually examined to confirm cell thermal runaway reactions and to determine how to best dispose of the battery pack.

6.9 Post-Test Requirements

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

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

6.10 Acceptance Criteria

6.10.1 The purpose of SCTRI testing is to assume that a single cell within a RESS will undergo a thermal runaway reaction due to an unspecified cause and determine whether that reaction will pose a significant hazard in two primary areas: hazards to the occupant and hazards to the surrounding environment.

6.10.2 Hazards to the Occupant:

6.10.2.1 The cabin must remain tenable for sufficient time to allow safe egress of vehicle occupants after they perceive that a serious failure has occurred with the battery pack, or for 1 hour after initiation of a single cell thermal runaway event that does not provide significant warning properties to the occupants. See Section 7.10 for further discussion.

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

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

6.10.3 Hazards to the Surrounding Environment:

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

6.10.3.2 The vehicle should not ignite as a result of SCTRI testing.

6.10.3.3 Vent gases emitted by the vehicle as a result of SCTRI testing should not ignite.

6.10.3.4 There should be no explosion as a result of SCTRI testing.

7. TEST PROCEDURE RATIONALE

7.1 Mechanisms of Thermal Runaway Reactions in Li-ion Cells and Subsequent Propagation

Thermal runaway refers to rapid self-heating of a battery cell derived from an exothermic chemical reaction of the highly oxidizing positive electrode and the highly reducing negative electrode. In a thermal runaway reaction, a cell rapidly releases its stored energy. It will occur if the thermal stability limits of the cell chemistry are exceeded (i.e., if the rate of heat generation within the cell exceeds the rate of heat loss). This can occur within a small local area of the cell and then propagate through the bulk of the cell (typical of a cell internal short circuit failure), or it can occur throughout the bulk of the cell (typical of external heat exposure). For any cell chemistry or design, there will be a variety of mechanisms that can cause the cell to exceed its thermal stability limits. For Li-ion cell chemistries specifically, thermal runaway reactions can be caused by thermal abuse, mechanical abuse, electrical abuse, poor cell electrochemical design, and internal cell faults associated with cell manufacturing defects.

To assess the safety of a practical RESS for an automotive application, the causes of thermal runaway reactions can be grouped into two categories: inducing thermal runaway in multiple cells almost simultaneously and inducing thermal runaway in only a single cell.

Causes of simultaneous multiple cell thermal runaway reactions in RESSs tend to be extreme events such as energetic collisions that can induce mechanical damage to multiple cells within a battery pack, bulk heat exposure such as from an adjacent fire, and severe overcharge of multiple cells caused by failure of pack protection electronics and/or charging systems. There are a number of vehicle and battery pack standards that address events that may be likely to cause multiple cell thermal runaway reactions such as vehicle crash tests described in the Federally Mandated Vehicle Safety Standards (FMVSS) and battery abuse tests described in standards developed by organizations such as the Society of Automotive Engineers (SAE), Underwriters Laboratories (UL), the United Nations (UN), US Department of Transportation (DOT), the Institute of Electrical and Electronics Engineering (IEEE), Japanese Industrial Standards (JIS), and the International Electrotechnical Commission (IEC).

Causes of single cell thermal runaway reactions in a RESS can be much more subtle than those events causing simultaneous multiple cell thermal runaway. They can include development of cell internal short circuits due to highly localized heating, highly localized mechanical damage, or latent manufacturing defects that become active as a cell ages. From a typical consumer's perspective, these faults can seem to occur "without warning", or "spontaneously"; they can appear "unprovoked". Although not truly spontaneous (some latent fault is the cause of failure), single cell thermal runaway failures can occur as single point failures; no external abuse condition is required for one of these failures to occur. Thus, spontaneous or unprovoked single cell failures should be expected and mitigated in RESS designs.

Once a cell has experienced thermal runaway, it will be hot and transfer heat to its surroundings, including adjacent cells through conductive, convective, and radiative heating modes. Depending on a number of factors including chemistry, state of charge, geometry, and module or battery pack architecture, a single cell may be able to transfer sufficient heat such that a neighboring cell also exceeds its thermal stability limits and undergoes a thermal runaway reaction. In this way, cell thermal runaway reactions can propagate throughout an entire battery pack. Although thermal runaway of a single cell can pose an appreciable hazard on its own, the extent of the resulting hazard is strongly dependent on the likelihood that the thermal runaway reaction propagates to adjacent cells, or compromises other battery or vehicle systems to create a hazard.

A number of Li-ion battery standards and industry best practices address and limit single cell susceptibility to a wide range of thermal runaway causes. However, these standards and best practices have not been able to eliminate all plausible causes of "spontaneous" single cell thermal runaway reactions, which are rare, varied, and difficult to detect. Looking forward, as cell designs and chemistries continue to evolve, it is likely that new cell designs will be susceptible to different mechanisms of thermal runaway initiation, and it will take some time for standards and industry best practices to mitigate the new mechanisms of failure. Thus, the purpose of Single Cell Thermal Runaway Initiation (SCTRI) testing is not to determine the likelihood that a single cell will undergo a thermal runaway reaction due to any particular cause or load case. The purpose of SCTRI testing is to assume that a single cell within a RESS will undergo a thermal runaway reaction due to an unspecified cause, and to then determine whether that reaction will pose a significant hazard to the vehicle's occupant or the surrounding environment.

The only standards at the time of this writing to address hazards associated with single cell thermal runaway within a RESS are propagation resistance tests found in SAE J2464 "Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing", UL 2580 "Standard for Batteries for Use in Electric Vehicles" which references SAE J2464, and UL 1973 "Batteries for Use in Light Electric Rail (LER)".

SAE J2464 states:

> *4.4.5 Passive Propagation Resistance Test (Module or Pack Level)*
>
> *This test evaluates the ability of a DUT to withstand a single cell thermal runaway event so that a thermal runaway event does not propagate to adjacent cells. It is recommended that the DUT manufacturer first perform these tests at the module level.*
>
> *4.4.5.1 Test Description*
>
> *The DUT is charged to 100% SOC. All external circuits, cooling systems, or other devices are turned off or disconnected. If liquid cooling is used, the liquid may remain in the DUT without circulation. The DUT is heated until the cells stabilize at 55°C or the maximum operating temperature, whichever is greater. One cell within the DUT at a locations described below is uniformly heated in-situ to a temperature of 400°C (or until the cell enters thermal runaway) in less than 5 min (for example, using resistive heating or thermal conductive heat transfer using an external heat source). The method used to create a thermal runaway in one cell will be described and documented in the report. After one of the above conditions is met, the heater is turned off and DUT is observed for 1 h. Other methods to initiate thermal runaway in one cell are allowed. This above procedure shall be repeated with cells in different locations that represent various thermal environments/relationships within the pack. The following heated cell locations are suggested for a DUT resembling a rectangular prism…:*
>
> *1) The geometric corner of the Module or Pack.*
>
> *2) At the midpoint of an edge.*
>
> *3) At the center of one face.*
>
> *4) The interior of the Module or Pack 1/4 the distance from the center of a face (B) to the opposite face.*
>
> *5) The interior of the Module or Pack 1/4 the distance from the center of a face (C) to the opposite face.*

Note that SAE 2464 does not provide specific methods for assessing the effect of either a single cell thermal runaway reaction or a propagating reaction on the vehicle occupant or surrounding environment. The intent of the test method is to determine if thermal runaway propagation will occur. This standard does not explore the interaction of the RESS with the vehicle.

UL 1973 states:

> *37.1 The electric energy storage system shall be designed to prevent a single cell failure within the system from cascading into a fire and explosion of the DUT. This test is applicable to lithium ion technologies.*

> *37.2 The fully charged electric energy storage system...is to be subjected to the internal fire test which consists of heating one internal cell that is centrally located within the DUT until thermal runaway or otherwise forcing the failure of a cell through any means necessary and determining whether or not that failure remains safely controlled within the DUT. Once the thermal runaway is initiated, the mechanism used to create thermal runaway is shut off or stopped and the DUT is subjected to a 1-h observation period.*
>
> *Exception No. 1: Testing on a cell that is other than centrally located within the DUT may additionally be conducted if it is not clear which is the worst case scenario. The location of the failed cell is to be documented for each test.*

Note that the UL standard considers the effects of a thermal runaway reactions on vehicle or surroundings, but only considers the hazards of fire or explosion. The UL standard does not consider the hazards associated with vent gas toxicity.

The Single Cell Thermal Runaway Initiation (SCTRI) test procedure goes beyond SAE J2464 and UL 1973, by providing a) a framework for evaluating and verifying possible thermal runaway initiation methods, b) a more detailed full-scale test methodology with examples depicting how tests can be conducted, and c) a method for evaluating the interaction of a RESS with a vehicle in terms of cabin tenability as well as hazards to surroundings.

7.2 Evaluation of Single Cell Initiation Methods for Li-Ion Cells

Single cell thermal runaway initiation methods should be designed to mimic expected spontaneous field failures. For Li-ion cells, an initiation method should mimic an internal short circuit (i.e., one of the most common causes of Li-ion cell thermal runaway reactions in the field). A number of organizations have proposed methods for mimicking Li-ion internal short circuit failure modes, but not all of the proposed methods can be readily adapted for testing within a full battery pack nor are they effective for all types of cell geometries. It is important to note that if a cell does not undergo a thermal runaway reaction with a particular method of initiation, this is <u>not</u> evidence that the cell cannot undergo thermal runaway or that the cell does not pose a spontaneous thermal runaway risk.

For purposes of SCTRI testing, the performance of an initiation method should be evaluated on the basis of the following factors:

- Initiating device effect on neighboring cells (e.g., does the <u>initiating device</u> cause direct heating of or damage to neighboring cells?). If an initiating device causes pre-heating of neighboring cells, this might be observed in an extended time to thermal runaway of the initiating cell (i.e., a low "efficiency" initiating method).

- Comparison of the energy added to the system by the initiating method to the total energy in the cell, brick, or RESS. If an initiating method is adding significant energy to the system, rather than to the initiating cell, the low "efficiency" of the method may be observed as an extended time to thermal runaway of the initiating cell. Note that addition of energy to the system is not un-representative of spontaneous cell field failures. In many instances, field failures occur during charging of a cell, at which time a charging system may add substantial energy to the system. In addition, with many pack architectures, cells connected in parallel to a faulting cell can also provide substantial energy that heats the faulting cell to thermal runaway (see Figure *2*).

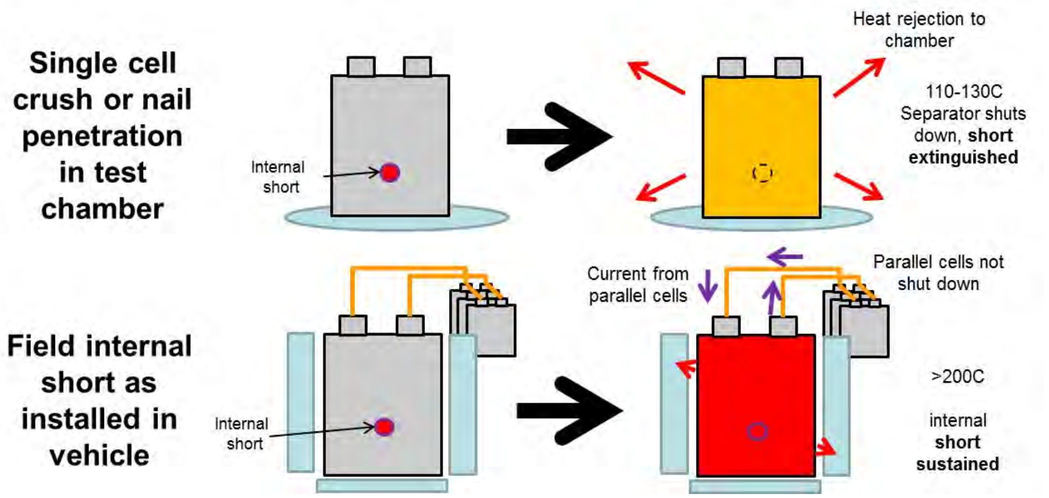

Figure 2 - An example of a cell thermal runaway initiation method that may not cause thermal runaway of a single unconnected cell but may cause thermal runaway when that cell is connected in parallel to other cells.

- Effect on SOC of the initiator cell (e.g., does the initiator method cause cell overcharge and thus elevate the cell SOC beyond what would be expected in the field, producing an uncharacteristically energetic thermal runaway reaction?).

- Effect of the initiation method on gas flow path(s) from the initiator cell (e.g., nail penetration can create a gas flow path in an area unrelated to the cell normal venting path). This could positively or negatively affect the test outcome.

- Effect of the initiation method on mechanical boundary conditions (e.g., can the initiating device be mounted within a RESS without significantly compromising the RESS enclosure?).

- Effect of the initiation method on thermal boundary conditions such as the air spaces between adjacent cell or objects, heat conduction to other cells or structures in the battery module/pack, the conductivity of the materials, and the radiation heat flow paths.

- Effect of the initiation method on electrical boundary conditions such as the number of cells that are connected in parallel, the energy of these cells, and whether or not they can continue to resistively heat the initiating cell after thermal runaway has occurred.

- Whether the initiation method requires that cells be modified or that non-production cells be used.

- Applicability of the method to module and pack configurations.

- Reliability of the method to initiate thermal runaway.

Each initiation method will have its own strengths and weaknesses with regard to the listed factors, the specific chemistry, and the cell, module, and pack form factor. For example, mechanically induced short circuiting by nail penetration or crush typically results in minimal additional energy added to the system. It can also provide a fast time to thermal runaway. However, mechanical initiation mechanisms often introduce non-representative gas exhaust paths. They can also be experimentally difficult to implement in a full RESS enclosure that will be mounted on a vehicle, without compromising the RESS enclosure itself.

The testing agency may find it useful to try a few different possible initiation methods and comparing results before settling on a final test method. Section 8.1 describes the evaluation of a few experimentally convenient and low cost initiation methods for Li-ion cells of different styles. An initiation method that is not mentioned in Section 8.1 may also be used as long as its appropriateness can be demonstrated given the factors and considerations mentioned previously.

7.3 Examples of Thermal Runaway Initiation Methods Applicable for Li-ion Cells

7.3.1 Thermal Initiation Methods

The most direct way to exceed the thermal stability limit of a Li-ion cell is to subject it to external heating. A common and experimentally convenient method for initiating single cell thermal runaway in a Li-ion battery pack is to apply an externally powered heater to an individual cell (conductive heating). Other thermal initiation methods include laser heating, radiant heating, and applying external chemical heat sources to cells (thermite). Internal heating methods have also been explored (e.g., micro-heaters can be inserted directly into electrodes). With all these methods, the testing agency needs to remain particularly aware of the potential for heating adjacent cells, not just the initiating cell during activation.

7.3.2 Mechanical Initiation Methods

Mechanical methods for simulating Li-ion cell internal faults have been researched extensively. These include nail penetration tests, blunt object crush tests, and pinch tests. For example, Underwriters Laboratories has proposed a blunt nail crush test. Oak Ridge National Laboratory (ORNL) has investigated pinch testing.

Mechanical methods of initiation typically result in minimal additional energy added to the system. They can also provide a fast time to thermal runaway. However, mechanical initiation can also introduce non-representative gas exhaust paths, alter the shape of the cell boundary (which can affect heat transfer to neighboring cells), and alter thermal boundary conditions. They can also be experimentally difficult to implement in a full RESS enclosure that will be mounted on a vehicle without compromising the RESS enclosure itself.

7.3.3 Electrical Initiation Methods

In the past, cell overcharge was considered a convenient method for inducing a single cell thermal runaway reaction. However, this method has become increasingly difficult to apply. Many cylindrical cells incorporate effective charge interrupt devices (CIDs) that prevent cell overcharge and polymer cells tend to swell until electrodes are sufficiently separated to prevent further charging. Cell overcharge can also produce an uncharacteristically energetic reaction in the initiating cell that can damage surrounding cells in a non-representative manner. Other electrical initiation methods have been used to initiate thermal runaway in cells. For example, Patent US8421469 B2 describes a “Method and apparatus for electrically cycling a battery cell to simulate an internal short.” These methods tend to be highly cell design dependent and can take considerable effort to develop.

7.3.4 Introduction of Electrode Defects

Several researchers have developed methods to introduce defects into a cell electrode and then activate the defects to induce cell thermal runaway. For example, the National Renewable Energy Laboratory (NREL) has run tests where they have inserted a wax device in between the electrode layers of a pouch cell. This wax device will melt away once heated and start an internal short circuit. These methods generally require implementation of specially built cells, and thus the cooperation of the cell manufacturer. In addition, transport of cells specifically modified to allow triggering of thermal runaway reactions poses challenges with transportation safety. Finally, these cells need to be safely charged and installed in a fully charged battery pack, which can be difficult with some pack architectures.

7.4 Vehicles and RESS Test Temperature

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

- It describes the most likely conditions for a RESS vehicle not in use or with low charge or discharge rates. Many vehicle charge rates are low and produce minimal heating during extended charge periods (e.g., more than three hours). Although extreme fast charging techniques produce higher heating rates, it may not be conducted frequently over the life of the vehicle.

- It is a moderate temperature and experimentally convenient. Testing is most likely to be conducted in an outdoor environment with variable ambient temperatures. After exiting a conditioning chamber, a vehicle must be sited and the data logging equipment connected. During that setup time, vehicle temperature is likely to drift toward the ambient temperature. Ambient is likely to be relatively close to 25°C (compared to 55°C as specified for module level tests in SAE J2464).

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

7.5 Electrical Preconditioning of Cells, Modules, and RESS

The test procedure specifies that the cells, modules, and RESS used for testing be as new and uncycled as practical (i.e., less than one year old and having accumulated less than five charge/discharge cycles).

7.6 100% SOC Requirement

SCTRI testing is conducted on a fully energized RESS (i.e., all cells at 100% SOC). This condition was selected because most spontaneous thermal runaway field failures occur when cells are fully charged. An internal short circuit in a Li-ion cell is most likely to develop at a fully charged condition and is most likely to heat a fully charged cell to thermal runaway. Furthermore, Li-ion cell field failure experience indicates that most thermal runaway failures occur when cells are fully charged. Neighbor cells are also most susceptible to thermal runaway propagation when in a fully charged (100% SOC) condition.

7.7 Thermocouple Instrumentation

The procedure requires only limited temperature measurements during testing, specifically to confirm that thermal runaway of the initiating cell has occurred and to monitor air cabin temperatures. Based on the testing examples described in Section 7, it is evident that, although temperature measurements are useful for understanding thermal propagation from a research perspective, these measurements are not necessary to determine whether a single cell thermal runaway reaction will result in a hazard to vehicle occupants or the surrounding environment. Nonetheless, the testing agency may wish to collect a far greater number of temperature measurements than the minimum required. Examples in Section 7 can provide guidance regarding the utility of measurements taken at various locations within a RESS and the vehicle.

7.8 Gas Sampling

The test procedure suggests conducting in-cabin gas sampling, but does not require it. Based on the testing examples described in Section 7, it is evident that for Li-ion cell thermal runaway testing, a smoke alarm mounted within the vehicle cabin will provide a good indication of whether vent gases are entering the cabin and if the cabin remains tenable. However, a gas sampling device can provide more detailed information; thus, a testing agency may choose to implement this type of sensor. Should a cell chemistry produce hazardous vent gases that may not cause activation of a smoke alarm, the testing agency should use a gas sampling device or alternative detector to monitor the cabin air.

7.9 Post-Test Observation

If thermal runaway initiation fails or if there is no propagation (i.e., only the initiating cell enters thermal runaway), the RESS should be monitored for at least 28 days to ensure no additional cells undergo a thermal runaway reaction. The RESS should then be fully discharged prior to storage or disposal.

If propagation occurs, but the RESS is not completely consumed, the RESS will likely have become substantially damaged and should be monitored for at least 28 days to ensure no additional cells undergo a thermal runaway reaction. The remaining cells should then be fully discharged prior to storage or disposal.

If thermal runaway propagation occurs during testing and it can be verified that the RESS is completely consumed, no extended observation time is necessary prior to storage or disposal.

7.10 Cabin Tenability Requirements

Cabin tenability will potentially depend on exposure to smoke and other components of thermal runaway vent gases as well as cabin temperature. If appreciable quantities of vent gases enter the vehicle cabin during SCTRI testing, or if the cabin becomes appreciably heated, then a careful assessment of the probable effect of the combination of these factors on cabin occupants should be conducted to determine tenability. One important factor is whether occupants will have received sufficient warning from visual, audible, or function cues to understand that an unsafe condition is imminent and have sufficient time to exit the vehicle safely before tenability is threatened. Safe evacuation assessment should include the time required to safely stop the vehicle (including time to find a safe stopping location) and assist passengers that may have limited mobility.

The effect of combustion products and various hazardous gases, as well as how high temperature exposure influences tenability can be found in references such as the Society of Fire Protection Engineers (SFPE) Fire Protection Handbook. Fire protection literature can also provide guidance regarding egress times.

8. APPENDIX A

This appendix provides example SCTRI results using three different Li-ion cell formats (i.e., cylindrical, prismatic, and pouch). Various thermal runaway initiation methods are first evaluated at the cell level. The most most effective techniques are then applied at the coupon and module-level, as needed, to refine the initiation method and evaluate interactions with neighboring cells. Once the best initiation method has been identified and optimized for each cell format, full-scale vehicle testing is conducted. The purpose of this test report is to illustrate the SCTRI method and application; it is not intended to be a performance and safety evaluation for each manufacturer. Thus, ranking the cells/vehicles relative to the primary acceptance criteria (i.e., hazards to the occupant and the surrounding environment) is not within the scope of this report.

8.1 Li-ion Single Cell Thermal Runaway Initiation Methods

8.1.1 Introduction

A variety of thermal runaway initiation methods were applied to Li-ion cells of different form factors to demonstrate the initiation method selection process. Initiation methods were selected that have been known to cause thermal runaway in a reasonable amount of time, require little to no special modification of cells, can be conveniently applied to battery module and pack tests, do not significantly affect the thermal, mechanical, or electrical boundary conditions of a RESS, and require very limited capital investment or experimental development. The tested methods were:

- Conductive heating: cells wrapped in nichrome wire
- Mechanical damage: nail penetration
- Conductive heating: hand-made film heater
- Conductive heating: off-the-shelf film heater
- Conductive heating: multiple off-the shelf film heaters
- Conductive heating: thick film resistor

The methods were tested at a single cell level, and then, based on performance, were down-selected for coupon or module level verification testing. A final selection was made for application to full-scale vehicle testing.

The cells used for this demonstration were used in mass produced EVs. They were either supplied by the EV manufacturer, or harvested from a production RESS (i.e., separated from their respective modules and not electrically connected to any other cells). The tested cells represent the three most common form factors found in electric vehicles (i.e., cylindrical cells, prismatic cells, and pouch cells).

- **Cell A:** small cylindrical cell (Figure 3). The cylindrical cells had an 18 mm diameter and a 65 mm height. They had a rated capacity of 3 Ah and a mass of 47 g.
- **Cell B:** large hard case prismatic cell (Figure 4). The prismatic cells were 171 mm tall, not including the terminal screws, 101 mm wide and 43 mm deep. They had a rated capacity of 50 Ah and a mass of 1720 g.
- **Cell C:** large pouch cell (Figure 5). The pouch cells were 290 mm long and 216 mm wide. They had a rated capacity of 32.5 Ah and a mass of 787 g.

Figure 3 - Cell A; small cylindrical cell.

Figure 4 - Cell B; large hard case prismatic cell.

Figure 5 - Cell C; large pouch cell.

8.1.2 Test Equipment

- Personal protective equipment (PPE): respirators, safety glasses, and chemical resistant gloves
- Vent hood
- Voltage measurement and data logging system: National Instruments (NI) 9205 ±10V data acquisition module with an accuracy of ±6.22 mV
- Temperature measurement and data logging system: NI 9213
- Data translation system: MEASUREPoint DT8874
- Type-K thermocouples
- Stopwatch with and accuracy of ±1 second
- Various thermal runaway initiation devices (heaters, nail penetration equipment)

8.1.3 Test Parameters

All of the cell-level tests were conducted with the conditions shown in Table 1.

Table 1 - Cell-Level Test Parameters

Temperature	25±2°C
State of Charge (SOC)	95% - 100%

8.1.4 General Test Methods

For each test:

- The initiating device was installed on the cell.
- Two thermocouples were installed on the cell.
- Voltage measurement leads were installed on the cell.
- The test setup was photographed.
- The initiating device was activated, data acquisition was started, a timer was started, and a video recording was started.
- The time when the cell visually and audibly entered thermal runaway was recorded.

- The test was ended after thermal runaway was complete.

The following measurements were made for each test:

- A voltage trace of the cell showing the drop of voltage at the point of thermal runaway reaction.
- Two cell surface temperatures up to the point of thermal runaway reaction.
- Time required from the start of the test to achieve thermal runaway.
- Video recording of the entire test.
- Photograph of the cell after testing.

The time to runaway was defined as the time elapsed from activation of the initiating device to the point at which the measured cell temperature showed a significant change in slope. However, thermocouples often became detached after thermal runaway events began.[2] Thus, examination of video recordings and stopwatch data were also used to confirm the runaway reaction of the cell.

For small cells, the average of the two cell temperature measurements at the moment of initiation was reported as the average cell initiation temperature. For large cells, where a significant temperature difference was observed between the two thermocouples due to large thermal gradients, the higher of the two measurements was reported as the highest temperature at initiation. The highest temperature was reported because, as discussed in Section 7.1, thermal runaway can begin in a portion of a cell, and thus the cell highest temperature is most relevant. The highest temperature at the time of initiation of cell thermal runaway is an indication of the thermal stability limit of that cell. It can be used in subsequent testing to judge whether neighbor cells have been heated excessively by an initiation method.

The energy input that is required to initiate thermal runaway was compared to the electrical energy contained in the cell. It was also compared to the electrical energy of the parallel group of cells (as implemented in the RESS), since a short circuit in one cell can source current from any cell in parallel.

8.1.5 Cylindrical Cell Initiation Method Testing

Four thermal runaway initiation test methods were tried on small cylindrical cells (i.e., Cell A).

8.1.5.1 Conductive Heating - Cell Wrapped With Nichrome Wire:

This method was selected because the heater is well thermally coupled to the cell, which should result in a short time to thermal runaway and low input energy to the system. It requires no changes to the electrical systems of the cell or battery and does not affect the designed gas flow or mechanical features of the cell. This method can be applied to production cells, although perhaps not easily in an already-constructed and tightly packaged module configuration. Depending on battery pack architecture, this method may affect some of the

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[2] It is possible to apply thermocouples in a manner to obtain thermal runaway temperatures. However this generally requires more extensive setup time, and is generally unnecessary to demonstrate successful initiation thermal runaway and to determine time to initiation of thermal runaway.

heat transfer characteristics of the cells and modules by altering the gaps between cells. An example of a cell wrapped in nichrome wire is shown in Figure 6.

For this trial, 30 gauge nichrome wire was wrapped approximately 10 times around a cell for use as a resistance heater. The wire was held against the cell using polyimide tape. The tape was also used as a barrier to prevent short circuits between the wraps of wire. The resistance of the wire was measured to determine the voltage needed to produce 50 W of heating.

Figure 6 - Cylindrical cell with nichrome wire wrap.

8.1.5.2 Mechanical Damage - Nail Penetration:

This method was selected for trial because it was not expected to add significant thermal energy to the cell. It can provide a very short time to thermal runaway with minimal effect on the state of charge of the initiating cell and temperatures of the neighboring cells. It requires no changes to the electrical systems of the cell or battery. No special modifications to the cell are required and it can be implemented with production cells. If the nail is used to penetrate the top cap of a cylindrical cell, where there is already a designed vent, it should have minimal impact on the gas flow from the cell during a thermal runaway reaction. Axial penetration was selected over the more common radial penetration direction because a radial penetration would alter the natural gas flow patterns of a thermal runaway event. Radial penetration is also difficult to accomplish within the RESS that will ultimately be tested. Note that nail penetration initiation methods have been found to be unreliable (i.e., the nail must cause short circuiting between active material layers in the electrode). If a short circuit develops between current collectors, the cell may not self-heat sufficiently to undergo a thermal runaway reaction.

For this trial, a 1” long steel nail with a 1/8” diameter, shown in Figure 7, was attached to an electric ram. The cell was oriented vertically and penetrated axially through the center. The ram continued to press until the entire nail was inserted into the cell. The nail was not removed until thermal runaway ended. Figure 8 shows a schematic diagram of the test setup.

Figure 7 - Nail used in penetration test.

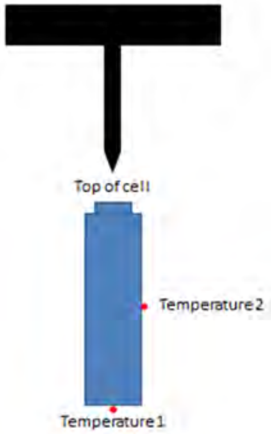

Figure 8 - Schematic diagram of nail penetration method.

8.1.5.3 Conductive Heating - Hand-Made Film Heater:

This method was selected for trial because the heater is well thermally coupled to the cell, which should result in a short time to thermal runaway and low input energy to the system. It is a smaller power heater than the nichrome wrapped wire heater, but it provides a more localized heating zone and can be easier to install in a module. The hand-made film heater requires no changes to the electrical systems of the cell or battery and does not affect the designed gas flow or mechanical features; the heater is attached to the side of the cell can. This method can be applied to production cells. The small-gauge wire allows the film heater to be used in many battery modules and packs without special modifications. Depending on pack architecture, this method may affect some of the heat transfer characteristics of the cells and modules by altering the gaps between cells. However, because this heater is applied to a smaller area of the cell, it should provide less disruption than a nichrome wrapped wire device, and can be oriented to minimize the disruption. An example of a hand-made film heater is shown in Figure 9.

For this trial, a film heater was made using 30 gauge nichrome wire. The wire was wrapped in a back and forth pattern around eight pins to form a ½” x 2” rectangular pad. The wire wraps were held together using a polyimide tape. The film heater was placed against one side of the cell and attached to it using polyimide tape. The heater was oriented such that the long side of heater was parallel to the axial direction of the cell. The cell side wall temperature measurement was made 180 degrees opposite of the heater. A diagram of this setup is shown in Figure 10 along with the location of the temperature measurements. A constant current of 1.8 A was run through the heater, resulting in approximately 30 W of heating applied to the cell. The current was not increased past 1.8 A to prevent melting the nichrome wire.

Figure 9 - Hand-made film heater.

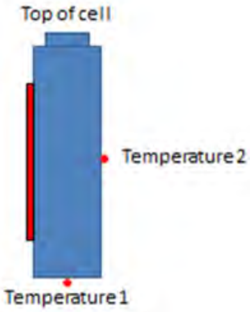

Figure 10 - Schematic of hand-made film heater.

8.1.5.4 Conductive Heating - Off-the-Shelf Film Heater:

This method was selected for trial because the heater is well thermally coupled to the cell, which should result in a short time to thermal runaway and low input energy to the system. It is a smaller power heater than the nichrome wrapped wire heater, but it provides a more localized heating zone and can be easier to install in a module. It has a similar heating profile as the hand-made film heater, but it is a more convenient and consistent option. The off-the shelf film heater requires no changes to the electrical systems of the cell or battery and does not affect the designed gas flow or mechanical features; the heater is attached to the side of the cell can. This method can be applied to production cells. The thin nature of the heater will allow it to be used in many battery modules and packs without special modifications. Depending on pack architecture, this method may affect some of the heat transfer characteristics of the cells and modules by altering the gaps between cells. However, because this heater is applied to a smaller area of the cell and is very thin, it should provide less disruption than a nichrome wrapped wire device or a hand-made film heater and can be oriented to minimize the disruption. An example of an off-the-shelf film heater is shown in Figure 11.

For this trial, an off-the-shelf film heater was purchased from McMaster-Carr, part number 35475K283. This heater has a ½" x 2" rectangular pad and is rated to 10 W/sq. in. It has an adhesive backing which is used to attach to the cell. The cell side wall temperature measurements for this method are taken 180 degrees opposite of the heater. The setup of for this method is the same as for the hand-made film heater shown in Figure 10. The heater has a measured resistance of 76Ω, thus applying 0.65 A will produce approximately 32 W of heating. Applying a higher current will cause the heater to become open circuit from overheating.

Figure 11 - Off-the-shelf film heater.

8.1.6 Cylindrical Cell Initiation Method Results

A summary of the results for the different initiation methods attempted on the small cylindrical cells (Cell A) is shown in Table 2. It includes time to thermal runaway, average temperature at initiation, the energy ratio for the initiation cell (i.e., energy required to initiate thermal runaway divided by the electrical energy of the initiating cell), and the energy ratio for cells in parallel (i.e., energy required to initiate thermal runaway divided by the electrical energy of parallel group of cells as implemented in the RESS).

The nichrome wrap heater method successfully initiated all the cells in three trials. The temperature and voltage traces for the nichrome wrap heater trials are shown in Figure 12 through Figure 29. Images captured from the test videos (e.g., Figure 15) clearly demonstrate that the cell underwent thermal runaway. A video screen capture immediately after the runaway event shows that the cell steel casing is glowing bright orange (Figure 16), from which it can be estimated that the cell wall temperatures reached at least 900°C. Figure 17 shows two of the cells after testing. The wrapped heater method demonstrated the shortest time to thermal runaway among the heater based methods. It required no special modifications to the battery cell and showed no signs of obstructing the designed venting features. However, this method may be difficult to apply to a pre-built battery module, and the large heater area around the circumference of the cell may add significant pre-heating to the neighboring cells. This method was further investigated in coupon verification testing (Section 8.2).

The nail penetration test only successfully initiated one of the two samples in the trial. The temperature and voltage traces for the nail penetration trials are shown below in Figure 18 and Figure 19; the second penetration trial failed to produce a thermal runaway event. In the successful trial, thermal runaway began almost immediately after the nail penetration. The cell casing color was orange (see Figure 20), indicating that a casing temperature of at least 900°C was achieved. The cells from the successful and failed nail penetration trials are shown in Figure 21 and Figure 22, respectively. After the nail from the second trial was fully inserted into the cell and it failed to go into runaway, the ram was used to try to crush the cell in an attempt to induce thermal runaway. Even with this additional deformation, the cell failed to go into runaway. This method required no additional preparation of the cell prior to the test. Due to limited reliability of this method, nail penetration was eliminated from further testing with the small cylindrical cells.

Both the hand-made and off-the-shelf thin film heaters successfully initiated thermal runaway for the cells with all five trials having similar results. The temperature and voltage traces for the hand-made film heater trials are shown in Figure 23 through Figure 25. One of the cells from the hand-made film heater trials is shown undergoing thermal runaway in Figure 26; Figure 27 shows the cell after testing. The temperature and voltage traces for the off-the-shelf heater trials are shown in Figure 28 and Figure 29. One of the cells from the off-the shelf film heater trial is shown undergoing thermal runaway in Figure 30; Figure 31 shows the cells after testing. These methods required a slightly longer time to achieve thermal runaway than the wrapped cell method, which can be attributed to their lower heating power. They can be easily applied to production cells and their smaller size makes them easier to attach to a cell in a battery module or pack. They did not obstruct the design venting features and their smaller, more localized heating is less likely to pre-heat the neighboring cells or influence thermal boundary conditions. These methods were further investigated in coupon verification testing (Section 8.2).

Table 2 - Summary of Single Cylindrical Cell Initiation Method Results (Manufacturer A)

Initiation Method	Time to Runaway [Min:Sec]	Avg. Temperature at Initiation [°C]	Energy Ratio (Relative to Input Energy)	
			Initiating Cell	**Parallel Cells**
Nichrome #1	3:16	151	0.22	0.003
Nichrome #2	4:02	140	0.27	0.004
Nichrome #3	3:20	126	0.22	0.003
Nail Penetration #1	0:02	22	0	0
Nail Penetration #2	No Runaway	N/A	N/A	N/A
Hand-made Film Heater #1	5:50	159	0.23	0.003
Hand-made Film Heater #2	8:58	158	0.36	0.005
Hand-made Film Heater #3	5:49	167	0.23	0.003
Off the Shelf Film Heater #1	6:06	162	0.24	0.003
Off the Shelf Film Heater #2	7:34	166	0.30	0.004

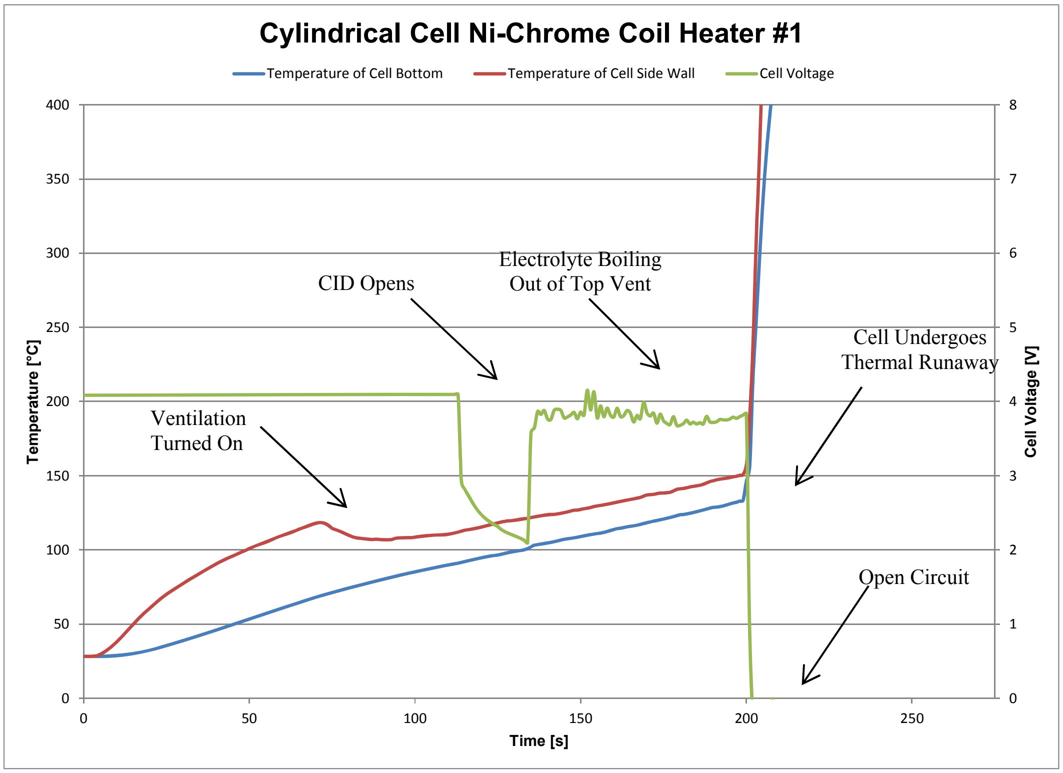

Figure 12 - Temperature and voltage traces for nichrome wrap heater Trial #1.

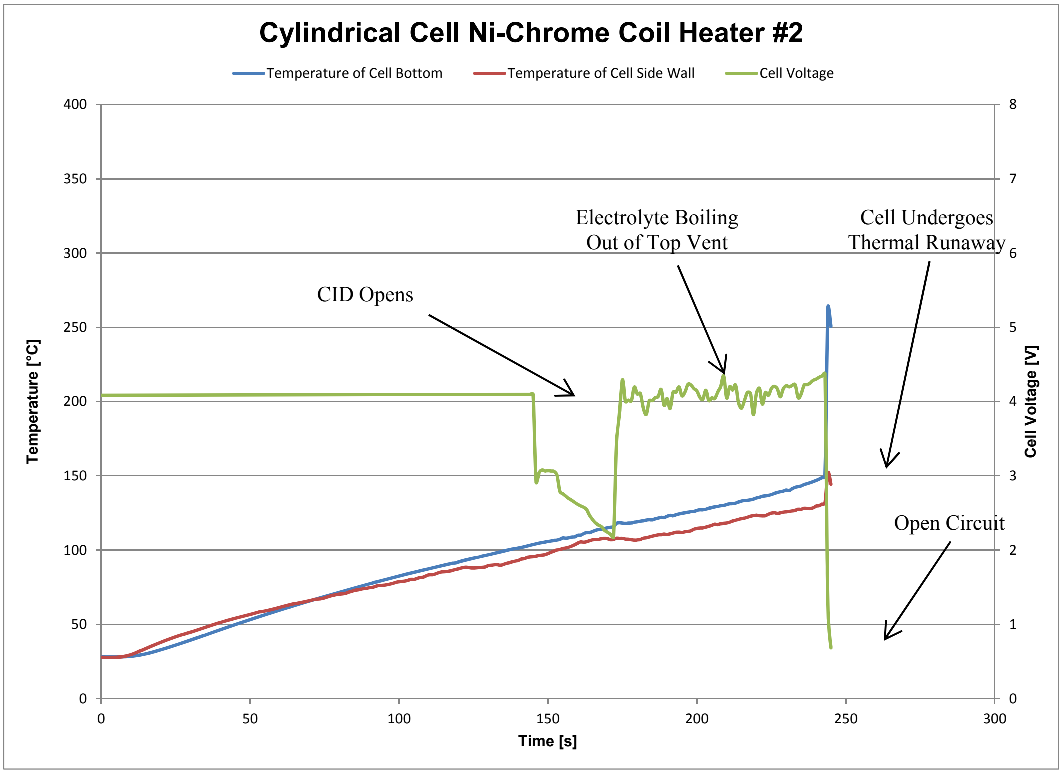

Figure 13 - Temperature and voltage traces for nichrome wrap heater Trial #2.

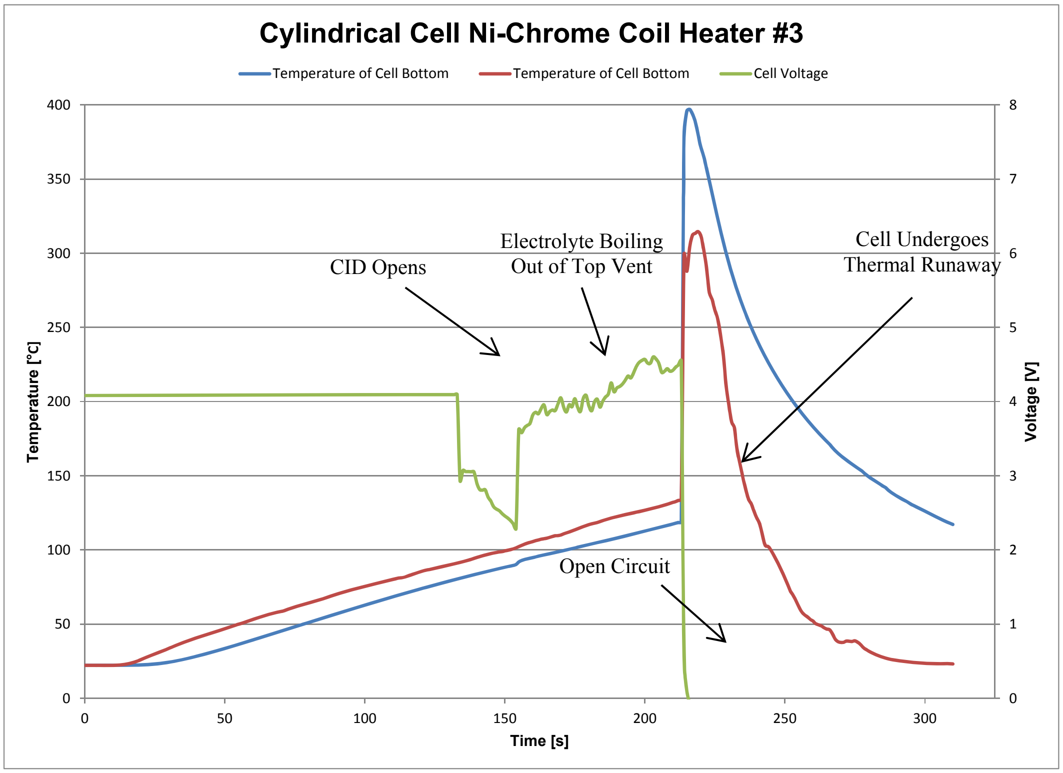

Figure 14 - Temperature and voltage traces for nichrome wrap heater Trial #3.

Figure 15 - Cylindrical cell undergoing thermal runaway; nichrome wrap heater method.

Figure 16 - Cylindrical nichrome wrap heater cell immediately after runaway.

Figure 17 - Cells after nichrome wrap heater trials.

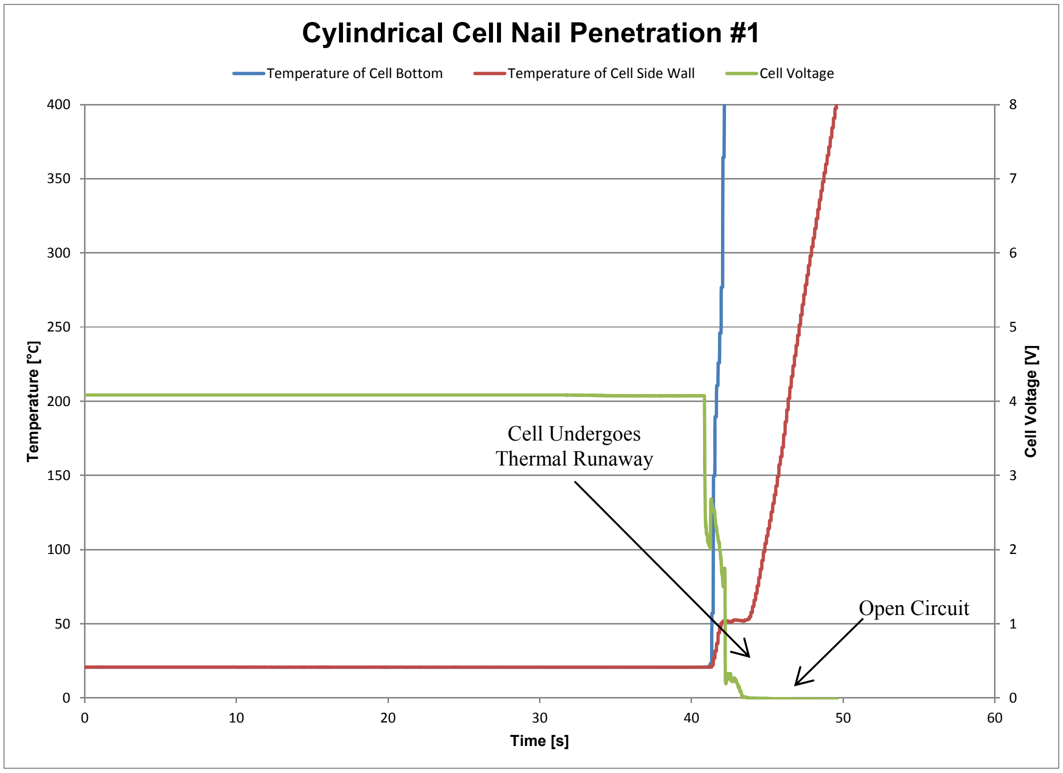

Figure 18 - Temperature and voltage traces for nail penetration Trial #1.

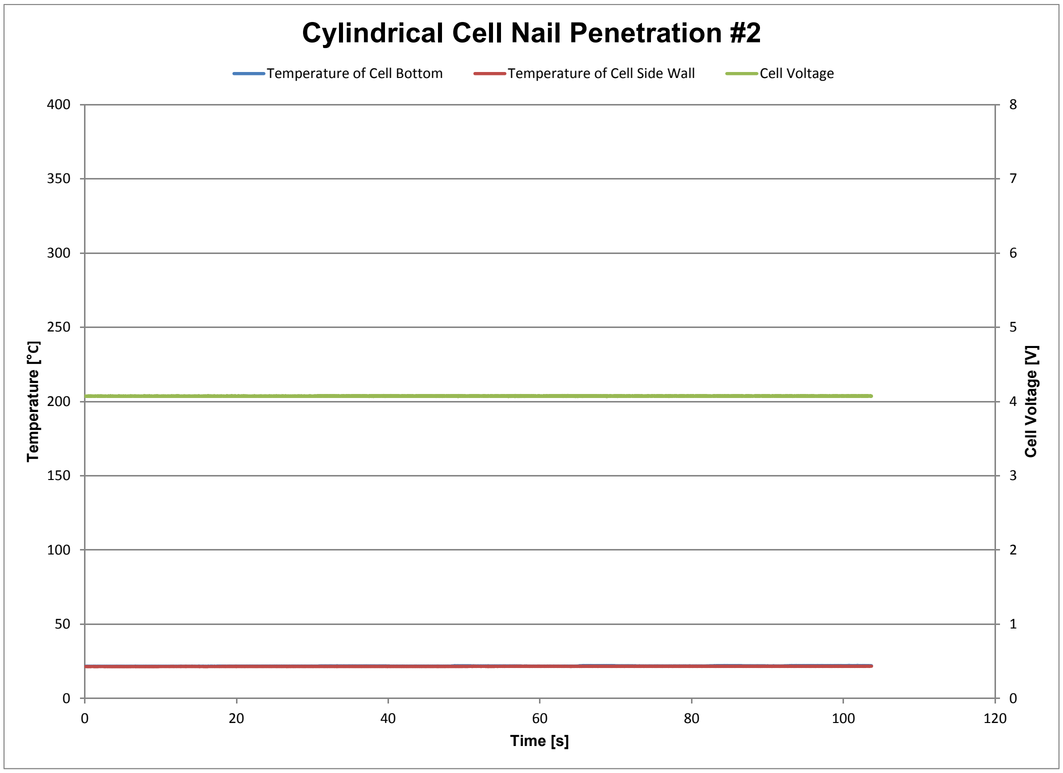

Figure 19 - Temperature and voltage traces for nail penetration Trial #2.

Figure 20 - Cylindrical cell immediately after nail penetration induced thermal runaway.

Figure 21 - Cylindrical cell after successful nail penetration trial.

Figure 22 - Cylindrical cell after failed nail penetration trial.

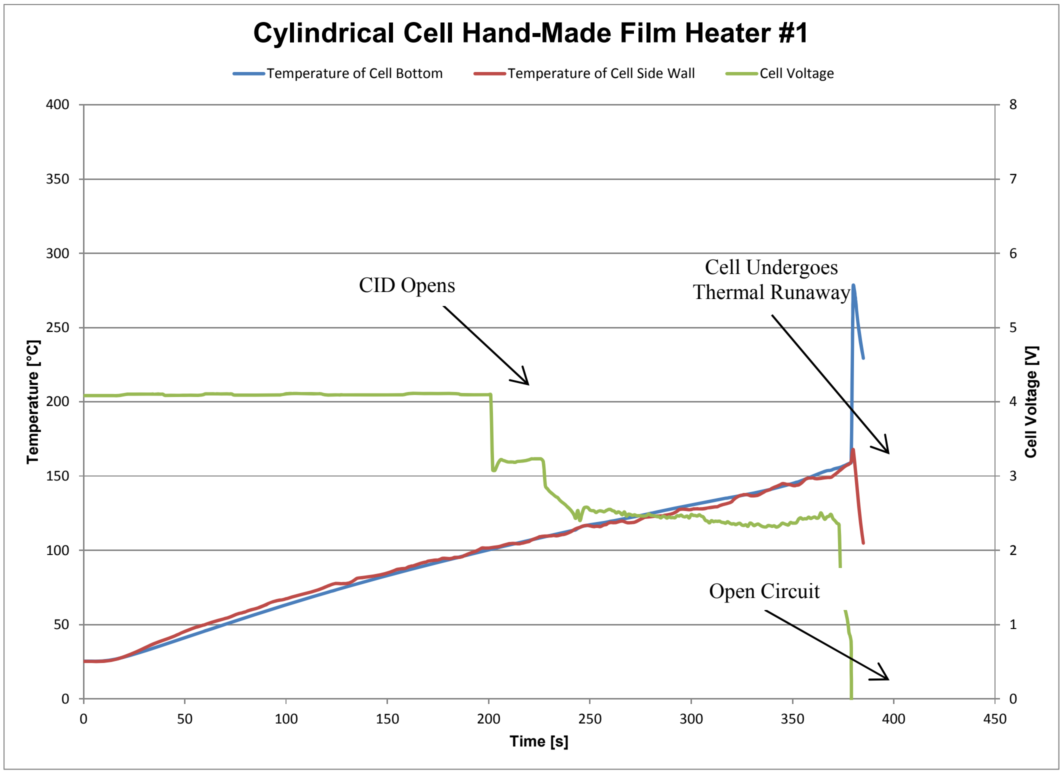

Figure 23 - Temperature and voltage traces for hand-made film heater Trial #1.

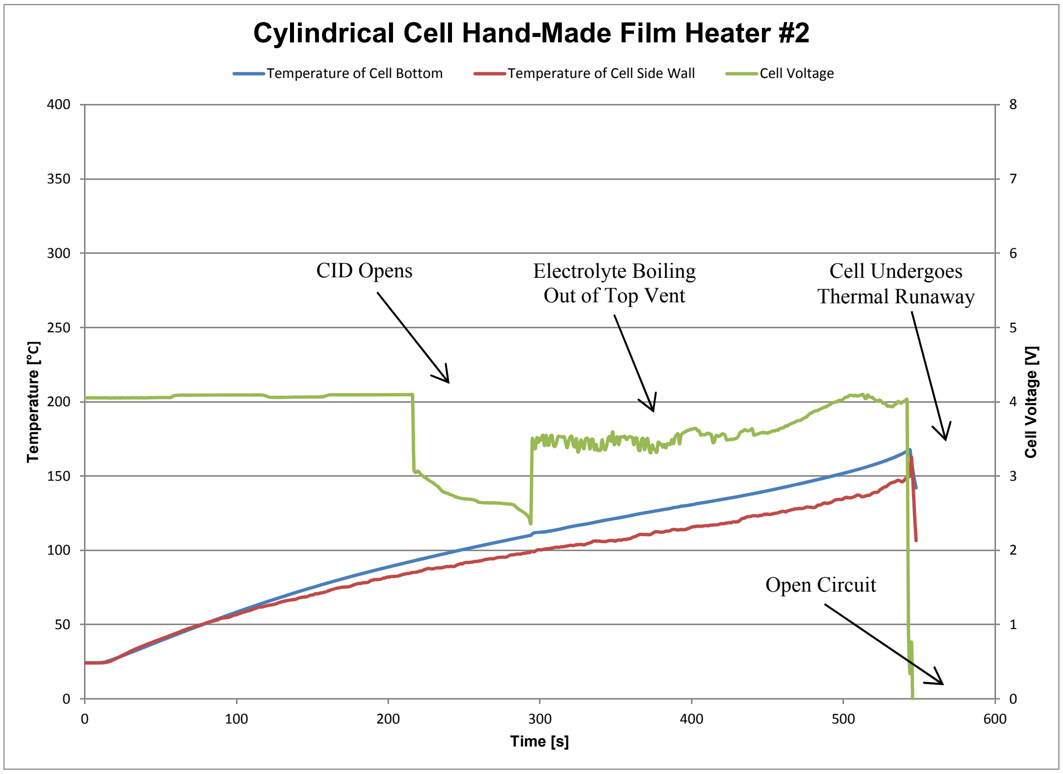

Figure 24 - Temperature and voltage traces for hand-made film heater Trial #2.

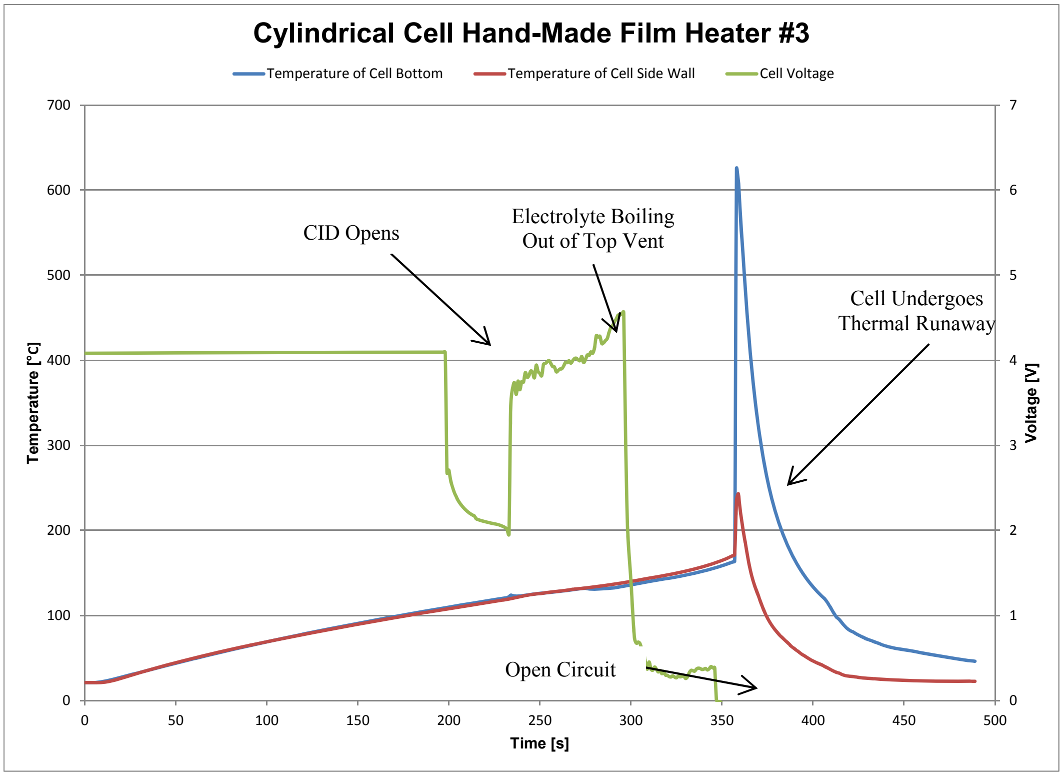

Figure 25 - Temperature and voltage traces for hand-made film heater Trial #3.

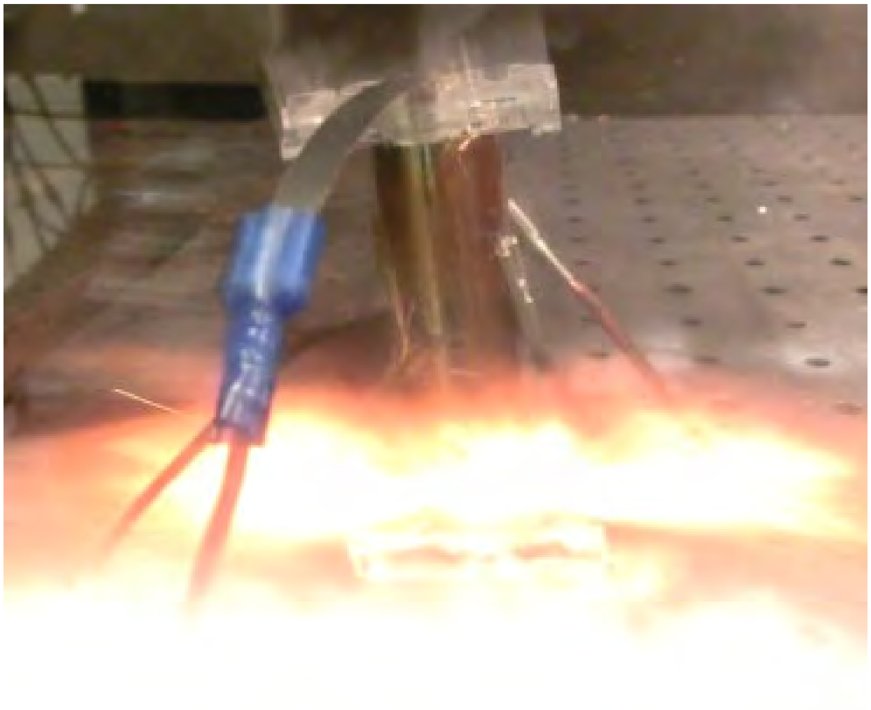

Figure 26 - Cylindrical cell undergoing thermal runaway; hand-made film heater method.

Figure 27 - Cylindrical cell after a hand-made film heater trial.

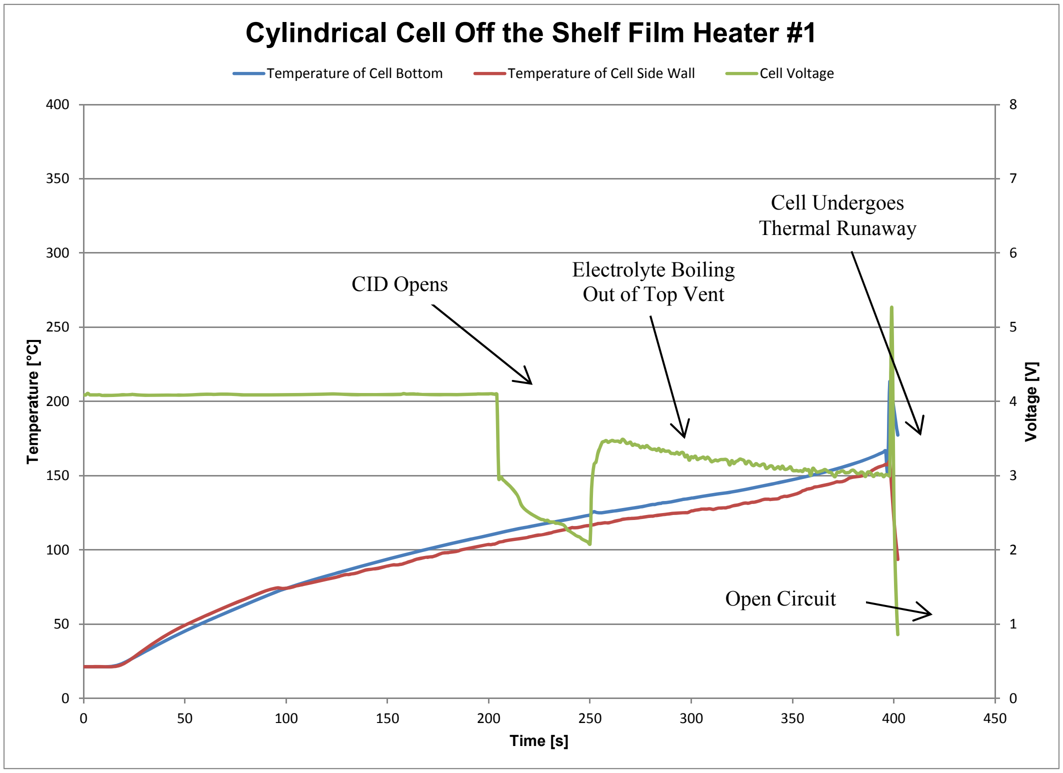

Figure 28 - Temperature and voltage traces for off-the-shelf film heater Trial #1.

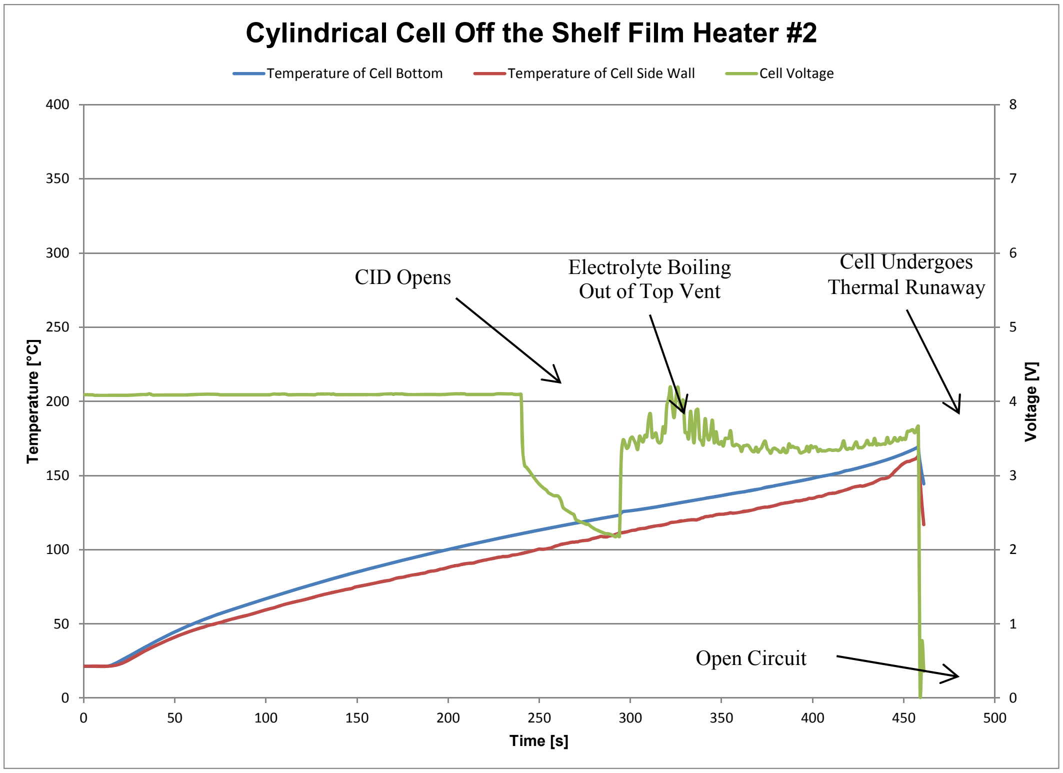

Figure 29 - Temperature and voltage traces for off-the-shelf film heater Trial #2.

Figure 30 - Cylindrical cell undergoing thermal runaway; off-the-shelf heater method.

Figure 31 - Cylindrical cells after off-the-shelf film heater trials.

8.1.7 Prismatic Cell Initiation Method Testing

Four thermal runaway initiation test methods were tried on large hard case prismatic cells (i.e., Cell B).

8.1.7.1 Conductive Heating - Off-the-Shelf Film Heater:

This method was selected for trial because the heater is well thermally coupled to the cell, which should result in a short time to thermal runaway and overall low input energy to the system. A large heater was attached to the largest cell face to apply a high amount of distributed heat as quickly as possible. However, due to the large heating area, this method may also add appreciable heat to neighboring cells prior to initiation. It requires no changes to the electrical systems of the cell or battery. The heater is attached to the side of the cell and does not affect the designed gas flow or mechanical features. This method can be implemented with production cells and can be easily implemented into the battery module and RESS.

For this trial, a large off-the-shelf film heater was purchased from McMaster-Carr, part number 35475K753 (Figure 32). The heater had a 4” x 6” rectangular pad and was rated to 10 W/ sq. in. The heater had an adhesive backing which was used to attach to the large face of the cell. As connected to 120 V_{AC}, the heater was rated to 240 W. One thermocouple was located on the opposite face of the cell and the second thermocouple was placed on an adjacent face. A schematic diagram of the test setup is shown in Figure 33.

In the first trial, the cell was left completely exposed to the ambient air. The cell was strapped down to a large aluminum plate to secure it during the test and to prevent uncontrolled cell motion during thermal runaway. This setup is shown in (Figure 34). For the second trial, in an effort to reduce the time to thermal runaway and the total energy added to the system, a layer of 1/8" thick flexible ceramic insulation was wrapped around the cell to prevent the heat from escaping to the ambient air (Figure 35).

Figure 32 - Large off-the-shelf film heater.

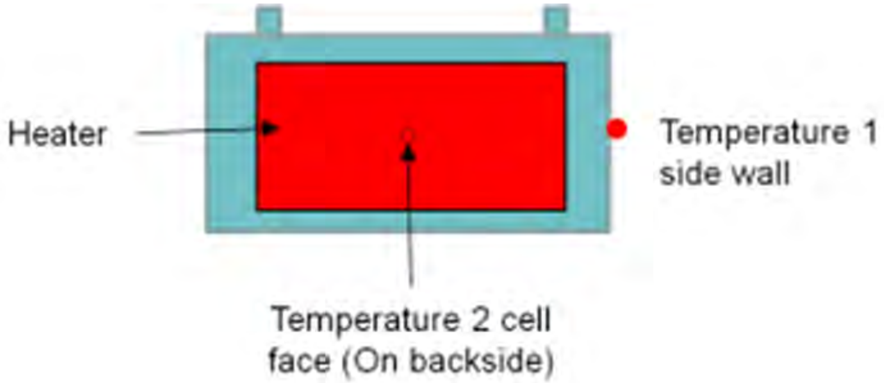

Figure 33 - Schematic of large off-the-shelf film heater setup.

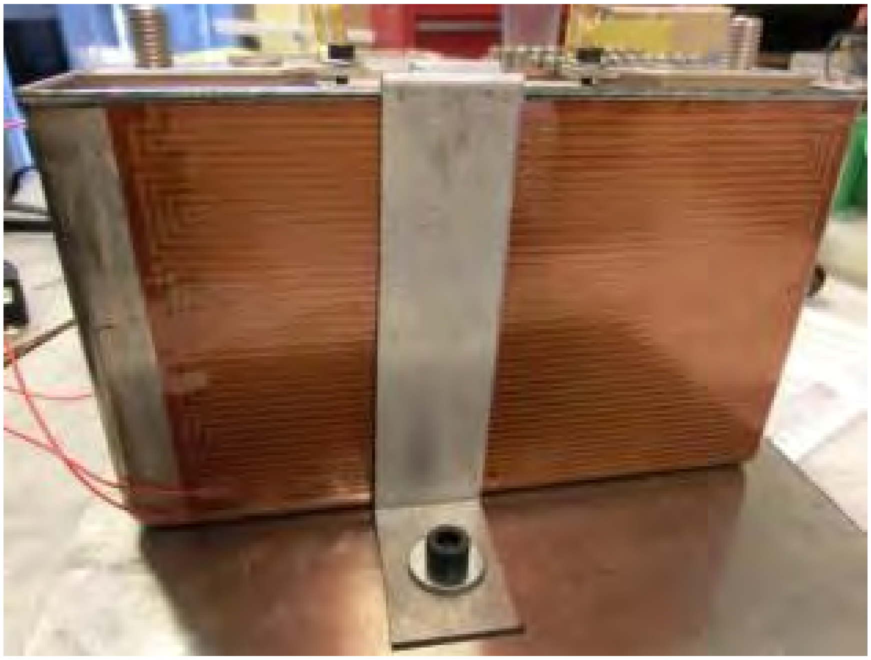

Figure 34 - Prismatic cell Trial #1 setup.

Figure 35 - Prismatic cell Trial #2 setup.

8.1.7.2 Conductive Heating - Multiple Off-the-Shelf Film Heaters:

This method was selected for trial because the heaters are well thermally coupled to the cell, which should result in a short time to thermal runaway and overall low input energy to the system. Two small heaters were selected to try heating cell surfaces that would not be adjacent to other cells in the battery pack configuration. Thus, two heaters were applied to the smaller side walls of the cell. Insulation was added to decrease the time required to cause thermal runaway. This method requires no changes to the electrical systems of the cell or battery. The heaters are attached to the sides of the cell and do not affect the designed gas flow or mechanical features. This method can be applied to production cells and can be easily implemented into the battery module and RESS.

For this trial, two small film heaters were purchased from the McMaster-Carr, part number 35475K334. The heaters had a 1” x 3” rectangular pad with a rated heat output of 10 W/sq. in. With two heaters applied to the cell, the total heat input into the cell was 60 W. The heaters were attached to the narrow faces of the cell (Figure 36). Thermocouples were located on the large faces of the cell. A schematic diagram of the test setup is shown in Figure 37.

Figure 36 - One of the dual side heater pads.

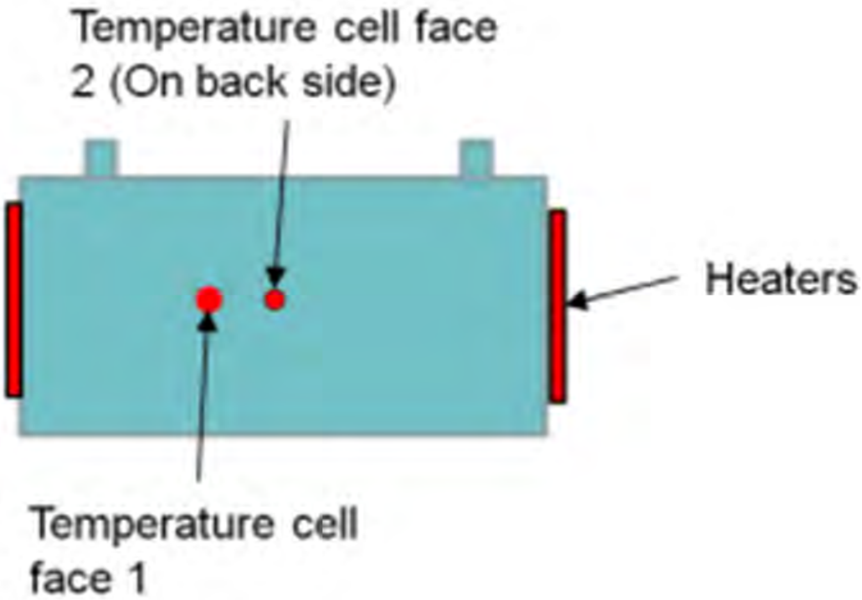

Figure 37 - Schematic of dual side heater pad setup.

8.1.7.3 Mechanical Damage - Nail Penetration:

This method was selected for trial because it was not expected to add significant energy to the cell. It can provide a very short time to thermal runaway with minimal effect on the state of charge of the initiating cell and minimal preheating of neighboring cells. It requires no changes to the electrical systems of the cell or battery. No special modifications to the cell are required and it can be implemented with production cells. If the nail is used to penetrate the vent location on top of the case (specific to the Cell B design), it will have little impact on the gas flow from the cell during a thermal runaway reaction. For the Cell B design in particular, it was determined that the nail must penetrate near the edge of the circular vent. If the nail were to penetrate along the center line of the cell, it could wedge between the two internal electrode windings and fail to cause a mechanical short circuit (Figure 38). Note, however, that nail penetration initiation methods have been found to be unreliable; the nail must cause short circuiting between active material layers in the electrode. If a short circuit develops between current collectors, the cell may not self-heat sufficiently to undergo a thermal runaway reaction. In addition, this method may be difficult to implement within the physical constraints of the battery enclosure.

For the first nail penetration trial, a 1” long steel nail with a 1/8” diameter (Figure 7) was used to penetrate the top vent of the cell. The nail was attached to a mechanical drop fixture. During the first trial, the nail was allowed to remain in the cell for more than 70 minutes. For the second nail penetration trial, a 3” long steel nail with a blunt tip was used to penetrate the top vent of the cell. A longer, blunter nail was used in an attempt to cause more internal damage to the cell.

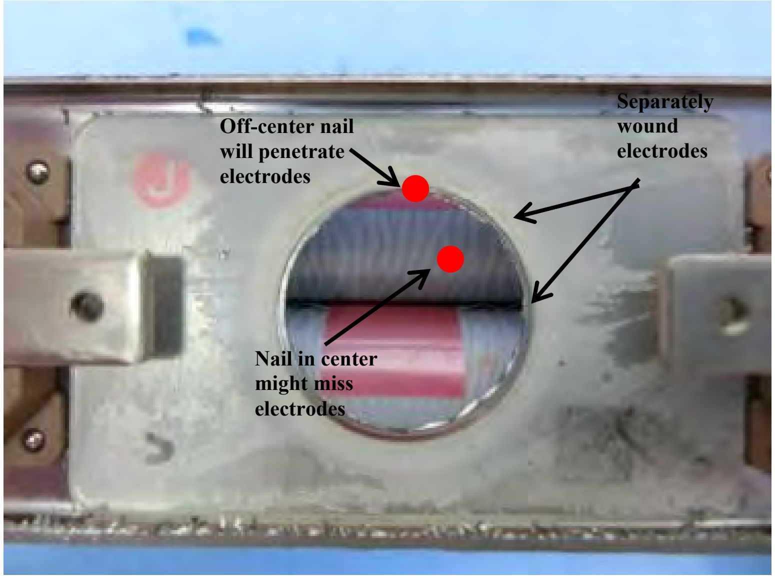

Figure 38 - Top view of prismatic cell, looking through a removed vent.

8.1.7.4 Conductive Heating - Thick Film Resistor:

This method was selected for trial because it allows for a large amount of heat to be transferred very locally to the cell at a density of approximately 150 W/sq. in. A high heat flux should result in a short time to thermal runaway, little change in the cell state of charge, and little heating of the neighboring cells prior to initiation. This method will not obstruct the designed venting features of the cell. If the resistor is mounted in a way that will allow it to detach once thermal runaway has initiated, it should not obstruct the heat transfer characteristics of the cell. However, the thickness of the resistor might make installation challenging due to the tightly packaged cells in the battery pack.

For this trial, a thick film resistor (Figure 39) measuring approximately 2” x 2” x 1” was attached to the side of the cell. The resistor had a rated power of 600 W and resistance of 10Ω. Thermal joint compound was placed between the resistor base and the cell face to aid in the heat transfer from the resistor to the cell. The resistor was attached using vinyl electrical tape so that once the cell entered thermal runaway the tape would melt and allow the resistor to become detached from the cell. Schematically this test is setup was identical to that of the large film heater test (Figure 33).

Figure 39 - Thick film resistor.

8.1.8 Hard Case Prismatic Initiation Method Results

A summary of the results for the different initiation methods attempted on the prismatic cells is shown in Table 3. It includes time to thermal runaway, temperature at initiation, the energy ratio for the initiation cell (i.e., energy required to initiate thermal runaway divided by the electrical energy of the initiating cell), and the energy ratio for cells in parallel (i.e., energy required to initiate thermal runaway divided by the electrical energy of parallel group of cells as implemented in the RESS). Since there was a large difference in temperature measurements between the faces of the cells due to a large internal temperature gradient, the highest of the two temperature measurements was reported.

The large film heater method successfully initiated cells with and without added insulation. The addition of a thin layer of insulation reduced the time to thermal runaway by approximately one-half. The temperature and voltage traces for the first trial are shown in Figure 40. Once thermal runaway began, both measured cell temperatures rose quickly in unison. The temperature traces show that the cell reached a maximum temperature of 613°C. Figure 41 shows the cell emitting smoke during the thermal runaway event. Figure 42 shows the cell after thermal runaway. The temperature and voltage traces for the second trial can be seen in Figure 43. The results from this trial were very similar to the first trial, although time to thermal runaway was shorter. In this trial, the highest measured temperature was 563°C and the cell cooling rate was reduced due to the presence of insulation. Figure 44 shows the cell undergoing thermal runaway. The large film heater method required no modifications to the production cell and did not obstruct the designed venting features. The large heater area, however, could result in pre-heating effects on neighboring cells. Because of the effectiveness of the large film heater method and the straightforward architecture of the Manufacturer B RESS, it was selected for application to full-scale vehicle testing and no further coupon or module testing was performed.

The dual side film heater method failed to produce a thermal runaway reaction in a sufficiently short amount of time. Figure 45 shows the voltage and temperature traces for this trial. Testing was aborted approximately 45 minutes after heating began. The testing agency judged that if this method were attempted in a RESS, cell heating would be further retarded by heat loss to surrounding components. The cell experienced a maximum temperature of 72°C before the test was aborted and there were no observable changes in the cell voltage throughout the test. The cell was monitored for approximately 60 minutes after the test was aborted to ensure that a delayed thermal runaway due to heat redistribution within the cell did not occur. Once measured cell temperatures fell below 40°C it was considered unlikely that the cell would experience a delayed runaway and the monitoring was ended. As a result, the dual side film heater method was eliminated from further testing with the hard case prismatic cells.

The nail penetration method was also unsuccessful in inducing a thermal runaway reaction in the hard case prismatic cells. The temperature and voltage traces for the first nail penetration trial can be seen in Figure 46. In this test, the nail was allowed to remain in the cell for more than 70 minutes, after which time the test was aborted (i.e., the nail was removed). The cell did not undergo thermal runaway, although there was significant temperature rise (up to 80°C). It is possible that the cell could have undergone thermal runaway reaction if the nail were allowed to remain for a much longer time and the SOC did not drop sufficiently to prevent it from occuring. Figure 47 shows the relatively small amount of localized damage from the nail penetration. The voltage and temperature traces for the second nail penetration trial can be seen in Figure 48. Application of a longer, blunter nail did result in a faster temperature rise within the cell; it reached 110°C within 60 minutes. However, the cell still did not undergo a thermal runaway reaction. The voltage dropped by approximately 0.3 V over the course of this test. It is possible that the cell could have undergone thermal runaway reaction if the nail were allowed to remain for a much longer time and the SOC did not drop sufficiently to prevent it from occuring. Because it did not achieve thermal runaway, the nail penetration method was eliminated from further testing with the hard case prismatic cells.

The thick film resistor method was also unsuccessful in inducing a thermal runaway reaction in the hard case prismatic cell. The resistor itself overheated and failed before it could cause any significant heating of the cells. Because this initiation method was not reliable, it was eliminated from further testing with the hard case prismatic cells.

Table 3 - Summary of Single Prismatic Cell Initiation Method Results (Manufacturer B)

Initiation Method	Time to Runaway [Min:Sec]	Highest Temperature at Initiation [°C]	Energy Ratio (Relative to Input Energy)	
			Initiating Cell	Parallel Cells
Large Side Heater Pad #1, No Surrounding Insulation	18:06	132	0.39[3]	0.39
Large Side Heater Pad #2, Insulated Cell	9:16	89	0.20	0.20
Dual Side Heater Pad, Insulated Cell	No Runaway (45:40)	(72)	0.25	0.25
Nail Penetration #1	No Runaway (70:25)	(78)	~0	~0
Nail Penetration #2	No Runaway (60:29)	(113)	~0	~0
Thick Film Resistor	No Runaway	N/A	N/A	N/A

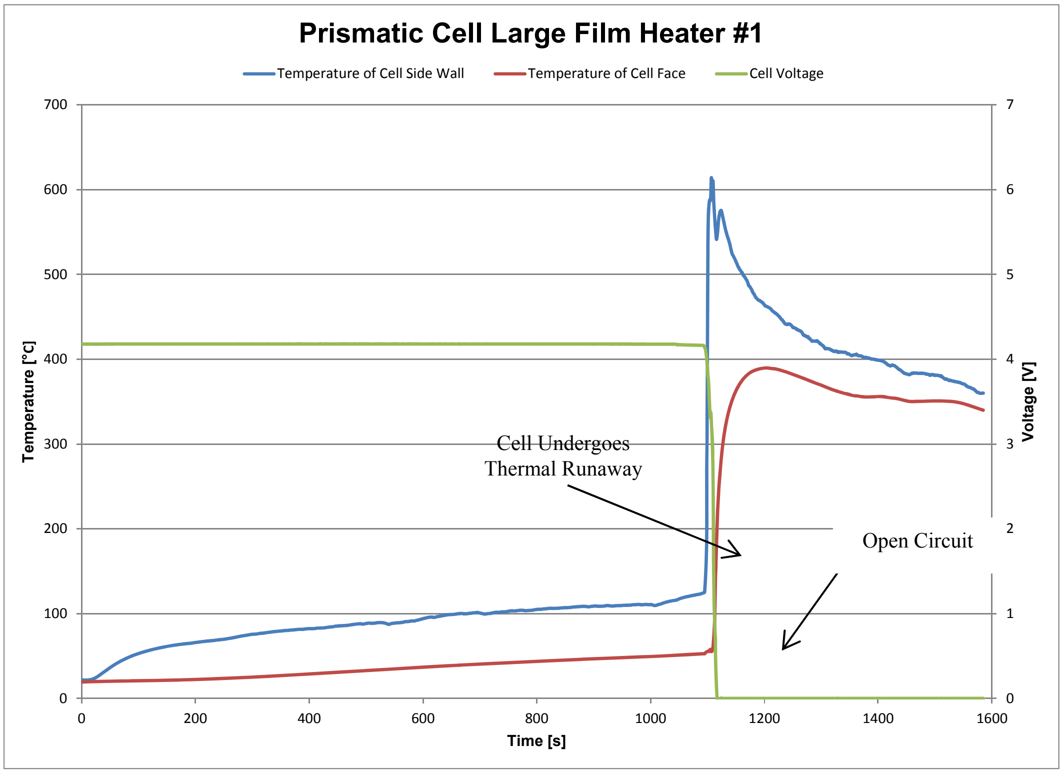

Figure 40 - Temperature and voltage traces for large film heater Trial #1.

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[3] Since one side of the heater is exposed to ambient air, the full amount energy shown may not have gone into the cell.

Figure 41 - Prismatic cell during thermal runaway; large film heater Trial #1.

Figure 42 - Prismatic cell after thermal runaway.

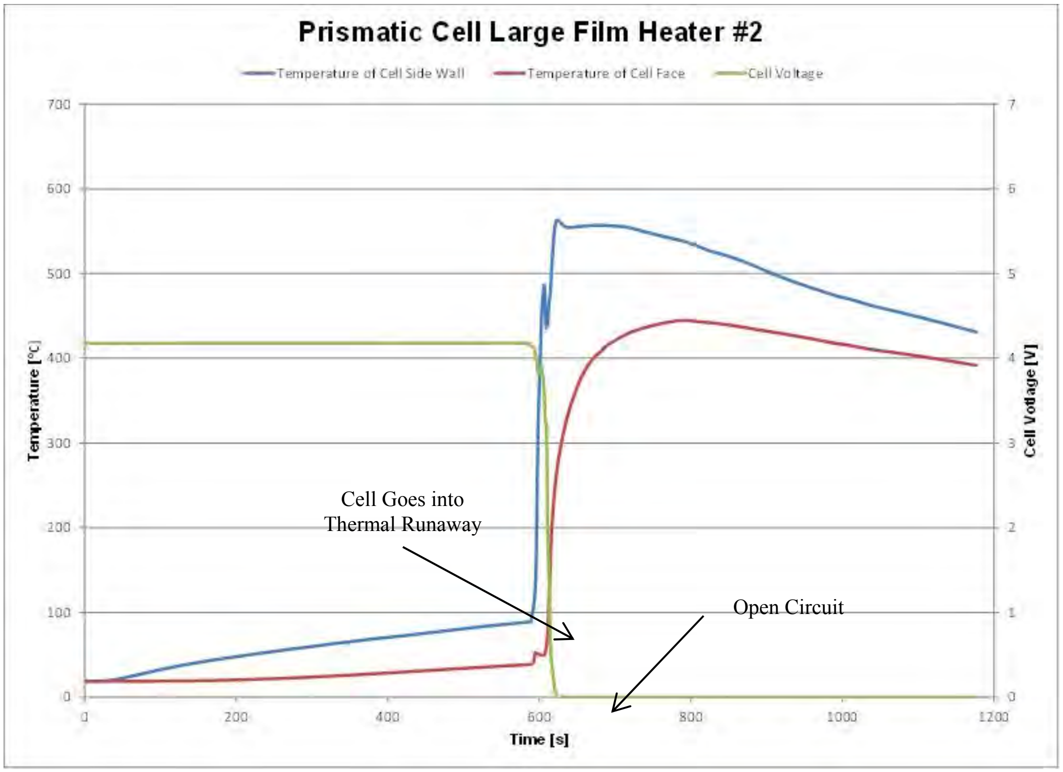

Figure 43 - Temperature and voltage traces for large film heater Trial #2.

Figure 44 - Prismatic cell undergoing thermal runaway; large film heater Trial #2.

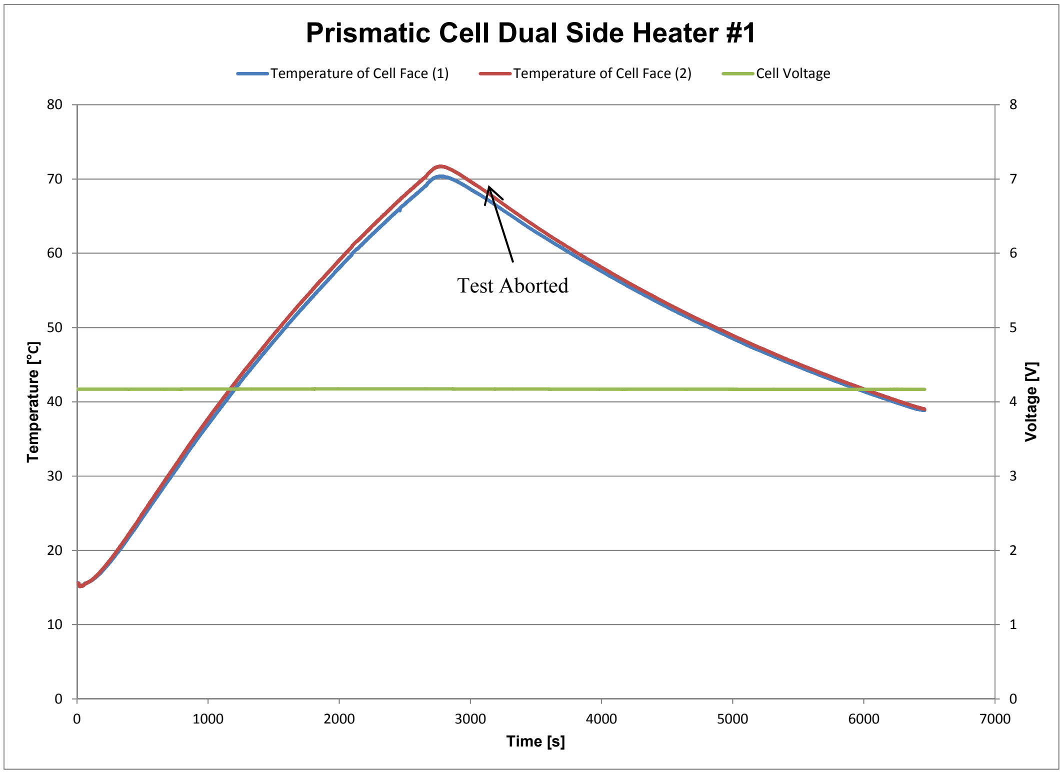

Figure 45 - Voltage and temperature traces for dual side film heater Trial #1.

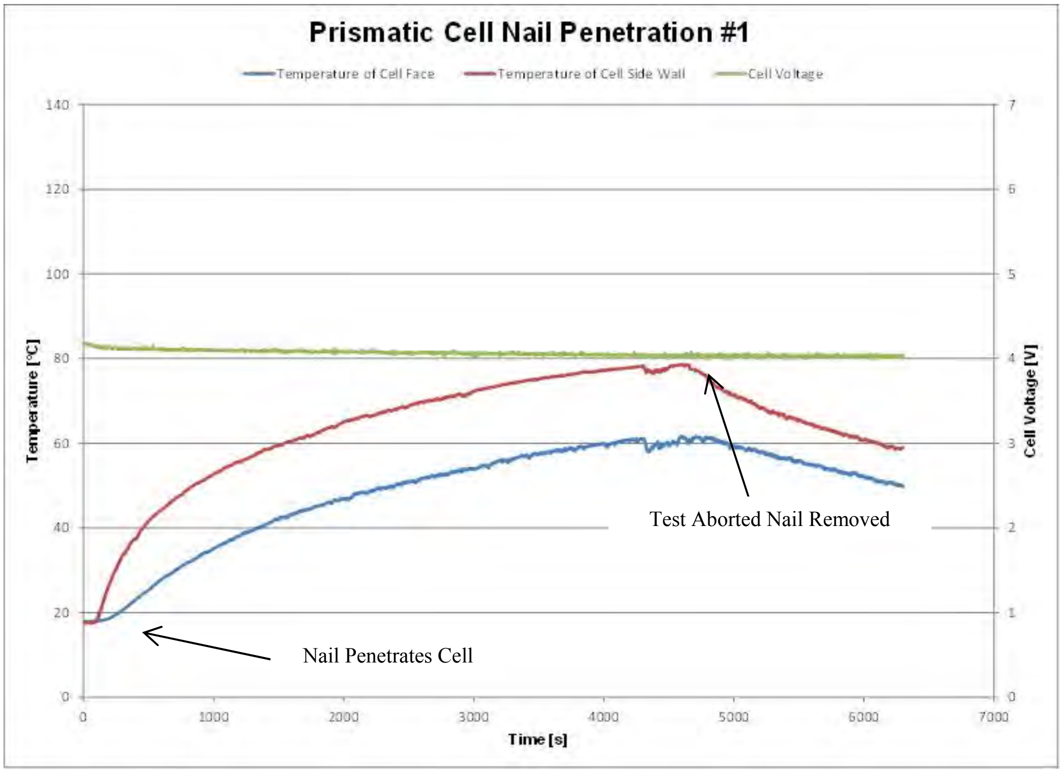

Figure 46 - Voltage and temperature traces for nail penetration Trail #1.

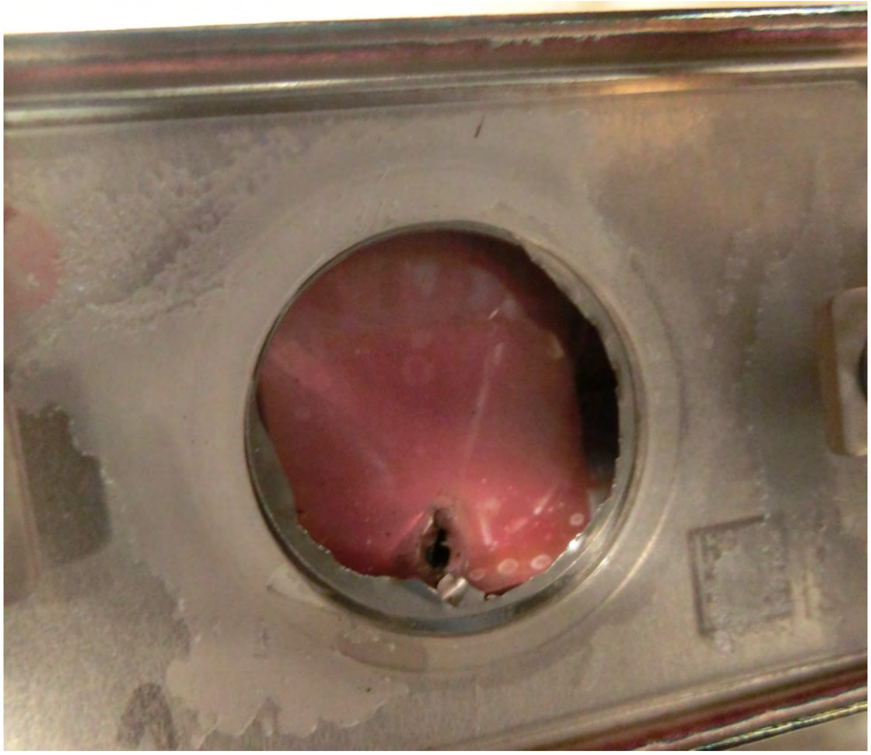

Figure 47 - Nail penetration damage.

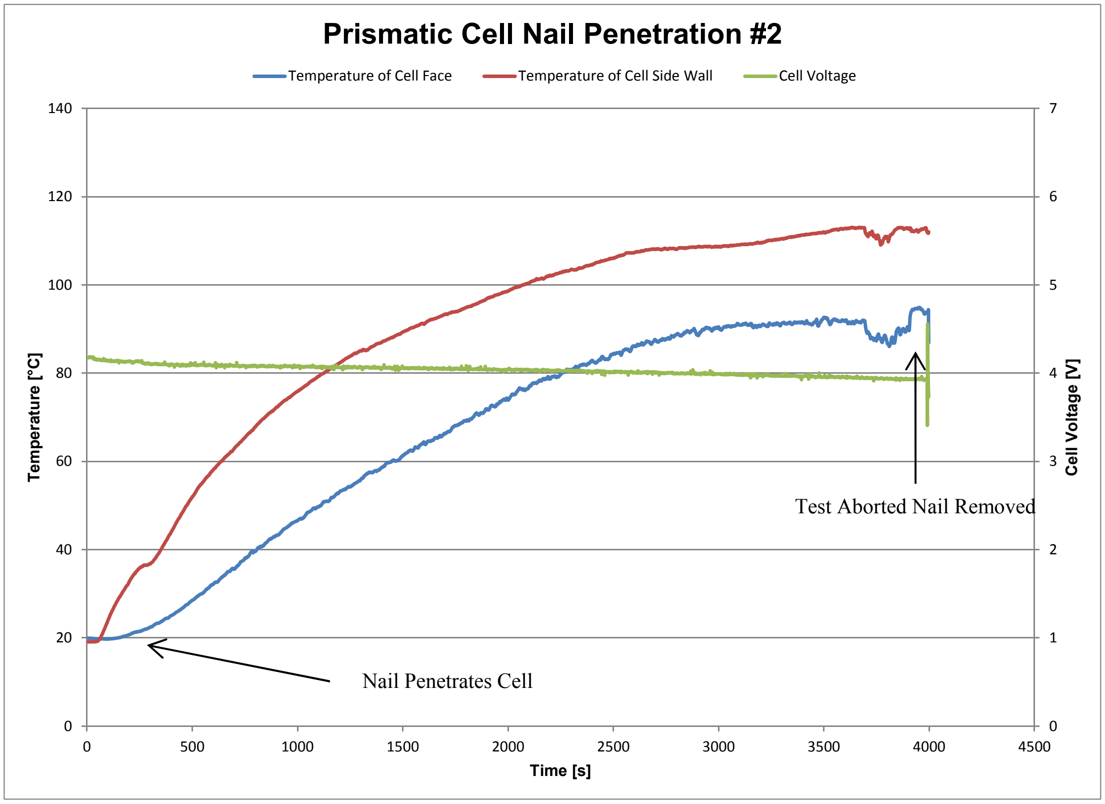

Figure 48 - Voltage and temperature traces for nail penetration Trial #2.

8.1.9 Pouch Cell Initiation Method Testing

One thermal runaway initiation test method was tried on pouch cells (i.e., Cell C).

8.1.9.1 Conductive Heating - Off-the-Shelf Film Heater:

This method was selected for trial because the heater is well thermally coupled to the cell, which should result in a short time to thermal runaway and overall low input energy to the system. A large heater was selected to apply a large amount of distributed heat into the cell as quickly as possible. A large heat flux should provide a shorter time to initiate runaway. However, due to the proximity of other cell surfaces as installed in the module, initiation of a center cell may add appreciable heat to neighboring cells prior to initiation. This method requires no changes to the electrical systems of the cell or battery. The heater is attached to the side of the cell and does not affect the designed gas flow or mechanical features. It can be applied to production cells and can be easily implemented into the battery module and RESS.

For this trial, a large off-the-shelf film heater was purchased from McMaster-Carr, part number 35475K753. The heater was a 4” x 6” rectangular pad rated to 10 W/sq. in (Figure 32). The heater had an adhesive backing which was used to attach it to the face of the cell. For this trial, the heater was connected to a DC power supply and the power to the heater was ramped to ensure that a hot-spot on the heater did not cause localized melting or burn-through of the cell pouch material. Three thermocouples were installed for this trial (i.e., one directly under the heater, one on the cell beside the heater, and one on the side of the cell opposite the heater).

8.1.10 Pouch Cell Initiation Method Results

A summary of the results for the initiation method attempted on the pouch cell is shown in Table 4. It includes time to thermal runaway, temperature at initiation, the energy ratio for the initiation cell (i.e., energy required to initiate thermal runaway divided by the electrical energy of the initiating cell), and the energy ratio for cells in parallel (i.e., energy required to initiate thermal runaway divided by the electrical energy of parallel group of cells as implemented in the RESS). Since there was a large difference in temperature measurements, the highest of the three temperature measurements was reported.

The large off the shelf film heater successfully initiated a thermal runaway reaction in the pouch cell after approximately 31 minutes. The hottest temperature measured during the test was directly underneath the heater (i.e., “Heater Temperature” in Figure 49) which measured 290°C. The thermal energy input from the heater was approximately 22% of the cell’s electrical energy, and 11% of the electrical energy of a parallel group in the pack configuration. During this test, the cell was not thermally insulated; in a module configuration, more heat might be retained resulting in a shorter time to thermal runaway. Also, heater power was increased during the test; setting the heater immediately to the highest value could result in shorter time to thermal runaway.

The thermal runaway reaction of an unconstrained pouch cell appeared different than thermal runaway of a hard case cell. Prior to venting, the pouch cell swelled (Figure 50). Ultimately, the increasing internal pressure and generated heat resulted in failure of either the heat sealed seams of the pouch cell or the pouch material itself, causing the cell to rupture and vent flammable gas. During this trial, the vented gases ignited (Figure 51). When a pouch cell is constrained within a module or RESS, it may not be able to swell, and the resulting gas flow pathways may appear different. In module level verification testing (Section 8.2), the effect of constraining the cell was studied.

Because of the module architecture and experience with the film heater method, no additional thermal runaway initiation methodologies were tried with pouch cells.

Table 4 - Summary of Single Pouch Cell Initiation Method Results (Manufacturer C)

Initiation Method	**Time to Runaway [Min:Sec]**	**Highest Temperature at Initiation [°C]**	**Energy Ratio (Relative to Input Energy)**	
			Initiating Cell	**Parallel Cells**
Large Film Heater	31:00	290	0.22	0.11

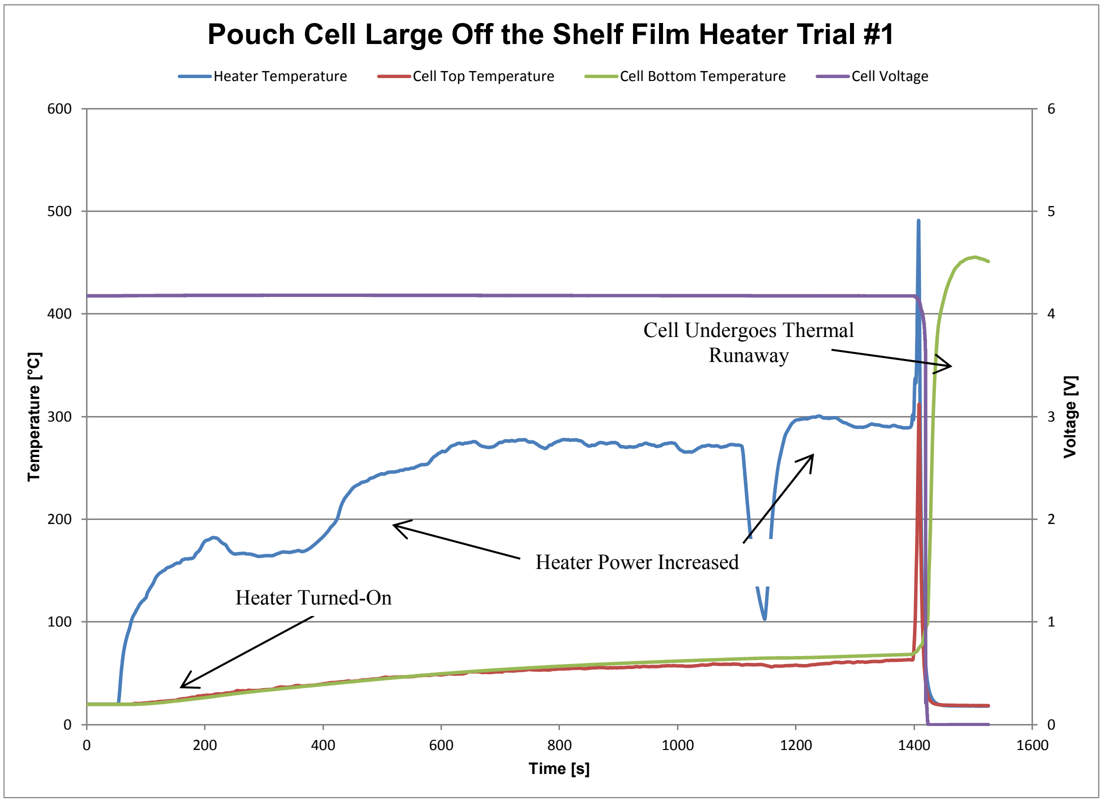

Figure 49 - Voltage and temperature traces for pouch cell large off-the-shelf film heater Trial #1.

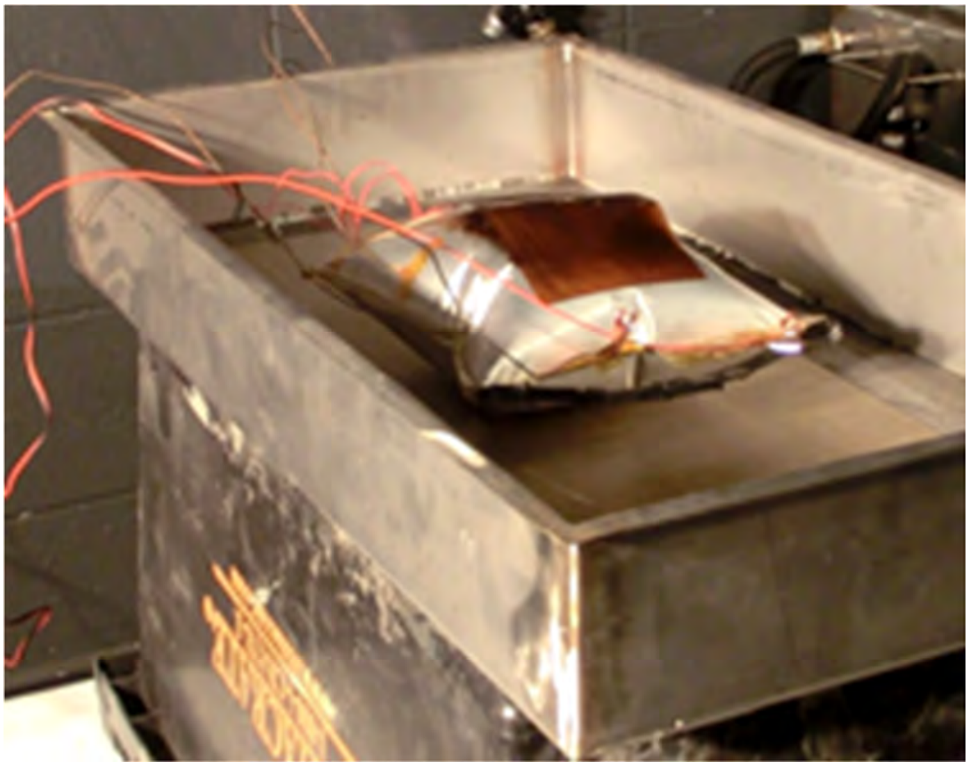

Figure 50 - Pouch cell just before thermal runaway.

Figure 51 - Ignition of thermal runaway gases from pouch cell.

8.2 Examples of Single Cell Thermal Runaway Initiation Verification Methods (Coupon or Module Level Testing)

8.2.1 Introduction

The purpose of coupon or module level initiation trials is to validate a single cell thermal runaway initiation method prior to its application on a full-scale RESS vehicle. It is intended to ensure that a method of initiation identified during single cell testing will be effective at the pack level, including interaction effects (if any) with neighboring cells and other battery module components. It is also intended to allow refinement of the method prior to installing an initiating device in a RESS. For example, coupon or module level testing can help determine where a specific initiation method will cause significant heating of neighboring cells and if it is necessary to develop mitigation strategies to prevent neighbor heating, such as selection of heater installation location, installation of insulation around heaters, etc.

Examples of cell-level thermal runaway initiation mechanism development were provided in Section 8.1. Building on that work, this section provides examples of how initiation methods that appeared promising at the single cell level should be validated for testing at full-scale. The goals of this testing included:

- Determine if the selected initiation method was appropriate for cells constrained within a module.
- Determine how the initiation method could be implemented in the module without significantly affecting gas flow pathways and boundary conditions
- Determine what modifications to the module enclosure would be necessary to install the heaters.
- Determine if modifications to the module would have significant effects on the performance of module.

Manufacturer A small cylindrical cells were tested at the coupon level with three potential initiation devices, including the wrapped nichrome wire device, the hand-made film heater device, and the off-the shelf film heater. These methods were the most consistent at the cell level and had the least effect on the boundary conditions of the test (see Section 8.1.6).

Because of the effectiveness of the large film heater method and the straightforward architecture of the Manufacturer B RESS, the film heater method was selected for application to full-scale vehicle testing and no coupon or module testing was performed.

Manufacturer C pouch cells were tested at the module level with an off-the-shelf film heater.

8.2.2 Test Equipment

- Personal protective equipment (PPE): respirators, safety glasses, and chemical resistant gloves
- Vent hood
- Temperature measurement and data logging system: National Instruments NI 9213
- Data Translation system: MEASUREPoint DT8874
- Type-K Thermocouples

- Stopwatch with and accuracy of ±1 second
- Various thermal runaway initiation devices selected based on single cell testing

8.2.3 Test Parameters

All of the tests were conducted with the conditions shown in Table 5.

Table 5 - Coupon or Module Level Test Parameters

Temperature	25±2°C
Initiating Cell SOC	95% - 100%
Neighboring Cell SOC	Various, depending on test configuration

8.2.4 General Test Methods

For each test:

- The initiating device was installed on a cell and the initiating cell was placed in a coupon configuration, or the initiating device was placed on a cell installed in a module.
- Thermocouples were applied to neighbor cells.
- The initiating device was activated, data acquisition was started and a timer was started.
- The time when the initiating cell audibly underwent thermal runaway was recorded.
- The test was continued until all neighbor cells showed evidence of cooling.

The following measurements were made for each test:

- Surface temperatures of neighbor cells.
- Time required from the start of the test to achieve thermal runaway.
- Occurrence of any secondary thermal runaway reactions.

The time to runaway was best determined by an audible indication of a thermal runaway reaction. Temperature traces of neighbor cells were used to report the average change in cell temperature from the beginning of a trial to the point of the initiator cell thermal runaway. They were also used to report the maximum neighbor cell temperature after thermal runaway had occurred.

8.2.5 Cylindrical Cell Verification Coupon Level Testing

A cylindrical cell coupon cluster was developed to compare possible cell thermal runaway initiation devices in a multi-cell environment based on time-to-runaway of the initiating cell, heat addition to neighbor cells, and reliability and robustness of the initiation method. The arrangement was based on the layout of cells present in modules from Manufacturer A (the cells were also provided by Manufacturer A). The coupon cluster consisted of seven cells arranged in a circular pattern. The initiator cell with an attached initiating device was located in the center of the cluster, and was surrounded by six neighboring cells. A schematic of this coupon cluster is shown in Figure 52. The initiating cell was charged to 100% SOC at 25°C.

Thermocouples were applied to four neighbor cells (labeled 1-4 in the schematic). Neighbor cells were charged to only 30% SOC to limit the likelihood of a thermal runaway propagation. This was an experimentally convenient method to study neighbor cell preheating by the initiator cell, without the effects of self-heating of neighbor cells. The cluster of seven cells was then wrapped in a layer of 1/8” ceramic insulation to help simulate the largely adiabatic environment of a full module. An example cluster coupon is shown in Figure 53.

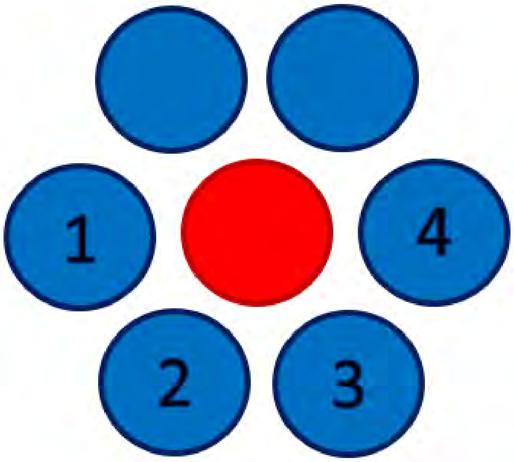

Figure 52 - Seven cell cluster module coupon.

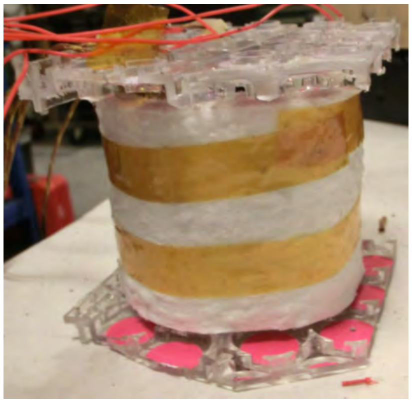

Figure 53 - Example module cluster coupon.

8.2.6 Cylindrical Cell Verification Coupon Level Results

A summary of the test results for the module coupon cluster tests is shown below in Table 6. Reported measurements included time-to-runaway, the average change in temperature experienced by neighboring cells at the time of thermal runaway for the initiating cell (i.e., amount of pre-heating), the maximum measured temperature of the neighbor cells after the initiating cell underwent a thermal runaway reaction, and the energy input to the heater as a fraction of the amount of electrical energy in the parallel group.

The first nichrome wrapped wire device trial produced a time to runaway of approximately 4 minutes. The temperature traces of the four neighbor cells can be seen in Figure 54. Data prior to the initiator cell entering thermal runaway is unavailable due to electrical interference during the heating portions of this trial. The interference disappeared immediately after the initiator cell went into runaway and the heater was turned off. Approximately 5 minutes after the initiator cell underwent a thermal runaway reaction, an additional cell (Cell 1) underwent a thermal runway reaction.

The second nichrome wrapped wire device trial also produced a time to runaway of approximately 4 minutes. The temperature traces of the four neighbor cells can be seen in Figure 55. At the time of thermal runaway, neighbor cells were preheated by approximately 20°C. The thermal runaway event from the initiator cell caused the thermocouples to become detached from the neighboring cells, so maximum neighbor cell temperatures after thermal runaway of the initiator cell occurred are not known. However, there were no visible or audible signs that any of the neighboring cells underwent a thermal runaway reaction after the initiator cell.

The first hand-made film heater device trial produced a time to runaway of approximately 7½ minutes. The temperature traces of the four neighbor cells can be seen in Figure 56. Prior to thermal runaway, neighbor cells were preheated by approximately 29°C. The highest measured neighbor cell temperature after the initiator cell underwent thermal runway was 93°C. None of the neighboring cells went into thermal runaway after the initiator cell.

The second hand-made film heater device trial produced a time to runaway of 6 minutes. The temperature traces of the four neighbor cells can be seen in Figure 57. During this time the neighbor cell temperatures increased by an average of 45°C. The maximum measured temperature achieved by a neighbor cell after the initiator cell underwent thermal runway was 168°C. None of the neighbor cells underwent a thermal runaway reaction.

The first off-the-shelf film heater device trial produced a time to runaway of approximately 6 minutes. The temperature traces of the four neighbor cells can be seen in Figure 58. Prior to thermal runaway, neighbor cells were preheated by approximately 18°C. After the initiator cell underwent thermal runaway, the maximum temperature reached by a neighbor cell was 77°C. None of the neighbor cells underwent thermal runaway.

The second off-the-shelf film heater device trial also produced a time to runaway of approximately 6 minutes. The temperature traces of the four neighbor cells can be seen in Figure 59. Prior to thermal runaway, neighbor cells were preheated by approximately 29°C. After the initiator cell underwent thermal runaway, the maximum temperature reached by a neighbor cell was 133°C. None of the neighbor cells underwent thermal runaway.

Based on these coupon tests, the off-the-shelf film heater device was selected for testing with Manufacturer A cells at a module level. It produced short times to thermal runaway and also resulted in very limited pre-heating of neighboring cells. The nichrome wrap method produced shorter times to thermal runaway, but the instance of a secondary cell thermal runaway reaction when compared to results of other heater tests suggests that the nichrome wrapped wire device may cause significant pre-heating of adjacent cells, may be sensitive to variations in setup, and/or alter thermal boundary conditions.

Table 6 - Summary of Cylindrical Cell Module Coupon Cluster Test (Manufacturer A)

Initiation Method	Time to Runaway [Min:Sec]	Neighbor Cell Avg. Rise in Temperature [°C]	Neighbor Cell Maximum Temperature [°C]	Energy Ratio Parallel Cells
Nichrome Wrap #1	4:22	N/A	Thermal Runaway	0.005
Nichrome Wrap #2	3:40	20	N/A	0.004
Hand-Made Film Heater #1	7:32	29	93	0.005
Hand-Made Film Heater #2	6:12	45	168	0.004
Off the Shelf Film Heater #1	5:53	18	77	0.004
Off the Shelf Film Heater #2	6:08	29	133	0.004

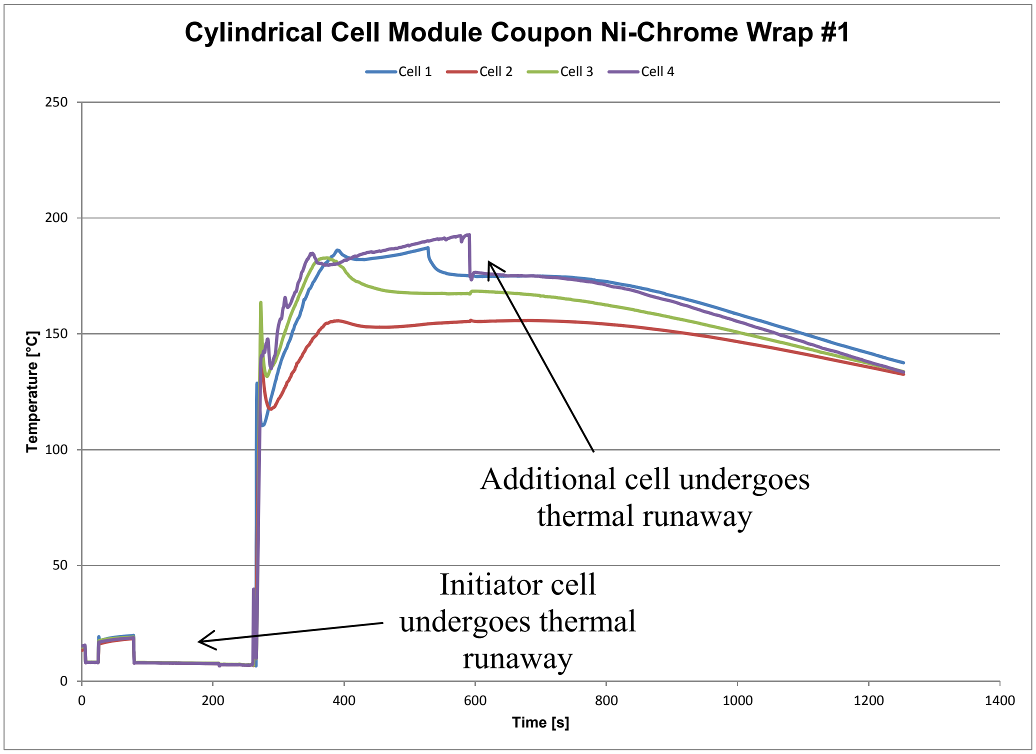

Figure 54 - Temperature traces for nichrome wrap Trial #1.

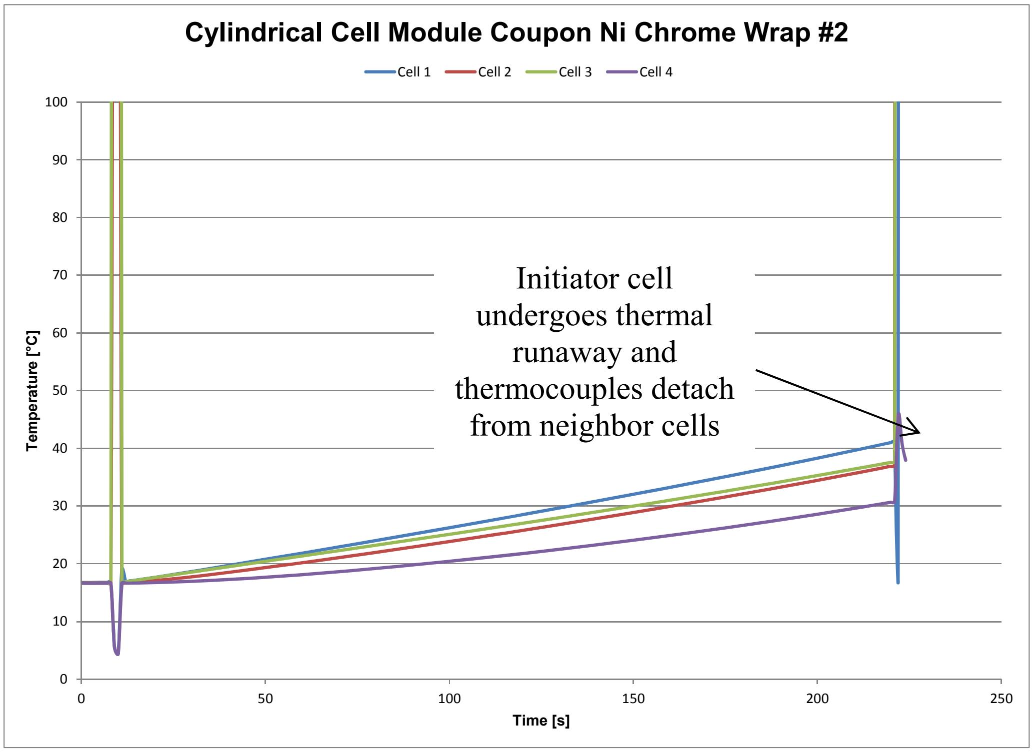

Figure 55 - Temperature traces for nichrome wrap Trial #2.

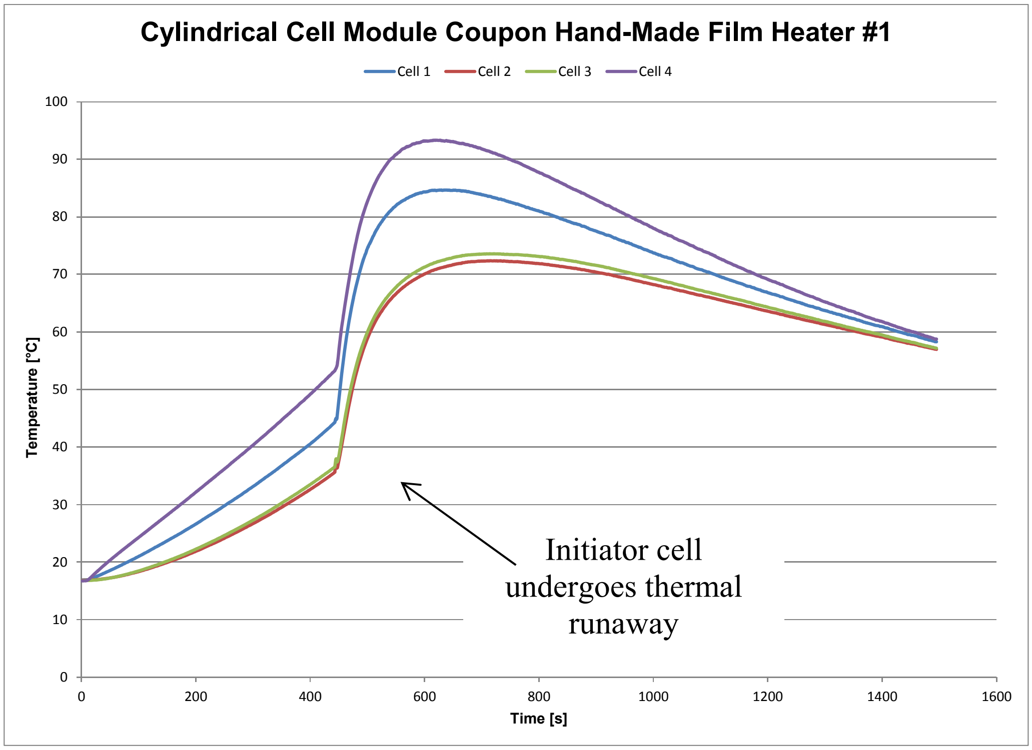

Figure 56 - Temperature traces for hand-made film heater Trial #1.

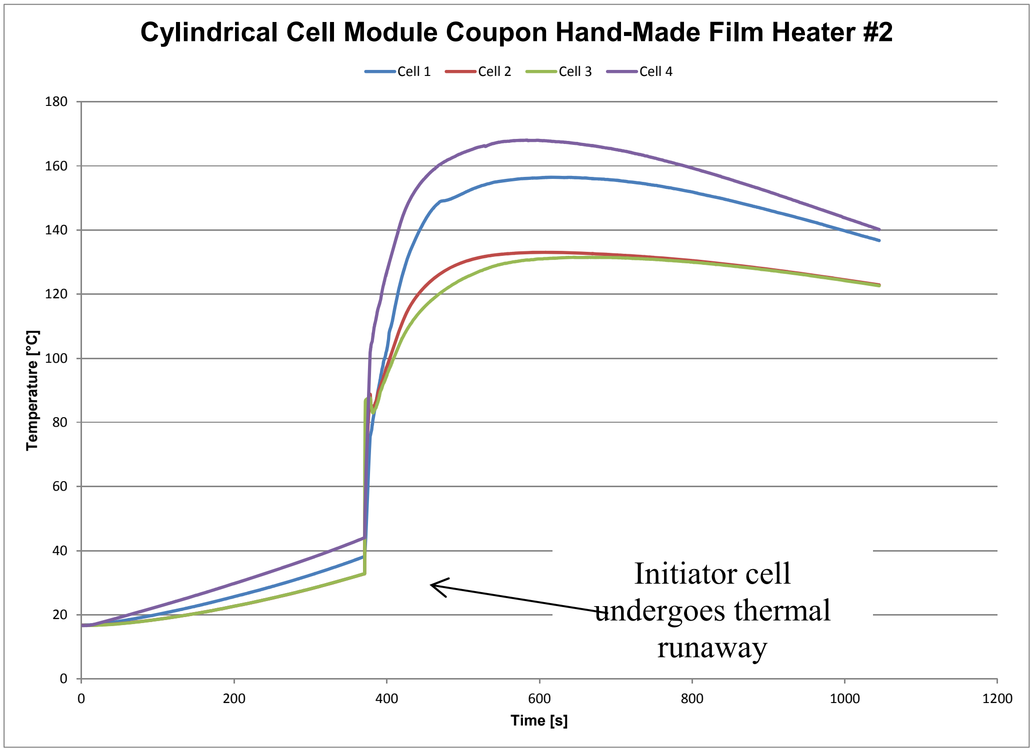

Figure 57 - Temperature traces for hand-made film heater Trial #2.

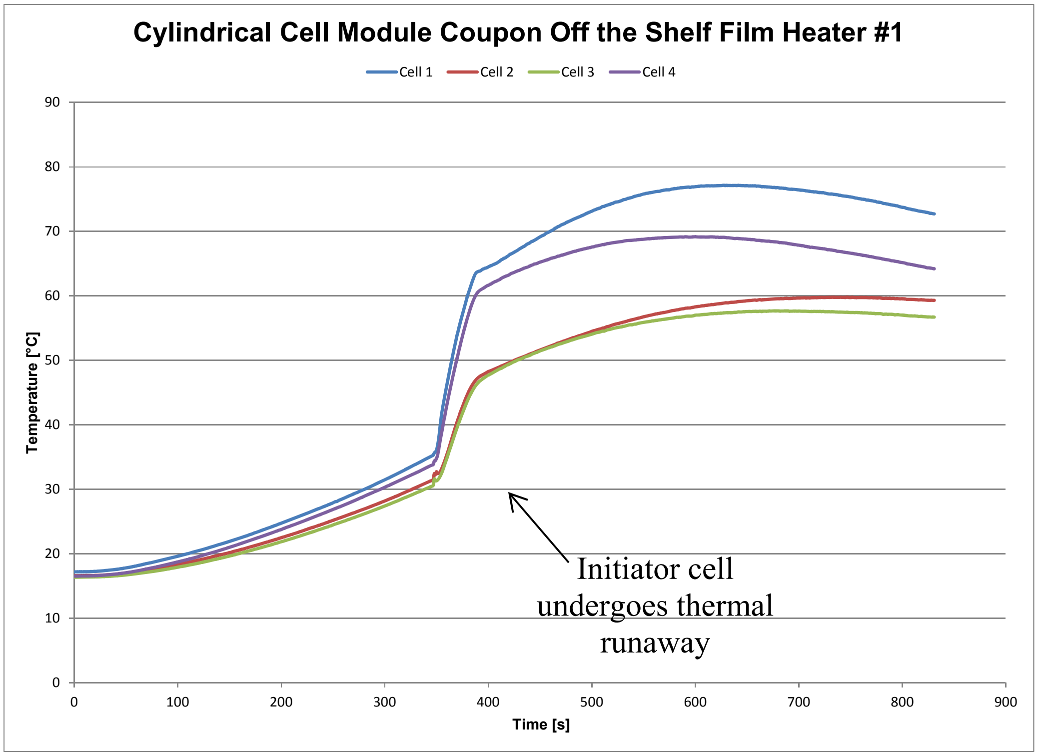

Figure 58 - Temperature traces for off-the-shelf film heater Trial #1.

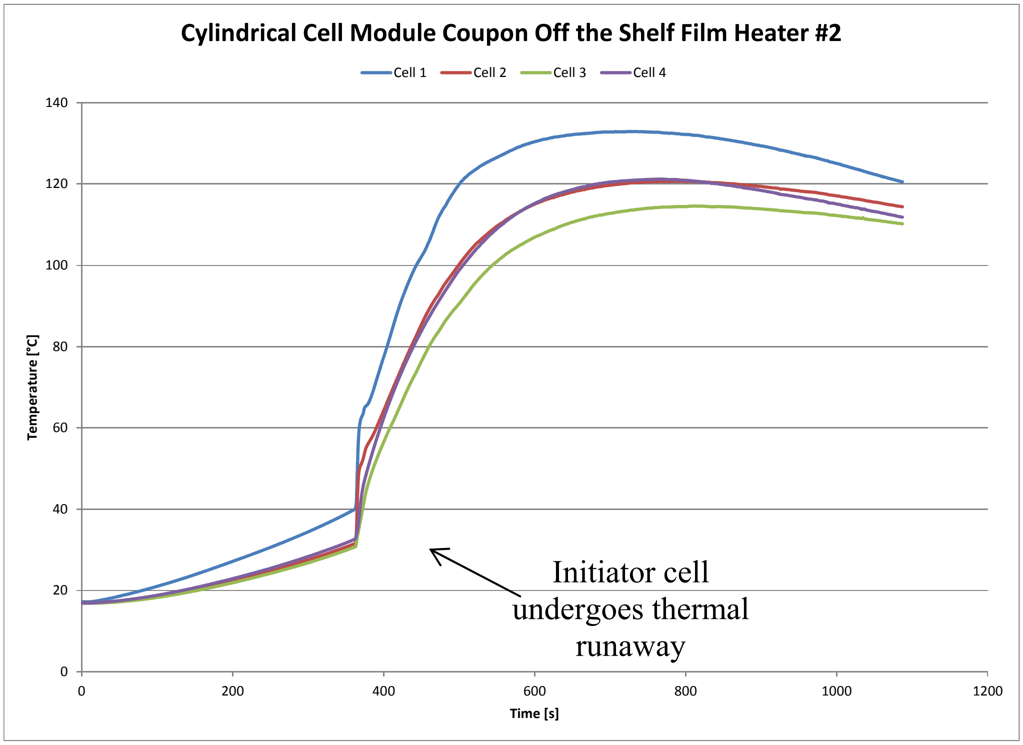

Figure 59 - Temperature traces for off-the-shelf film heater Trial #2.

8.2.7 Cylindrical Cell Verification Module Level Testing

Manufacturer A provided information regarding the module architecture that implements the small cylindrical cells; specifically, locations that are the most thermally stressful to cells in their battery module. These locations, labeled as Cell A, B, C, & D in Figure 60 and shown in red, were selected as the thermal runaway initiation locations for module-level testing.

Initiating cells were charged to 100% SOC. Cells adjacent to initiating cells (neighbor cells), colored orange in Figure 60, were also charged to 100% SOC. Thermocouples were applied to neighbor cells. Since the purpose of this testing was to assess the effectiveness of the cell thermal runaway initiation device and not to examine the likelihood or character of a thermal runaway propagation, the cells further removed from the initiators, colored yellow and marked with an "X" in Figure 60 were discharged. The discharged cells would provide an appropriate thermal and mechanical boundary condition for the test and not allow a thermal runaway reaction to propagate. This enables four initiation trials to be completed using a single module.

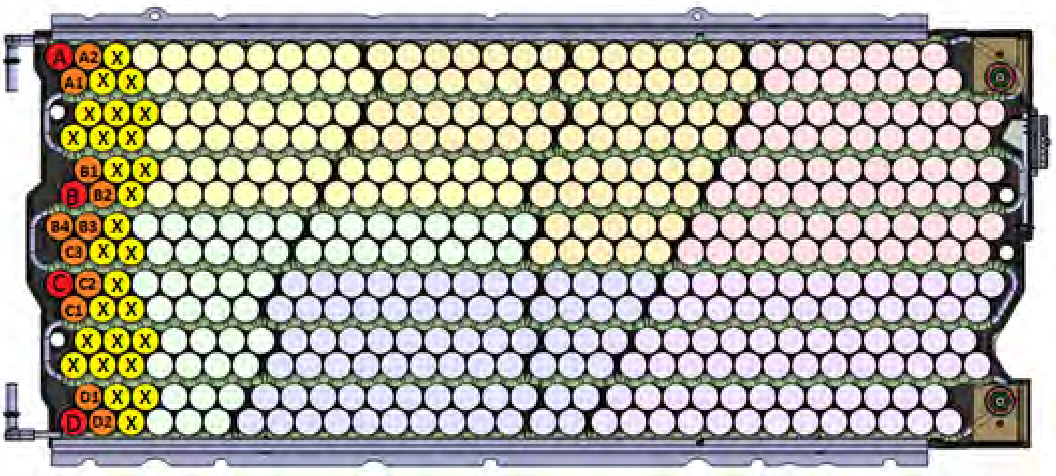

Figure 60 - Schematic of the full module SCTRI Test.

Figure 61 - Thin film heater attached to cell.

For the module level test, the thin film heaters were applied to the sides of the cells. Some small portions of plastic had to be trimmed to allow the heater to be fully adhered to the cell. The cell with the applied heater can be seen within a module in Figure 61.

Because this module architecture included a coolant system, cell temperatures at the start of test could be conveniently controlled. Cells were brought to 25±2°C prior to each initiation trial.

8.2.8 Cylindrical Cell Verification Module Level Results

During module level testing, three of the four trials resulted in successful initiation of a single cell thermal runaway reaction. The temperature traces for these tests are shown in Figure 62. The heater that was attached to the cell at Site A burned out before the cell could undergo thermal runaway (this trial is not shown on the temperature trace). However, trials at initiation sites C, D, and B were successful. Examining the temperature trace from left to right, test events were as follows:

- The cooling pump was running after the initiation trial at Site A failed.

- The cooling pump was turned off after cells surrounding Site C reached 25°C and the film heater attached to the cell at Site C was activated.

- Cell C heating was initiated. Neighbor cells were affected by the heater; Cells C1-C3 reached temperatures of 50-60°C before Cell C underwent a thermal runaway reaction. This thermal runaway reaction was marked by an audible pop and emission of smoke from the module as well as a spike in thermocouple temperatures. Time to thermal runaway was approximately 15 minutes.

- After Cell C underwent thermal runaway, Cells C1-C3 heated rapidly and then began to cool down. Cell C1 reached a maximum temperature of 136°C. None of the neighbor cells (C1-C3) underwent a thermal runaway reaction.

- After cells had cooled appreciably and no further thermal runaway reactions appeared likely, the coolant pump was turned on.

- The cooling pump was turned off after cells surrounding Site D reached 25°C and the film heater attached to the cell at Site D was activated.

- Cell D heating was initiated. Neighbor cells were affected by the heater; Cell D1 reached a temperature of approximately 50°C before Cell D underwent a thermal runaway reaction. This thermal runaway reaction was marked by an audible pop and emission of smoke from the module as well as a spike in thermocouple temperatures. Time to thermal runaway was approximately 10 minutes.

- After Cell D underwent thermal runaway, Cells D1 and D2 heated rapidly and then began to cool down. Cell D1 reached a maximum temperature of 110°C. None of the neighbor cells (D1 or D2) underwent a thermal runaway reaction.

- After cells had cooled appreciably and no further thermal runaway reactions appeared likely, the coolant pump was turned on.

- The cooling pump was turned off after cells surrounding Site B reached 25°C and the film heater attached to the cell at Site B was activated.

- Cell B heating was initiated. Neighbor cells were affected by the heater; Cells B1–B4 reached temperatures of 50-60°C before Cell B underwent a thermal runaway reaction. This thermal runaway reaction was marked by an audible pop and emission of smoke from the module as well as a spike in thermocouple temperatures. Time to thermal runaway was approximately 20 minutes.

- After Cell B underwent thermal runaway, Cells B1-B4 heated rapidly and then began to cool down. None of the neighbor cells (B1-B4) underwent a thermal runaway reaction. Maximum temperature of cells B1-B4 are unavailable due to electrical noise in the measurement.

- After cells had cooled appreciably and no further thermal runaway reactions appeared likely, the coolant pump was turned on.

A summary of the results of the four initiation location trials can be found in Table 7.

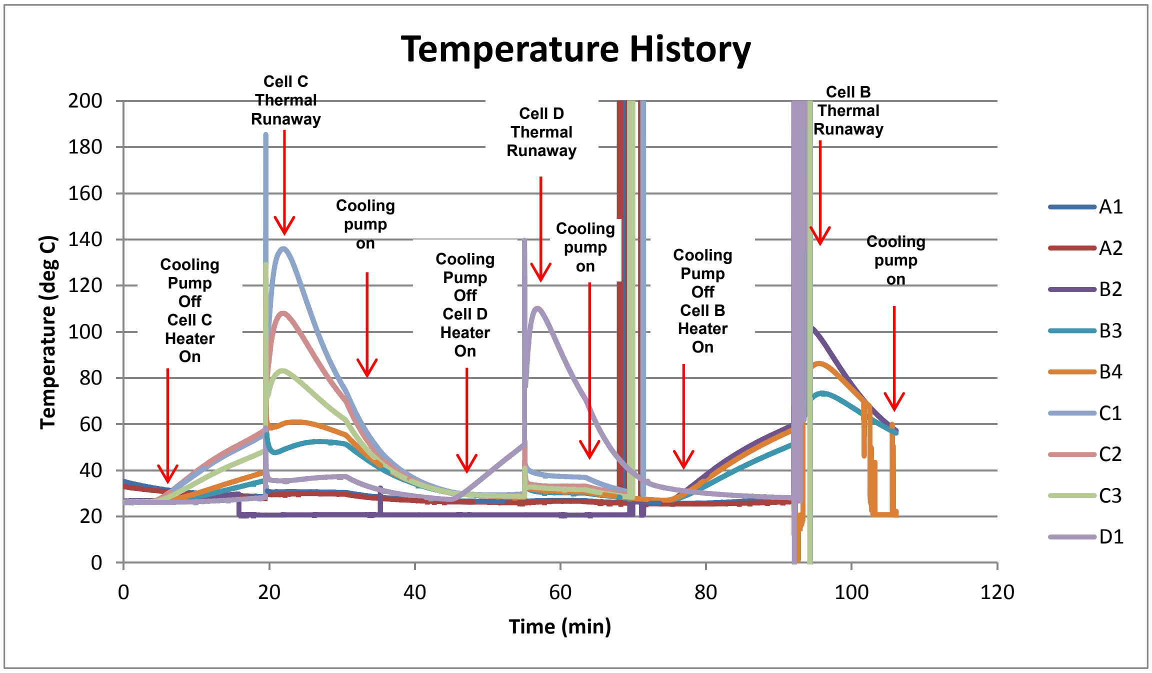

Figure 62 - Temperature traces for the module level testing; three of four trials.

Table 7 - Summary of Cylindrical Cell Module Level Testing (Manufacturer A)

Initiation Trial	Time to Runaway [Min]	Neighbor Cell Avg. Rise in Temperature [°C]	Neighbor Cell Maximum Temperature [°C]	Energy Ratio Parallel Cells
Location A	No Runaway (Heater failure)	N/A	N/A	N/A
Location B	17	29	>100 (noise in data)	0.011
Location C	16.5	28	136	0.011
Location D	10	14	110	0.007

Module level verification testing of the off-the-shelf film heater showed that this method could be applied with limited modification to the module or surrounding RESS and consistently induce a single cell thermal runaway. It produced times to thermal runaway of 10-20 minutes. It resulted in some heating of neighbor cells, which increased by 15-30°C during initiator heating and reached 50-60°C before thermal runaway of the initiator cell occurred. Propagation of thermal runaway to neighbor cells, however, did not occur. The method is subject to some experimental failure (one of four initiation attempts failed) and thus, it would be prudent to install multiple thermal runaway initiation devices within a single battery RESS as backups should the first initiation device fail to achieve runaway.

8.2.9 Pouch Cell Verification Testing

Manufacturer C RESS architecture implemented modules composed of four pouch cells stacked within a metal enclosure. Each metal enclosure (module) had exposed terminals for electrical connections. A representative pouch cell module is shown in Figure 63.

Pouch cell verification testing was conducted in two stages. The initial trial was conducted on a single 4-cell module, but thermal runaway resulted in significant swelling of a single module. Since the Manufacturer C RESS architecture constrains modules in such a way as to prevent swelling, a second trial was conducted on a constrained 3-module stack.

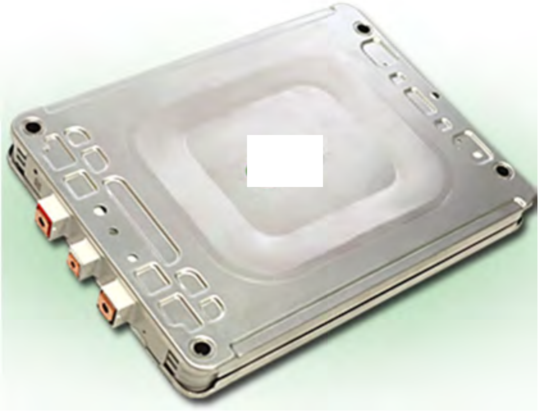

Figure 63 - Representative pouch cell module.

8.2.10 Single Module Trial

A large off-the-shelf film heater was selected as the initiating device for Manufacturer C pouch cells. In the module configuration, the heater was installed between the outside of an edge cell and an insulator. A schematic of the module is shown in Figure 64; the heater is red, the cells are yellow and insulation is blue. Thermocouples T0-T4 were installed between the cells and on the outside of the enclosure. All of the cells for this trial were charged to 100% SOC.

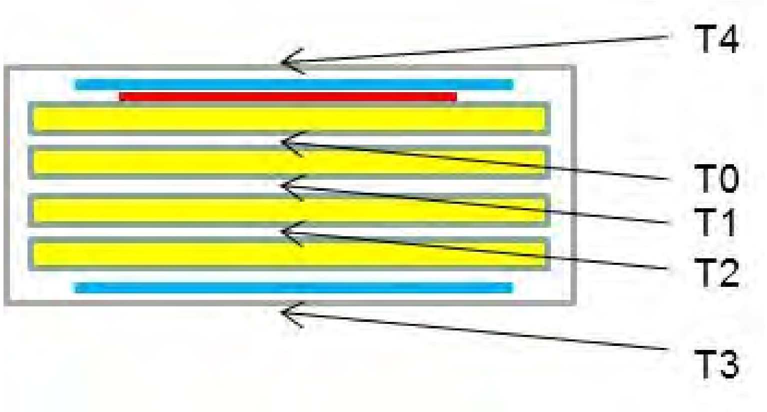

Figure 64 - Schematic of single module pouch cell test.

The single module trial resulted in a time to runaway of approximately 7 minutes. The thermocouple traces can be seen in Figure 65. Due to the presence of insulation, the case exterior thermocouple (T4) signal lagged the audible indications of thermal runaway by approximately 30 seconds. The traces show that, even though the heater was applying appreciable energy to the system (the temperature on the case exterior was rising steadily), neighboring cells remained within 5°C of initial temperatures until the first thermal runaway reaction occurred. The maximum temperature reached inside of the module enclosure was 721°C, consistent with thermal runaway reaction temperatures.

When the initiator cell underwent thermal runaway, it expanded, as seen in the single cell test, and caused deformation of the module enclosure (Figure 66). Vented gases ignited almost immediately after the first cell underwent thermal runaway. A second cell underwent thermal runaway approximately 1½ minutes after the initiating cell. The remaining cells underwent thermal runaway reactions with approximately 40 second delays.

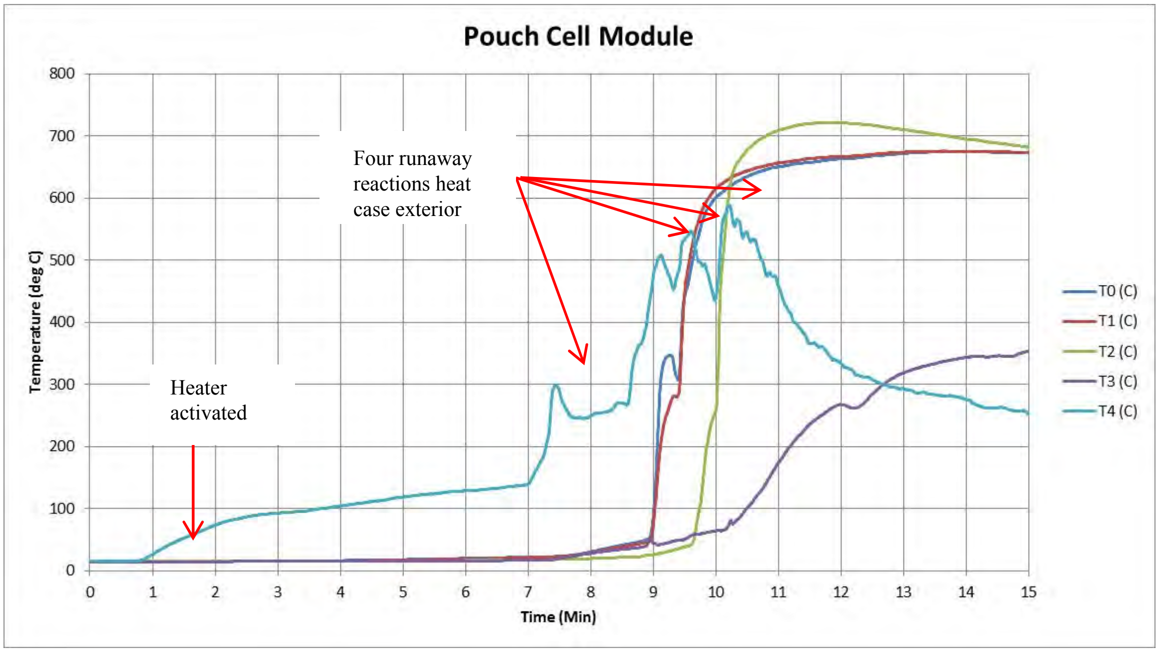

Figure 65 - Temperature traces for the single module pouch cell trial.

Figure 66 - Pouch cell module deformation.

8.2.11 Three-Module Trial

A second trial was conducted with three modules stacked on top of each other to replicate the battery pack configuration (Figure 67). The modules were held together using a threaded rod inserted through the existing holes in the corners. Metal bracing from the RESS unit was also installed to replicate the constraints on modules within the RESS. The installed heater was placed in the center of the stackup.

Within the initiating module, all four cells were charged to 100% SOC. Adjoining cells in the adjacent modules were also charged to 100% SOC to study the propagation times between modules. The outermost cells in the stack-up were fully discharged. Thermocouples were placed in between each of the cells and between the module enclosures (T0-T15). The schematic of the test setup is shown in Figure 68; discharged cells are yellow, fully charged cells are orange, the heater is red, and the insulation is blue.

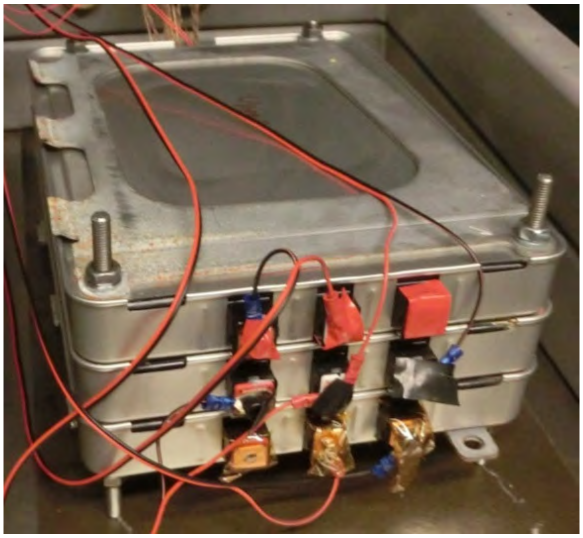

Figure 67 - Three-module pouch cell test setup.

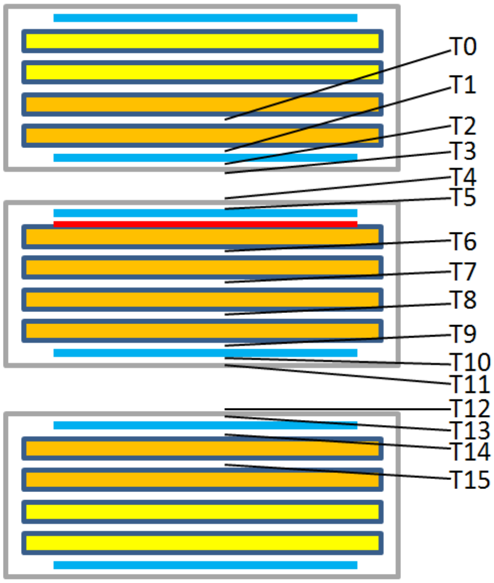

Figure 68 - Schematic of three-module pouch cell test.

The three-module trial resulted in an initiator time to runaway of approximately 7½ minutes. The thermocouple traces for cells within the initiating module can be seen in Figure 69 (note that heating started about 1½ minutes after data collection started, so time to thermal runaway is shown at approximately 9 minutes). The neighboring cell temperatures increased by an average of 11°C prior to the initiation of the first cell. The maximum temperature reached inside of the module enclosure was 853°C, which is consistent with thermal runaway reaction temperatures.

When the first cell went into thermal runaway and expanded, deformation of the case occurred. However, the degree of deformation was less than observed in a single module (Figure 71).

Figure 70 shows the thermocouple traces for both the initiating and neighbor modules over the full 25 minutes. After the first cell underwent a thermal runaway reaction, adjacent cells within the same module also underwent thermal runaway, which is similar to the single module test results. Vented gases ignited approximately 5 minutes after the first cell went into thermal runaway (i.e., no flames until approximately 14 minutes from beginning of test).

Thermal runaway propagated to the neighboring modules within approximately 10 minutes of thermal runaway initiation of the central module (see Figure 70, where the neighboring modules went into runaway around 18-20 minutes). The temperature traces show no change in slope at the time of ignition. Therefore, it unlikely that the ignition of the runaway gases had significant effect on the thermal runaway of the cells in the neighboring modules. The propagation likely occurred due to mechanical heat transfer from the initiation module.

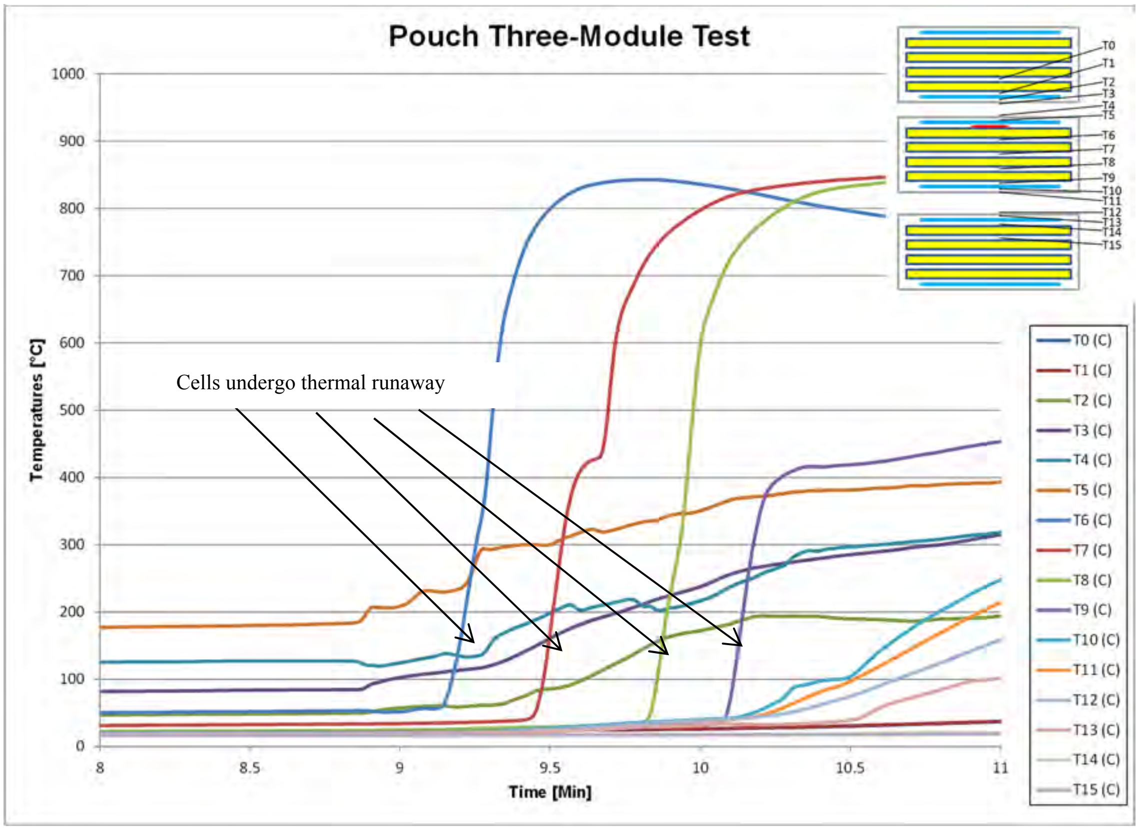

Figure 69 - Temperature traces for the center module.

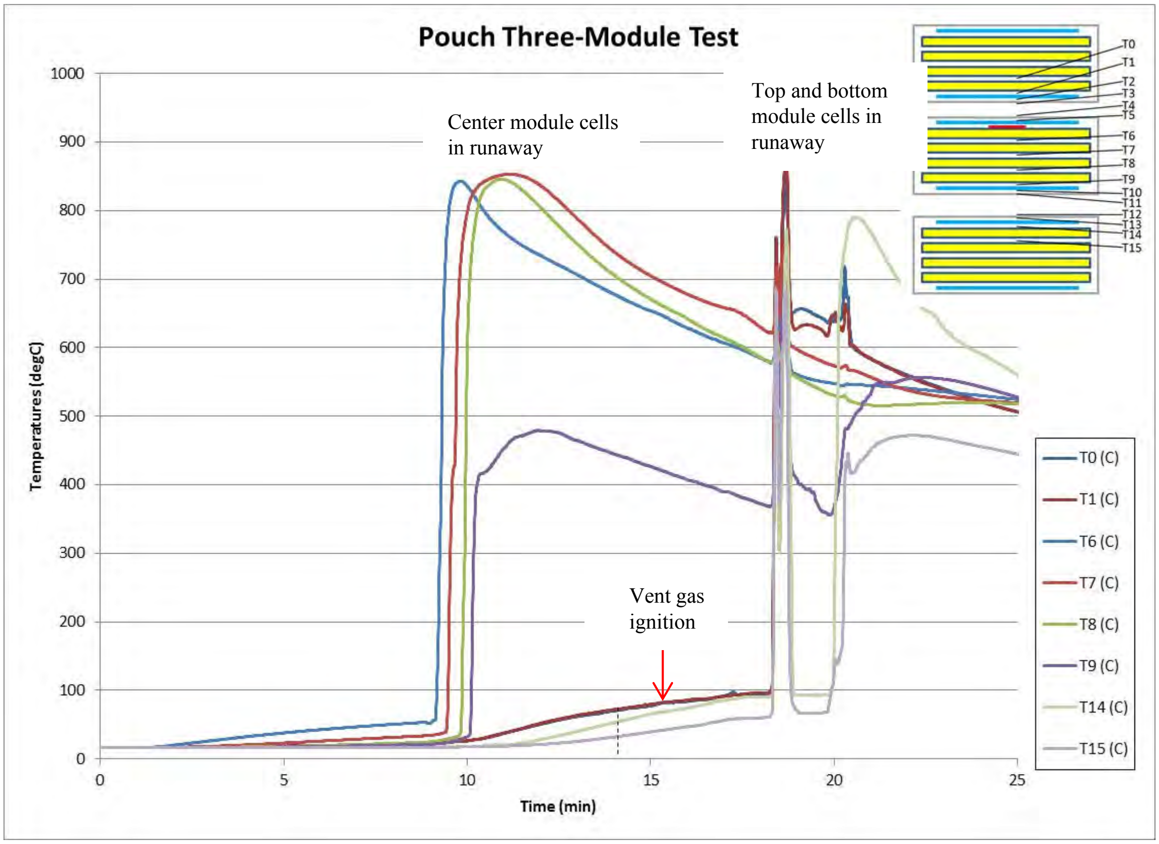

Figure 70 - Temperature traces for the neighboring modules.

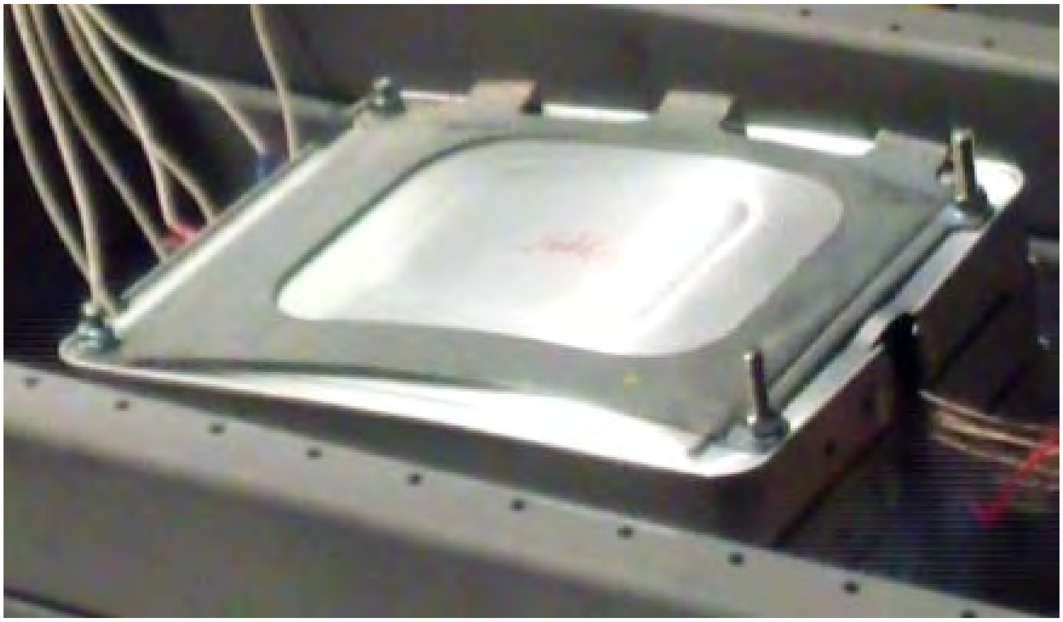

Figure 71 - Deformation of pouch cell three-module stack.

A summary of the pouch cell verification testing results is shown in Table 8. Based on the short and consistent time to thermal runaway and the small preheating effect on neighbor cells, this method was selected for the full-scale vehicle SCTRI testing.

Table 8 - Summary of Polymer Cell Module Level Testing (Manufacturer C)

Initiation Trial	Time to Runaway [Min:Sec]	Neighbor Cell Avg. Rise in Temperature [°C]	Neighbor Cell Maximum Temperature [°C]	Energy Ratio Parallel Cells
Single Module	7:00	< 5	Thermal runaway	0.11
3-Module Stack	7:30	11	Thermal runaway	0.12

8.3 Full-Scale Vehicle SCTRI Testing Examples

For demonstrative purposes, full-scale vehicle SCTRI tests were conducted with three EVs, each having a different Li-ion cell form factor:

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

Vehicles used for this testing were previously subjected to NHTSA New Car Assessment Program (NCAP) crash testing. Although the RESSs appeared undamaged from crash testing, vehicle structures were no longer entirely representative of production vehicles. Thus, the following discussion should only be used as a guide for conducting SCTRI testing; the results of the testing may not accurately represent the SCTRI performance of a non-crashed vehicle.

8.3.1 Manufacture A Vehicle: RESS Contains Small Cylindrical Cells

The RESS from Manufacturer A consisted of a large flat unit mounted to the floor of the vehicle. Within the RESS, small cylindrical cells were grouped into 14 modules. Cells within the modules were arranged in a single layer, with their long axis perpendicular to the ground (i.e., when the battery is mounted in the vehicle).

For this vehicle, a small film heater single cell initiation method was selected. A description of the selection process and rational for selection of this method can be found in Sections 8.1.5 and 8.1.6. Verification testing of the selected cell initiation method was completed with both a coupon and module configuration. The results of this testing are described in Sections 8.2.5 through 8.2.7.

8.3.2 Manufacturer A SCTRI Test Specific Equipment:

- Off-the-shelf film heater: 0.5" x 2" polyimide heater (McMaster-Carr Part #35475K283).
- Pass-throughs: Liquid-tight cord grips (McMaster-Carr Part #6907K9).
- Thermocouple DAQ: Data Translation MEASUREPoint DT8874.
- Smoke Detector: First Alert P1000 Detector.
- Gas Sensor: MultiRAE Lite Multi-Gas Detector, configured to measure oxygen, methane, carbon monoxide and percent of Lower Explosive Limit (LEL).

8.3.3 Manufacturer A RESS Preparation Procedure

The Manufacturer A vehicle was subjected to a frontal crash test per NCAP. The resulting damage, however, disabled the onboard charging system. Thus, the RESS unit was removed from the vehicle and charged to 100% SOC in accordance with the manufacturer's specifications.

The RESS was opened using chisels and pry bars to break the seal, as shown in Figure 72. However, the battery pack covers were warped due to the removal process and new covers were obtained from the manufacturer.

A module on the driver's side near the front was chosen as the cell thermal runaway initiation location since it was the most likely to result in propagation and affect the cabin occupants. The selected module was surrounded by thinner cross members to allow for the worst-case propagation from the initiator module to a neighbor module (i.e., shorter conduction length, lower stiffness in bending if pressure or gas sealing became a factor).

The cell thermal runaway initiation location within the selected module was chosen based on its architecture. A cell on the edge of the module was used since it cannot radiate or conduct heat to multiple neighbor cells. Thus, lower heat dissipation rates are expected for an edge cell compared to a cell within the center of a module. Two cell initiation locations were chosen, one as a backup should initiation at the primary heater fail to result in a thermal runaway reaction. Figure 73 shows the locations of the initiator cells within a specific module, the location of the module within the RESS, and thermocouple placement within the pack.

Figure 74 shows the heater. A minor modification was made to the plastic module case to allow the adhesive-backed heater to rest completely against the cell surface. This modification was similar to the modification made during module testing.

For test development and demonstrative purposes, more thermocouples were installed than would be required to conduct the SCTRI test per the procedure in Section 6.3. Thermocouples were installed on the initiating cell module and throughout the RESS interior (Figure 75). They were placed near the initiating cell, on adjacent modules, and on the corners of the RESS.

Thermocouples were also installed on the module current collectors (Figure 75). Although attaching thermocouples directly to neighboring cells might have provided more accurate cell temperature measurements, that configuration would have been more difficult to achieve, would have been less repeatable across a variety of test labs, and would not have provided appreciably more useful information.

The thermocouple beads were wrapped in polyimide tape to provide electrical insulation. While such insulation might not remain intact if a thermal runaway event occurs adjacent to the thermocouple, it will provide sufficient electrical insulation for non-propagated modules. In addition, electrically insulating thermocouple wires are important for a safe test setup. If not electrically insulated, bare thermocouple ends might short circuit during setup (e.g., wire routing through grommets).

Figure 76 shows the thermocouple and heater wires as they exit the battery pack. The wires were routed along the center spine of the pack and exited the front top cover through a liquid-tight pass-through. A nut and O-ring sealed the pass-through to the panel and a constricting rubber sleeve sealed the wires to the pass-through.

Since the contactors could not be operated by the vehicle itself (i.e., post-crash test) and access to the high-voltage chain was needed outside the enclosure to perform isolation tests, electrical leads were connected to the battery side of the contactors and run into a touch-safe connector through grommets in the enclosure. This connector (Figure 77) was subjected to further insulation and protection and was treated with great care as it represented an always-live connection to the 350 V battery pack.

The battery pack was sealed in accordance with the manufacturer's specifications (Figure 78) using replacement covers from the manufacturer. The pack-vehicle interface "blanket" was installed on top of the pack, with thermocouples fastened on top of that cover to monitor temperatures between the pack and the vehicle. The pack was filled with coolant per manufacturer specification through the fitting near the front top cover.

Figure 72 - Opening the cylindrical pack.

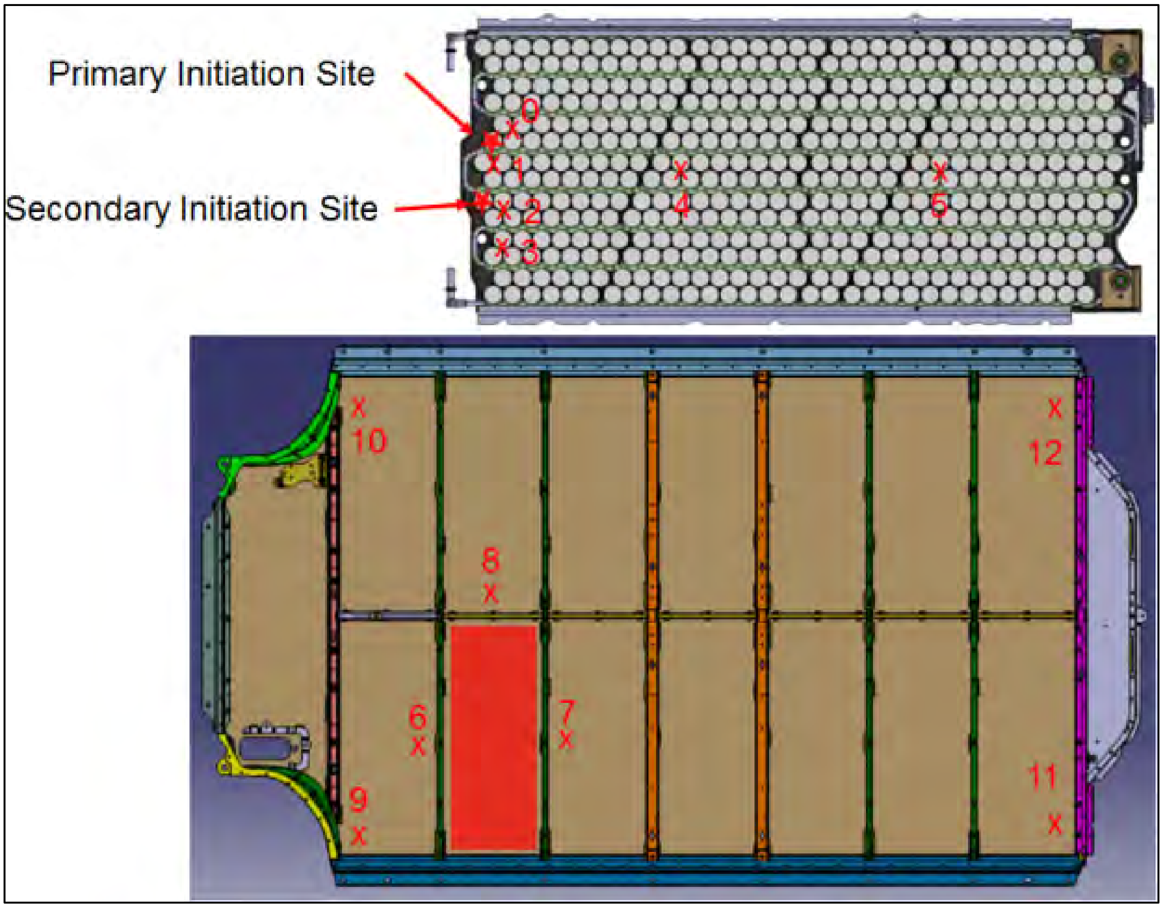

Figure 73 - Heater and thermocouple locations for the cylindrical battery pack.

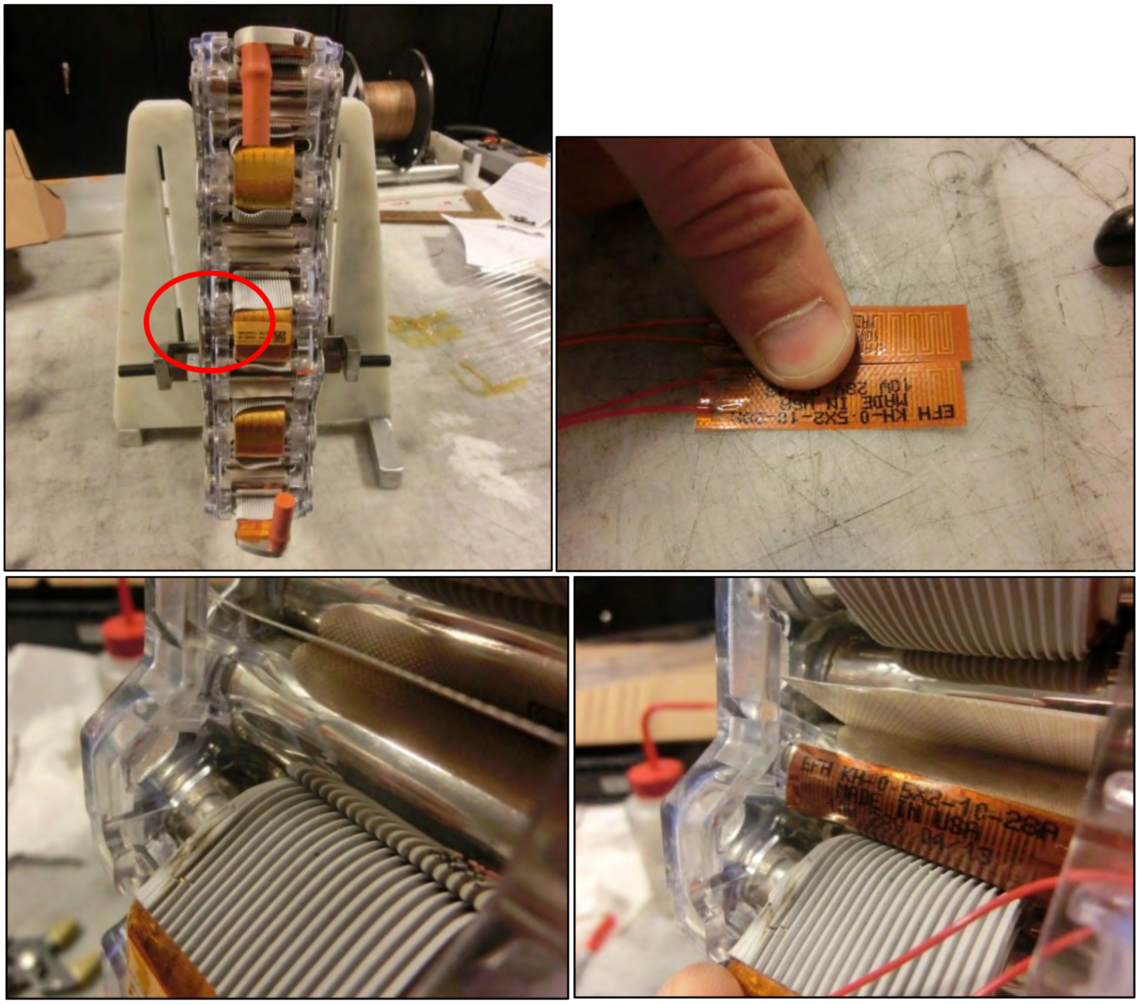

Figure 74 - Top left: the module on end. Top right: the 0.5" x 2" heater, trimmed slightly to fit the module. Bottom left: a plastic rib trimmed to allow access for heater installation. Bottom right: the heater installed.

Figure 75 - Left: a thermocouple taped to the module current collector. Right: thermocouples attached to the initiator module, with the ends running towards the center of the pack.

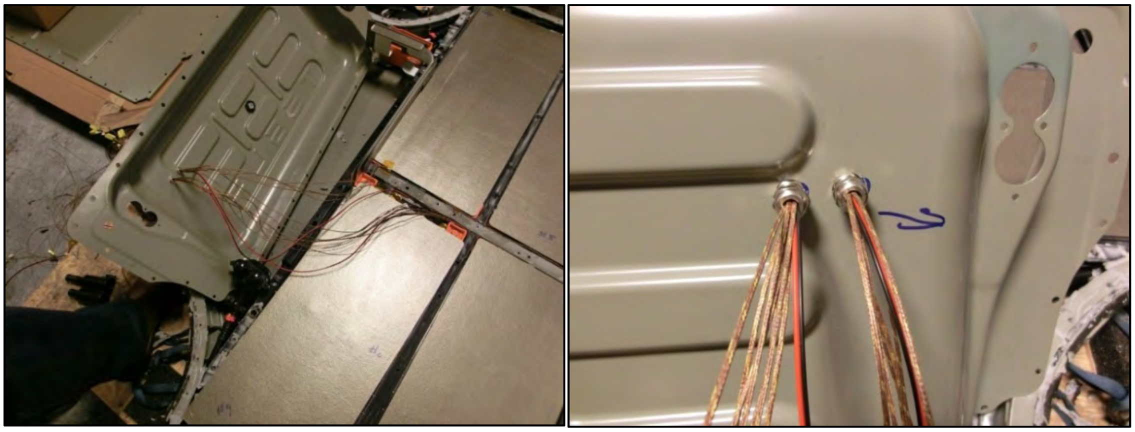

Figure 76 - The pass-through used for thermocouple and heater wires in the cylindrical battery pack.

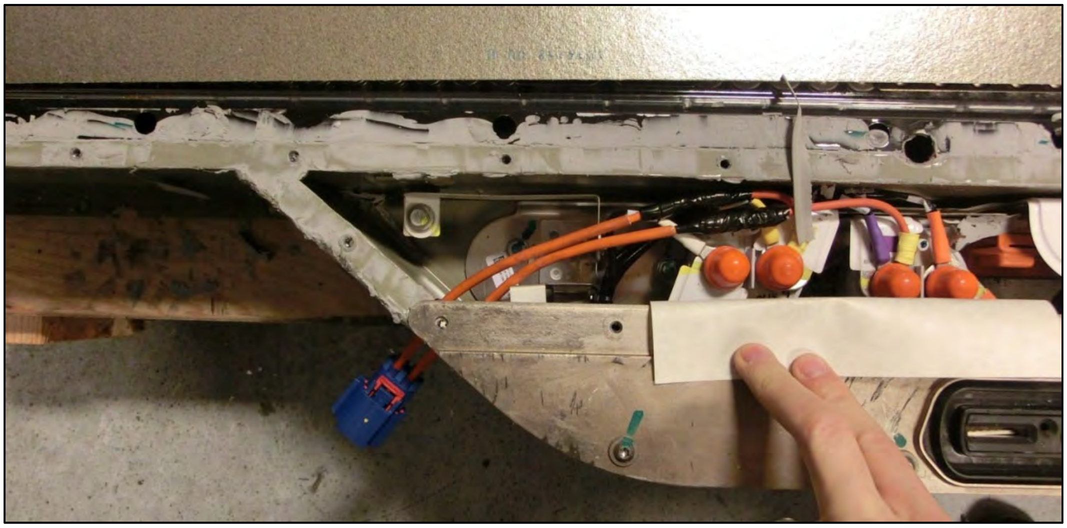

Figure 77 - The connector used for accessing the HV chain for isolation testing.

Figure 78 - The cylindrical battery pack with sealant applied to seal the flat main cover to the front cover.

8.3.4 Manufacturer A Vehicle Preparation Procedure

The Manufacturer A vehicle used to demonstrate SCTRI testing is shown in Figure 79. This vehicle had previously undergone a frontal crash test per NCAP. The battery from this vehicle showed no signs of damage, other than having been opened and re-sealed following the crash test.

The vehicle was prepared by removing unnecessary flammable material (Figure 80). Material was removed to limit the extent and intensity of any vehicle fire that might occur. However, flammable materials that might be important for understanding hazard to the occupant in the case of a propagating thermal runaway reaction were left in place. Flammables closest to the battery pack were left intact (e.g., carpets, bottom seats), as well as some materials at the top of the vehicle (e.g., portions of headliner), but many other materials were removed (e.g., dashboard and center console, seatbacks, headrests, door trim). To reduce the risk of projectiles during testing, all airbags that had not been deployed during the previous crash test were removed.

Thermocouples were installed on various remaining flammable materials, including seat cushions carpets, and the headliner. They were also installed to measure air temperatures at occupant head locations. Diagrams of thermocouple locations are shown in Figure 81.

A photoelectric smoke alarm (First Alert P1000) was installed on the center of the dashboard to detect the presence of particulate inside the cabin. A probe for gas sampling was installed through the roof at the location of the driver’s head.

To seal the cabin and allow measurement of gases that might enter from a thermal runaway reaction, windows that had been rolled down or were broken were covered with 0.010” clear plastic film.

The RESS was then mounted and bolted to the underside of the vehicle. The connector to the high voltage in the RESS was carefully monitored, secured and protected.

Figure 79 - The frontal crash Manufacturer A vehicle used for the demonstration of SCTRI testing.

Figure 80 - Top left, top right, bottom left: flammables removed from the vehicle and thermocouples installed. Bottom right: the battery pack ready to be mounted to the vehicle.

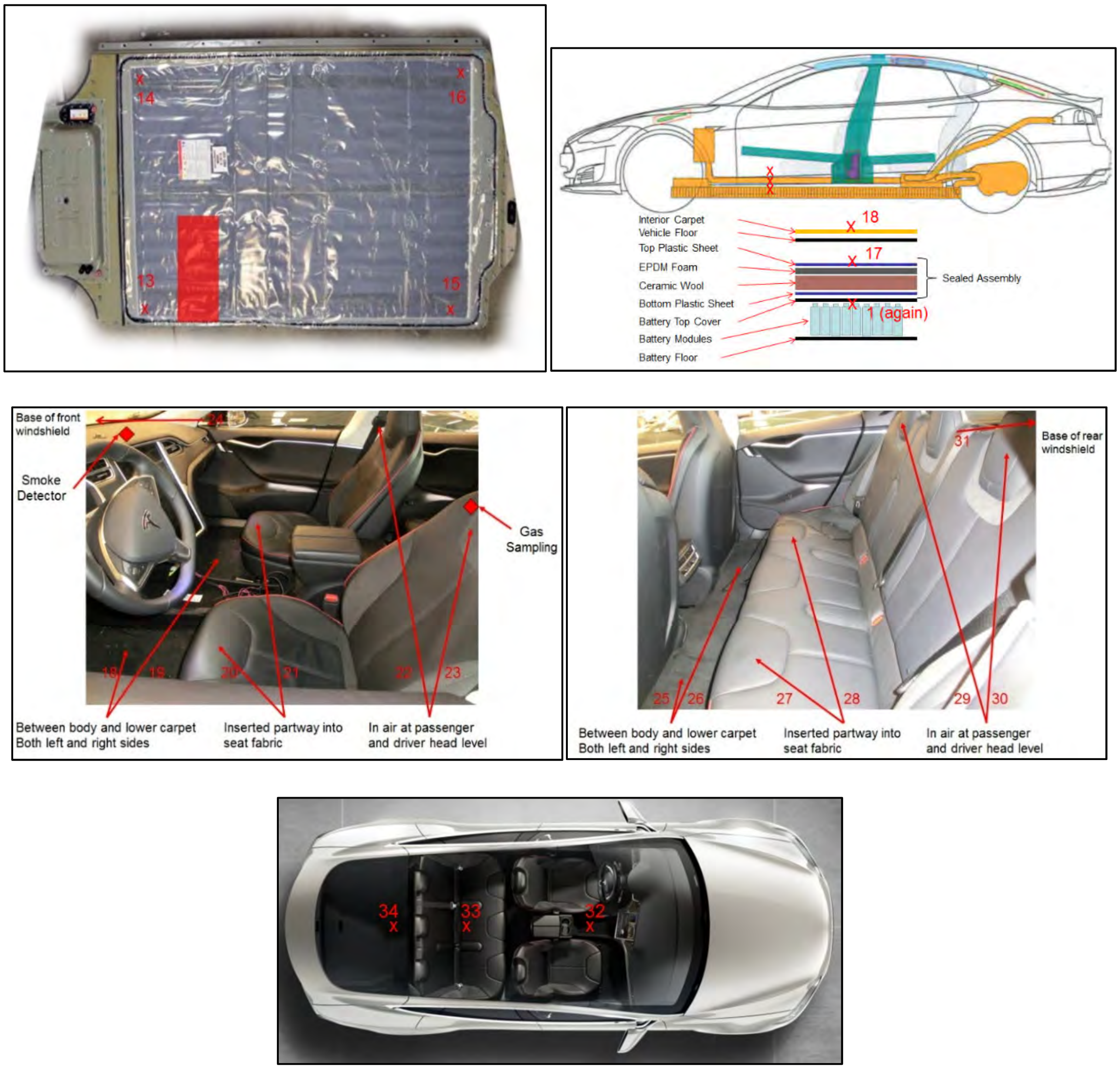

Figure 81 - Vehicle thermocouple locations for the Manufacturer A vehicle.

8.3.5 Manufacturer A Vehicle Preconditioning

At the test site, the vehicle was loaded into a thermal chamber and preconditioned to 25°C. After a 12-hour soak, the pack was within 25±2°C. The vehicle was removed from the conditioning chamber and placed at the testing location. At the time of testing, the outdoor ambient temperature was 3°C.

8.3.6 Manufacturer A SCTRI Test Execution

Thermocouples and the gas sensor were connected to data logging equipment.

Battery voltage and isolation were measured with a handheld voltage and insulation meter. Dielectric withstand voltage was measured with a hipot tester.

Video and data recording were started. A stopwatch was also started.

Once there was confirmation that video was being recorded and data signals were being properly logged, power was applied to the installed heater (47 V, 0.6 A, 28 W, as determined from cell-level testing).

The vehicle was observed and audible or visible signs of a thermal runaway reaction were noted.

Once the initiating thermal runaway reaction was observed (i.e., with an audible noise and a visual indication of gas escape from the pack – Figure 82), power to the heater was switched off.

Video and data were left recording until all thermocouple temperatures were decreasing and below 60°C.

Battery voltage and isolation were measured with a handheld voltage and insulation meter. The dielectric withstand voltage was measured with a hipot tester. An external power supply was connected between the negative battery terminal and the enclosure and ramped up to 353 V. The power supply remained connected for an hour, during which the RESS was monitored for any further thermal runaway reactions. After an hour the power supply was disconnected. Isolation and dielectric withstand voltage tests were repeated.

Figure 82 - Smoke escaping the battery pack as a result of thermal runaway of the initiating cell.

8.3.7 Manufacturer A SCTRI Testing Results

The SCTRI test with Manufacturer A vehicle and RESS was conducted successfully. A summary of test results is provided in Table 9. Single cell thermal runaway initiation occurred after approximately 26 minutes, longer than required for single cell testing, likely due to interaction with the module components. A clear pop noise was heard and some gray smoke was seen exiting the battery pack near the initiator bay (Figure 82). The smoke subsided within a few seconds, and no further thermal runaway events were noticed. The smoke alarm inside the cabin did not trigger. There was no ignition of flammable gases.

Figure 83 shows the temperature measurements inside the initiation module bay as well as a plot of all the temperature measurements. At the same time the pop was heard and smoke was observed, the initiator bay temperatures momentarily jumped by 5-20°C. As expected, T0 and T1 increased the most due to their proximity to the initiator cell. Other temperatures, not shown, were flat throughout the test. All temperatures were steady below 60°C and declining after 20 minutes; data logging was then stopped.

Gas composition measurements from inside the cabin at driver head level are shown in Figure 84. The oxygen, methane, and carbon monoxide concentration as well as the percentage of the LEL (Lower Explosive Limit) were measured. No deviation from ambient conditions (21% oxygen, no flammables) was recorded during or after the event. The smoke detector that was installed inside the cabin did not trigger. Based on the results from the gas sensor and smoke detector, it is unlikely that any run away gasses entered the passenger compartment.

Isolation resistance and dielectric withstand voltage measurements before testing indicated that internal isolation of the RESS had not been significantly compromised by installation of test equipment. Isolation resistance and dielectric withstand voltage were severely reduced after the initial cell thermal runaway, but a post-test exposure to elevated voltage did not cause any additional thermal events.

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

Table 9 - Summary of Manufacturer A SCTRI Testing Results

Pre-Test	Pack Voltage	350 V
	Isolation – 1000 V handheld insulation resistance meter	5.6 MΩ between the negative battery terminal and enclosure
	Dielectric withstand voltage – hipot tester	7.5 mA limit exceeded at 1.67 kV (target: 1.7 kV) A second test immediately afterward exceed the 7.5 mA limit at 1.18 kV
Test	Time to thermal runaway of initiating cell	25 minutes, 40 seconds
	Energy ratio for cells in parallel	0.01
	Indication of initiation of thermal runaway	Audible sound, subsequent release of gray smoke from the battery pack
	Time to cabin smoke alarm activation	Alarm did not activate
	Time to 2nd thermal runaway reaction	No additional thermal runaway reactions
	Indication of 2nd thermal runaway	No additional thermal runaway reactions
	Time to flaming combustion	No ignition of combustibles
Post- Test	Pack voltage	350 V
	Isolation – 1000 V handheld insulation resistance meter	0 MΩ between the negative battery terminal and enclosure
	Dielectric withstand voltage – hipot tester	7.5 mA current limit was exceeded at 0.79 kV
	Isolation testing power supply maximum current	0.002 A
	Time to thermal runaway of additional cells	No additional thermal runaway reactions
Final	Isolation – 1000 V handheld insulation resistance meter	0 MΩ between the negative battery terminal and enclosure
	Dielectric withstand voltage – hipot tester	7.5 mA current limit exceeded at 1.59 kV

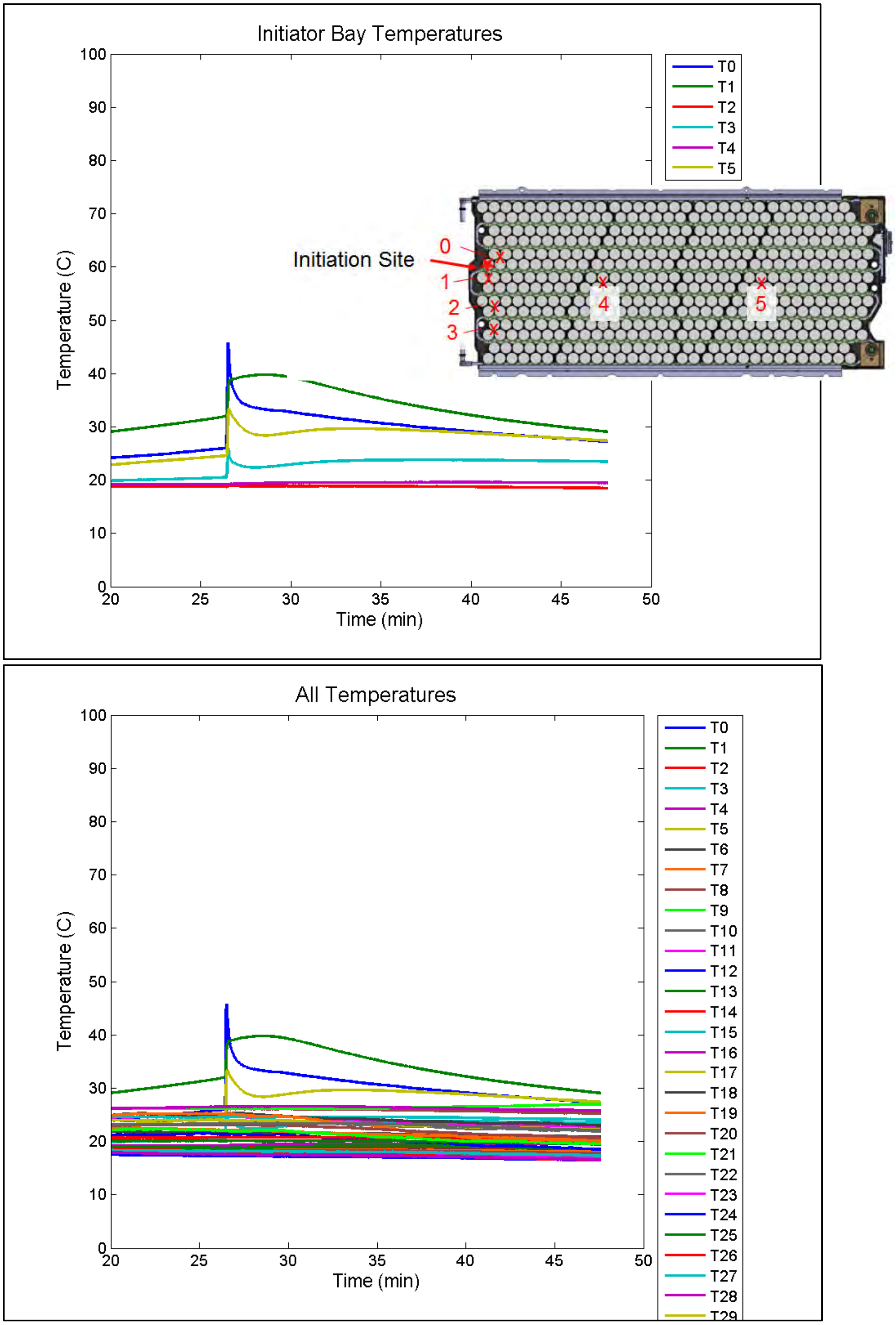

Figure 83 - Top: battery temperatures in the initiator bay. Bottom: all temperatures. Plots start at 20 minutes to crop out prior erroneous readings as thermocouple connections underwent troubleshooting.

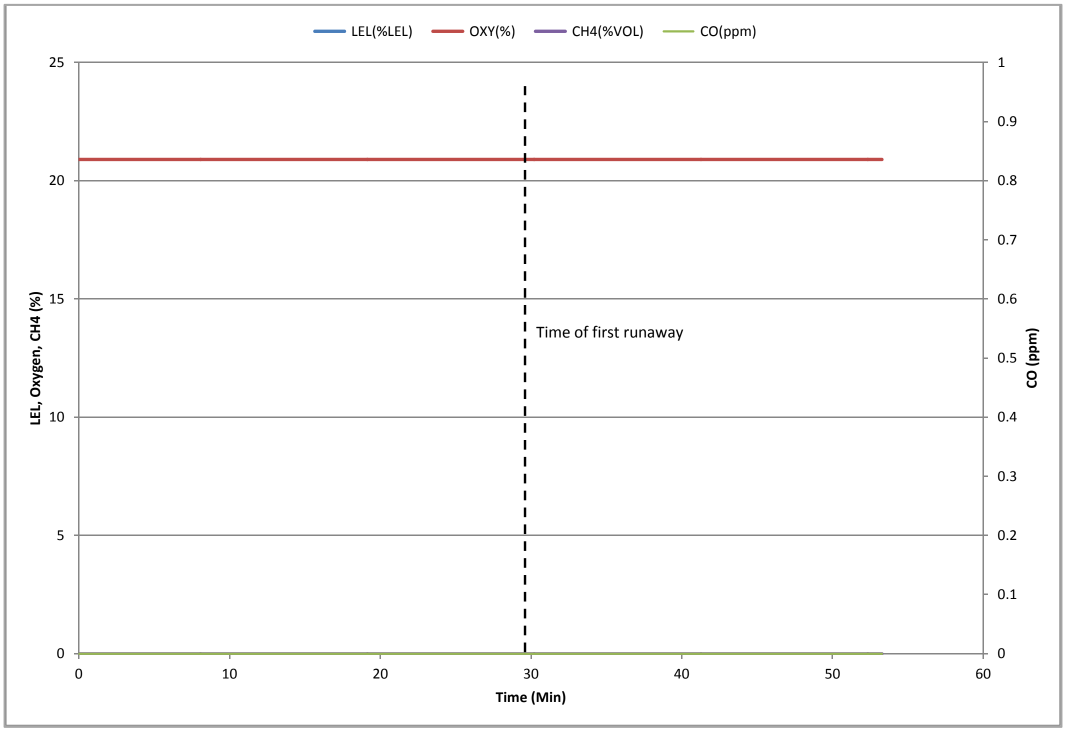

Figure 84 - Manufacturer A SCTRI testing; cabin air composition measurements.

8.3.8 Manufacture B Vehicle: RESS Contains Hard Case Prismatic Cells

The RESS from Manufacturer B consisted of a unit that was mounted to the floor of the vehicle. Within the RESS, hard case prismatic cells were arranged in “stacks” of eight cells connected in series. Cells were arranged surrounding a central electronics area (Figure 85).

For this vehicle, a large film heater single cell initiation method was selected. A description of the selection process and rational for selection of this method can be found in Sections 8.1.7 and 8.1.8. Verification testing of the selected cell initiation method was coincident with single cell testing (Section 8.1.8).

8.3.9 Manufacturer B SCTRI Test Specific Equipment

- Off-the-shelf film heater: 4” x 6” polyimide heater (McMaster-Carr Part #35475K753).
- Pass-throughs: Liquid-tight cord grips (McMaster-Carr Part #6907K9).
- Thermocouple DAQ: Data Translation MEASUREPoint DT8874.
- Smoke Detector: First Alert P1000 Detector.
- Gas Sensor: MultiRAE Lite Multi-Gas Detector, configured to measure oxygen, methane, carbon monoxide and % of LEL.

8.3.10 Manufacturer B RESS Preparation Procedure

The Manufacturer B vehicle was subjected to a side impact crash test per NCAP. The resulting damage, however, disabled the onboard charging system. Thus, each 8-cell stack was removed from the battery pack, instrumented with voltage sense leads, and charged to 100% SOC per the manufacturer's specification using the test lab's charger and battery management system.

After the cell stacks were fully charged, one of the stacks was disassembled and a single cell was removed. The surrounding yellow plastic insulation was removed and a large film heater was attached to the face of the cell. The plastic insulation was replaced and restrained using a small strip of polyimide tape (Figure 86). The cell was then re-assembled into a stack. This process was repeated with a second cell stack to prepare an alternate initiation location. Once both stacks were reassembled, they were re-installed into the battery pack along with the other stacks.

The cell thermal runaway initiation location was chosen based on pack architecture. A cell on the edge of a stack was used since it cannot radiate or conduct heat to multiple neighbor cells. Thus, lower heat dissipation rates are expected for an edge cell compared to a cell within the center of a stack. The heater was placed on the open side of the cell. If the heater was placed on the side of the cell facing the neighboring cell, it could potentially heat both cells simultaneously, causing excessive heating of a neighbor cell and/or alter the thermal boundary condition created by the neighbor cell. Edge cells near the center electronics section of the battery pack were chosen as they were deemed more likely to propagate to the other side of the battery pack. Figure 85 shows the locations of the initiator cells (primary and auxiliary locations) for the prismatic cell battery pack.

Thermocouples were installed near the initiating cell(s), on an additional cell within the same stack, and at the corners of the RESS. Thermocouples were attached to cells by making a small incision in the plastic shrink wrap encasing the cells and attaching the welded bead of the thermocouple with a small amount of adhesive (Figure 87). All of the thermocouple and heater wires were then routed through liquid-tight pass-throughs that had been threaded into tapped holes on the side of the battery pack (Figure 87).

The battery pack was closed and sealed. It was manufactured with a reusable seal and a bolt-on cover, so the original cover and seal were used to close the battery pack.

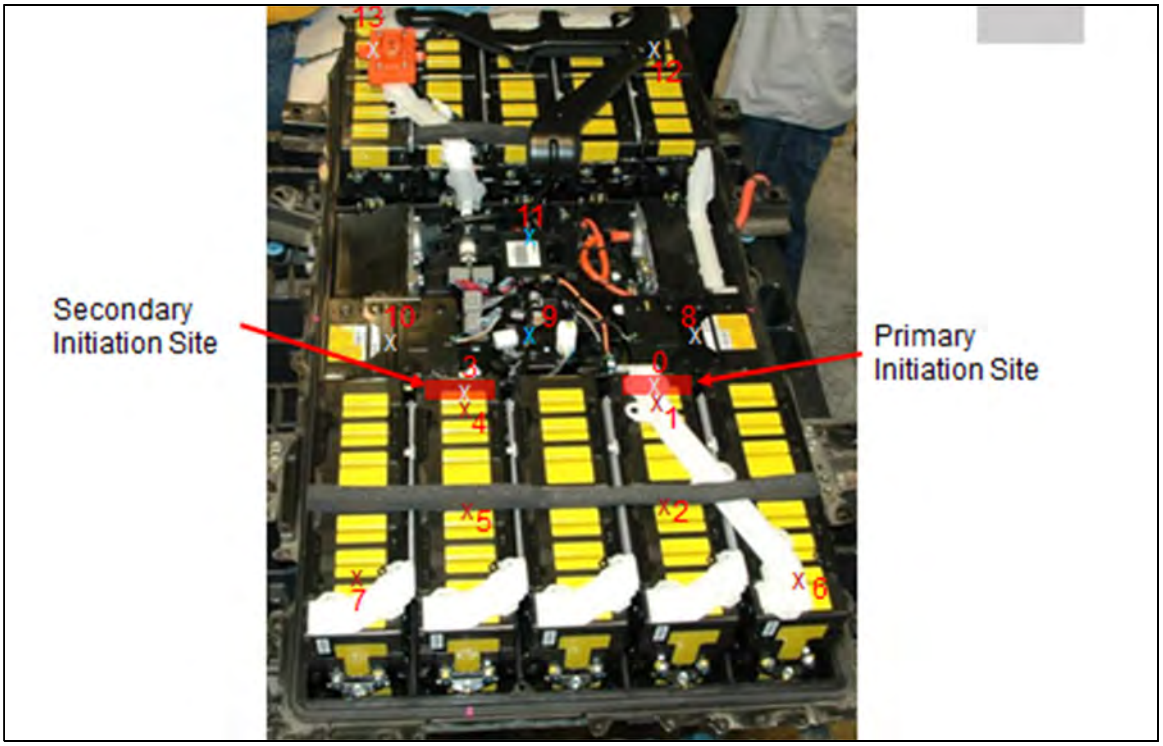

Figure 85 - Prismatic battery pack internal thermocouple and initiation locations.

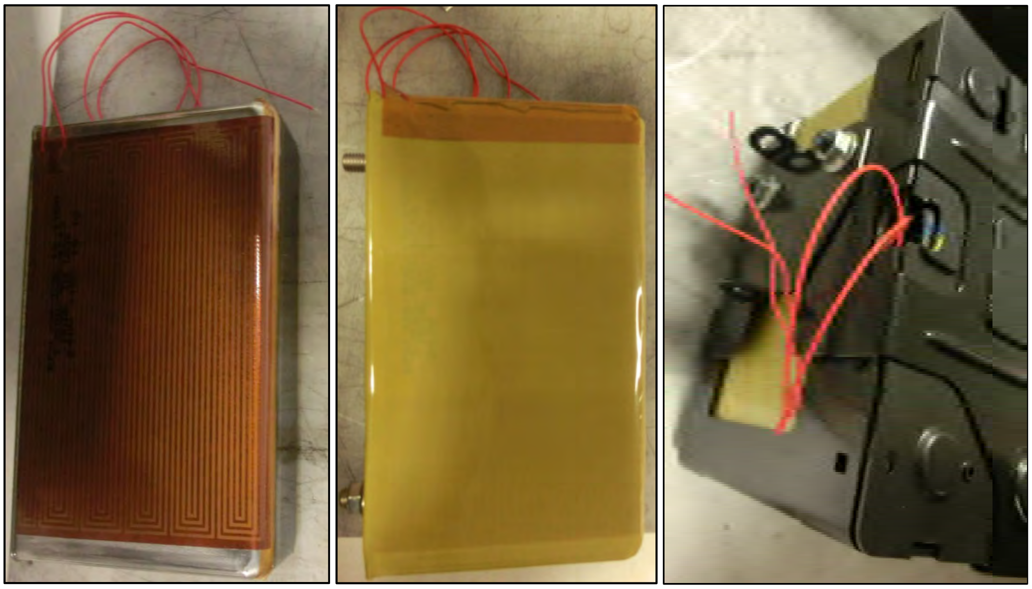

Figure 86 - Left: film heater attached to cell. Middle: plastic insulation reattached to cell. Right: cell reinstalled into stack.

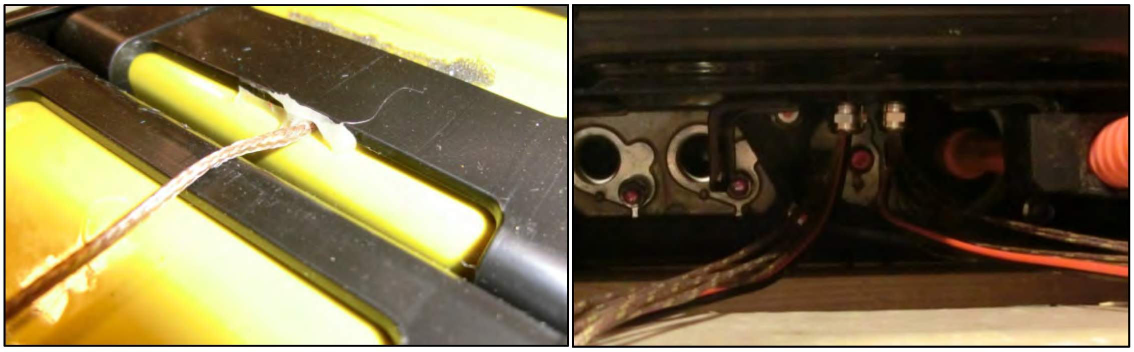

Figure 87 - Left: thermocouple attached to a cell. Right: pass-throughs for thermocouples.

8.3.11 Manufacturer B Vehicle Preparation Procedure

The Manufacturer B vehicle used to demonstrate SCTRI testing is shown in Figure 88. This vehicle had previously undergone a side impact crash per NCAP. There was little to no damage from the side impact on the battery pack, although it had been opened and re-sealed following crash testing.

The vehicle was prepared by removing unnecessary flammable material (Figure 89). Material was removed to limit the extent and intensity of any vehicle fire that might occur. However, flammable materials that might be important for understanding hazard to the occupant in the case of a propagating thermal runaway reaction were left in place. Flammables closest to the battery pack were left intact (e.g., carpets, bottom seats, etc.), as well as some materials at the top of the vehicle (e.g., portions of headliner), but many other materials were removed (e.g., dashboard and center console, seatbacks, headrests, door trim). To reduce the risk of projectiles during testing, all airbags that had not been deployed during the previous crash test were removed.

Thermocouples were installed in various remaining flammable materials, including seat cushions, carpets, and the headliner. They were also installed to measure air temperatures at occupant head locations.

A photoelectric smoke alarm (First Alert P1000) was installed on the center of the dashboard to detect the presence of particulate inside the cabin. A probe for gas sampling was installed through the roof at the location of the driver's head.

To seal the cabin and allow measurement of gases that might enter from a thermal runaway reaction, windows that had been rolled down or were broken were covered with 0.010" clear plastic film.

The RESS was then mounted and bolted to the underside of the vehicle.

Figure 88 - Side impact Manufacturer B vehicle used for SCTRI testing.

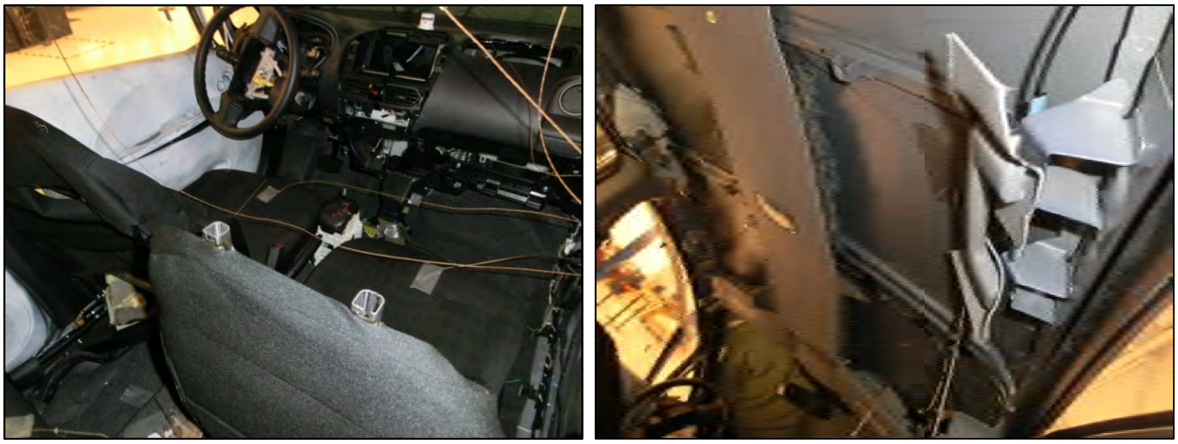

Figure 89 - Manufacture B vehicle interiors after flammables removal.

8.3.12 Manufacturer B Vehicle Preconditioning

At the test site, the vehicle was loaded into a thermal chamber to be preconditioned to 25°C. After a 6-hour soak, the pack was at 25±5°C. The vehicle was removed from the conditioning chamber and placed at the testing location.

8.3.13 Manufacturer B SCTRI Test Execution

The vehicle was set on cinderblocks and the tires were removed (for safety and flammability reasons).

Thermocouples and the gas sensor were connected to data logging equipment.

Video and data recording were started. A stopwatch was also started.

Once there was confirmation that video was being recorded and data signals were being properly logged, power was applied to the installed heater (120 V, 1.9 A, 228 W, as determined from cell-level testing).

The vehicle was observed and audible or visible signs of a thermal runaway reaction were noted.

Once the initiating thermal runaway reaction was observed with an audible noise and a visual indication of gas escape from the pack, power to the heater was switched off.

Video and data were left recording until all thermocouple temperatures were decreasing and below 60°C.

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

The handheld insulation meter indicated 0.0 MΩ of isolation and the voltmeter indicated that the service disconnect busbar was approximately 120 V above the vehicle potential. A dielectric withstand test was attempted, but the 7.5 mA maximum current was achieved at 0.0 kV, indicating that the loss of isolation had a very low resistance. The 1-hour power supply test was attempted, but after making the connections, the voltage reading was slightly negative and the current value was at the saturation value, indicating that too much current was flowing even without the power supply providing additional voltage. The test was aborted to avoid over-current damage to the power supply.

8.3.14 Manufacturer B SCTRI Test Results

The SCTRI test with the Manufacturer B vehicle and RESS was conducted successfully. A summary of the results is provided in Table 10. Single cell thermal runaway initiation occurred after 11 minutes and 17 seconds. There was an audible popping noise followed by emission of a large amount of smoke from the underside of the vehicle (Figure 90). One minute later, the smoke alarm that was mounted on the dashboard inside the cabin was triggered. Approximately 10 minutes later the next cell underwent thermal runaway. Subsequent cells underwent thermal runaway in 4-5 minute intervals (Figure 91). A total of eight cells underwent thermal runaway during the test. The battery pack was allowed to sit for almost 3 hours after the last thermal runaway occurred as the remaining cells cooled. There was no ignition of flammable gases.

Figure 92 shows the temperature measurements inside the battery pack. After 11 minutes a large temperature spike can be seen from T0, attached to the initiator cell, indicating that the initiator cell underwent thermal runaway. Meanwhile, small temperature spikes can be seen from thermocouples on neighboring cells as the hot runaway gases pass over them. After the first cell went into runaway, temperatures at T1, attached to the neighboring cell started to climb, until that cell underwent thermal runaway. As subsequent cells that did not have thermocouples attached to them underwent thermal runaway reactions, small temperature spikes were measured by more remotely located thermocouples.

During the events, the battery cover was primarily heated above the initiation location (Figure 93). The cover exterior temperature peaked approximately 50 minutes after the initiating cell underwent thermal runaway. Inside the cabin, the rear carpet reached a peak temperature just below 40°C approximately 50 minutes after the initiating cell underwent thermal runaway (Figure 94). This was the only area in the cabin to show any significant increases in temperature.

Gas composition measurements from inside the cabin at approximately driver head level are shown in Figure 95. The oxygen, methane, and carbon monoxide concentration as well as the percentage of the LEL (Lower Explosive Limit) were measured. Almost immediately after the first cell underwent thermal runaway, there was increase in the carbon monoxide concentration and %LEL. Carbon monoxide levels increased almost immediately to over 400 ppm. As a reference, the Occupational Safety and Health Administration (OSHA) ceiling limit[4] for CO is 200 ppm. The carbon monoxide concentration and %LEL spikes closely follow the timing of the cell thermal runaway reactions runaways. During the time of the 7th and 8th runaway, there is a noticeable drop in the oxygen concentration and an increase in the methane concentration. The %LEL, methane, and carbon monoxide reached maximums of 16%, 0.6%, and 1520 ppm, respectively. The oxygen concentration dropped from 20.9% to 20.5%. After the last cell went into runaway, the levels of %LEL, methane, and carbon monoxide started to decrease.

Isolation measurement attempts after SCTRI testing showed that battery isolation to the enclosure had been severely compromised as a result of the cell thermal runaway reactions that occurred.

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

Table 10 - Summary of Manufacturer B SCTRI Testing Results

Pre-Test	Pack Voltage	365 V nominal[5]
	Isolation – 1000 V handheld insulation resistance meter	Measurement not possible[5]
	Dielectric withstand voltage – hipot tester	Measurement not possible[5]
Test	Time to thermal runaway of initiating cell	11 minutes 27 seconds
	Energy ratio for cells in parallel	0.25
	Indication of initiation of thermal runaway	Audible sound, subsequent release of smoke from the battery pack

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[4] The ceiling limit is the maximum concentration which a person may be exposed to at any time.

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

	Time to cabin smoke alarm activation	12 minutes 28 seconds
	Time to 2nd thermal runaway reaction	21 minutes 11 seconds
	Indication of 2nd thermal runaway	Audible sound, subsequent release of smoke from the battery pack
	Time to 3rd thermal runaway reaction	26 minutes 6 seconds
	Indication of 3rd thermal runaway	Audible sound, subsequent release of smoke from the battery pack
	Time to 4th thermal runaway reaction	31 minutes 10 seconds
	Indication of 4th thermal runaway	Audible sound, subsequent release of smoke from the battery pack
	Time to 5th thermal runaway reaction	38 minutes 59 seconds
	Indication of 5th thermal runaway	Audible sound, subsequent release of smoke from the battery pack
	Time to 6th thermal runaway reaction	43 minutes 57 seconds
	Indication of 6th thermal runaway	Audible sound, subsequent release of smoke from the battery pack
	Time to 7th thermal runaway reaction	49 minutes 3 seconds
	Indication of 7th thermal runaway	Audible sound, subsequent release of smoke from the battery pack
	Time to 8th thermal runaway reaction	53 minutes 27 seconds
	Indication of 8th thermal runaway	Audible sound, subsequent release of smoke from the battery pack
	Time to flaming combustion	No ignition of combustibles
Post- Test	Pack voltage	Accurate measurement was not possible due to burned string of cells
	Isolation – 1000 V handheld insulation resistance meter	0.0 MΩ between the negative service disconnect terminal and enclosure
	Dielectric withstand voltage – hipot tester	7.5 mA current limit was exceeded at 0.0 kV - large loss of isolation
	Isolation testing power supply maximum current	Test aborted
	Time to thermal runaway of additional cells	N/A (test aborted)
Final	Isolation – 1000 V handheld insulation resistance meter	N/A (test aborted)
	Dielectric withstand voltage – hipot tester	N/A (test aborted)

Figure 90 - Left: smoke starting during first runaway. Right: peak smoke emission during the first runaway.

Figure 91 - Darkest smoke during the seventh runaway.

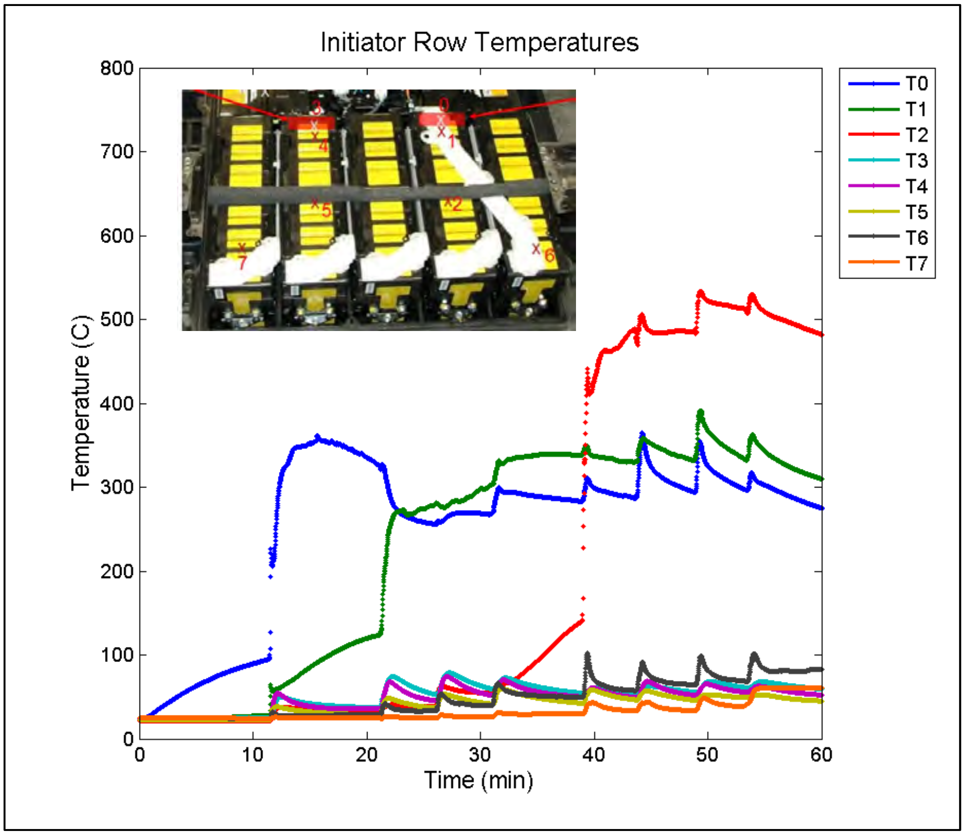

Figure 92 - Temperatures near the initiation location.

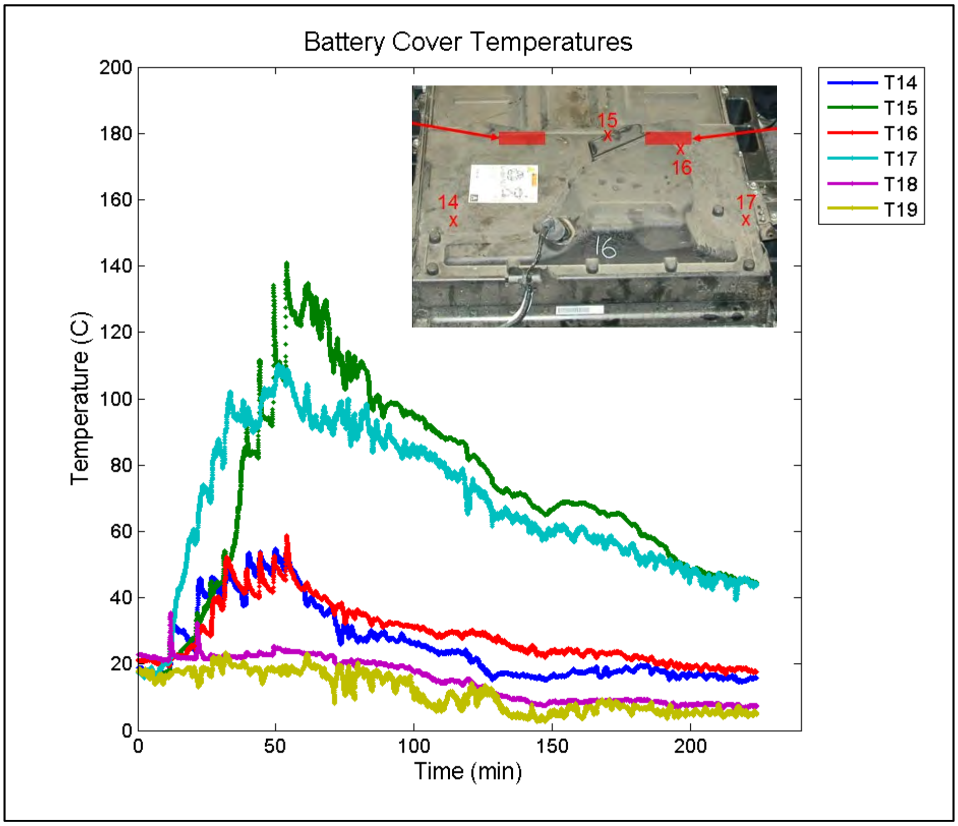

Figure 93 - Battery cover temperatures.

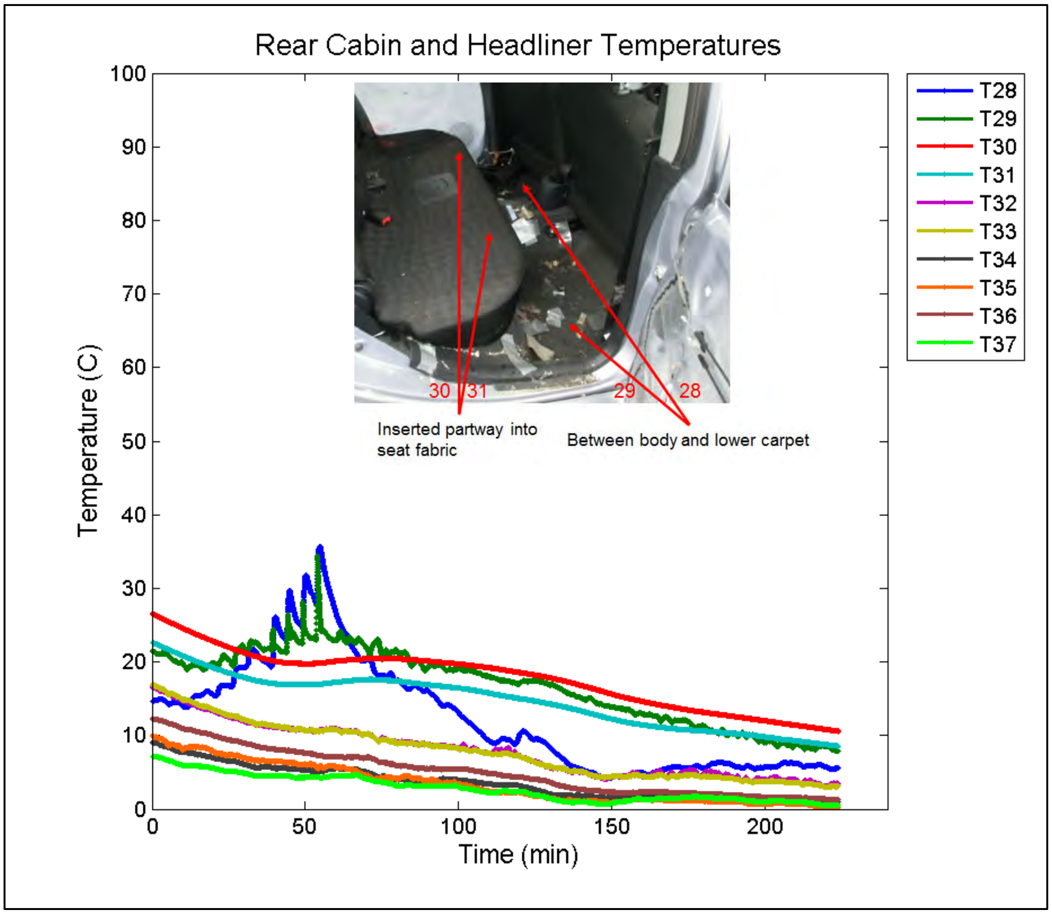

Figure 94 - Rear cabin and headliner temperatures.

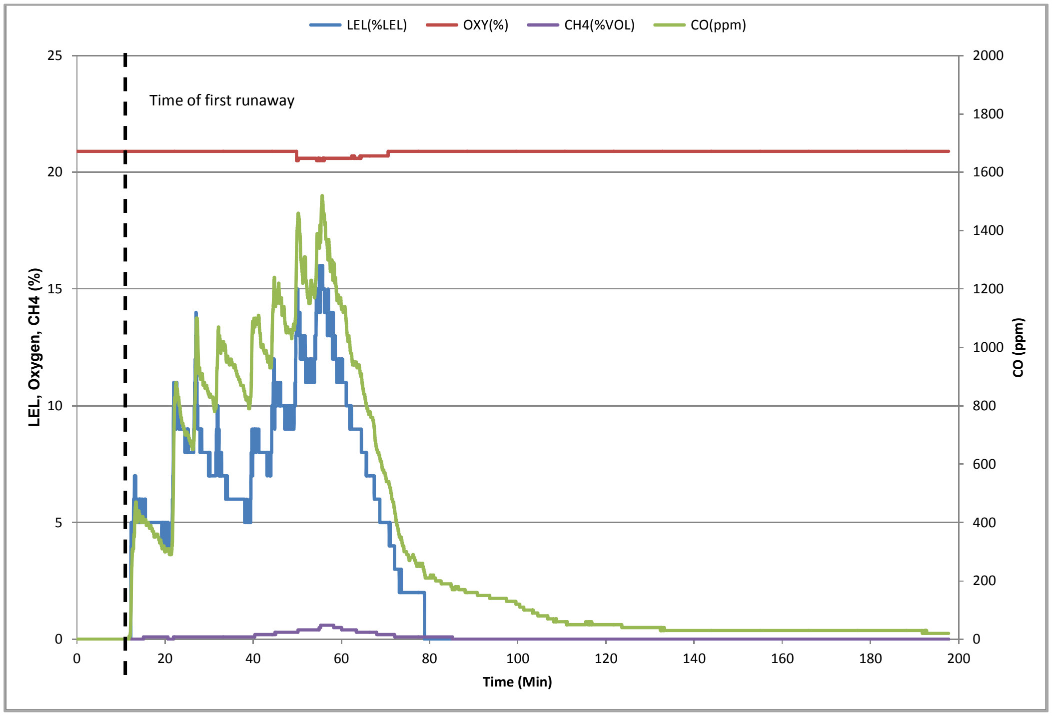

Figure 95 - Manufacturer B SCTRI testing; cabin air composition measurements.

8.3.15 Manufacturer C: RESS Contains Pouch Cells

The RESS from Manufacturer C consisted of a unit that was mounted to the floor of the vehicle. Within the RESS, modules were arranged in groups of four pouch cells. The modules were arranged in various groupings throughout the pack (Figure 96).

For this vehicle, a large film heater single cell initiation method was selected. A description of the selection process and rational for selection of this method can be found in Sections 8.1.9 and 8.1.10. Verification testing of the selected cell initiation method was completed with two module configurations. The results of this testing are described in Sections 8.2.9 through 8.2.11.

8.3.16 Manufacturer C SCTRI Test Specific Equipment:

- Off-the-shelf film heater: 4” x 6” polyimide heater (McMaster-Carr Part #35475K753).
- Pass-throughs: Liquid-tight cord grips (McMaster-Carr Part #6907K9).
- Thermocouple DAQ: Data Translation MEASUREPoint DT8874.
- Smoke detector: First Alert P1000 Detector.
- Gas sensor: MultiRAE Lite Multi-Gas Detector, configured to measure oxygen, methane, carbon monoxide and % of LEL.

8.3.17 Manufacturer C RESS Preparation Procedure

The Manufacturer C vehicle was subjected to a frontal crash test per NCAP. The resulting damage, however, disabled the onboard charging system. Thus, the battery pack was charged after it was removed from the vehicle. Because the communication protocols for the battery management system were unknown, the integrated sense voltage leads could not be used to monitor full pack charging. Instead, modules were removed from the battery pack in groups. Each group of modules was instrumented with sense leads at every module terminal and charged with the test laboratory’s charger and battery management system. The pack was charged to 100% SOC in accordance with the manufacturer’s specifications.

Due to the strong adhesive sealant, the battery pack was opened using pry tools and hammers. The cover suffered minor local deformations as shown in Figure 97, but these were flattened and the cover was later resealed with generous application of sealant.

The cell thermal runaway initiation location was chosen to be the most likely to result in propagation of thermal runaway. A module in the center of the rear stack was selected as a worst-case initiation location (Figure 96), since it would be in close thermal contact with a large number of contiguous cells and offer the greatest chance for propagating across air gaps. Since the initiation method involved a large flat heater, a cell at the edge of a module was used for initiation. Placing the heater between cells in a module would likely heat them both and potentially initiate thermal runaway in two cells rather than one. This initiation method had been subjected to verification testing (Section 8.2.9).

Figure 98 shows the heater installation. After pack opening and selective bus bar removal, the rear stack of 24 modules was taken out. Two modules were removed from this stack and one edge of the sheet metal case was folded up for access. The 4” x 6” heater pad had its adhesive backing removed, and then was slid between the cell and the insulator. The case was then folded back flat. A second module was prepared as an auxiliary initiator in case the first initiator failed to achieve thermal runaway.

Thermocouples were applied as shown in Figure 99. Each thermocouple bead was wrapped in polyimide tape to provide electrical insulation from module components and ensure that there would not be a safety hazard if bare thermocouple leads were to come into electrical contact. Each taped thermocouple bead was inserted between the center two cells of each module as indicated in Figure 99. Implanting the sensors inside modules shielded them from transient heating due to the flow of hot gas from nearby thermal runaway reactions. The leads were routed out through liquid-tight pass-throughs, which had been threaded into tapped holes in the flange containing the HV connector and sealed with an O-ring.

The pack was re-sealed as in Figure 100, which shows the generous application of Three Bond RTV sealant in place of the original cover adhesive that had been peeled away during opening and was no longer tacky. A sufficient amount of Three Bond was used to fill any imperfections in the outer edge of the cover, which had been locally deformed during removal. The sealant was allowed a week to dry before testing continued.

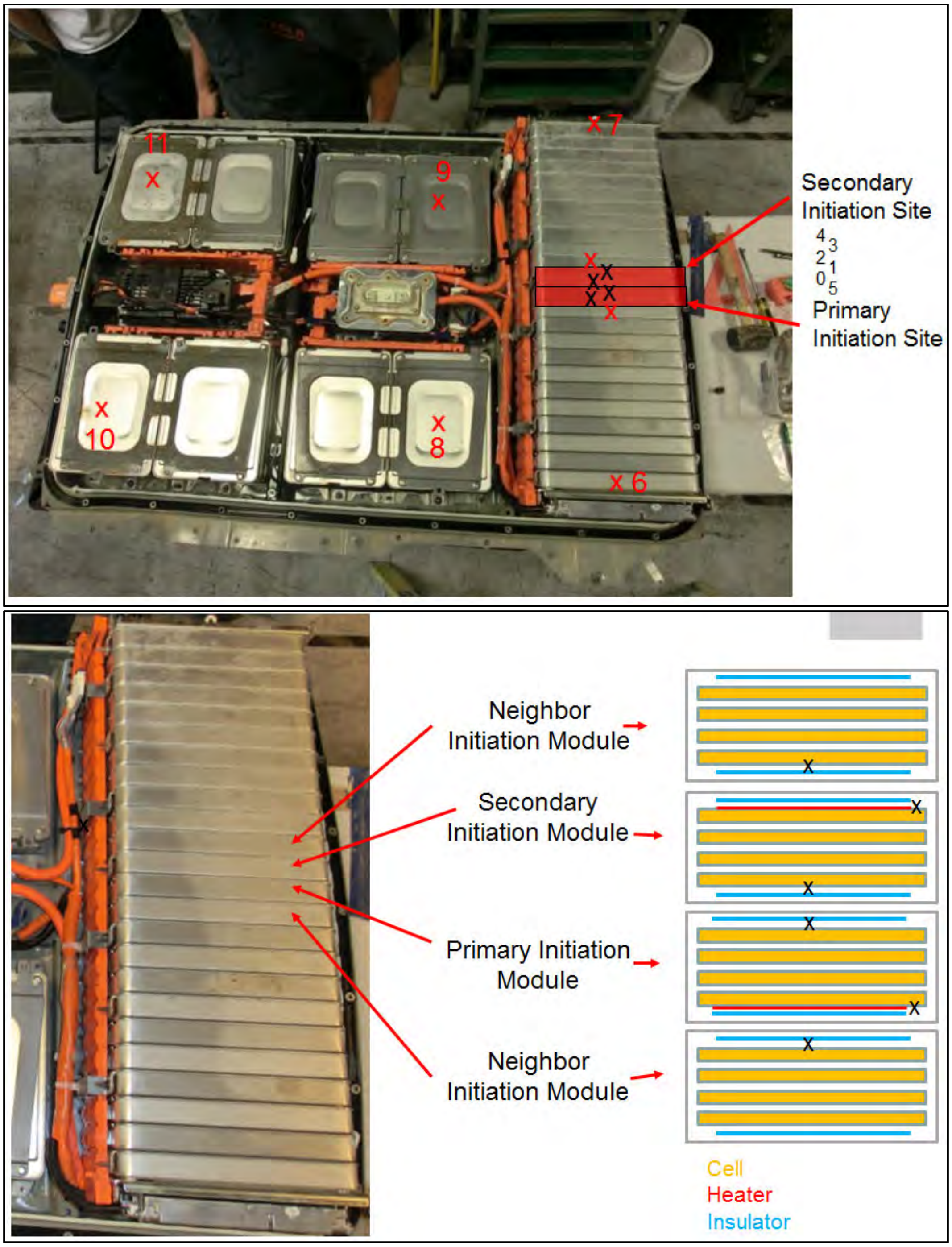

Figure 96 - The thermocouple and heater map for the pouch cell battery pack. For TCs 8-11, the top module in the stack was instrumented. Except where indicated, TCs are between the two center cells in the module.

Figure 97 - The cover after removal from the battery pack.

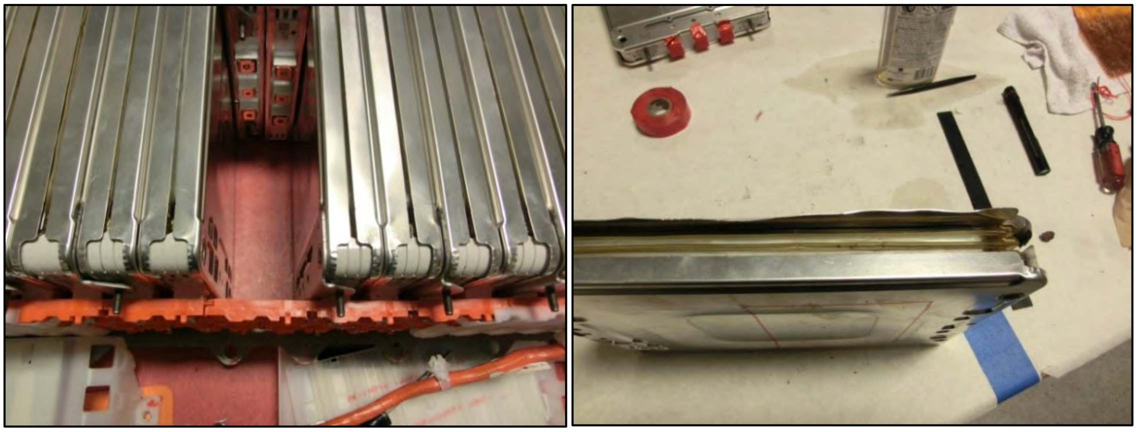

Figure 98 - Left: modules were removed from the center of the rear stack. Right: A flap of the sheet metal case was folded up for heater installation access. Red marker on the bottom case indicates the projection of the heater pad.

Figure 99 - Left: plastic strip used between the center two cells in a module to install a thermocouple. Right: all thermocouples routed through the pack, exiting through grommets, and the pack with a bead of sealant applied around the perimeter.

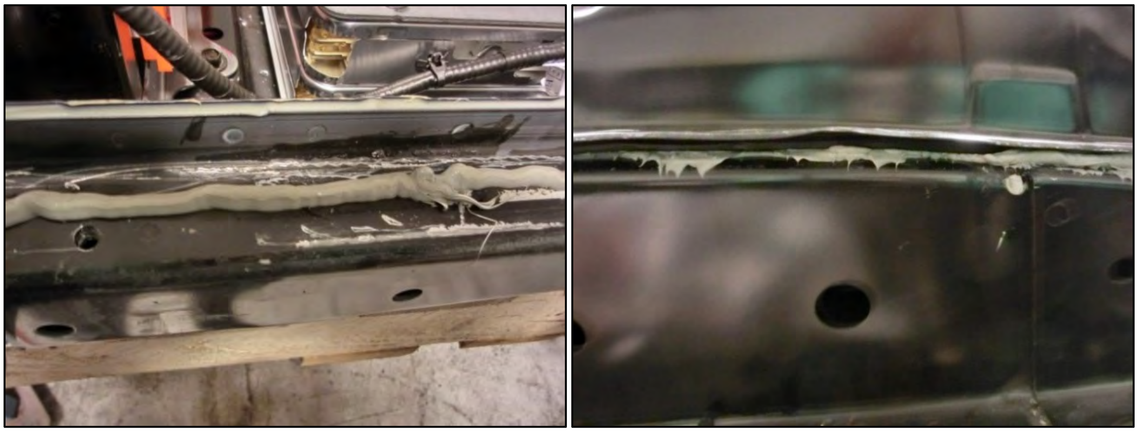

Figure 100 - Left: the generous silicone bead applied to the perimeter of the battery pack to compensate for the missing adhesive. Right: squeeze-out filling local deformations in the cover.

8.3.18 Manufacturer C Vehicle Preparation Procedure

The Manufacturer C vehicle used to demonstrate SCTRI testing is shown in Figure 101. This vehicle had previously undergone a frontal crash per NCAP. There was little to no damage from the impact on the battery pack, although it had been opened and re-sealed following crash testing.

The vehicle was prepared by removing unnecessary flammable material (Figure 102). Material was removed to limit the extent and intensity of any vehicle fire that might occur. However, flammable materials that might be important for understanding hazard to the occupant in the case of a propagating thermal runaway reaction were left in place. Flammables closest to the battery pack were left intact (e.g., carpets, bottom seats), as well as some materials at the top of the vehicle (e.g., portions of headliner), but many other materials were removed (e.g., dashboard and center console, seatbacks, headrests, door trim). To reduce the risk of projectiles during testing, all airbags that had not been deployed during the previous crash test were removed.

Thermocouples were installed in various remaining flammable materials (e.g., seat cushions, carpets, and the headliner). They were also installed to measure air temperatures at occupant head locations.

A photoelectric smoke alarm (First Alert P1000) was installed on the center of the dashboard to detect the presence of particulate inside the cabin. A probe for gas sampling was installed through the roof at the location of the driver's head.

To seal the cabin and allow measurement of gases that might enter from a thermal runaway reaction, windows that had been rolled down or were broken were covered with 0.010" clear plastic film.

The RESS was mounted and bolted to the underside of the vehicle.

Figure 101 - The Manufacturer C frontal crash vehicle used for the test.

Figure 102 - The Manufacturer C vehicle with thermocouples installed and many flammable materials removed.

8.3.19 Manufacturer C Vehicle Preconditioning

Once transported to the test site, the vehicle was loaded into the thermal chamber to be preconditioned. After a 24-hour soak, the pack had reached 35°C. The vehicle was removed from the thermal chamber and allowed to sit in the 5°C outdoor environment for 2 hours to cool to 30°C.

8.3.20 Manufacturer C SCTRI Test Execution

The vehicle was set on cinderblocks and the tires were removed (for safety and flammability reasons).

Thermocouples and the gas sensor were connected to data logging equipment.

Video and data recording were started. A stopwatch was also started.

Once there was confirmation that video was being recorded and data signals were being properly logged, power was applied to the installed heater (120 V, 1.8 A, 216 W, as determined from cell-level testing).

The vehicle was observed and audible or visible signs of a thermal runaway reaction were noted.

Once the initiating thermal runaway reaction was observed (with audible noise and a visual indication of gas escape from the pack, see Figure 103), power to the heater was switched off.

Video and data were left recording until the event was deemed complete, for this test when all cells were consumed and the resulting fire was subsiding.

8.3.21 Manufacturer C SCTRI Test Results

The SCTRI test with the Manufacturer C vehicle and RESS was conducted successfully. A summary of the results is provided in Table 11.

Single cell thermal runaway initiation occurred after 6 minutes 55 seconds of heating (Figure 103). There was an audible noise followed by emission of smoke from the underside of the vehicle. Three additional thermal runaway events occurred in the module over the next 90 seconds. About 7 minutes later, a similar event (four thermal runaway reactions in rapid succession) was observed. Additional events occured at increments between 2 minutes and 5 seconds, resulting in a steady smoke stream exiting the rear of the vehicle. At approximately 20 minutes, the smoke alarm within the vehicle activated. At 23 minutes, ignition of the vent gases occurred (Figure 104). Burning vent gases ignited the vehicle rear bumper. The cell runaways and vehicle fire continued, and flames were observed inside the cabin at approximately 28 minutes. The fire continued until approximately 50-55 minutes after heater initiation (Figure 105).

Temperature histories of the initiator modules are shown in Figure 106. Thermocouple T0, which was attached to the initiator cell, measured a steady rise in temperature as the nearby cell surface was also heated (T5) until approximately 7 minutes when the first cell underwent a thermal runaway reaction and the temperature rose sharply. Thermocouple T1, which was mounted on the opposite side of the initiating module, measured relatively cool temperatures until a thermal runaway reaction occurred in the neighboring cell at approximately 8 minutes. The temperature measured by thermocouples T5 mounted in a module adjacent to the initiating cell shows limited conductive heat input from the initiator module until thermal runaway occurs. After the initial thermal runaway reaction, the temperature at T5 (and also at T2), rose sharply to 300°C. Temperatures plateaued at 300°C for a number of minutes before thermal runaway propagated to adjacent modules. Temperature measurements at T3 indicate thermal runaway occurred within this module before propagating to the next module; the temperature spike measured by T4 lags that of T3 by a number of minutes.

Figure 107 shows temperatures measured at further distances from the initiating cell. These temperatures remained low even after ignition of the vent gases at approximately 23 minutes, suggesting that thermal runaway was still progressing throughout the RESS. Within 40 minutes of the test, all corners of the RESS had undergone thermal runaway. Thermocouple signals became noisy late in testing (i.e., after the vehicle had ignited and burned for a number of minutes). This was likely due to electrical noise in the DAQ.

An alternative means of summarizing the temperature data is provided in Figure 108, which shows the time each instrumented cell/module went into runaway. In the first module, the time differential was approximately one minute (i.e., 7:15 to 8:15), while the neighbor module propagated from its first to last cell in 30 seconds (i.e., 15:30 to 16:00). As the event progressed and more surfaces became hot, the preheating of each module became more intense and evenly distributed. Thus, propagation within each module and from module to module became faster.

Figure 109 through Figure 113 show the vehicle temperature measurement data. Sensors on the battery cover recorded temperature peaks directly above the initiation site within minutes of thermal runaway intitiation. Subsequent thermal peaks followed as sections of the battery pack became heated by thermal runaway reactions. Vehicle interior temperature measurements showed that the vehicle cabin (carpets, seats, headliner, and air temperatures near occupant head levels) remained cool until ignition of vent gases occurred and flames entered the cabin at approximately 28 minutes.

Gas composition measurements from inside the cabin at approximately driver head level are shown in Figure 113. The oxygen, methane, and carbon monoxide concentrations as well as the percentage of the LEL were measured. A few minutes after the first thermal runaway reaction occurred, but before the second module underwent thermal runaway, the concentration of carbon monoxide inside the cabin started to increase. Shortly after each module underwent thermal runaway, there was a step change in cabin carbon monoxide concentration; it exceeded 200 ppm at the time of vent gas ignition, approximately 3 minutes after the smoke alarm activated. For reference the Occupational Safety and Health Administration (OSHA) ceiling limit[6] for CO is 200 ppm.

No post-test isolation measurements were performed since the entire battery pack had been consumed.

Table 11 - Summary of Manufacturer C SCTRI Testing Results

Pre-Test	Pack Voltage	398 V nominal[7]
	Isolation – 1000 V handheld insulation resistance meter	Measurement not possible[7]
	Dielectric withstand voltage – hipot tester	Measurement not possible[7]
Test	Time to thermal runaway of initiating cell	6 minutes 55 seconds
	Indication of initiation of thermal runaway	Audible sound, subsequent release of smoke from the battery pack
	Time to cabin smoke alarm activation	20 minutes 36 seconds
	Time to 2nd thermal runaway reaction	7 minutes 5 seconds – multiple cells within initiating module
	Indication of 2nd thermal runaway	Audible sound, subsequent release of smoke from the battery pack

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[6] The ceiling limit is the maximum concentration of a chemical to which a person may be exposed to at any time.

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

	Time to 3rd thermal runaway reaction	14 minutes 45 seconds through 16 minutes – multiple cells within a module
	Indication of 3rd thermal runaway	Audible sound, subsequent release of smoke from the battery pack
	Time to 4th thermal runaway reaction	18 minutes 51 seconds
	Indication of 4th thermal runaway	Audible sound, subsequent release of smoke from the battery pack
	Time to 5th thermal runaway reaction	21 minutes 40 seconds through 23 minutes – multiple cells within a module
	Indication of 5th thermal runaway	Audible sound, subsequent release of smoke from the battery pack
	Additional thermal runaway reactions	Multiple thermal runaway reactions were audible after vehicle ignition – reactions continued until vehicle was consumed.
	Time to flaming combustion	23 minutes
Post- Test	Pack voltage	N/A (battery was entirely consumed / burned)
	Isolation – 1000 V handheld insulation resistance meter	N/A (battery was entirely consumed / burned)
	Dielectric withstand voltage – hipot tester	N/A (battery was entirely consumed / burned)
	Isolation testing power supply maximum current	N/A (battery was entirely consumed / burned)
	Time to thermal runaway of additional cells	N/A (battery was entirely consumed / burned)
Final	Isolation – 1000 V handheld insulation resistance meter	N/A (battery was entirely consumed / burned)
	Dielectric withstand voltage – hipot tester	N/A (battery was entirely consumed / burned)

Figure 103 - Top left: 7:07, beginning of first runaway. Top right: 8:16, fourth cell runaway in the first module. Bottom left: 14:47, second module begins after lull. Bottom right: 22:10, several modules into event, ignition coming soon. Between runaways, the smoke cleared and resembled the top left image.

Figure 104 - Top left: 23:41, ignition has occurred. Top right: 26:44, rear flames continue. Bottom left: 28:22, flames inside cabin. Bottom right: 30:53, many internal flames.

Figure 105 - Top left: 31:56, tallest flames. Top right: 36:04, vehicle fire concentrated in front. Bottom left: 46:03, event subsiding. Bottom right: 51:03, event nearing completion.

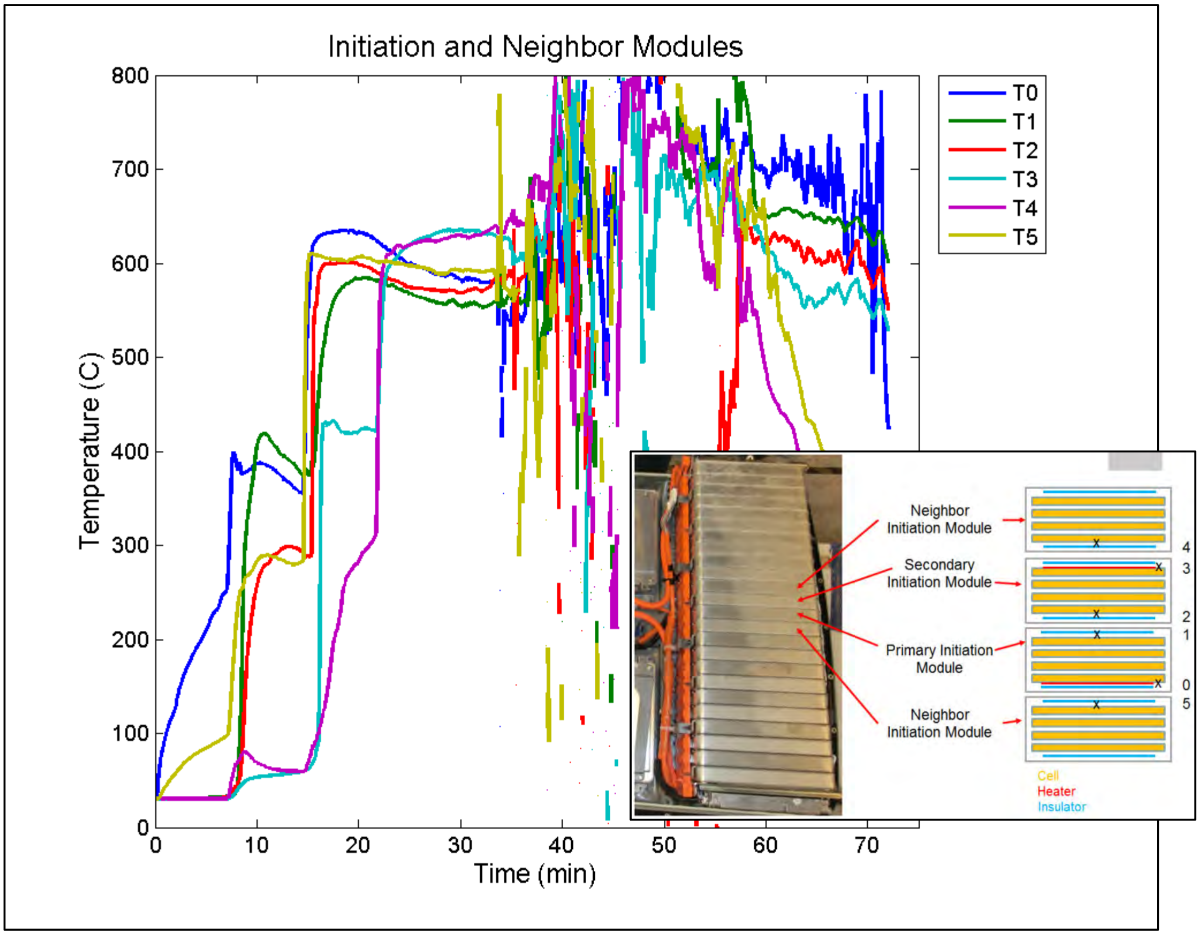

Figure 106 - Manufacturer C SCTRI test; temperatures near initiating modules.

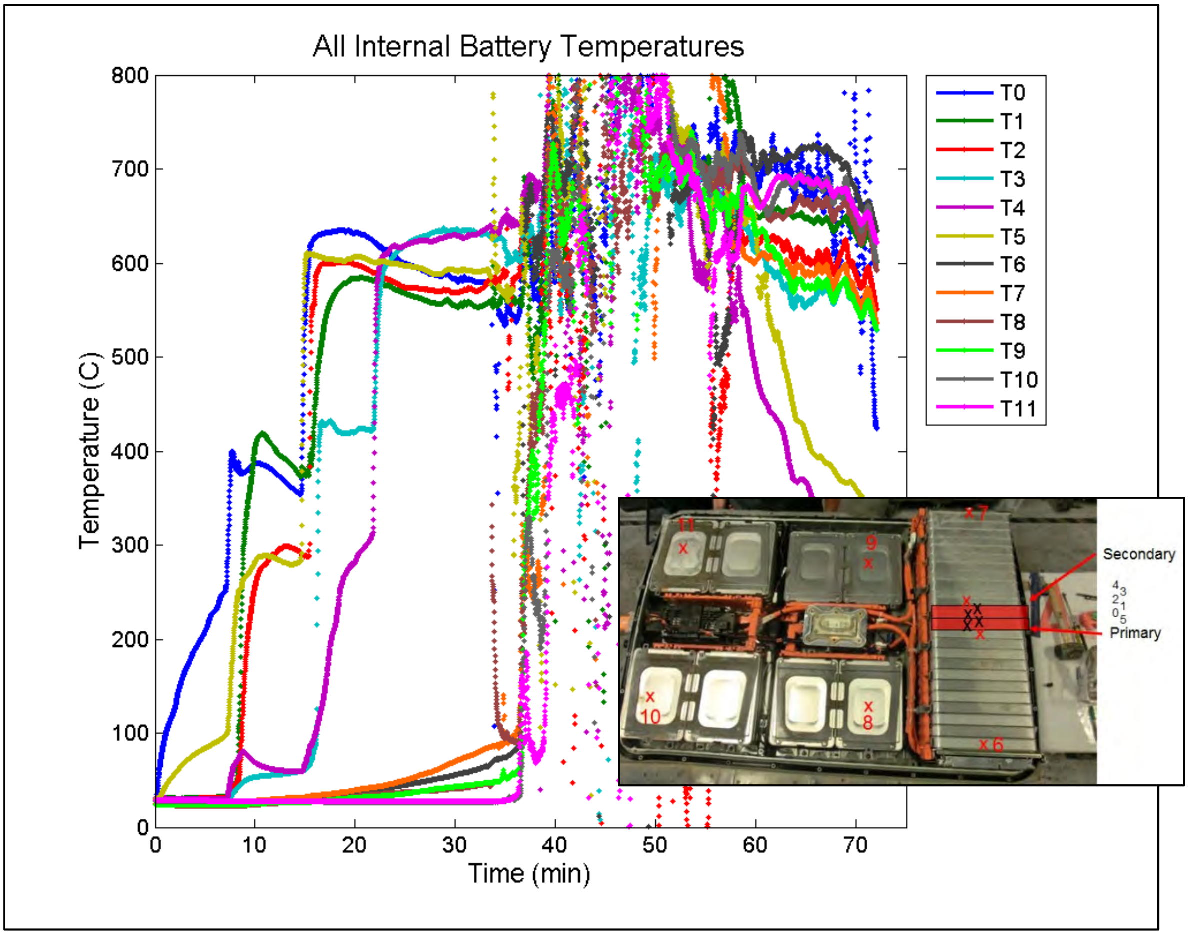

Figure 107 - Manufacturer C SCTRI test; all internal battery temperatures.

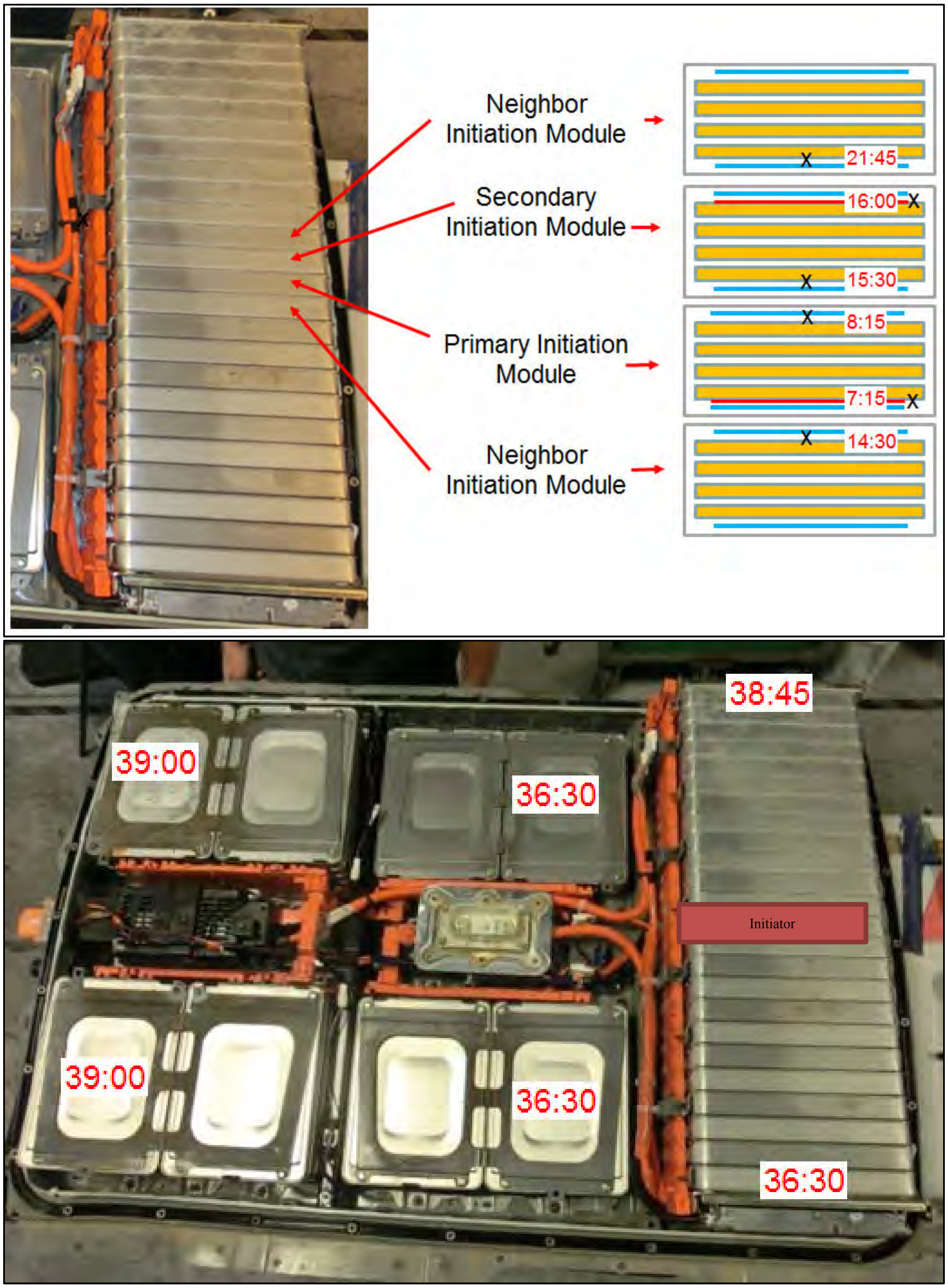

Figure 108 - Estimates of runaway time from temperature traces (mm:ss), rounded to the nearest 0:15.

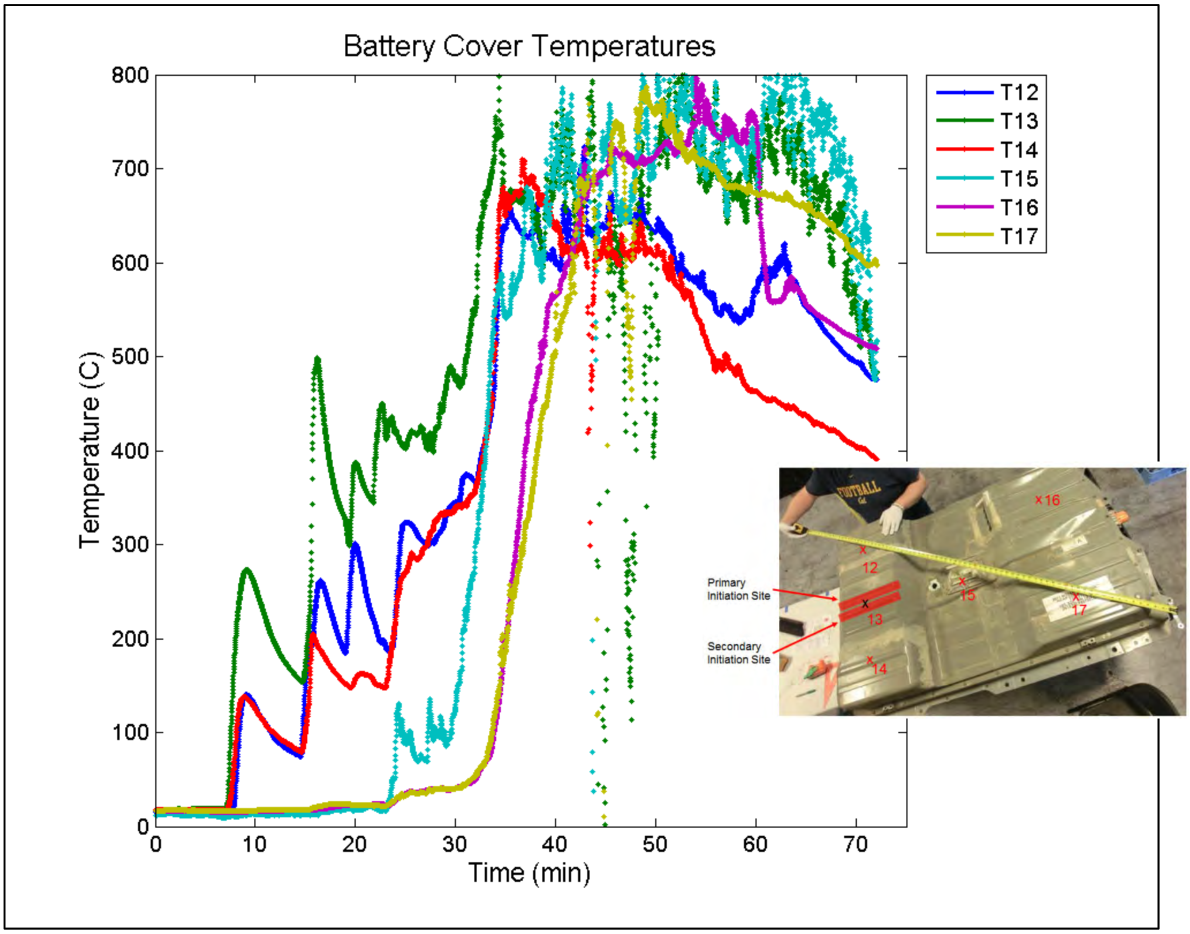

Figure 109 - Manufacturer C SCTRI test; temperatures measured on the battery cover.

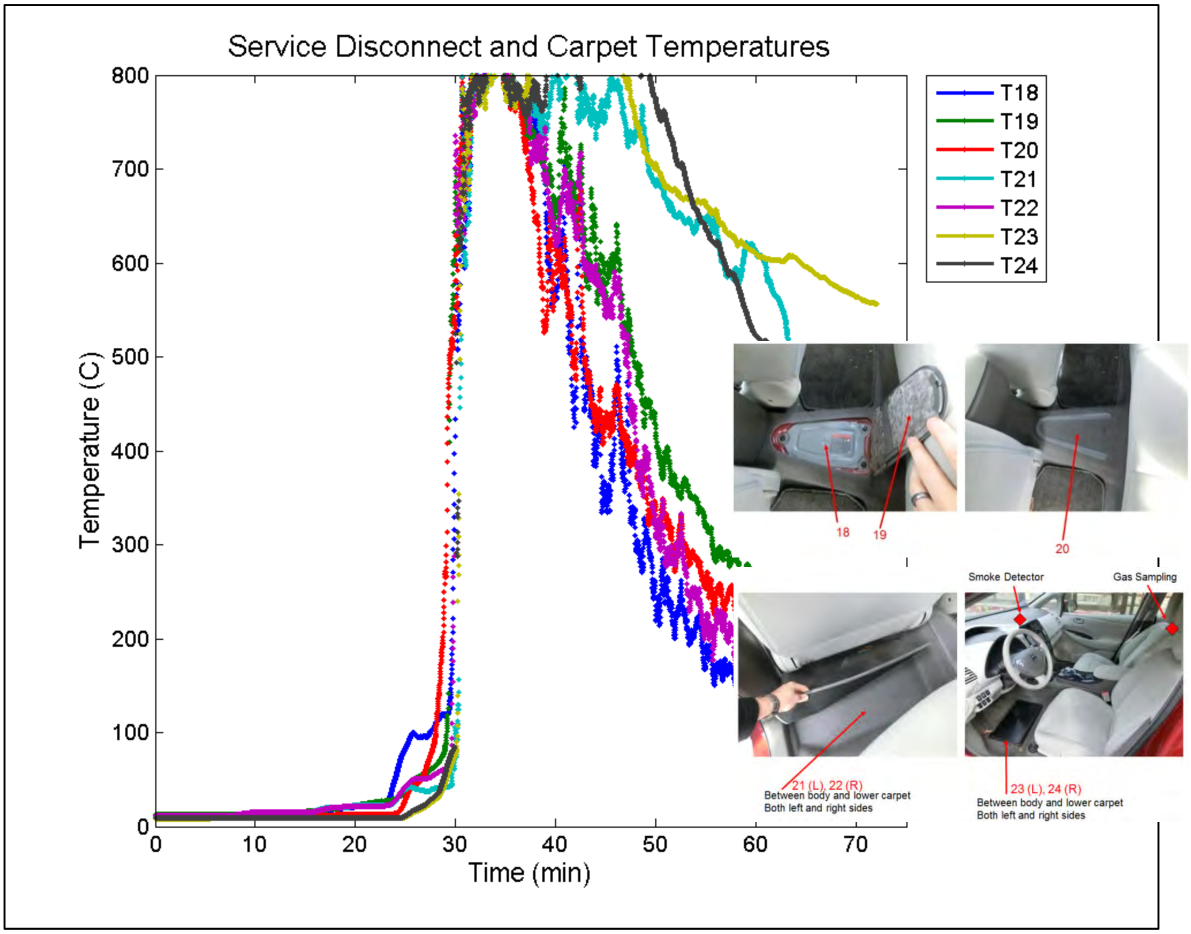

Figure 110 - Manufacturer C SCTRI test; temperatures measured at the vehicle service disconnect and at floor level.

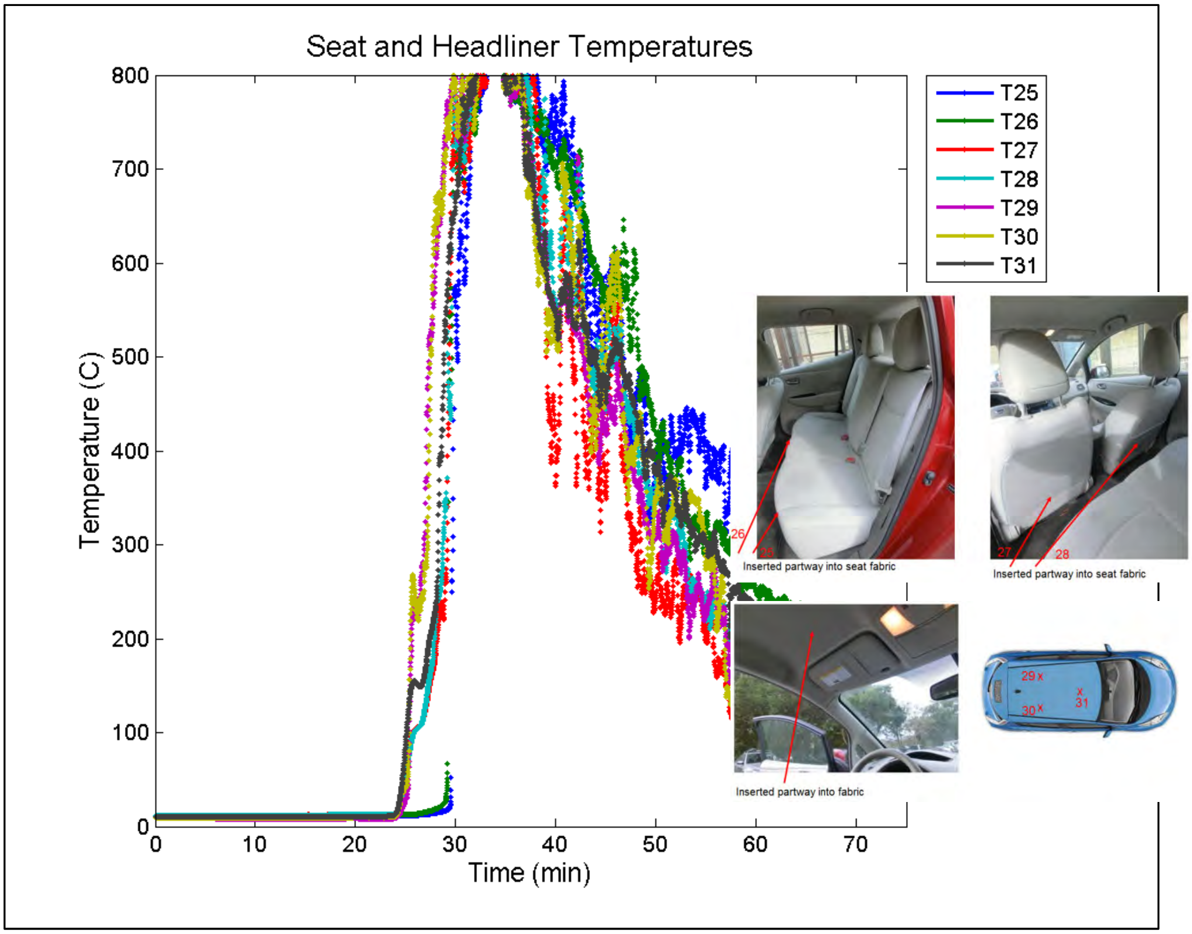

Figure 111 - Manufacturer C SCTRI test; temperatures measured at seat level and at the headliner.

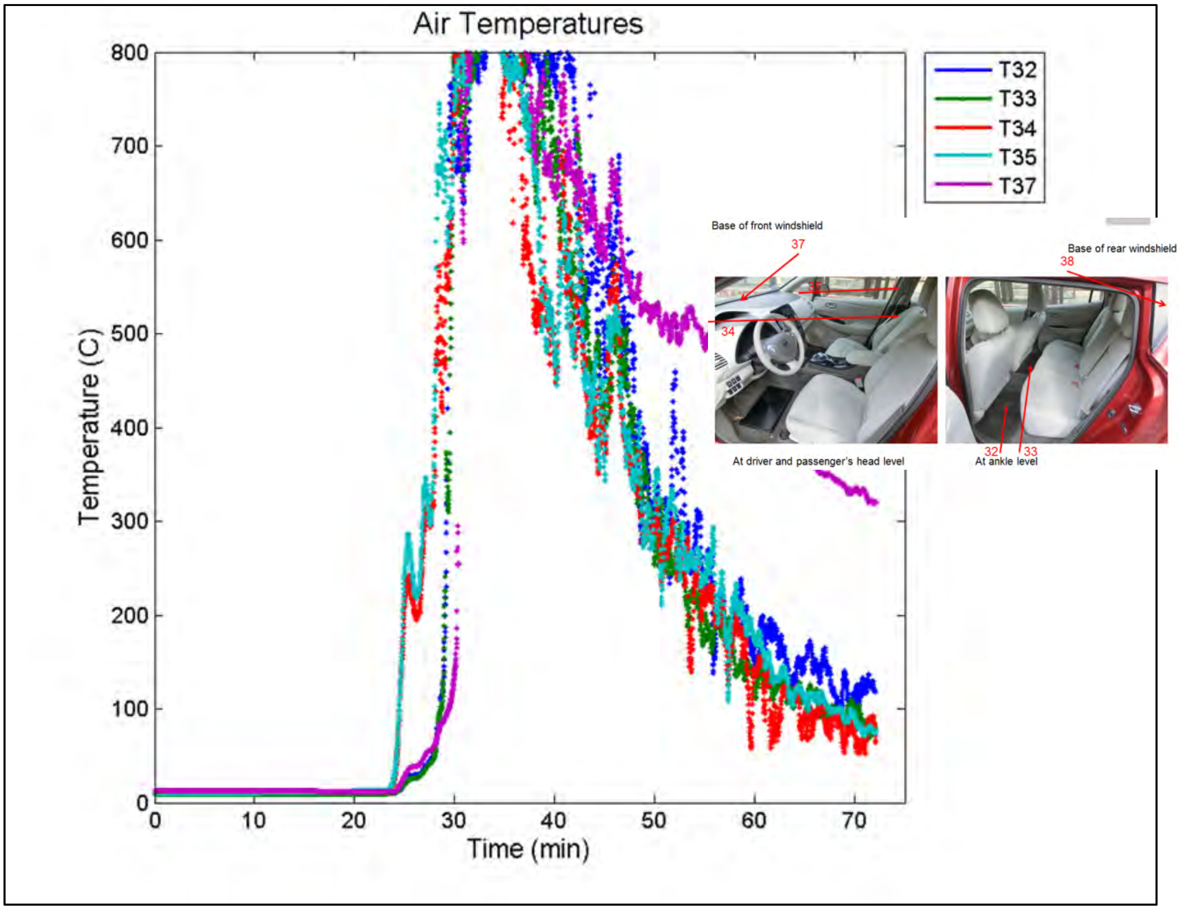

Figure 112 - Manufacturer C SCTRI test; air temperatures measured at driver head level.

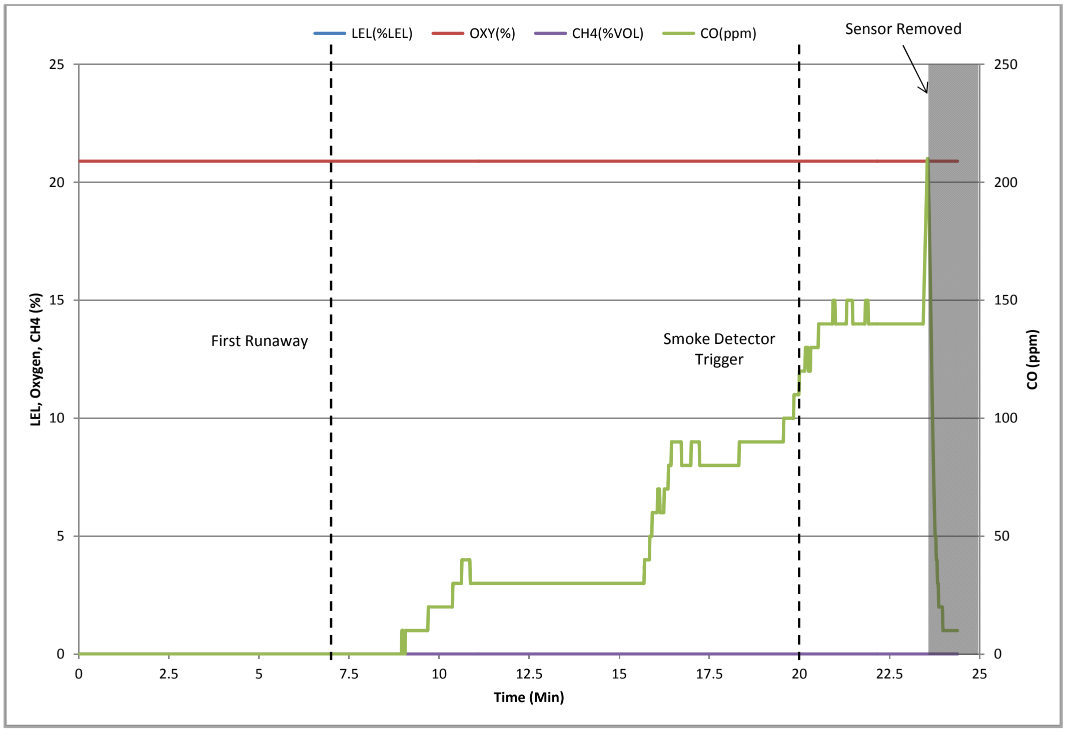

Figure 113 - Manufacturer C SCTRI test cabin gas composition measurements; the sensor was removed once vehicle ignition occurred.

VEHICLE SEQUENTIAL TESTING AFTER 5000 MILE PRECONDITIONING

Test Procedure and Report

1. PURPOSE

Electric propulsion in a Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV), and Electric Vehicle (EV) platform relies on Rechargeable Energy Storage Systems (RESSs), commonly referred to as batteries. However, 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 that are different than those associated with an internal combustion engine. Among the potential risks, RESS cells and associated components can experience aging mechanisms that can affect their performance, including safety. The intent of this test procedure is to ensure that the RESS components, particularly the battery cells, are robust enough to meet typical safety performance requirements after an aggressive aging sequence.

2. SCOPE

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

The test procedure described is composed of three parts:

- 5000 mile preconditioning;
- Sequential testing; and
- Destructive discharge.

The 5000 mile preconditioning sequence (Section 7.1) is used to age the RESS with real-world electrical, mechanical, thermal, and environmental loads.

Sequential testing (Sections 7.2 through 7.9) evaluates the robustness of the RESS after preconditioning. The tests were selected based on widely accepted standards that represent commonly experienced single point failure modes. They were placed in a specific sequence with the intention of revealing and exacerbating a range of potential RESS failure modes while also reducing the number of required test articles. The RESS should be able to withstand the applied abuse and failure conditions without posing a hazard to the vehicle occupant or the surrounding environment.

Following sequential testing, a destructive discharge procedure is provided (Section 7.10) to remove stranded energy from a RESS if it is damaged such that discharge using vehicle systems or external electrical means is not possible.

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 the Society of Automotive Engineeres (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 Government Publications

Available from https://www.gpo.gov/fdsys/granule/CFR-2012-title40-vol19/CFR-2012-title40-vol19-sec86-159-08.

- Code of Federal Regulations 40 CFR Parts 86.115 through 86.208 and Appendix C

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 Electrotechnical Commission (IEC): 446 Main Street 16th Floor, Worcester, MA 01608, Tel: 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

Retrieved from the Institute of Electrical and Electronic Engineers (IEEE) Standards Activities: 445 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-562-5527, www.standards.ieee.org.

- IEEE 1725 Standard for Rechargeable Batteries for Cellular Telephones

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

3.2.3 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 Battery 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: 617-770-3000, www.nfpa.org.

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

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

3.2.5 NREL Publications

Retrieved from the National Renewable Energy Laboratory (NREL):
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.

3.2.6 UN Publications

Available from United Nations (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 UL Publications

Available from Underwriters Laboratories Inc. (UL): 333 Pfingsten Road, Northbrook, IL 60062-2096, Tel: 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 Standard for 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" https://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" http://www.prba.org/wpcontent/uploads/UL_Presentation.ppt.

3.2.8 Government Publications

Retrieved from: https://www.gpo.gov/fdsys/granule/CFR-2010-title49-vol2/CFR-2010-title49-vol2-sec173-185.

- 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 RESS aging sequence that is consistent with expected in-vehicle usage, but applied aggressively over a short period of time.

Active device

A device that contains or is connected to a component having an operating and non-operating state (e.g., an electric pump or resistance 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. It calculates and communicates battery status and state of function to the vehicle system for energy flow management. In the event of a system failure, the BMS can also open contactors and isolate the battery from the rest of the hybrid system.

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 RESS state of charge (SOC) may fluctuate, but on-average is maintained at a constant level while driving. For example, in an HEV, the internal combustion engine and associated generator may provide power to generally maintain the battery SOC during vehicle operation.

Charge Depletion Mode

An operating mode in which the RESS SOC may fluctuate, but on-average decreases while driving. Energy may also flow into the battery (e.g., from power generated by an internal combustion engine or regenerative braking), but it is generally discharged during this mode.

Charge Mode

A mode in which the RESS is able to accept charging power while 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 devices.

Curb Weight

The weight of a motor vehicle with standard equipment; maximum capacity of engine fuel, oil, and coolant; and, if so equipped, air conditioning and additional weight optional engine.

DC Link

An electrical interface to a high voltage bus on the vehicle or RESS that is used to introduce specific fault conditions for evaluation purposes. If the vehicle is equipped with an automatic disconnect that is physically contained within the RESS or direct current bus, the DC link shall be connected to the electrical bus on the traction side of the automatic disconnect. If the vehicle has 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.

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, thus 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”. The Occupational Safety and Health Administration (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 on 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.

Environmental Protection Agency-US06 (EPA-US06)

A simulated discharge cycle with high acceleration and speed based on Appendix C of 40 CFR Part 86; the required operational precision is specified in 86.159-08. For the purposes of this procedure, only the cycle speed and time requirements are applied.

EV: Electric Vehicle

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

Explosion

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

Fire

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

Gross Vehicle Weight Rating (GVWR)

The value specified by the manufacturer as the loaded weight of a single vehicle.

HEV: Hybrid Electric Vehicle (HEV)

An automobile type vehicle, powered by an internal combustion engine and an electric motor that draws stored energy from a rechargeable energy storage device for power assist.

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 (i.e., inserted into voids in the crystallographic structure of) or otherwise react with the cathode. The ions reverse direction during charging and are intercalated into the anode material.

Material Safety Data Sheet (MSDS)

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

Passive device

A device that performs its role simply due to its presence and material properties (e.g., a heat radiating fin).

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.

Rough Road (RR)

A driving test pattern that includes vertical and torsional input events.

Sequential Tests

A specified order of tests that are designed to evaluate the safety performance of a single RESS.

State of Charge (SOC)

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

Steady State

A condition where the RESS temperature remains within ±2°C for 30 minutes and the SOC remains within ±1% for 60 minutes. Alternatively, a steady state condition occurs when the rate of change in SOC over the previous hour indicates that discharging or charging will require more than 10 hours to complete.

Stranded Energy

Energy contained within a RESS that cannot be removed through a normal discharge (e.g., a damaged RESS).

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 0 V 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.

Utility Factor (UF)

A ratio of the number of miles driven under charge-depleting mode to the total number of miles driven. UF takes into account the 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. The 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.

Urban Dynamometer Driving Schedule (UDDS)

A simulated urban drive cycle based on Appendix C of 40 CFR Part 86; the required operational precision is specified in 86.115-78. For the purposes of this procedure, only the cycle speed and time requirements are 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.

Wide Open Throttle + Rough Road (WOT + RR)

A driving test pattern which includes WOT accelerations, decelerations that engage the vehicle regenerative braking system, and traverses through vertical and torsional input test roads.

5. GENERAL TEST REQUIREMENTS

5.1 General Precautions

5.1.1 Conducting preconditioning and sequential testing on any vehicle or RESS is potentially hazardous. The individuals conducting testing should become familiar with the operation and potential hazards associated with the test vehicle, including its various fuel systems and RESS; appropriate personal protective equipment (PPE) should also be assembled. A Material Safety Data Sheet (MSDS) or Emergency Response Guide (ERG) may provide relevant information.

5.1.2 RESSs are heavy, but they 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 Preparing a RESS for sequential testing after preconditioning, or examining 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 always be handled carefully.

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 completely burn.

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

5.1.4.2 The testing facility should be prepared to mitigate the hazards of an unintentional ignition of emitted flammable gases. Potential methods of mitigation include flammable gas monitoring, remotely activating 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 smoke or fire detectors and remotely activating appropriate fire suppression systems.

5.1.4.4 A vehicle fire can produce a significant quantity of smoke. If an air scrubbing system is used, the filters should be appropriate for vehicle burn testing and the specific cell chemistry implemented in the RESS. System filters should be protected from ignition. If testing is 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 (including possible rekindling) have ceased.

5.1.5 It is often difficult to visually determine if 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 for personnel to decide when it is appropriate to approach a test article. 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 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

5.2.1.1 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 (e.g., voltmeters) and electrical safety PPE (e.g., high voltage gloves) should be used if high voltage connections are to be handled.

5.2.2.2 When using high current and voltage DC power supplies, there is a chance of hazardous electrical shock; any produced spark may ignite flammable materials or gases. A safe clearance from the vehicle should always be maintained while DC power supplies are in use for testing.

5.2.3 Destructive Discharge

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

5.2.3.2 Preparing a RESS for destructive discharge can involve exposure to high voltage systems. Test personnel should use PPE and engineering controls that are appropriate for the mitigation of high voltage hazards.

5.2.3.3 Should a salt bath method for destructive discharge be selected, the testing agency should follow the guidance in Section 7.10, and be prepared for the described hazards.

5.3 Safety Requirements

5.3.1 The testing agency must develop a specific safety plan for each vehicle under test, including a list of required PPE. This safety plan should be based on information provided by the manufacturer regarding vehicle architecture, RESS chemistry and pack 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

5.4.1 Preconditioning facility and equipment requirements:

5.4.1.1 A test track facility allowing wide open throttle (WOT) operation.

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

5.4.1.3 A dynamometer for high speed testing.

5.4.1.4 A mountain driving route(s) that must include elements such as steep ascents and descents and mountain road corners (Table 1). The route(s) shall include at least eight ascents/descents greater than 500 m (more than 1600 ft.) and another four with more than 1,000 m (more than 3200 ft.). It must include at least 2000 corners and should be on public roads.

Table 1 - Required Mountain Route Drive Elements

Mountain Route Driving Element	Minimum Test Plan
Mountain Road Mileage	300 miles
Ascents & descents > 500 m	8 ascents & 8 descents
Ascents & descents > 1,000 m	4 ascents & 4 descents
Mountain road corners	2000 corners

5.4.1.5 A gravel road route must produce appreciable dust throughout the drive. It shall be at least 10 miles long.

5.4.1.6 A city route must 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. It shall be at least 90 miles long.

5.4.1.7 Chargers that encompass both low rate charging (typically Level 1) and the highest possible charging rate compatible with the test article (e.g., a Level 3 charger or an extreme fast charger that enables a 200-mile range within 10 minutes of charging a depleted battery).

5.4.1.8 Thermal chamber for high temperature and high humidity charging of the vehicle. The chamber must be capable of producing a 45°C / 95% relative humidity environment.

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

5.4.1.10 A rain booth for simulating heavy rain conditions. The booth should be capable of applying at least 500 GPM of water divided into at least 125 GPM per side (top, bottom, right, and left).

5.4.1.11 A drizzle booth for vehicle charging under drizzle conditions. The booth should be capable of applying at least 10 GPM of water on the top side.

5.4.1.12 A salt spray applicator.

5.4.1.13 A car wash booth.

5.4.1.14 A 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 Chargers that encompass both low rate charging (typically Level 1) and the highest possible charging rate compatible with the test article (e.g., a Level 3 charger or an extreme fast charger that enables a 200-mile range within 10 minutes of charging a depleted battery).

5.4.2.2 A dynamometer facility with a thermal chamber(s) capable of maintaining temperatures between -20 and 40°C for extended 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 and data logging equipment, including:

- Voltage probes
- Current probe
- Thermocouples
- Interface for the 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 the DC link (Section 7.3):

- An over-discharge resistor or load to be attached to the DC link.

- An overcurrent source for applying an overcharge to the RESS through the DC link. It should be a power supply capable of producing a maximum current consistent with regenerative braking or a faulting charger at near full charge (i.e., the maximum 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 overcharge to the RESS through the DC link. It should be a power supply capable of producing a maximum voltage consistent with regenerative braking or a faulting charger. 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.

- A 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 (if necessary).

5.4.4 The facility must be capable of proper disposal or recycling of damaged/burned RESSs or other byproducts of testing in compliance with environmental regulations.

5.5 Test Equipment Calibration

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

- Type of equipment, manufacturer, model number, etc.
- Measurement range
- Accuracy
- Calibration interval
- Type of standard used (calibration traceability of the standard must be evident)

6. TEST PROCEDURE

6.1 Test Type

6.1.1 Preconditioning is designed to accelerate RESS aging using aggressive drive profiles for at least 5000 miles. It is a non-destructive test for the full-scale vehicle.

6.1.2 Sequential testing is designed to verify that the RESS and fundamental safety systems continue to function after significant preconditioning and not pose a significant hazard to the vehicle's occupants or the surrounding environment. It is a potentially destructive test for the full-scale vehicle.

6.1.3 At the end of sequential testing, the RESS may require a destructive discharge per the manufacturer's instructions or using a salt bath method as described in Section 6.6.8.

6.2 Device Under Test

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

6.3 Test Guidelines

6.3.1 Testing will require one vehicle with its RESS. For preconditioning, the durability vehicle and RESS should be new (i.e., less than one year old, and with less than five charge/discharge cycles applied to the RESS). After preconditioning, the aged RESS may need to be placed in a new test vehicle for sequential testing. The RESS may be provided by the manufacturer or vehicle OEM with the necessary modifications for conducting sequential testing.

6.4 Test Parameters

6.4.1 Preconditioning test parameters are:

- RESS cell beginning test temperature: As specified
- Beginning pack state: Cells less than one year old and accumulated <5 electrical cycles
- Beginning SOC of the RESS: 99% to 100% of the maximum normal operating SOC
- Beginning energy of vehicle: Fully charged RESS; full fuel tank (HEV, PHEV)[1]

6.4.2 Sequential test parameters are:

- RESS cell beginning test temperature: As specified
- Beginning pack state: At least 5000 miles of preconditioning or equivalent
- Beginning SOC of the RESS: As specified
- Beginning energy of vehicle: As specified

6.5 DUT Preconditioning

6.5.1 The preconditioning sequence is performed on the full vehicle and RESS to prepare it for sequential testing.

6.5.2 Vehicle Preparation for Preconditioning

6.5.2.1 Vehicle Components: record the vehicle model and trim type.

6.5.2.2 Vehicle Mass: the manufacturer should provide a vehicle design weight and ballasting diagram, along with a recommendation on the percent-of-test-distance that should be applied for each ballasting level and configuration. This is typically based on the expected vehicle use profile. If unavailable, test weights can be divided as shown in Table 2.

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

Table 2 - Vehicle Weight Conditions for Preconditioning Testing

Vehicle Weight Condition	% of Test Distance	Relative Weight
Curb weight	5%	Curb weight
GVWR	95%	GVWR

6.5.2.3 Tire Pressure: set vehicle tire pressure (cold) to the manufacturer's specification.

6.5.2.4 Vehicle Posture: ensure that the vehicle posture is ±3 mm of the manufacturer's specification at the test weight.

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[1] See Section 4.0

6.5.2.5 Wheel Alignment: check wheel alignment to ensure it is within the manufacturer's specification. Note that the alignment shall be performed at the designated curb weight. If the wheel alignment is out of specification, adjust it to the mean level and record data.

6.5.2.6 Safety Inspection: perform a pre-test safety inspection as detailed in a RESS-specific test plan.

6.5.3 Facility Preparation for Preconditioning

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

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

6.5.4 Preconditioning Sequence

6.5.4.1 A variety of preconditioning events should be applied to the test vehicle (see Section 7.1); the minimum requirements are summarized in Table 3.

6.5.4.2 Preconditioning events can be applied in various ways. A recommended sequence is shown in Table 4.

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

6.5.4.4 Should the vehicle suffer a mechanical problem unrelated to the RESS during preconditioning (e.g., a flat tire), the vehicle should be repaired and testing should resume. Record any such events along with the associated repair times.

Table 3 - Summary of Vehicle Preconditioning Event Minimum Requirements

Preconditioning Event	Minimum Required
Wide Open Throttle (WOT) + Rough Road (RR) mileage	2500 miles
High Speed mileage	2000 miles
Mountain Route mileage	400 miles
City Route mileage	90 miles
Gravel road mileage	10 miles
Mountain Route corners	2000 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 hours
Hot Charge	20 hours
Drizzle Charge	20 hours
Car Wash	2
Salt Spray	1
Rain Booth hours	0.5 hours
HV Pack Removal & Reinstall	1
Normal 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	**5000**
Maximum Total Test Distance	**10,000**

Table 4 - Sequencing of Preconditioning Events

Phase	Driving Profile / Event	Percent of Total Cycles	Charging
1	WOT + RR	50%	Mix of highest level and low level ambient temperature charging
2	High Speed Driving	50%	
3	Salt Spray Exposure		Mix of highest level and low level ambient temperature charging, cold chamber charging, hot chamber charging, and drizzle chamber charging
	WOT + RR	12.5%	
	Mountain Route	100%	
	Gravel Road Route	100%	
	Car Wash		
	WOT + RR	12.5%	
	City Route	100%	
	Rain Exposure		
4	High Speed Driving	50%	
5	Car Wash		
	RESS Removal and Installation		
	WOT + RR	25%	

6.5.4.5 WOT + RR Driving Pattern

The wide open throttle plus rough road (WOT + RR) driving pattern contains a mixture of WOT accelerations, decelerations that engage the vehicle regenerative braking system, and traverses through vertical and torsional input test roads. Elements of the WOT + RR pattern are described in Table 5.

The speed profile is shown in Table 6; WOT accelerations are conducted to V, where V is 80% of the vehicle's maximum speed or 80 mph, whichever is lower. Approximately half of the planned WOT + RR drive cycles are conducted in the first phase of preconditioning (see Table 5). Additional WOT + RR drive cycles are sequenced in Phases 3 and 5.

WOT + RR patterns are conducted in rapid succession, with periodic pauses as needed for charging and/or refueling:

- An EV should be recharged when the SOC reaches 20±10%.
- An HEV should be refueled as needed.
- A PHEV should be subjected to electrical charging consistent with its utility factor (UF). The number of miles driven in charge depletion mode shall be at least the UF multiplied by the planned WOT + RR miles. SAE J2841 defines utility factors for vehicles in the US fleet.

Table 5 - WOT + RR Pattern Elements for Preconditioning

Pattern Elements	**Distance**
Total pattern length	1.5 miles (maximum)
Vertical input pattern (e.g., rope road, see Figure 21)	0.05 miles (minimum)
Torsional input pattern (e.g., wave road, see Figure 22)	0.05 miles (minimum)

Table 6 - WOT + RR Speed Profile for Preconditioning

Speed*	**Operation**	**Number per Pattern**
0 − V	WOT	1
V − 40 mph	Full regenerative braking and light brake application	1
40 mph − V	WOT	1
V − 20 mph	Full regenerative braking and medium brake application	1

*** V is either 80% of vehicle max speed or 80 mph, whichever is lower.**

6.5.4.6 High Speed Driving

The high speed driving pattern involves extended high speed operation combined with 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 highest speed used in this test is 85% of the vehicle's maximum specification or 80 mph, whichever is higher. Table 7 shows the required driving pattern elements; the test distance is 100 miles. An example high speed profile that meets these requirements is shown in Figure 1. Approximately half of the planned high speed drives shall be conducted in rapid succession in Phase 2 of preconditioning (see Table 4). The remaining high speed drives shall be sequenced in Phase 4.

High speed driving patterns are conducted in rapid succession, with periodic pauses for charging and/or refueling:

- An EV should be recharged as needed, between test patterns or planned pauses within the test pattern if the vehicle has less than a 100-mile range.
- An HEV should be fueled at the beginning of each test pattern.
- A PHEV should be charged to 100% SOC at the beginning of every test pattern.

Table 7 - High Speed Driving Pattern Elements

Event	Per 100 Miles
Test Distance	100 miles
60% of max speed	20 miles
70% of max speed	15 miles
80% of max speed	15 miles
85% of max speed, but not less than 80 mph	50 miles

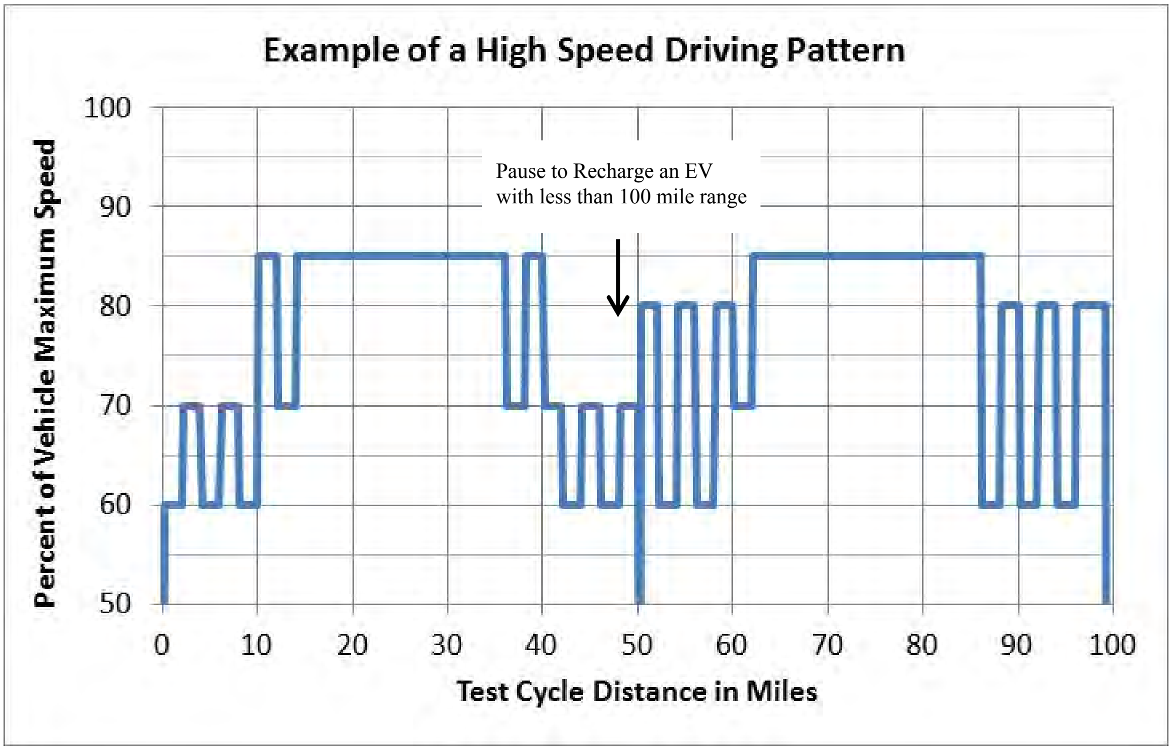

Figure 1 - Example of a high speed driving pattern for an EV.

6.5.4.7 Mountain route driving is sequenced in Phase 3 of preconditioning (see Table 4). The route must be on a public roadway and driven in a manner consistent with general traffic. It must include the minimum number of assents, descents, and corners described in Table 3. At least 400 miles of mountain route driving is required, but it can be divided in multiple sessions as needed within Phase 3.

6.5.4.8 Gravel route driving is sequenced in Phase 3 of preconditioning (see Table 4). This route must produce appreciable dust throughout the drive. At least 10 miles of gravel route driving is required, but it can be divided in multiple sessions as needed within Phase 3.

6.5.4.9 City route driving is sequenced in Phase 3, 4, or 5 of preconditioning (see Table 4). It must be conducted on a public roadway within a high density urban environment and driven in a manner consistent with general traffic. At least 90 miles of city route driving is required, but it can be divided in multiple sessions as needed.

6.5.4.10 Salt spray exposure is sequenced in Phase 3 of preconditioning (see Table 4). Approximately 1 L of 3% NaCl solution, or equivalent, shall be applied evenly to all external surfaces of the test vehicle. The salt spray solution shall remain on the vehicle for at least two days before initiating a car wash, rain exposure, or drizzle chamber charge.

6.5.4.11 A car wash is sequenced in Phases 3 and 5 of preconditioning (see Table 4). It shall be conducted in a typical car wash booth.

6.5.4.12 Rain exposure is sequenced in Phase 3, 4, or 5 of preconditioning (see Table 4). It is conducted within a rain booth that applies at least 500 GPM of water, divided into 125 GPM per vehicle side (top, bottom, right, and left). A minimum of 0.5 hours of rain exposure is required, but it can be divided in multiple sessions as needed.

6.5.4.13 Ambient temperature charges are sequenced in all phases of preconditioning (see Table 4) and may be conducted with a range of charging systems; public chargers may be used as available. As specified in Table 3, more than 50% of charge time must be at the highest allowable level specified by the vehicle. The remaining charge sessions may be accomplished at any level.

6.5.4.14 Cold chamber charging is sequenced in Phase 3, 4, or 5 of preconditioning (see Table 3). It is conducted in a thermal chamber set at −30°C. The vehicle is placed in the chamber and the RESS is cooled to at least −10°C, or for a minimum of 6 hours, before charging is initiated. At least 20 hours of cold chamber charging is required, but it can be divided in multiple sessions as needed.

For an EV or PHEV, cold chamber charging must begin with the RESS at no more than 30% SOC. Charging must continue until normally terminated by the vehicle (i.e., at a fully charged state). If charging does not initiate, then the chamber temperature should be raised by 10°C. The vehicle should be allowed to thermalize to the new temperature for at least 6 hours and charging should be attempted again. Repeat this procedure until charging initiates. If charging has not terminated within 20 hours of initiation, it should be manually shutdown. After a cold charge session, the vehicle should be removed from the chamber and allowed to thermalize at ambient temperatures for at least 6 hours; it should then be fully charged at ambient temperatures. Ideally, ambient temperature should be 25±5°C.

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

6.5.4.15 Hot chamber charging is sequenced in Phase 3, 4, or 5 of preconditioning (see Table 3). It is conducted in a thermal chamber set at a minimum of 45°C / 95% relative humidity. The vehicle should be placed into the chamber and allowed to warm to at least 40°C, or for a minimum of 6 hours before charging is initiated. At least 20 hours of hot chamber charging is required, but it can be divided in multiple sessions as needed.

For an EV of PHEV, charging of the RESS shall begin at no more than 30% SOC. Charging must continue until normally terminated by the vehicle (i.e., at a fully charged state). If charging does not initiate, then the chamber temperature should be reduced by 10°C. The vehicle should be allowed to thermalize to the new temperature for at least 6 hours and charging should be attempted again. Repeat this procedure until charging initiates. If charging has not terminated within 20 hours of initiation, it should be manually shutdown. After a hot charge session, the vehicle should be removed from the chamber and allowed to thermalize at ambient temperatures for at least 6 hours; it should then be fully charged at ambient temperatures. Ideally, ambient temperature should be 25±5°C.

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

6.5.4.16 Drizzle chamber charging is sequenced in Phase 3, 4, or 5 of preconditioning (see Table 3). It is conducted within a drizzle chamber that applies at least 12 GPM of water to the top of the vehicle. At least 20 hours of drizzle chamber charging is required, but it can be divided in multiple sessions as needed.

For an EV of PHEV, charging shall begin with the RESS at no more than 30% SOC. Charging shall continue until normally terminated by the vehicle (i.e., at a fully charged state).

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

6.5.5 Sequential Testing Preparation Procedure

6.5.5.1 The vehicle and its RESS shall be photographed. Any anomalies shall be documented.

6.5.5.2 DC link equipment shall be prepared as specified in Section 7.3.

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

6.5.5.4 If the battery pack must be opened to install 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 insulation resistance meter. A testing agency may also choose to conduct a dielectric withstand test using a hipot tester.

6.5.5.5 After installation of experimental equipment, 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. Isolation measurements as per Section 6.6.3.7 should be made after pack closing to ensure that installed instrumentation and any necessary modifications have not significantly degraded the electrical isolation of the RESS. 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.

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

6.5.5.7 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.

6.5.5.8 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 (e.g., at locations within the cabin adjacent to the RESS). The location of all sensors shall be documented.

6.5.5.9 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.

6.5.5.10 The vehicle, as prepared for testing, shall be photographed.

6.6 Sequential Test Methodology

6.6.1 General Testing Procedures

6.6.1.1 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.

6.6.1.2 Assuming a fire occurs, 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.

6.6.1.3 Sensors should be installed to monitor and record RESS temperature, voltage, current, and SOC. These measurements may be logged using a data link established with the vehicle CAN bus. Otherwise, data logging should be configured to collect at least one measurement per second.

6.6.1.4 Any connectors to sensors should be sufficiently long for a data acquisition system to be located a safe distance from a vehicle undergoing a complete burn and remain intact. Data acquisition equipment may be protected from heat using shielding or insulation.

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

6.6.1.6 The initiation of temperature logging and video recording should be synchronized (e.g., 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.

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

6.6.2.1 If a RESS is thermally coupled to an active heater, use the manufacturer's recommendations to induce or simulate a failure that renders the heater inoperable (see Section 7.4). If the pack does not rely on heaters, or uses only passive heating, no action is required.

6.6.2.2 For a vehicle with only a charge depleting operational mode (i.e., an EV), determine the RESS maximum sustained discharge power load 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.

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

6.6.2.4 For a vehicle with charge sustaining operations modes (e.g., an HEV or PHEV), add sufficient fuel to fill the fuel tank to at least 50% of its total volume.

6.6.2.5 Place the vehicle with a failed RESS heating system on a dynamometer in a temperature controlled chamber at −20±2°C (see Section 0 for further discussion). The vehicle shall remain in the chamber for a sufficient time to thermally equalize (at least 6 hours). The chamber temperature shall be logged during the soak period.

6.6.2.6 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.

6.6.2.7 If an EV or PHEV is being tested, connect it to a charging system capable of supplying the vehicle's maximum allowable charge rate and attempt to charge. Allow normal charge termination, or terminate charging one hour after the vehicle reaches a steady state.

The RESS has reached steady state when temperature remains within ±2°C for 30 minutes and the SOC remains within ±1% for 60 minutes, or when the rate of change in SOC over the previous hour indicates that charging will require more than 10 hours to complete (see Section 0 for further discussion).

If an HEV is being tested, move to Section 6.6.2.8.

6.6.2.8 Immediately after charging is completed (i.e., within 10 minutes), disconnect the vehicle from the charging system, place the vehicle into drive, and begin cycling as defined below.

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 steady state.

For a vehicle with charge sustaining operational modes (HEV or PHEV), apply one UDDS discharge cycle, followed by one EPA-US06 discharge cycle. Repeat the alternating discharge cycles until the vehicle will no longer provide motive power from either the RESS or the alternate fuel source. Discharge cycles should be initiated in rapid succession, with no more than 5 minutes between the end of one discharge cycle and the beginning of the next cycle. If the vehicle is unable to provide the requested speed at low temperature, maintain the highest achievable speed for sufficient time to cover the designated distance before proceeding with the next step in the cycle profile sequence.

6.6.2.9 For an HEV, this test will terminate when discharge is complete, continue to Section 6.6.2.12.

6.6.2.10 For an EV or PHEV, immediately after discharge terminates (i.e., within 10 minutes), connect it to a charging system capable of supplying the vehicle's maximum allowable charge rate and attempt to charge. Allow normal charge termination, or terminate charging one hour after the vehicle reaches a steady state.

6.6.2.11 Terminate testing 24 hours after initiation (Section 6.6.2.7) regardless of how many test steps have been achieved.

6.6.2.12 Return the vehicle to 25±5°C and restore heating system functionality. Allow a sufficient time for the RESS to thermally equalize (at least 6 hours).

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

6.6.3.1 If a RESS is thermally coupled to an active cooling system, use the manufacturer's recommendations to induce or simulate a failure that renders the cooling system inoperable (see Section 7.5). If the pack does not rely on an active cooling system, no action is required.

6.6.3.2 For an EV or PHEV, charge the RESS at 25±5°C, until normal charge termination occurs (i.e., a fully charged state). For an HEV, complete a single UDDS discharge cycle at an ambient temperature of 25±5°C.

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

6.6.3.4 Place the vehicle with a failed RESS cooling system on a dynamometer in a temperature controlled chamber. The chamber shall be set to the manufacturer's specified maximum operating ambient air temperature, which shall be no less than 40°C (see Section 0 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 the soak period.

6.6.3.5 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.

6.6.3.6 Place the vehicle into drive and begin cycling as defined below.

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 defined in Section 6.6.2.2. Continue the discharge until the vehicle either reaches 5% SOC, no longer provides motive power, or one hour after it has reached steady state (see Section 4).

For a vehicle with charge sustaining operational modes (HEV or PHEV), apply one UDDS discharge cycle, followed by one EPA-US06 discharge cycle. Repeat the alternating discharge cycles until the vehicle will no longer provide motive power from either the RESS or the alternate fuel source. Discharge cycles should be initiated in rapid succession, with no more than 5 minutes between the end of one discharge cycle and the beginning of the next cycle. If the vehicle is unable to provide the requested speed at high temperature, maintain the highest achievable speed for sufficient time to cover the designated distance before proceeding with the next step in the cycle profile sequence.

6.6.3.7 For an EV or PHEV, immediately after discharge terminates (i.e., within 10 minutes), connect it to a charging system capable of supplying the vehicle's maximum allowable charge rate and attempt to charge. Allow normal charge termination, or terminate charging one hour after the vehicle reaches a steady state.

6.6.3.8 For an HEV or PHEV, refuel the vehicle (fill the fuel tank to 100% capacity).

6.6.3.9 Immediately after charging is completed (i.e., within 10 minutes) or after the vehicle has been refueled, disconnect the vehicle from the charging system and repeat Section 6.6.3.6.

6.6.3.10 Terminate testing 24 hours after initiation (Section 6.6.3.6) regardless of how many test steps have been achieved.

6.6.3.11 Return the vehicle to 25±5°C and restore cooling system functionality. Allow a sufficient time for the RESS to thermally equalize (at least 6 hours).

6.6.4 Vehicle RESS Over-Discharge

6.6.4.1 Connect the RESS to the DC link (see Section 7.3). Installation may require removing and re-installing the RESS from the vehicle.

6.6.4.2 For an EV or PHEV, discharge the vehicle RESS to 10±5% SOC. For an HEV or PHEV, remove fuel from the fuel tank so that it is 5±1% full.

6.6.4.3 Chock the vehicle to prevent rolling or creep.

6.6.4.4 Testing can be performed without a thermal chamber, provided that the ambient air does not inhibit discharge of the RESS.

6.6.4.5 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.

6.6.4.6 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 (see Figure 5 in Section 7.3). Allow the RESS to discharge at a power load of 1 kW.

Continue to discharge for a maximum of 8 hours or until terminated by the RESS (this may result in a DC link voltage of 0 V).

Isolate the discharge resistor in the DC link (i.e., open the discharge circuit).

6.6.4.7 If the vehicle does not have separate driving and charge modes (i.e., an HEV), proceed to Section 6.6.4.9.

6.6.4.8 Charge Mode Over-Discharge Attempt:

This test is only applicable to vehicles with separate driving and charging modes (i.e., an EV or PHEV). Connect the vehicle to a Level 1 charger[2] and recharge the RESS to the lowest operational SOC at which vehicle will enter a drive mode using energy from the RESS only (as specified by the manufacturer).

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

Install the over-discharge resistor into the terminals of the DC link connection box, and close the positive and negative terminal switches (see Figure 5 in Section 7.3). Allow the RESS to discharge at a power load of 1 kW.

Continue to discharge the RESS for a maximum of 8 hours or until terminated by the RESS (this may result in a DC link voltage of 0 V).

6.6.4.9 Isolate the discharge resistor in the DC link (i.e., open the discharge circuit).

6.6.5 Vehicle RESS Overcurrent Overcharge

6.6.5.1 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 to 100% SOC and then discharging it slightly (e.g., by using the vehicle cabin heater, AC system, or through driving).

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

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

6.6.5.4 Confirm the DC link connection is properly installed and that all terminal switches are open within the switchboard.

6.6.5.5 Select an appropriate power supply for this test based on the maximum charging power.

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[2] 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.

Determine the maximum overcurrent that will be applied to the RESS. It is based on the maximum current that can be supplied by regenerative braking or a faulting charger. The vehicle manufacturer may provide guidance.

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 overcurrent to obtain the maximum charging power.

6.6.5.6 Connect the overcurrent power supply to the DC link (see Figure 6 in Section 7.3). Set the current and voltage limit on the power supply based on Sections 6.6.5.5.

6.6.5.7 Testing can be performed without a thermal chamber, provided that the ambient air does not inhibit discharge of the RESS.

6.6.5.8 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.

6.6.5.9 Place the vehicle into charging mode. For an EV or PHEV, connect a Level 1 charger[3] to the vehicle and initiate charging. For an HEV, place the vehicle in an operational mode. Allow charging currents to stabilize.

6.6.5.10 Turn on the overcurrent power supply connected to the DC link and linearly increase its current over 1000 seconds from zero to the maximum charging current determined in Section 6.6.5.5.

6.6.5.11 Continue the charging session while applying the overcurrent for a maximum of 24 hours, or until the automatic disconnect in the RESS opens and remains open for at least 2 hours, or a failure occurs (smoke, fire, or explosion).

6.6.6 Vehicle RESS Overvoltage Overcharge

6.6.6.1 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 to 100% SOC and then discharging it slightly (e.g., by using the vehicle cabin heater, AC system, or through driving).

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

6.6.6.3 Confirm the DC link connection is properly installed and that all terminal switches are open within the switchboard.

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[3] 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 6.6.5.5 is based on having only Level 1 charging in addition to the fault current.

6.6.6.4 Select an appropriate power supply for this test based on the maximum theoretical voltage and current limit.

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.

Determine the appropriate current limit by dividing 1.4 kW (i.e., the Level 1 charging power) by the maximum theoretical voltage.

6.6.6.5 Connect the overvoltage power supply as described in Section 7.3 (see Figure 6) to the DC link. Set its voltage and current limits to the values determined in Section 6.6.6.4. If the overvoltage power supply 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.

6.6.6.6 Testing can be performed without a thermal chamber, provided that the ambient air does not inhibit discharge of the RESS.

6.6.6.7 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.

6.6.6.8 Place the vehicle into charge mode. For an EV or PHEV, connect a Level 1 charger to the vehicle and initiate charging. For an HEV, place the vehicle in an operational mode. Allow charging currents to stabilize.

6.6.6.9 Once charging has begun, turn on the overvoltage power supply, and close the positive and negative terminal switches on the DC link.

6.6.6.10 Continue the charging session while applying the overvoltage for a maximum of 24 hours or until the automatic disconnect in the RESS opens and remains open for at least 2 hours or a failure occurs (smoke, fire, or explosion).

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

6.6.7 RESS External Short Circuit

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

6.6.7.2 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 to 100% SOC and then discharging it slightly (e.g., by using the vehicle cabin heater, AC system, or through driving).

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

6.6.7.4 Chock the vehicle to prevent rolling or creep.

6.6.7.5 Testing can be performed without a thermal chamber, provided that the ambient air does not inhibit discharge of the RESS.

6.6.7.6 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.

6.6.7.7 Place the vehicle into drive mode.

6.6.7.8 Connect the short circuit device to the DC link (see Figure 7 in Section 7.3).

6.6.7.9 Close the switches on the DC link positive and negative tap boxes. This causes 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.

6.6.7.10 If the RESS does not interrupt current flow automatically, manually shutdown the short circuit using appropriate PPE. Continue to monitor the RESS until its temperature has remained stable for 60 minutes (within ±2°C).

6.6.7.11 Once the test has concluded, disconnect the short circuit device.

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

6.6.7.13 In the event of a test failure, photograph the vehicle with installed RESS.

6.6.7.14 Remove the RESS from the vehicle and photograph the RESS.

6.6.8 RESS Destructive Discharge

6.6.8.1 Sequential testing may result in a damaged RESS with stranded energy that cannot be removed using normal electrical discharge. If so, this RESS destructive discharge procedure can be used to remove stranded energy prior to storage and/or disposal.

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

If no manufacturer-provided destructive discharge method is available, and the RESS is composed of Li-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 7.10.

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

6.6.8.4 Remove the RESS cover and examine the physical construction of the battery pack. Removal of the cover can expose high voltage components; appropriate safety precautions and PPE shall 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 also the mechanical architecture of the RESS, including individual module or cell dimensions and (if flooded) whether water will contact individual cells.

6.6.8.5 Use the gathered information regarding RESS architecture to determine whether it can be subjected a single salt bath as a unit, or if it should be divided into subcomponents for destructive discharge. Single cell salt bath trials, as described in Section 7.10, may be required prior to attempting a module or RESS level salt bath destructive discharge.

6.6.8.6 Prepare one or more salt bath(s), see Section 7.10.

6.6.8.7 Prepare the RESS or its subcomponents for salt bath immersion. Remove covers and eliminate tortuous water flow paths. Connect the RESS to a hoist or other device for allowing rapid submersion in the salt bath.

6.6.8.8 Immerse the RESS or its components in the salt bath.

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

6.6.8.10 Remove the destructively discharged item using appropriate PPE from the salt bath and prepare it for recycling.

6.6.8.11 Prepare the liquid waste from the salt bath for proper disposal and removal.

6.7 Measured Data

6.7.1 Test reports should include the following information:

6.7.1.1 A description of the preconditioning vehicle used, including the following elements:

- Vehicle model
- Vehicle trim type
- Vehicle curb weight
- Vehicle design weight
- Vehicle tire pressure at start of test

6.7.1.2 A description of the preconditioning procedure used, including the following elements:

- Summary of preconditioning events relative to requirements
- Summary of preconditioning sequence

- Description of WOT + RR driving 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 rain exposure water application
- Description of ambient charging levels
- Description of drizzle charge water application

6.7.1.3 Preconditioning summary and driver logs, including the following elements:

- 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

6.7.1.4 Location of all sensors installed for sequential testing, including the following elements:

- 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

6.7.1.5 For each sequential test conducted, the test report should include the following materials:

- Photographs of vehicle and RESS prior to sequential testing
- If the RESS was opened for test preparation, then photographs of RESS before and after equipment installation
- If the 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

6.7.1.6 If needed, a description of the destructive discharge method used and an assessment of its efficacy.

6.8 Post-Test Requirements

6.8.1 After sequential testing, the vehicle without the RESS may be undamaged and used for other purposes.

6.8.2 After destructive discharge, the RESS remains may require special handling for disposal or recycling. The testing agency should ensure that its remains are disposed of or recycled in accordance with environmental regulations.

6.9 Acceptance Criteria

6.9.1 Acceptance criteria for sequential testing are divided into two categories: hazard to the occupant, and hazard to the surrounding environment.

6.9.2 Hazards to the Occupant

6.9.2.1 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 which provides significant warning properties to the occupants.

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

6.9.2.3 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.

6.9.3 Hazards to the Surrounding Environment

6.9.3.1 The vehicle must not pose an ignition or mechanical hazard to the surrounding environment throughout sequential testing.

6.9.3.2 The vehicle should not ignite as a result of sequential testing.

6.9.3.3 Vent gases emitted by the vehicle as a result of sequential testing should not ignite.

6.9.3.4 There should be no explosion as a result of sequential testing.

7. TEST PROCEDURE RATIONALE

7.1 5000 Mile Preconditioning

A number of testing standards, 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 Li-ion batteries, require testing of both new (uncycled) and aged (cycled) cells or battery packs. This acknowledges that cells of any chemistry are subject to a variety of aging mechanisms that can affect their performance, including safety. 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 the consumer electronics industry, where cells are electrically cycled under relatively uniform, ambient temperature conditions.

RESS cells and and other components for vehicle applications are also subject to aging mechanisms that can affect their performance, including safety. This is further complicated by the fact that RESS construction, as well as sensing and control approaches, continue to evolve. Extensive reliability data remains unavailable for many potential battery systems. Although electrical cycling remains an important aging mechanism, a vehicle RESS is subject to a number of additional mechanical, thermal, and environmental aging mechanisms that affect safety. The simultaneous or intermingled application of these aging mechanisms are, therefore, important for safety evaluation. For example, electrically charging a RESS with 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 these circumstances (or similar events) 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 external short circuits.

Preconditioning a full RESS by applying multiple, relevant, usage conditions specific to an actual vehicle presents many experimental challenges for a laboratory setting. Facilities capable of simultaneous charge, discharge, and temperature control during aging are rare. Equipment requirements are also significant, including large format battery charge and discharge stations. Testing in a laboratory setting using traditional equipment (dynamometer, four-post vibration fixture, vehicle thermal chamber) would not capture all relevant load conditions and it would be difficult to implement simultaneous or repetitive load conditions without incurring substantial experimental costs. Additionally, the appropriate preconditioning load levels for each RESS would have to be experimentally determined from test drives prior to laboratory-based testing.

In comparison, installing a RESS in its associated prototype or production vehicle reduces the experimental challenges observed for laboratory-based testing. The test vehicle can be subjected to a combination of both actual driving conditions and high acceleration factor driving conditions. It 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. Additionally, the use of a common drive sequence applies loads that are unique to the individual vehicles under test while also enabling comparisons between RESSs.

Preconditioning testing enables meaningful assessments of the RESS robustness and safety. The tests should apply sufficient electrical, mechanical, thermal, and environmental loads to the RESS without overly degrading the capacity. For consumer electronics, the UN and UL standards require that preconditioning consists of approximately 50 electrical cycles on the battery. A typical consumer electronics device would be expected to complete around 500 cycles in its lifetime. Thus, the UN and UL requirement represents 1/10th of the expected cycle life. Similarly, subjecting a RESS to 5000 miles of preconditioning 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 loads (electrical, mechanical, and thermal), a 5000 mile drive sequence can apply greater loading than would be encountered by a typical consumer-owned vehicle over the same distance.

The intent of preconditioning and subsequent sequential testing is to ensure that aging of the RESS components has been adequately considered and executed during the design and manufacturing process, specifically from a safety perspective. The preconditioning procedure is not rigidly defined because it is more important that representative aging be applied to a RESS rather than a specific sequence. Thus, the preconditioning test procedure is designed to be relatively non-burdensome to a testing agency and allows for variability between test facilities.

The preconditioning sequence mixes a large number of high acceleration driving patterns with some low acceleration factor driving patterns. High acceleration factors concentrate potentially damaging electrical, mechanical, and thermal loads whereas low acceleration factors apply a greater variety of less common potentially damaging loads. Various charging conditions and environmental loads are also applied throughout the sequence. The primary elements of the preconditioning sequence are described in Sections 7.1.1 through 7.1.12.

The order of the preconditioning sequence has been loosely defined to allow convenient scheduling by a test agency. Although segment miles are not rigidly defined in this procedure, at least half of the high acceleration factor driving patterns must be completed before application of the less typical low acceleration factor driving patterns, events, challenging charging conditions, and supplemental environmental loads. The different phases in the preconditioning sequence (see Table 4) provide suggested variations in both driving profiles and charging sequences.

7.1.1 WOT + RR Driving

WOT + RR driving has a high acceleration factor compared to typical consumer driving patterns. It is sequenced in Phases 1, 3 and 5 of preconditioning (see Table 4) 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 normal driving, but in a compressed format. The purpose is to accelerate any potential damage to RESS cells and other components. For example, if a Li-ion cell within a RESS has a poorly designed or manufactured electrode, vibrational and torsional loads may cause flaking, while high current charging can result in lithium plating on the regions subject to flaking, ultimately reducing safety performance of the cell.

7.1.2 High Speed Driving

High speed driving has a high acceleration factor compared to typical consumer driving patterns. It is sequenced in Phases 2 and 4 of preconditioning (see Table 4) 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, that might come from significant expressway driving, but in a compressed format. The purpose is to accelerate any potential damage to RESS cells and other components.

7.1.3 Mountain Route

The mountain route has a high acceleration factor compared to typical consumer driving patterns. It is sequenced in Phase 3 of preconditioning (see Table 4) to apply a range of loads after the vehicle has already been subjected to a significant portion of WOT, vibrational, and high speed loads. This mountain route is conducted on public roads for real world variability to the preconditioning process. Driving on a public roadway results in a broad range of simultaneous accelerations, decelerations, lateral loads, vibrations, and environmental loads. These conditions might have unexpected effects on a RESS that are difficult to program in a closed track or dynamometer program. The loads include:

- Extended hill climbs with variable accelerations yielding high but variable loads on the RESS.
- Extended hill descents with variable braking yielding variable regenerative charging of the RESS.
- Extensive cornering and lateral movement of the vehicle yielding 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, humidity and pressure.

7.1.4 Gravel Road Route

The gravel road route has a low acceleration factor compared to typical consumer driving patterns. It is intended to expose the RESS to a high concentration of dust and road debris while simultaneously applying high vibrational loads. This route is sequenced in Phase 3 of preconditioning (see Table 4), when the RESS has already been exposed to some vibrational loads that may compromise seals and allow entry of dust and debris.

7.1.5 City Route

The city route has a low acceleration factor for damage compared to typical consumer driving patterns. It is sequenced in Phase 3 of preconditioning (see Table 4) to apply a range of loads after the RESS has already been subjected to a significant portion of WOT, vibrational, and high speed loads. This route is conducted on public roads in a high density urban environment for real world variability to the preconditioning process. Driving on a public roadway results in a broad range of simultaneous accelerations, decelerations, lateral loads, vibrations, and environmental loads. These conditions might have unexpected effects on a RESS that are difficult to program in a closed track or dynamometer program. The loads include:

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

7.1.6 Salt Spray

A salt spray simulates the presence of road salts that may infiltrate a RESS and cause loss of internal isolation, corrosion, or compromise various RESS components. It is sequenced in Phase 3 of preconditioning (see Table 4), when the RESS has already been exposed to some vibrational loads that may compromise seals and allow entry of salts. Additionally, any salt that enters a RESS will have some time to induce corrosion before sequential testing is initiated.

7.1.7 Rain Booth

A rain booth simulates heavy rain exposure that may penetrate a RESS and cause a loss of internal isolation or compromise various RESS components. It has been sequenced in Phase 3, 4, or 5 of preconditioning (see Table 4), when the RESS has already been exposed to some vibrational loads that may compromise seals and allow entry of moisture. The use of a rain booth ensure that preconditioning includes heavy rain simulations even if there is no precipitation during test track or public road driving.

7.1.8 Cold Charge

Cold charging (or cold soaking for an HEV) provides a thermal cycle that can result in failure for a range of RESS components. The cold temperature creates thermal stresses from differences in the coefficients of thermal expansion. It can also create condensation within a battery pack. For Li-ion cells, cold charging can induce non-ideal reactions such as lithium plating that can ultimately affect its safety. Non-ideal reactions are more likely to occur if cell electrodes have become damaged due to significant vibrational, torsional, or electrical loading. Cold charging is sequenced in Phase 3, 4, or 5 of preconditioning (see Table 4), when the RESS has already been subjected to 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) provides a thermal cycle that can result in failure, particularly those exposed to high current loads. The hot temperature creates thermal stresses from differences in the coefficients of thermal expansion. It can also accelerate plastic creep. Hot charging is sequenced in Phase 3, 4, or 5 of preconditioning (see Table 4), when the RESS has already been subjected to a significant portion of WOT, vibrational, and high speed loads that might compromise components with poor robustness.

7.1.10 Drizzle Chamber Charge

Drizzle chamber charging ensures that preconditioning includes light rain conditions for EV and PHEV charge sessions (or HEV exposure to light rain) even if there is no precipitation during test track or public road driving. It is sequenced in Phase 3, 4, or 5 of preconditioning (see Table 4) 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.

7.1.11 Car Wash

Car washes are intended to expose the RESS to typical detergents and surfactants that could accelerate the infiltration of road salt or dirt into various crevices. It is sequenced in Phases 3 and 5 of preconditioning (see Table 4), when the RESS has already been subjected to a significant portion of WOT, vibrational, and high speed loads that might compromise components with poor robustness.

7.1.12 RESS Removal and Re-Install

A RESS removal and re-installation simulates maintenance that may occur on a vehicle. It is sequenced in Phase 5 of preconditioning (see Table 4), when the RESS has already been subjected to a significant portion of WOT, vibrational, and high speed loads that might compromise components with poor robustness.

7.2 Sequential Testing

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. The vehicle sequential tests are designed to evaluate the robustness of a RESS by applying normal and expected stresses after accelerated aging. The selected stress conditions come from a number of widely accepted battery pack test methods that represent commonly experienced single point failure modes. These tests are adapted for application to large format RESSs installed in production vehicles. The sequence consists of a low temperature test with a failed heating system, a high temperature test with a failed cooling system, over-discharge, overcurrent overcharge, overvoltage overcharge, and an external short circuit test; see Sections 7.4 through 7.9 for further dicussion.

The test sequence is intended to reveal and exacerbate a range of potential failure modes using a minimum number of test articles. It is derived from the approach used in the UN Manual of Tests and Criteria, which identifies five tests for Li-ion systems that are conducted in a specific order (T1-T5). The order ensures that tests which may cause damage to cells or battery packs without any clear indication of a problem (e.g., altitude simulation, thermal cycling, vibration, and mechanical shock) are followed by an external short circuit test. This not only tests the article's robustness to an external short circuit, but is also likely to indicate whether the article accrued serious damage in previous tests.

In direct comparison to many standard tests which are conducted on cells or small battery packs, the ambient conditions and loads specified by the sequential testing in this procedure may seem relatively benign. Thus, a RESS should remain unaltered by the imposed electrical and environmental boundary conditions during testing with the possible exception of the external short circuit. This, however, is only true if the RESS properly engages its safety architecture, assuming it has not been compromised in some way by the preconditioning sequence or previous tests within the sequence.

7.3 DC Link Function and Installation

A DC link is required for the RESS over-discharge, overcurrent overcharge, overvoltage overcharge, and external short circuit tests. A variety of devices can be connected to the DC link to achieve the required electrical conditions. The requirements for a DC link include:

- The OEM should provide the testing agency with documentation detailing how a DC link can be installed with minimum disruption to the vehicle systems. Generally, the required 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.
- The 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 the cable gauge size requirements.
- 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 the maximum use voltage (U) plus 1695 V (i.e., U + 1695 V).
- Joints or terminals shall be capable of secure and low resistance connections (e.g., 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.
- The vehicle shall be able to charge and discharge normally with the DC link connection installed.

Figure 2 shows an example DC link configuration to the RESS through a junction box. This setup corresponds to the vehicle design used for demonstration testing in Section 8. Figures 3 through 4 show the required elements of the DC link. The key components include a switchboard, a discharge resistor unit, and a power supply. The switchboard contains a short circuit box and 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.

Figures 5 through 7 show possible DC link connections for various sequential tests. Figure 5 shows a configuration for performing the over-discharge test. The short circuit box shall remain open when a discharge resistor is connected to the tap boxes. The unit should allow for resistors to be placed in parallel or in series so that the overall resistance can be configured to produce a

1 kW discharge at a variety of RESS operational voltages (e.g., Figure 3 shows ten separate 20Ω resistors). The requirements for this configuration include:

- 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 (e.g., with air blowing fans) to maintain a safe operating temperature.

Figure 6 shows a DC link configuration for both the overcurrent overcharge and overvoltage overcharge tests. The short circuit box is open and both tap boxes are used to make a connection to a power supply (e.g., see Figure 4).

To perform the short circuit test, only the switchboard is required and the tap boxes are open circuit with nothing connected, as shown in Figure 7. The example shown in Figure 4 contains two 630 A fuses in parallel and at least 2/0 American Wire Gauge (AWG) cable or equivalent bus bar size. The requirements for this configuration include:

- Appropriate information regarding sizing of the fuses in the vehicle and RESS should be provided by the 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.
- Since the vehicle or RESS must interrupt the short circuit test, the short circuit box should be sized appropriately. The test is valid only if the fuse in the box remains intact after the short circuit test. Otherwise, the fuse needs to be resized and the test repeated.

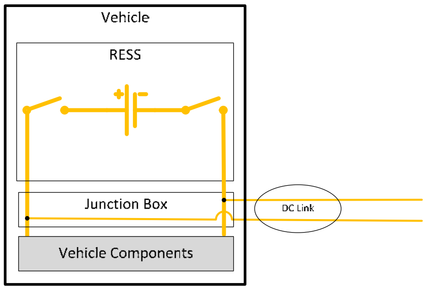


Figure 2 - An example DC link configuration.

Figure 3 - 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 temperature.

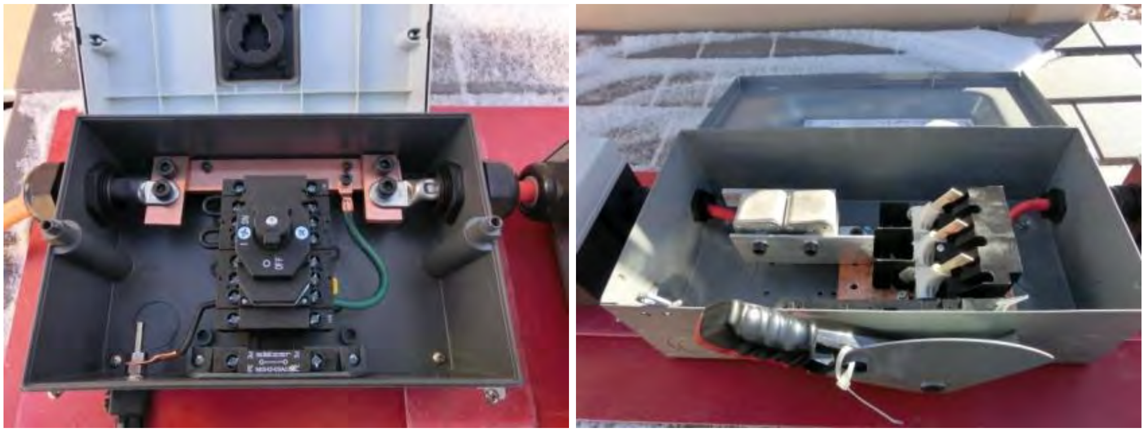


Figure 4 - The interior of a tap box (left) and the fused short circuit box (right). The fused shorting switch connects directly to the copper bus-bar inside the tap boxes.

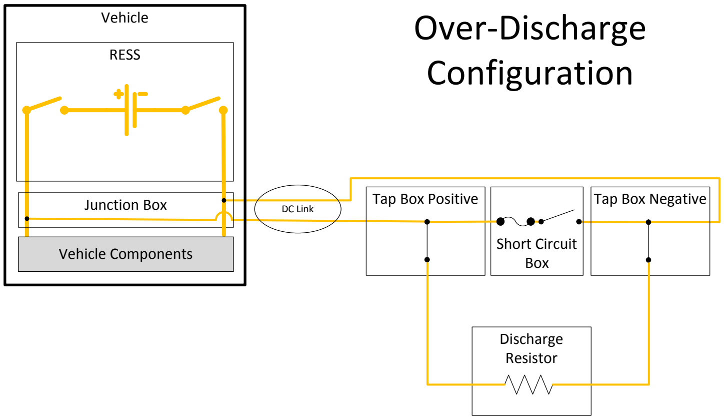


Figure 5 - An example DC link with a switchboard and discharge resistor configured for the over-discharge test.

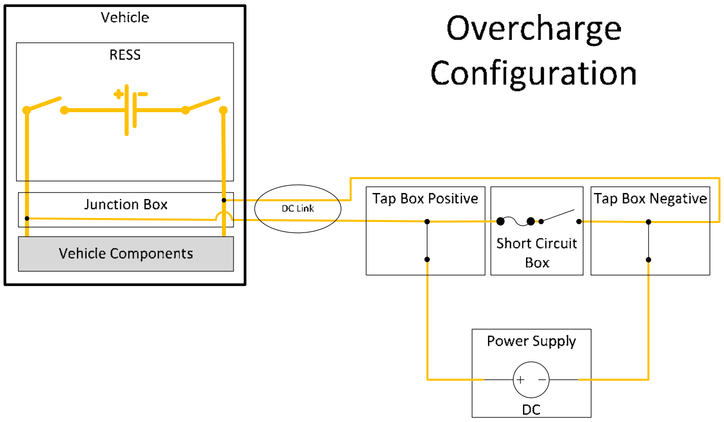


Figure 6 - An example DC link with a switchboard and power supply configured for overcharge tests.

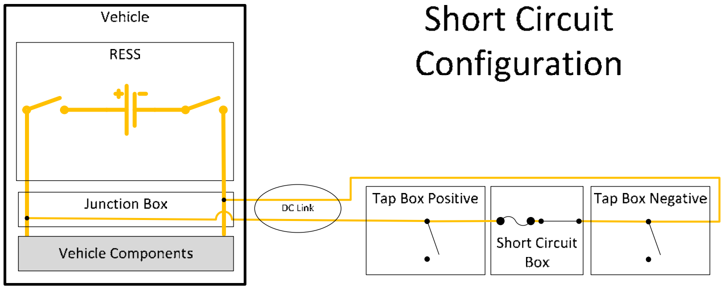


Figure 7 - An example DC link with a switchboard configured for the short circuit test.

7.4 Low Temperature, Failed Heating System Simulation

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

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

- IEEE 1625 requires that an article be exposed to 75°C for 4 hours, followed by 20°C for 2 hours, −20°C for 4 hours, and then 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, −40°C for 4 hours, and then 20°C for 2 hours.
- SAE J2464 requires that an article be exposed to 70°C for at least 1 hour, followed by −40°C for at least 1 hour.

Although low temperature operational tests are not specified in the existing standards, a RESS installed in a vehicle will likely implement temperature monitoring and control systems to prevent undesirable operation. Thus, a low-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.

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

An OEM 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. It 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.

Many vehicles will respond to abnormal temperature regimes by entering a mode in which only very low power is allowed to be delivered. In this mode, fully charging or discharging a RESS might require significant time. Thus, a steady state guideline has been implemented to place the requisite amount of stress on the vehicle systems while also allowing the test agency to plan test time appropriately.

7.5 High Temperature, Failed Cooling System Simulation

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

High temperature storage and operation tests are common in cell and battery pack standards. 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 contains 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 J2464 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 which rely on integral cooling systems be designed to shut down if the cooling system fails, unless it can be demonstrated that the failure does not result in a hazardous situation. The standard goes on to define a test that applies both charge and discharge to a RESS at its maximum specified operating ambient conditions with the cooling system disabled.

An ambient temperature condition of at least 40°C has been selected for this test procedure, regardless of the OEM specified maximum ambient operating temperature. It is a realistic condition that a user is likely to encounter.

An OEM may provide guidance as to how a RESS cooling system within its vehicle may be disabled in a minimally invasive fashion to simulate a non-operating condition. It 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 RESS would always forbid charge or discharge on any detected failure of that cooling system, then a software patch to shut down a cooling system which resulted in an inoperable RESS would be acceptable.

Many vehicles will respond to abnormal temperature regimes by entering a mode in which only very low power is allowed to be delivered. In this mode, fully charging or discharging a RESS might require significant time. Thus, a steady state guideline has been implemented to place the requisite amount of stress on the vehicle systems while also allowing the test agency to plan test time appropriately.

7.6 Over-Discharge

Many battery chemistries can experience undesirable aging, electrolyte leakage, swelling or even violent failure if over-discharged. Although over-discharge of Li-ion cells generally appears benign, it could cause damage to the electrodes and compromise cell stability and safety on subsequent recharges. Cell aging and capacity imbalances can increase susceptibility to over-discharge, particularly if the voltage sensing is not sufficiently robust. A properly designed RESS will prevent cell over-discharge.

Over-discharge tests are common in cell and battery pack standards. For example:

- IEEE 1625 requires that a battery pack have at least one under-voltage protection circuit that disables a discharge to the external system. It further requires single cell forced over-discharge testing.
- IEEE 1725 requires that a single cell be discharged to 0 V 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 the 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.

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

7.7 Overcurrent Overcharge

Overcharge is generally considered one of the most hazardous failure modes for Li-ion cells. A significant overcharge can lead to cell thermal runaway, while a minor overcharge can result in lithium plating that compromises cell safety characteristics. Most Li-ion battery packs include multiple, overlapping safety systems to prevent significant overcharge of the cells, but minor overcharge is sometimes allowed under certain fault conditions. An overcharge may come from 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 overcurrent overcharge, charge voltage remains proper, but excessive current is delivered. This excessive current can cause plating of lithium on Li-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.

Over-current overcharge tests are common in cell and battery pack standards. For example:

- UL 1624 and 2054 require that a battery be charged for 7 hours at a current that is three times the manufacturer’s specified rate.
- UL 2271 requires that the pack isolate itself when its normal operating region for charging or discharging is exceeded.
- UN Test T.7 requires that the battery be subjected to a constant charging current of twice the manufacturer’s recommended rate, 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 for large RESSs. For example, two times the manufacturer-specified charging current as described in UN T.7 would be more than 200 kW for some vehicles on the market. Thus, for this procedure, it is reasonable to limit overcurrent to what 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.

Typically, a RESS will refuse to accept a charging current if it does not first request it from a charger. As such, simply applying a voltage to an isolated RESS, or to a RESS at 100% SOC will not be relevant. For this procedure, the RESS begins at 95% SOC. Normal charging is initiated prior to simulating a charger fault that applies an overcurrent to the RESS. The overcurrent is ramped slowly towards the maximum charging current in a similar manner to a failing charger device. This is also likely to produce the most overcharged battery.

7.8 Overvoltage Overcharge

Overcharge is generally considered one of the most hazardous failure modes for Li-ion cells. A significant overcharge can lead to cell thermal runaway, while a minor overcharge can result in lithium plating that compromises cell safety characteristics. Most Li-ion battery packs include multiple, overlapping safety systems to prevent significant overcharge of the cells, but minor overcharge is sometimes allowed under certain fault conditions. An overcharge may come from 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 overvoltage overcharge, the voltage exceeds proper limits, but the charge current remains within proper bounds. Overvoltage can cause plating of lithium on Li-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.

Overvoltage overcharge tests are common in cell and battery pack standards. For example:

- UL 2054 requires that a battery be charged using a voltage source that will apply 10 times the C_5 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 rate, 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.
- SAE J2464 requires that battery 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.

Application of a mild overvoltage condition consistent with a faulting charger is sufficient (i.e., 1.2 times the maximum charge voltage). Higher overvoltage conditions on a RESS is not generally practical and may cause damage to capacitors or other sensing circuits.

Typically, a RESS will refuse to accept a charging current if it does not first request it from a charger. As such, simply applying a voltage to an isolated RESS, or to a RESS at 100% SOC will not be relevant. For this procedure, the RESS begins at 95% SOC. Normal charging is initiated prior to simulating a charger fault that applies an overvoltage to the RESS.

7.9 External Short Circuit

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

External short circuit tests are common in cell and battery pack standards. For example:

- 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 (i.e., less than 5 mΩ) of RESS modules and packs. SAE J2464 also specifies a soft short circuit test (i.e., a short impedance matched to the DC impedance of the device under test) for 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 and at a load that draws a maximum current that is 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 and at a load that draws 90% of the short circuit protection current.
- UN Test T.5 specifies a short circuit test through a maximum resistance load of 100 mΩ.

A shorting resistance of 3 to 5 mΩ, consistent with SAE J2464 and J2929 test methods has been selected for this procedure. 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: Salt Bath Method

Destructive discharge is intended to ensure that a method exists to remove “stranded energy” from a RESS if necessary; it is not a stress test. A RESS will not typically allow over-discharge of cells to 0 V (i.e., less than 0% SOC). Thus, if over-discharge to approximately 0 V is required, individual RESS components may need to be accessed and electrically discharged individually. The destructive discharge is for stranded energy in a RESS that cannot be removed either through normal electrical discharge or through electrical discharge of individual RESS components.

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

- A RESS may become damaged in such a way that normal electrical discharge to low SOC is not allowed (e.g., a fuse may break the circuit). In this case, the RESS components may need to be accessed and electrically discharged individually.

- Individual cells within a RESS may also become damaged in such a way that electrical discharge is not possible (e.g., the separator may shutdown due to heating and prevent ion transfer between the 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 releases energy, such as a severe crush or external heating.

A destructive discharge will fully remove stranded energy from all RESS components. If electrical discharge at the system or component level is not sufficient to fully discharge a RESS, a destructive discharge method that can be effective for Li-ion battery packs is the salt bath method, where the system is submerged in a salt water solution.

7.10.1 Salt Bath Discharge Mechanism

The salt bath method destructively discharges cells or modules in two ways:

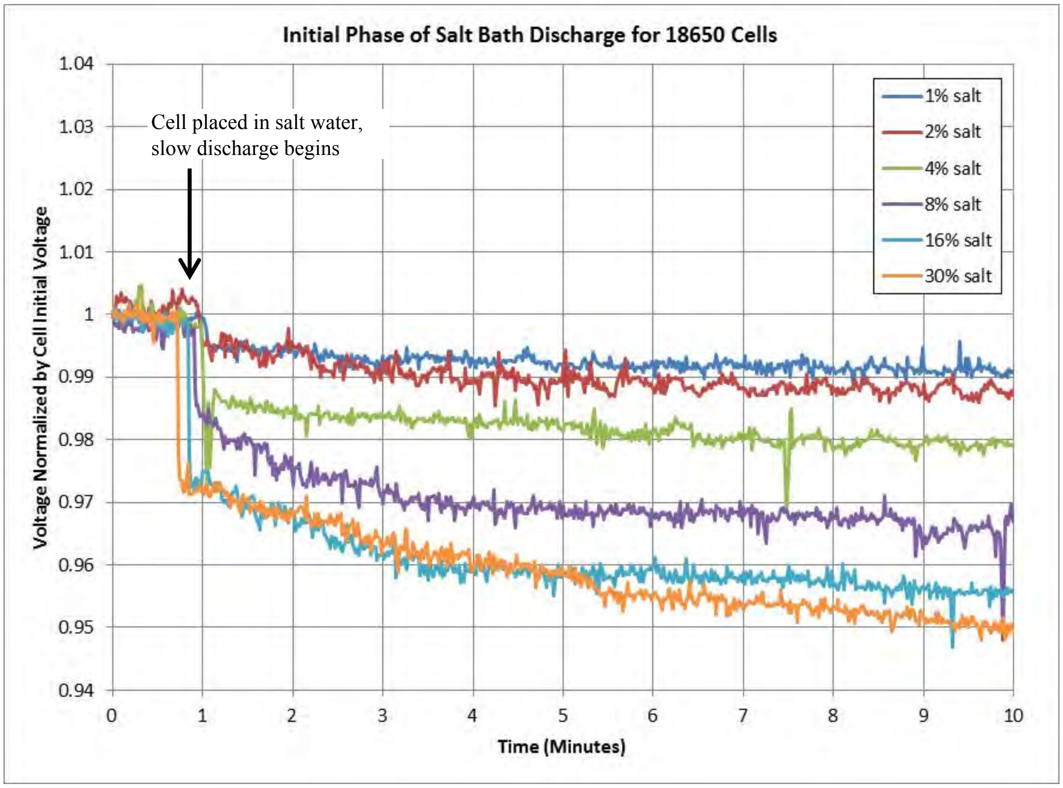
1. The salt solution will complete an electric circuit between elements at different potentials. Thus, for a cell that is capable of discharge (i.e., the separator is not shutdown) with intact terminals, the circuit is closed when salt water flows and the cell begins to slowly discharge. The higher the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

Verification testing of the salt bath discharge method was conducted using single 18650 Li-ion cells. Figure 8 shows the initial voltage decay of the cells when placed in salt baths of varying concentrations. Discharge begins when the cell enters the liquid, which is seen as a step change in voltage. As expected, the discharge rate increases with 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 both cell voltage and discharge rate occurs (Figure 9). Voltage measurements ultimately become noisy as the 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.

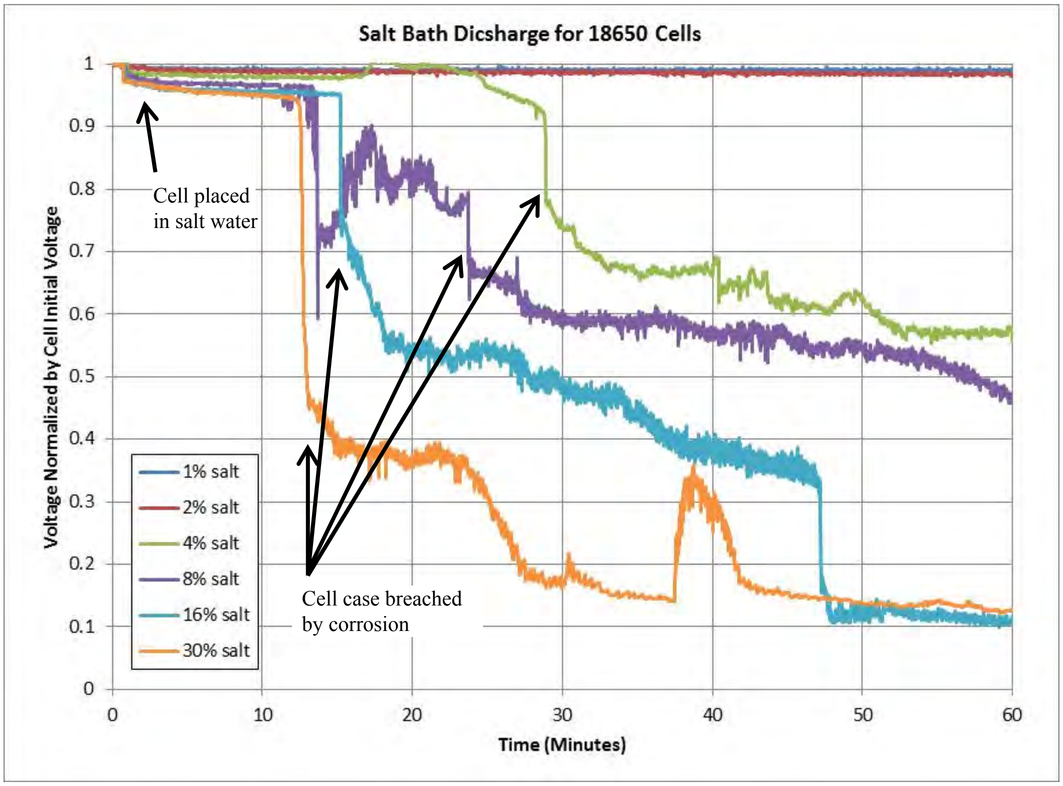
Accelerated Rate Calorimetery (ARC) and impact testing of 18650 cells removed from a salt bath after destructive discharge demonstrate that they no longer contain appreciable stored energy. Figure 11 shows that salt bath discharged cells exhibit self-heating rates similar to cells that have been deeply discharged by normal electrical methods. Additionally, self-heating rates for salt bath destructively discharged cells and electrically deep discharged cells are significantly lower than cells at 100 and 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 at least 24 hours and potentially for many days depending on the state and design of the immersed items.



Cell placed in salt water, slow discharge begins

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



Cell placed in salt water

Cell case breached by corrosion

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

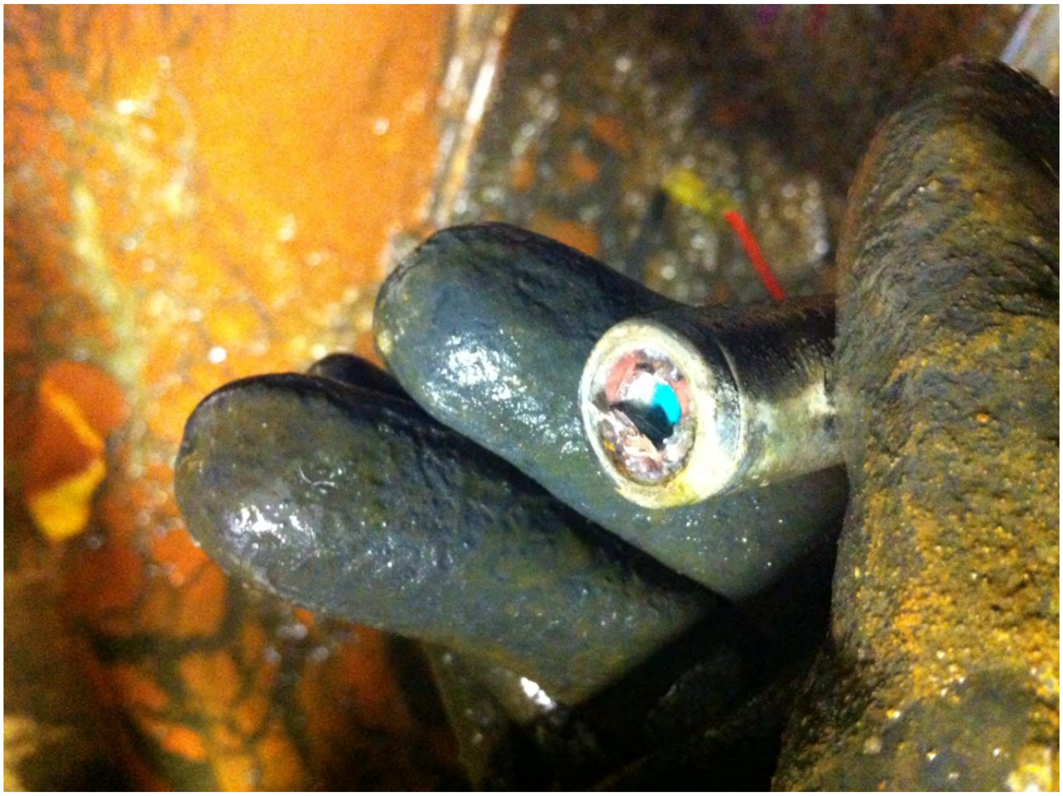


Figure 10 - An example of an 18650 cylindrical cell after a salt bath destructive discharge. The positive terminal has been removed by corrosion, thus exposing the cell interior.

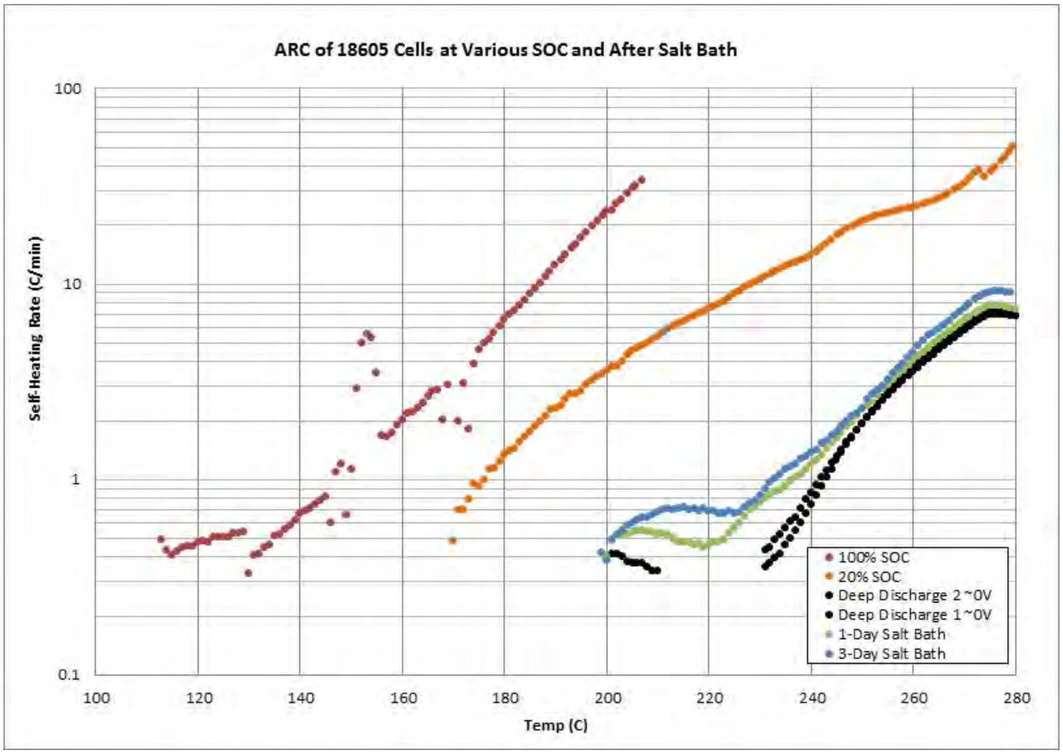


Figure 11 - ARC test results comparing the cell self-heating rates for three different conditions: salt bath destructive discharge, deep discharge (~0 V), and varying SOC conditions (20% or 100%).

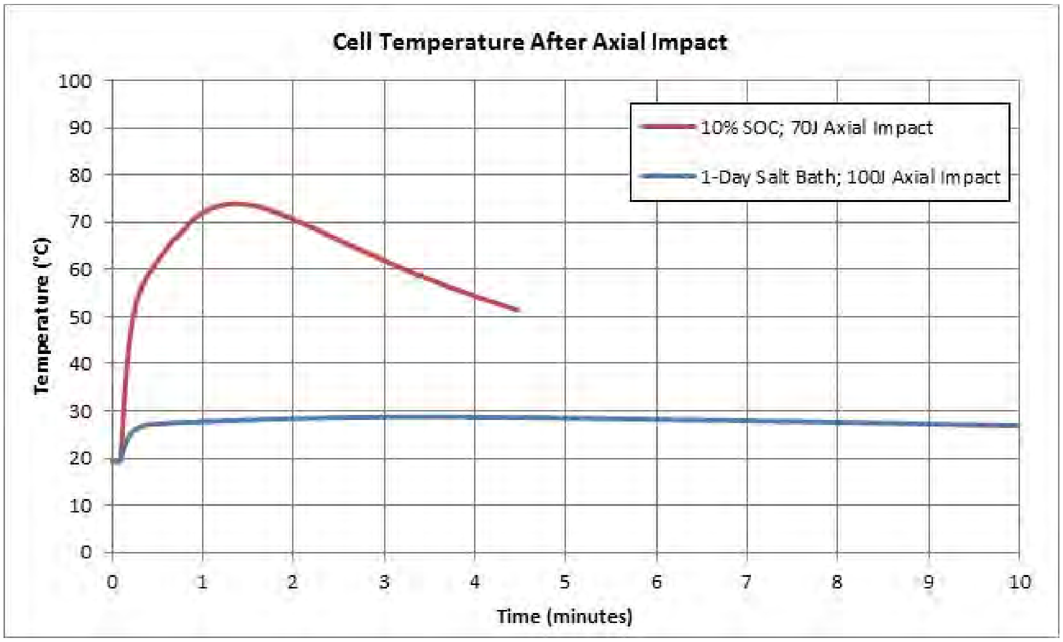


Figure 12 - A heating comparison of 18650 cells after axial impact. One cell was at 10% SOC and subjected to a 70J axial impact. The other cell was subjected to a 100J axial impact after one day of salt bath exposure.

7.10.2 Salt Bath Discharge Hazards

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

7.10.2.1 Electrolysis of Water.

Cell immersion will result in electrolysis of water and the production of hydrogen and oxygen gas. The gases bubble to the surface (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.

7.10.2.2 Potential for Arcing Between High Voltages

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

7.10.2.3 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 insufficient water is used, or if the water is not able to readily flood heated components, excessive heating can result in boiling and steam such that liquid is ejected from the salt bath. Battery components can become heated and potentially melt, or cause melting of the salt bath tank itself. Thus, obstructions such as battery covers that 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 of the submerged unit.

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

7.10.2.4 Potential for Inducing Cell Thermal Runaway Reactions

If the discharge reaction proceeds too quickly, it may undergo a thermal runaway reaction. The rate of reaction is affected by the concentration of salt or other ions in the water, the establishment of an electrical arc, or water entering the cell after corrosion occurs and oxidizing cell components. Based on 18650 cell tests, a thermal runaway reaction is unlikely to eject glowing sparks or flames from the bath if it is submerged at least 6 inches below the liquid surface. 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.

7.10.2.5 Composition of Released Gases and Liquid Residue

Gases produced over a salt bath were sampled. The samples were analyzed for a range of chemical compounds including metals, acid gases, and volatile organic compounds. The detected compounds (Table 8) were consistent with those present in the cells being destructively discharged, including current collectors (copper), electrode material (nickel, cobalt), and electrolyte constituents (lithium, and volatile organic compounds). No measured concentrations were above OSHA permissible exposure limit 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 8 - Results of Gas Sampling over a Destructive Discharge Salt Bath

Compound	Detected Over Salt Bath?
Chlorine gas	No
Hydrogen Peroxide	Yes
Lithium	Yes
Hydrochloric Acid	No
Hydrogen Sulfide	No
Aluminum	No
Calcium	Yes
Cobalt	Yes
Copper	Yes
Iron	No
Lead	No
Nickel	Yes
Zinc	No
Volatile Organic Compounds	Chloromethane Acetone Toluene Ethylbenzene

Figure 13 - An example of a salt bath with submerged modules. Note the bubbles of gas on the surface produced by electrolysis.

7.10.3 Considerations for Planning a Salt Bath Discharge

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

Depending on the architecture of the item being destructively discharged, and the amount of stranded energy, 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 it. The bath should be closely monitored for the first 1-3 hours to ensure that the water level has not dropped below the submerged unit. After 1-3 hours, periodic monitoring should be planned. A supply of extra water should be readily available at the salt bath location to replenish it as needed.

A 1% salt solution should be sufficient to accomplish destructive discharge of a Li-ion cell. Although higher salt concentrations can increase the discharge rate (Figures 8 and 9), it can also increase the production rate of gas compounds over the salt bath (e.g., hydrogen gas bubbling, etc.). Thus, increasing the salt solution should be conducted with caution. There is no need to monitor the salt concentration once a reaction begins, however, since the concentration of conductive ions in the bath will increase.

A hoist or similar device may be necessary to place units into the salt bath quickly and remove them for disposal. The unit to be submerged should be secured to the hoist with a non-conductive cable or rope.

When units are removed from a salt bath, they should be inspected to ensure that the case walls of every cell has been breached by corrosion. If not, the unit should be returned to the salt bath. The unit should be treated as a high voltage source until it can be confirmed that all cells have been successfully breached.

7.10.4 Considerations for Construction of a Salt Bath

A salt bath should be constructed from materials that are non-conductive and not susceptible to corrosion (e.g., plastic or other materials lined with plastic). The walls should be sufficiently sturdy to resist melting or puncture. A secondary containment system may also be required. The salt bath dimensions should be large enough to easily encompass the unit that will be destructively discharged. It should contain sufficient water and have enough headspace to allow for bubbling without overflowing. The water level must fully submerge the unit to absorb released heat and protect against ejection of flames or sparks. The container should have a loose lid that can be used to cover the bath after most reactions have terminated. This can help prevent access by animals or people during a long dwell period, or before the salt bath is emptied.

The salt bath should 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 A

This appendix provides example full-scale vehicle sequential testing results after preconditioning based on a cylindrical Li-ion cell format. The purpose of this test report is to illustrate the preconditioning and sequential test methods and application; it is not intended to be a performance and safety evaluation for a manufacturer. Thus, evaluating the RESS relative to the primary acceptance criteria (i.e., hazards to the occupant and the surrounding environment) is not within the scope of this report.

8.1 DC Link Installation Examples

For demonstrative purposes, DC link connection configurations are discussed for three different vehicles (Manufacturers A, B, and C). Additionally, the DC link configuration for an EV from Manufacturer A was installed and used for sequential testing after extensive preconditioning.

- 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 from the RESS arrive at a DC junction box beneath the rear seat of the vehicle (Figure 14, red box). Thus, the DC link can be installed at the junction box; removal of the RESS from the vehicle is not required.

A DC link was installed in this vehicle by:

- Removing the first responder cut loop to ensure that the RESS contactors remain open and all vehicle high voltage systems are de-energized.
- 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 15).
- Replacing the DC junction box cover.
- Reinstalling the first responder cut loop.

Figure 14 - Manufacturer A vehicle; the DC junction box beneath the rear seat with orange high voltage cables.

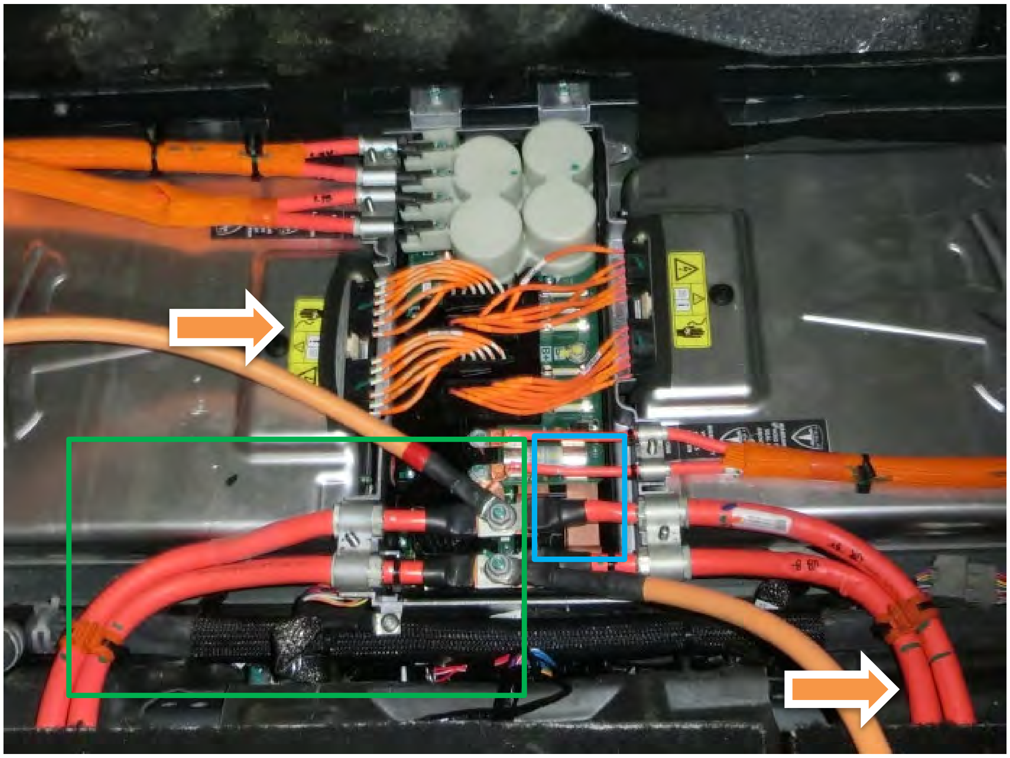


Figure 15 - Manufacturer A vehicle; the DC junction box with the cover removed and DC link installed. The RESS high voltage leads are on the lower left (green box). The vehicle high voltage leads that connect to the powertrain are the same size and color as the RESS high voltage leads. They connect to the RESS high voltage leads at a junction using lug nuts (blue box). The DC link connection cables are light orange (orange arrows) and are shown connected to the main DC junction using the existing lug nuts.

8.1.2 DC Link Connection Points: Manufacturer B Vehicle

The RESS from Manufacturer B consisted of a unit that was mounted to the floor of the vehicle. A vehicle that had previously undergone NHTSA New Car Assessment Program (NCAP) crash testing[4] was examined to determine whether a DC link could be conveniently installed.

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:

- Removing the service disconnect plug (from inside the vehicle cabin) to ensure that the RESS contactors remain open and all vehicle high voltage systems are de-energized.
- Connect the DC link terminal cables by splicing them into the pair of orange high voltage cables that enter the RESS (Figure 16), or by connecting to the RESS internal contacts and modifying the DC junction cover plate to allow a pass-through.
- Reinstalling the service disconnect plug.

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

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

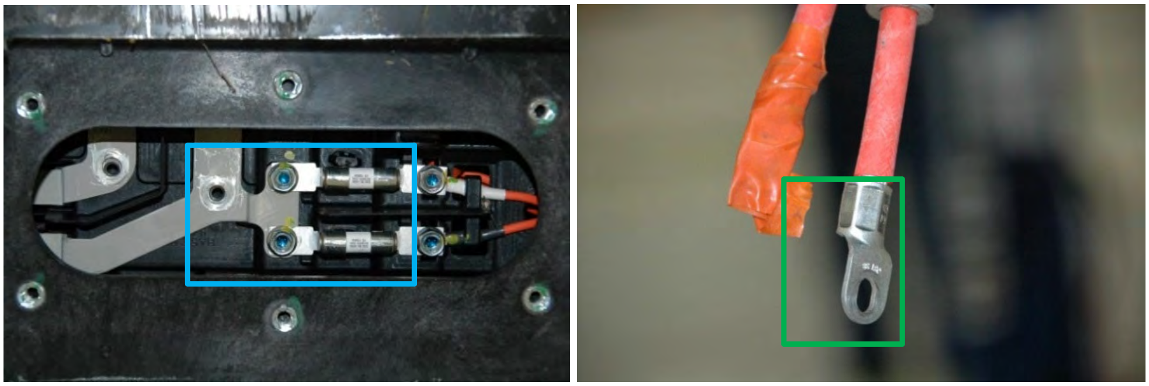

Figure 17 - Manufacturer B vehicle; the high voltage cable connection point (blue box; left image) inside the RESS with the cover plate removed and the high voltage cable connector end (green box, right image).

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 vehicle that had previously undergone NHTSA NCAP crash testing[54] was examined to determine whether a DC link could be conveniently installed.

The vehicle high voltage cables are individually insulated and carried inside a single common insulating orange high voltage line. The high voltage line is plugged directly into the RESS (Figure 18, green box and Figure 19). There is no convenient access port into the RESS to connect a DC link to the the high voltage lines.

A DC link could be installed in this vehicle by:

- Removing the service disconnect plug (from inside the vehicle cabin) to ensure that the RESS contactors remain open and all vehicle high voltage systems are de-energized.
- 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 manufacturer could be used to select a more convenient installation point.

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

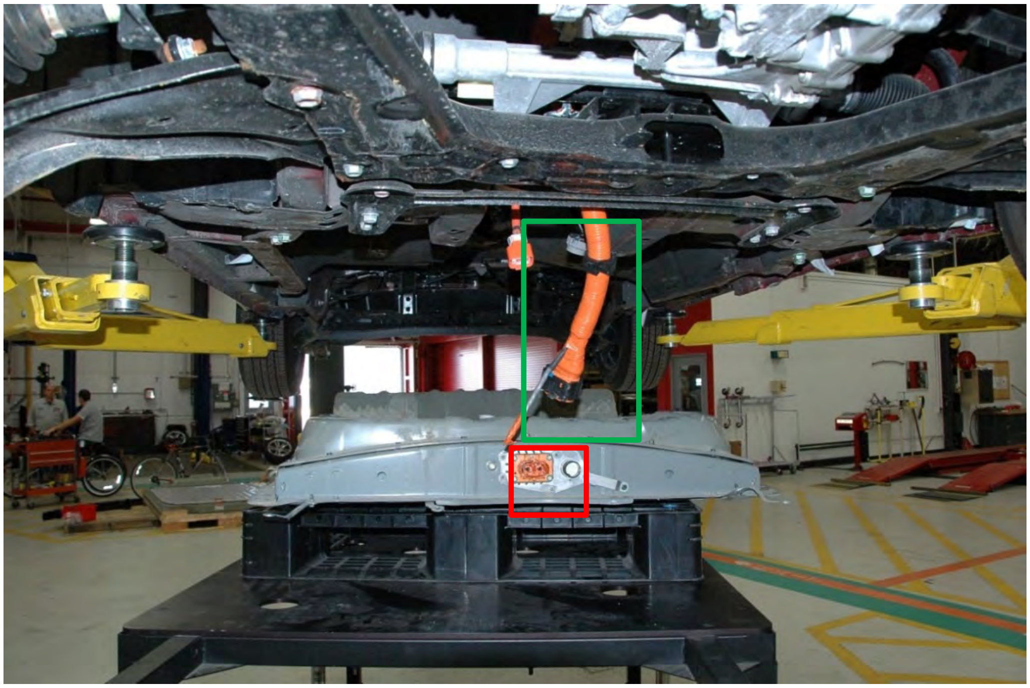

Figure 18 - Manufacturer C vehicle; RESS high voltage connection. The high voltage cable from the vehicle (green box) connects directly to the RESS (red box). The RESS was removed from the vehicle for demonstrative purposes. The high voltage connection can be accessed without RESS removal.

Figure 19 - Manufacturer C vehicle; high voltage cable connector.

8.2 Example Test Results: Manufacturer A Vehicle

8.2.1 Preconditioning Test Results

The RESS from Manufacturer A was subjected to the 5000 mile preconditioning sequence while installed in a durability test vehicle that was produced by the same manufacturer (Figure 20). The RESS was production quality and unused at the beginning of preconditioning (other than the cycles which were required during assembly).

The manufacturer provided a design weight and ballasting diagram for the vehicle. Prior to preconditioning, its weight was measured at both the front and rear axles (Table 9). During preconditioning, the vehicle weight condition was based on the manufacturer's recommendation that 5% of testing be with no ballast (i.e., curb weight) and 95% of testing be at the vehicle design weight (Table 10). The tire pressure was also set to specification (Table 11).

Following a shakedown drive on the test track, the vehicle was subjected to the preconditioning test events summarized in Table 12. The specific test sequence is shown in Table 13 and the corresponding recorded data are provided in Table 16.

Phase 1 of preconditioning included approximately half of the planned WOT + RR drives on a test track that was 1.22 miles long. It contained a mixture of wide open throttle accelerations, decelerations that engaged the vehicle regenerative braking system, and traverse of rope (Figure 21) and wave (Figure 22) roads for applying vibrational and torsional loads. Elements of the WOT + RR pattern are described in Table 37 and Table 1.

The speed profile is shown in Table 17. 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% using a mixture of Level 2 and Level 3 charging systems.

Phase 2 preconditioning included approximately half of the planned high speed drives with the vehicle installed on a dynamometer that was equipped with a velocity matching fan. The high speed driving pattern, shown in Figure 23, was conducted in rapid succession with periodic pauses for charging using a Level 3 charger.

Phase 3 preconditioning included another quarter of the planned WOT + RR drives along with other interspersed events, 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 L 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, and 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. Ideally, the vehicle would have instead been allowed to thermalize at 45°C before charging was 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. Ideally, the vehicle would have instead been allowed to thermalize at -30°C before charging was initiated.
- Ambient temperature charging was accomplished by using a mixture of Level 2 and Level 3 chargers.

Phase 4 preconditioning consisted of the remaining planned high speed drives using the same setup as the second phase of testing. The vehicle was recharged as needed using a Level 3 charger.

Phase 5 preconditioning began with a city route drive and rain booth exposure. Recharging was accomplished with a public Level 2 charger. The remaining WOT + RR drives were then completed with other interspersed events, including hot chamber charging, cold chamber charging, drizzle booth charging, a car wash, and RESS removal and re-installation. Drizzle booth charging (Figure 28) 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 2 and Level 3 chargers.

After preconditioning, the RESS was removed from the durability vehicle and installed in a test vehicle (i.e., a production vehicle from Manufacturer A, see Figure 29). The test vehicle was aligned and inspected by Manufacturer A. It was deemed appropriate for sequential testing despite having suffered mechanical damage to body components.

Table 9 - Durability Vehicle Weight

Vehicle Position	**Total**
Front Axle	2202 lbs
Rear Axle	2476 lbs
Total	4678 lbs

Table 10 - Vehicle Weight Conditions Used for Preconditioning Testing

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

Table 11 - Durability Vehicle Tire Pressures

Vehicle Position	**Left Hand Side**	**Right Hand Side**	**Specification**
Front Axle	38 psi	38 psi	38-42 psi
Rear Axle	40 psi	40 psi	40-42 psi

Table 12 - Summary of Vehicle Preconditioning Events

Preconditioning Event	**Miles Driven**	**Other Events**	**Minimum Required**
WOT + RR mileage	4664		2500
High Speed mileage	2679		2000
Mountain Route mileage	413		400
City Route mileage	148		90
Gravel road mileage	18		10
Vehicle repositioning mileage	494		0
Mountain Route corners		2000	2000
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 hours/charge)		21 hours	20 hours
Hot Charge (approximately 5 hours/charge)		23 hours	20 hours
Drizzle Charge (approximately 5 hours/charge)		19 hours	20 hours
Car Wash		2	2
Salt Spray		1	1
Rain Booth hours		0.66 hours	0.5 hours
HV Pack Removal & Reinstall		1	1
Level 2 charging hours (ambient temperature)		128	
Level 3 charging hours (ambient temperature)		159	
Total Preconditioning Distance	**8416**		5000

Table 13 - Sequencing of Preconditioning Events

Phase	Driving Profile	Driving Start Date	Charging / Event	Charging Start Date
1	WOT + RR (2388 miles)	10/11/2013	Mix of Level 2 and Level 3 charging	10/11/2013
2	High Speed (1238 miles)	10/25/2013	Level 3 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 (226 miles) and Gravel Route (18 miles)	10/30/2013	Level 2 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 2 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 (1441 miles)	11/3/2013	Level 3 charging	11/3/2013
5	City Route (148 miles)	11/5/2013	Level 2 charging	11/5/2013
	Rain Booth	11/6/2013		
	WOT + RR (790 miles)	11/6/2013	Level 3 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 2 and Level 3 charging with other charging	11/12/2013
			Cold Chamber	11/13/2013
			Cold Chamber	11/13/2013
			Drizzle Chamber	11/13/2013

Table 14 - WOT + RR Pattern Elements Used for Manufacturer A Preconditioning

Pattern Elements	Distance
Total pattern length	1.22 miles
Vertical input pattern (rope road, see Figure 21)	0.07 miles
Torsional input pattern (wave road, see Figure 22)	0.07 miles

Table 15 - WOT + RR Speed Profile Used for Manufacturer A Preconditioning

Speed	Operation	Number per Pattern
0 – 80 mph	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

Figure 20 - The durability vehicle used to apply the preconditioning sequence.

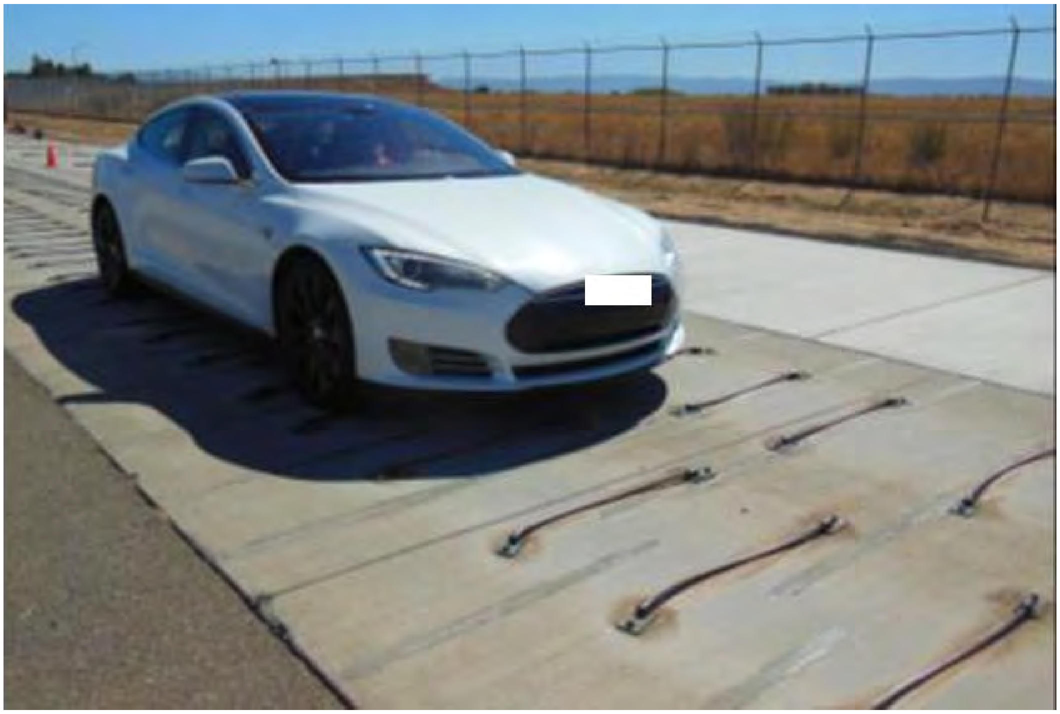

Figure 21 - An example of a vehicle on a rope road (i.e., rough road element).

Figure 22 - An example of a vehicle on a wave / sinusoidal road (i.e., rough road element).

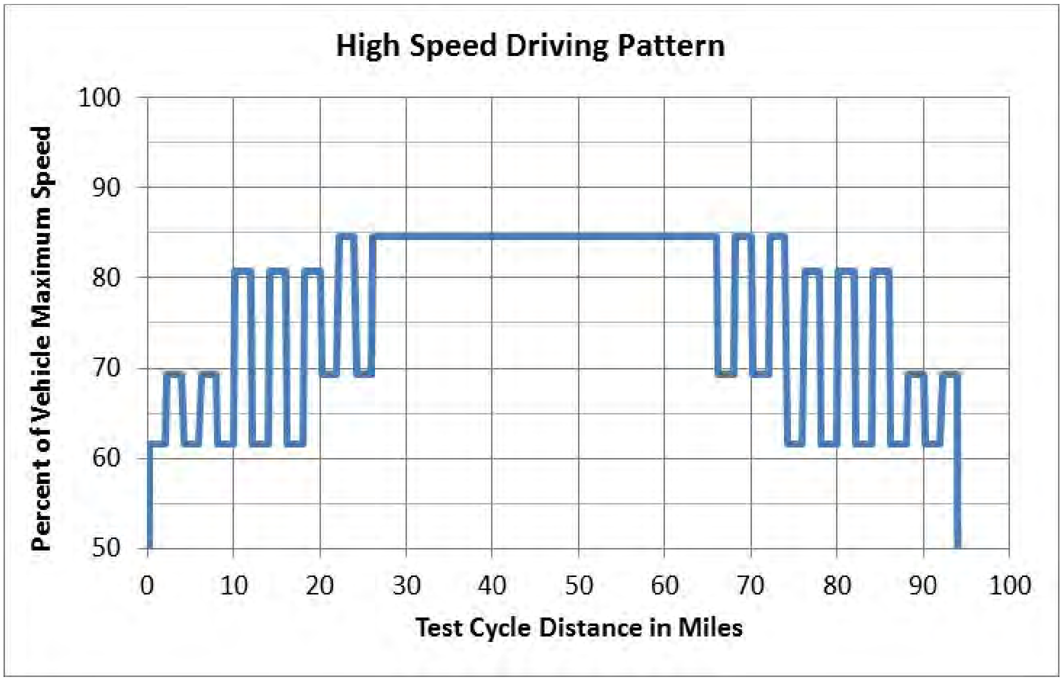

Figure 23 - High speed test pattern used for the Manufacturer A vehicle preconditioning.

Figure 24 - Salt spray applicator (left) and an example of a vehicle after salt spray application (right).

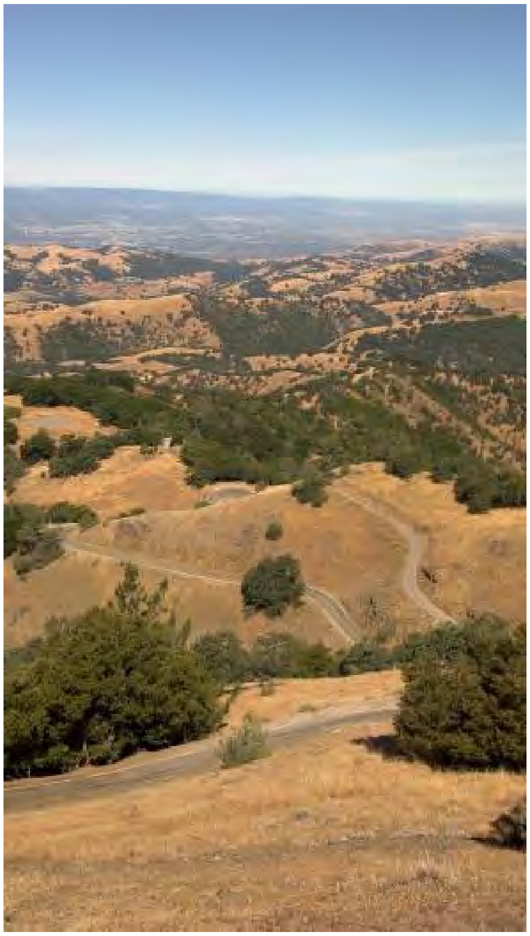

Figure 25 - Switchbacks on a mountain route.

Figure 26 - An example of gravel road driving.

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

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

Figure 29 - The test vehicle used for sequential testing.

Table 16 - 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 Sequential Test Results: General Procedures

During sequential testing, data were logged on a regular basis. The Manufacturer A vehicle internal CAN bus provided RESS voltage, current, SOC, maximum module temperature, and minimum module temperature. The measured SOC was used as a minimum estimate for remaining battery power. Additional data, such as chamber ambient temperatures, were recorded manually as required. Had smoke, fire, or another anomalous condition occurred, they would also have been manually recorded.

All discharge cycles were conducted using a dynamometer. For the Manufacturer A vehicle, a speed of 70 mph on a steep simulated grade was used for the RESS maximum sustained discharge power load. The power request was controlled using a manual pedal that required periodic position adjustment as the vehicle temperature changed and the operating system adjusted the amount of power delivered. 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 (e.g., see Figures 32 and 34 below).

8.2.3 Sequential Test Results: Charge and Discharge During Low Temperature Conditions

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

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

The test results are summarized in Table 17 and Figures 31 through 33. For Charge #1, the vehicle was connected to a Level 3 charger. The RESS did not allow charging to occur, which is a normal vehicle response to low RESS temperature with heating disabled. There was no change in 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 220).

Figure 32 shows the data collected during Discharge #1. The RESS power level was maintained manually; thus, the discharge current shows a sawtooth pattern due to the iterative process of increasing pedal position as the voltage dropped. The discharge current increased with decreasing RESS voltage (i.e., the power remained approximately constant at 70 kW) until a low SOC was reached, at which point the vehicle responded by limiting output power; a normal response. The vehicle normally terminated the discharge process when 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 was successfully initiated under these conditions, but the current was limited to approximately 18 A while the SOC was below 2.6%; a normal response. Once the SOC exceeded 2.6%, the charging current rose to approximately 270 A (typical of Level 3 charging) and charging proceeded normally. The 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 charge 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 17 - Summary of Charge and Discharge Results for the Low Temperature Test

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	−15.5°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 installed on the dynamometer. Solar load lights are used to provide illumination for the image, but were not used during testing. The coiled Level 3 charge cable can be seen on the left.

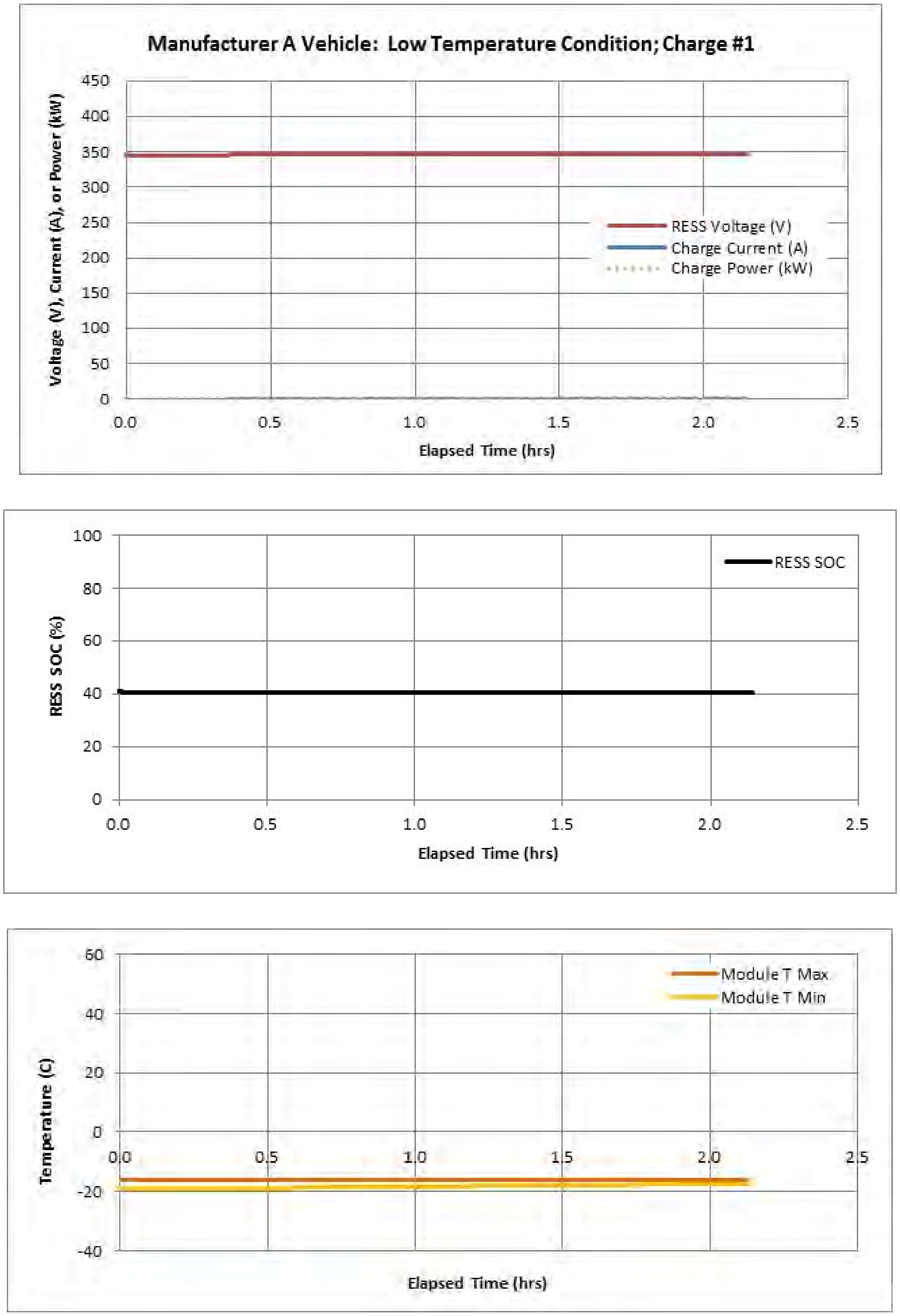

Figure 31 - Low temperature test; measured voltage, current, SOC, and temperature during Charge #1 at −20°C after an 18 hour soak. The vehicle did not allow charging, thus the RESS voltage and SOC remained constant.

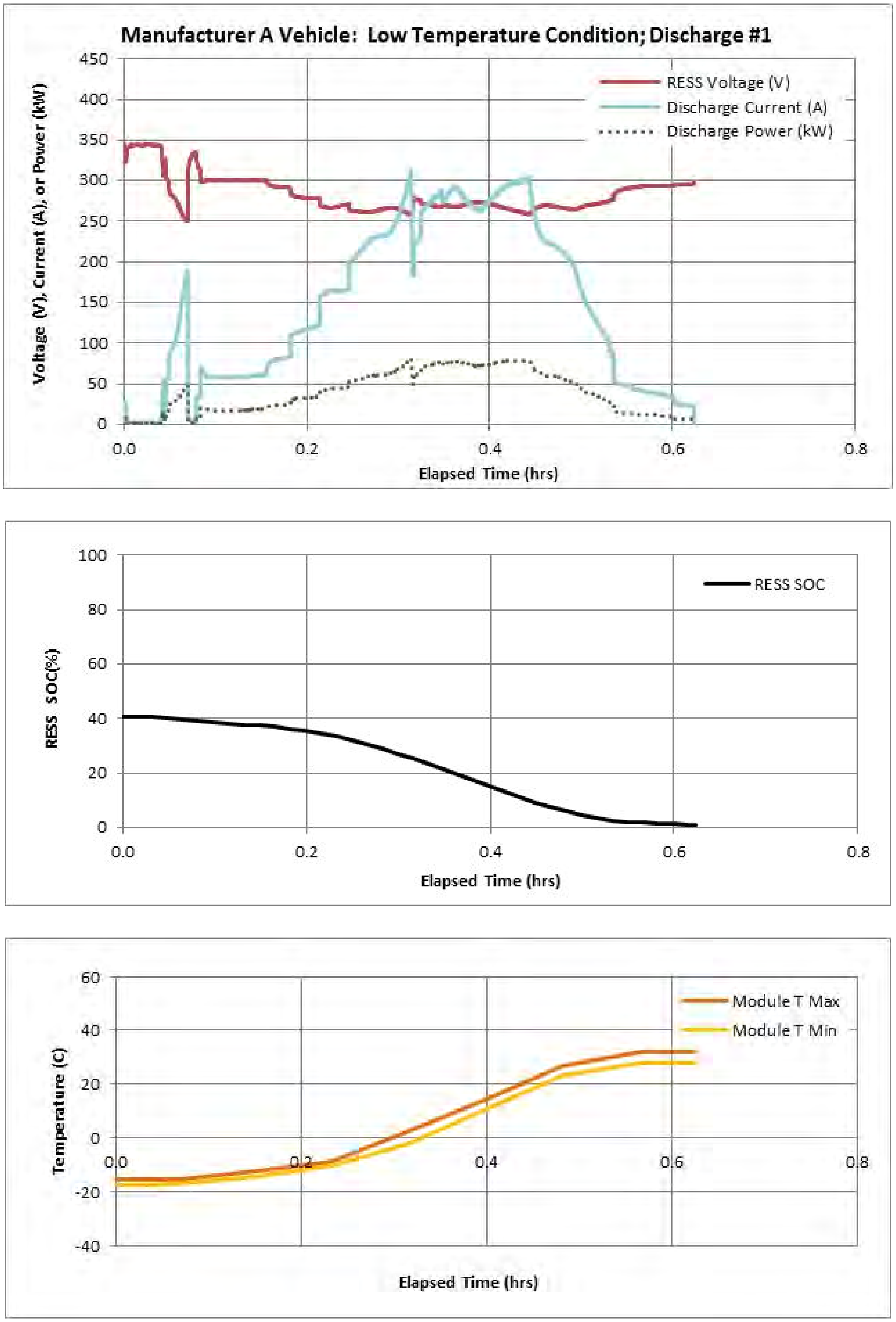

Figure 32 - Low temperature test; measured voltage, current, SOC, and temperature during Discharge #1 at −20°C.

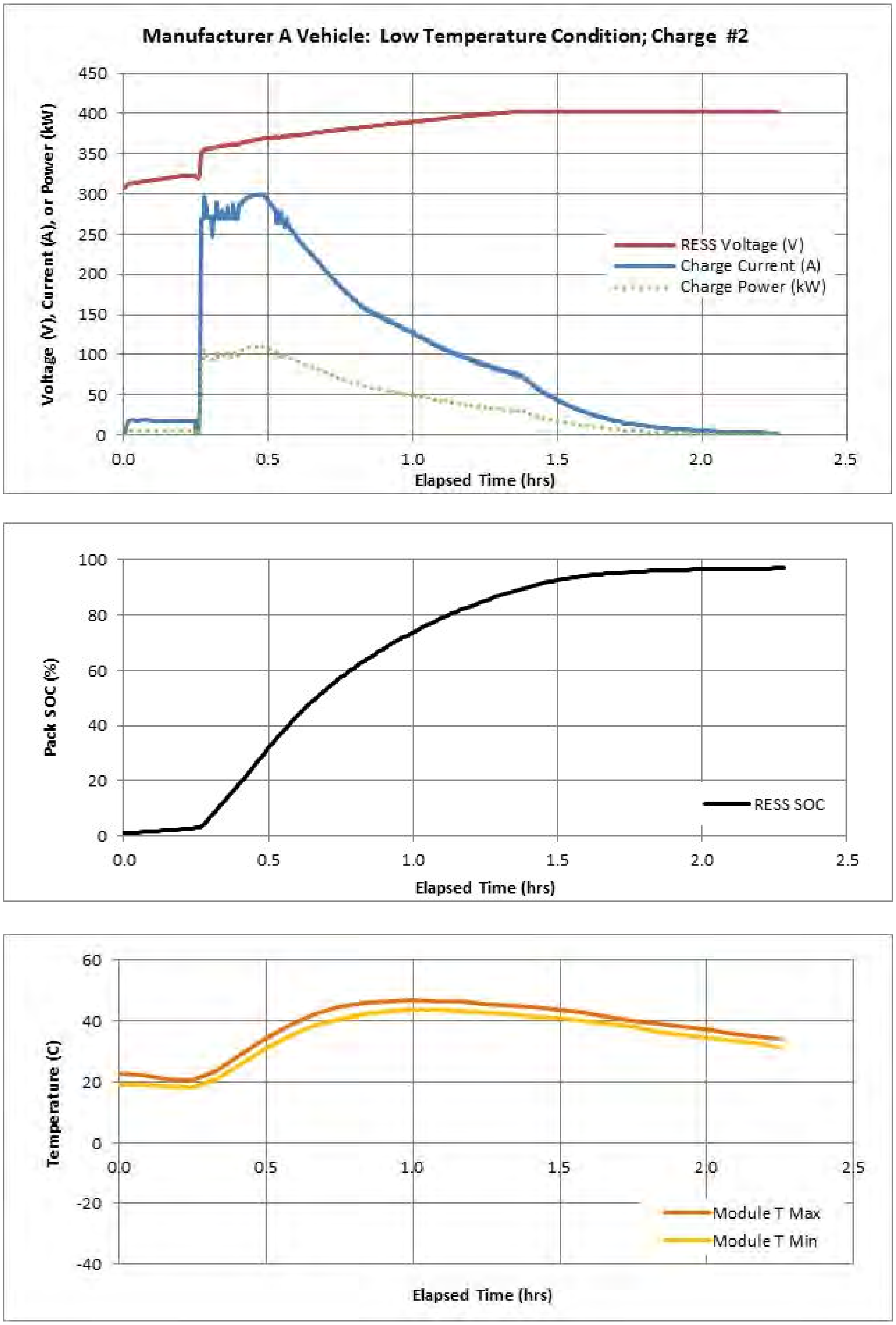

Figure 33 - Low temperature test; measured voltage, current, SOC, and temperature during Charge #2 at −20°C.

8.2.4 Sequential Test Results: Charge and Discharge During High Temperature Conditions

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

The RESS was brought to 100% SOC; the test vehicle was then 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 were within 40±2°C.

The test results are summarized in Table 18 and Figures 34 through 36. For Discharge #1 (Figure 34), the pedal position was increased until the discharge power reached approximately 70kW. The RESS power level was maintained manually; thus, the discharge current shows a sawtooth pattern due to the iterative process of increasing pedal position as the voltage dropped. When the RESS temperature reached approximately 60°C, its output power was limited to approximately 25 kW; a normal response. The output power continued to be limited and the RESS temperature did not increase any further. After approximately one hour at a 25 kW power output, the RESS reached 5% SOC and discharge was manually terminated for experimental convenience (this avoided the low SOC charging regime that would have limited the charge current and delayed the next stage of testing).

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

For Discharge #2 (Figure 36), the RESS temperature was slightly below 60°C, so the pedal position was increased until the discharge power reached 70 kW. When the RESS temperature reached 60°C, its output power was limited to approximately 25 kW; a normal response. The output power continued to be limited and the RESS temperature did not increase any further. When the RESS reached 5% SOC, discharge was manually terminated for experimental convenience.

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

Table 18 - Summary of Charge and Discharge Results for the High Temperature

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	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

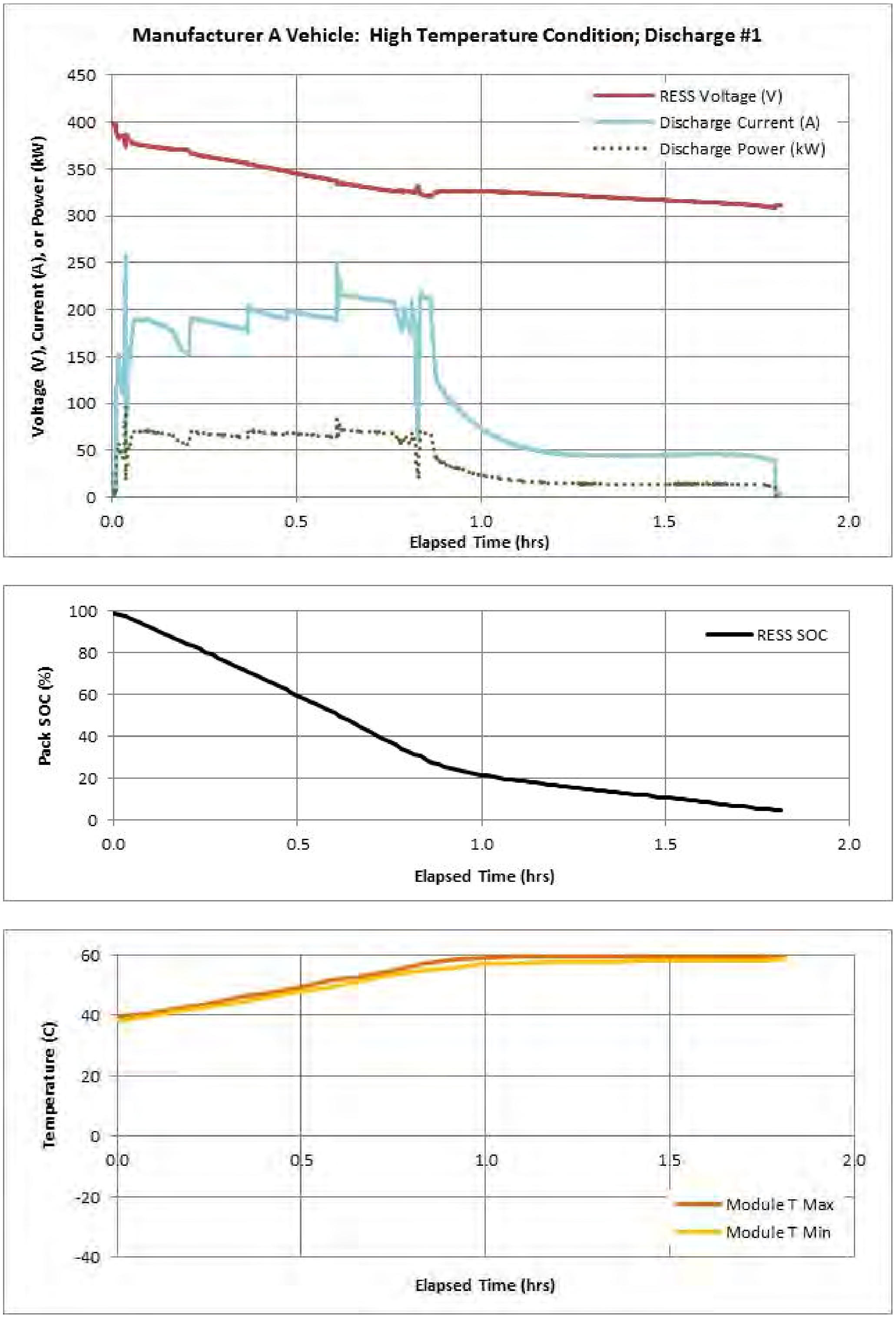

Figure 34 - High temperature test; measured voltage, current, SOC, and temperature during Discharge #1 at 40°C.

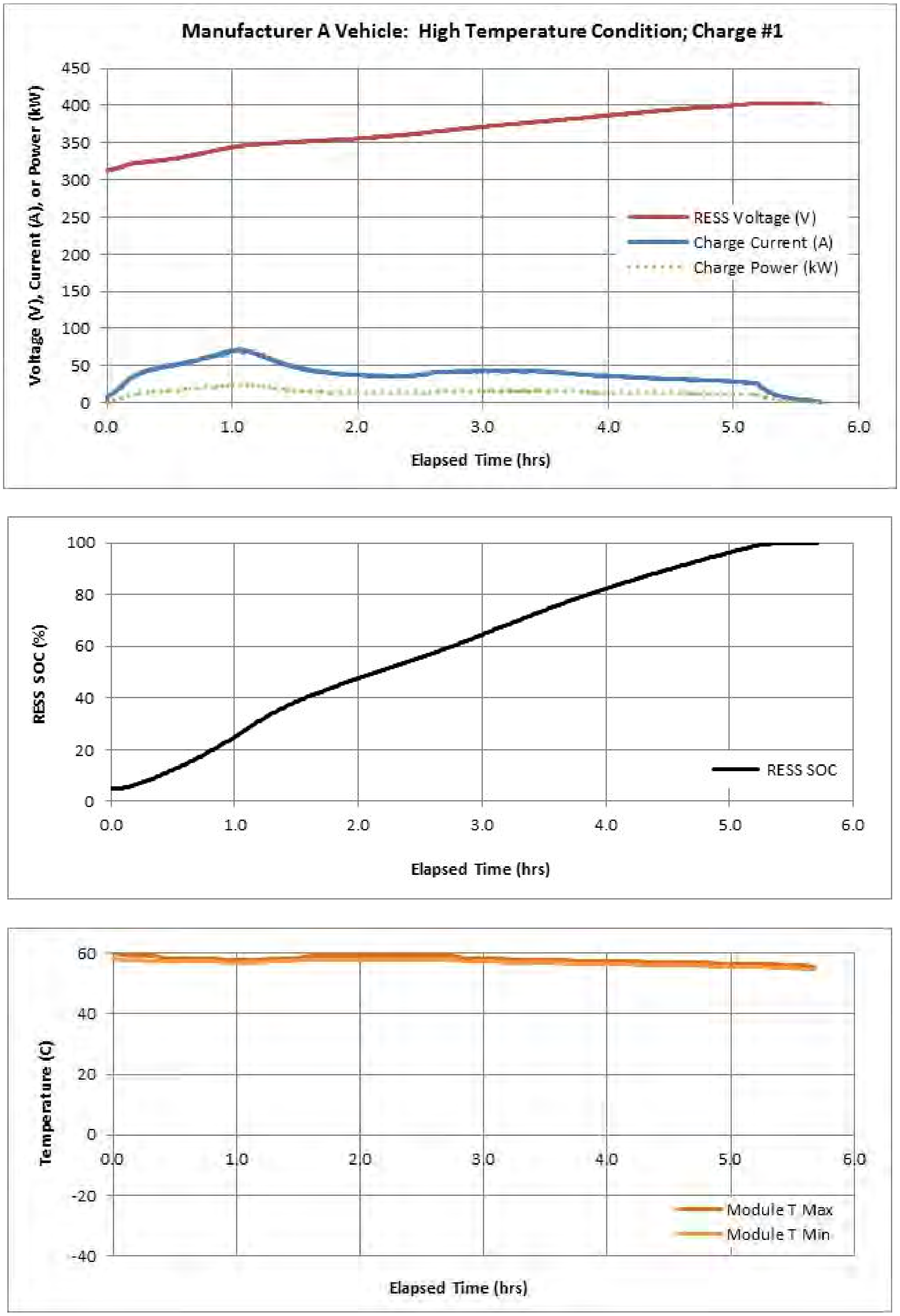

Figure 35 - High temperature test; measured voltage, current, SOC, and temperature during Charge #1 at 40°C.

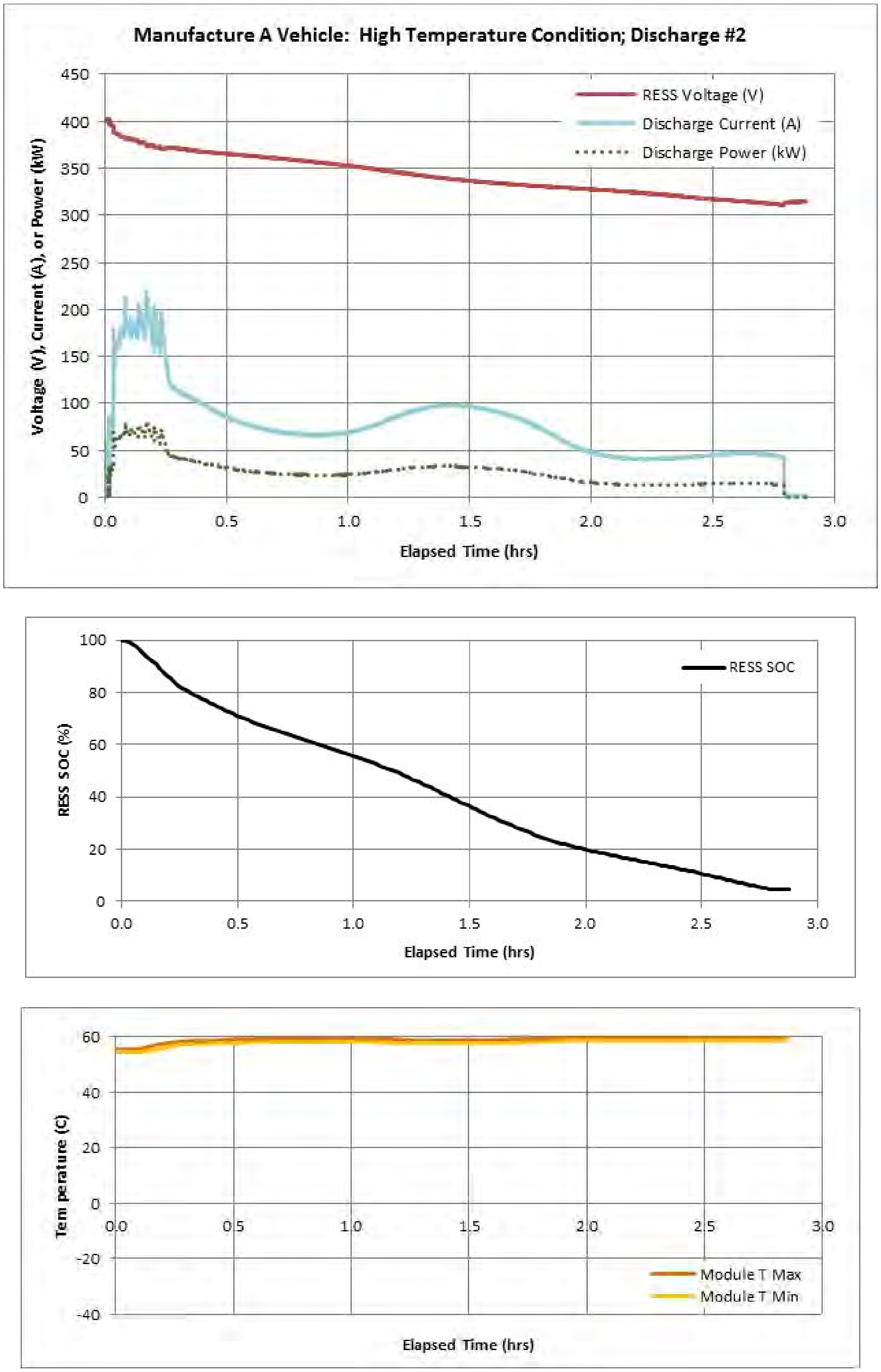

Figure 36 - High temperature test; measured voltage, current, SOC, and temperature achieved during Discharge #2 at 40°C.

8.2.5 Sequential Test Results: Over-Discharge

The over-discharge test was conducted with a DC link connection to the test vehicle (see Sections 7.3 and 8.1). The RESS was isolated by removing the first responder cut loop; this prevented the RESS from closing its contactors. The High Voltage Interlock (HVIL) system circuit was also opened; this prevented the vehicle from delivering 12 V power to keep the contactors closed. The rear seats were removed to expose the high voltage junction box. DC link cables were installed as shown in Figures 15 and 37. Once the DC link cables were installed, the HVIL circuit was closed and the first responder loop was re-installed. A 199Ω resistor was used in the DC link for a maximum rated power discharge of up to 3 kW. A flow of cold air was maintained to ensure that the discharge resistance remained constant throughout the test.

The test results are summarized in Table 19 and Figures 38 and 39. The RESS was at approximately 12% SOC when testing was initiated. The vehicle was placed in drive mode, but the accelerator was not depressed (i.e., it remained stationary). The DC link discharge resistor was placed into the circuit and allowed to discharge the RESS with a current draw of approximately 2 A, resulting in a discharge power of less than 1 kW (Figure 38). After approximately 4 hours, when the SOC approached 8%, the RESS terminated the discharge; a normal response. The DC link was then removed from the circuit.

The test vehicle was placed into charge mode and connected to a Level 1 charger. It was allowed to charge to the point where drive mode would engage if the charger was unplugged.

For the charge mode over-discharge attempt, only the AC supply side of the charge cable was disconnected while the vehicle was still in charge mode (i.e., the cable was still attached to the vehicle). The DC link discharge resistor was placed into the circuit and allowed to discharge the RESS with a current draw of approximately 2 A, resulting in a discharge power of less than 1 kW (Figure 39). After approximately 1 hour, when the SOC approached 7%, the RESS terminated the discharge; a normal response. The DC link was then removed from the circuit.

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

Table 19 - Summary of Drive and Charge Mode Results for the Over-Discharge Test

Operation	Drive Mode	Charge Mode
Time (hours)	4.2	N/A
Initial SOC	12%	8%
Final SOC	8%	7%
SOC change	-4%	-1%
Maximum RESS Temperature	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 on the lower left.

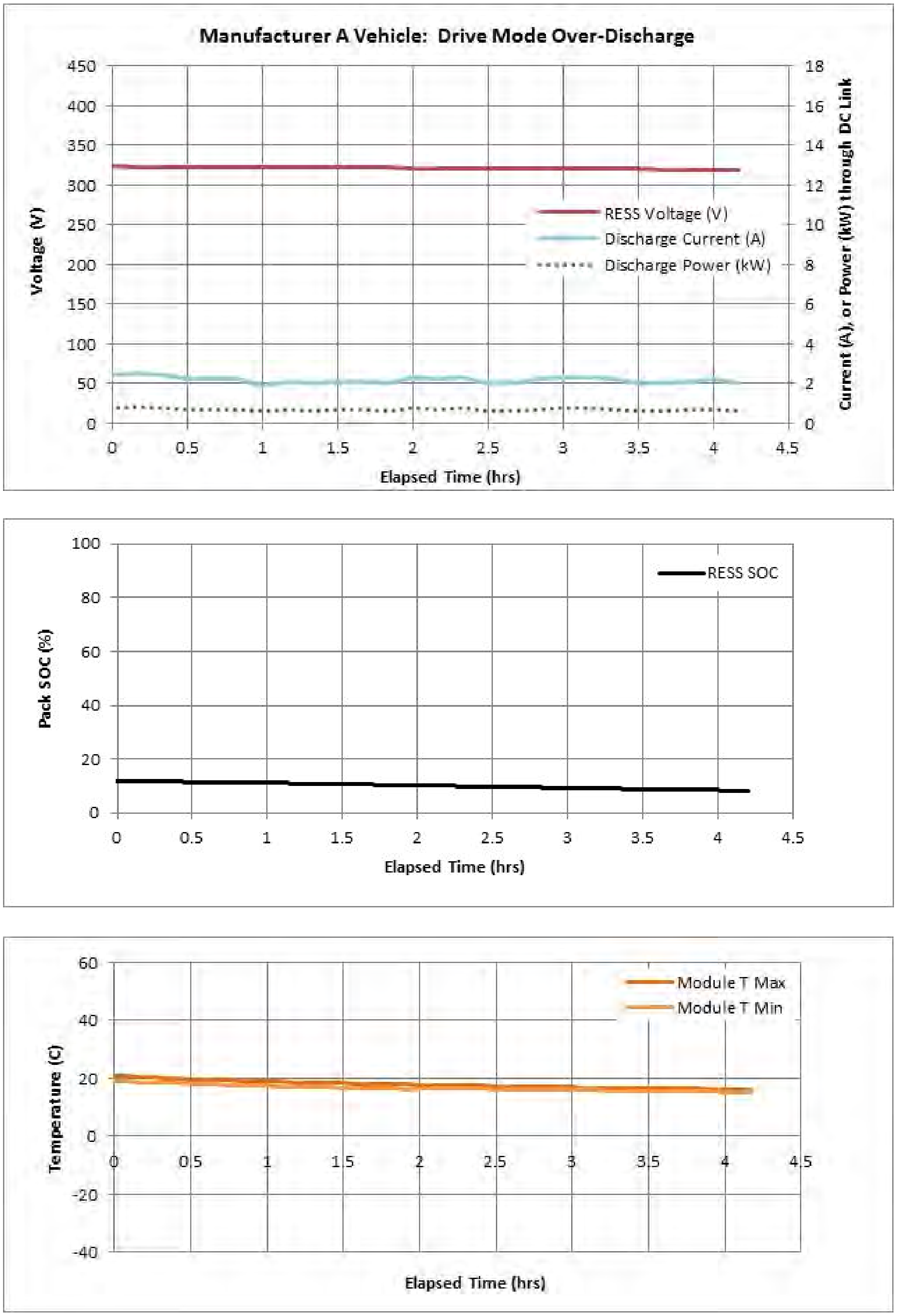

Figure 38 - Over-discharge test; measured voltage, current, SOC, and temperature during drive mode.

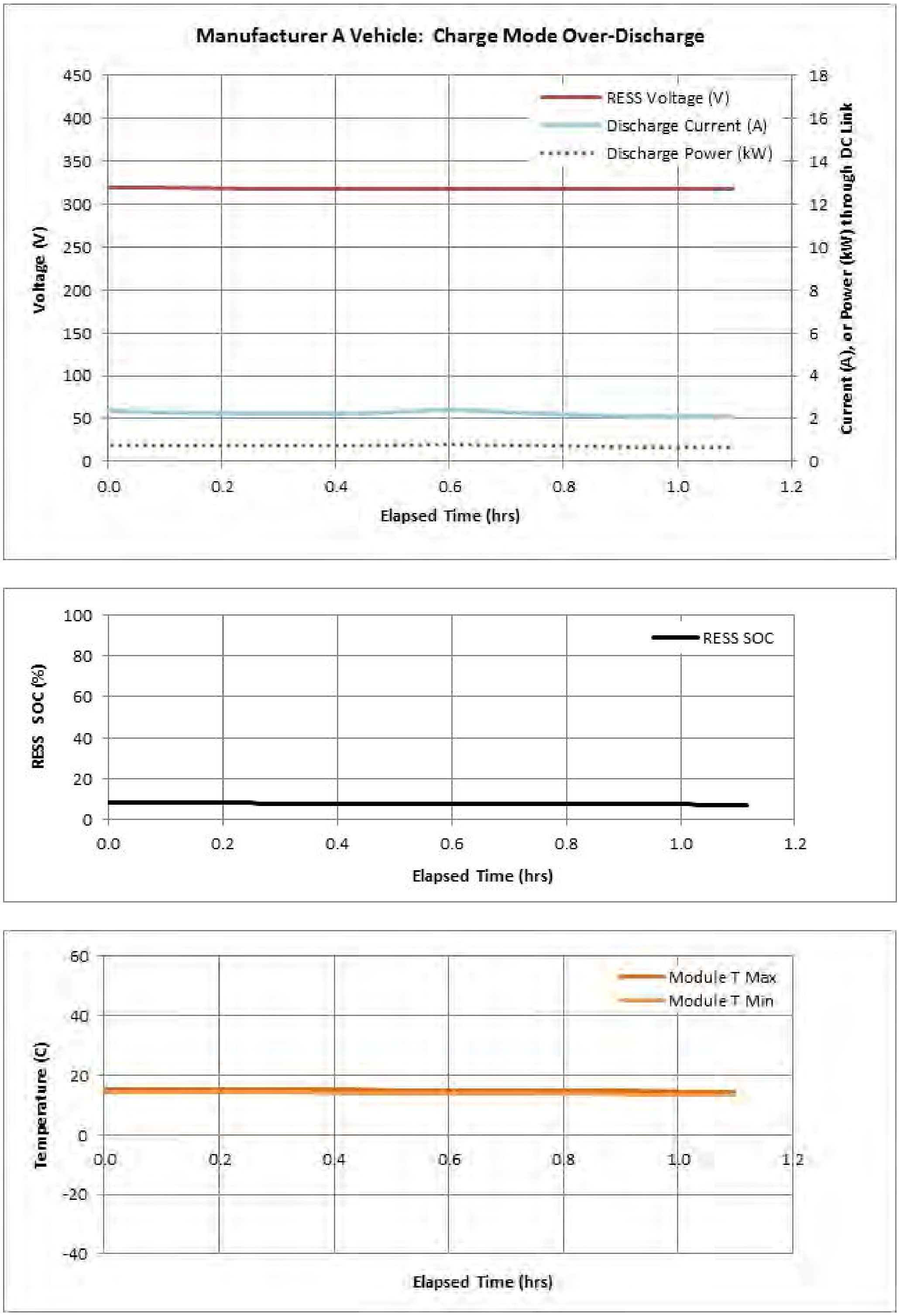

Figure 39 - Over-discharge test; measured voltage, current, SOC, and temperature during charge mode.

8.2.6 Sequential Test Results: Overcurrent Overcharge

For the overcurrent overcharge test, the RESS was brought to 95% SOC (i.e., a full charge followed by a 5% SOC discharge using the vehicle cabin heater). Once the DC link connections were verified, a Sorenson DCR-600 DC power supply (Figure 40) was connected as the overcurrent source. The Sorenson power limit (16A at 600 V or 9.6kW) exceeded the overcurrent shutdown limits of the RESS based on Manufacturer A specifications. The test was conducted outdoors in ambient temperatures.

The test results are summarized in Table 20 and Figure 41. The vehicle was connected to a Level 1 charger and the RESS charge current stabilized to 2A at 395 V (0.8 kW) within approximately 30 minutes. The overcurrent source was then activated and linearly increased. The RESS isolated itself from the power supply after 2 minutes, when the current had reached approximately 11.5 A at 396 V (4.6 kW). Although the overcurrent supply remained powered and connected to the DC link for 2 hours following isolation, there was no further charging. 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 20 - Summary of Over-Current Overcharge Test Results

Operation	Over-current overcharge
Time (hours)	2.5
Initial SOC	95%
Final SOC	95.6%
SOC change	+0.6%
Maximum RESS Temperature	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 overvoltage and overcurrent overcharge testing. It is rated for 600 V / 16 A (9.6 kW).

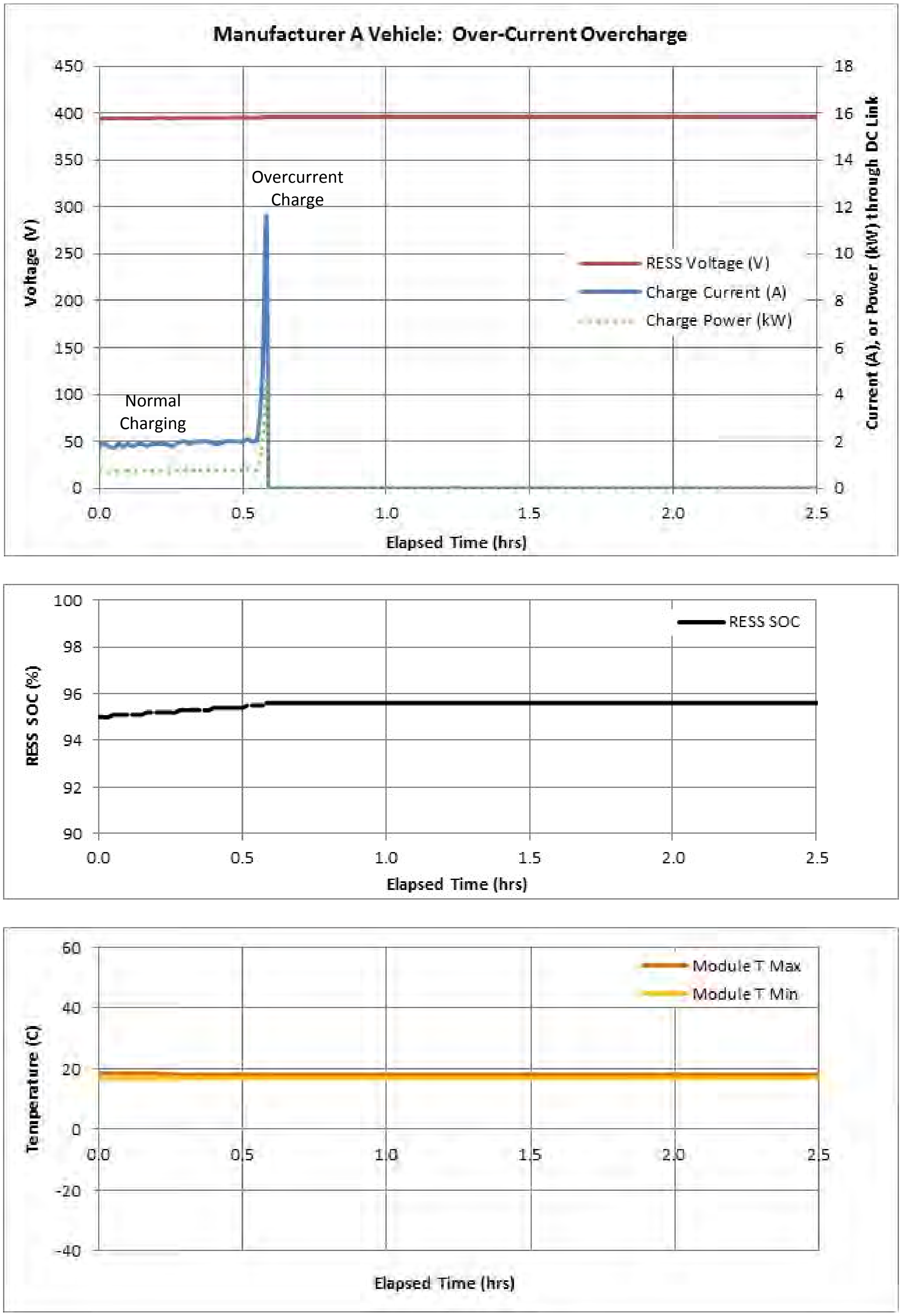

Figure 41 - Overcurrent overcharge test; measured voltage, current, SOC, and temperature.

8.2.7 Sequential Test Results: Overvoltage Overcharge

The RESS was at 96% SOC at the conclusion of the overcurrent overcharge test and was already capable of accepting charge. Once the DC link connections were verified, the Sorenson DCR-600 DC power supply (Figure 40) was connected as the overvoltage source. The voltage limit 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 to achieve the 1.4kW maximum charge rate. The test was conducted outdoors in ambient temperatures.

The test results are sumarized in Table 21 and Figure 42. The vehicle was connected to a Level 1 charger and the RESS charge current stabilized to 1.8A at 395 V (0.7kW) within approximately 10 minutes. The overvoltage source was then activated and the charge current increased to 3 A (1.2 kW applied power). The current remained constant until the RESS reached 100% SOC and charging was terminated; a normal response. The Sorenson remained powered and connected to the DC link for another 2 hours, but there was no further charging. The temperature remained stable throughout the test.

The vehicle suffered minor damage to some electronics when the RESS isolated itself from the external voltage supply. This is because the overvoltage source was set to 600 V instead of 440V, which was significantly higher than the maximum voltage that could be reasonably expected from a faulting charging system. Since the damage would prevent normal charge or discharge operations, minor repairs were completed based on guidance from Manufacturer A before proceeding to the next test. The RESS did not require repair.

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

Table 21 - Summary of Overvoltage Overcharge Test Results

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

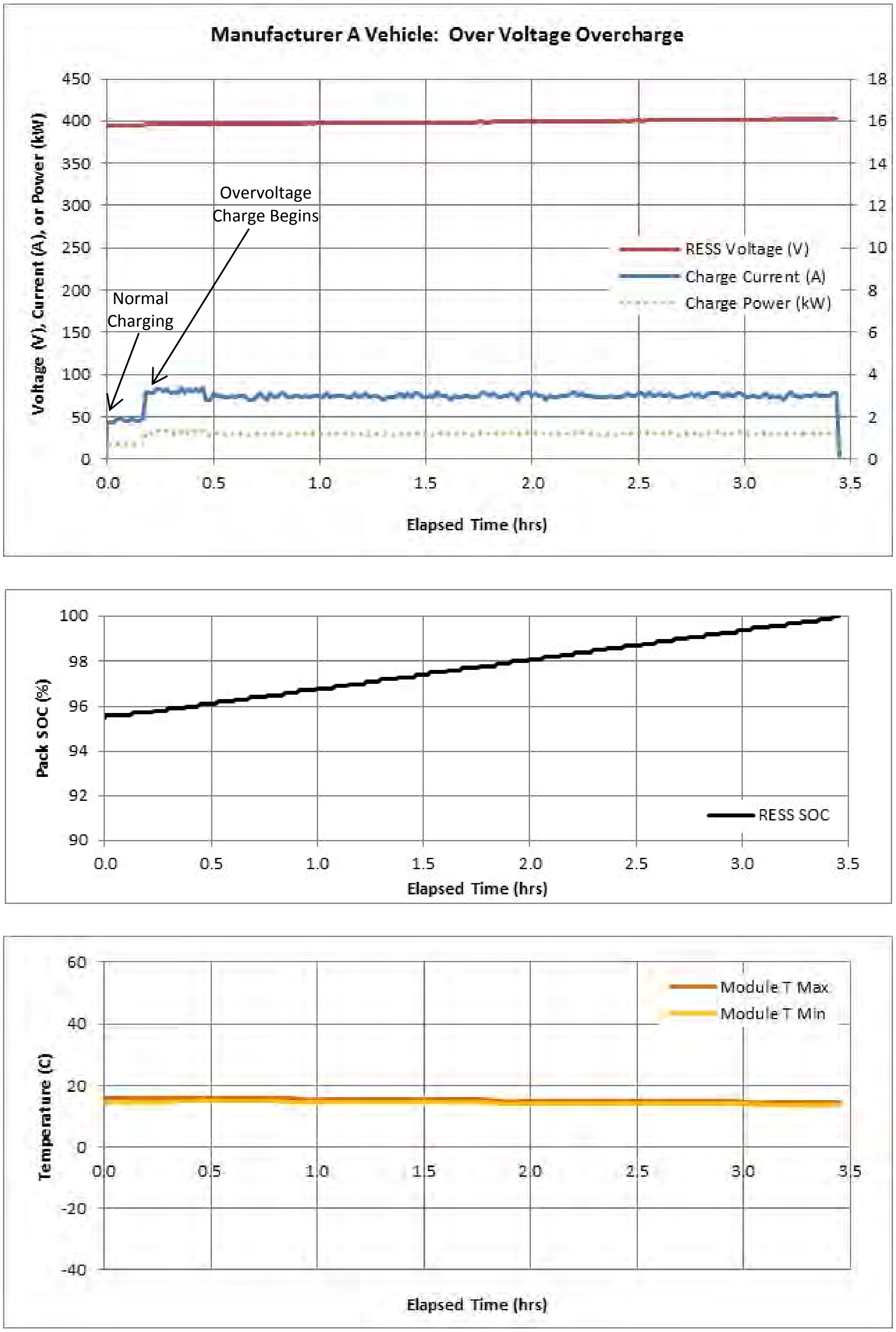

Figure 42 - Overvoltage overcharge test; measured voltage, current, SOC, and temperature.

8.2.8 Sequential Test Results: External Short Circuit

Connections to the DC Link were verified and the short circuit device was connected. It contained two parallel fuses rated at 630 A to protect itself should the vehicle and/or RESS continue to source current. Since the previous test ended at full charge, the RESS was brought to 95% SOC with a 5% SOC discharge using the vehicle cabin heater.The vehicle was allowed to equilibrate to approximately 20°C. The vehicle was placed in drive mode and the device switch on the DC link was closed to activate the RESS short circuit. The test was conducted outdoors in ambient temperatures.

The test results are summarized in Table 22. The RESS interrupted the current flow almost immediately upon short circuit. The vehicle was then monitored for one hour and the RESS temperature did not change. After the short circuit device switch was opened and disconnected from the DC link, the fuses were inspected and found to be intact. This verified 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 22 - Summary of External Short Circuit Test Results

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

8.2.9 Sequential Test Results: Destructive Discharge

Manufacturer A modules were subjected to a destructive discharge after the external short circuit test for demonstrative purposes. Two separate modules were placed in a 30 gallon plastic trash can filled with salt water. After 1-3 days of submersion, the modules were fully discharged and 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 also assessed for destructive discharge by salt bath, but the following concerns were raised:

- Although full RESSs have been successfully subjected to this method in the past, they have generally contained a fraction of the energy contained in this particular battery pack.

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

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

Thus, the results of this assessment indicated that destructive discharge should be conducted at an individual module level, which was already demonstrated.

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

VEHICLE WATER IMMERSION TEST

Test Procedure and Report

1. PURPOSE

Electric propulsion in a Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV) and Electric Vehicle (EV) platform relies on Rechargeable Energy Storage Systems (RESSs), commonly referred to as batteries. However, the automotive application and use of a RESS poses certain potential risks to vehicle operators and occupants that are different than those associated with an internal combustion engine. Seawater immersion of a RESS-based vehicle is a reasonably foreseeable hazard due to accidents or natural disasters. The purpose of this test procedure is to evaluate the potentially hazardous reactions of low voltage (LV) and high voltage (HV) components of a RESS vehicle while a) submerged in a conductive seawater solution and b) during the storage period afterwards.

2. SCOPE

This test procedure is applicable to all RESS-equipped HEV, PHEV and EV platforms. Specific guidance has been provided for application of the procedures to Li-ion based systems as it is the dominant chemistry in RESSs at the time of this writing. However, the approach provided could also be applied to a range of other cell chemistries. The scope includes a standardized immersion test with a specific salinity level followed by a 28-day observation period once the seawater has been pumped out. The procedure is composed of four parts:

- Pre-immersion: equipment and sensor setup
- Immersion: submerging the test vehicle in seawater within 10 minutes
- Extraction: pumping out the seawater within 10 minutes after 2 hours of immersion
- Post-extraction: observing the RESS behavior for a specified storage period

For statistical purposes, multiple samples could be tested with the procedures described herein. The immersion containers should be at least 1.0 m apart for safety reasons and the pumping hoses that are used to transfer seawater from the mixing tank should be long enough to comfortably reach the farthest container. Though outside the scope of this document, some samples may also be subjected to accelerated aging to determine the effects of immersion on RESS life and performance.

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 the Society of Automotive Engineeres (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 J2464 Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing (Section 4.35)
- SAE J2929 Electric and Hybrid Vehicle Propulsion Battery System Safety Standard - Lithium-based Rechargeable Cells (Section 4.4)

3.1.2 SNL Publications

Available from Sandia National Laboratories (SNL): 1515 Eubank SE, Albuquerque, NM 87123, Tel: 505-844-8066, www.sandia.gov.

- SAND2005-3123 FreedomCAR Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications (Sections 2.2.5 and 3.4)

3.1.3 UL Publications

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

- UL 2580 Batteries for Use in Electric Vehicles (Section 29)
- UL 2271 Batteries for Use in Light Electric Vehicle (LEV) Applications (Sections 38 and 39)

3.1.4 ISO Publications

Available from International Standards Organization (ISO) Central Secretariat: 1, ch. de la Voie-Creuse CP 56, CH-1211 Geneva 20 Switzerland, Tel.: +41-22-749-01-11, www.iso.org.

- ISO 6469-1 Electrically propelled road vehicles – Safety specifications – Part 1: On-board rechargeable energy storage system (RESS)
- ISO 6469-2 Electrically propelled road vehicles – Safety specifications – Part 2: Vehicle operational safety
- ISO 6469-3 Electrically propelled road vehicles – Safety specifications – Part 3: Electrical safety
- ISO 20653 Degrees of protection (IP code) – Protection of electrical equipment against foreign objects, water and access

3.1.5 US DOT Publications

Available from the United States Department of Transportation (US DOT) National Highway Traffic Safety Administration (NHTSA): 1200 New Jersey Avenue, SE West Building Washington, DC 20590, Tel: 202-366-4000, www.nhtsa.gov.

- Federal Motor Vehicle Safety Standards (FMVSS) 305 Electric Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection

- DOT HS 811 573 Chevrolet Volt Battery Incident Overview Report, January 2012

3.1.6 NRC Publications

Available from the National Research Council (NRC): http://www.nap.edu/catalog.php?record_id=11170.

- "Emergency and Continuous Exposure Guidance Levels for Selected Submarine Contaminants" Volume 1 (2007)

3.2 Related Publications

N/A

4. DEFINITIONS

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

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. It calculates and communicates battery status and state of function to the vehicle system for energy flow management. In the event of a system failure, the BMS can also open contactors and isolate the battery from the rest of the hybrid system.

Battery Module

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

Bus or Bus Bar

An electrical conductor that consists of a metallic strip or bar for local high current power distribution.

Cell Imbalance

The degree of variation in state of charge (SOC) for each cell within a RESS.

Contactor

A switching device typically found in a battery pack that is used to connect or disconnect the positive and/or negative bus.

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).

EV: Electric Vehicle

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

Hazard Severity level (HSL)

A rating system that categorizes the severity level of a RESS reaction to abuse conditions.

HEV: Hybrid Electric Vehicle (HEV)

An automobile type vehicle, powered by an internal combustion engine and an electric motor that draws stored energy from a rechargeable energy storage device for power assist.

Hot plate

An aluminum plate with installed electric resistance heaters that provide high temperature surfaces to adjacent cells.

Key On

The ignition position that enables accessory vehicle functions.

Key Start

The ignition position that enables vehicle mobility.

Material Safety Data Sheet (MSDS)

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

PHEV: Plug-in Hybrid Electric Vehicle

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

Personal Protective Equipment (PPE)

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

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.

Short Circuit

The flow of current along an unintended path with no or very low electrical impedance.

State of Charge (SOC)

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

Stranded Energy

Energy contained within a RESS that cannot be removed through a normal discharge (e.g., a damaged RESS).

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 0 V 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.

5. GENERAL TEST REQUIREMENTS

5.1 General Precautions

5.1.1 Conducting immersion testing is potentially hazardous. Test personnel should be aware of high voltage batteries and elevated bus voltages. Safe practices shall be used for both handling samples and conducting test operations.

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

5.1.1.2 Testing should be conducted in an outdoor environment to help ventilate any smoke, flammable vapors, or toxic vapors. The testing agency should also secure necessary burn permits in the event of a vehicle fire.

5.1.2 Testing is conducted with measurements at both high voltage (i.e., 60 V or higher) and low voltage (i.e., less than 60 V).

5.1.2.1 For high voltage (HV) measurements, access inside the RESS enclosure using intrusive and non-reversible changes to the battery pack may be necessary. This will require extra attention from test personnel to potential shock risks during the connections and subsequent handling of an HV wire harness. Appropriate personal protective equipment (PPE) shall be worn at all times when modifying the RESS.

5.1.2.2 Access to low voltage (LV) measurements may also need some intrusion. The exposed electrical terminals shall be protected from shorting to each other, a common chassis, or a local ground. At a minimum, the bus data from the 12 V battery shall be measured at its terminals. However, if another access point is possible without intruding into the 12 V wires (e.g., closer to the RESS), it can serve as a second LV signal closer to the components of interest, such as the battery monitoring board or other battery controller. Appropriate PPE shall be worn at all times when modifying the LV battery.

5.1.2.3 Note that the intrusive measures can be avoided if the required HV and LV data are accessible through the vehicle communication systems (e.g., the Controller Area Network bus data).

5.1.3 Test personnel shall be appropriately trained for the hazards associated with this test and have access to required PPE, which includes Class 0 insulated rubber gloves with leather outer gloves. Always inspect the insulated gloves for any defects that might compromise the insulating properties; do not wear them if they are damaged.

5.1.4 When working on or around high voltage systems, always follow the appropriate safety precautions. Read and follow the recommended service procedures for HV systems and parts.

5.1.5 Ensure that immersion containers, mixing tanks, and other metallic equipment are well grounded per standard practices and electrical codes.

5.1.6 Always observe high voltage warning labels (see Figure 1 for examples).

Figure 1 - Example high voltage warning labels (source: GM First Responder Guide).

5.2 Test-Specific Precautions

5.2.1 While working on a vehicle system, always ensure that the emergency parking brake is actuated if the wheels and tires are on the vehicle. Additionally, block the drive wheels to prevent unintended vehicle movement.

5.3 Safety Requirements

5.3.1 All preparations shall be completed prior to immersing the vehicle. No hands-on work shall be attempted after immersion has started.

5.3.2 Pumping immersion water into or out of the container shall be performed with gasoline powered pumps. Electric pumps shall not be used to avoid the risk of any AC shock hazard.

5.3.3 If a fire erupts during the 28-day post-extraction period, fresh water can be used put the fire out. Standard firefighting and personal protective gear shall be used when fighting a fire.

5.3.4 The immersion container shall be designed such that there are no shock hazards outside the container walls.

5.4 Test Facility/ Equipment Requirements

5.4.1 The following equipment is required to conduct the tests defined in this procedure. Ensure that the equipment scale/range is appropriate for testing.

5.4.1.1 The facility must have access to a suitable immersion container:

- It shall be large enough for a test vehicle with the doors fully open.
- It shall be of steel construction with sufficient wall rigidity and strength to withstand catastrophic vehicle events.
- The interior surfaces shall be painted white for maximum visibility during testing.
- It shall have a non-flammable shelter or roof to provide protection from the elements.

5.4.1.2 The facility must have a gasoline-powered immersion water pump (the pump shall also be used to promote water agitation during immersion).

5.4.1.3 The facility must have a mixing tank that holds sufficient seawater to immerse a vehicle.

5.4.1.4 The facility must have sufficient sea salt crystals (e.g., Dead Sea Works Sun Salt – Fine Sea Salt) to achieve the appropriate salinity level.

5.4.1.5 The facility must have equipment to measure water conductivity, density, and pH.

5.4.1.6 The facility must have temperature sensing capabilities. The thermocouple type shall be suitable for the given temperature range (e.g., type K). They shall be mounted to surfaces with pad type sensors and glued/bonded into place to resist dislocation under fire conditions.

5.4.1.7 The facility must have voltage sensors for both the LV and HV systems (internal and external to the RESS). The sensors shall be electrically isolated small gauge cables with mechanically secured sensing ends.

5.4.1.8 The facility must have gas detection sensors for Chlorine (Cl_2), Hydrogen (H_2) and Methane (CH_4). Gas sensing heads shall be partially sealed within a protective enclosure. The gas sensors shall be mounted a maximum of 30 cm above the longitudinal midpoint of open driver's door. See Section 7.2 for suggested locations.

5.4.1.9 The facility must have a data acquisition system (DAQ) for capturing measured parameters. See Section 7.4 for DAQ measurement rates and rationale.

5.4.1.10 The facility must have standard video recording equipment.

5.4.1.11 The facility must have digital photography equipment.

5.4.1.12 The facility must have an infrared camera to spot-measure thermal behavior and assess risk.

5.5 Test Equipment Calibration

5.5.1 A written calibration procedure shall be provided that includes, at a minimum, the following information for all measurement and test equipment:

- Type of equipment, manufacturer, model number, etc.
- Measurement range
- Accuracy
- Calibration interval
- Type of standard used (calibration traceability of the standard must be evident)

6. TEST PROCEDURE

6.1 Test Type

6.1.1 Vehicle immersion is a potentially abusive test that determines if the RESS and fundamental safety systems continue to function and not pose a significant hazard to the vehicle's occupants or bystanders.

6.2 Device under Test (DUT)

6.2.1 The device under test (DUT) shall be a full vehicle with an installed RESS.

6.2.2 The vehicle shall be resting on the immersion container floor with the wheels chocked and strapped to prevent movement. It shall be tested in the key-on condition following key-start or drive system activation. The drive selector shall be in 'Park', 'Neutral', or the equivalent. See Section 7.3 for rationale of the vehicle state during testing.

6.3 Test Guidelines

6.3.1 Testing will require one vehicle with its RESS. The RESS may be provided by the manufacturer or vehicle OEM (Original Equipment Manufacturer) with the necessary modifications for conducting immersion testing.

6.4 Test Parameters

- Vehicle and RESS beginning of test temperature: 25±5°C
- Ambient outdoor temperature: 25±5°C
- Seawater ambient temperature: 20±5°C
- Beginning SOC of the RESS: 99% to 100% of the maximum normal operating SOC
- Beginning OCV of the LV battery: 12.7±0.5 V
- Beginning energy of vehicle: Fully charged RESS; 5 L of fuel (HEV, PHEV)[1]

6.5 DUT Preconditioning

6.5.1 Vehicle Preparation

6.5.1.1 Document the date and time of receipt for each test vehicle. The VIN for each test sample shall also be documented.

6.5.1.2 Record the vehicle condition including:

- Confirmation that there is no exterior damage (e.g., no visible HV cable damage from crushing, pinching or abrasion, etc.).

- Photograph the test vehicle from all viewpoints to capture and record its condition; note any visual damage.

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[1] See Section 4.0

6.5.1.3 Remove any loose components from both the inside and outside of the test vehicle.

6.5.1.4 Remove all materials from the trunk that can float to avoid obscuring the video camera field of view.

6.5.1.5 Remove or disable all airbags.

6.5.1.6 Remove all gas-assisted struts or dampers.

6.5.1.7 Ensure that the tires are inflated to the manufacturer’s recommended pressure. The minimum tire pressure shall be 2 bar (i.e., 29 psi).

6.5.1.8 If necessary, remove the RESS from the test vehicle to make modifications for HV intrusive measurements. Document and photograph any RESS modifications.

6.5.1.9 Install sensors to enable HV isolation breakdown measurements. The objective is to assess changes in isolation resistance during and after immersion. Results shall be compared to the accepted range of >500 Ω/volt.

The voltage measurements taken at the HV bus shall be made by intruding into the RESS enclosure in the area of the HV contactors (see Figure 2). An external connection to the HV case may also be necessary (see Figure 3).

Isolation resistance measurements shall be taken between the HV bus and the vehicle chassis.

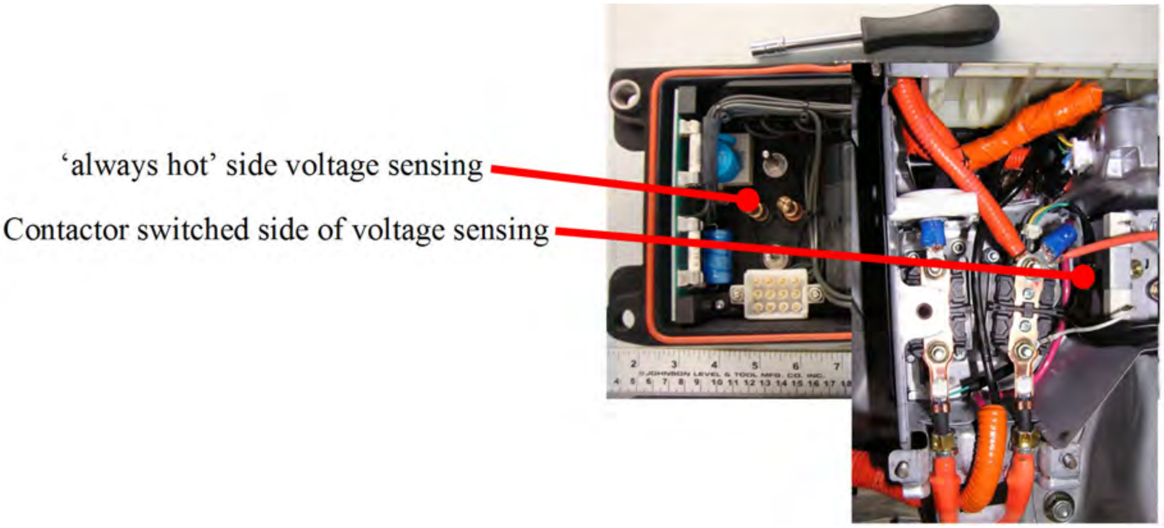

Figure 2 - Example contactor layout in a high voltage RESS.

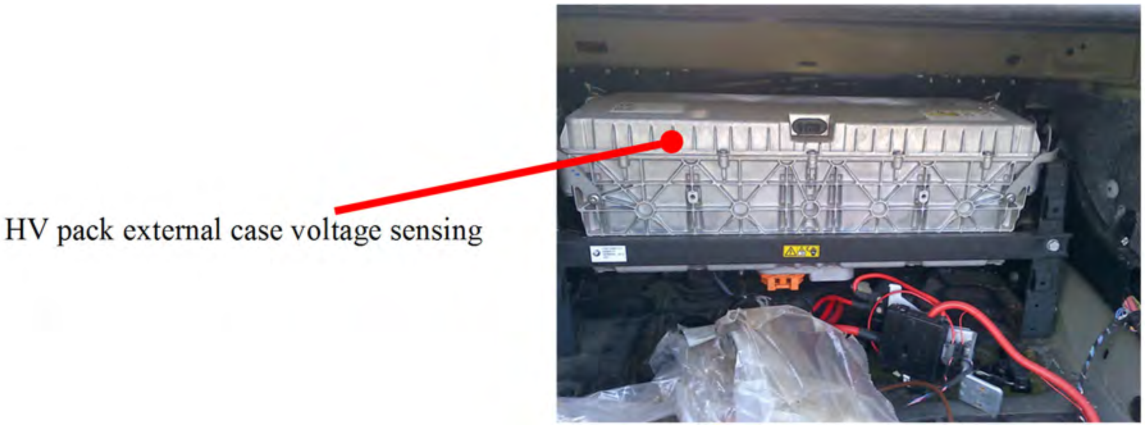

Figure 3 - Example HV RESS external case voltage sensing.

6.5.1.10 If necessary, install the RESS back into the test vehicle after HV sensors have been installed.

6.5.1.11 Check the health of the 12 V battery and replace if necessary to achieve LV minimum working voltage. The LV battery shall be 12.7±0.5 V (see Section 6.4) to ensure that all LV support for the HV system is in place and functioning.

6.5.1.12 Install cabling for LV, temperature, and gas detection sensors and secure them to the vehicle.

6.5.1.13 The temperature shall be measured externally at both the LV and HV battery enclosure. The definition of absolute locations is not critical as long as the thermocouples can sense quick changes so that trends are detected. At a minimum, eight thermocouples shall be placed as follows (for a representative thermal reading, thermocouples should not be placed on cooling fins):

- Four thermocouples on the outside surface of the RESS (see Figure 4). They can be placed on the topmost surface of the battery pack (preferred) or on the underside of the pack; the sensors should be on the RESS enclosure, not a secondary cover over the RESS.

- One thermocouple on the 12 V battery case (see Figure 5).

- One thermocouple on the Battery Electronic Control Module (BECM) (see Figure 6).

- Two thermocouples on the contactors inside the RESS

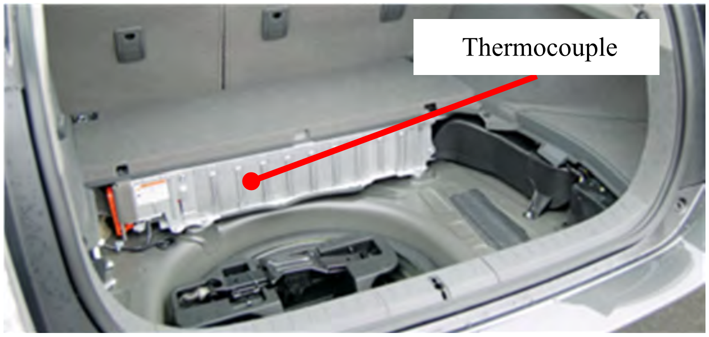

Figure 4 - Example thermocouple placement on the outside surface of an HV traction battery (one sensor shown, the other three sensors should be placed on other surfaces).

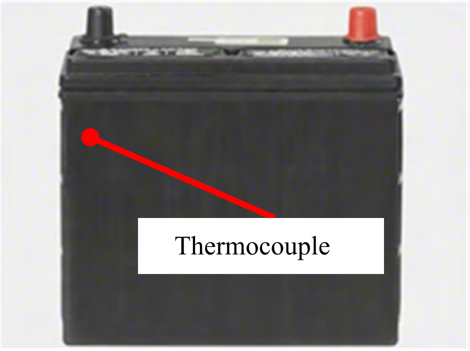

Figure 5 - Example thermocouple placement on the LV battery case.

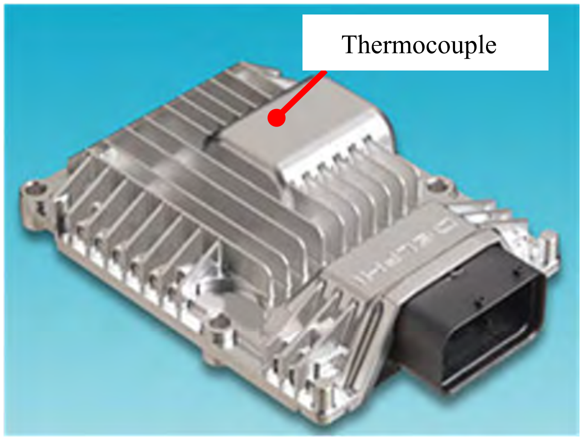

Figure 6 - Example thermocouple placement on the battery electronic control module.

6.5.1.14 Install gas detection monitors that will measure the evolution of chlorine, hydrogen and methane (see Section 7.2 for suggested sensor placement).

6.5.1.15 Verify the integrity of the sensors and cabling when connected to the DAQ.

6.5.1.16 For HEVs and PHEVs, add 5 L of gasoline from an empty fuel tank.

6.5.2 Immersion Water Solution Preparation

6.5.2.1 Fill the mixing tank with sufficient fresh water to immerse the vehicle to 1.0 m above the lowest portion of the RESS when installed in the vehicle (see Section 7.1).

6.5.2.2 Add sea salt crystals to the fresh water until the conductivity range is to specification. The sea salt crystals to fresh water ratio shall be 35 g/kg (see Section 7.1).

6.5.3 Immersion Container Preparation

6.5.3.1 Paint the interior of the immersion containers white for high visibility/ contrast in the video and photographs.

6.5.4 Immersion Solution Mixing Tank Preparation

6.5.4.1 Ensure that the pumping hoses are long enough to reach the immersion container comfortably.

6.5.5 Data Acquisition

6.5.5.1 Provide a reliable 120 V_{AC} supply backed by an uninterruptible power supply for powering the DAQ systems.

6.5.5.2 House the DAQ system in an instrumentation enclosure or trailer that is placed at a safe distance from the immersion container.

6.6 Test Methodology

6.6.1 Pre-test preparations:

6.6.1.1 Carefully move the test vehicle into the immersion container while taking care not to damage or dislocate the sensors and associated cabling.

6.6.1.2 Chock all four wheels in both directions, set the parking brake, and secure the vehicle from floating as the water fills the container.

6.6.1.3 Ensure that all the windows are in the fully down position.

6.6.1.4 Ensure there is no debris in the vehicle and immersion container. Remove any loose articles, wires, paper, insulation, etc.

6.6.1.5 On the container interior wall, in a visible location from outside the container, mark a fill line that is 1.0 m above the lowest point of the installed RESS for the test vehicle.

6.6.1.6 All vehicle doors shall be secured in fully open positions to fill the vehicle with seawater and help prevent floating. The minimum opening shall be 10 cm at the rear edge of the doors.

6.6.1.7 The hood and trunk shall also be secured in an open position with a minimum opening of 10 cm.

6.6.1.8 Secure the sensors and cabling.

6.6.1.9 Connect sense leads to the DAQ equipment.

6.6.1.10 Install a suitable cover over the immersion container to minimize temperature variation from diurnal changes and weather.

6.6.1.11 Seal the test container door with silicon caulking or equivalent to prevent water leaking. Allow sufficient time for the seal to cure before conducting the test.

6.6.1.12 Locate and install the video camera at one end of the vehicle, focusing on the front or rear, depending on RESS location.

6.6.1.13 Photographs the test setup.

6.6.2 Test initiation:

6.6.2.1 Zero the test clock to indicate test start time.

6.6.2.2 Start data collection from all sensors.

6.6.2.3 Set the test vehicle in active mode by moving the ignition to key-on and then key-start.

6.6.2.4 Move the PRNDL control to ‘P’ or ‘N’. At this point, the test vehicle LV and HV electrical systems are live.

6.6.2.5 Start video recording.

6.6.3 Water Immersion:

6.6.3.1 Take a 1 L sample of the immersion water from the mixing tank for immediate confirmation of salinity. Take another three 40 ml samples for analysis of conductivity, density and pH checks. Adjust the water salinity as needed until it meets specifications.

6.6.3.2 Pump seawater from the mixing tank into the immersion container within 10 minutes. Fill to the required level (i.e., 1.0 m above the deepest housing location of the RESS) and hold for 2 hours.

6.6.3.3 While the vehicle is in the salt water, check if there is any venting, fire or explosion. Video monitoring shall be recorded on cameras at a minimum frequency of 30 frames/second. Note that this frequency may be reduced to 5 frames/second after 24 hours from the end of immersion.

6.6.3.4 All sensors (voltage, temperature, gas sensors) shall collect data at a minimum of 1 Hz.

6.6.4 Seawater Extraction Period:

6.6.4.1 If the vehicle is safe to approach at the end of the 2-hour immersion period (based on recorded data), take one 1 L and three 40 ml samples of the water from the immersion container for later analysis and conduct on-site salinity, conductivity, density and pH checks.

6.6.4.2 Pump the salt water out of the immersion container and back into the mixing tank. The pumping should require no more than 10 minutes to help accurately define the end of the immersion duration period.

6.6.4.3 When the immersion container is empty, or at least below 50% of the tire sidewall height, record the time to initiate the post-extraction observation period.

6.6.5 Post-Extraction Period:

6.6.5.1 The test vehicle shall remain in the immersion container until the end of the post-extraction period. Unless a hazardous event occurs, the observation period for the test vehicle after water extraction shall be 28 days.

6.6.5.2 The video camera shall be positioned to detect any flames, sparks, arcing or visible cell venting as a result of LV short circuits, HV battery thermal issues, or ignition of flammable materials.

6.6.5.3 Direct measurements shall be used to calculate the internal RESS isolation loss, if any, during the test to detect leakage effects.

6.6.5.4 Data collection rates (as defined in Section 6.6.3.4) continues through this period. Video recording can be reduced to a minimum of 5 frames/second to make data file size handling manageable.

6.6.6 End of test actions:

6.6.6.1 Use PPE in all steps that require handling of the vehicle and battery pack.

6.6.6.2 Use an infrared camera to detect any hot spots within the LV components, HV components, or other areas in the test vehicle. Determine and assess the risks if thermal hot spots are present.

6.6.6.3 Check the voltages at seat locations relative to the RESS enclosure and determine if risks are evident.

6.6.6.4 Remove video camera.

6.6.6.5 Open the 12 V battery connections to de-energize all LV and HV components.

6.6.6.6 Open the immersion container doors by breaking the seal (see Section 6.6.1.11). Remove the test vehicle and place it in a secure location.

6.6.6.7 Photograph the test vehicle for evidence of changed conditions as noted in post-mortem analysis.

6.6.7 Post-mortem analysis:

6.6.7.1 The objective of post-mortem analysis is to identify any areas of the LV and HV system that have been affected by the immersion and post-extraction steps.

6.6.7.2 Use PPE in all steps that require handling of the vehicle and battery pack.

6.6.7.3 Collect any evidence of fire, short circuits, arcing, explosions or other hazards. If detected, attempt to identify the root cause.

- For the LV system, remove and examine the 12 V battery; record the voltage. Check LV components for damage such as arcing, overheating, etc.

- For the HV system, examine the RESS exterior, powertrain components, DC-DC converter, and AC-DC converters for evidence of heating, plastic softening/melting, arcing, cell venting, component rupture, disassembly, etc. Measure and calculate the internal HV isolation. Remove the RESS cover and visually examine for damage such as arcing, overheating, etc.

6.7 Measured Data

6.7.1 During immersion testing, the test vehicle shall be monitored remotely with voltage, temperature, and gas sensors. Video recording shall also be used to identify any visible signs of gassing or flames.

6.7.2 The test vehicle shall continue to be monitored remotely with voltage, temperature, and gas sensors for at least 28 days after the seawater has been extracted from the container. Video recording shall also continue to be used to identify any visible signs of gassing or flames.

6.7.3 A vehicle immersion test report should include the following information:

- Details of the immersion test setup, including the container specifications, level of salt in the water, etc.
- Locations of all installed sensors.
- Voltage of the LV and HV batteries before, during, and after testing.
- Video recording of the test.
- Temperature data and gas sensor data.
- Photographs of the battery pack both before after testing.
- Chemical analysis results of the immersion water.

6.7.4 A post-mortem analysis report should include the following information:

- Details of the vehicle and RESS status (condition, etc.) at beginning and end of test.
- Status of the installed LV and HV sensor connections at end of test. Also note if there is any stranded energy remaining in the RESS cells.
- Observations of any RESS contamination, heat damage (overheating, melting, burning, etc.), and phyisical damage (missing or broken parts).
- Photographic evidence of any damage.

6.8 Post-Test Requirements

6.8.1 After the 28-day observation period is complete, the vehicle and RESS should be disposed of or recycled in accordance with environmental regulations.

6.8.2 The used seawater should be considered contaminated and also be disposed of appropriately.

6.9 Acceptance Criteria

6.9.1 A pass/fail decision for water immersion testing is based on to two criteria: a) hazards created by seawater immersion that may inhibit escape times for the occupants and b) hazards after seawater immersion that may be harmful to both occupants and bystanders (for at least 28 days).

6.9.2 Hazards during Time to Evacuate:

6.9.2.1 If an electric shock hazard develops during immersion, it should not compromise the safety of occupants.

6.9.2.2 No hazardous level of harmful gases should be generated during immersion. In particular, carbon monoxide (CO) levels should be assessed according to relevant criteria such as the Emergency Exposure Guidance Level (EEGL)[2] set by National Research Council (see Section 3.1.6). The CO concentration is monitored from sample gas flow taken from the vehicle cabin. The test is considered failed if the concentration level reaches 1500 ppm within 10 minutes.

6.9.3 Post Immersion Hazards:

6.9.3.1 After immersion, the RESS condition shall be evaluated for the effects from immersion testing and appropriate actions shall be taken as needed.

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[2] EEGLs are defined as ceiling concentrations (concentrations not to be exceeded) of chemical substances in submarine air that will not cause irreversible harm to crew health or prevent the performance of essential tasks, such as closing a hatch or using a fire extinguisher, during emergency situations.

7. TEST PROCEDURE RATIONALE

7.1 Test Rationale and Description

Vehicle water immersion testing is carried out in four sequential steps. Figure 7 shows the steps as pre-immersion, immersion, extraction, and post-extraction. The immersion container shall be of steel construction with sufficient wall rigidity and strength to withstand the static pressure of the immersion seawater. The immersion containers shall also contain any shrapnel or fire. The container is not expected to be of commercial value after test completion.

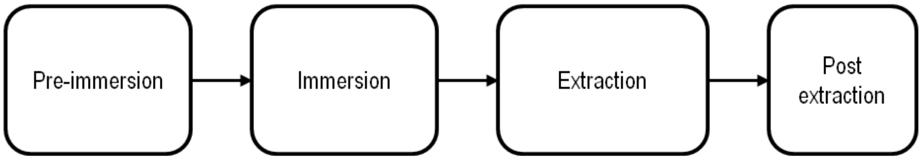


Figure 7 - Water immersion event steps.

Testing shall be conducted in a container large enough to ensure adequate immersion of the vehicle. Based on ISO 20653:2006(E), the seawater shall be taken to a depth of 1.0 m above the lowest housing location of the battery pack and held for 2 hours. The immersion height requirement of 1.0 m comes directly from the Ingress Protection Marking (IP67) under ISO 20653. It is assumed that the RESS, external HV components, and all LV components will be fully submerged at this level. The 2-hour immersion duration requirement is a compromise between the possibility of HV leakage driving excessive SOC loss and enough time to permit effective wetting to compromise LV and HV components. Excessive SOC loss could reduce the potential LV and HV risks in the post-extraction period and thereby reduce the overall value of these tests. Note, however, that actual underwater durations in real events may significantly exceed 2 hours.

The salinity level requirement of 35 g/kg (Section 6.5.2.2) is a midpoint between the globally observed range of 3.1% to 3.8% salinity. The desirable conductivity range for these tests is about 5 Siemens/m. Salinity, conductivity, density and pH shall be recorded for reference only.

During immersion, a circulation pump capable of a flow of about 4,000 liters/min will agitate the seawater to help ensure that no gas is collected in natural pockets in the vehicles. During extraction (after a 2-hour immersion period), the seawater shall be pumped out of the immersion container and into a holding tank while the vehicle remains in place. The pumping shall take place in about 10 minutes from the end of the 2-hour period. Upon completion of the extraction step, the immersion seawater will be disposed of per local waste disposal regulations.

After seawater extraction, the test vehicle shall start the post-extraction period while remaining in the immersion container. The duration of this step shall be 28 days (or sooner if a hazardous electrical or fire event occurs) since the longest known rest period after vehicle impact testing leading to fire is 3 weeks at the time of this writing (i.e., DOT HS 811 573 Chevrolet Volt Battery Incident Overview Report, see Section 3.1.5).

Samples of the immersion seawater shall be taken before and after the test. The samples shall be analyzed for pH, density and conductivity on-site. Water samples shall also be sent out to an accredited chemical analysis laboratory to be tested for the presence of lower molecular weight volatile organic compounds (VOC) using Gas Chromatography/Mass Spectroscopy (GC/MS) scan. The total oil and grease content of the water samples shall also be extracted and measured.

For RESS isolation measurements, the HV bus positive and negative voltages must be accessible during testing. The level of isolation will be assessed by comparing the internal HV values with the RESS enclosure. Isolation breakdown is calculated from FMVSS 305 (also ISO 6469-1, Section 6.1.3) since it is the recognized method to assess RESS isolation resistance. Additionally, the state of the contactors must also be measured to determine the presence of voltage. This includes both before and after the HV contactors inside the RESS as well as the LV control circuit.

The HV intrusive measurements require physical opening of the packs in the vicinity of the HV contactors. It is acknowledged that these intrusions will require experimental measures to a) seal the pack from seawater intrusion (if pack was originally sealed), b) provide robust electrical connections to the HV bus bars both before and after the contactors and LV connections to the contactor control terminals and, c) provide HV and LV sealed harness from the pack to outside the seawater immersion container to the DAQ. Vehicle manufacturers should provide detailed pack leak test procedures to assist in sealing the packs after intrusive openings are made.

Measurements taken during the immersion, extraction and post-extraction also include: a) voltage of 12 V battery (and 12 V bus if possible), b) temperature at the 12 V battery enclosure, RESS enclosure, control module and near contactor assembly, c) video recording from one camera, d) selected photographs and e) detection of gases Cl_2, H_2 and CH_4 (see Section 7.2).

7.2 Measured Gases Selection and Sensor Locations

There are two possible means of forming gases in this immersion test: a) water electrolysis and b) Li-ion cell venting. Water electrolysis will happen when LV or HV current leakage passes through the conductive salt water. Hydrogen and oxygen gas evolve as a result of this process. Monitoring the presence of these gases provides an indication of electrical isolation loss and current leakage. Hydrogen gas is hard to detect since it is highly diffusive, buoyant and quickly mixes with the ambient air. However, due to the background of oxygen in the air, monitoring O_2 is impossible. Accordingly, H_2 monitoring shall be used. Although the potential for production of Cl_2 as a result of water electrolysis is thermodynamically impossible, there are enough unknowns and uncontrolled variables in the test procedure that Cl_2 monitoring should also be undertaken. As a result, the effort to detect water electrolysis activity will need to be through monitoring of both H_2 and Cl_2 gas. See Figure 8 for example sensor placement.

An external short circuit that may form as a result of the immersion test can drive the RESS cells into thermal runaway under the right conditions. Various reactions and decompositions that happen due to thermal runaway will cause the cell to vent several gases. Among these gases, CO_2, CO and CH_4 are predominantly formed. CO_2 detection suffers from high background interference and hence is considered impractical. Research done by third party test organizations has shown that methane (CH_4) is more frequently observed than carbon monoxide (CO). Thus, a CH_4 gas sensor shall be used in this test to detect Li-ion cell thermal runaway and venting (see Figure 8).

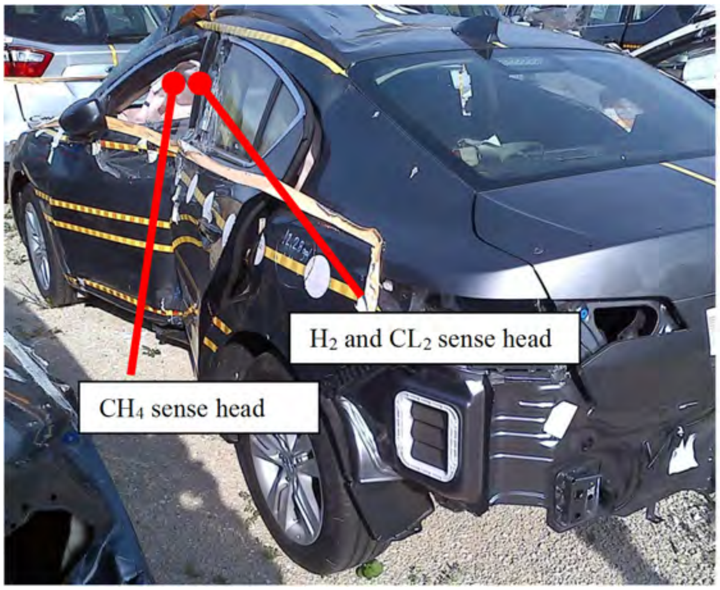


Figure 8 - Example sensor locations for CH_4 and CL_2.

7.3 Rationale for the vehicle state

7.3.1 3D Position

The sample vehicle shall be centrally located on the horizontal floor of the immersion container. Other orientations could be used, but they may change the exposure of the electrical systems to the seawater. It is assumed that the upright stationary position, combined with seawater agitation and the 2-hour immersion period, replicates the static behavior of a vehicle in an immersion situation after the initial dynamics are over.

7.3.2 RESS SOC:

The RESS SOC will be known as a function of open-circuit voltage throughout the test since there will be intrusive voltage measurements on both sides of the HV contactors. The RESS should be charged to the maximum SOC condition recommended by the vehicle manufacturer as a worst-case scenario for immersion. The method for detecting isolation loss is discussed in Section 7.1.

7.3.3 Internal Combustion Engines:

In HEV and PHEVs, the internal combustion engine may be operating as a worst-case scenario for immersion.

7.3.4 Key Position:

The test vehicle may be in the fully-on state with LV and HV systems and power to all powertrain components except the drive motor as a worst-case scenario for immersion.

7.4 DAQ measurement rates and rationale

This test requires continual data monitoring over a period as long as 28 days. Reactions by the vehicle LV and HV systems to seawater immersion may provoke an electrical or thermal event at any time during the test period.

A DAQ system shall continuously monitor temperature, voltage and gas detection. A separate system shall record video activity. The minimum required voltage and temperature channels number up to 16. These values should be collected at a minimum of two digits of precision, which amounts to approximately 112 bytes of text data per line in the data file. At the planned rate of 1 Hz, the amount of data stored over 24 hours will be on the order of 9.7 Mb per sample. A rate of 1 Hz is considered appropriate for capturing voltage and temperature events for this test since there are no externally induced dynamic events.

Video shall be recorded at a minimum of 30 frames per second during the 2 hour immersion period, and at 5 frames per second during the post-extraction period. Each sample will therefore require approximately 4 Tb of storage for the test duration.

8. APPENDIX A

This appendix provides example immersion results for various vehicles. Testing was conducted for demonstration purposes only; some of the test conditions were outside of the designated boundaries (e.g., ambient temperature). Thus, this report is not intended to be a performance and safety evaluation for each manufacturer/vehicle. Ranking the vehicles relative to the primary acceptance criteria (i.e., hazards to the occupant or bystanders) is not within the scope of this report.

8.1 General Test and Setup

8.1.1 Test Description

Immersion testing was conduced on 12 vehicles consisting of HEVs, PHEVs, and EVs (see Table 1). The vehicles were either new or had been previously subjected to NHTSA New Car Assessment Program (NCAP) crash testing. In cases where the vehicle was subjected to crash testing, both the LV battery and the HV RESS were examined prior to conducting the immersion test. Some of the test vehicles needed a replacement LV battery, but all HV RESSs were functional. Immersion testing was conducted in both summer and late winter conditions. Each vehicle was subjected to one immersion test with the exception of the Ford Focus EV, which was immersed twice due to its dual battery pack.

Table 1 - Water Immersion Tests

Weather	Vehicle				Salinity Level
	OEM	**Make**	**Type**	**Condition**	
Winter	Ford	C-Max	HEV	Side Impact Test	35 g/kg
		Fusion-1	PHEV	Side Impact Test	35 g/kg
		Fusion-2	PHEV	Side Impact Test	35 g/kg
	Nissan	Leaf-1	EV	Side Impact Test	35 g/kg
		Leaf-2	EV	New	35 g/kg
	Chevy	Volt-1	PHEV	New, minor scuffs	35 g/kg
Summer	Nissan	Leaf-3	EV	Side Impact Test	35 g/kg
	Mitsubishi	iMiev	EV	Side Impact Test	35 g/kg
	Hyundai	Sonata	HEV	Front Impact Test	35 g/kg
	Ford	Focus UP	EV	Front Impact Test	17.5 g/kg
		Focus LP	EV	Front Impact Test	17.5 g/kg
	Chevy	Volt-2	PHEV	New	35 g/kg

The test vehicles were placed in seawater immersion containers having dimensions of 2.1 m (H) x 2.4 m (W) x 6.0 m (L); the interiors were painted white for maximum visibility during testing. The containers were made with steel having sufficient wall rigidity and strength to withstand the static pressure of the immersion seawater. This also helped to contain any shrapnel or fire if either occured as result of immersion.

The vehicle rested on the immersion container floor with the wheels chocked to prevent movement. It was tested in the key-on condition following key-start and drive system activation.

In most cases, the vehicle was immersed in seawater made with sea salt crystals and fresh water formulated to be 35 g/kg (see Table 1). Since the Ford Focus EV consisted of two battery packs, the target salinity was cut in half to 17.5 g/kg and the immersion testing was repeated twice (see Sections 8.3.4 and 8.3.5). While the desirable conductivity range for testing was about 5 Siemens/m, it is known that this value is strongly influenced by temperature. Prior to testing in winter conditions, a brief study was conducted to determine the water conductivity at different temperatures. At 8°C, the conductivity was measured at 6.7 Siemens /m; at -2°C, the conductivity was measured at 6.6 Siemens /m. Note, however, that salinity adjustments were not made to avoid undesired secondary effects.

Seawater immersion was taken to a depth of 1.0 m above the deepest housing location of the battery pack (see Section 6.5.2). After 2 hours, the seawater was pumped out within about 10 minutes while the vehicle remained in place. Since the Ford Focus EV consisted of two battery packs, the immersion time was cut in half to 1 hour and the test was repeated twice (see Sections 8.3.4 and 8.3.5).

Samples of the immersion seawater were taken before and after each test. They were analyzed on-site for pH, density and conductivity. Additional samples were sent to Maxxam Analytics, Inc. to measure the total oil and grease content as well as identify any lower molecular weight VOCs.

Isolation resistance measurements are described in ISO 6469-1 with the first equation as the default calculation method. The voltages between the positive and negative bus bars and the battery case were recorded (i.e., U_1 and U'_1). For stable voltage readings, a wait period of about five minutes was implemented before these voltages were recorded. The lower voltage value in absolute terms was assigned to U'_1 and a 50 kΩ resistor (greater than 135 Ω/V pack working voltage) was placed in parallel to U'_1. After 30 seconds stabilization period, the new voltages were recorded (U_2 and U'_2).

8.1.2 Sealing Trials of Feedthroughs

In cases where the RESS required water tight seals around the sense lead feedthroughs, a sealing trial was performed prior to any RESS intrusion. In the trial, similar wires that were to be used for the test were passed through one side of a ¾-inch steel tube and sealed with Armor Coat quick setting epoxy adhesive. After the wires were fixed firmly in position by the epoxy, another layer of sealing was added around the measurement wires using Room-Temperature-Vulcanizing (RTV) silicone (i.e., Momentive Performance Materials, RTV 6700 series adhesive). The other side of the tube was connected to an air pressure line. A 10 psi pressure was then applied to the tube (i.e., over 6 times the hydrostatic pressure of a 1.0 m column of water). The sealed area of the tube was immersed in water and observed for bubbles while the pressure was being applied. The sealed area was then soaked under 3.5% salt water mix for 24 hours and the 10 psi pressure was applied again. No air leakage was observed before and after soaking, proving the effectiveness of the sealing method.

8.1.3 Test Location

Test sites were located in rural areas, approximately 700 m from the main road. They were closed to public access, securely gated on all sides, and locked at all times to prevent unauthorized access. A video and lighting system ensured continual site monitoring for the entire duration of the test. Physical checks performed by lab personnel were documented to indicate the date, time and duration of the inspection.

For winter testing, the site dimensions were approximately 25 m x 29 m and contained seven immersion containers, one of which was used as a liquid holding/distribution station. For summer testing, the site dimensions were approximately 18 m x 37 m and contained six immersion containers, one of which was used as a liquid holding/distribution station. Each test station was equipped with a roof for protection against any environmental contaminants.

There was also a heated office trailer on-site that was used as a command module. To protect the integrity of the recorded data, all computers used for the purpose of this test were password guarded. The passwords were only accessible to authorized personnel.

8.1.4 Test Monitoring

The vehicles were monitored over the entire duration of the test. A data acquisition system was used to record temperature, voltage and gas detection. Video activity was recorded using a standard camera. Physical checks were performed on an as-needed basis. Measurements taken during the immersion, extraction and post-extraction steps included:

- LV (12 V) battery voltage
- RESS voltage (both before and after the contactors)

- HV positive and negative contactor control voltage
- Voltage between HV positive and the enclosure
- Voltage between HV negative and the enclosure
- Isolation resistance (calculated)
- Temperature at the 12 V battery enclosure, RESS enclosure, and vehicle, powertrain, or battery controller
- Ambient temperature (for winter test conditions only)
- Video recording from one camera
- Selected photographs
- Detection of gases (Cl_2, H_2 and CH_4)

8.1.5 Test Equipment and Uncertainty

The measurement uncertainties for the data acquisition system associated with each test vehicle used in the various immersion tests are shown in Table 2. Other test equipment uncertainies for all immersion tests are summarized in Table 3. Note that incorporating uncertainty analysis in the measured data was outside the scope of this report.

8.1.6 Safety Measures

Immersion testing presented additional risks beyond those typically found in battery pack assessments under controlled lab environments. While all staff were trained in safe handling of HV RESSs, visitors may not have been. Accordingly, all visitors were escorted while at the remote test site and equipped with safety glasses. Notices to that effect were posted at the entrance to the test area of the property and were emailed to all scheduled visitors. Additionally, all visitors were advised of the risks associated with this test program and the limits of their activity. They were also advised of the emergency response measures that were to be followed and what they would be asked to do in the event of an emergency. Visitors were not to approach or enter any of the immersion containers.

A brief safety review was held at the beginning of each day. The topics included a) who was expected on-site that day, and b) a reminder of safety requirements and PPE (e.g., safety glasses, emergency procedures, and limits of where escorted visitors can go).

Table 2 - Data Acquisition System Uncertainty

Vehicle		**Classification Number**	**Measurement Uncertainty (K-factor=2) Confidence Level=95%**
Winter	**Summer**		
C-Max	Leaf-3	QDAQ001	Temperature: 1.50°C Low Voltage: 0.067 V High Voltage: 0.156 V
Fusion-1	Sonata	QDAQ002	Temperature: 1.53°C Low Voltage: 0.249 V High Voltage: 0.156 V
Leaf-1	iMiev	QDAQ003	Temperature: 1.56°C Low Voltage: 0.076 V High Voltage: 0.205 V
Volt-1	Focus LP	QDAQ004	Temperature: 1.51°C Low Voltage: 0.073 V High Voltage: 0.162 V
Leaf-2	Focus UP	QDAQ005	Temperature: 1.36°C Low Voltage: 0.057 V High Voltage: 0.144 V
Fusion-2	Volt-2	QDAQ006	Temperature: 1.43°C Low Voltage: 0.029 V High Voltage: 0.125 V

Table 3 - Other Equipment Uncertainty

Equipment Description	**Classification Number**	**Measurement Uncertainty (K-factor=2) Confidence Level=95%**
Temperature gauge	TH-070-01	1.9°C
Data acquisition system	DATA-AQ-06	0.002 V_{DC}
Conductivity meter (calibrated using A2LA certified solution)	OM-CM-01	Reference only
PH meter	OM-PH-01	Reference only
Hydrometer	SG-HYD-02	0.12 g/m^3

8.2 Water Immersion in Winter Conditions

8.2.1 Ford C-Max SE HEV

The Ford C-Max SE was a new production HEV previously used for side impact testing, see Table 4. Figure 9 shows the as-received vehicle from multiple angles. Figure 10 shows some of the equipment used for testing, including the DAQ system, the gas sensor, the video camera, and the immersion tank.

Table 4 - Ford C-Max HEV Details

Vehicle Class	Passenger Car
Manufacturer	Ford
Make	C-Max
Model	SE
Date of Manufacture	Aug-12
VIN	1FADP5AU0DL501685
Condition	Damaged (side impact)
Vehicle Type	HEV

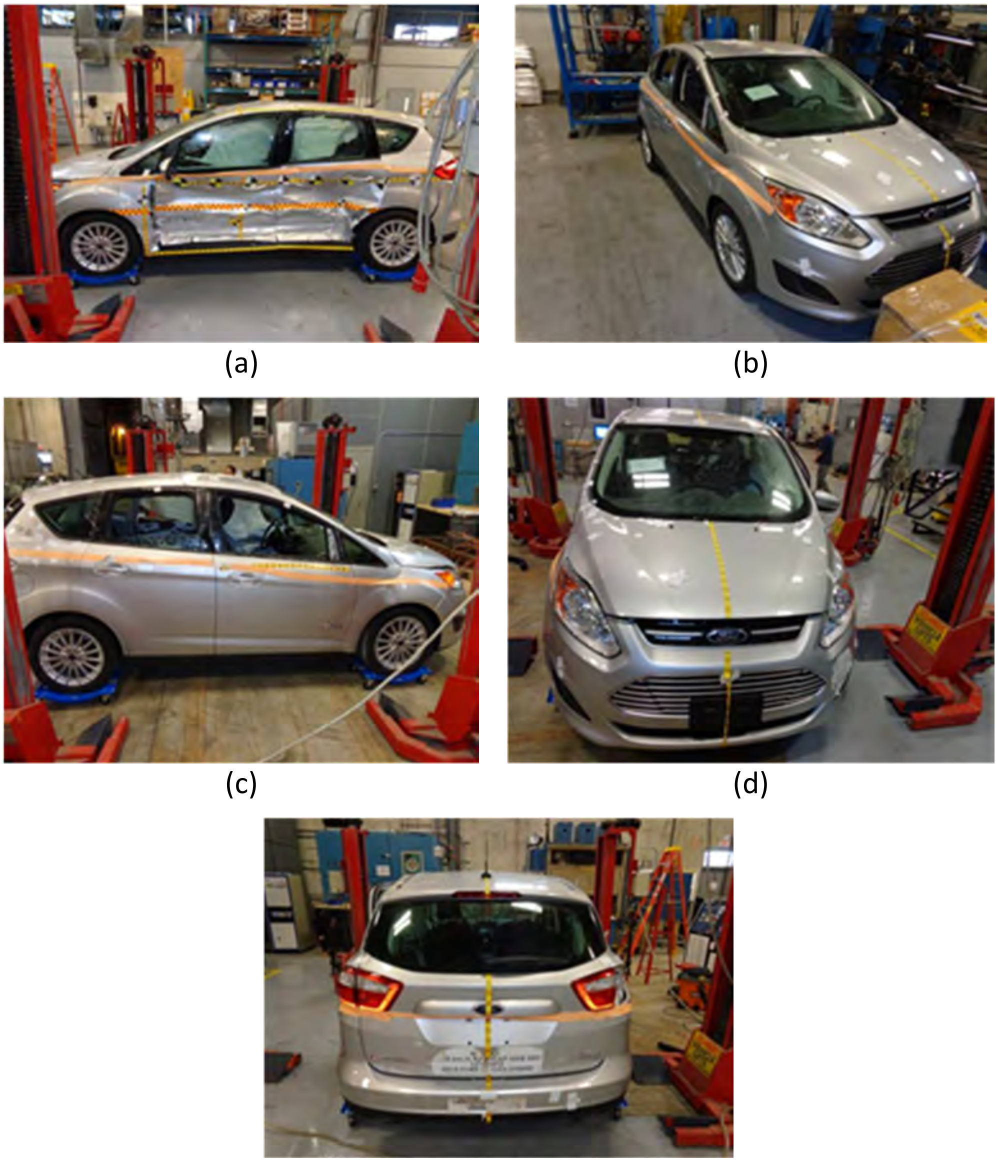
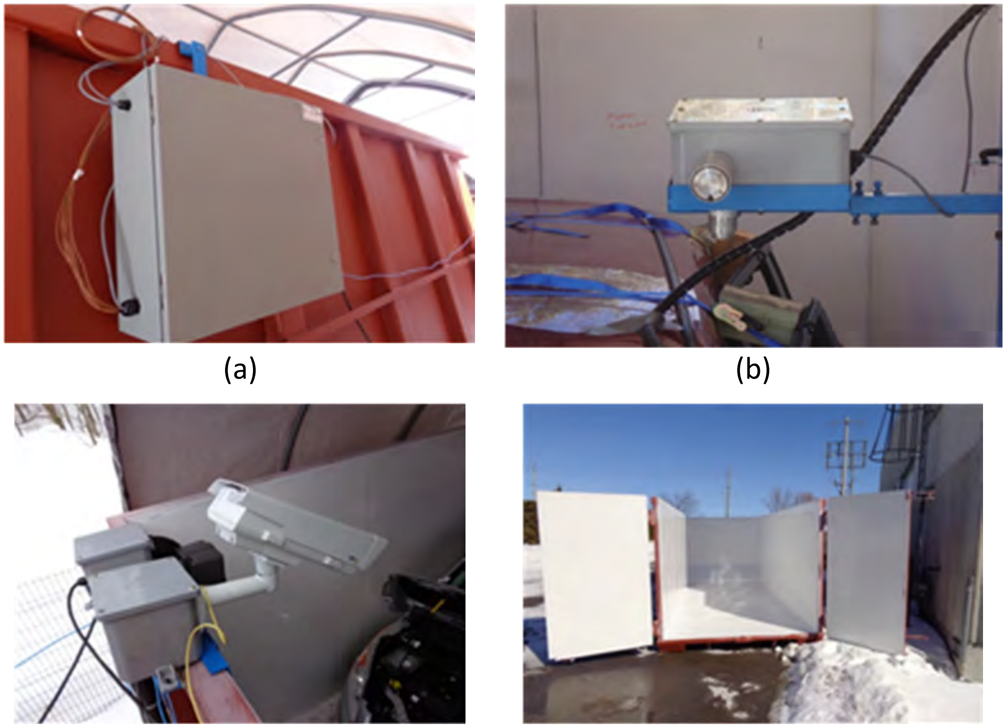

(a) (b)
(c) (d)
(e)

Figure 9 - Ford C-Max HEV initial vehicle condition: a) left view, b) front ¾ view, c) right view, d) front view, and e) rear view.



(a) (b)

(c) (d)

Figure 10 - Immersion test equipment: a) DAQ system, b) gas sensor, c) video camera, and d) immersion container.

8.2.1.1 Sample Preparation

As received, the vehicle was not operational since all of the fluids (engine oil, brake fluid etc.) had been drained and needed to be refilled. Also, the 12 V battery could not be charged and needed to be replaced. The HV RESS was visually inspected and no damage from the side impact test was observed. All the loose interior parts were tagged and removed from the cabin. The vehicle was then successfully put in the key on position with the battery indicator showing below half. The key was turned to the start position and the gasoline engine started running. Once it was confirmed that the vehicle was operational, it was turned off for sensor installation.

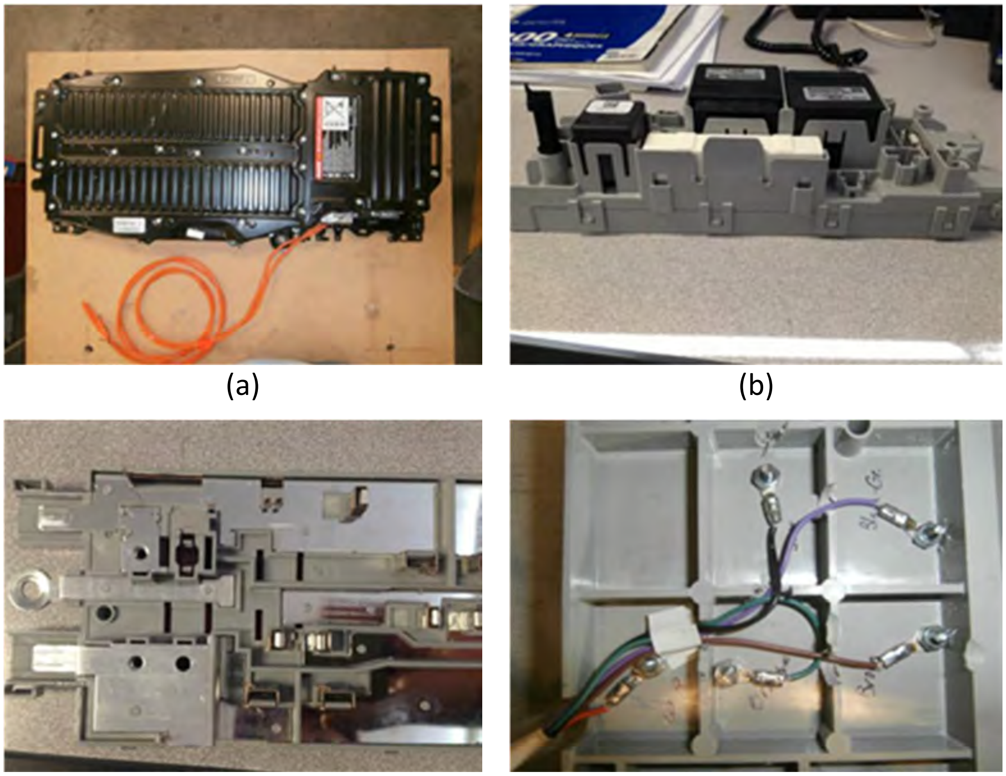
For HV and isolation measurements, the RESS was removed from the vehicle and the contactor assembly was taken apart. The voltage sensors were tightly screwed to the bus bars of the assembly (see Figure 11). Since the RESS was not encased and sealed, no special measures to seal the measurement wire feedthroughs were needed. The contactor was reassembled and reinstalled in the pack; the RESS was then placed back into the vehicle. Voltage sense cables were also installed on the 12 V battery. The vehicle was re-tested for operation and no issues were encountered.

A total of eight thermocouples were installed as specified in test procedure (see Section 6.5.1.13), including the RESS enclosure, near contactors, the control unit, and the 12 V battery. Thermocouple locations are provided in Table 5 and shown in Figure 12. The thermocouples were held in position using epoxy adhesive.

Three gas sensors were also mounted above the driver window (see Section 7.2).

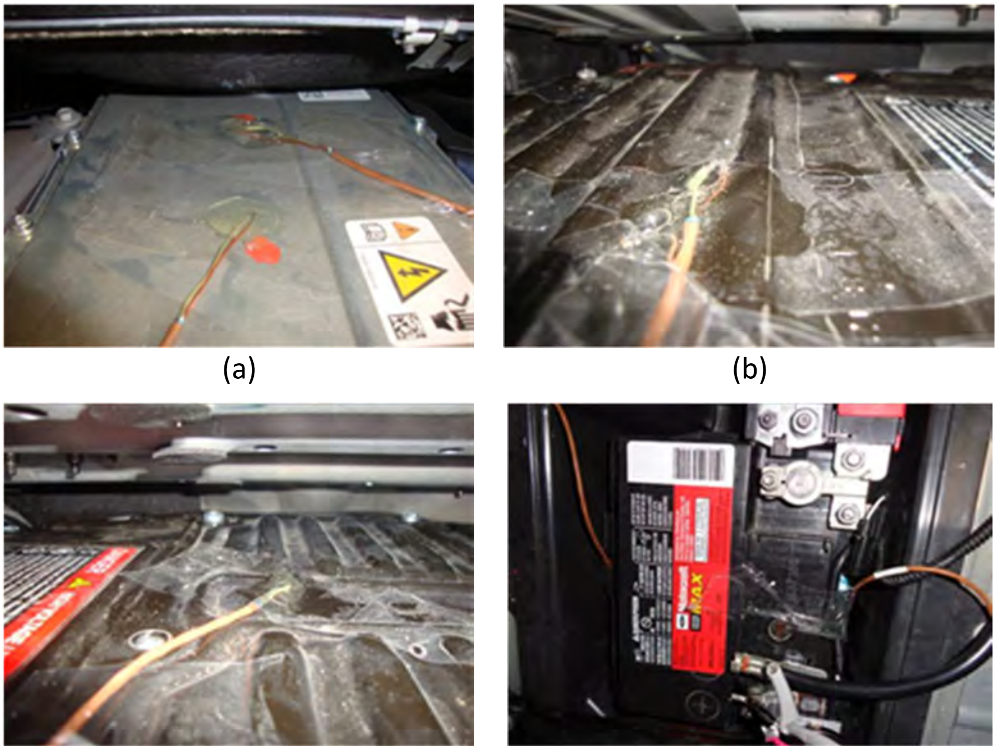
Table 5 - Ford C-Max HEV Thermocouple Placement

Number	Location
TC1, TC2	Control unit
TC3, TC4	Center of the RESS
TC5, TC6	Near contactors
TC7, TC8	12 V battery


(a) (b)

(c) (d)

Figure 11 - Ford C-Max HEV HV connections: a) RESS removed from vehicle, b) contactor assembly, c) underside of contactor assembly, and d) measurement wires screwed to bus bars.



(a) (b)

(c) (d)

Figure 12 - Ford C-Max HEV HV thermocouple placement: a) TC1 and TC2 on the control unit, b) TC3 on the center of the RESS, c) TC6 near the contactor, and d) TC7 and TC8 on the 12 V battery.

8.2.1.2 Test Conditions

Testing was performed outdoors in ambient temperatures. The beginning of test temperature was -5.97°C. A temporary enclosure over the top of the immersion container was installed to keep rain and snow from entering the vehicle during testing. There was no precipitation on the day the vehicle was immersed. The vehicle remained in the immersion container during the post-extraction observation period.

8.2.1.3 Immersion Test Results

The test event log is summarized in Table 6. Isolation resistance measurements were performed approximately every 6 minutes. Figures 13 through 23 show measured data for the initial 9 hours of the test as follows:

- Figure 13 - Temperature profile for the first 9 hours of testing
- Figure 14 - Temperature profile for the first 30 minutes of testing
- Figure 15 - Gas sensing current for the first 9 hours of testing
- Figure 16 - 12 V control voltage for the first 9 hours of testing
- Figure 17 - 12 V control voltage for the first 30 minutes of testing
- Figure 18 - Electrode to chassis voltage for the first 9 hours of testing

- Figure 19 - Electrode to chassis voltage for the first 15 minutes of testing
- Figure 20 - RESS voltage for the first 9 hours of testing
- Figure 21 - RESS voltage for the first 15 minutes of testing
- Figure 22 - Isolation resistance for the first 9 hours of testing
- Figure 23 - Isolation resistance for the first 30 minutes of testing

Figures 24 through 28 show measured data for the final 10 hours of the test as follows:

- Figure 24 - Temperature profile for the last 10 hours of testing
- Figure 25 - Gas sensing current for the last 10 hours of testing
- Figure 26 - 12 V control voltage for the last 10 hours of testing
- Figure 27 - RESS voltage for the last 10 hours of testing
- Figure 28 - Isolation resistance for the last 10 hours of testing

Table 6 - Ford C-Max HEV Test Event Log

Date	Time	Test Time (hh:mm)	Event
3/25/2014	5:55 PM	N/A	• Video and data logging initiated.
3/25/2014	6:04 PM	N/A	• The vehicle was started (key-on, key-start, gear shift at Park). • The RESS voltage pre-contactor (HVpre_P_N) increased from approximately 275 V to approximately 285 V.
3/25/2014	6:05 PM	00:00	• Initiated filling the vehicle container with salt water.
3/25/2014	6:08 PM	00:03	• Isolation resistance decreased from 9.9 MΩ to 4.4 MΩ.
3/25/2014	6:10 PM	00:05	• Average ambient temperature before immersion was -5°C. • The temperature recorded by the thermocouples on the 12 V battery quickly increased to -1.8°C and then gradually approached 3°C. • The BECM temperature had started increasing from the beginning of the test and reached a maximum of 1.77°C by this time.
3/25/2014	6:10 PM	00:05	• Video observation: Smoke was seen coming out of the engine compartment. It continued for one minute.
3/25/2014	6:11 PM	00:06	• The RESS voltages pre- and post-contactors (HVpre_P_N and HVpost_P_N) started to decrease. After 15 seconds, HVpost_P_N dropped to values near -50 V and then rose to 0 V during the next 30 minutes. HVpre_P_N also rapidly dropped to near 50 V and then approached 0 V over the next 6 hours. • The LV battery voltage also started to decrease at this moment and reached 0 V after 5 hours. The positive and negative contactor coil voltages sharply increased to 20 V

Date	Time	Test Time (hh:mm)	Event
			(i.e., the data acquisition channel limit) and returned to average values near -10 V (i.e., -15 V to -5 V fluctuation) 7 seconds later. They also reached 0 V within 5 hours. • Note: the coil voltages oscillated around -10 V and opening of the contactor was indicated by short pulses to 0 V.
3/25/2014	6:12 PM	00:07	• The RESS temperature (i.e., TC3, TC4 on the case near the contactors and TC5, TC6 centered on the RESS) started to increase. The maximum temperature recorded at this stage was 20°C near the contactors.
3/25/2014	6:13 PM	00:08	• Isolation resistance decreased from 4.4 MΩ to 4.1 kΩ.
3/25/2014	6:19 PM	00:14	• Isolation resistance decreased from 4.1 kΩ to 0.77 kΩ. The isolation resistance remained at these low values because the RESS-to-chassis voltages dropped to zero. • Note: The fluctuations on the RESS-to-chassis voltages prior to this point are possibly due to the interference of the vehicle's isolation resistance measurements.
3/25/2014	6:25 PM	00:20	• Filling completed.
3/25/2014	6:25 PM	00:20	• Video observation: Bubbles were seen forming at various locations of engine compartment, continuing throughout the immersion step.
3/25/2014	8:27 PM	02:22	• Extraction step initiated (i.e., water pumped out of the container).
3/25/2014	8:42 PM	02:37	• Extraction step completed.
3/25/2014	8:45 PM	02:40	• The 12 V battery temperature increased by approximately 3°C.
• There were no changes in recorded gas sensing during the period mentioned above. • No further noticeable changes in voltage, temperature and gas sensing were recorded from this point to the end of the post-extraction period except for temperature variations following the environmental conditions.			

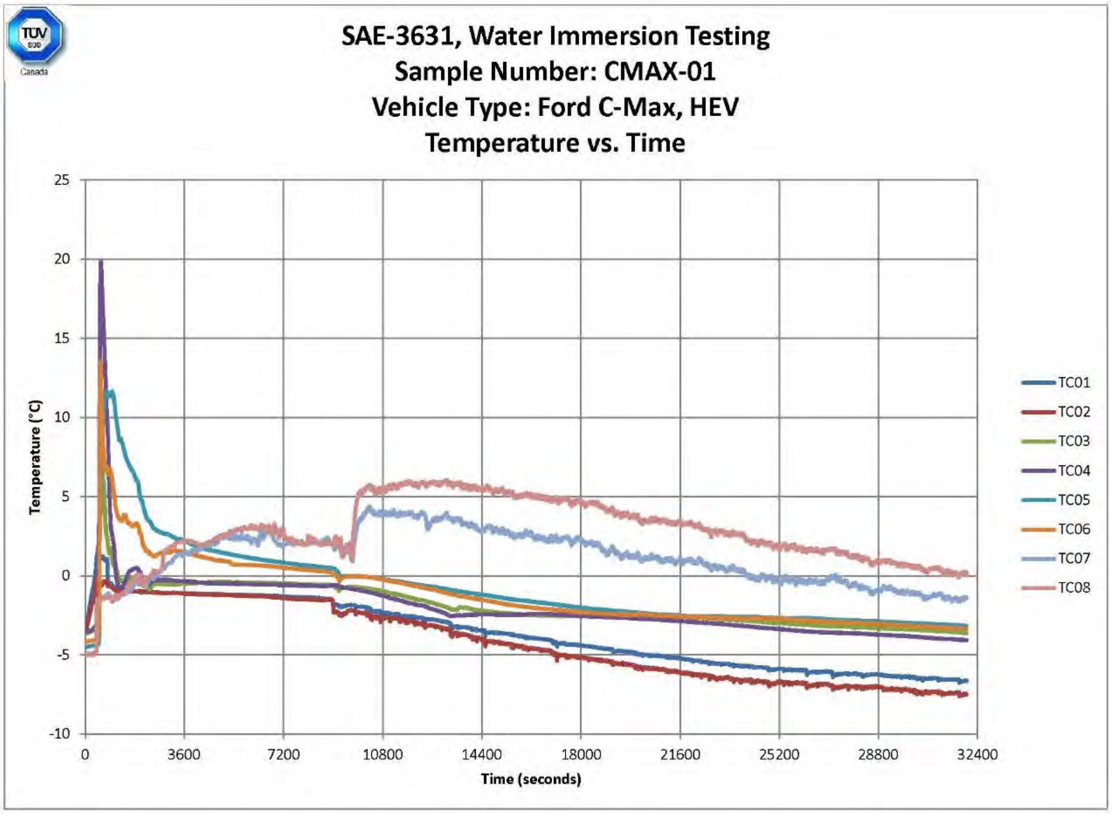


Figure 13 - Ford C-Max HEV temperature profile for the first 9 hours of testing.

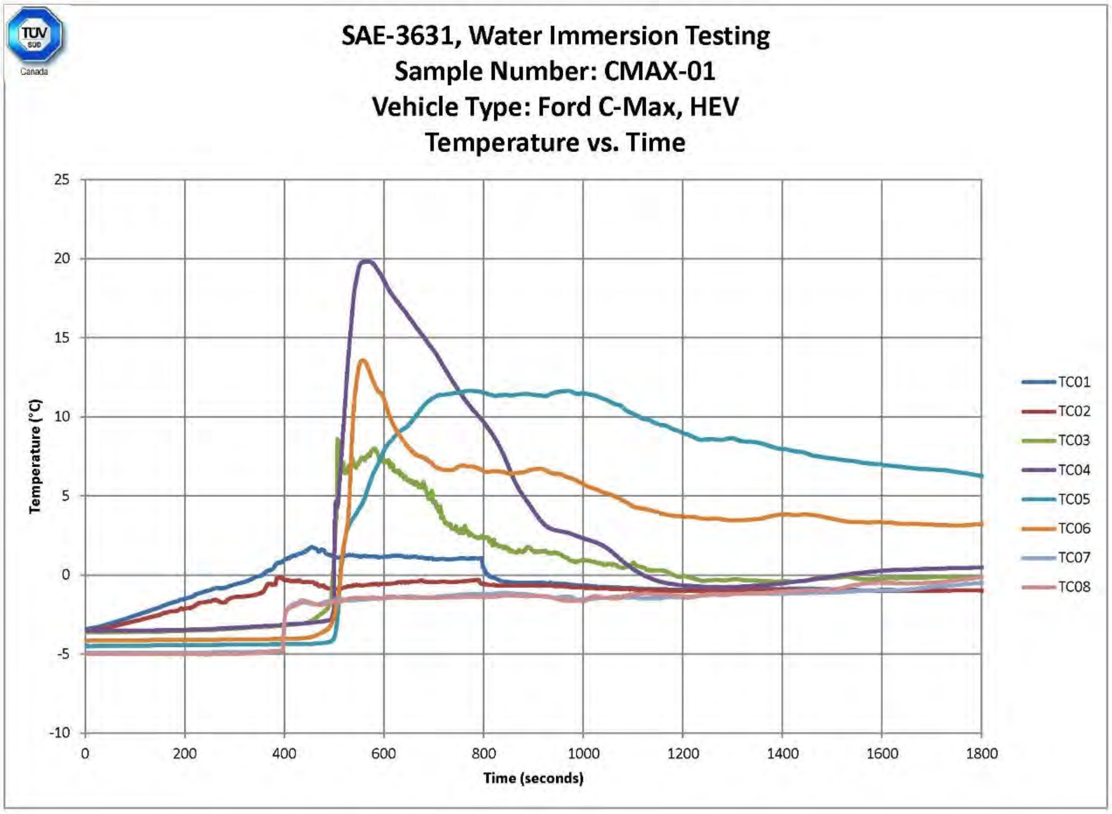


Figure 14 - Ford C-Max HEV temperature profile for the first 30 minutes of testing.

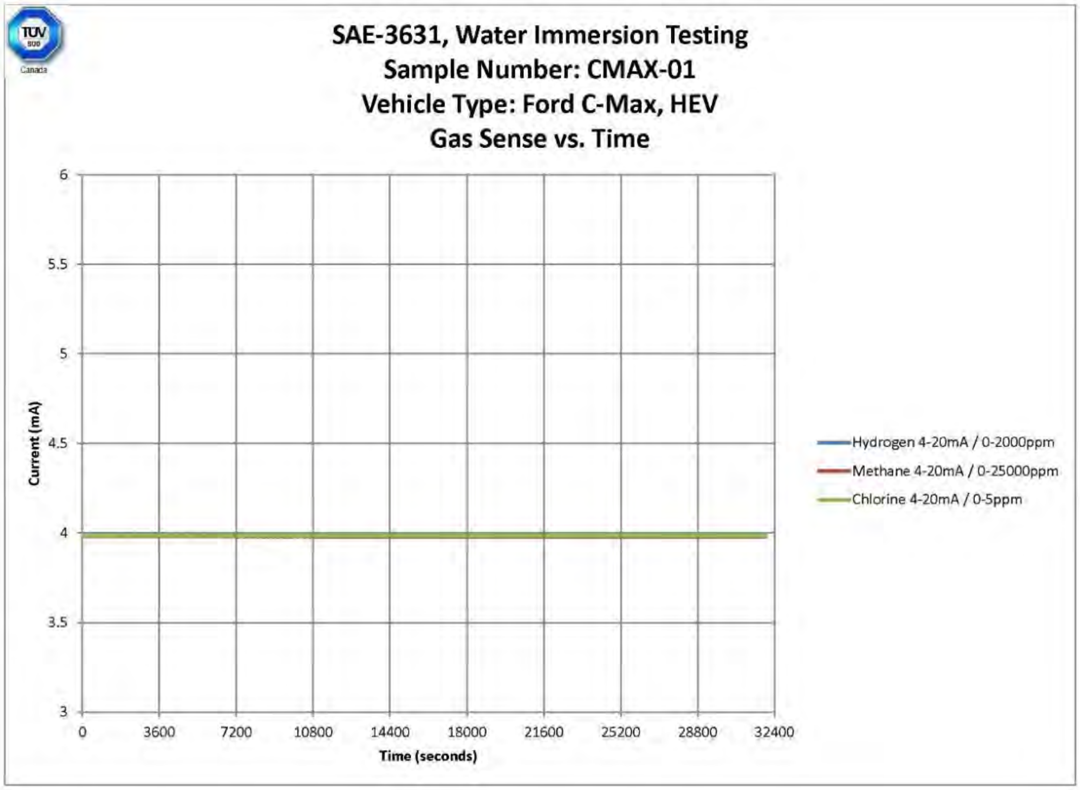


Figure 15 - Ford C-Max HEV gas sensing current for the first 9 hours of testing.

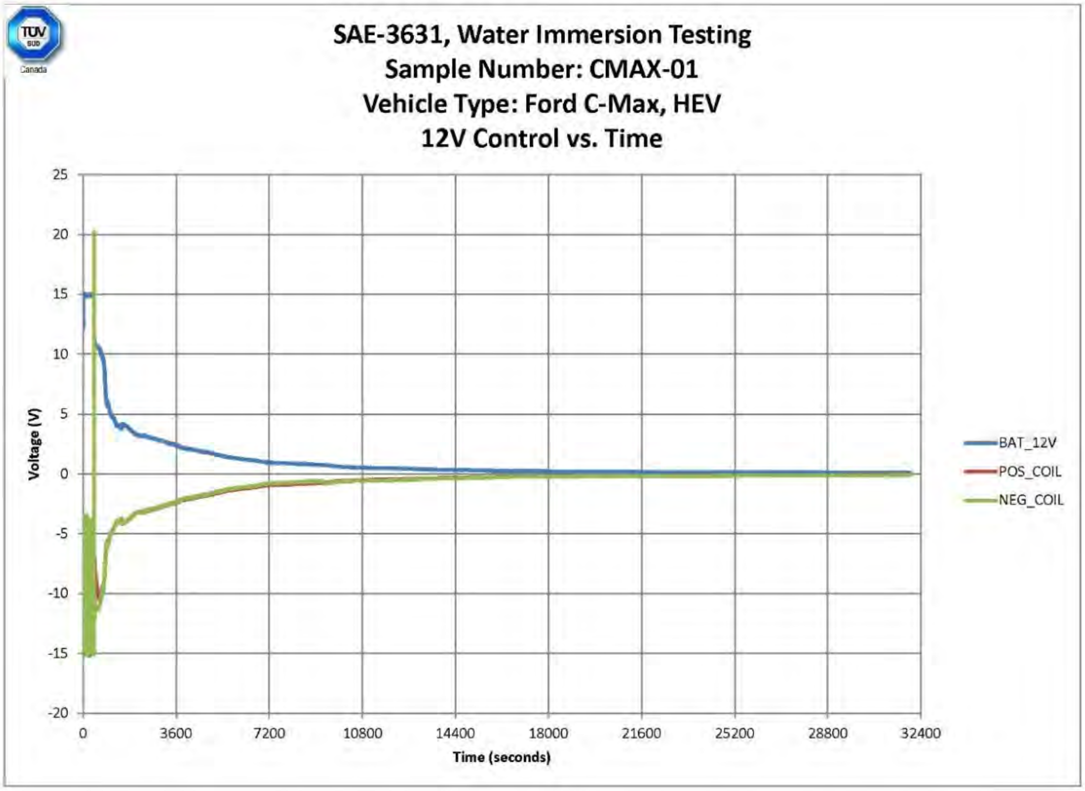


Figure 16 - Ford C-Max HEV 12 V control voltage for the first 9 hours of testing.

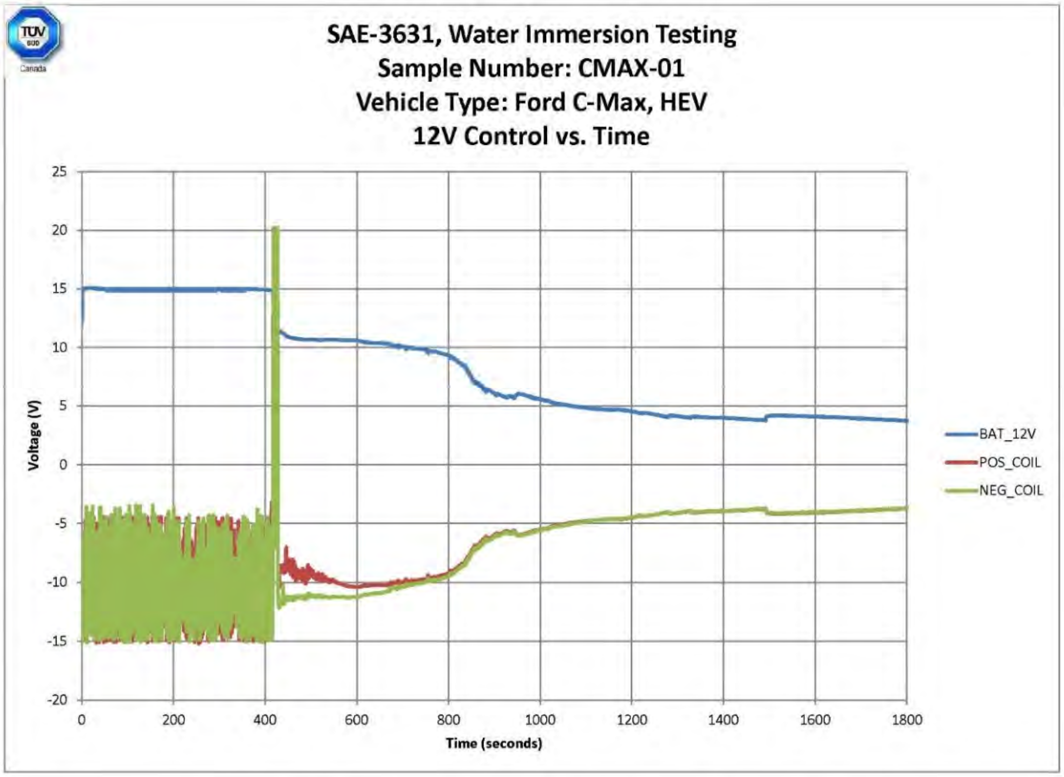


Figure 17 - Ford C-Max HEV 12 V control voltage for the first 30 minutes of testing.

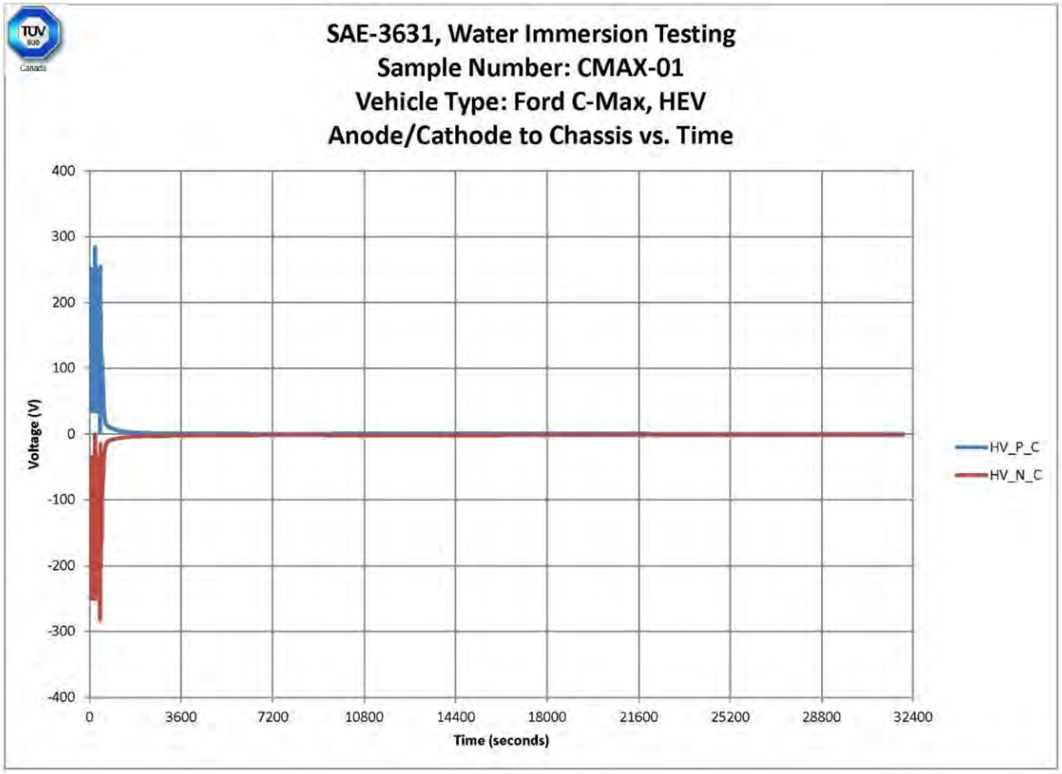


Figure 18 - Ford C-Max HEV electrode to chassis voltage for the sfirst 9 hours of testing.

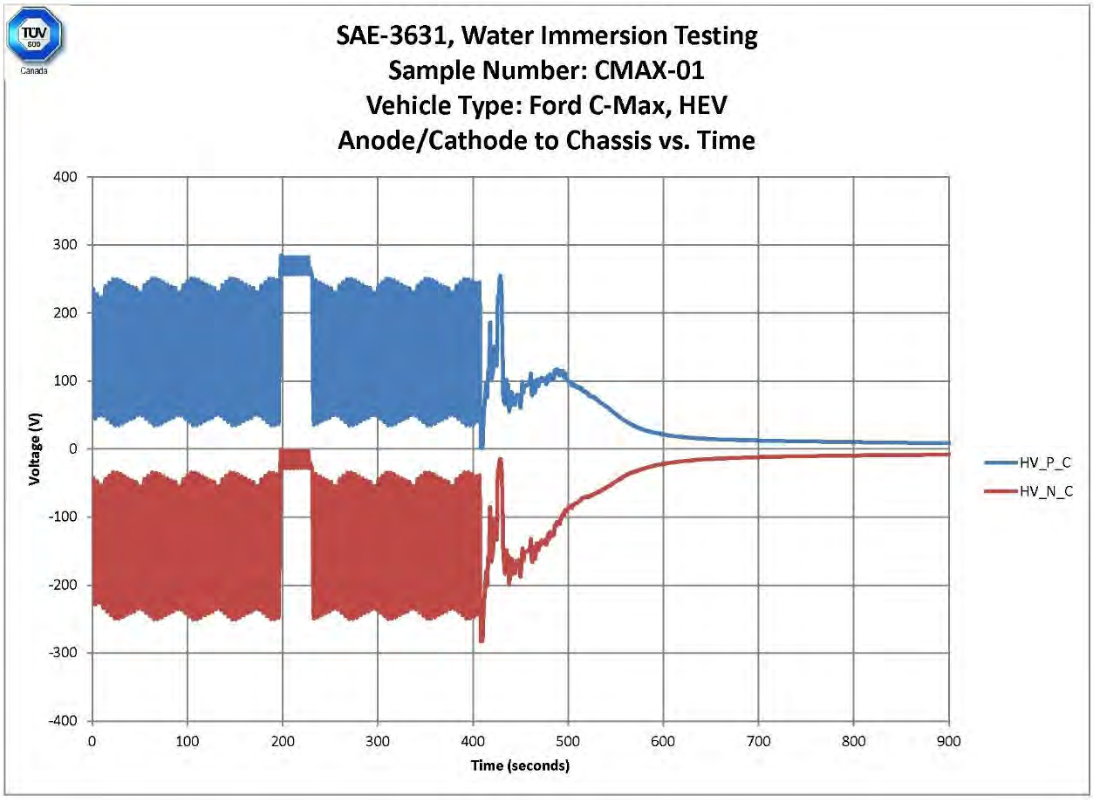


Figure 19 - Ford C-Max HEV electrode to chassis voltage for the first 15 minutes of testing.

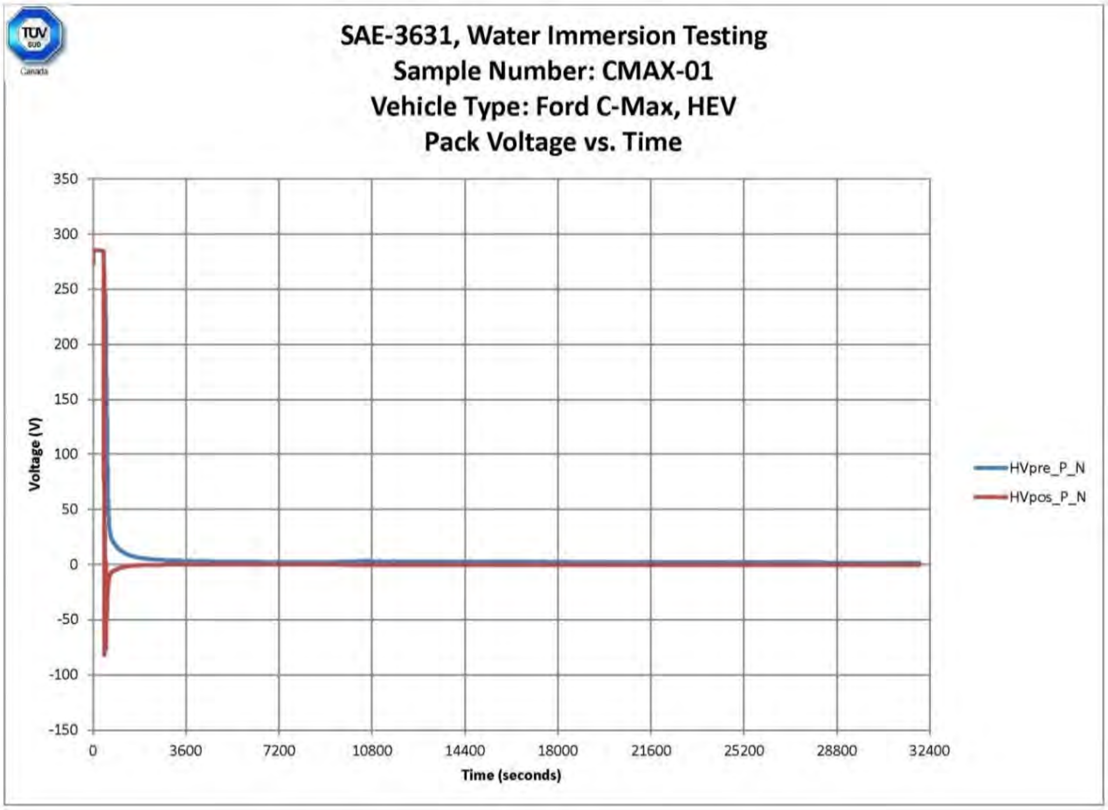


Figure 20 - Ford C-Max HEV RESS voltage for the first 9 hours of testing.

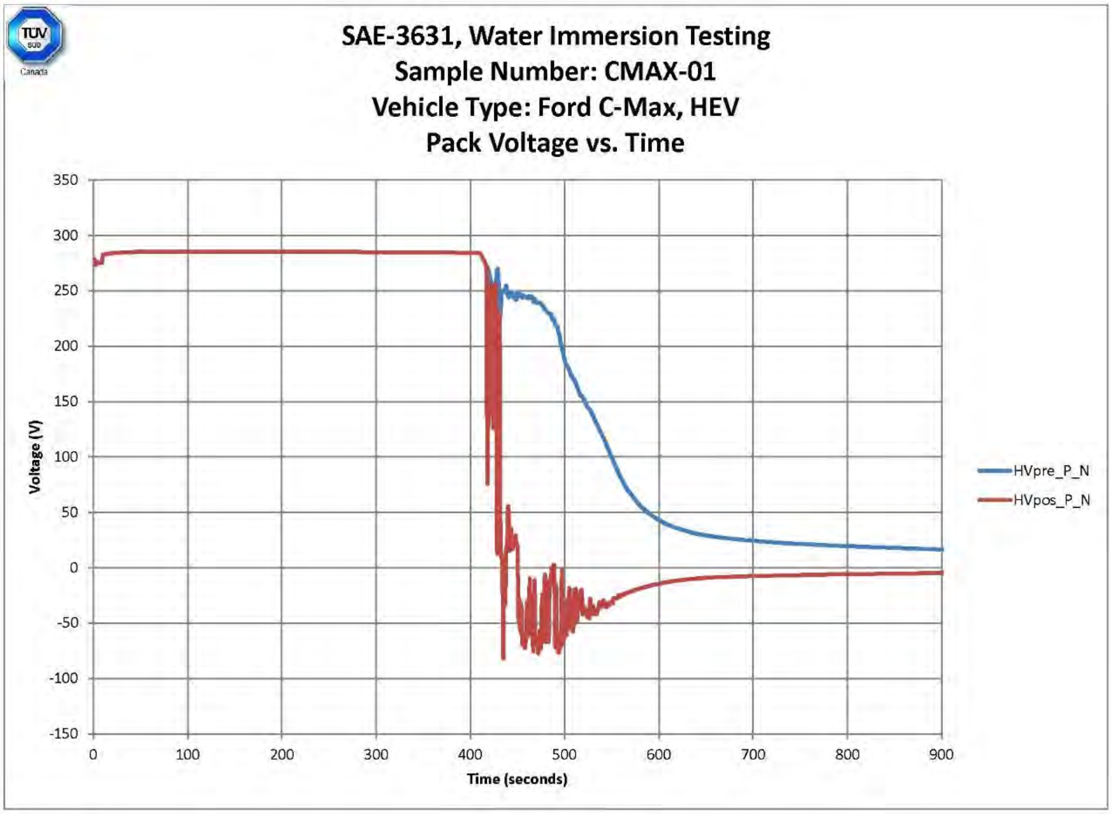


Figure 21 - Ford C-Max HEV RESS voltage for the first 15 minutes of testing.

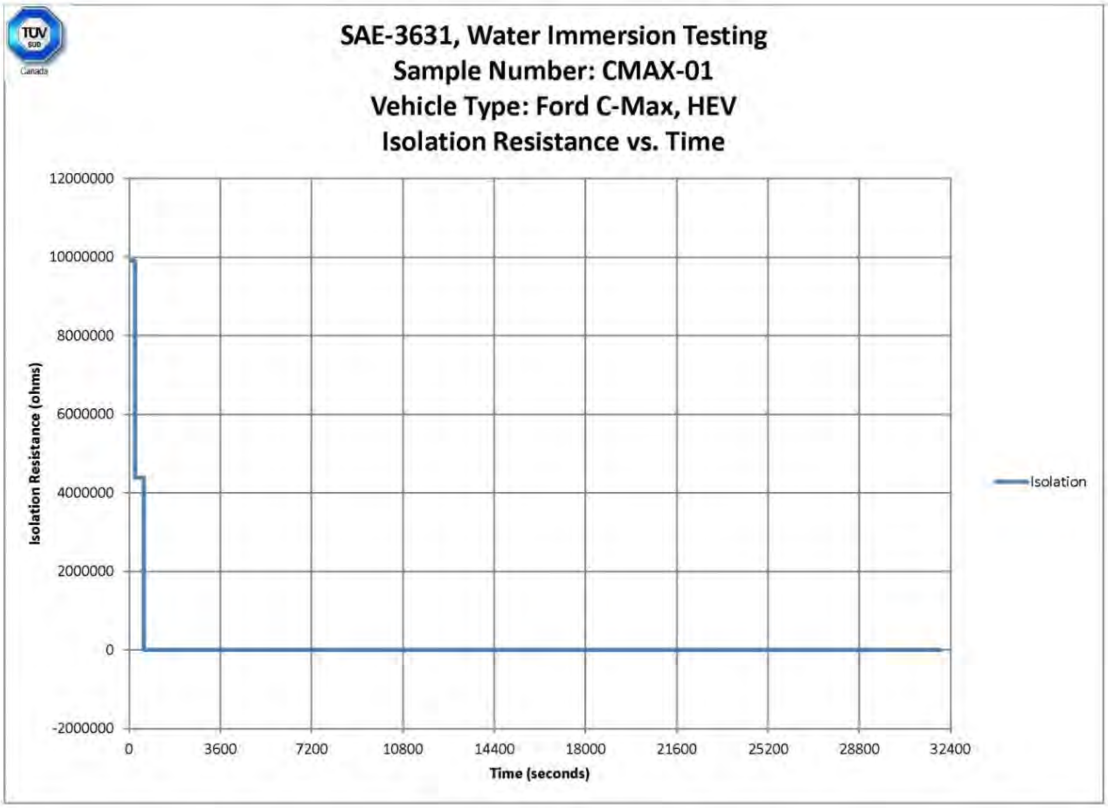


Figure 22 - Ford C-Max HEV isolation resistance for the first 9 hours of testing.

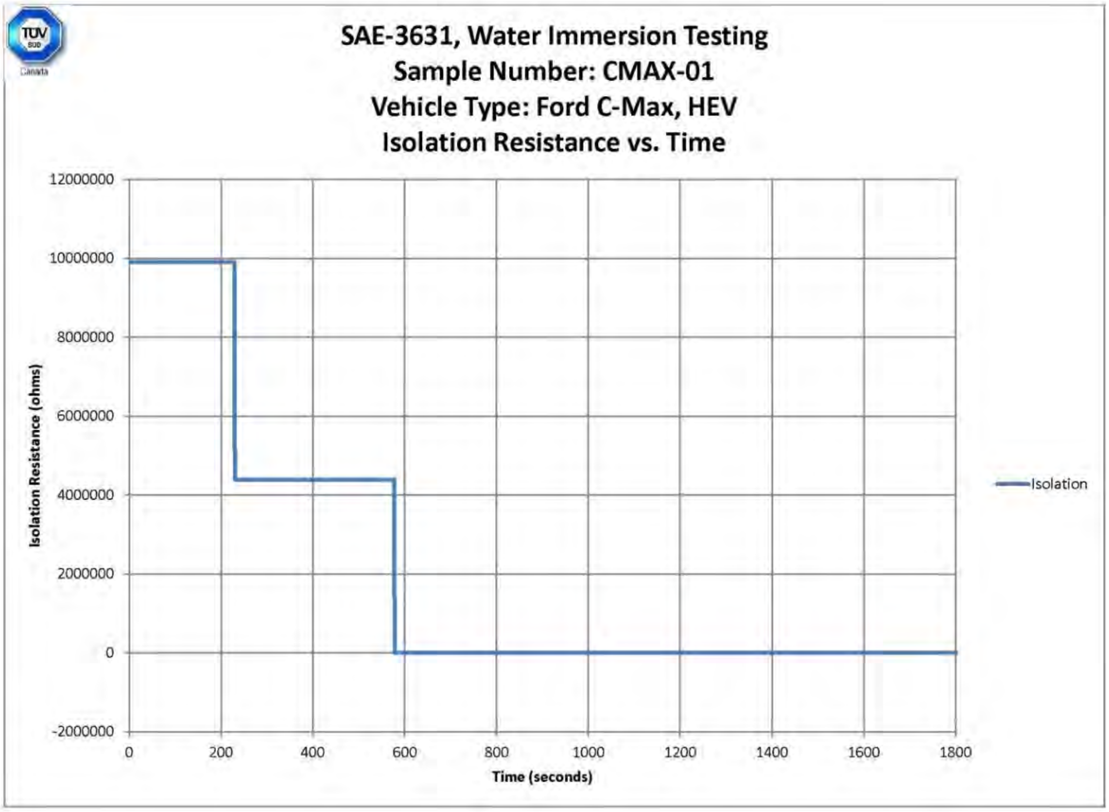


Figure 23 - Ford C-Max HEV isolation resistance for the first 30 minutes of testing.

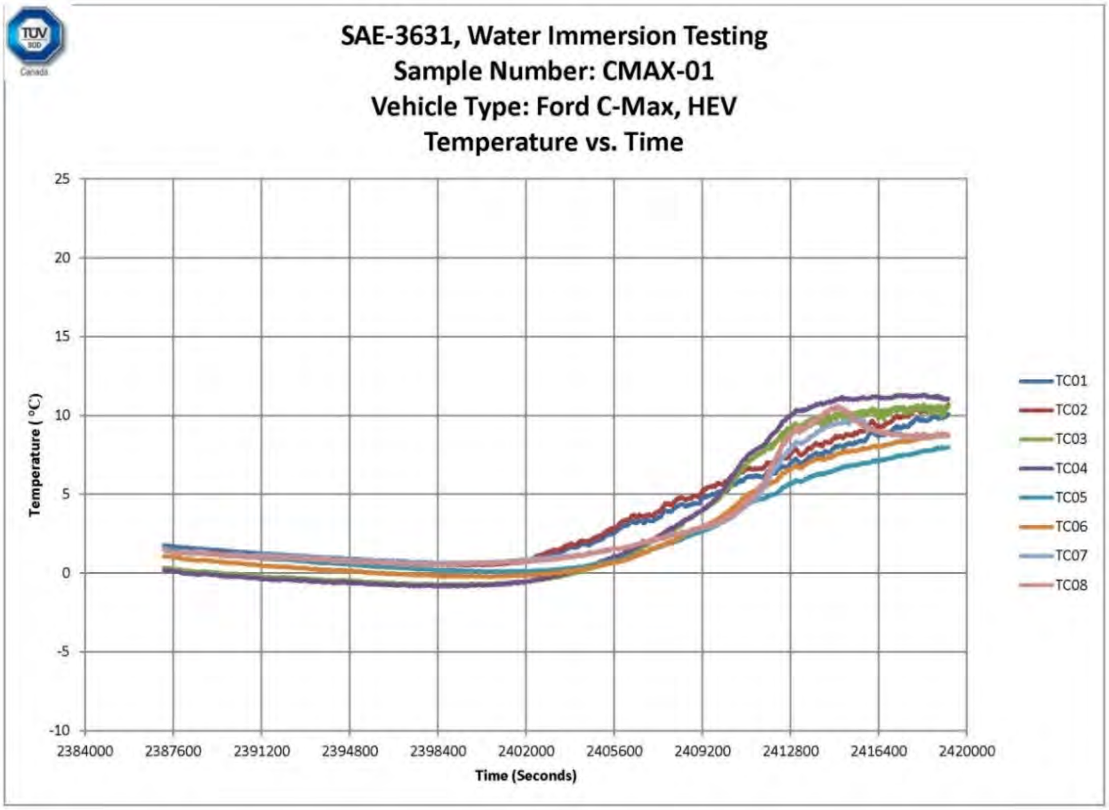


Figure 24 - Ford C-Max HEV temperature profile for the last 10 hours of testing.

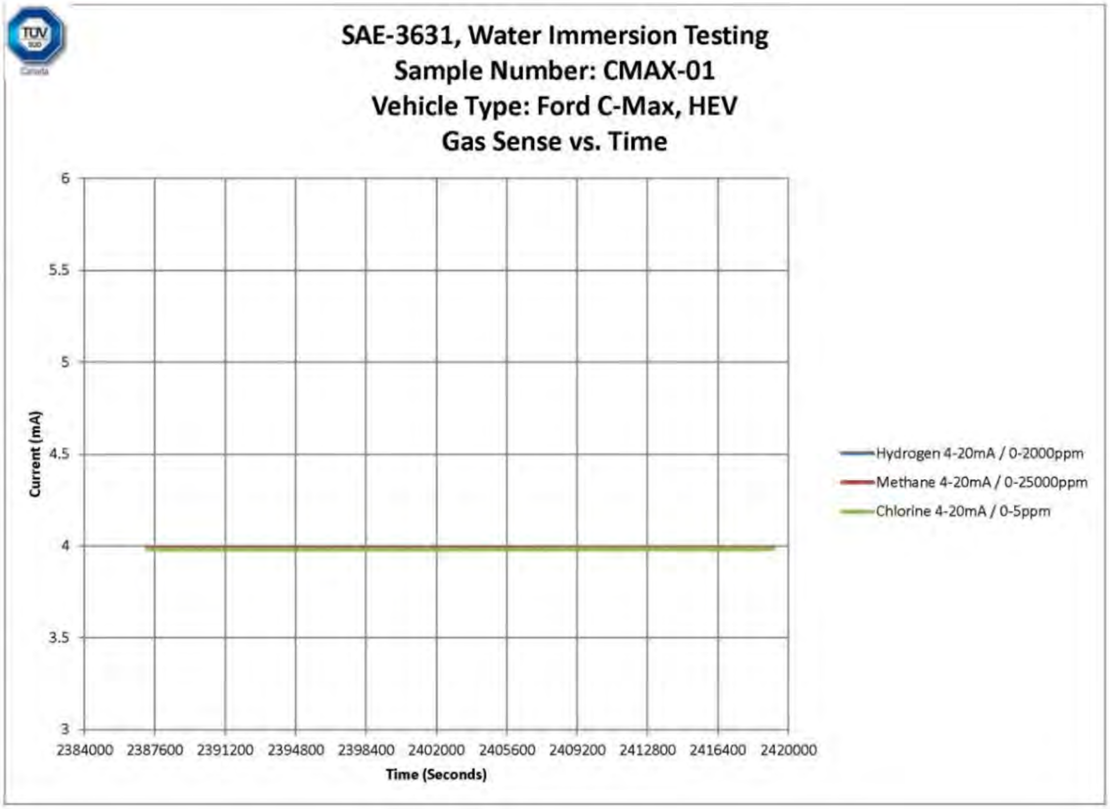


Figure 25 - Ford C-Max HEV gas sensing current for the last 10 hours of testing.

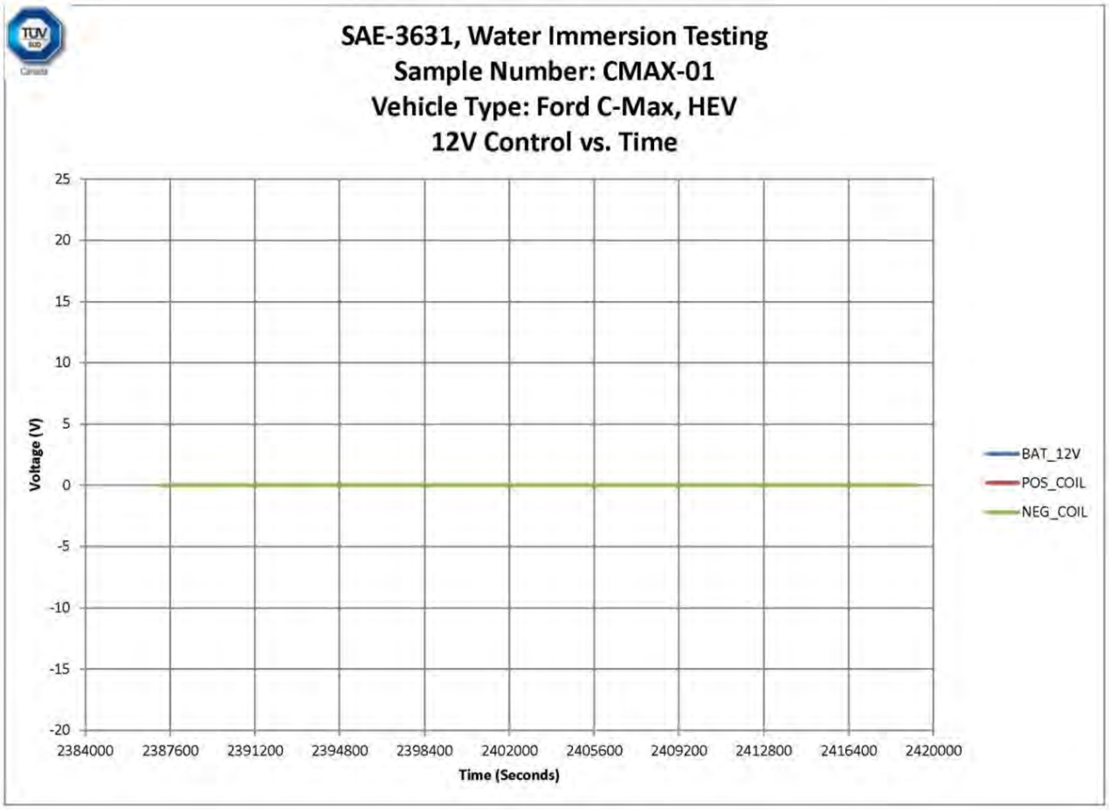


Figure 26 - Ford C-Max HEV 12 V control voltage for the last 10 hours of testing.

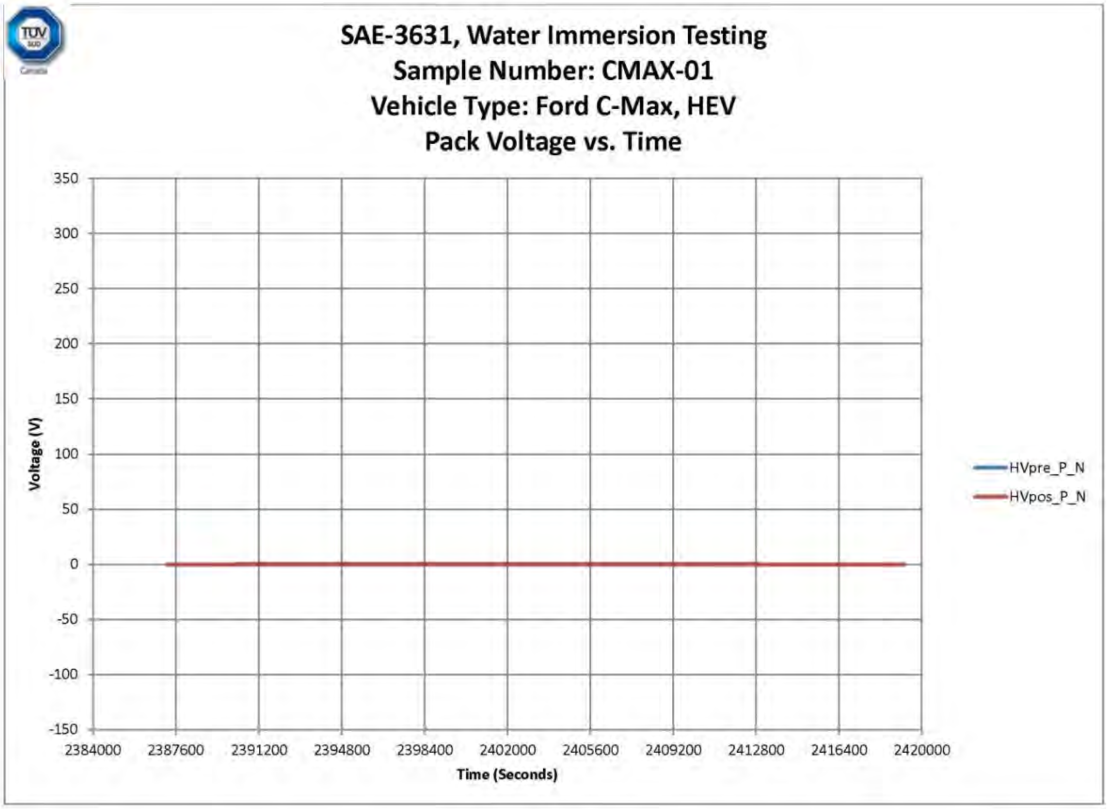


Figure 27 - Ford C-Max HEV RESS voltage for the last 10 hours of testing.

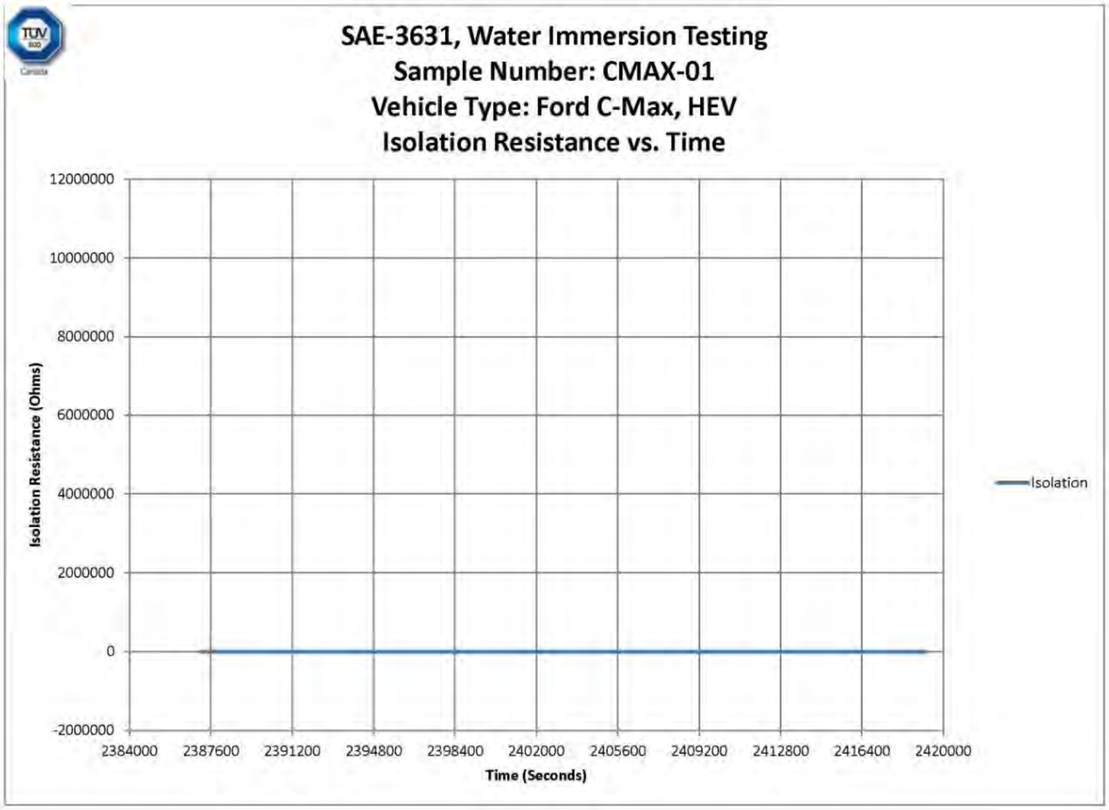


Figure 28 - Ford C-Max HEV isolation resistance for the last 10 hours of testing.

8.2.1.4 Seawater Analysis Results

Seawater samples were taken before and after immersion. They were measured on-site for pH, density and conductivity; the results are summarized in Table 7. Table 8 shows the VOCs that were above the reportable detection limit, as determined from Maxxam Analytics, Inc. Note that the samples were also analyzed for other VOCs that were below the reportable limit. Table 9 shows the total oil and grease content from the samples.

Table 7 - Ford C-Max HEV Conductivity, Salinity, Density, and pH

Time	Conductivity (mS/cm)	Salinity (wt%)	Density (g/cm³)	pH
Pre-immersion	45.6	2.67	1.020	7.4
Post-immersion	46.4	2.72	1.021	7.5

Table 8 - Ford C-Max HEV VOCs above Reportable Detection Limit

Volatile Organics	Units	Pre-Immersion	Post-Immersion	RDL*
Benzene	μg/L	1.3	1.1	1.0
p+m-Xylene	μg/L	<1.0	1.1	1.0
Xylene (Total)	μg/L	<1.0	1.1	1.0

*RDL=Reportable Detection Limit

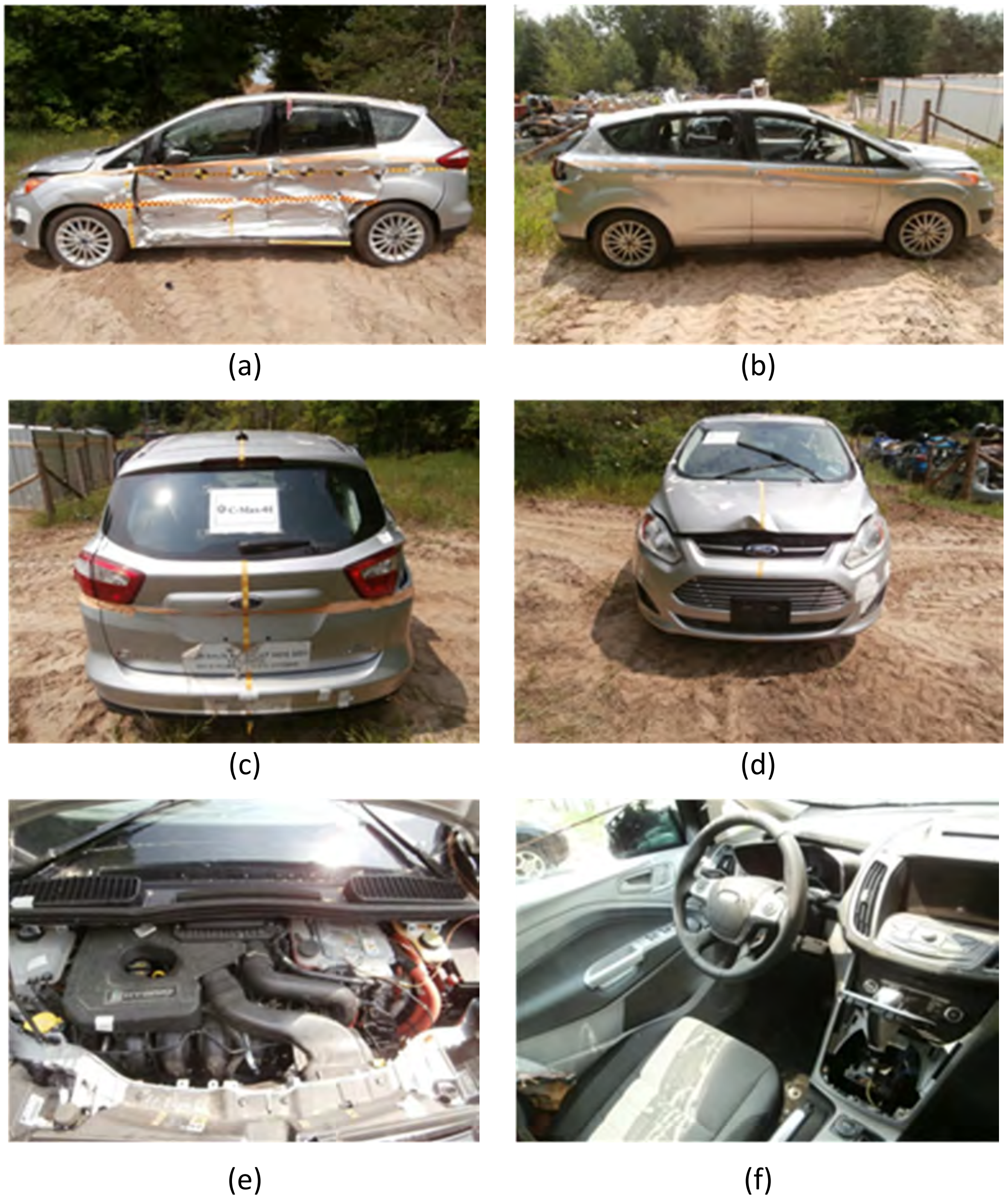
Table 9 - Ford C-Max HEV Total Oil and Grease Content

Petroleum Hydrocarbons	Units	Pre-Immersion	Post-Immersion	RDL*
Total oil and grease	mg/L	<0.50	<0.50	0.50

*RDL=Reportable Detection Limit

8.2.1.5 Post-Mortem Analysis

Figure 29 shows the vehicle from multiple angles after testing was complete. Post-mortem analysis did not indicate any evidence of behaviors that could result in a Hazard Severity Level (HSL) higher than 4 (i.e., no anticipated fires, ruptures, or explosions) based on European Council for Automotive Research (EUCAR) standards. Although the temperature increased inside the RESS during immersion, it quickly declined to ambient levels after 4 hours and followed the diurnal ambient values until the end of the test. Additionally, the water immersion caused the RESS voltage to drop from 285 V to 0 V within the first hour of immersion and stayed at 0 V until end of the test. Therefore, no post-mortem analysis was conducted on the battery pack.



(a) (b) (c) (d) (e) (f)

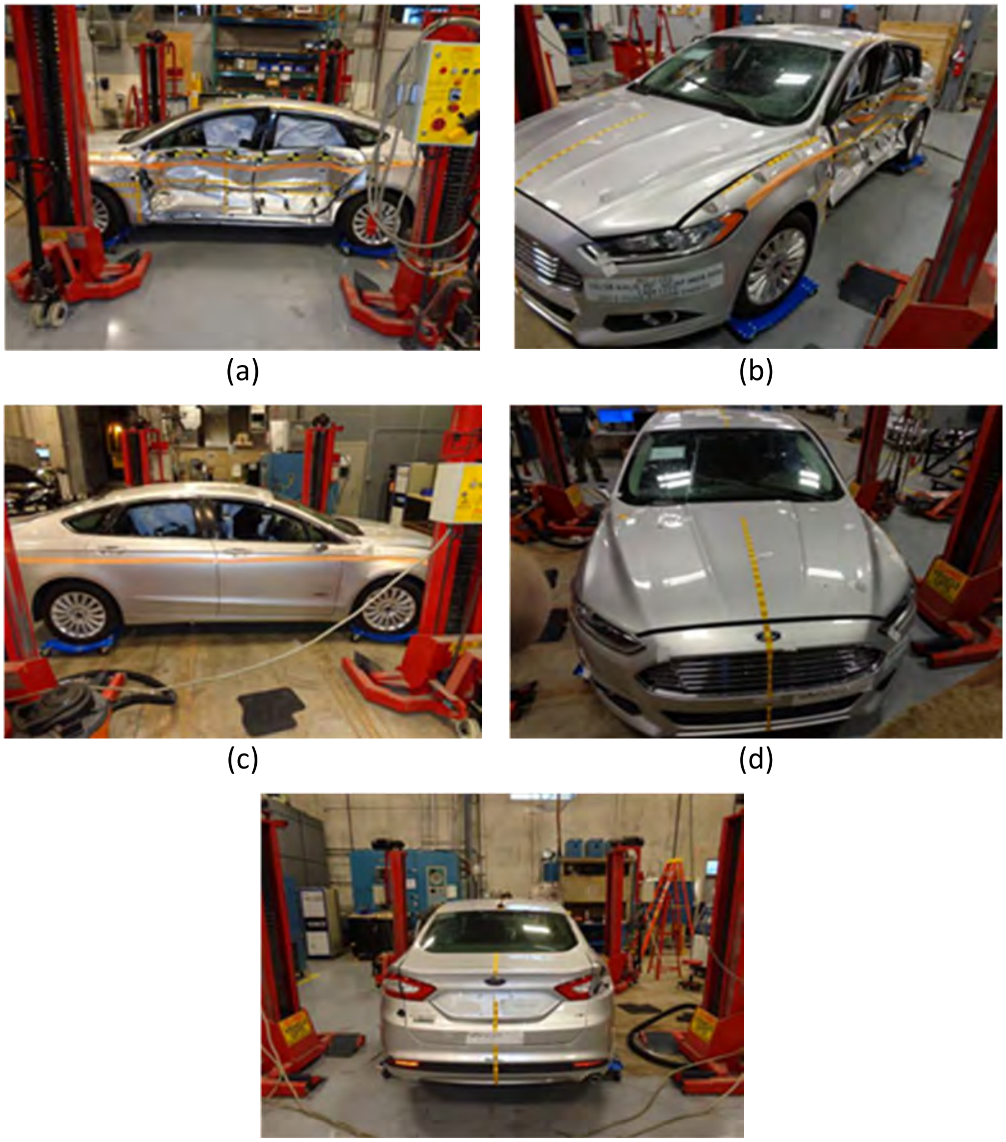
Figure 29 - Ford C-Max HEV post-test vehicle condition: a) left view, b) right view, c) rear view, d) front view, e) engine bay, and f) driver's seat.

8.2.2 Ford Fusion SE PHEV

The Ford Fusion SE (Fusion-1) was a new production PHEV previously used for side impact testing, see Table 10. Figure 30 shows the as-received vehicle from multiple angles. Figure 10 (above) shows some of the equipment used for testing, including the DAQ system, the gas sensor, the video camera, and the immersion tank.

Table 10 - Ford Fusion-1 PHEV Details

Vehicle Class	Passenger Car
Manufacturer	Ford
Make	Fusion Energi
Model	SE PHEV
Date of Manufacture	Feb-12
VIN	3FA6P0PU4DR252084
Condition	Damaged (side impact)
Vehicle Type	PHEV



(a) (b)

(c) (d)

(e)

Figure 30 - Ford Fusion-1 PHEV initial vehicle condition: a) left view, b) front ¾ view, c) right view, d) front view, and e) rear view.

8.2.2.1 Sample Preparation

As received, the vehicle was not operational since all of the fluids (engine oil, brake fluid etc.) had been drained and needed to be refilled. It was also noted that the fuel tank was leaking; further inspection showed that the cover had been cut and a hole drilled into the tank. The fuel tank was patched with epoxy resin. The 12 V battery was below the minimum voltage and needed to be restored to health. The HV RESS was visually inspected and no damage from the side impact test was observed. All the loose interior parts were tagged and removed from the cabin. The vehicle was then successfully turned to the start position; it functioned in EV mode showing 75% charge. The engine was started and the transmission was placed into low gear. Once it was confirmed that the vehicle was operational, it was turned off for sensor installation.

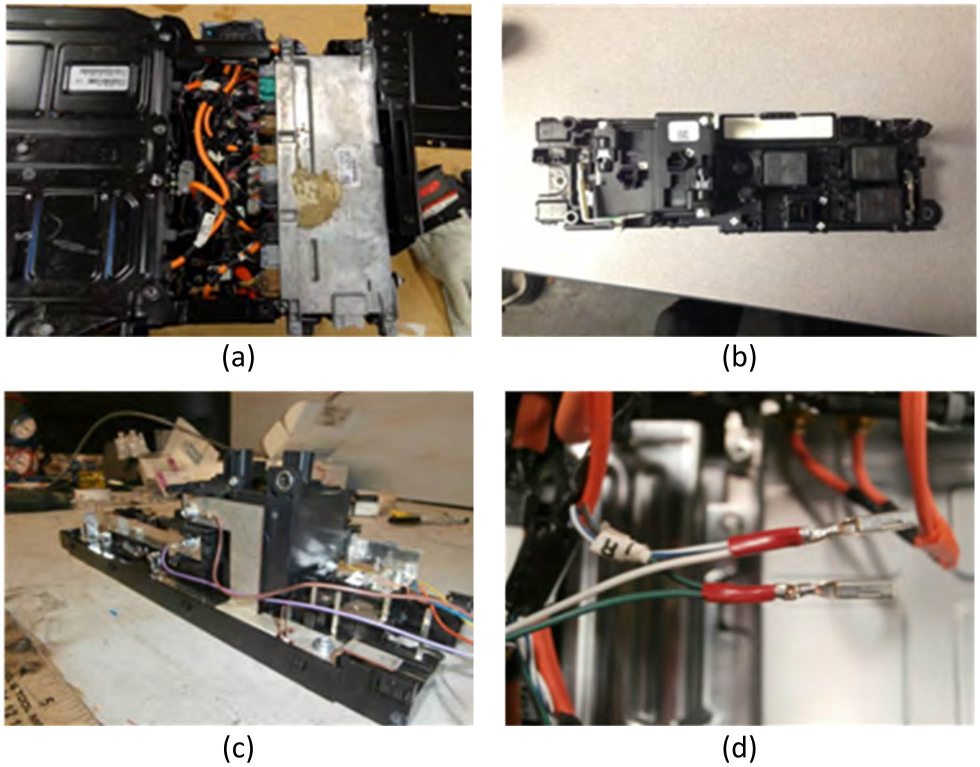
For HV and isolation measurements, the RESS was removed from the vehicle and the contactor assembly was taken apart. The voltage sensors were tightly screwed to the bus bars of the assembly (see Figure 31). Since the RESS was not encased and sealed, no special measures to seal the measurement wire feedthroughs were needed. The contactor was reassembled and reinstalled in the pack; the RESS was then placed back into the vehicle. Voltage sense cables were also installed on the 12 V battery. The vehicle was re-tested for operation and no issues were encountered.

A total of eight thermocouples were installed as specified in test procedure (see Section 6.5.1.13), including the RESS enclosure, near contactors, the control unit, and the 12 V battery. Thermocouple locations are provided in Table 11 and shown in Figure 32. The thermocouples were held in position using epoxy adhesive.

Three gas sensors were also mounted above the driver window (see Section 7.2).

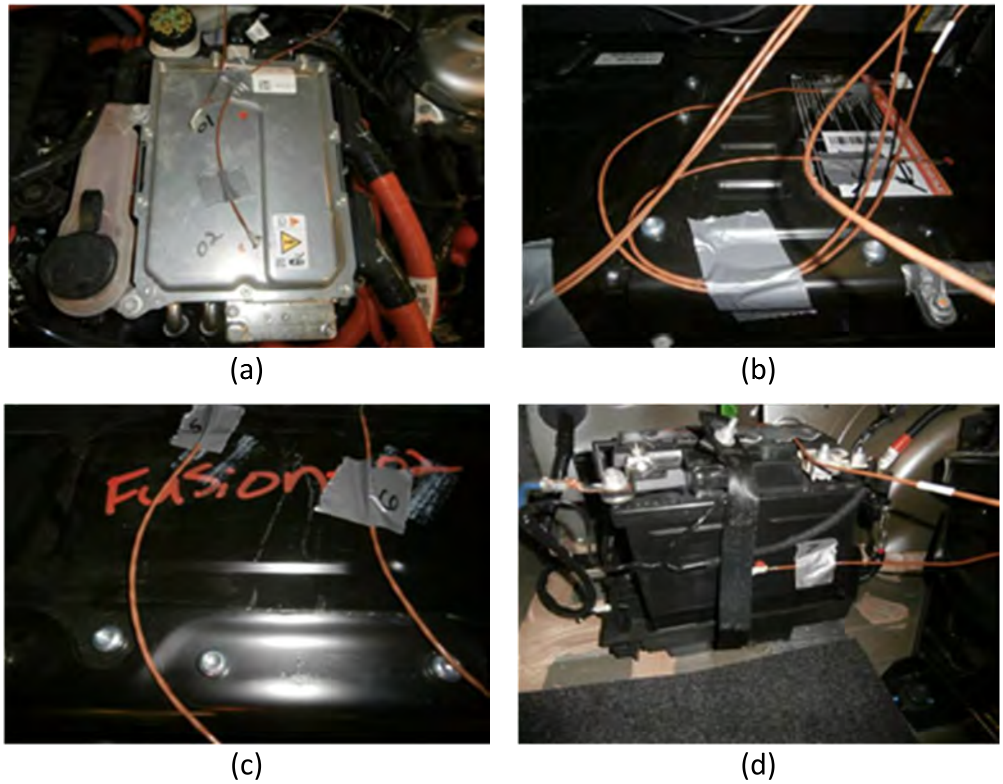
Table 11 - Ford Fusion-1 PHEV Thermocouple Placement

Number	Location
TC1, TC2	Control unit
TC3, TC4	Near contactors
TC5, TC6	Center of the RESS
TC7, TC8	12 V battery


(a) (b)

(c) (d)

Figure 31 - Ford Fusion-1 PHEV HV connections: a) RESS removed from vehicle, b) contactor assembly, c) wires screwed to contactor assembly, and d) wires soldered to pin connectors.



(a) (b)

(c) (d)

Figure 32 - Ford Fusion-1 PHEV HV thermocouple placement: a) TC1 and TC2 on the control unit, b) TC3 and TC4 on the center of the RESS, c) TC5 and TC6 near the contactor, and d) TC7 and TC8 on the 12 V battery.

8.2.2.2 Test Conditions

Testing was performed outdoors in ambient temperatures. The beginning of test temperature was -7.39°C. A temporary enclosure over the top of the immersion container was installed to keep rain and snow from entering the vehicle during testing. There was no precipitation on the day the vehicle was immersed. The vehicle remained in the immersion container during the post-extraction observation period.

8.2.2.3 Immersion Test Results

The test event log is summarized in Table 12. Isolation resistance measurements were performed approximately every 6 minutes. Figures 33 through 43 show measured data for the initial 9 hours of the test as follows:

- Figure 33 - Temperature profile for the first 9 hours of testing
- Figure 34 - Temperature profile for the first 30 minutes of testing
- Figure 35 - Gas sensing current for the first 9 hours of testing
- Figure 36 - 12 V control voltage for the first 9 hours of testing
- Figure 37 - 12 V control voltage for the first 30 minutes of testing
- Figure 38 - Electrode to chassis voltage for the first 9 hours of testing
- Figure 39 - Electrode to chassis voltage for the first 30 minutes of testing

- Figure 40 - RESS voltage for the first 9 hours of testing
- Figure 41 - RESS voltage for the first 1 hour of testing
- Figure 42 - Isolation resistance for the first 9 hours of testing
- Figure 43 - Isolation resistance for the first 30 minutes of testing

Figures 44 through 48 show measured data for the final 10 hours of the test as follows:

- Figure 44 - Temperature profile for the last 10 hours of testing
- Figure 45 - Gas sensing current for the last 10 hours of testing
- Figure 46 - 12 V control voltage for the last 10 hours of testing
- Figure 47 - RESS voltage for the last 10 hours of testing
- Figure 48 - Isolation resistance for the last 10 hours of testing

Table 12 - Ford Fusion-1 PHEV Test Event Log

Date	Time	Test Time (hh:mm)	Event
3/24/2014	4:49 PM	N/A	• Video and data logging initiated.
3/24/2014	4:50 PM	N/A	• The vehicle was started (key-on, key-start, gear shift to Drive).
3/24/2014	4:51 PM	00:00	• Initiated filling the vehicle container with salt water.
3/24/2014	4.53 PM	00:02	• Isolation resistance decreased from 10 MΩ to 4.2 MΩ.
3/24/2014	4:58 PM	00:07	• Average ambient temperature before immersion was -7°C. • The temperature recorded by the thermocouples on the 12 V battery quickly increased to -0.9°C.
3/24/2014	4.59 PM	00:08	• The post-contactor RESS voltage (HVpos_P_N) dropped to zero. • The LV battery voltage started to decrease at this moment and quickly dropped to 5 V and then reached 0 V after 4.5 hours. • Simultaneously, the contactor coil voltages (POS_COIL and NEG_COIL) decreased to 5 V, but reached values near 0 V within 30 minutes. • Isolation resistance decreased from 4.2 MΩ to a negative value.
3/24/2014	5:00 PM	00:09	• The RESS pre-contactor voltage (HVpre_P_N) started to decrease. • At the same time, HVpos_P_N sharply increased to approximately 250 V. • Both pack voltages continued to decrease for 50 seconds and then started to increase temporarily. HVpos_P_N reached 0 V within 1 hour; HVpre_P_N reached 0 V within 2 hours.

Date	**Time**	**Test Time (hh:mm)**	**Event**
3/24/2014	5:02 PM	00:11	• The pack temperature (TC3, TC4 on the case near the contactors and TC5, TC6 centered on the RESS) started to increase. • The maximum temperature recorded at this stage was 33°C on the case. The RESS temperature decreased to an average of 5°C after 4 minutes. • The BECM temperature had started increasing from the beginning of the test and reached a maximum of 5°C by this time. • A spike in pack voltages (HVpre_P_N, HVpos_P_N) was observed as well.
3/24/2014	5:03 PM	00:12	• Video observation: Bubbles were seen forming in the engine compartment. They continued to form throughout the immersion step.
3/24/2014	5:05 PM	00:14	• Isolation resistance dropped to zero. It remained at zero because the RESS-to-chassis voltages dropped to zero. • Note: The fluctuations on the RESS-to-chassis voltages prior to this point are possibly due to the interference of the vehicles isolation resistance measurements.
3/24/2014	5:08 PM	00:17	• The water fill stopped; the fill level was about 7 inches below the target due to equipment issues.
3/24/2014	7:03 PM	02:12	• Extraction step initiated (i.e., water pumped out of the container).
3/24/2014	7:25 PM	02:34	• Extraction step completed.
• There were no changes in recorded gas sensing during the period mentioned above. • No further changes in voltage, temperature and gas sensing were recorded from this point to the end of the post-extraction period except for temperature variations following the environmental conditions.			

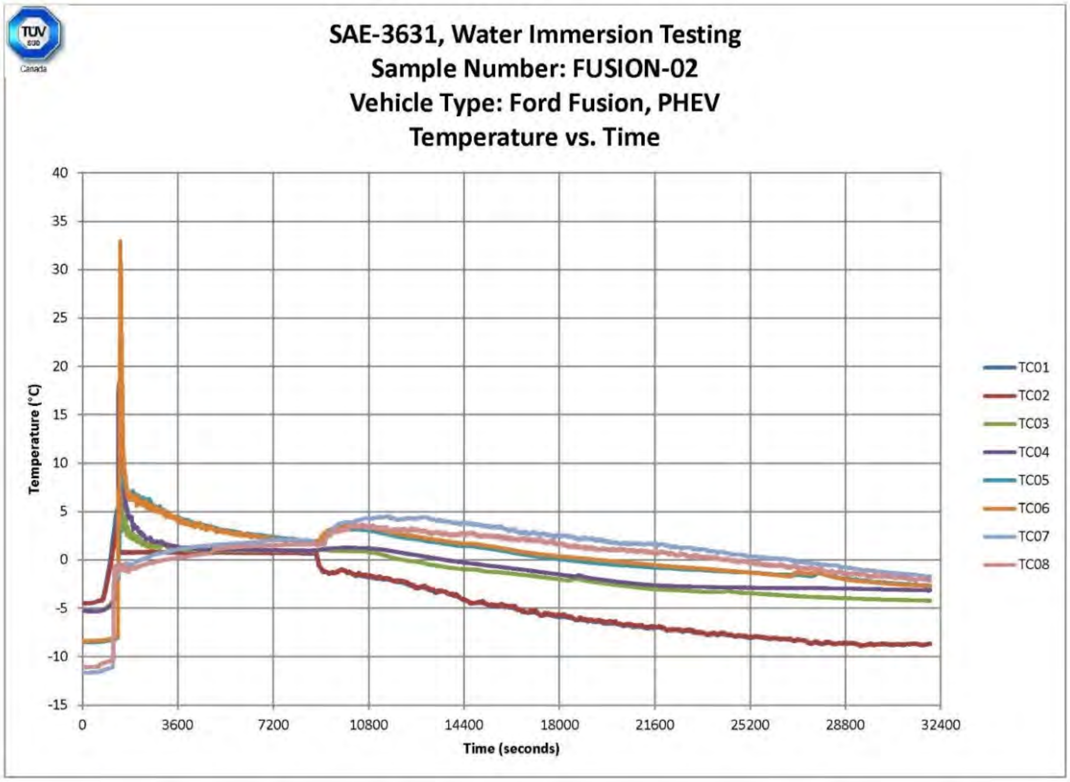


Figure 33 - Ford Fusion-1 PHEV temperature profile for the first 9 hours of testing.

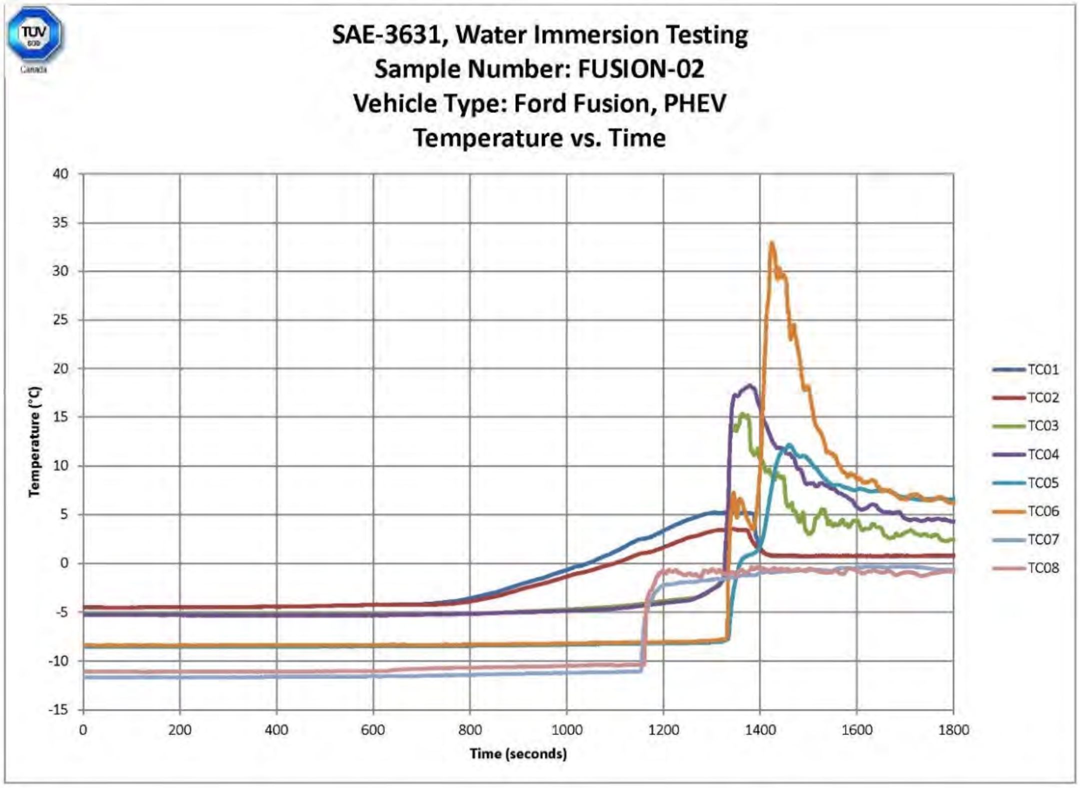


Figure 34 - Ford Fusion-1 PHEV temperature profile for the first 30 minutes of testing.

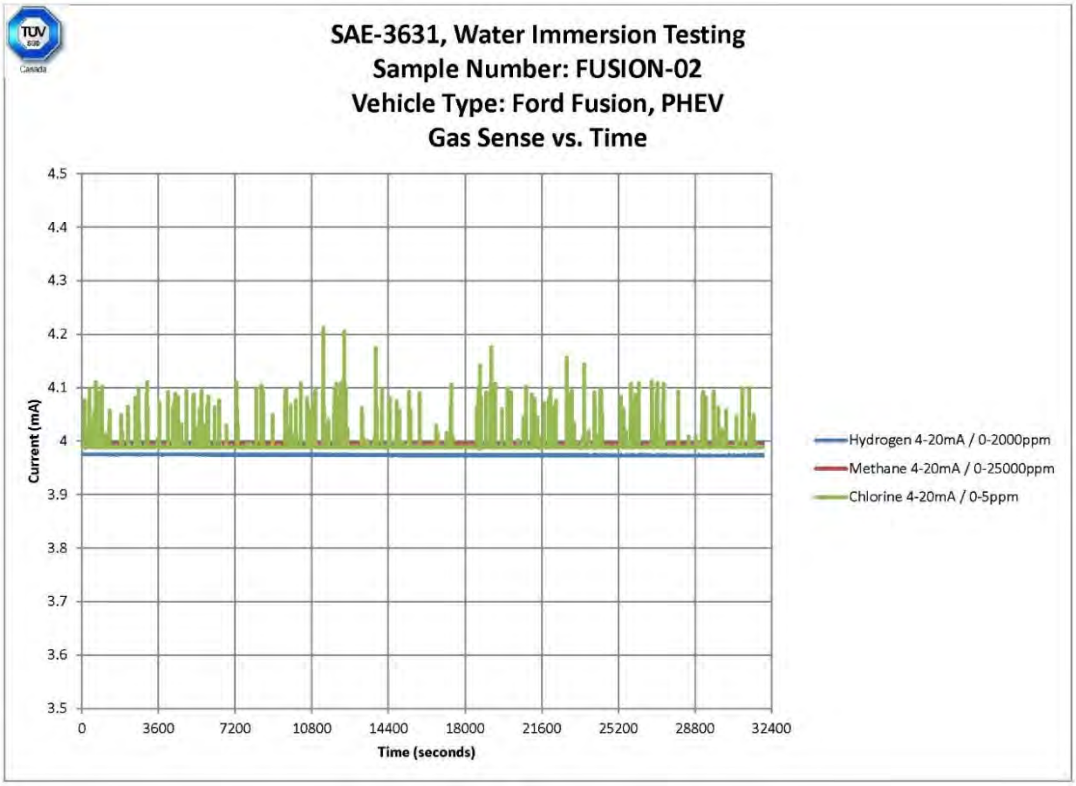


Figure 35 - Ford Fusion-1 PHEV gas sensing current for the first 9 hours of testing.

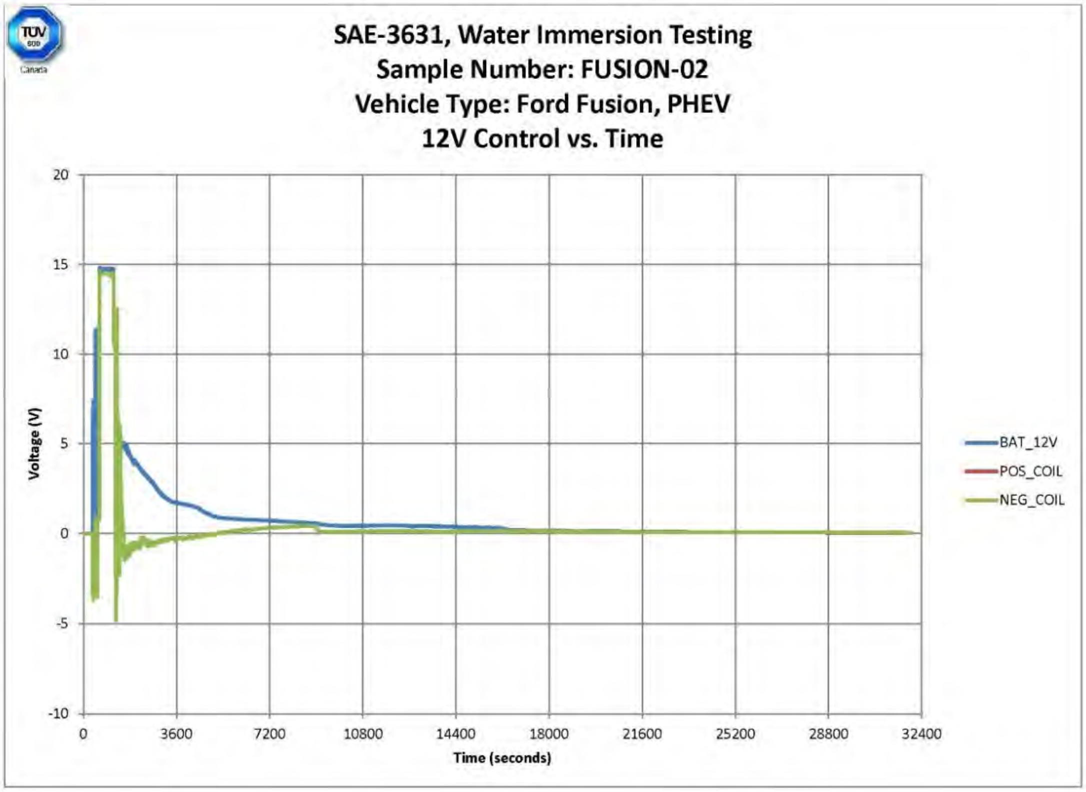


Figure 36 - Ford Fusion-1 PHEV 12 V control voltage for the first 9 hours of testing.

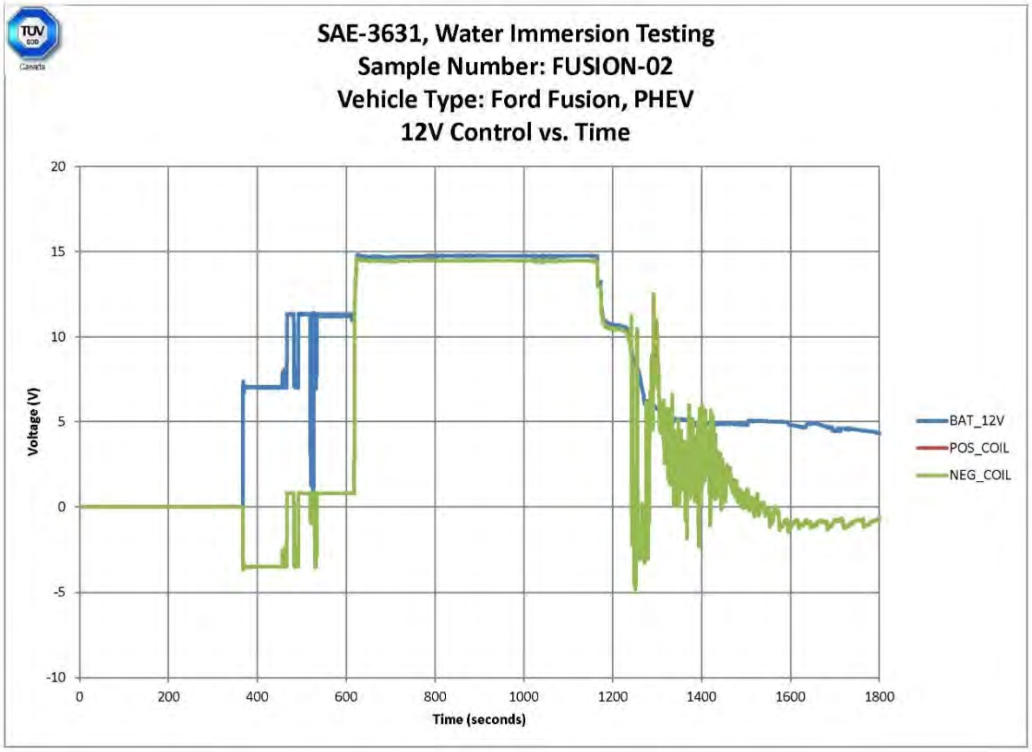


Figure 37 - Ford Fusion-1 PHEV 12 V control voltage for the first 30 minutes of testing.

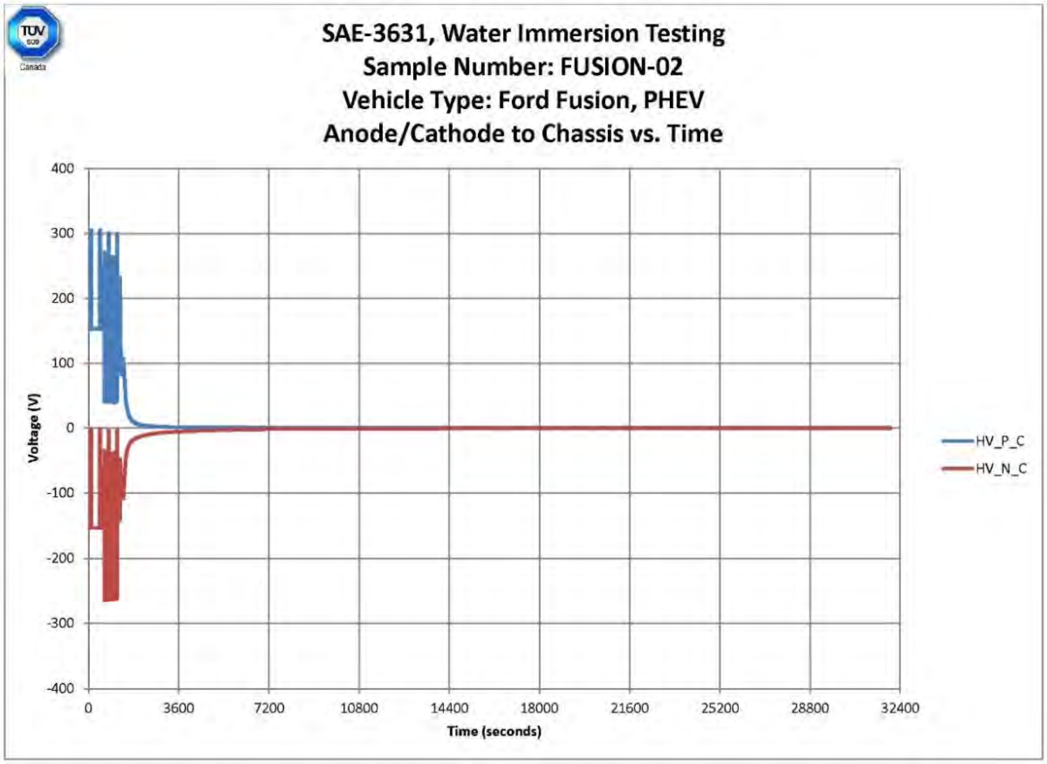


Figure 38 - Ford Fusion-1 PHEV electrode to chassis voltage for the first 9 hours of testing.

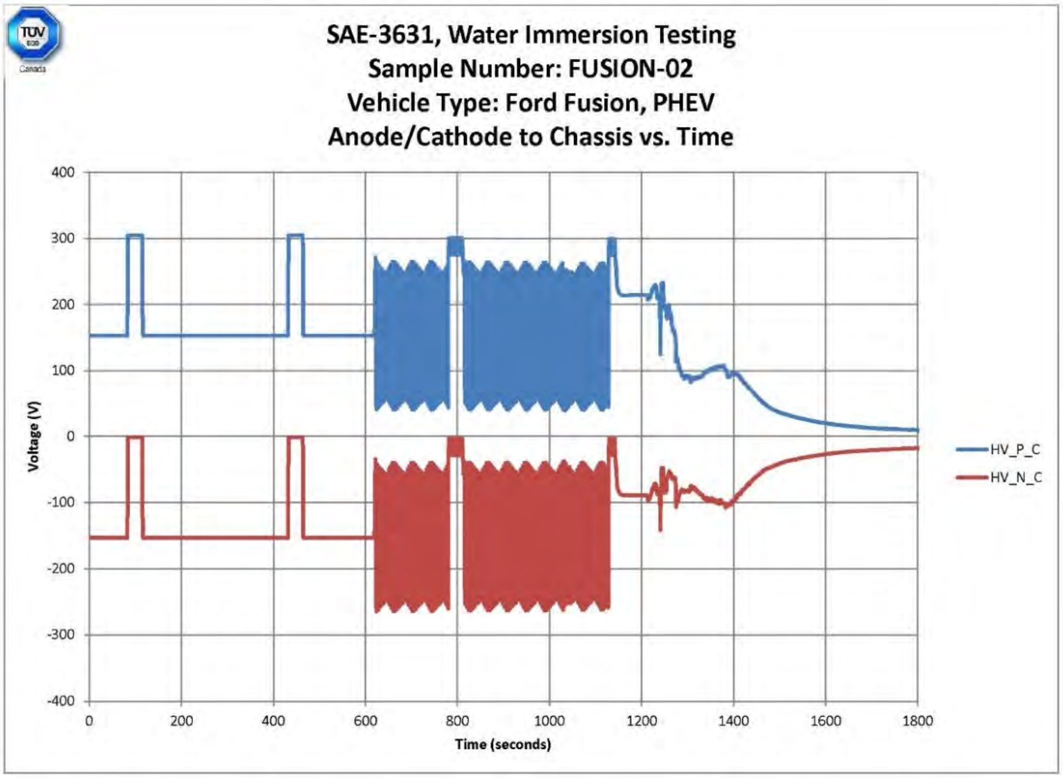


Figure 39 - Ford Fusion-1 PHEV electrode to chassis voltage for the first 30 minutes of testing.

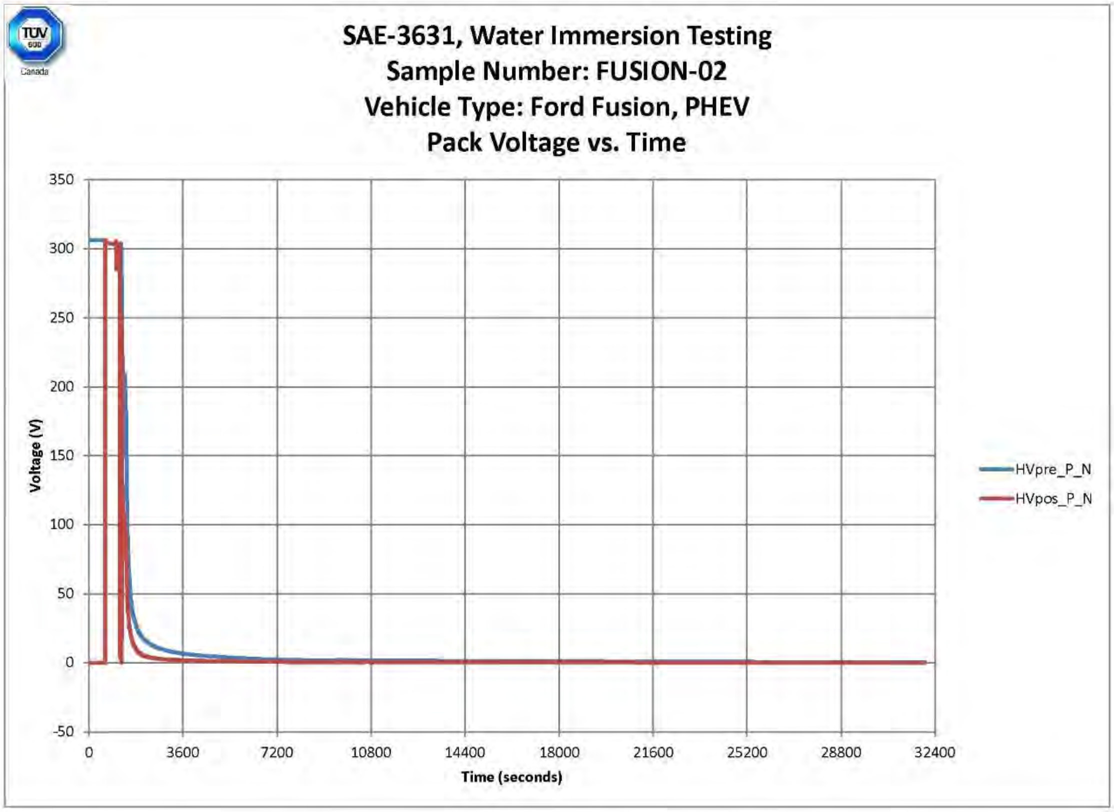


Figure 40 - Ford Fusion-1 PHEV RESS voltage for the first 9 hours of testing.

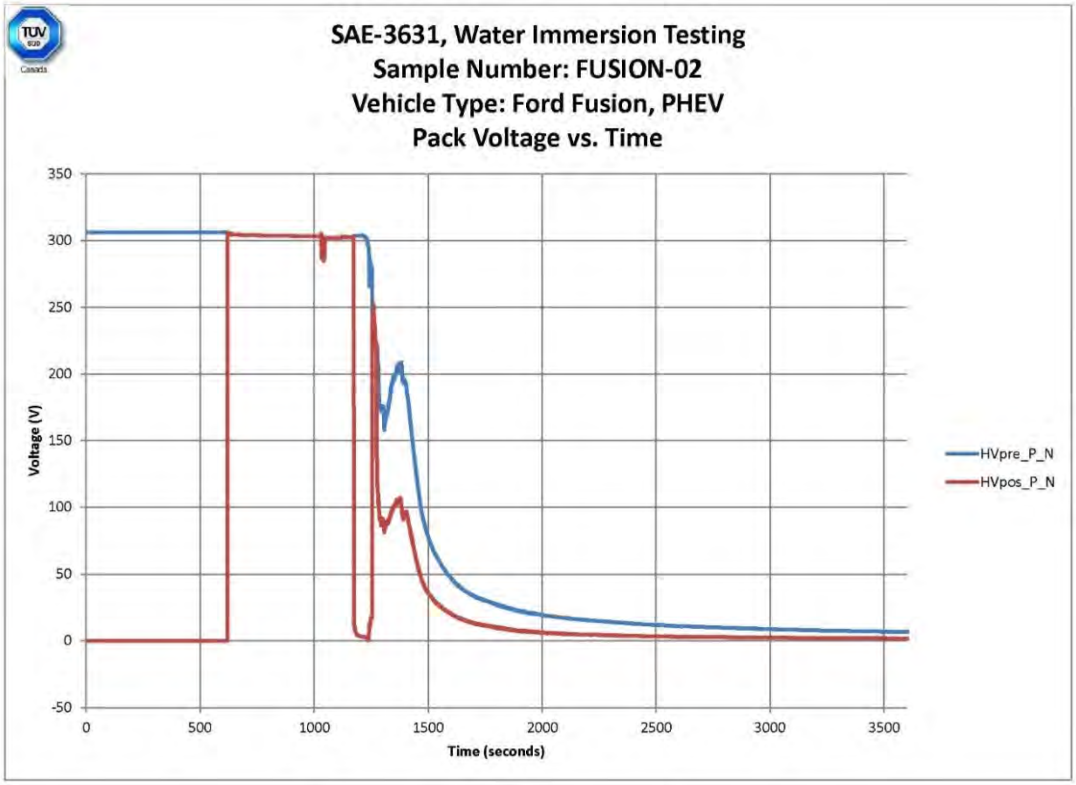


Figure 41 - Ford Fusion-1 PHEV RESS voltage for the first 1 hour of testing.

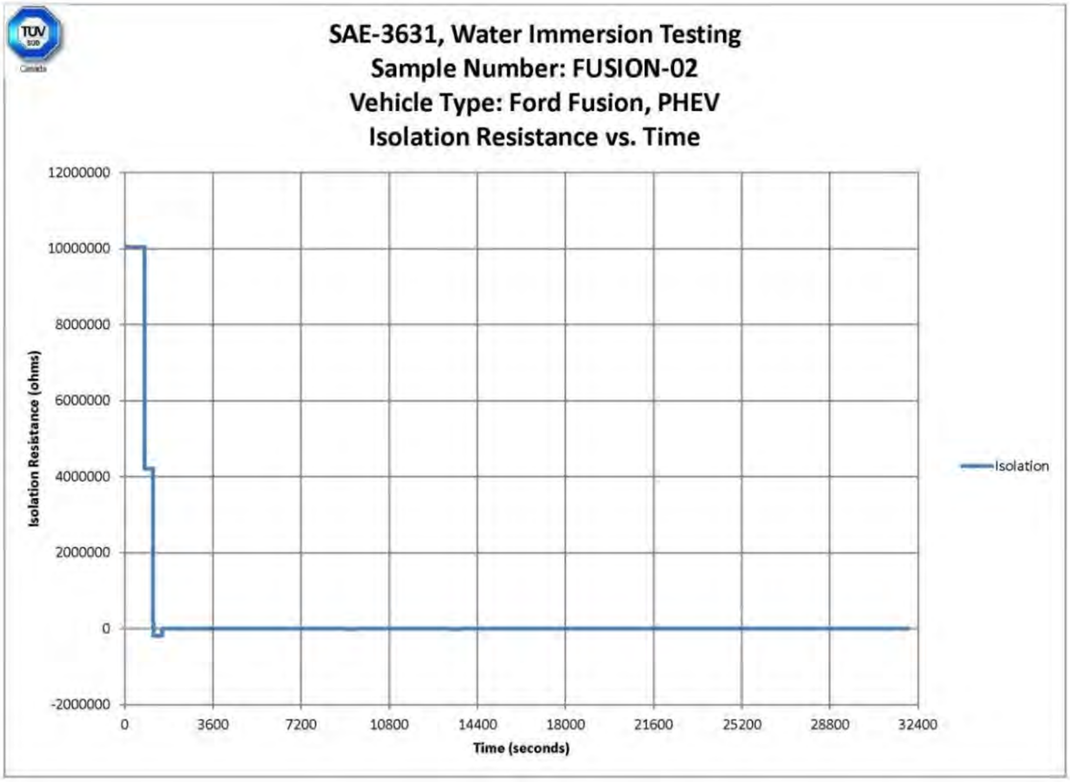


Figure 42 - Ford Fusion-1 PHEV isolation resistance for the first 9 hours of testing.

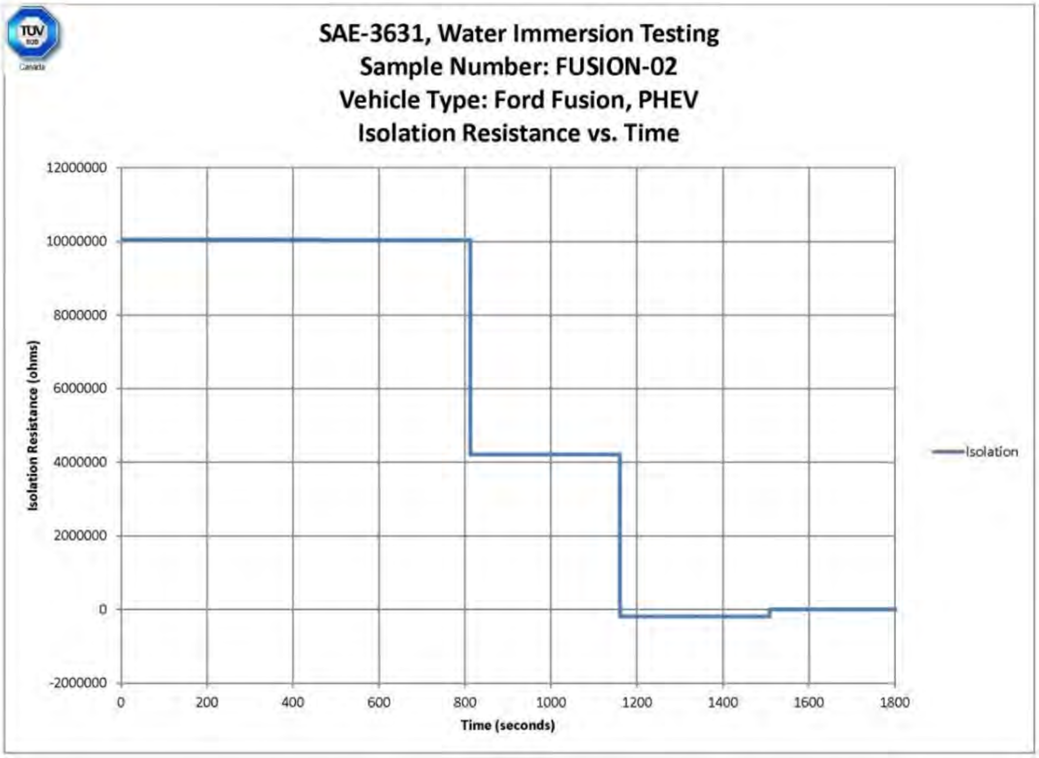


Figure 43 - Ford Fusion-1 PHEV isolation resistance for the first 30 minutes of testing.

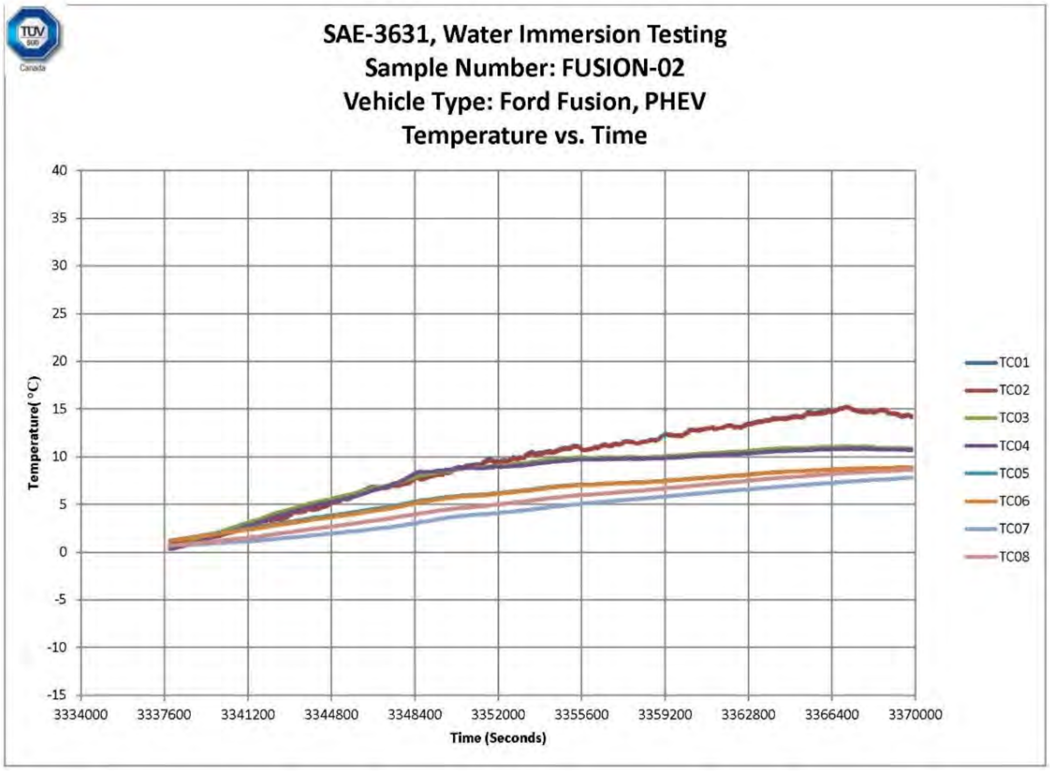


Figure 44 - Ford Fusion-1 PHEV temperature profile for the last 10 hours of testing.

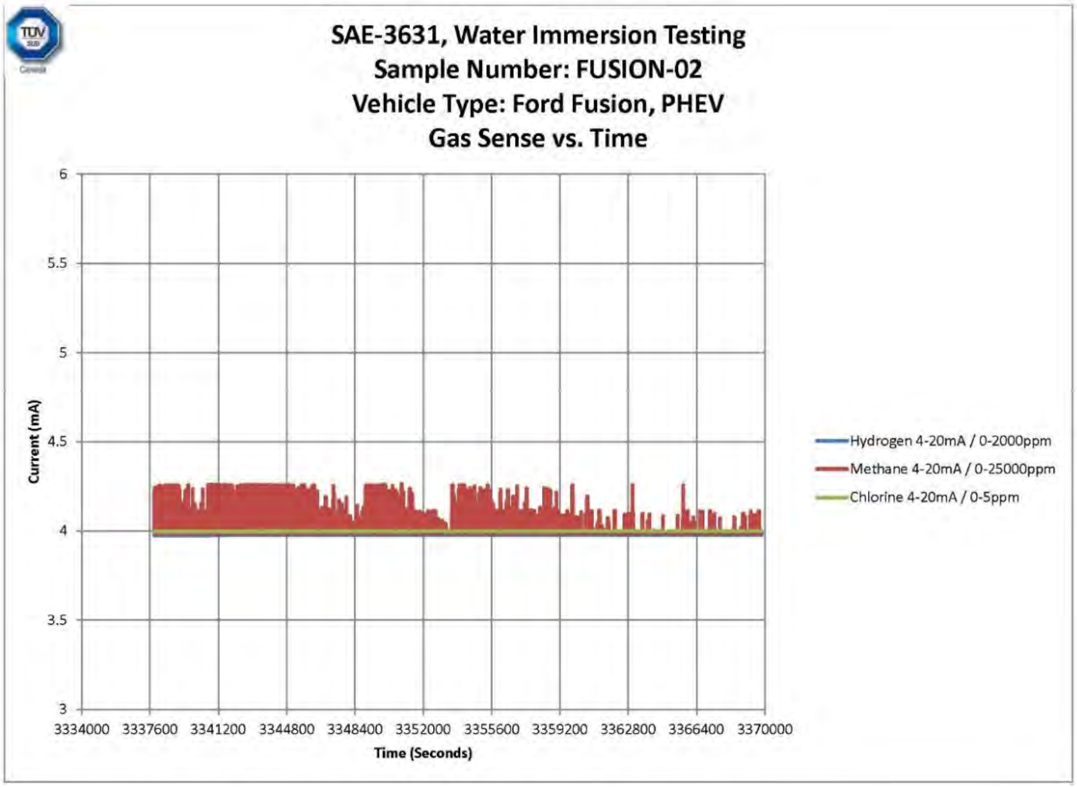


Figure 45 - Ford Fusion-1 PHEV gas sensing current for the last 10 hours of testing.

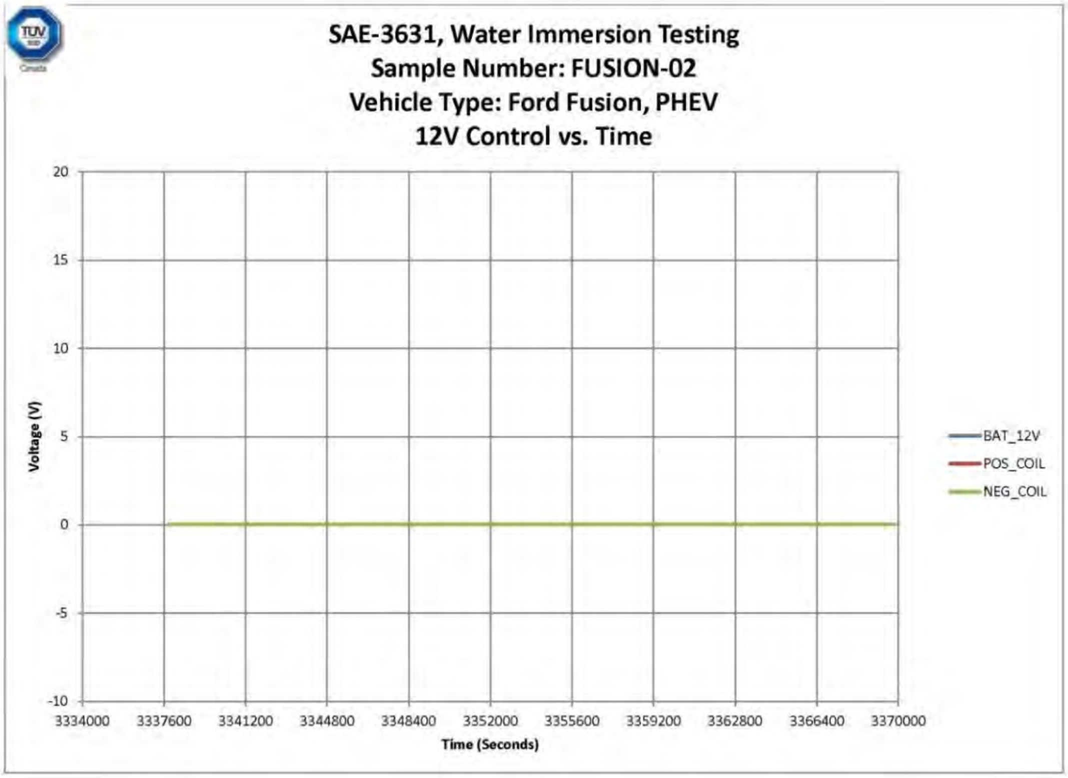


Figure 46 - Ford Fusion-1 PHEV 12 V control voltage for the last 10 hours of testing.

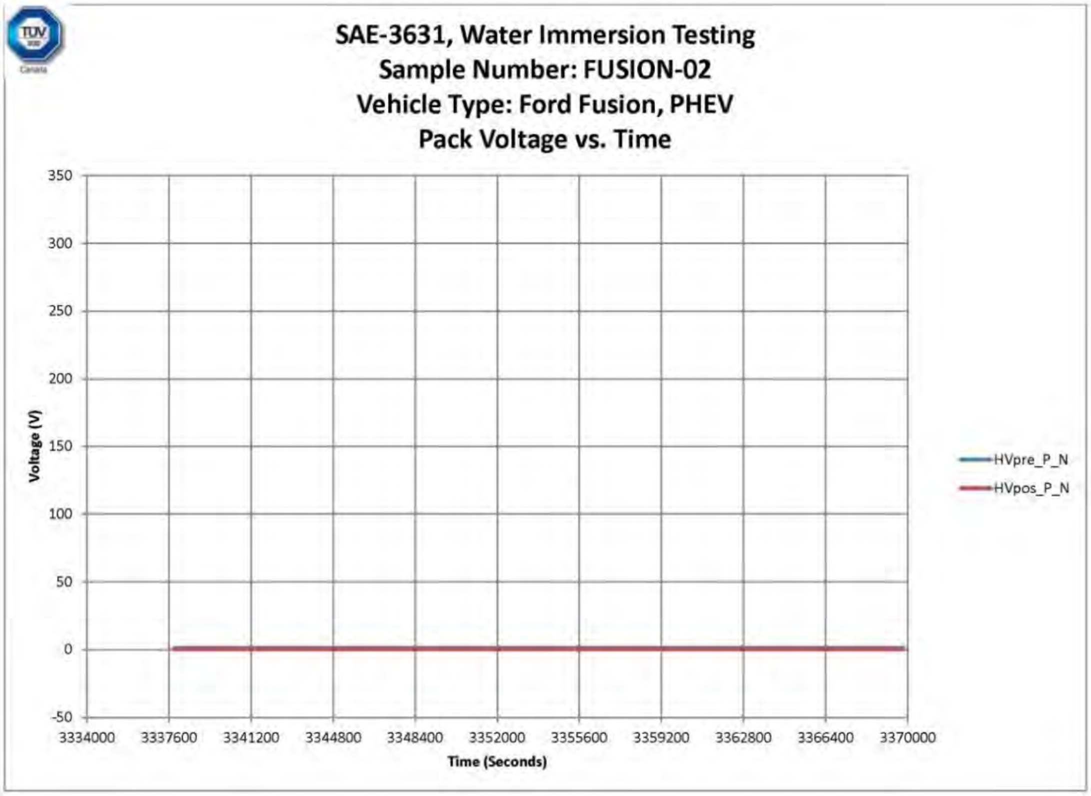


Figure 47 - Ford Fusion-1 PHEV RESS voltage for the last 10 hours of testing.

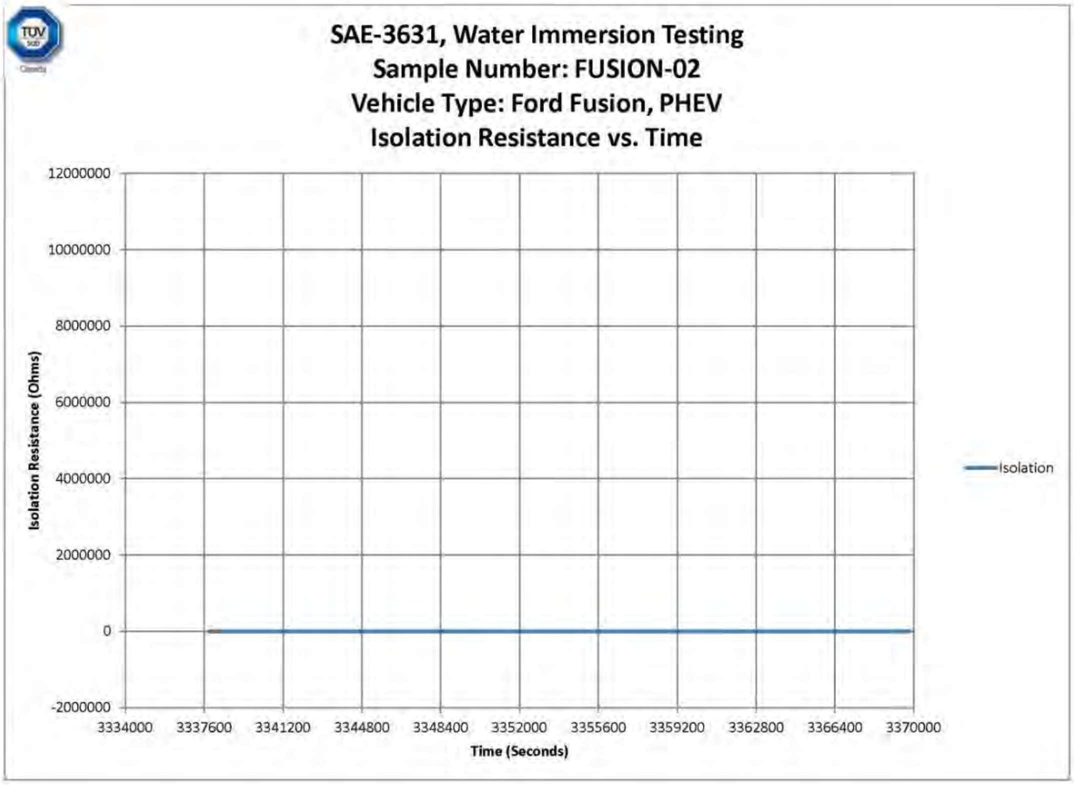


Figure 48 - Ford Fusion-1 PHEV isolation resistance for the last 10 hours of testing.

8.2.2.4 Seawater Analysis Results

Seawater samples were taken before and after immersion. They were measured on-site for pH, density and conductivity; the results are summarized in Table 13. Table 14 shows the VOCs that were above the reportable detection limit, as determined from Maxxam Analytics, Inc. Note that the samples were also analyzed for other VOCs that were below the reportable limit. Table 15 shows the total oil and grease content from the samples.

Table 13 - Ford Fusion-1 PHEV Conductivity, Salinity, Density, and pH

Time	Conductivity (mS/cm)	Salinity (wt%)	Density (g/cm³)	pH
Pre-immersion	51.1	3.10	1.024	7.4
Post-immersion	51.1	3.15	1.024	7.4

Table 14 - Ford Fusion-1 PHEV VOCs above Reportable Detection Limit

Volatile Organics	Units	Pre-Immersion	Post-Immersion	RDL*
Benzene	µg/L	<0.50	0.56	0.50

*RDL=Reportable Detection Limit

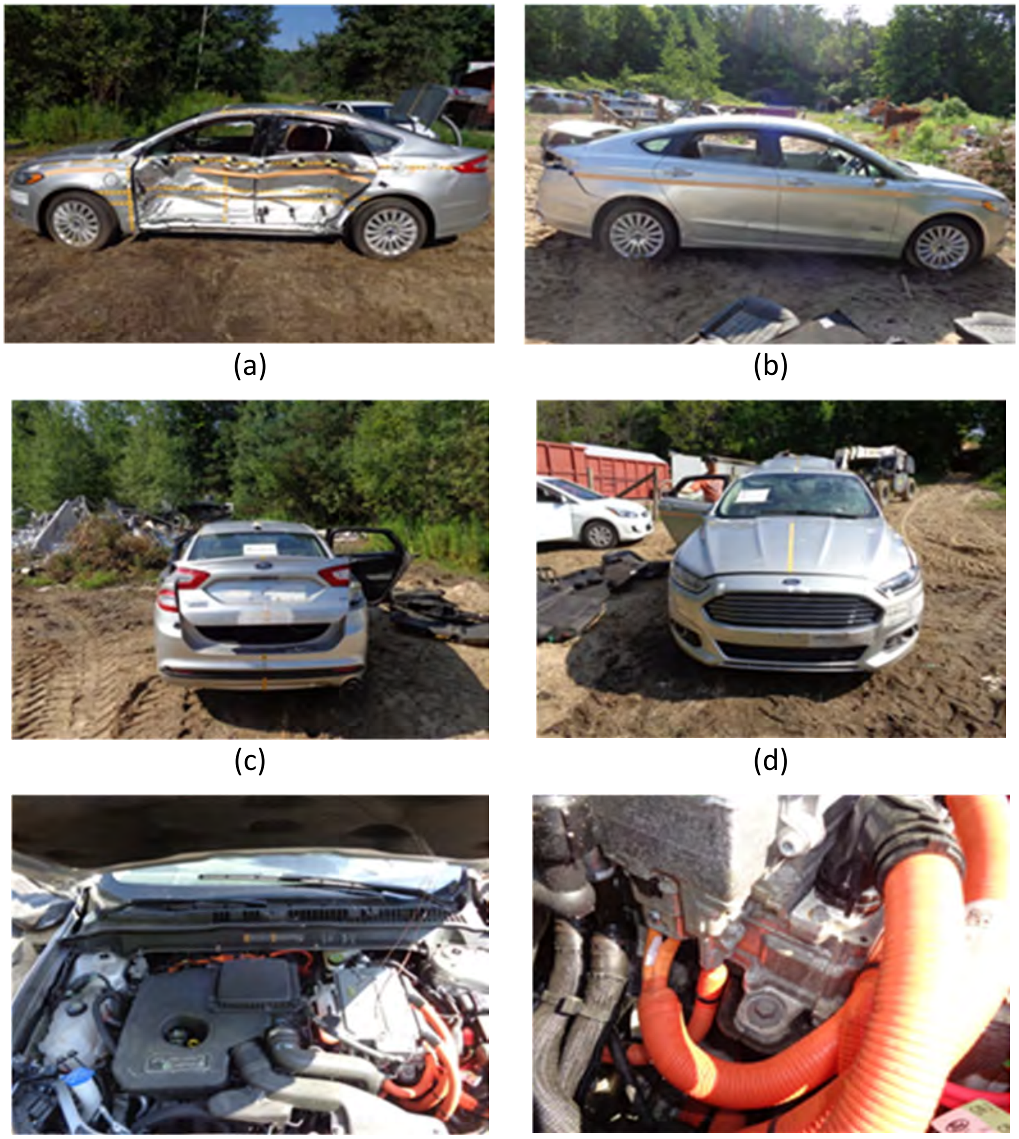
Table 15 - Ford Fusion-1 PHEV Total Oil and Grease Content

Petroleum Hydrocarbons	Units	Pre-Immersion	Post-Immersion	RDL*
Total oil and grease	mg/L	<0.50	<0.50	0.50

*RDL=Reportable Detection Limit

8.2.2.5 Post-Mortem Analysis

Figures 49 through 52 show the vehicle and RESS from multiple angles after testing was complete. Post-mortem analysis did not indicate any evidence of behaviors that could result in an HSL higher than 4 (i.e., no anticipated fires, ruptures, or explosions) based on EUCAR standards. Although the temperature increased inside the RESS during immersion from -8°C to 30°C, it quickly declined to ambient levels after 3 hours and followed the diurnal ambient values until the end of the test. Additionally, the water immersion caused the RESS voltage to drop from 306 V to 8 V within the first hour of immersion; it then went down to 0 V until the end of the test. Therefore, no post-mortem analysis was conducted on the battery pack.



(a) (b)

(c) (d)

(e) (f)

Figure 49 - Ford Fusion-1 PHEV post-test vehicle condition: a) left view, b) right view, c) rear view, d) front view, e) engine bay, and f) engine bay close-up.

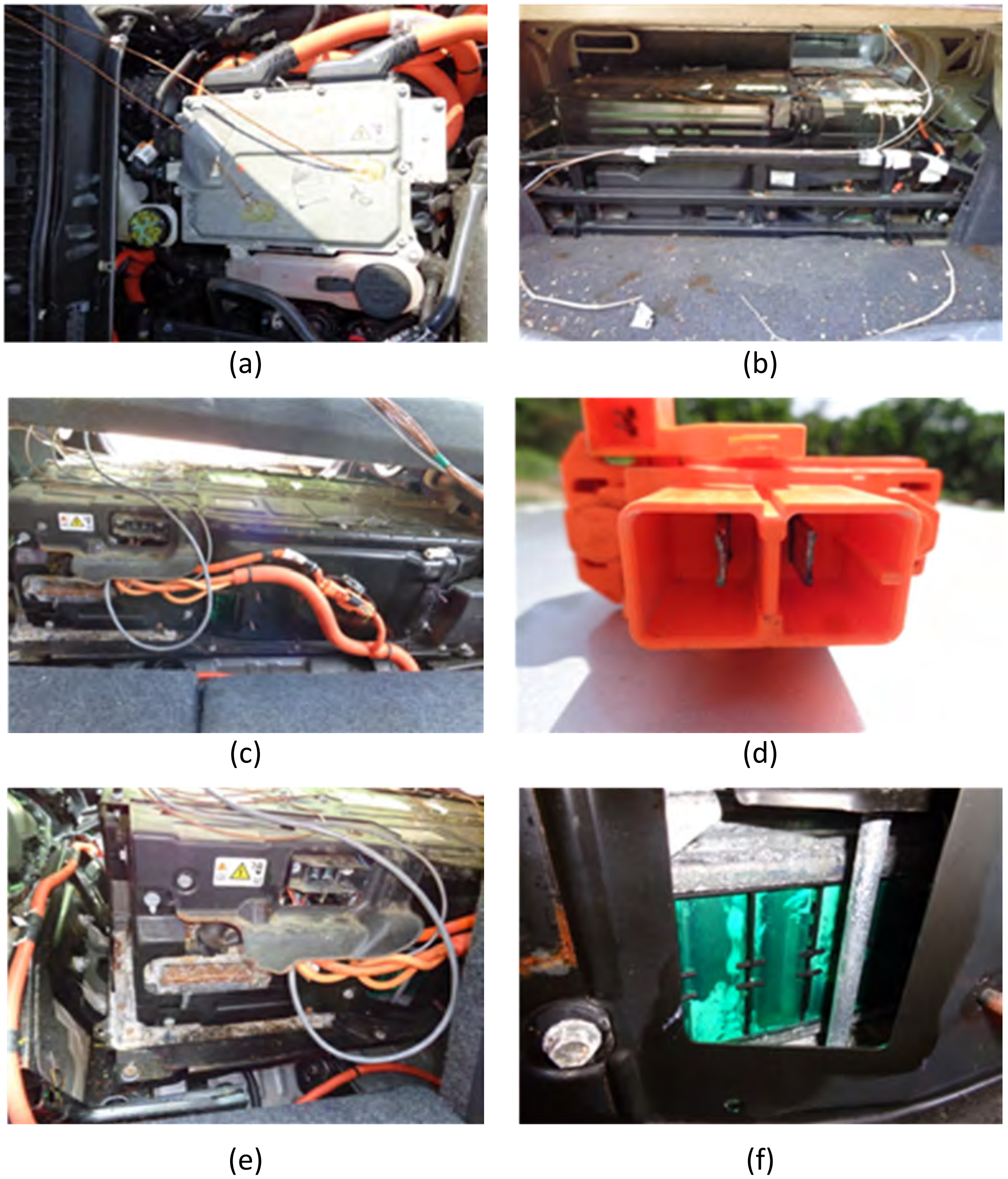


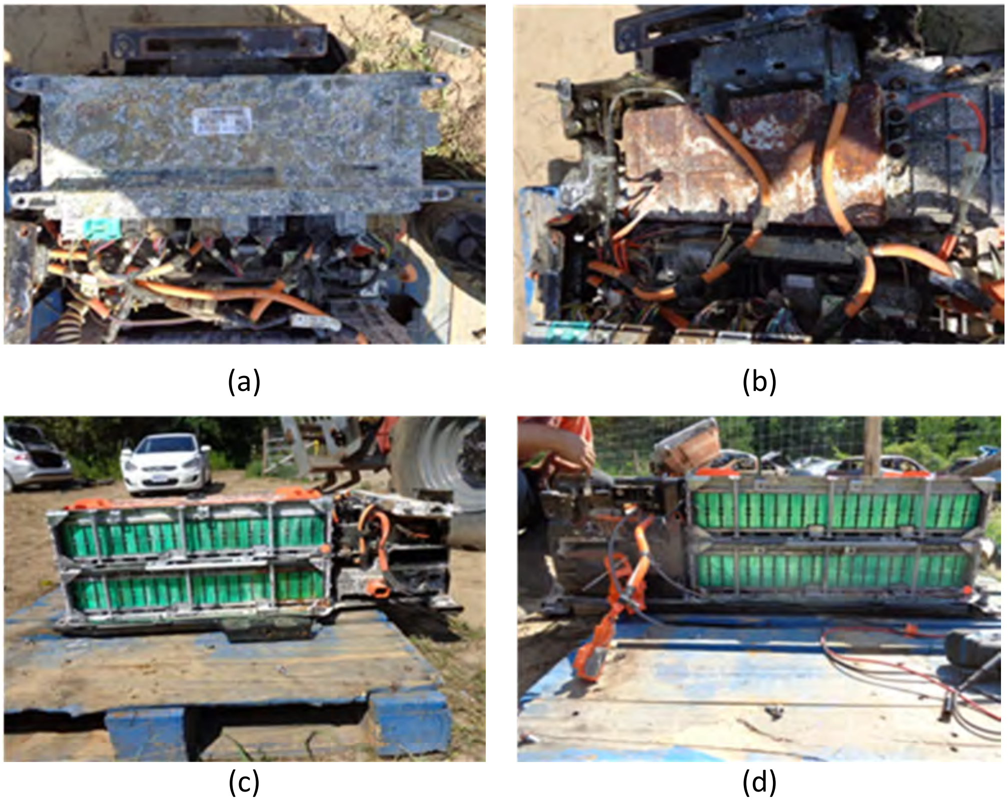
Figure 50 - Ford Fusion-1 PHEV post-test vehicle condition: a) control unit, b) interior trunk, c) interior cabin, RESS front, d) manual service disconnect, e) interior cabin charging harness, and f) cell close-up.

(a) (b)

(c) (d)

(e) (f)

Figure 51 - Ford Fusion-1 PHEV post-test RESS condition: a) rear exterior, b) front view close-up, c) exterior right view, d) exterior left view, e) interior top view, and f) bus bar close-up.


(a) (b)

(c) (d)

Figure 52 - Ford Fusion-1 PHEV post-test RESS condition: a) voltage sense control unit, b) exposed components beneath control unit, c) interior rear view, and d) interior front view.

8.2.3 Nissan Leaf SV/SL EV

The Nissan Leaf SV/SL (Leaf-1) was a new production EV previously used for side impact testing, see Table 16. Figure 53 shows the as-received vehicle from multiple angles. Figure 10 (above) shows some of the equipment used for testing, including the DAQ system, the gas sensor, the video camera, and the immersion tank.

Table 16 - Nissan Leaf-1 EV Details

Vehicle Class	Passenger Car
Manufacturer	Nissan
Make	Leaf
Model	SV/SL
Date of Manufacture	Apr-11
VIN	JN1AZ0CP3BT002476
Condition	Damaged (side impact)
Vehicle Type	EV

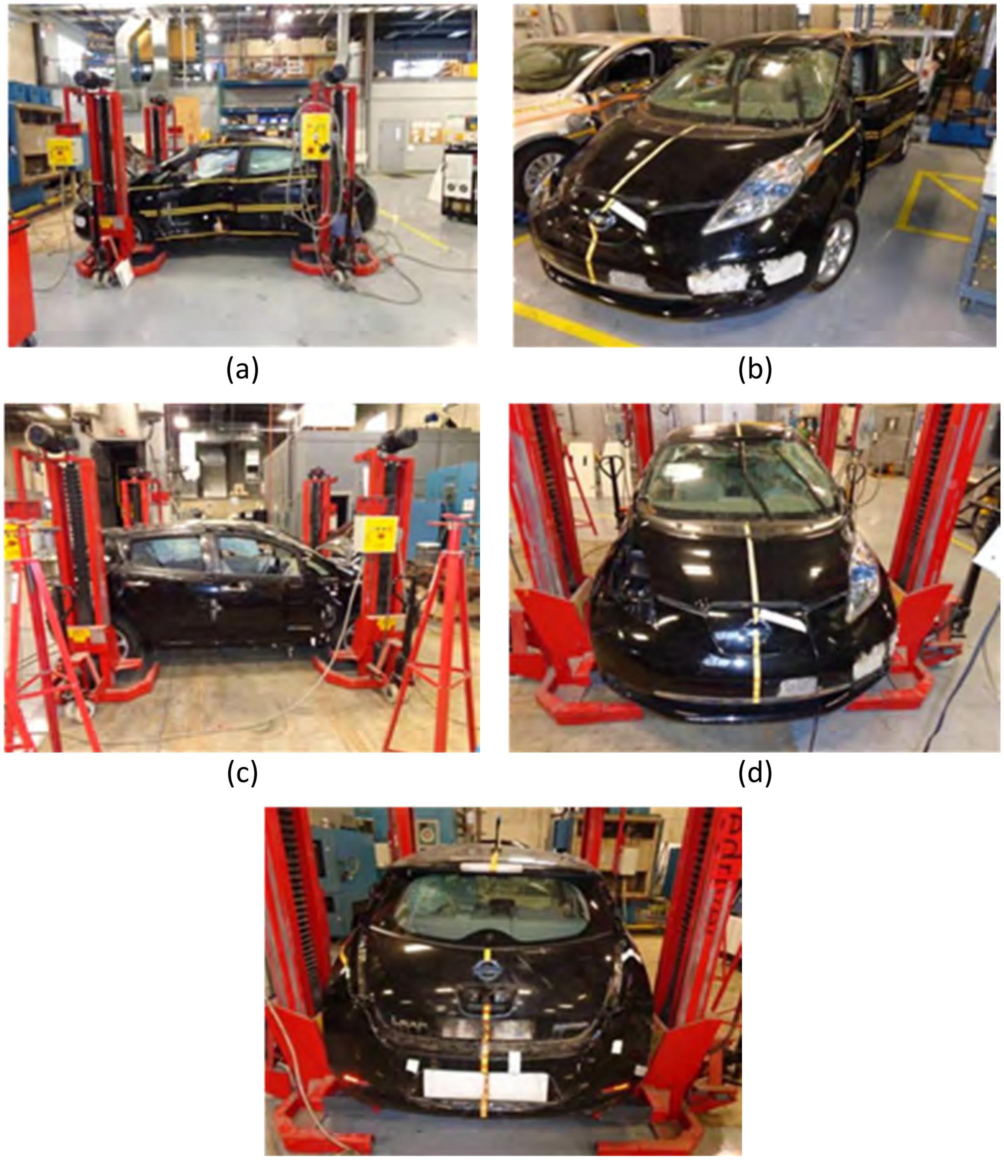

(a) (b)
(c) (d)
(e)

Figure 53 - Nissan Leaf-1 EV initial vehicle condition: a) left view, b) front ¾ view, c) right view, d) front view, and e) rear view.

8.2.3.1 Sample Preparation

All the loose interior parts of the vehicle were tagged and removed from the cabin. The vehicle was then lifted and inspected for damage. The RESS was missing 10 of the 14 mounting bolts and the HV cables were disconnected. There was also a slight visual separation along the centerline of the RESS front to rear. With no major visual defects to the pack, however, it was deemed safe enough to attempt reconnecting it to the vehicle. The 12 V battery was put on 0.75 A charge to attempt to bring it back to health.

The 12 V battery was then removed from the charger, the HV cables reconnected, the manual service disconnect was reinstalled, and the 12 V leads were connected. The vehicle was able to be powered on and shifted from P to F and R with no issues. The parking brake, however, would not release electronically and had to be bypassed (i.e., using the manual lockout in the trunk, as per the owner's manual). The vehicle display showed that the battery pack was almost fully discharged with a "Motor power is limited" warning. Once it was confirmed that the vehicle was operational, it was turned off for sensor installation.

For HV and isolation measurements, the RESS was removed from the vehicle (see Figure 54) and a note was found on the top stating that it had been discharged down to 10% SOC almost 24 months earlier. After photos were taken, the bolts were removed to separate the cover; the contactors were then removed from the RESS. Voltage sense leads were soldered to the contractor control circuits and screwed tightly to the bus bars (see Figure 54). The pack was then sealed to prevent water intrusion through the sense leads exiting the pack (see Section 8.1.2). The contactor was reassembled and re-installed and the RESS was placed back into the vehicle. Voltage sense cables were also installed on the 12 V battery.

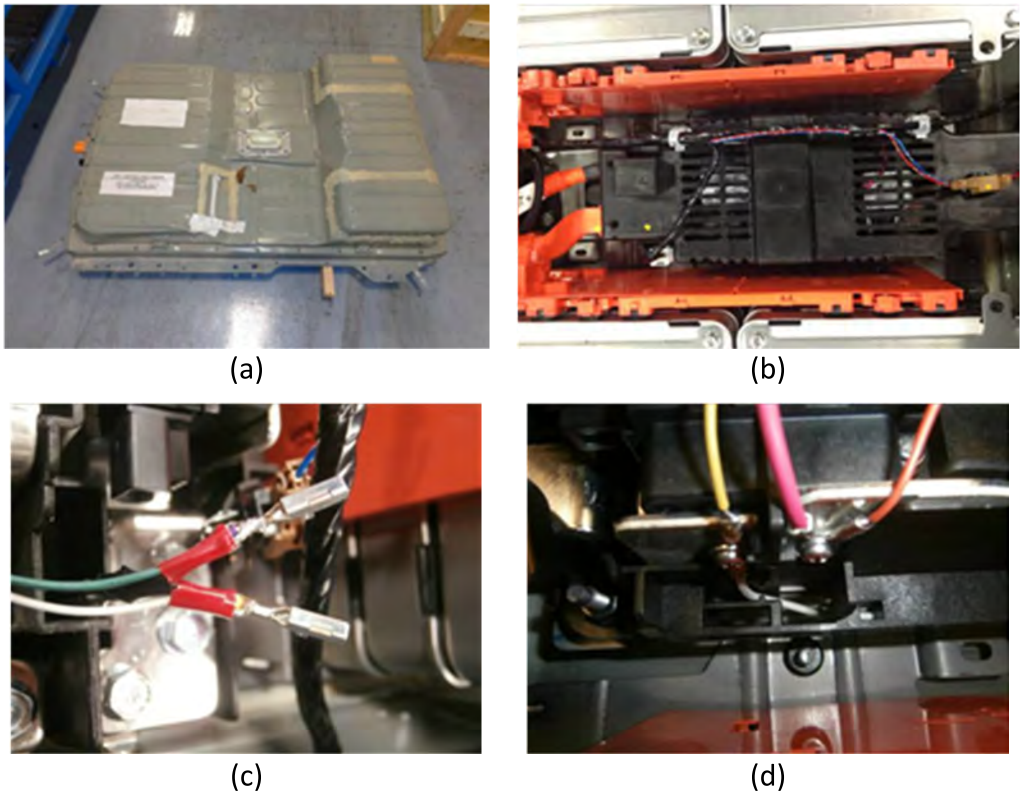
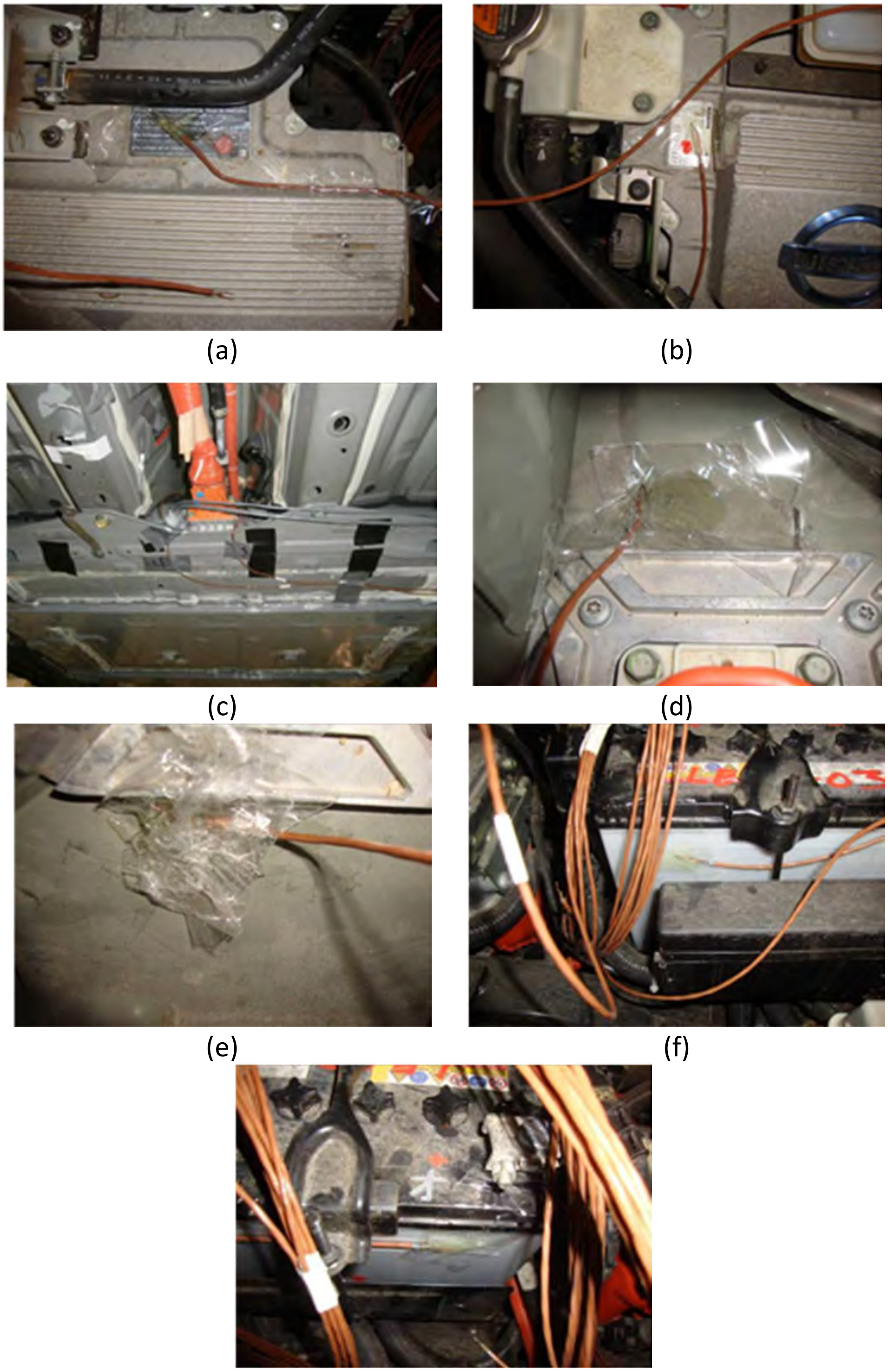

(a) (b) (c) (d)

Figure 54 - Nissan Leaf-1 EV HV connections: a) RESS removed from vehicle, b) contactor assembly, c) wires soldered to contactor control circuit, and d) wires screwed to bus bar.

A total of eight thermocouples were installed as specified in test procedure (see Section 6.5.1.13), including the RESS enclosure, near contactors, the control unit, and the 12 V battery. Thermocouple locations are provided in Table 17 and shown in Figure 55. The thermocouples were held in position using epoxy adhesive.



(a) (b)

(c) (d)

(e) (f)

(g)

Figure 55 - Nissan Leaf-1 EV HV thermocouple placement: a) TC1 on the control unit, b) TC2 on the control unit, c) TC3 and TC4 on the center of the RESS, d) TC5 near the contactor, e) TC6 near the contactor, f) TC7 on the 12 V battery, and g) TC8 on the 12 V battery.

Table 17 - Nissan Leaf-1 EV Thermocouple Placement

Number	Location
TC1, TC2	Control unit
TC3, TC4	Near contactors
TC5, TC6	Center of the RESS
TC7, TC8	12 V battery

Three gas sensors were also mounted above the driver window (see Section 7.2).

The vehicle was again tested for operation, but it was unable to move due to lack of charge. A Level 1 charger (120 V) was installed and charged the vehicle for 3 hours. The vehicle was re-tested for operation and no issues were noted. The interior was re-assembled as much as possible with the parts provided.

8.2.3.2 Test Conditions

Testing was performed outdoors in ambient temperatures. The beginning of test temperature was -11.55°C. A temporary enclosure over the top of the immersion container was installed to keep rain and snow from entering the vehicle during testing. There was no precipitation on the day the vehicle was immersed. The vehicle remained in the immersion container during the post-extraction observation period.

8.2.3.3 Immersion Test Results

The test event log is summarized in Table 18. Isolation resistance measurements were performed approximately every 6 minutes. Figures 56 through 63 show measured data for the initial 9 hours of the test as follows:

- Figure 56 - Temperature profile for the first 9 hours of testing
- Figure 57 - Gas sensing current for the first 9 hours of testing
- Figure 58 - 12 V control voltage for the first 9 hours of testing
- Figure 59 - 12 V control voltage for the first 30 minutes of testing
- Figure 60 - Electrode to chassis voltage for the first 9 hours of testing
- Figure 61 - RESS voltage for the first 9 hours of testing
- Figure 62 - Isolation resistance for the first 9 hours of testing
- Figure 63 - Isolation resistance for the first 1 hour of testing

Figures 64 through 68 show measured data for the final 10 hours of the test as follows:

- Figure 64 - Temperature profile for the last 10 hours of testing
- Figure 65 - Gas sensing current for the last 10 hours of testing
- Figure 66 - 12 V control voltage for the last 10 hours of testing
- Figure 67 - RESS voltage for the last 10 hours of testing
- Figure 68 - Isolation resistance for the last 10 hours of testing

Table 18 - Nissan Leaf-1 EV Test Event Log

Date	Time	Test Time (hh:mm)	Event
3/25/2014	10:59 AM	N/A	• Video and data logging initiated.
3/25/2014	11:13 AM	N/A	• The vehicle was started (key-on, key-start, gear shift to Forward).
3/25/2014	11:17 AM	00:00	• Initiated filling the vehicle container with salt water.
3/25/2014	11:21 AM	00:04	• Isolation resistance decreased from 8 MΩ to 0Ω.
3/25/2014	11:22 AM	00:05	• Average ambient temperature before immersion was -12°C. • The pack temperature (TC5, TC6 on the case) increased to -3°C.
3/25/2014	11:23 AM	00:06	• The RESS post-contactor voltage (HVpos_P_N) and the contactor coil voltages (POS_COIL and NEG_COIL) dropped to zero. • The LV battery voltage sharply decreased to approximately 10 V from 14.7 V and then reached 0 V within 6 hours. • The temperature from the thermocouples installed on the RESS case near the contactors (TC3 and TC4) increased to -2°C.
3/25/2014	11:26 AM	00:09	• Isolation resistance increased to 8 MΩ.
3/25/2014	11:32 AM	00:15	• Isolation resistance decreased to 3.9 MΩ.
3/25/2014	11:34 AM	00:17	• The temperature recorded by the thermocouples on the 12 V battery (TC7 and TC8) quickly increased to -3°C. • The BECM temperature (TC1 and TC2) started increasing from the beginning of the test and jumped to 3°C at this moment.
3/25/2014	11:38 AM	00:21	• Isolation resistance decreased to values near 0Ω.
3/25/2014	12:47 PM	01:30	• Thermocouples on the HV and LV batteries, most notably TC6 on the case, showed a gradual temperature increase.
3/25/2014	12:03 PM	00:46	• Filling completed.
3/25/2014	12:13 PM	00:56	• The RESS pre-contactor voltage (HVpre_P_N) started to decrease slowly from approximately 357.8 V to approximately 350 V within 75 minutes.
3/25/2014	1:32 PM	02:15	• HVpre_P_N sharply dropped to approximately 283 V. • Simultaneously, the cathode-to-chassis voltage (HV_P_C) dropped from 203 V to 139 V. • HVpre_P_N continued to decrease and reached approximately 170 V by the end of the extraction

Date	Time	Test Time (hh:mm)	Event
			step. • In a similar trend, the anode-to-chassis voltage (HV_N_C) decreased from approximately -150 V to approximately -32 V.
3/25/2014	2:03 PM	02:46	• Extraction step initiated (i.e., water pumped out of the container).
3/25/2014	2:06 PM	02:49	• The increasing trend of HV and LV temperature was suddenly interrupted and the temperatures fell to 0°C within 1 to 2 minutes.
3/25/2014	2:07 PM	02:50	• The LV battery temperature rose to 6.3°C in 3 minutes and then gradually increased to a maximum of 12°C.
3/25/2014	2:17 PM	03:00	• The RESS case temperature started to rise and reached a maximum of 28.4°C within 10 minutes.
3/25/2014	5:40 PM	02:33	• The LV battery voltage increased from 0.1 V to 0.5 V for 15 minutes before dropping back to 0.1 V.
3/25/2014	2:22 PM	03:05	• Extraction step completed.
• There were no changes in recorded gas sensing during the period mentioned above (the Chlorine sensor was not functional in this test). • The RESS pre-contactor voltage (HVpre_P_N) continued to decrease during the post-extraction step. The last recorded HVpre_P_N voltage was 138.7 V. • The HV_P_C and HV_N_C also continued to change. The last recorded data were 122 V and -16.5 V, respectively. • No further noticeable changes in LV battery voltage, coil voltages, temperature, and gas sensing were recorded from this point to the end of the post-extraction period except for temperature variations following the environmental conditions.			

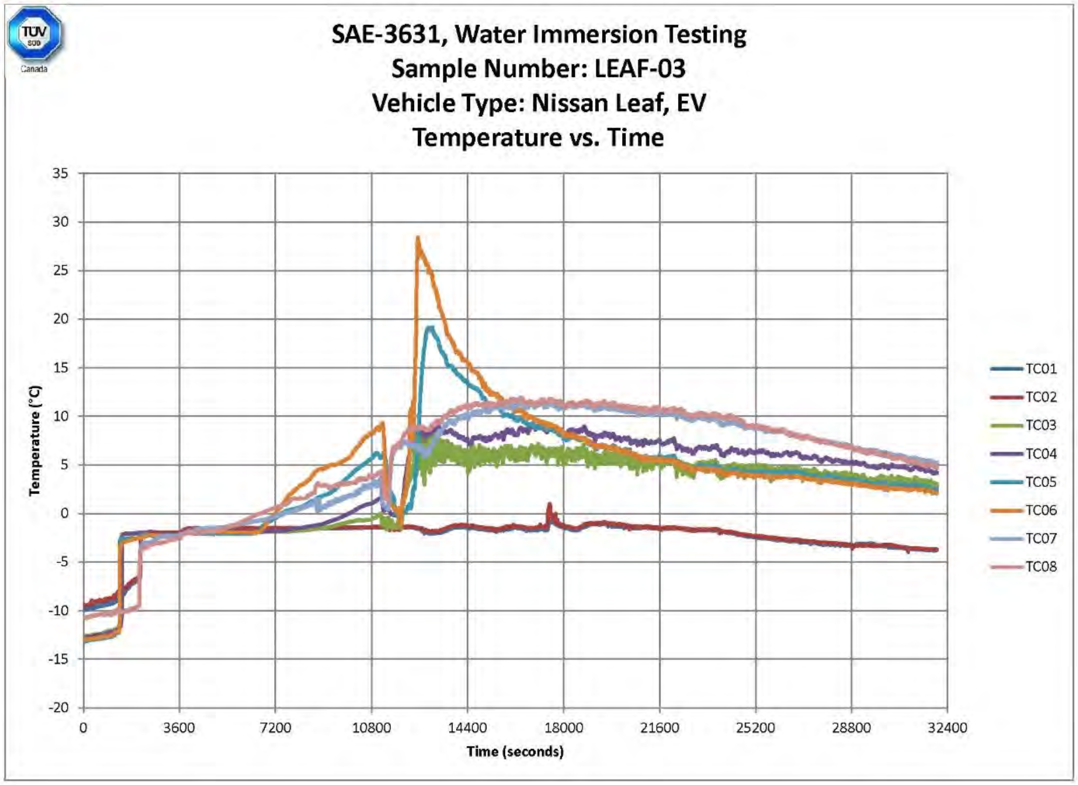


Figure 56 - Nissan Leaf-1 EV temperature profile for the first 9 hours of testing.

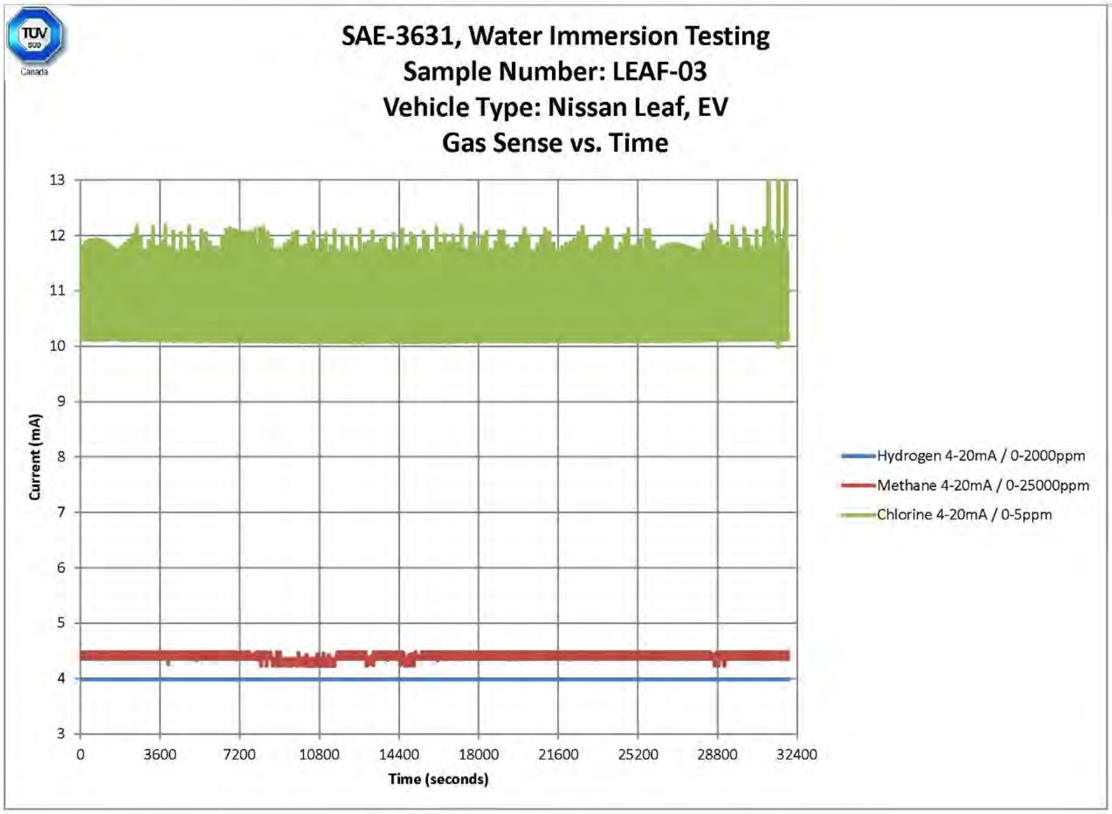


Figure 57 - Nissan Leaf-1 EV gas sensing current for the first 9 hours of testing.

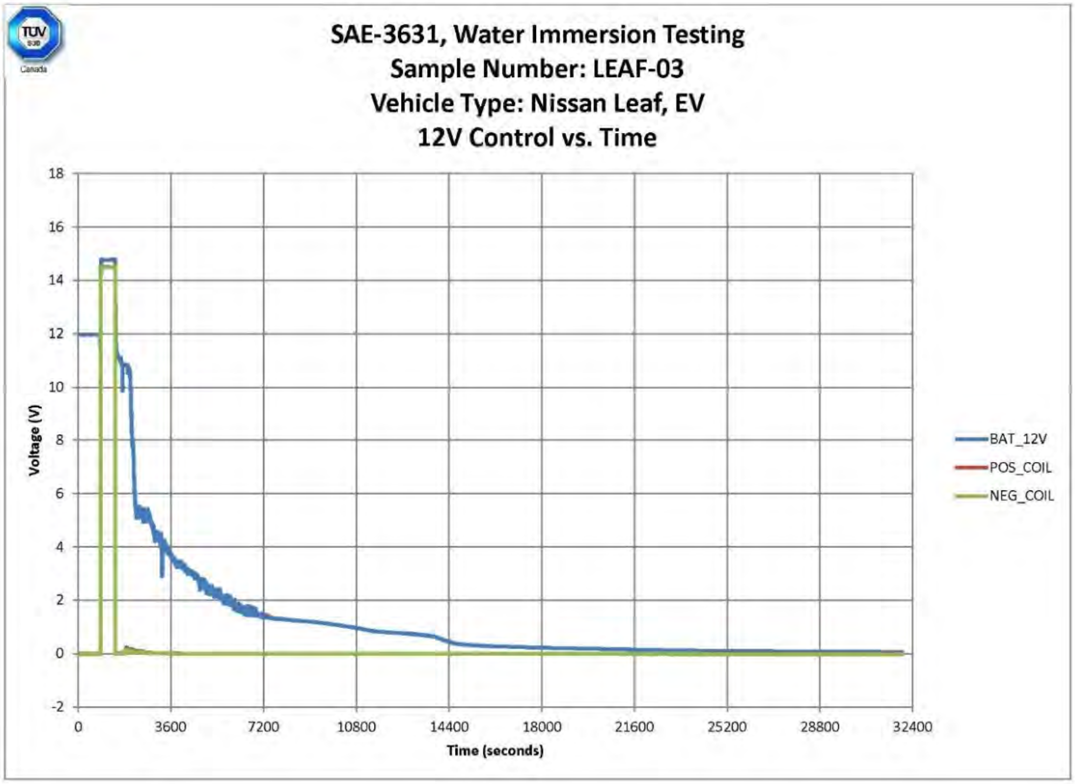


Figure 58 - Nissan Leaf-1 EV 12 V control voltage for the first 9 hours of testing.

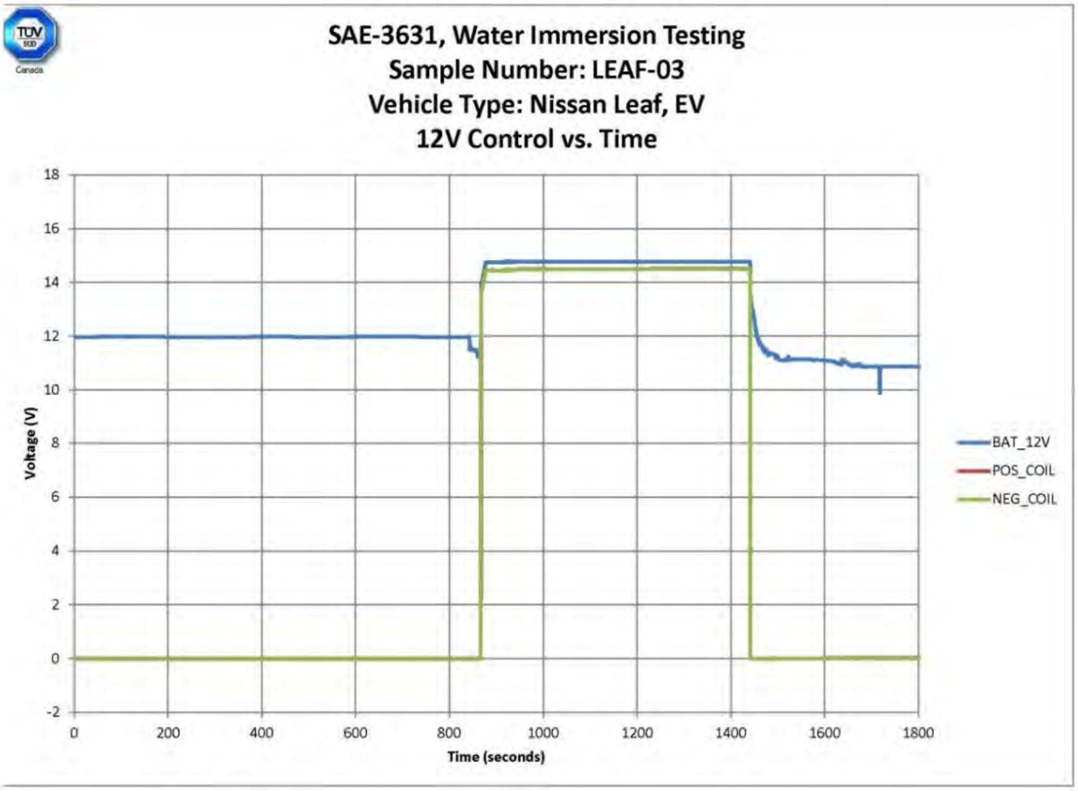


Figure 59 - Nissan Leaf-1 EV 12 V control voltage for the first 30 minutes of testing.

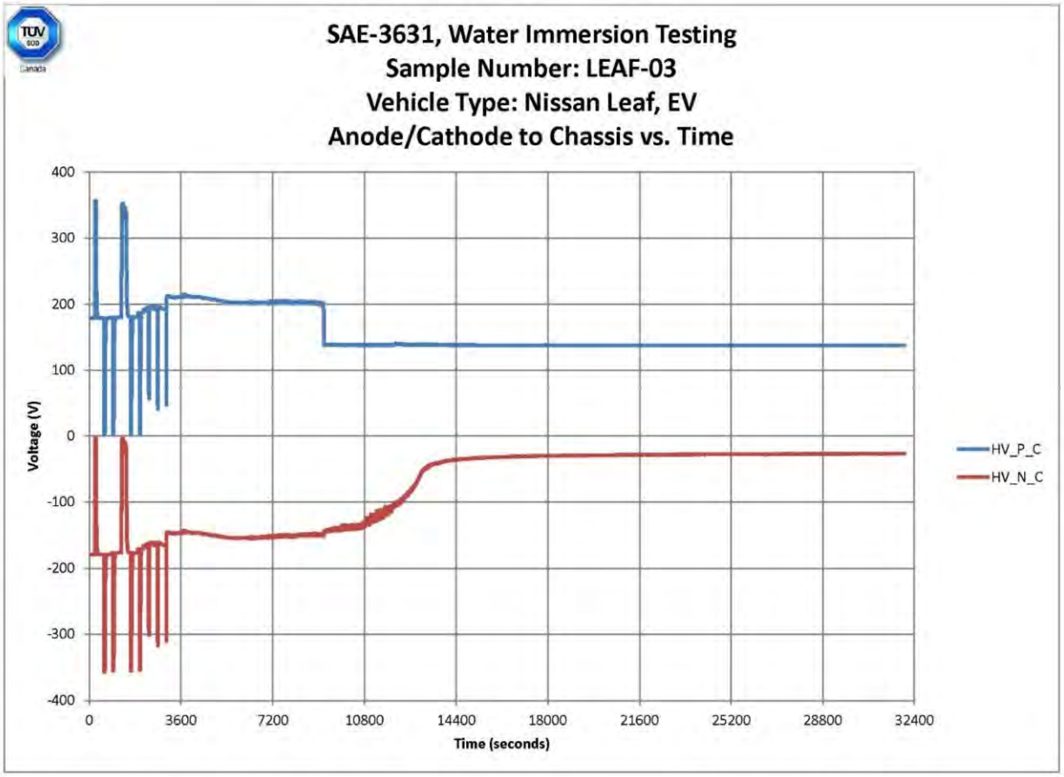


Figure 60 - Nissan Leaf-1 EV electrode to chassis voltage for the first 9 hours of testing.

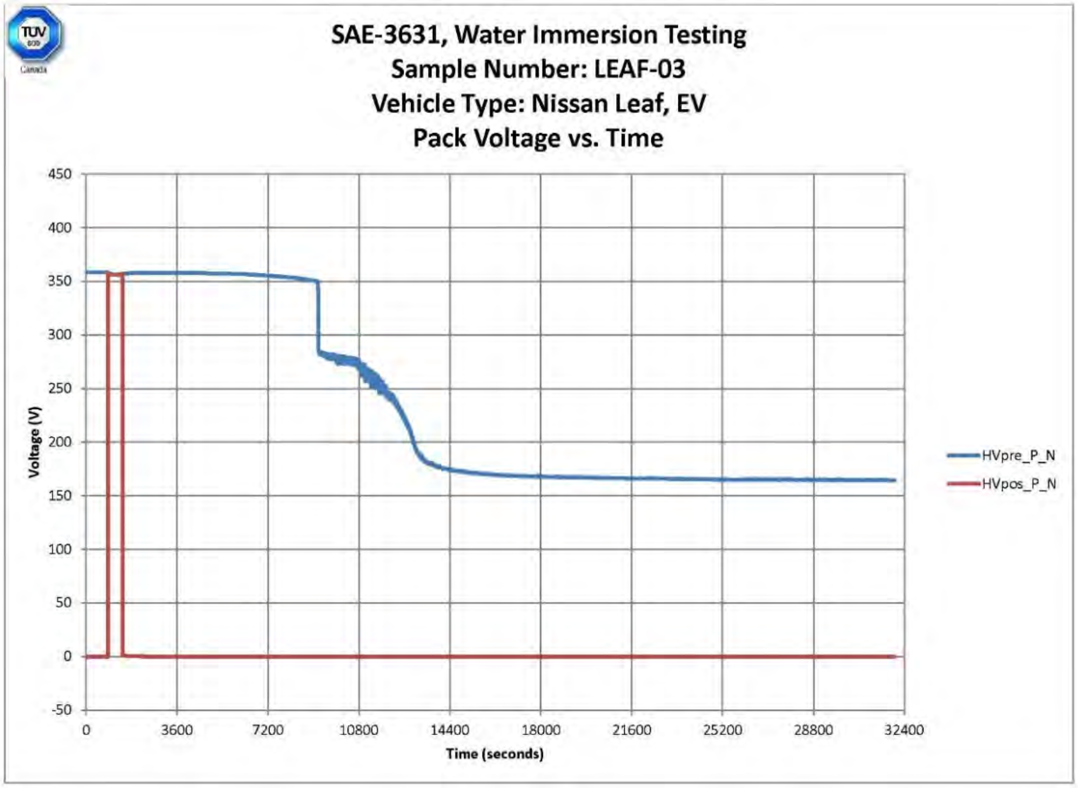


Figure 61 - Nissan Leaf-1 EV RESS voltage for the first 9 hours of testing.

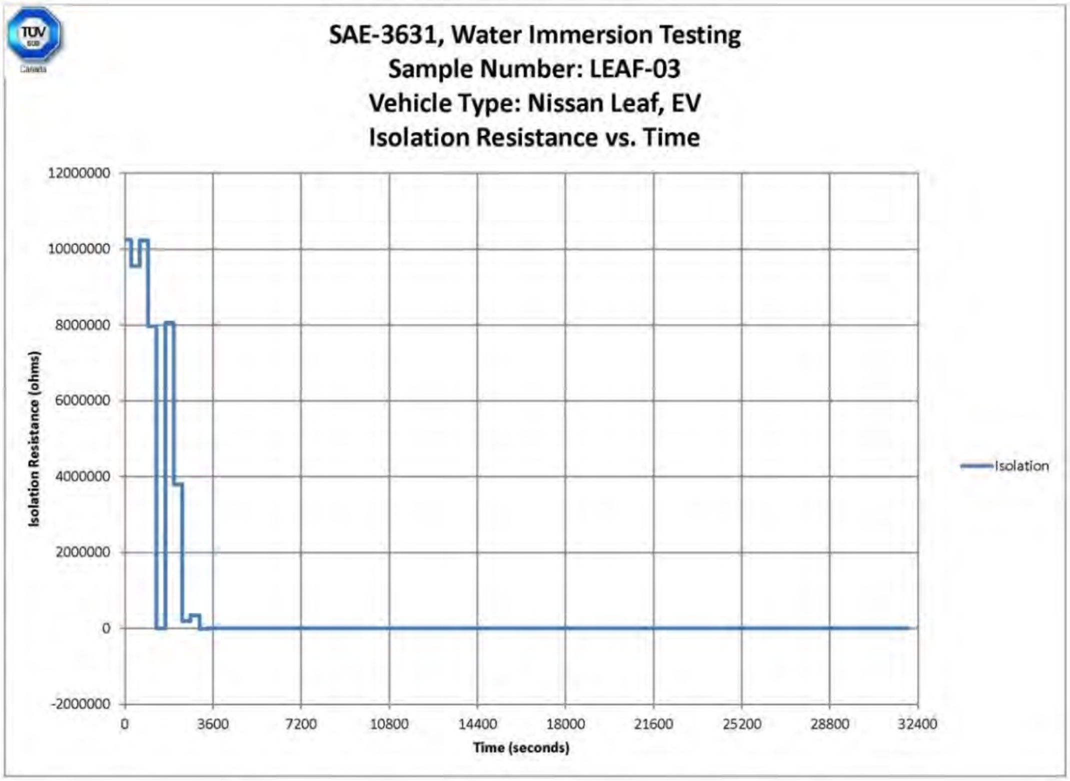


Figure 62 - Nissan Leaf-1 EV isolation resistance for the first 9 hours of testing.

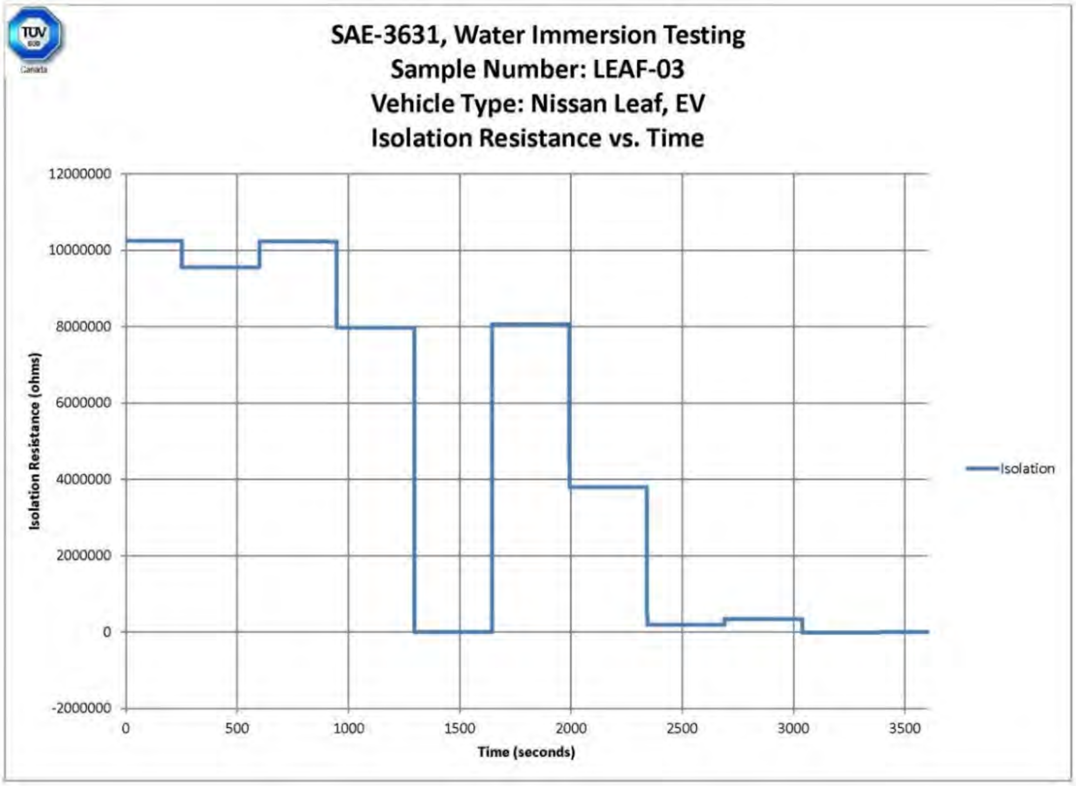


Figure 63 - Nissan Leaf-1 EV isolation resistance for the first 1 hour of testing.

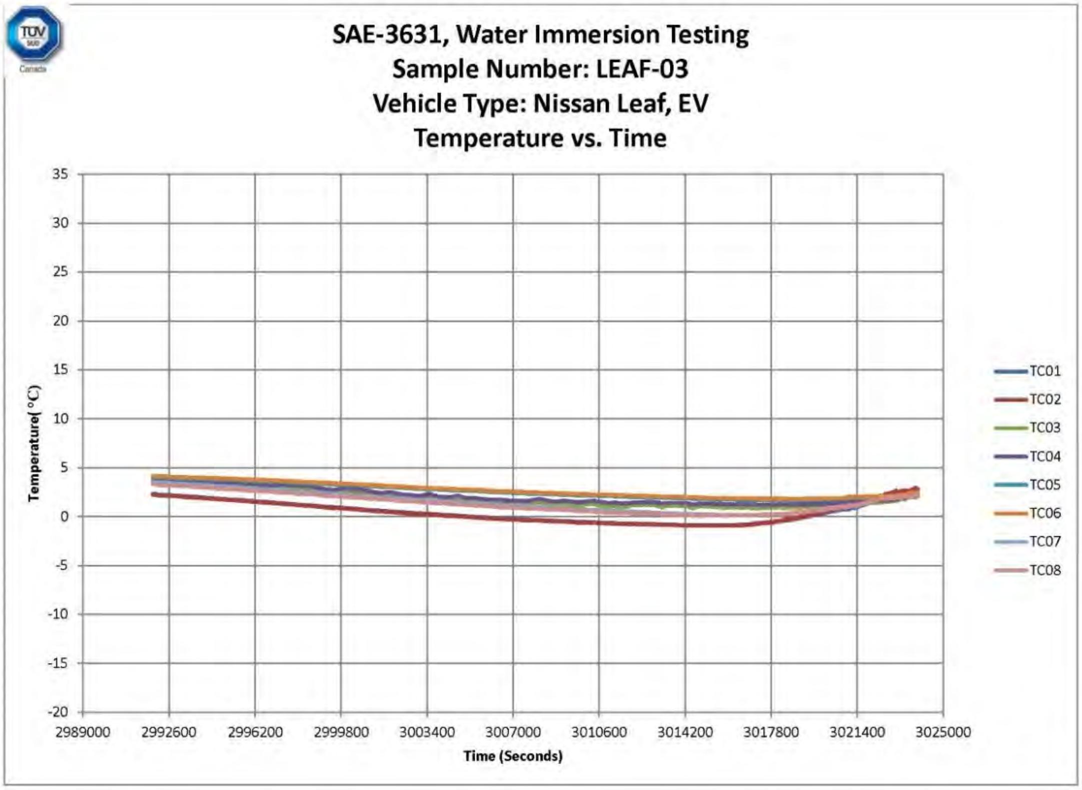


Figure 64 - Nissan Leaf-1 EV temperature profile for the last 10 hours of testing.

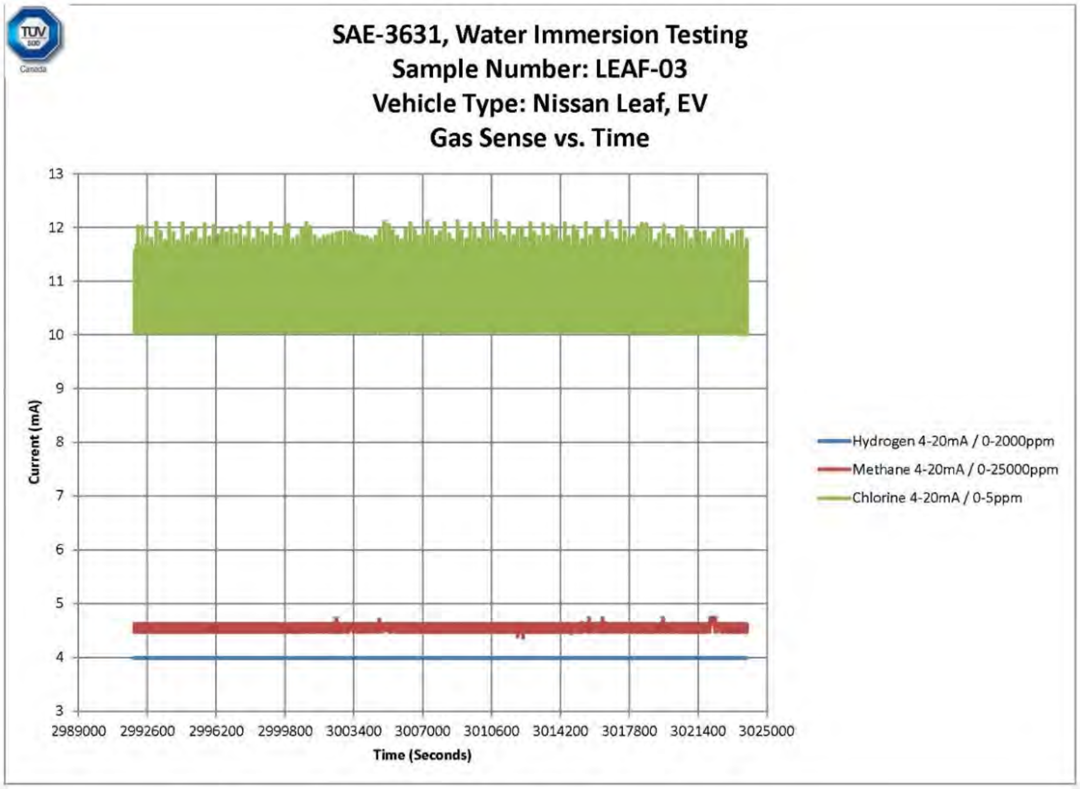


Figure 65 - Nissan Leaf-1 EV gas sensing current for the last 10 hours of testing.

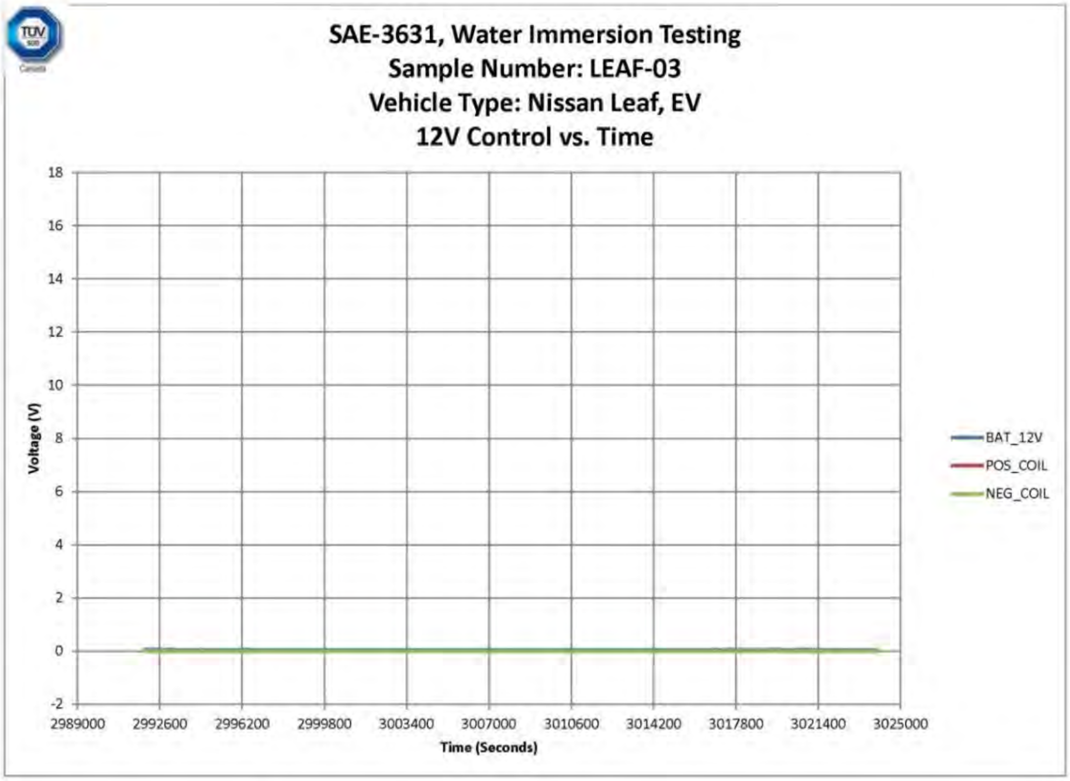


Figure 66 - Nissan Leaf-1 EV 12 V control voltage for the last 10 hours of testing.

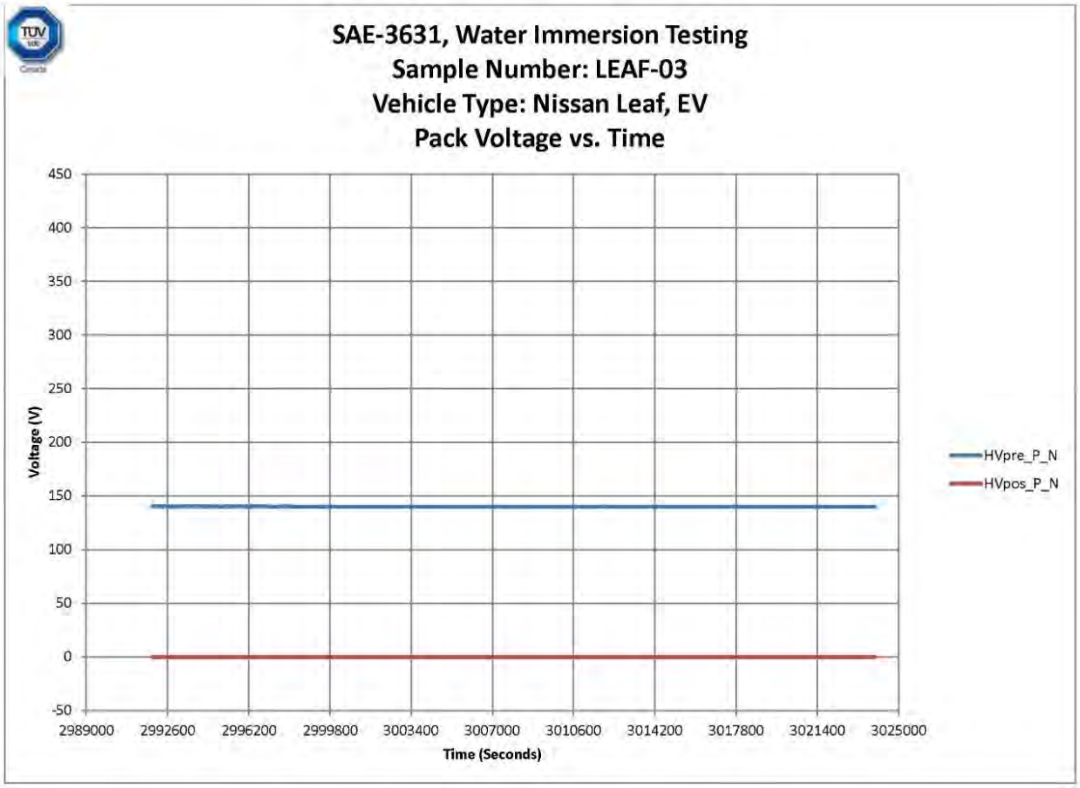


Figure 67 - Nissan Leaf-1 EV RESS voltage for the last 10 hours of testing.

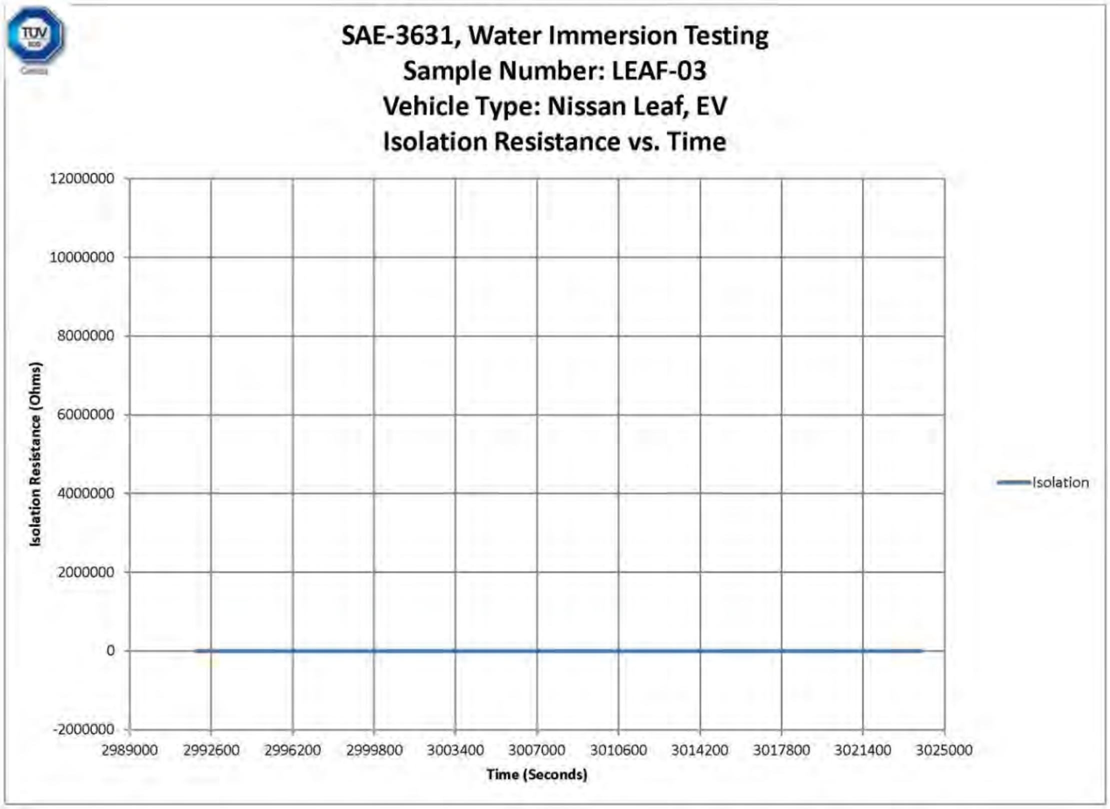


Figure 68 - Nissan Leaf-1 EV isolation resistance for the last 10 hours of testing.

8.2.3.4 Seawater Analysis Results

Seawater samples were taken before and after immersion. They were measured on-site for pH, density and conductivity; the results are summarized in Table 19. Samples were also sent to Maxxam Analytics, Inc. to evaluate VOCs; no VOCs were found to be above the reportable limit. Table 20 shows the total oil and grease content from the samples.

Table 19 - Nissan Leaf-1 EV Conductivity, Salinity, Density, and pH

Time	Conductivity (mS/cm)	Salinity (wt%)	Density (g/cm³)	pH
Pre-immersion	49.7	2.92	1.022	7.3
Post-immersion	48.0	2.85	1.022	7.4

Table 20 - Nissan Leaf-1 EV Total Oil and Grease Content

Petroleum Hydrocarbons	Units	Pre-Immersion	Post-Immersion	RDL*
Total oil and grease	mg/L	<0.50	<0.50	0.50

*RDL=Reportable Detection Limit

8.2.3.5 Post-Mortem Analysis

Figure 69 shows the vehicle from multiple angles after testing was complete. Post-mortem analysis did not indicate any evidence of behaviors that could result in an HSL higher than 4 (i.e., no anticipated fires, ruptures, or explosions) based on EUCAR standards. Although the RESS temperature increased from -2°C just after immersion to 28°C, it quickly declined to ambient levels after 9 hours and followed the diurnal ambient values until the end of the test. In addition, the water immersion caused the RESS voltage to drop from 358 V to 170 V within the first 4 hours of the test and declined slowly to 140 V at end of test. Therefore, no post-mortem analysis was conducted on the battery pack.

(a) (b)

(c) (d)

(e) (f)

Figure 69 - Nissan Leaf-1 EV post-test vehicle condition: a) left view, b) right view, c) front view, d) rear view, e) engine bay, and f) front seats.

8.2.4 GM Volt PHEV

The GM Chevrolet Volt (Volt-1) was a new production PHEV, see Table 21. Figure 70 shows the as-received vehicle from multiple angles. Figure 10 (above) shows some of the equipment used for testing, including the DAQ system, the gas sensor, the video camera, and the immersion tank.

Table 21 - GM Volt-1 PHEV Details

Vehicle Class	Passenger Car
Manufacturer	GM
Make	Chevrolet
Model	Volt
Date of Manufacture	May 2012
VIN	1G1RA6E40CU127047
Condition	New (minor scuffs)
Vehicle Type	PHEV

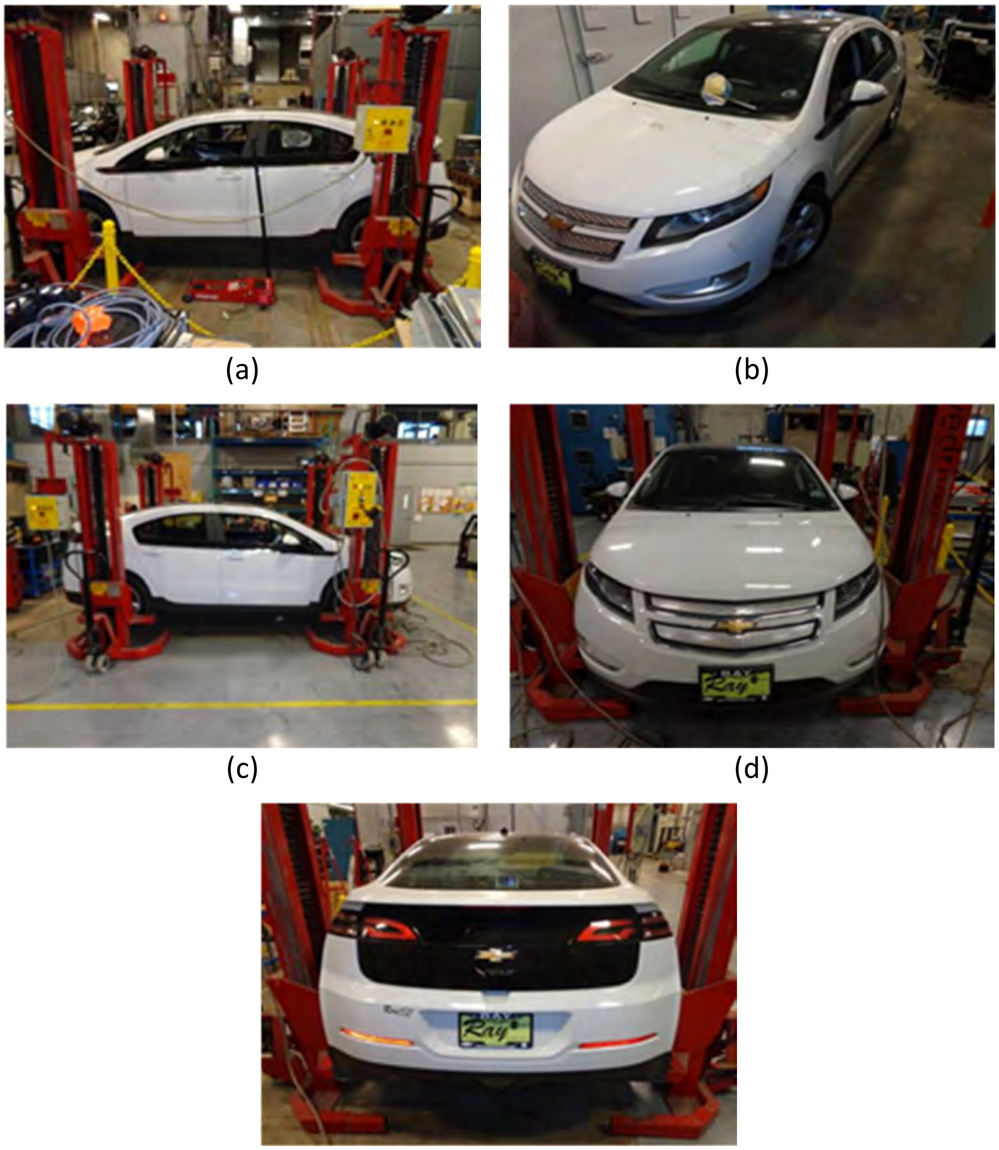
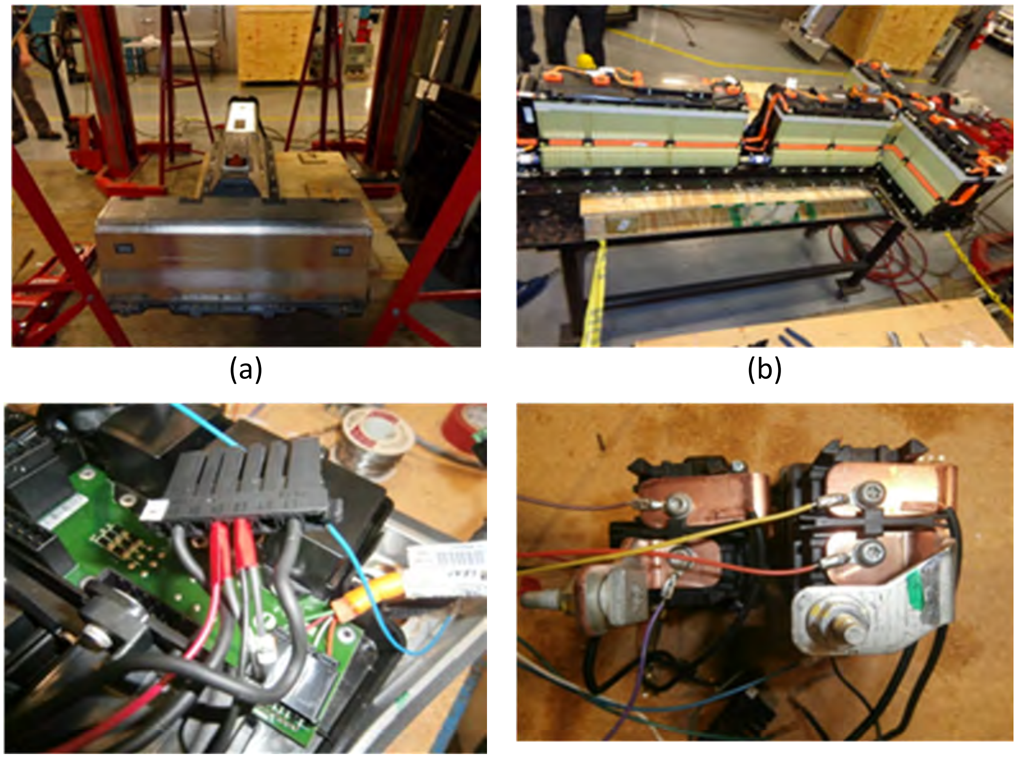

(a) (b) (c) (d) (e)

Figure 70 - GM Volt-1 PHEV initial vehicle condition: a) left view, b) front ¾ view, c) right view, d) front view, and e) rear view.

8.2.4.1 Sample Preparation

As received, the vehicle was new, undamaged (with minor scuffs), and in an operational state. The display showed approximately 70% SOC in the battery pack and slightly over a half tank of gasoline. All the loose interior parts were tagged and removed from the cabin. The 12 V battery was also restored to health.

For HV and isolation measurements, the RESS was removed from the vehicle and the contactor assembly was taken apart. The voltage sensors were tightly screwed to the bus bars of the assembly or soldered to the pins of the electrical connectors (see Figure 71). The RESS was then sealed to prevent water intrusion through the sense leads exiting the pack (see Section 8.1.2). The contactor was reassembled and re-installed and the RESS was placed back into the vehicle. Voltage sense cables were also installed on the 12 V battery.



(a) (b)

(c) (d)

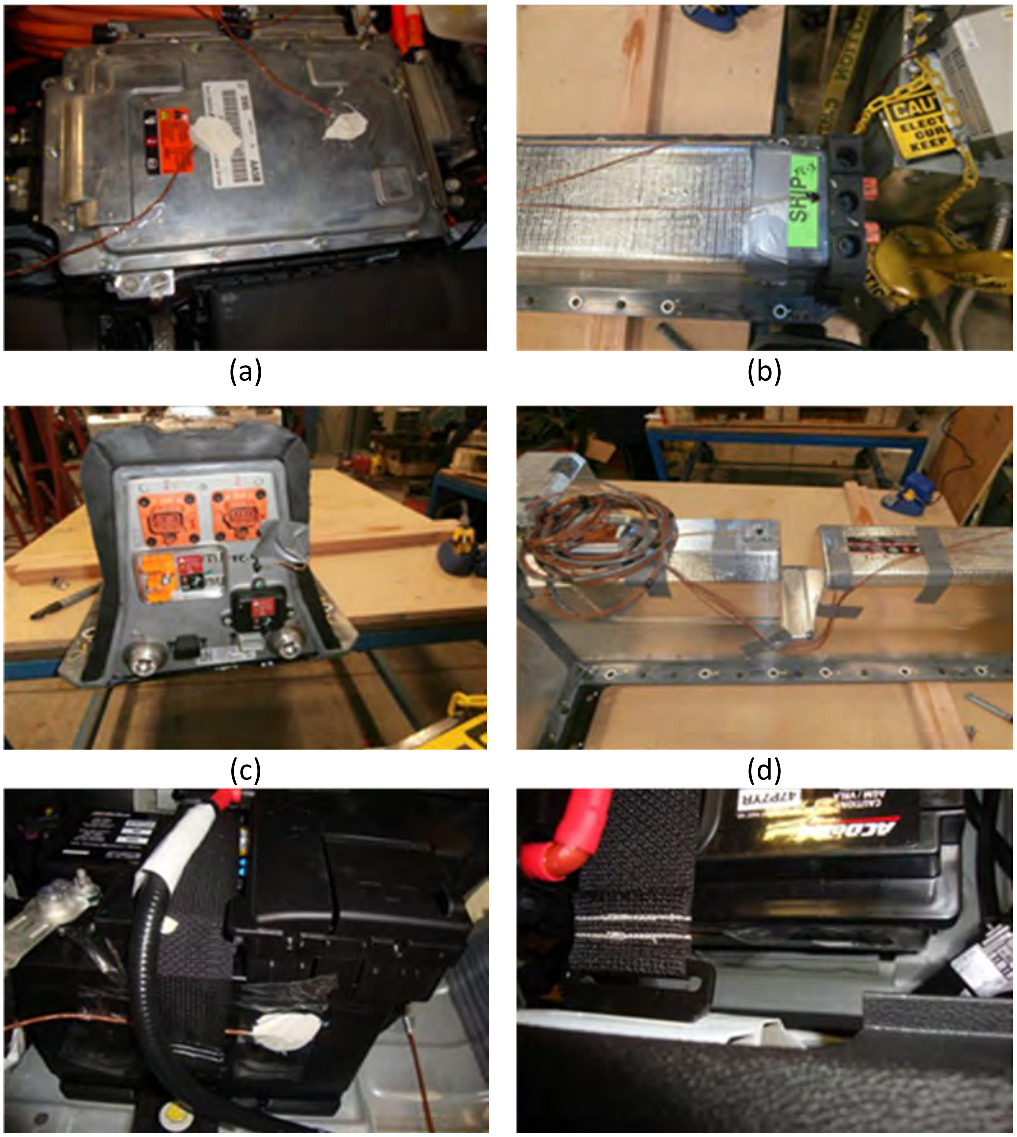
Figure 71 - GM Volt-1 PHEV connections: a) RESS removed from vehicle, b) RESS with cover removed, c) contactor assembly, and d) measurement wires screwed to bus bars.

A total of eight thermocouples were installed as specified in test procedure (see Section 6.5.1.13), including the RESS enclosure, near contactors, the control unit, and the 12 V battery. Thermocouple locations are provided in Table 22 and shown in Figure 72. The thermocouples were held in position using epoxy adhesive.

Three gas sensors were also mounted above the driver window (see Section 7.2).

Table 22 - GM Volt-1 PHEV Thermocouple Placement

Number	**Location**
TC1, TC2	Control unit
TC3, TC4	Near contactors
TC5, TC6	Center of the RESS
TC7, TC8	12 V battery



(a) (b) (c) (d) (e) (f)

Figure 72 - GM Volt-1 PHEV thermocouple placement: a) TC1 and TC2 on the control unit, b) TC3 near the contactor, c) TC4 near the contactor, d) TC5 and TC6 on the RESS, e) TC7 on the 12 V battery, and f) TC8 on the 12 V battery.

8.2.4.2 Test Conditions

Testing was performed outdoors in ambient temperatures. The beginning of test temperature was -12.4°C. A temporary enclosure over the top of the immersion container was installed to keep rain and snow from entering the vehicle during testing. There was no precipitation on the day the vehicle was immersed. The vehicle remained in the immersion container during the post-extraction observation period.

8.2.4.3 Immersion Test Results

The test event log is summarized in Table 23. Isolation resistance measurements were performed approximately every 6 minutes. Figures 73 through 79 show measured data for the initial 9 hours of the test as follows:

- Figure 73 - Temperature profile for the first 8.3 hours of testing
- Figure 74 - Gas sensing current for the first 8.3 hours of testing
- Figure 75 - 12 V control voltage for the first 4.2 hours of testing
- Figure 76 - 12 V control voltage for the next 3.5 hours of testing
- Figure 77 - Electrode to chassis voltage for the first 9 hours of testing
- Figure 78 - RESS voltage for the first 9 hours of testing
- Figure 79 - Isolation resistance for the first 9 hours of testing

Table 23 - GM Volt-1 PHEV Test Event Log

Date	Time	Test Time (hh:mm)	Event
3/26/2014	10:10 AM	N/A	• Video initiated.
3/26/2014	10:11 AM	N/A	• Data logging initiated.
3/26/2014	10:18 AM	N/A	• The vehicle was started (key-on, key-start, gear shift to Drive). • The RESS pre-contactor voltage (HVpre_P_N) rose from approximately 365 V to approximately 380 V and then settled at 375 V.
3/26/2014	10:19 AM	00:00	• Initiated filling the vehicle container with salt water.
3/26/2014	10:22 AM	00:03	• Isolation resistance decreased from 3.78 MΩ to 1.43 MΩ.
3/26/2014	10:25 AM	00:06	• Average ambient temperature before immersion was -12°C. • The pack temperature (TC3 and TC4 near the contactors) increased to -3°C (i.e., temperature of the salt water).
3/26/2014	10:25 AM	00:06	• The vehicle floated and moved forward inside the container. • Smoke was seen coming out of the engine compartment. • The pack voltage dropped to 320 V.
3/26/2014	10:27 AM	00:08	• The HV battery contactor opened; this was indicated by a loss of post-contactor voltage (HVpos_P_N) and contactor coil voltages (POS_COIL and NEG_COIL). The pack voltage increased to 361 V. • The LV battery voltage loss also began at this point. • Thermocouples installed on the RESS case (TC5

Date	Time	Test Time (hh:mm)	Event
			and TC6) and the LV battery (TC7 and TC8) started to show a temperature increase to the salt water temperature.
3/26/2014	10:27 AM	00:08	• Isolation resistance increased to 3.71 MΩ.
3/26/2014	10:28 AM	00:09	• The BECM temperature (TC1 and TC2) increased to the salt water temperature.
3/26/2014	10:32 AM	00:13	• Filling completed.
3/26/2014	10:33 AM	00:14	• Isolation resistance decreased from 3.71 MΩ to 10.6 kΩ.
3/26/2014	10:34 AM	00:15	• Bubbles were seen forming at various locations of the engine compartment, continuing throughout the immersion step.
3/26/2014	10:39 AM	00:20	• Isolation resistance increased from 10.6 kΩ to 3.8 MΩ.
3/26/2014	10:55 AM	00:36	• Isolation resistance decreased from 3.6 MΩ to 2.1 MΩ.
3/26/2014	11:02 AM	00:43	• Isolation resistance decreased from 2.1 MΩ to 8.8 kΩ. • The isolation value continued to drop mainly due to voltage decrease between positive bar and chassis (HV_P_C).
3/26/2014	12:32 PM	02:13	• Extraction step initiated (i.e., water pumped out of the container).
3/26/2014	12:45 PM	02:26	• Extraction step completed.
3/26/2014	12:45 PM	02:26	• Isolation resistance decreased to less than 1 kΩ. This is because no voltage change was recorded after applying the constant 50 kΩ resistor.
3/26/2014	3:27 PM	05:08	• The voltage between positive bus bar and chassis (HV_P_C) sharply decreased to near zero values.
3/26/2014	4:08 PM	05:49	• The RESS voltage dropped from 361.6 V to 359.4 V and later settled at 361 V. • Concurrently, the LV battery showed an increase from 0.1 V to 0.78 V and returned to 0.1 V.
3/26/2014	4:43 PM	06:22	• The voltage between the negative bus bar and chassis (HV_N_C) approached 0 V while the HV_P_C increased to above 330 V.
3/26/2014	4:44 PM	06:23	• HVpos_P_N rose from zero to above 330 V and continued to vary between 250 V to 330 V. • The positive coil voltage (POS_COIL) peaked at 20 V and then dropped to -20 V. The positive and negative coil voltages continued to vary between -20 V to 20 V. • The temperature from the thermocouples installed

Date	Time	Test Time (hh:mm)	Event
			on the RESS enclosurenear the contactors (TC3 and TC4) start to rise.
3/26/2014	5:16 PM	06:57	• HVpos_P_N started to closely follow HVpre_P_N. The difference was less than 1 V. • The thermocouples placed at the center of the RESS enclosurestarted to record temperature rise.
3/26/2014	5:35 PM	07:16	• The RESS voltages (pre- and post-contactor) dropped to zero. • Voltages between the positive and negative bus bars and the chassis started to show the exact same values.
3/26/2014	5:36 PM	07:17	• Smoke was seen coming from the console. The smoke volume increased intermittently over the next 10 minutes, as indicated by visible smoke coming out of the windows.
3/26/2014	5:47 PM	07:28	• The smoke thickened and started to come from under the hood.
3/26/2014	6:03 PM	07:44	• Small flames developed under the hood and quickly increased.
3/26/2014	6:04 PM	07:45	• Chlorine gas was detected. The BECM temperature increased sharply due to the fire. No temperature rise was recorded on the 12 V battery before data logging stopped.
3/26/2014	6:07 PM	07:48	• The video feed was lost due to camera damage.
3/26/2014	6:21 PM	08:02	• Data acquisition stopped due to the fire.

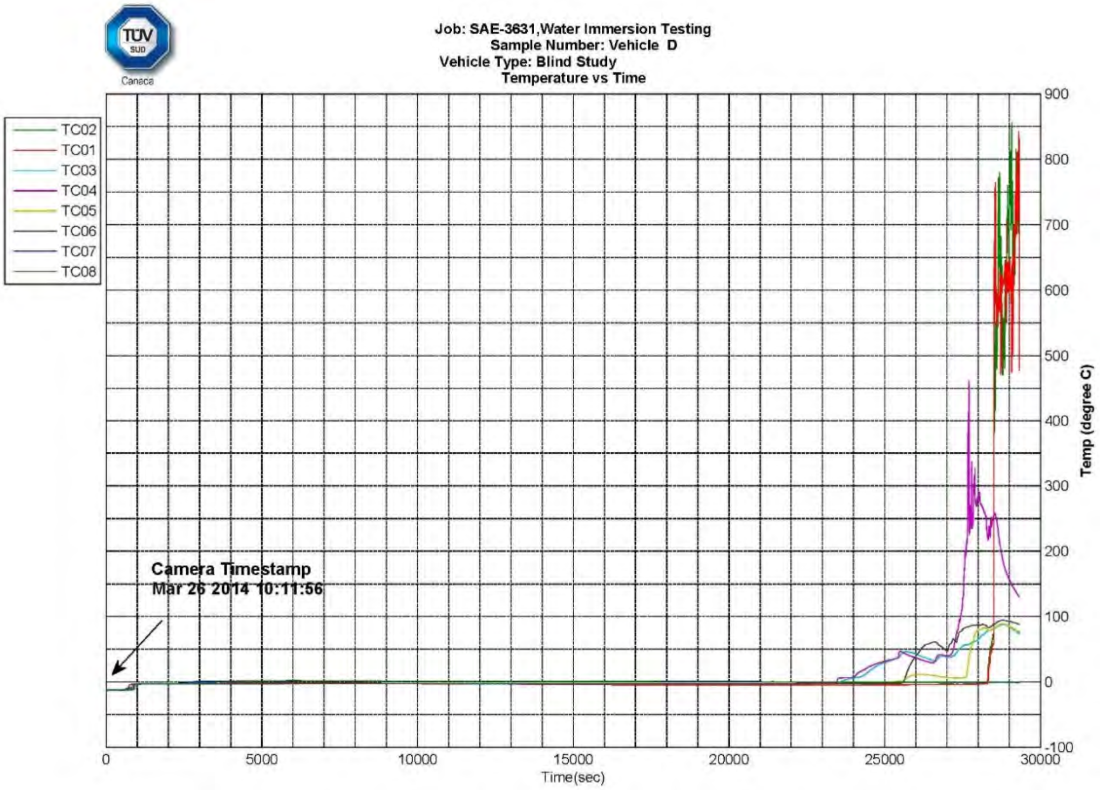


Figure 73 - GM Volt-1 PHEV temperature profile for the first 8.3 hours of testing.

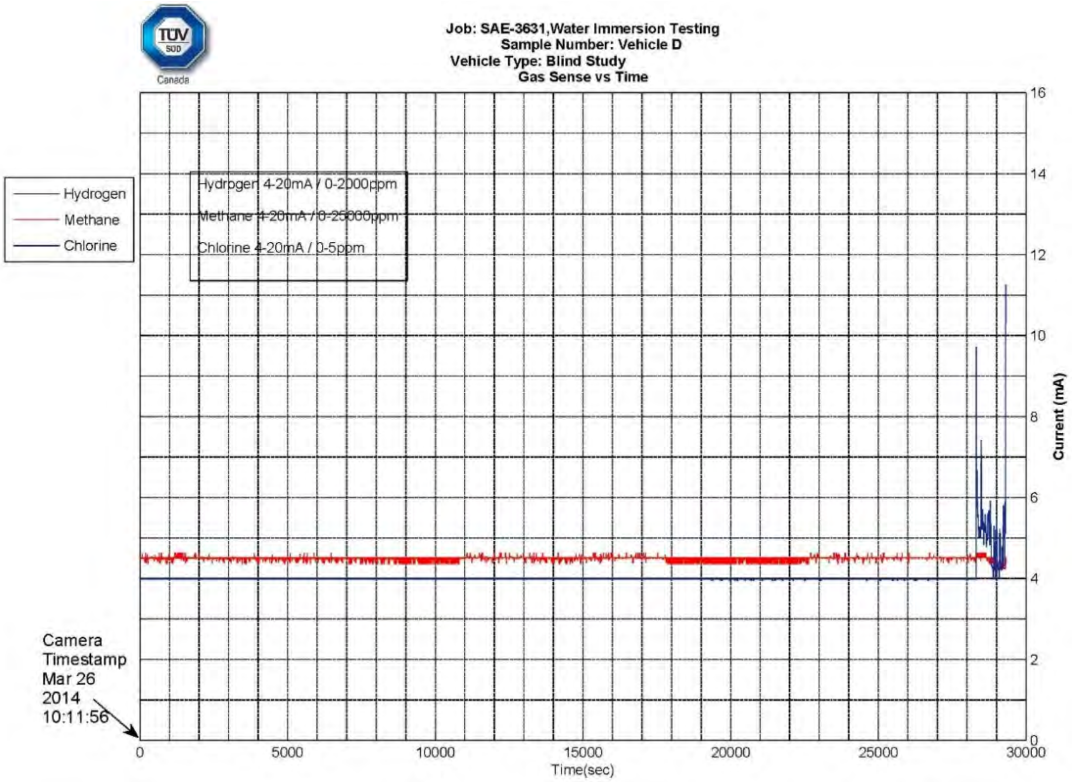


Figure 74 - GM Volt-1 PHEV gas sensing current for the first 8.3 hours of testing.

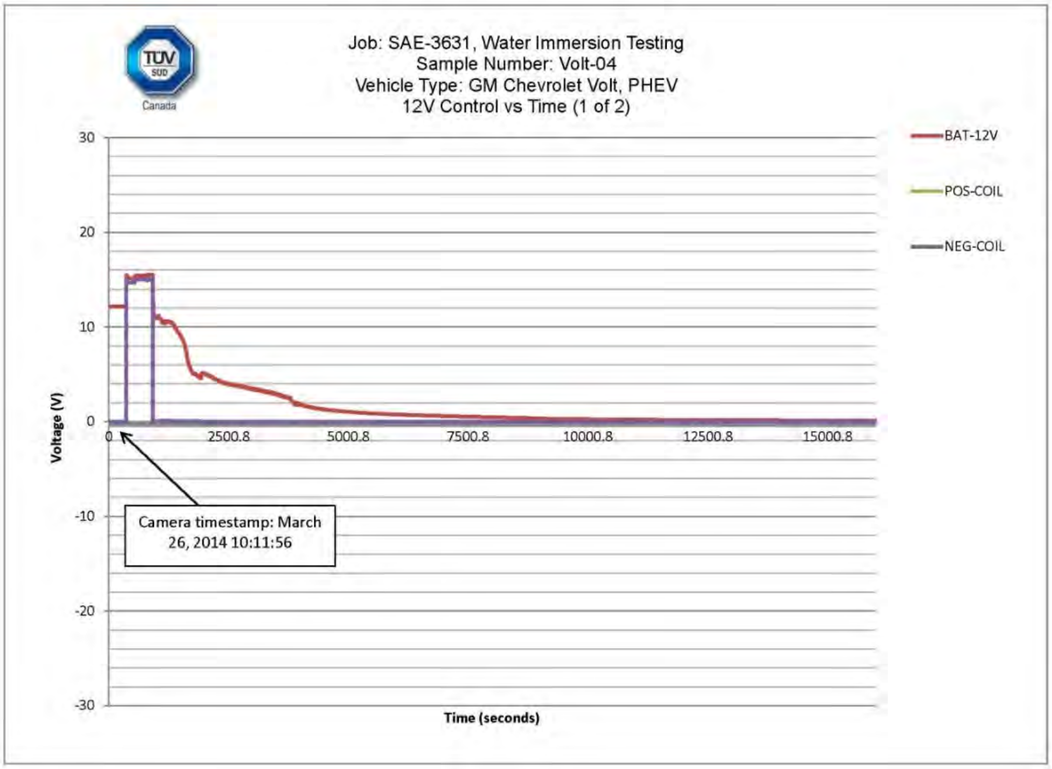


Figure 75 - GM Volt-1 PHEV 12 V control voltage for the first 4.2 hours of testing.

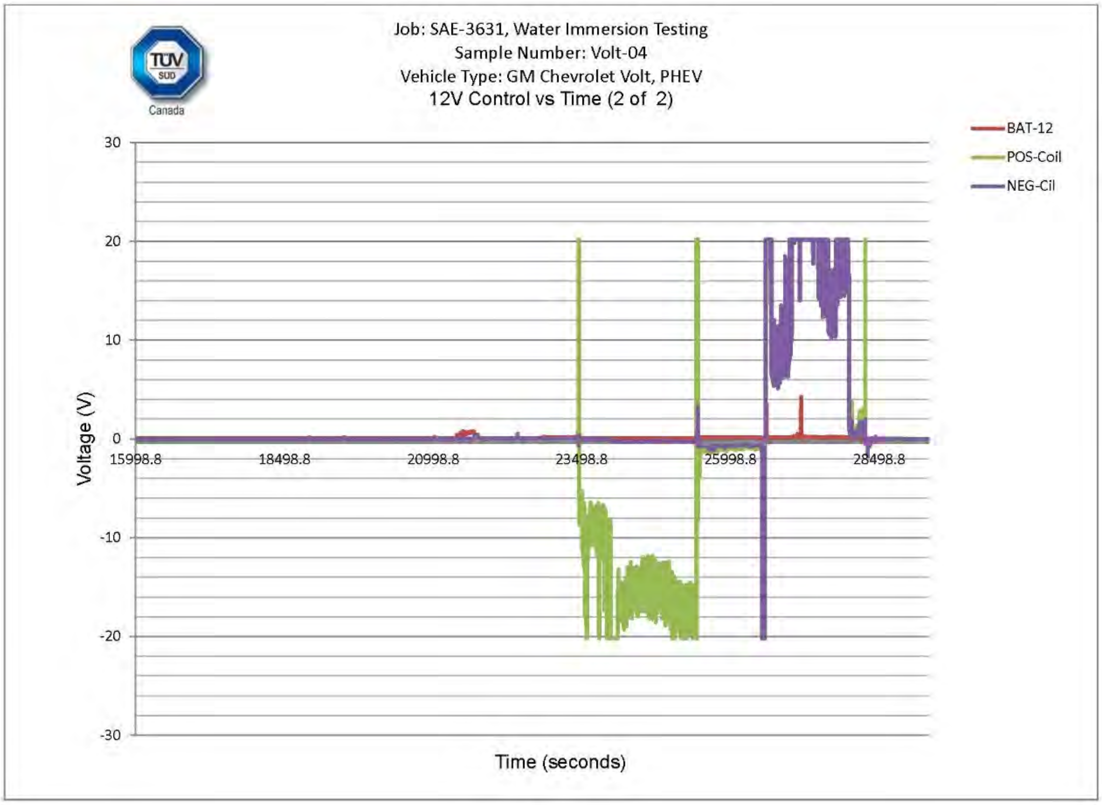


Figure 76 - GM Volt-1 PHEV 12 V control voltage for the next 3.5 hours of testing.

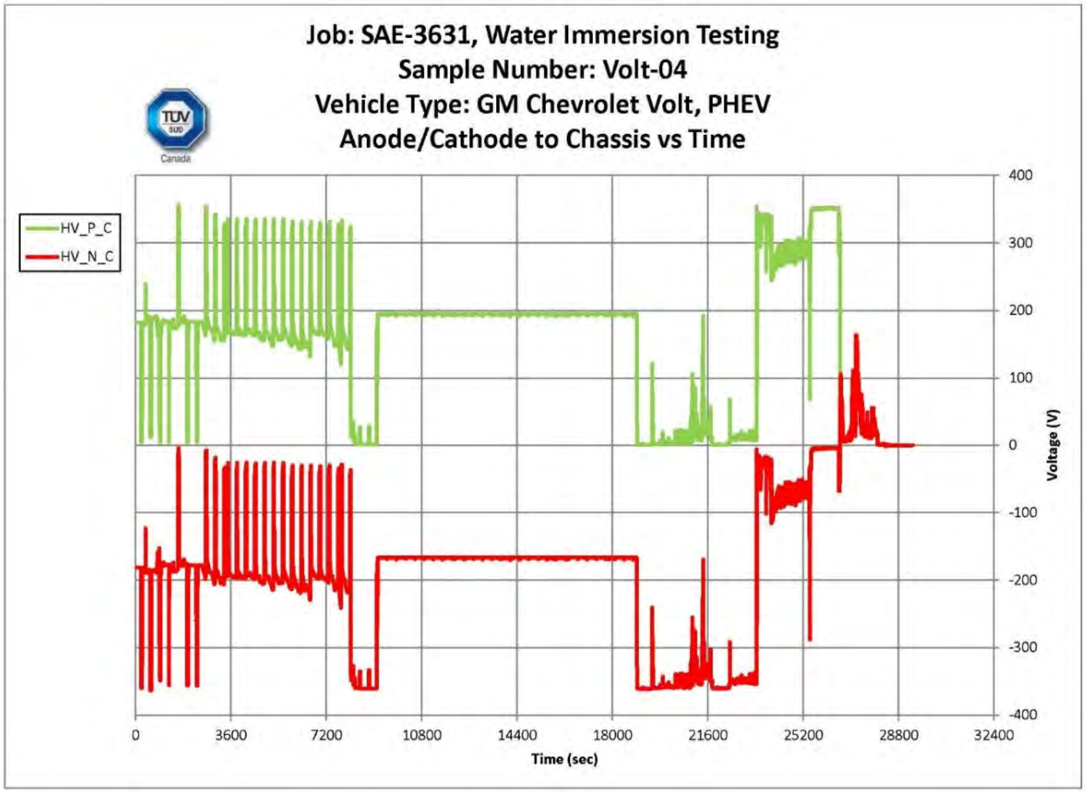


Figure 77 - GM Volt-1 PHEV electrode to chassis voltage for the first 9 hours of testing.

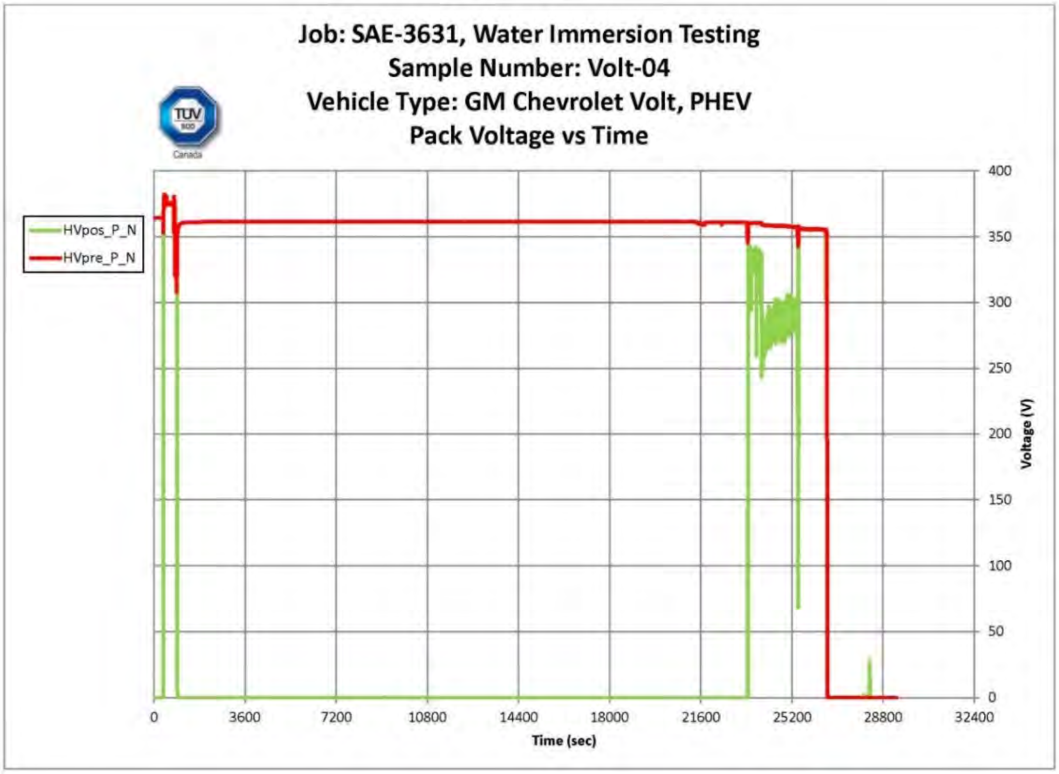


Figure 78 - GM Volt-1 PHEV RESS voltage for the first 9 hours of testing.

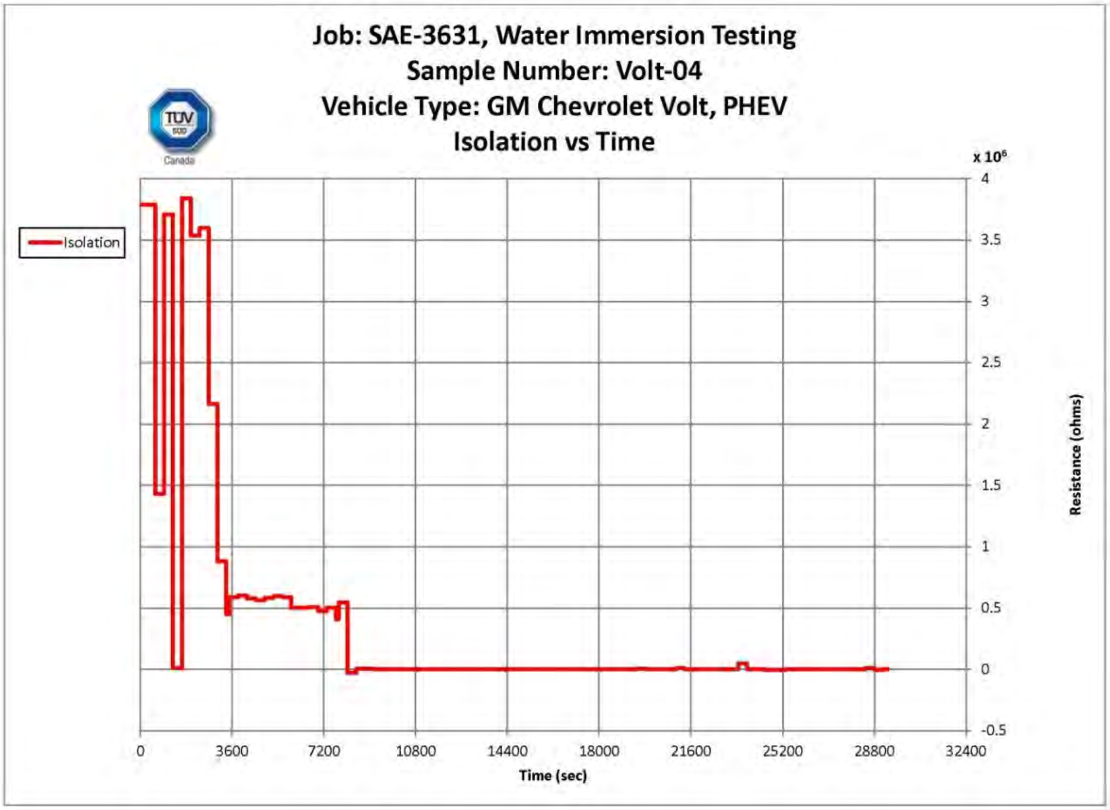


Figure 79 - GM Volt-1 PHEV isolation resistance for the first 9 hours of testing.

8.2.4.4 Seawater Analysis Results

Seawater samples were taken before and after immersion. They were measured on-site for pH, density and conductivity; the results are summarized in Table 24. Table 25 shows the VOCs that were above the reportable detection limit, as determined from Maxxam Analytics, Inc. Note that the samples were also analyzed for other VOCs that were below the reportable limit. Table 26 shows the total oil and grease content from the samples.

Table 24 - GM Volt-1 PHEV Conductivity, Salinity, Density, and pH

Time	Conductivity (mS/cm)	Salinity (wt%)	Density (g/cm^3)	pH
Pre-immersion	51.0	3.15	1.024	7.5
Post-immersion	50.7	3.13	1.023	7.3

Table 25 - GM Volt-1 PHEV VOCs above Reportable Detection Limit

Volatile Organics	Units	Pre-Immersion		Post-Immersion	
		Sample	RDL*	Sample	RDL*
Benzene	µg/L	1.4	1.0	<2.0	2.0

*RDL=Reportable Detection Limit

Table 26 - GM Volt-1 PHEV Total Oil and Grease Content

Petroleum Hydrocarbons	Units	Pre-Immersion	Post-Immersion	RDL*
Total oil and grease	mg/L	<0.50	<0.50	0.50

*RDL=Reportable Detection Limit

8.2.4.5 Post Test Actions

Following vehicle immersion, some preparation was required for safety removal and further analysis. The roof was cut off of the vehicle to gain access to the interior without being in a confined space. Burnt materials were then removed from the vehicle tunnel and holes were drilled into the RESS headspace to allow water to enter. It was noticed that the section of the RESS that runs laterally in the vehicle had no structural integrity, only glass fiber was remaining. In total, four holes were drilled, one in the front module ahead of the manual service disconnect (MSD), one behind the MSD, and two in the “T” part of the pack. There were also existing holes that seemed to result from the fire as well under the rear seats. Following the drilling of the holes, the vehicle was submerged for a second time to ensure all energy was removed from the RESS. The vehicle was chained in place inside the immersion container and shipped to be extracted for post-mortem analysis.

8.2.4.6 Post-Mortem Analysis

The vehicle fire was kept under control by blowing snow into the immersion container. This also prevented the fire from propagating to the other test vehicles located nearby. The fire, however, damaged the temporary enclosures on two adjacent vehicles, but no damage was noted to the vehicles themselves. The GM Volt was left to cool for several days and a FLIR camera was used to verify its temperature. A tarp was placed inside the bin covering the vehicle to protect it from precipitation.

The RESS was removed from the burned vehicle chassis and readied for teardown. Voltage measurements were attempted but most HV access points including the MSD were damaged beyond functionality. Figure 80 shows the vehicle damage (front and rear view).

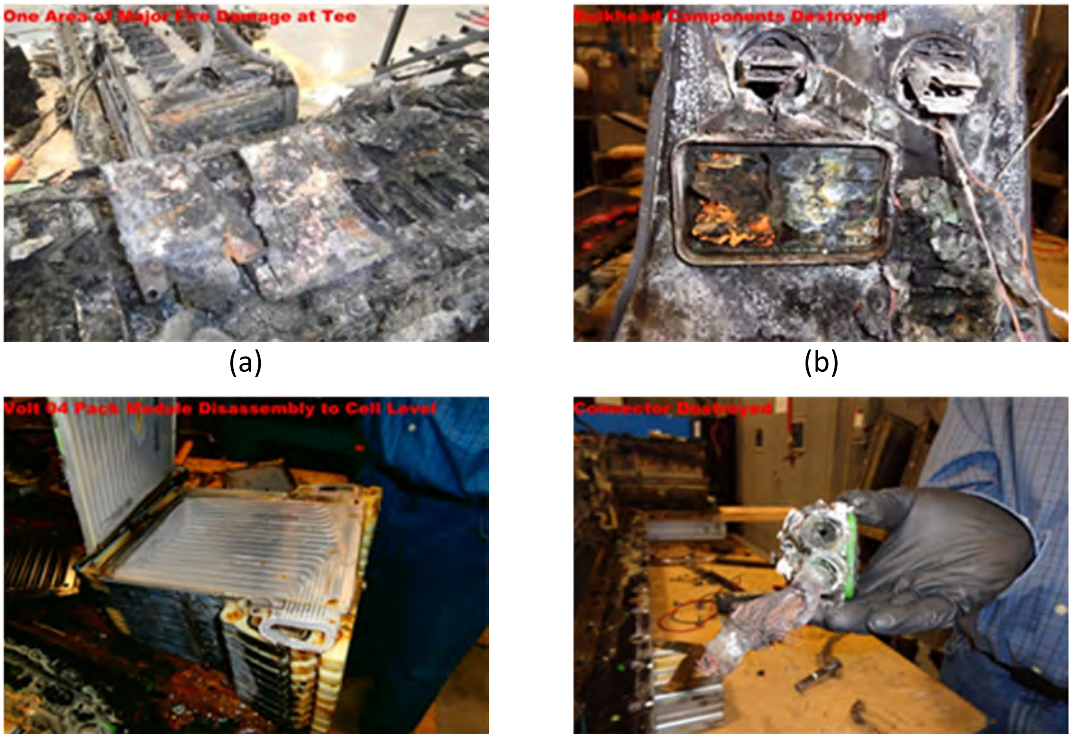
(a) (b)

Figure 80 - GM Volt-1 PHEV post-test vehicle condition: a) front view and b) rear view.

Figures 81 and 82 show the extent of RESS damage due to the fire:

- Figure 81(a): Maximum fire damage occurred at the RESS “Tee”; cells were penetrated.
- Figure 81(b): The connectors, sensor wires, and bulkhead panel show the extent of the fire and heat damage at the front of the RESS.
- Figure 81(c): From a module dissassembly to the the cell level, it was observed that the cooling plates between cells were still intact.
- Figure 81(d): Heat damage was observed on the voltage sensing wires and salt deposits were on connector.

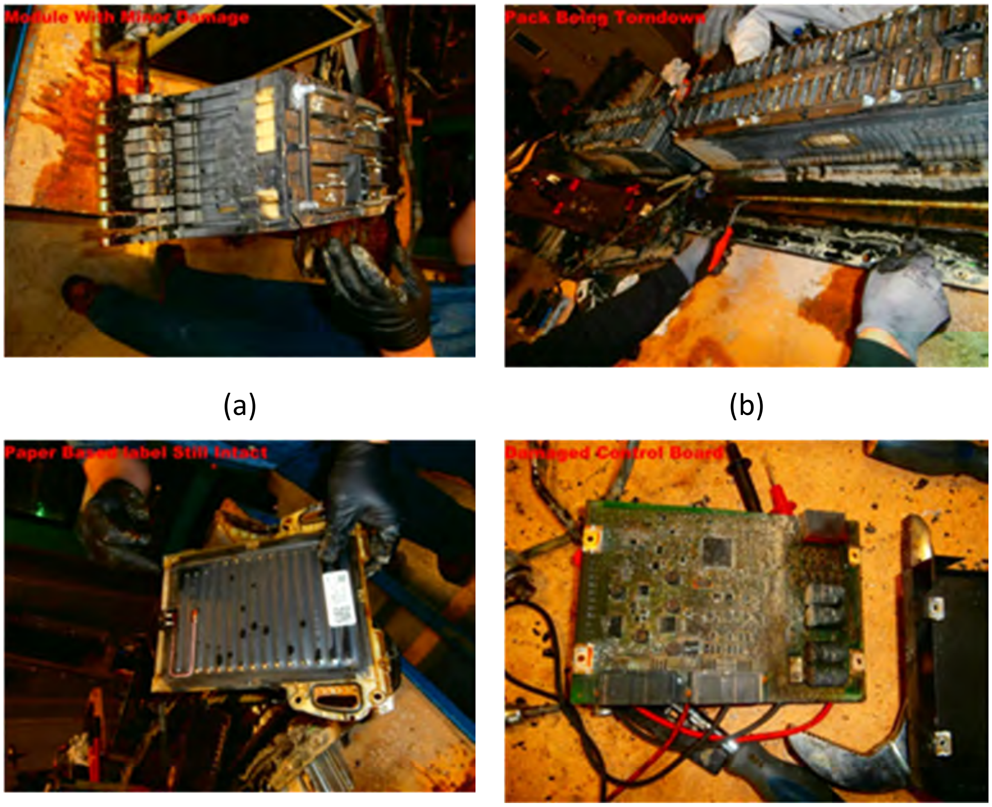
- Figure 82(a): A dismantled module was still structurally intact with some salt deposits.
- Figure 82(b): Visual discoloration of RESS was observed, as well as residue of salt water.
- Figure 82(c): An intact paper label was still adhered the bulkhead.
- Figure 82(d): The extent of damage from heat to one typical control board.



(a) (b)

(c) (d)

Figure 81 - GM Volt-1 PHEV post-test vehicle condition: a) RESS Tee, b) bulkhead, c) RESS dissasembly, and d) connectors.



(a) (b) (c) (d)

Figure 82 - GM Volt-1 PHEV post-test vehicle condition: a) module with minor damage, b) RESS tear-down, c) intact label, and d) control board.

8.2.5 Nissan Leaf SV/SL EV

A second Nissan Leaf SV/SL (Leaf-2) was a new production EV, see Table 27. Figure 83 shows the as-received vehicle from multiple angles. Figure 10 (above) shows some of the equipment used for testing, including the DAQ system, the gas sensor, the video camera, and the immersion tank.

Table 27 - Nissan Leaf-2 EV Details

Vehicle Class	Passenger Car
Manufacturer	Nissan
Make	Leaf
Model	SV/SL
Date of Manufacture	Jun-12
VIN	JN1AZ0CP1CT019374
Condition	New
Vehicle Type	EV

(a)

(b)

(c)

(d)

(e)

Figure 83 -Nissan Leaf-2 EV initial vehicle condition: a) left view, b) front ¾ view, c) right view, d) front view, and e) rear view.

8.2.5.1 Sample Preparation

As received, the vehicle was undamaged and in a operational condition. The vehicle display showed approximately 50% SOC in the RESS. All the loose interior parts were tagged and removed from the cabin. The 12 V battery was then disconnected, followed by the MSD. The vehicle was raised on a lift and the underbody plastics were removed to gain access to the RESS.

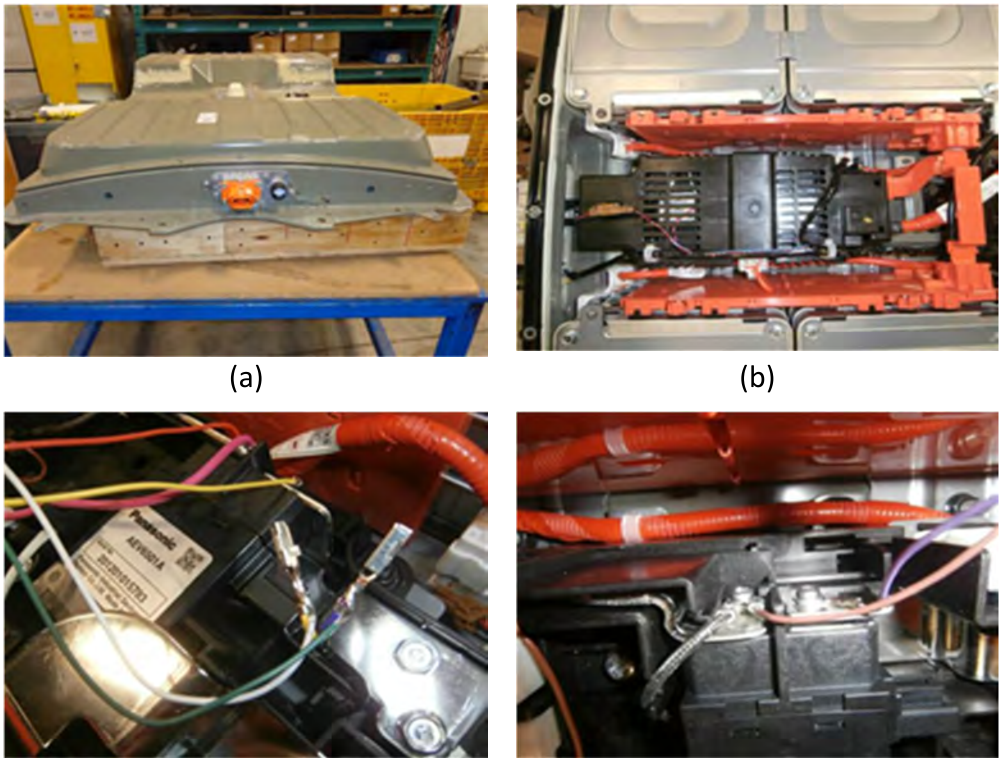
For HV and isolation measurements, the RESS was removed from the vehicle (see Figure 84); the enclosure and contactors were then removed as well. Voltage sense leads were tightly screwed to the bus bars of the assembly or soldered to the pins of the electrical connectors. The RESS was sealed to prevent water intrusion through the sense leads exiting the pack (see Section 8.1.2). The contactor was reassembled and re-installed and the RESS was placed back into the vehicle. Voltage sense cables were also installed on the 12 V battery.

A total of eight thermocouples were installed as specified in test procedure (see Section 6.5.1.13), including the RESS enclosure, near contactors, the control unit, and the 12 V battery. Thermocouple locations are provided in Table 28 and shown in Figure 85. The thermocouples were held in position using epoxy adhesive.

Three gas sensors were also mounted above the driver window (see Section 7.2).

Table 28 - Nissan Leaf-2 EV Thermocouple Placement

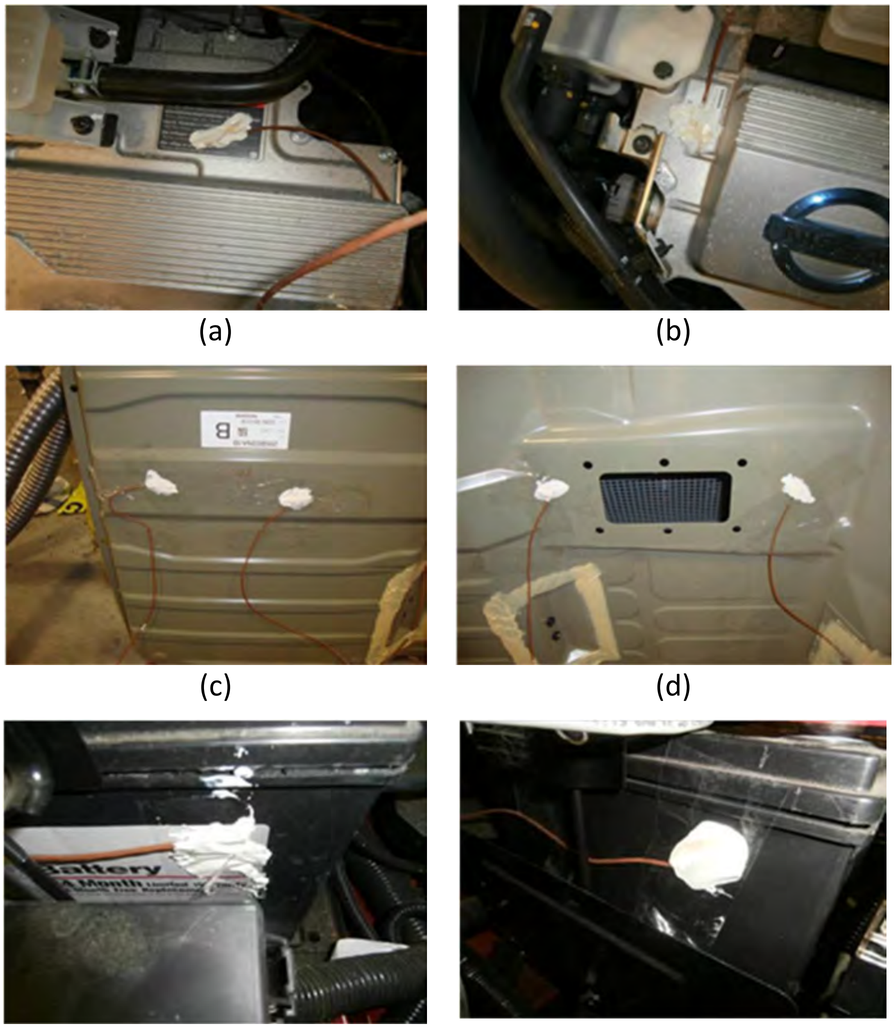
Number	Location
TC1, TC2	Control unit
TC3, TC4	Near contactors
TC5, TC6	Center of the RESS
TC7, TC8	12 V battery



(a) (b)

(c) (d)

Figure 84 - Nissan Leaf-2 EV HV connections: a) RESS removed from vehicle, b) contactor assembly, c) measurement wires soldered to contactor control circuit, and d) measurement wires screwed to bus bar.



(a) (b) (c) (d) (e) (f)

Figure 85 - Nissan Leaf-2 EV HV thermocouple placement: a) TC1 on the control unit, b) TC2 on the control unit, c) TC3 and TC4 near the contactors, d) TC5 and TC6 on the RESS, e) TC7 on the 12 V battery, and f) TC8 on the 12 V battery.

8.2.5.2 Test Conditions

Testing was performed outdoors in ambient temperatures. The beginning of test temperature was -4.64°C. A temporary enclosure over the top of the immersion container was installed to keep rain and snow from entering the vehicle during testing. There was no precipitation on the day the vehicle was immersed. The vehicle remained in the immersion container during the post-extraction observation period.

8.2.5.3 Immersion Test Results

The test event log is summarized in Table 29. The Volt-1 fire (Section 8.2.4) resulted in the loss of all data acquisition information, except video, for the first 7 hours of testing (including the immersion of the vehicle in seawater).
Figures 86 through 91 show measured data for the first available 9 hours of the test as follows:

- Figure 86 - Temperature profile for the first available 9 hours of testing
- Figure 87 - Gas sensing current for the first available 9 hours of testing
- Figure 88 - 12 V control voltage for the first available 9 hours of testing
- Figure 89 - Electrode to chassis voltage for the first available 9 hours of testing
- Figure 90 - RESS voltage for the first available 9 hours of testing
- Figure 91 - Isolation resistance for the first available 9 hours of testing

Figures 92 through 96 show measured data for the final 10 hours of the test as follows:

- Figure 92 - Temperature profile for the last 10 hours of testing
- Figure 93 - Gas sensing current for the last 10 hours of testing
- Figure 94 - 12 V control voltage for the last 10 hours of testing
- Figure 95 - RESS voltage for the last 10 hours of testing
- Figure 96 - Isolation resistance for the last 10 hours of testing

Table 29 - Nissan Leaf-2 EV Test Event Log

<table>
<tr><th>Date</th><th>Time</th><th>Test Time (hh:mm)</th><th>Event</th></tr>
<tr><td>3/26/2014</td><td>12:58 PM</td><td>N/A</td><td>• Video and data logging initiated.</td></tr>
<tr><td>3/26/2014</td><td>1:03 PM</td><td>N/A</td><td>• The vehicle was started (key-on, key-start, gear shift to Drive).</td></tr>
<tr><td>3/26/2014</td><td>1:04 PM</td><td>00:00</td><td>• Initiated filling the vehicle container with salt water.</td></tr>
<tr><td>3/26/2014</td><td>1:08 PM</td><td>00:04</td><td>• The contactors opened.</td></tr>
<tr><td>3/26/2014</td><td>1:19 PM</td><td>00:15</td><td>• Filling completed.</td></tr>
<tr><td>3/26/2014</td><td>1:20 PM</td><td>00:16</td><td>• Video observation: Bubbles were seen forming in the engine compartment. They continued to form throughout the immersion step.</td></tr>
<tr><td>3/26/2014</td><td>3:20 PM</td><td>02:16</td><td>• Extraction step initiated (i.e., water pumped out of the container).</td></tr>
<tr><td>3/26/2014</td><td>3:34 PM</td><td>02:30</td><td>• Extraction step completed.</td></tr>
<tr><td colspan="4">• The test data for the immersion period are lost due to a data acquisition system malfunction.
• The post-extraction recorded data show that the RESS retained its original voltage of 371 V and the isolation resistance of approximately 10 MΩ. The LV battery was drained and showed 0 V. The RESS post-contactor voltage was also 0 V.
• No further noticeable changes in voltage, temperature and gas sensing were recorded from this point to the end of the post-extraction period except for temperature variations following the environmental conditions.</td></tr>
</table>

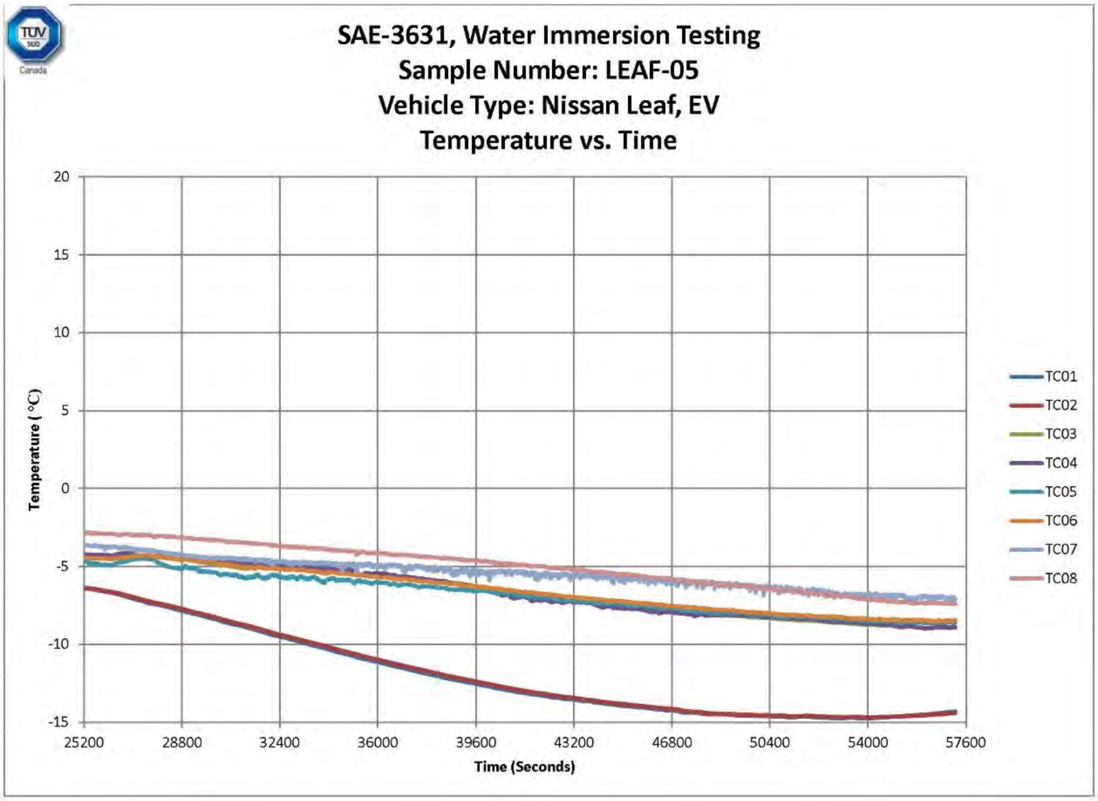


Figure 86 - Nissan Leaf-2 EV temperature profile for 9 hours of testing.

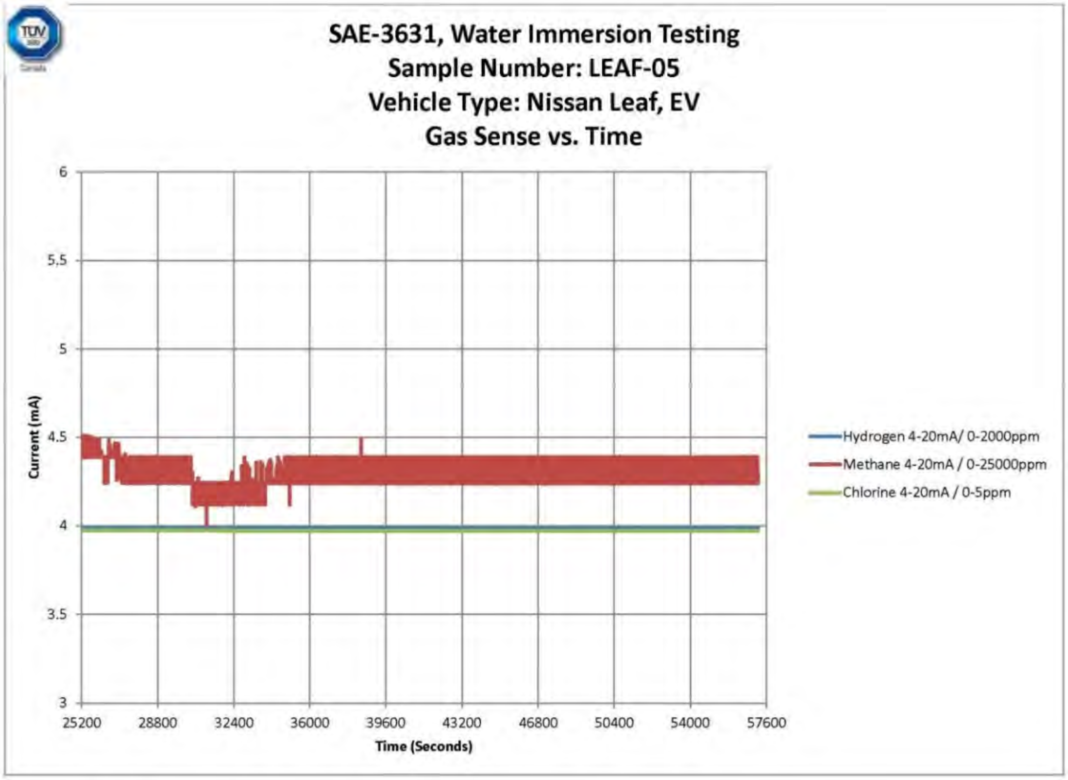


Figure 87 - Nissan Leaf-2 EV gas sensing current for 9 hours of testing.

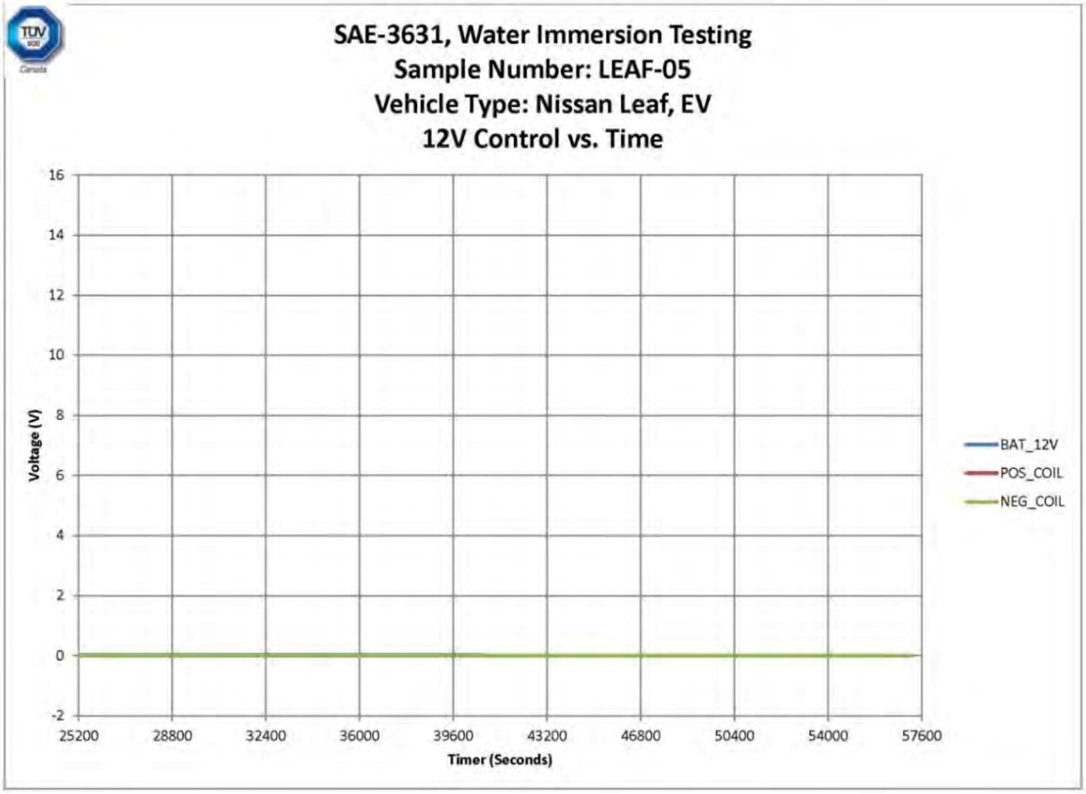


Figure 88 - Nissan Leaf-2 EV 12 V control voltage for 9 hours of testing.

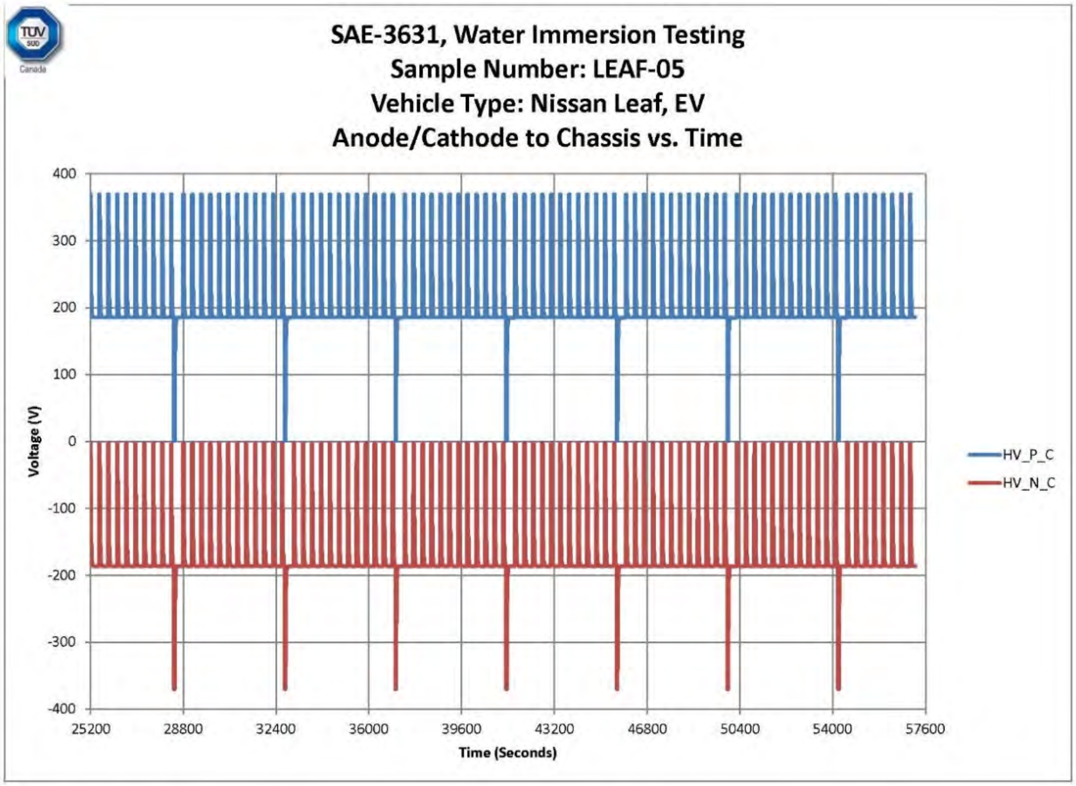


Figure 89 - Nissan Leaf-2 EV electrode to chassis voltage for 9 hours of testing.

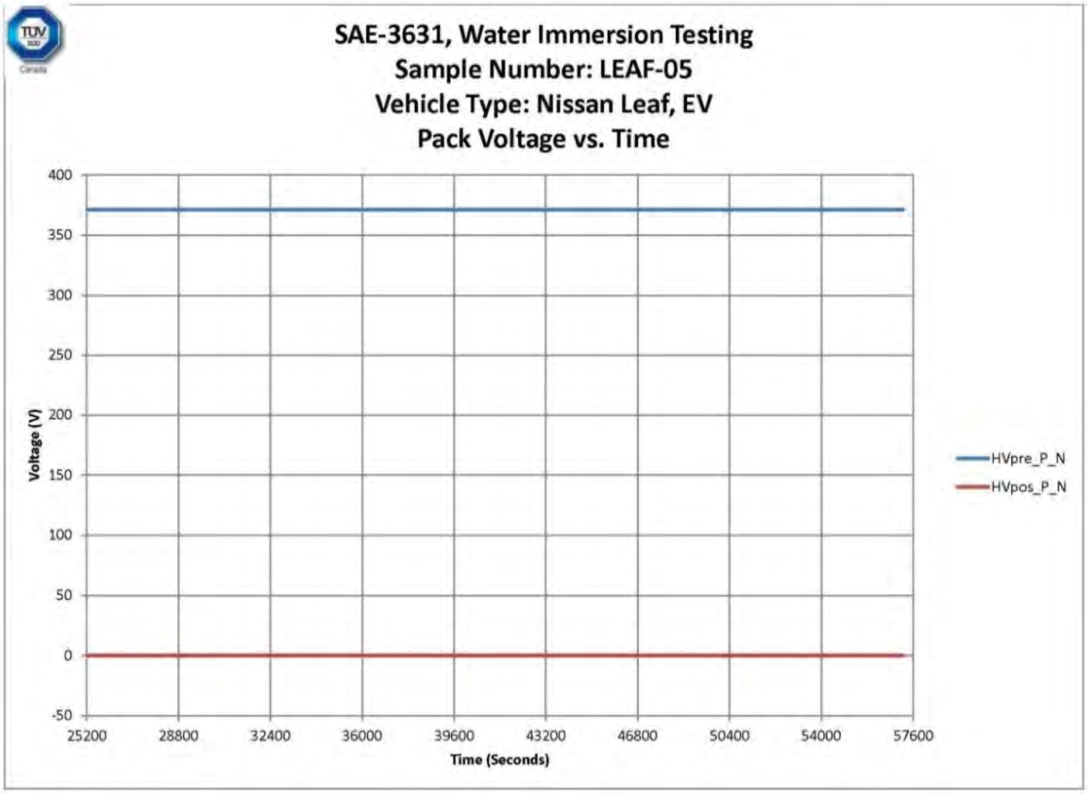


Figure 90 - Nissan Leaf-2 EV RESS voltage for 9 hours of testing.

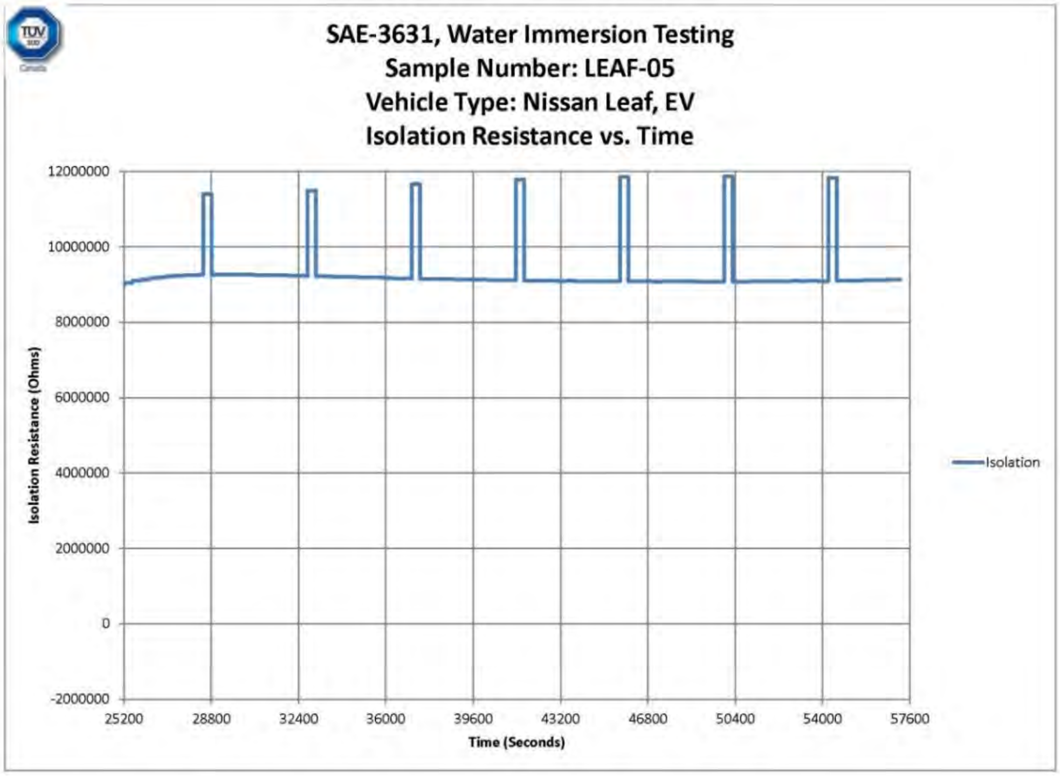


Figure 91 - Nissan Leaf-2 EV isolation resistance for 9 hours of testing.

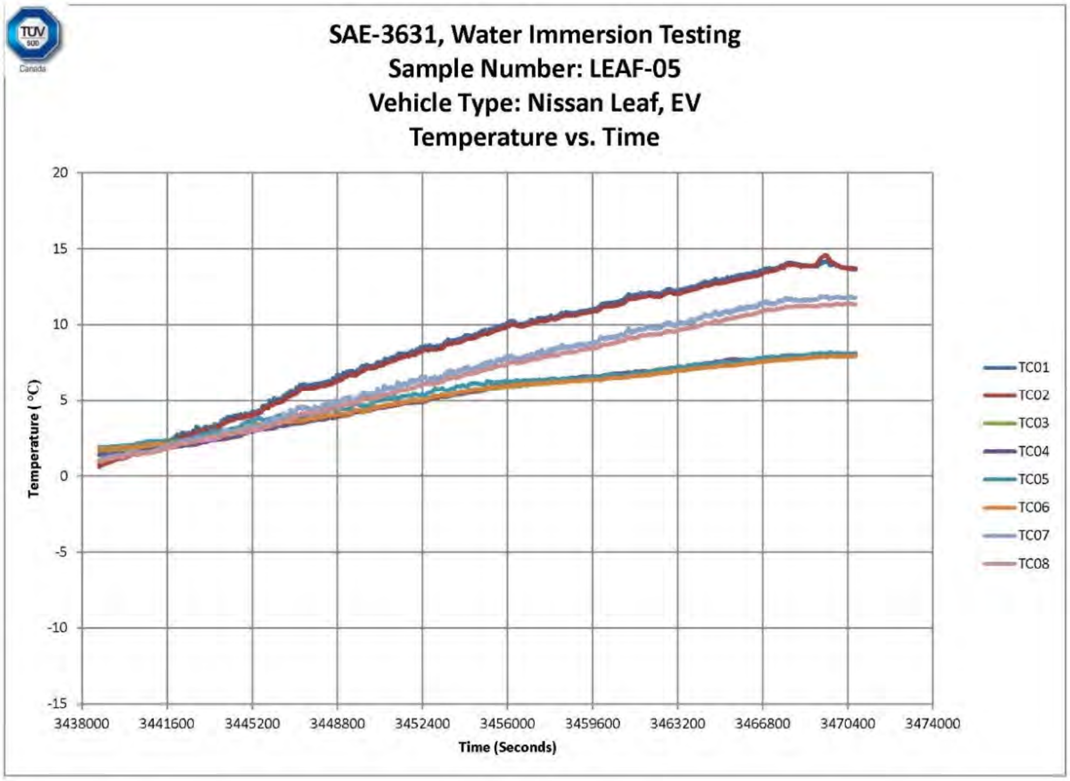


Figure 92 - Nissan Leaf-2 EV temperature profile for the last 10 hours of testing.

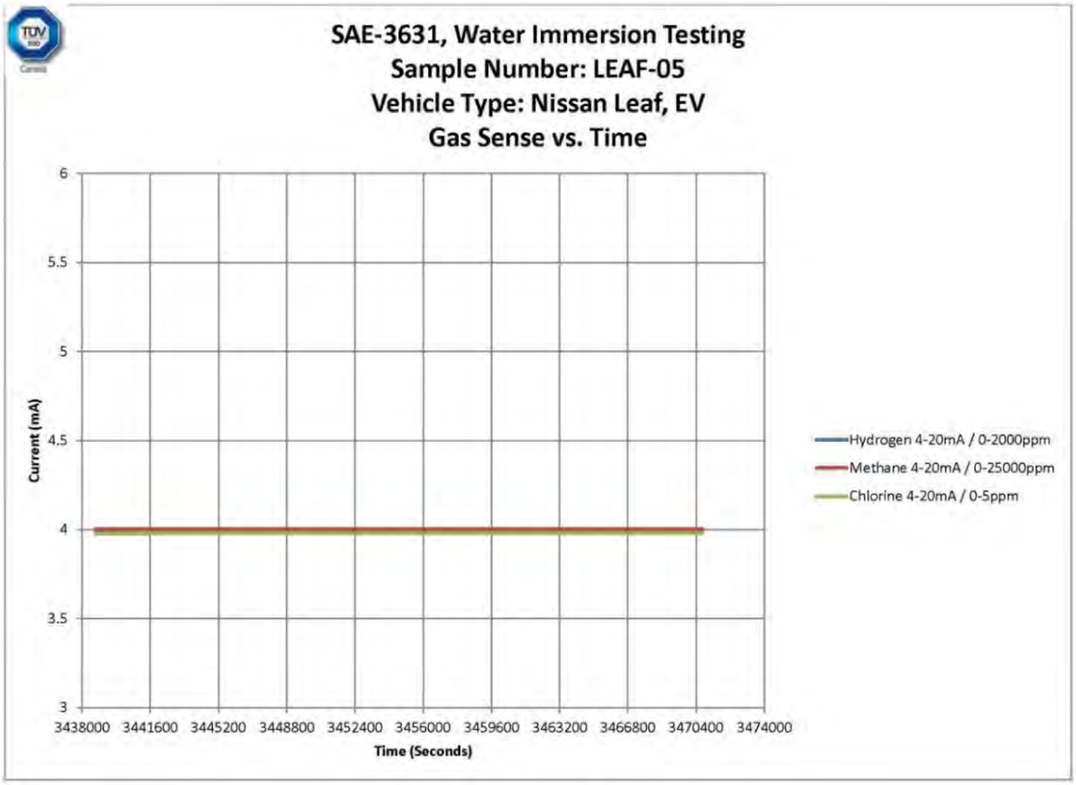


Figure 93 - Nissan Leaf-2 EV gas sensing current for the last 10 hours of testing.

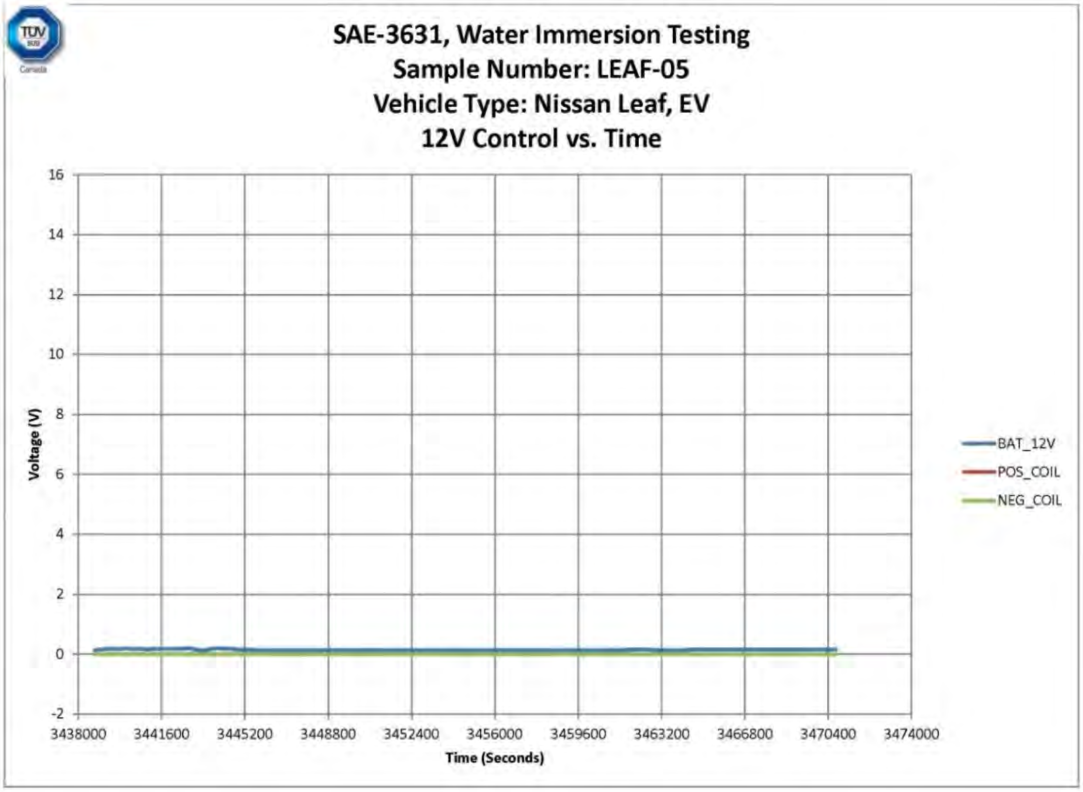


Figure 94 - Nissan Leaf-2 EV 12 V control voltage for the last 10 hours of testing.

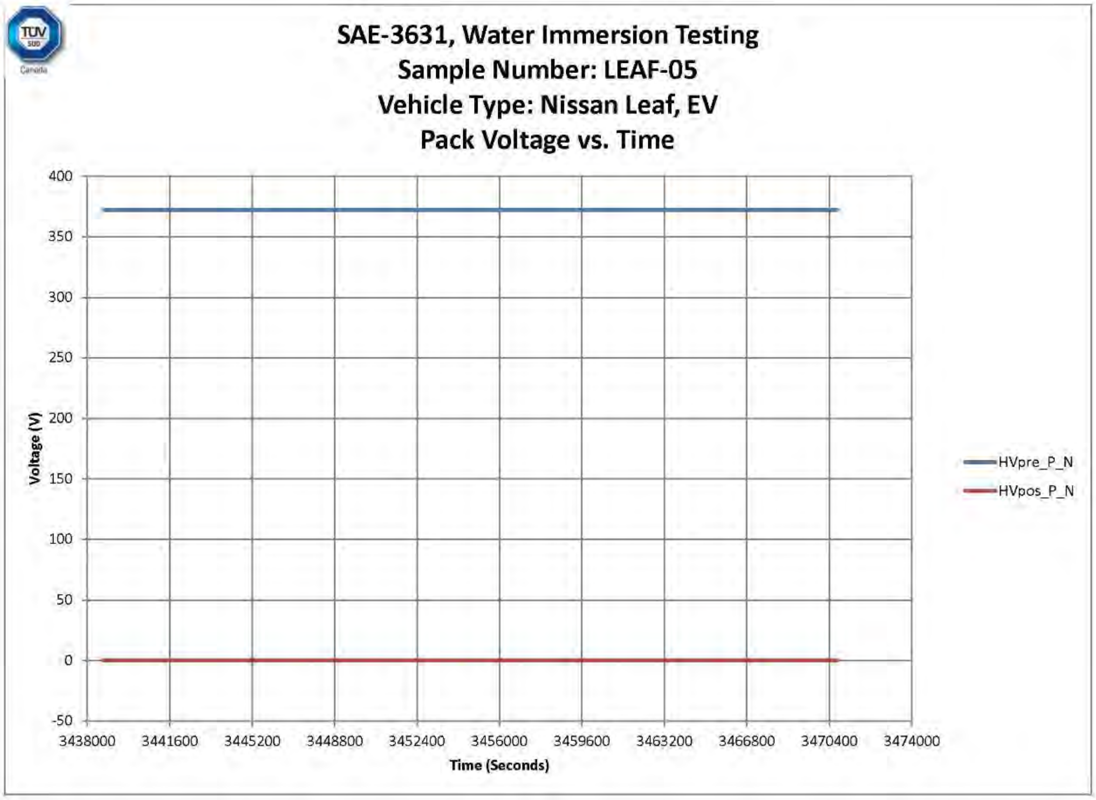


Figure 95 - Nissan Leaf-2 EV RESS voltage for the last 10 hours of testing.

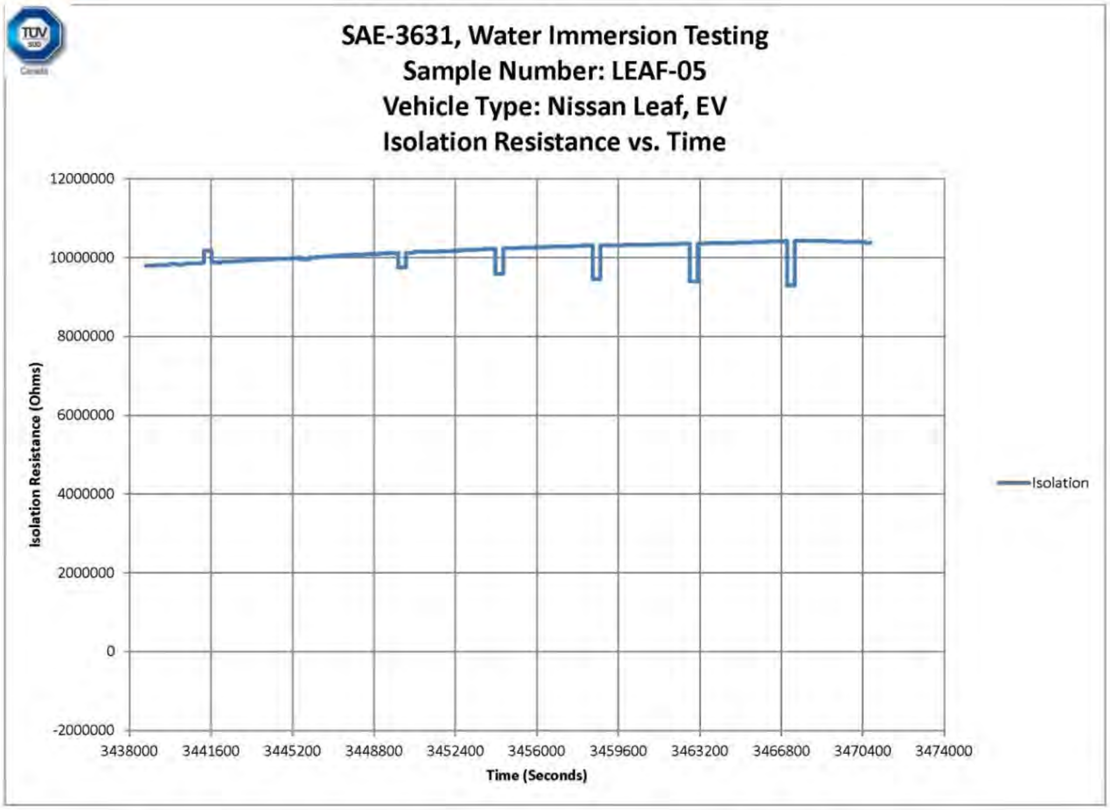


Figure 96 - Nissan Leaf-2 EV isolation resistance for the last 10 hours of testing.

8.2.5.4 Seawater Analysis Results

Seawater samples were taken before and after immersion. They were measured on-site for pH, density and conductivity; the results are summarized in Table 30. Samples were also sent to Maxxam Analytics, Inc. to evaluate VOCs; no VOCs were found to be above the reportable limit. Table 31 shows the total oil and grease content from the samples.

Table 30 - Nissan Leaf-2 EV Conductivity, Salinity, Density, and pH

Time	Conductivity (mS/cm)	Salinity (wt%)	Density (g/cm³)	pH
Pre-immersion	50.5	3.08	1.023	7.4
Post-immersion	50.6	3.08	1.024	7.3

Table 31 - Nissan Leaf-2 EV Total Oil and Grease Content

Petroleum Hydrocarbons	Units	Pre-Immersion	Post-Immersion	RDL*
Total oil and grease	mg/L	0.60	0.80	0.50

*RDL=Reportable Detection Limit

8.2.5.5 Post-Mortem Analysis

Figure 97 shows the vehicle from multiple angles after testing was complete. Post-mortem analysis did not indicate any evidence of behaviors that could result in an HSL higher than 4 (i.e., no anticipated fires, ruptures, or explosions) based on EUCAR standards. Temperatures increased inside the battery to air temperature after immersion in colder water. Diurnal values, however, started at about 8 hours after immersion and continued until the end of the test. Additionally, water immersion had no effect on the RESS voltage; it remained at 372 V. Therefore, no post-mortem analysis was conducted on the battery pack.

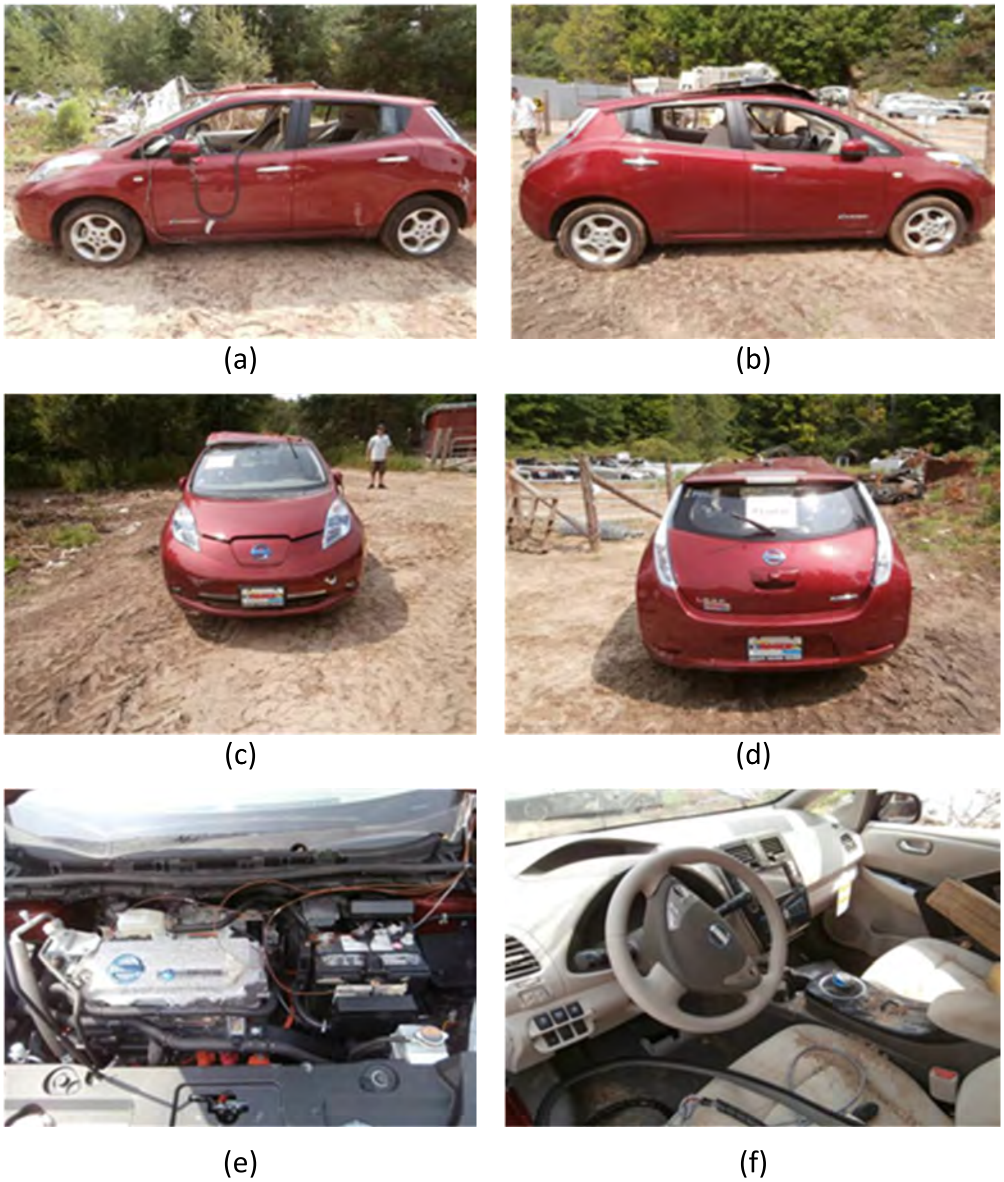

(a) (b) (c) (d) (e) (f)

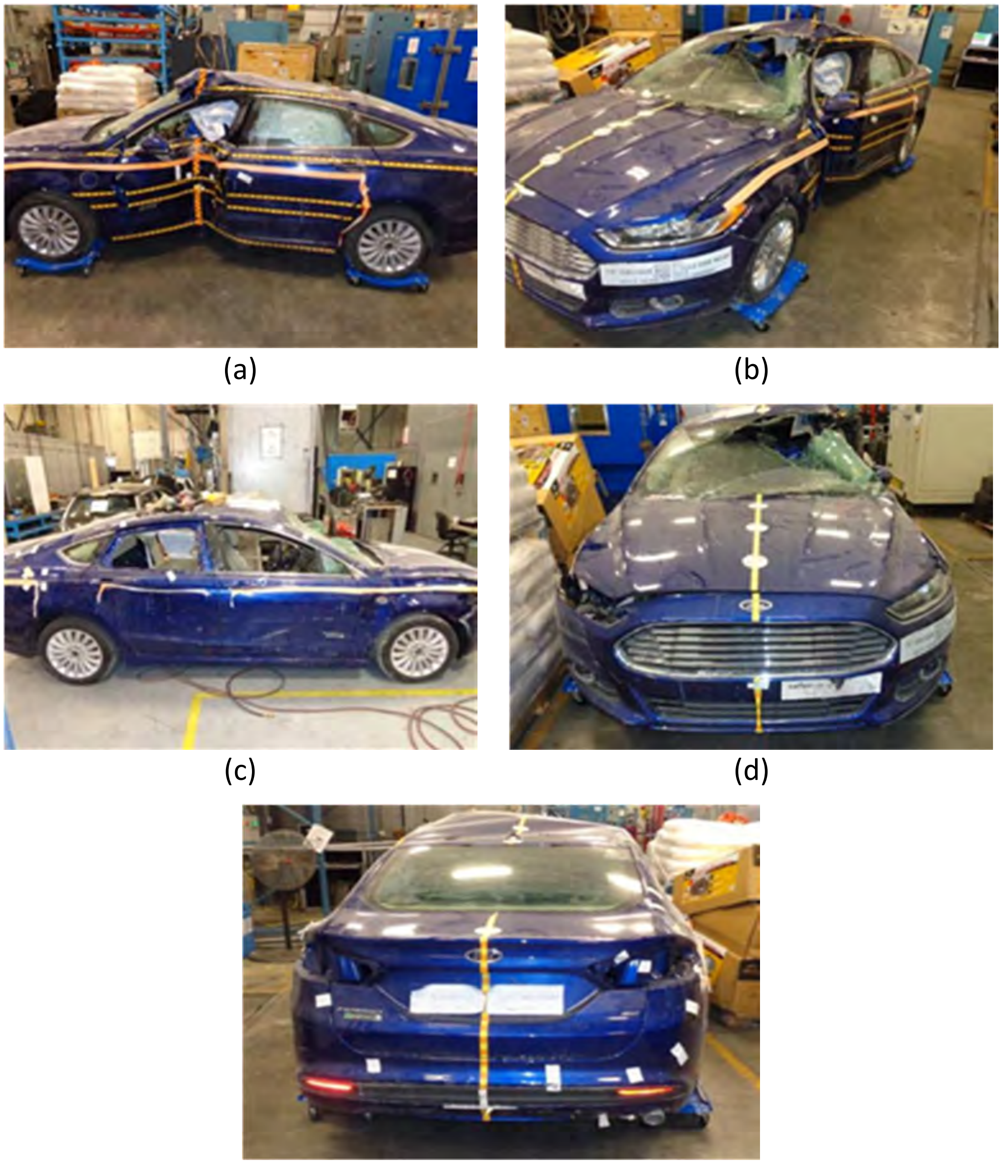
Figure 97 - Nissan Leaf-2 EV post-test vehicle condition: a) left view, b) right view, c) front view, d) rear view, e) engine bay, and f) front seats.

8.2.6 Ford Fusion Energi SE PHEV

The Ford Fusion Energi (Fusion-2) was a new production PHEV previously used for side impact testing, see Table 32. Figure 98 shows the as-received vehicle from multiple angles. Figure 10 (above) shows some of the equipment used for testing, including the DAQ system, the gas sensor, the video camera, and the immersion tank.

Table 32 - Ford Fusion-2 PHEV Details

Vehicle Class	Passenger Car
Manufacturer	Ford
Make	Fusion Energi
Model	SE PHEV
Date of Manufacture	Feb-12
VIN	3FA6P0PU2DR252083
Condition	Damaged (side impact)
Vehicle Type	PHEV



(a) (b)

(c) (d)

(e)

Figure 98 - Ford Fusion-2 PHEV initial vehicle condition: a) left view, b) front ¾ view, c) right view, d) front view, and e) rear view.

8.2.6.1 Sample Preparation

As received, the vehicle was operational but damaged from side impact testing. Due to the extent of the damage, the vehicle pedals were not accessible with the driver door attached. The door was removed to gain access to the controls. All the loose interior parts were tagged and removed from the cabin. The windshield was also removed for safety due to the amount of broken glass. The fuel gauge registered low and the dashboard display indicated approximately 30% charge for the RESS. The 12 V battery was then removed followed by the MSD and the HV cables.

For HV and isolation measurements, the rear seats, trunk interior and RESS were removed from the vehicle. The top and side covers were removed from the contactor end of the RESS to access and take apart the contactor assembly. The voltage sensors were tightly screwed to the bus bars of the assembly or soldered to the pins of the electrical connectors (see Figure 99). The RESS was sealed to prevent water intrusion through the sense leads exiting the pack (see Section 8.1.2). The contactor was reassembled and re-installed; the RESS was then placed back into the vehicle. The vehicle was tested for operation and the interior was reassembled the best it could be based on parts provided and the condition of the vehicle. The driver door, however, was not re-installed. Voltage sense cables were also installed on the 12 V battery.

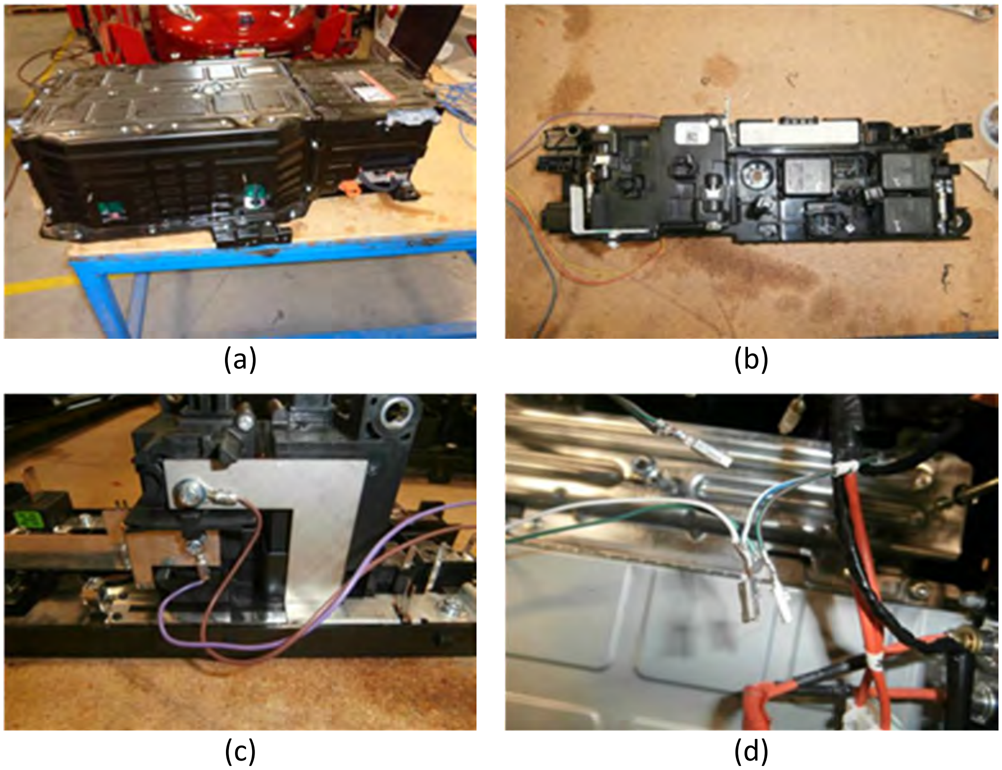


Figure 99 - Ford Fusion-2 PHEV HV connections: a) RESS removed from vehicle, b) contactor assembly, c) measurement wires screwed to a bus bar, and d) measurement wires soldered to pin connectors.

A total of eight thermocouples were installed as specified in test procedure (see Section 6.5.1.13), including the RESS enclosure, near contactors, the control unit, and the 12 V battery. Thermocouple locations are provided in Table 33 and shown in Figure 100. The thermocouples were held in position using epoxy adhesive.

Three gas sensors were also mounted above the driver window (see Section 7.2).

Table 33 - Ford Fusion-2 PHEV Thermocouple Placement

Number	Location
TC1, TC2	Control unit
TC3, TC4	Center of the RESS
TC5, TC6	Near contactors
TC7, TC8	12 V battery

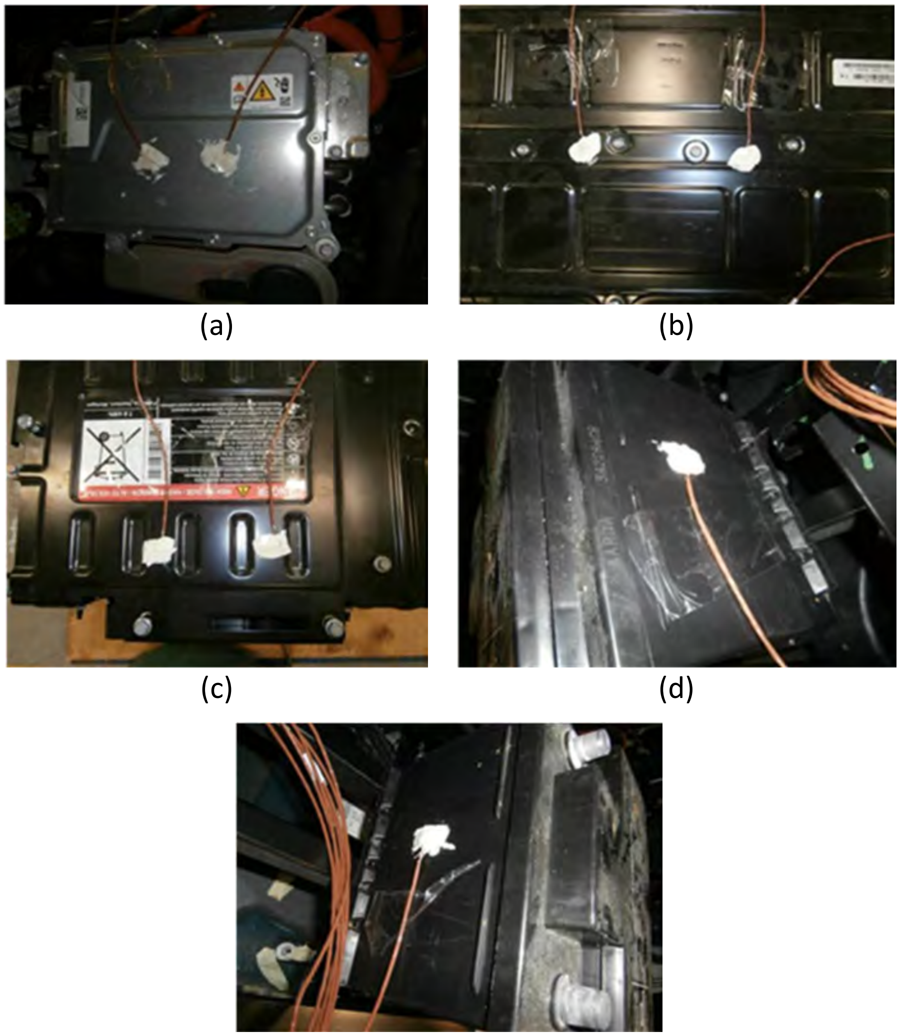

(a) (b) (c) (d) (e)

Figure 100 - Ford Fusion-2 PHEV HV thermocouple placement: a) TC1 and TC2 on the control unit, b) TC3 and TC4 on the center of the RESS, c) TC5 and TC6 near the contactor, and d) TC7 on the 12 V battery, and e) TC8 on the 12 V battery.

8.2.6.2 Test Conditions

Testing was performed outdoors in ambient temperatures. The beginning of test temperature was -5.12°C. A temporary enclosure over the top of the immersion container was installed to keep rain and snow from entering the vehicle during testing. There was no precipitation on the day the vehicle was immersed. The vehicle remained in the immersion container during the post-extraction observation period.

8.2.6.3 Immersion Test Results

The test event log is summarized in Table 34. Isolation resistance measurements were performed approximately every 6 minutes. Figures 101 through 113 show measured data for the initial 9 hours of the test as follows:

- Figure 101 - Temperature profile for the first 9 hours of testing
- Figure 102 - Temperature profile for the first 1 hour of testing
- Figure 103 - Gas sensing current for the first 9 hours of testing
- Figure 104 - 12 V control voltage for the first 9 hours of testing
- Figure 105 - 12 V control voltage for the first 1 hour of testing
- Figure 106 - Positive coil voltage for the first 1 hour of testing
- Figure 107 - Electrode to chassis voltage for the first 9 hours of testing
- Figure 108 - Electrode to chassis voltage for the first 1.3 hours of testing
- Figure 109 - RESS voltage for the first 9 hours of testing
- Figure 110 - HV post-contactor voltage for the first 1 hour of testing
- Figure 111 - HV pre-contactor voltage for the first 1 hour of testing
- Figure 112 - Isolation resistance for the first 9 hours of testing
- Figure 113 - Isolation resistance for the first 30 minutes of testing

Figures 114 through 118 show measured data for the final 10 hours of the test as follows:

- Figure 114 - Temperature profile for the last 10 hours of testing
- Figure 115 - Gas sensing current for the last 10 hours of testing
- Figure 116 - 12 V control voltage for the last 10 hours of testing
- Figure 117 - RESS voltage for the last 10 hours of testing
- Figure 118 - Isolation resistance for the last 10 hours of testing

Table 34 - Ford Fusion-2 PHEV Test Event Log

Date	Time	Test Time (hh:mm)	Event
3/25/2014	2:52 PM	N/A	• Video and data logging initiated.
3/25/2014	3:01 PM	N/A	• The vehicle was started (key-on, key-start, gear shift to Drive).
3/25/2014	3:07 PM	00:00	• Initiated filling the vehicle container with salt water.
3/25/2014	3:07 PM	00:00	• Isolation resistance decreased from 9.66 MΩ to 4.2 MΩ. • The drop may possibly be due to the interference of the vehicle's isolation resistance measurements. The interference also caused fluctuations on the RESS-to-chassis voltages.
3/25/2014	3:16 PM	00:09	• Average ambient temperature before immersion was -7°C. • The temperature recorded by the thermocouples on the 12 V battery (TC7) quickly increased to -3.4°C.
3/25/2014	3:17 PM	00:10	• The RESS post-contactor voltage (HVpos_P_N) dropped to zero. • The LV battery voltage and the contactor coil voltages (POS_COIL and NEG_COIL) sharply decreased to approximately 5 V and then reached 0 V within 2 minutes.
3/25/2014	3:18 PM	00:11	• Isolation resistance decreased to zero.
3/25/2014	3:19 PM	00:12	• The RESS pre-contactor voltage (HVpre_P_N) started to decrease. • At the same time, HVpos_P_N sharply increased to approximately 280 V, coinciding with the contactor coil voltage spikes to 20 V (the data acquisition channel limit). • Both pack voltages continued to decrease for 1 minute and then started to increase temporarily. HVpos_P_N and HVpre_P_N reached values near 0 V within 2 hours.
3/25/2014	3:19 PM	00:12	• Video observation: Smoke is seen rising from the right top portion of the trunk near the battery pack and at times from the rear passenger window and left potion of the trunk. Smoking continues for 3 to 4 minutes.
3/25/2014	3:20 PM	00:13	• The temperature from the thermocouples installed on the RESS case (TC5, TC6 near the contactors; TC3, TC4 on the RESS center) started to increase. The maximum temperature recorded at this stage was 20.7°C on the case. • The pack temperature decreased to an average of 2°C after 30 minutes. • The BECM temperature (TC2) had started increasing from the beginning of test and reached a maximum of

Date	Time	Test Time (hh:mm)	Event
			11°C by this time. • A spike in HVpos_P_N and HVpre_P_N voltage is observed as well.
3/25/2014	3:22 PM	00:15	• A sharp decrease in HVpos_P_N and HVpre_P_N voltage is observed (from 225 V to 110 V).
3/25/2014	3:30 PM	00:23	• Filling completed. • Bubbles were seen forming outside the vehicle near the driver side rear door. They continued to form throughout the immersion step.
3/25/2014	5:30 PM	02:23	• Extraction step initiated (i.e., water pumped out of the container).
3/25/2014	5:40 PM	02:33	• The LV battery voltage increased from 0.1 V to 0.5 V for 15 minutes before dropping back to 0.1 V.
3/25/2014	5:48 PM	02:41	• Extraction step completed.
• There were no changes in recorded gas sensing during the period mentioned above. • No further changes in voltage, temperature and gas sensing were recorded from this point to the end of the post-extraction period except for temperature variations following the environmental conditions.			

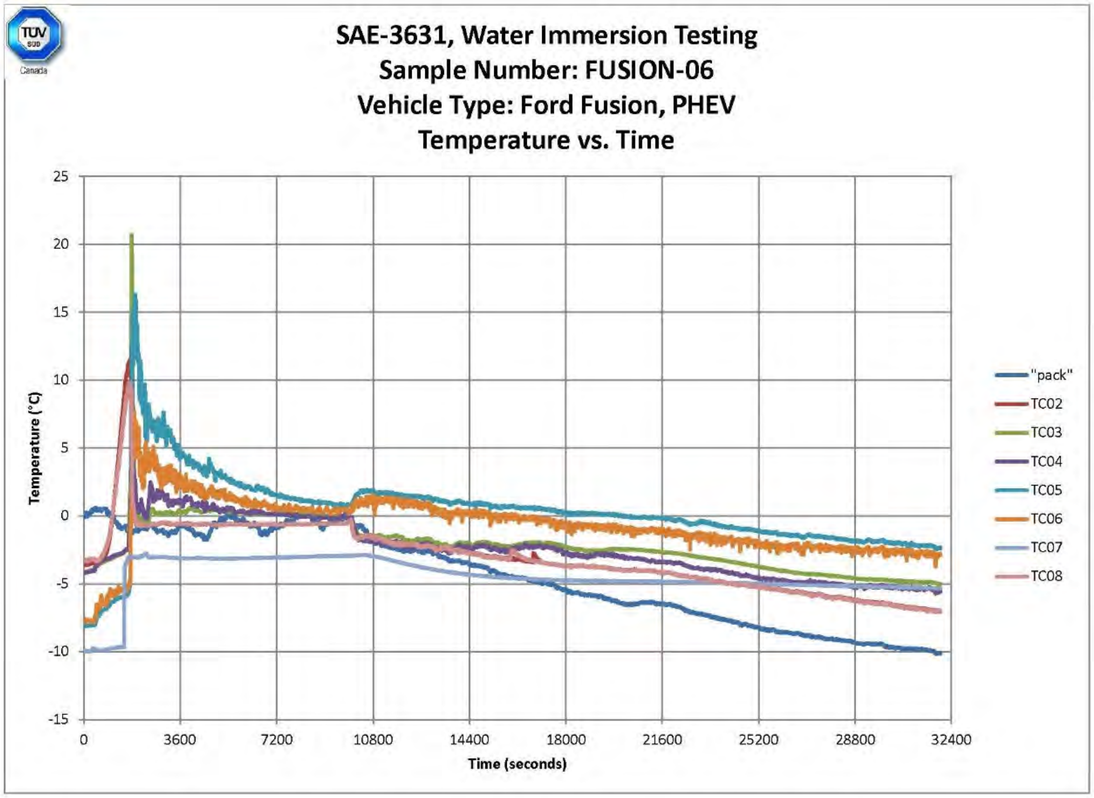


Figure 101 - Ford Fusion-2 PHEV temperature profile for the first 9 hours of testing.

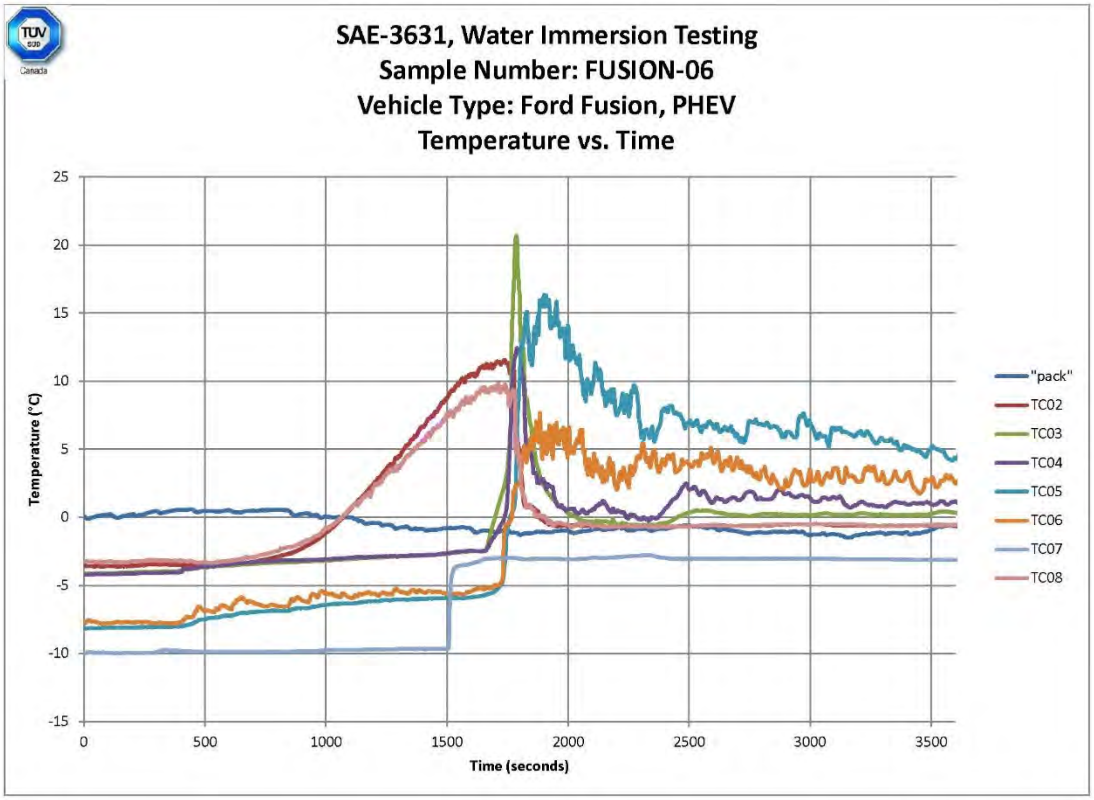


Figure 102 - Ford Fusion-2 PHEV temperature profile for the first 1 hour of testing.

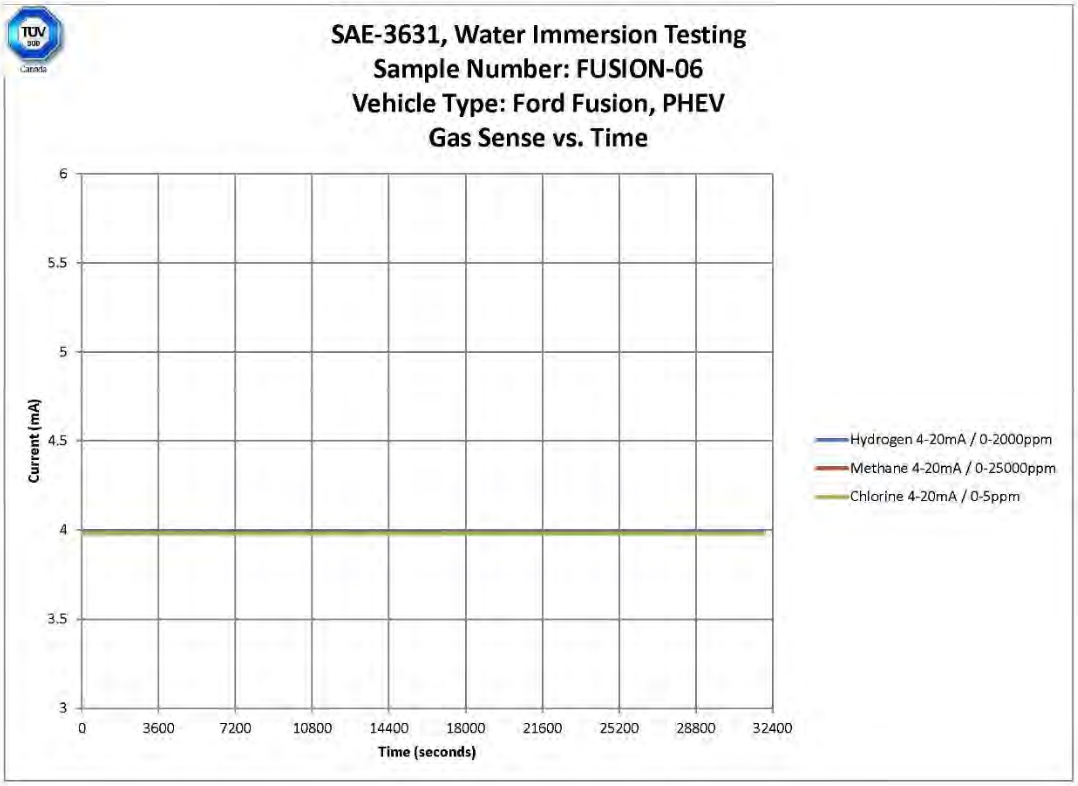


Figure 103 - Ford Fusion-2 PHEV gas sensing current for the first 9 hours of testing.

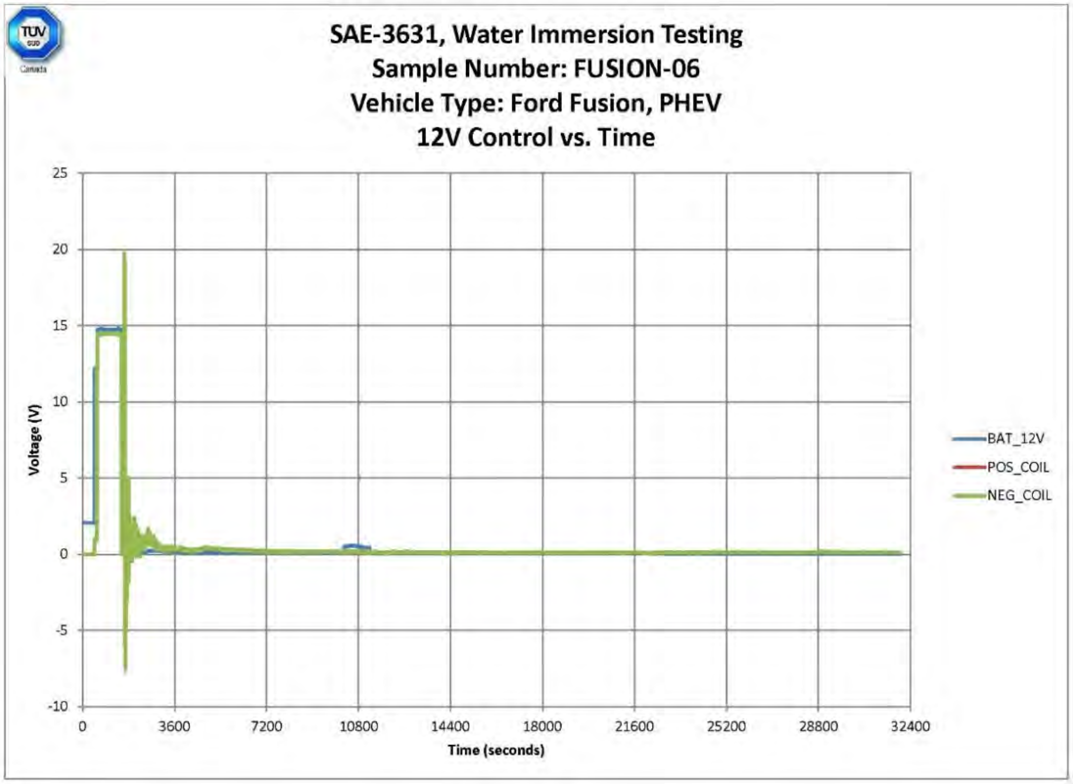


Figure 104 - Ford Fusion-2 PHEV 12 V control voltage for the first 1 hour of testing.

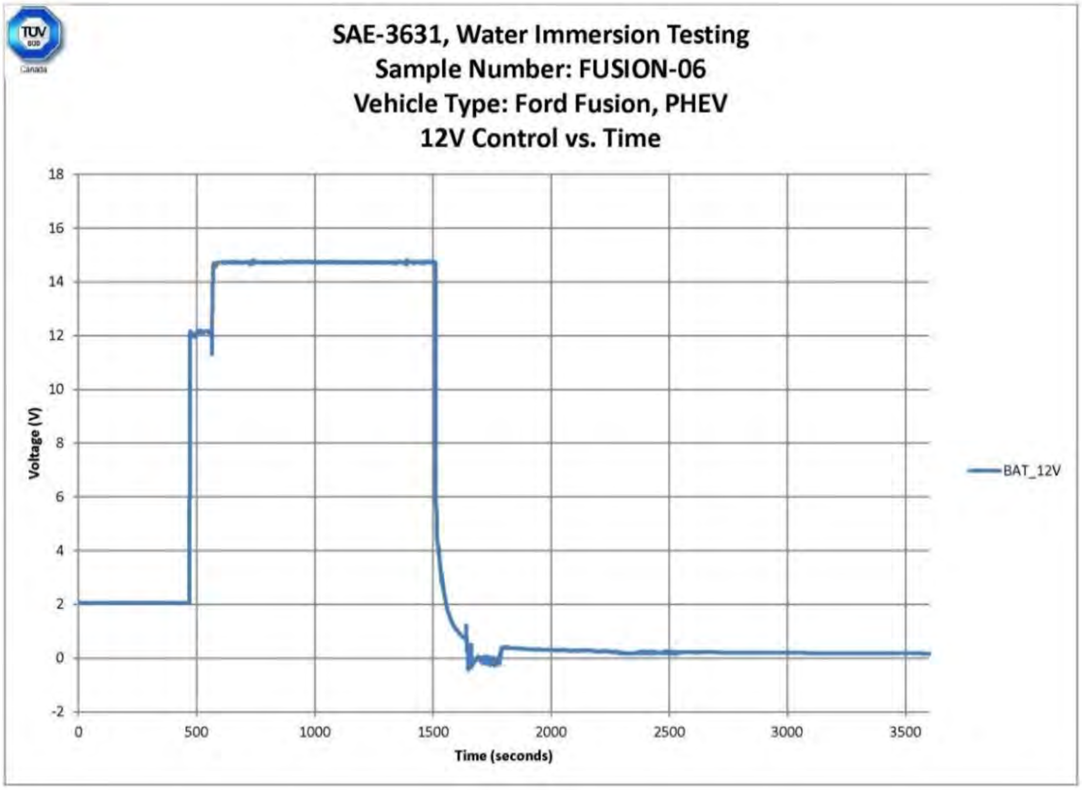


Figure 105 - Ford Fusion-2 PHEV 12 V control voltage for the first 1 hour of testing.

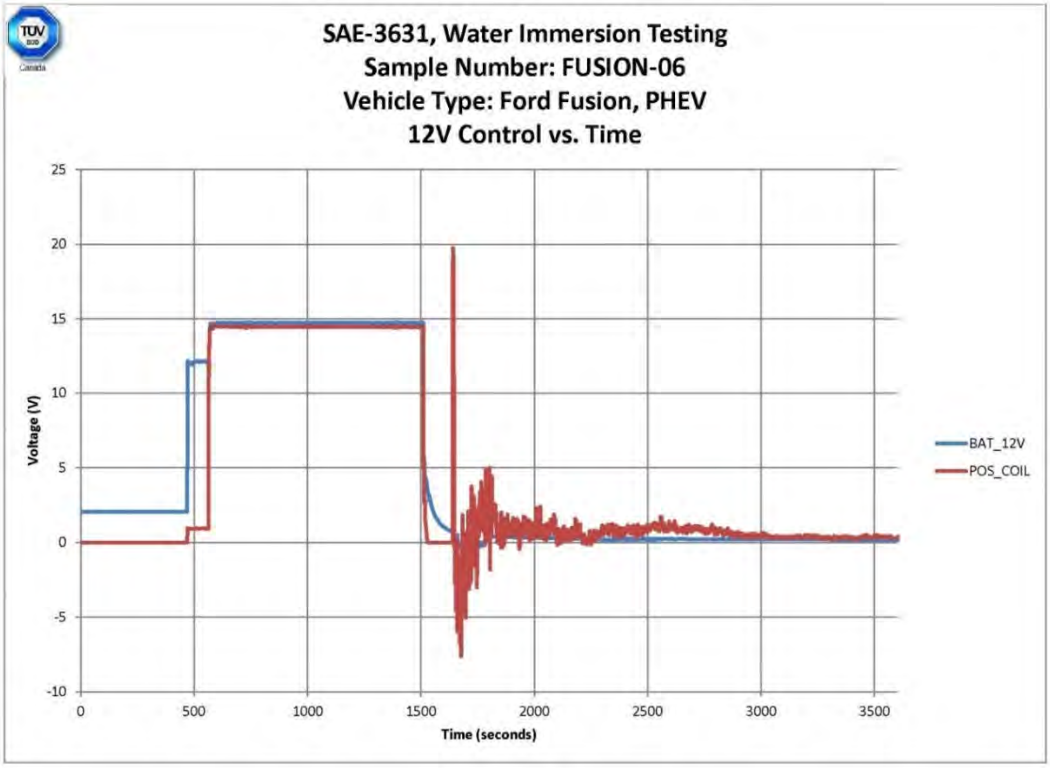


Figure 106 - Ford Fusion-2 PHEV positive coil voltage for the first 1 hour of testing.

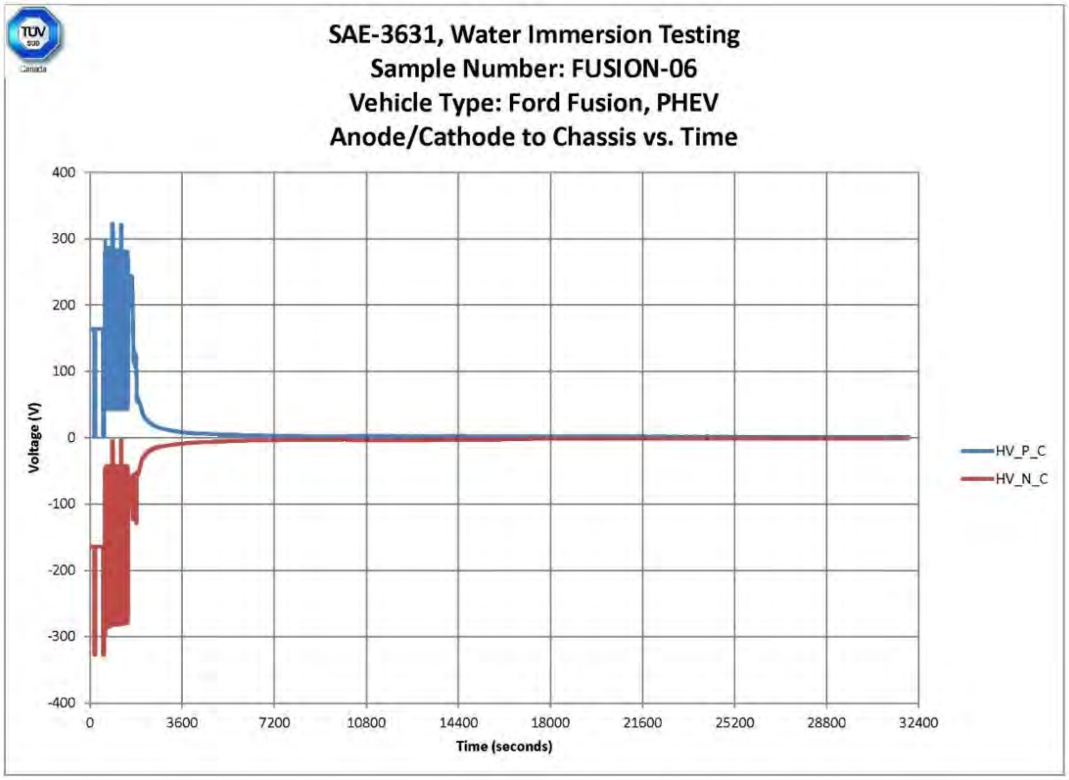


Figure 107 - Ford Fusion-2 PHEV electrode to chassis voltage for the first 9 hours of testing.

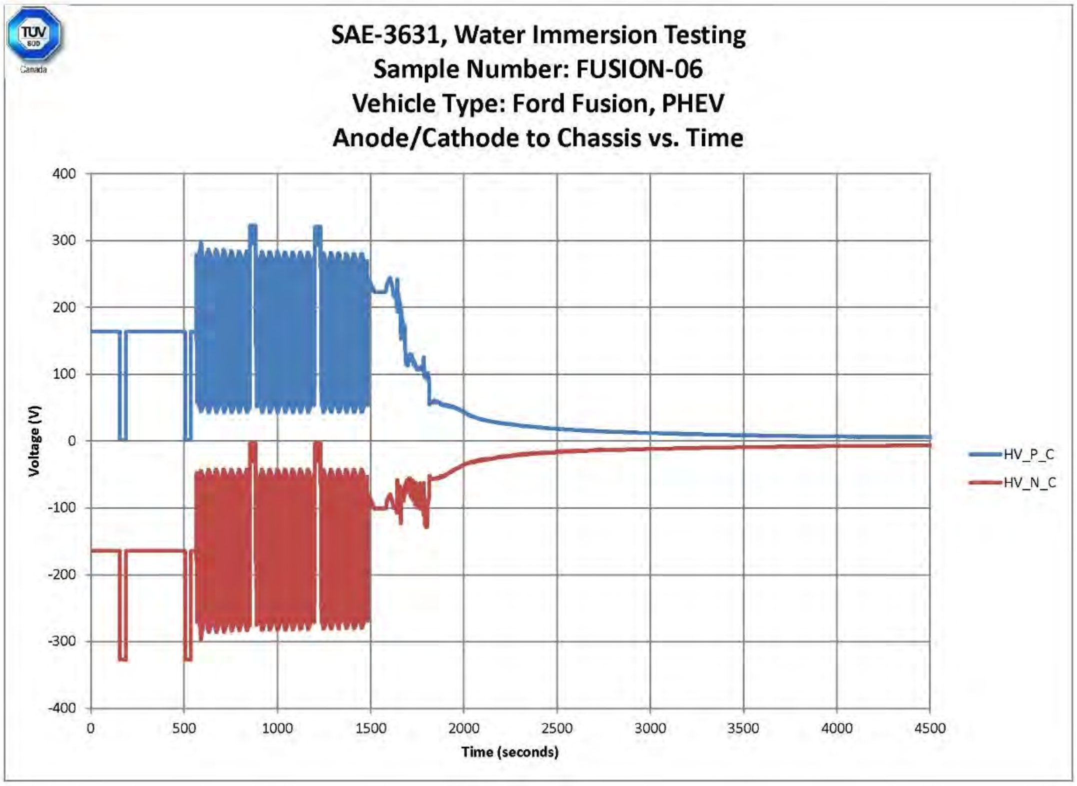


Figure 108 - Ford Fusion-2 PHEV electrode to chassis voltage for the first 1.3 hours of testing.

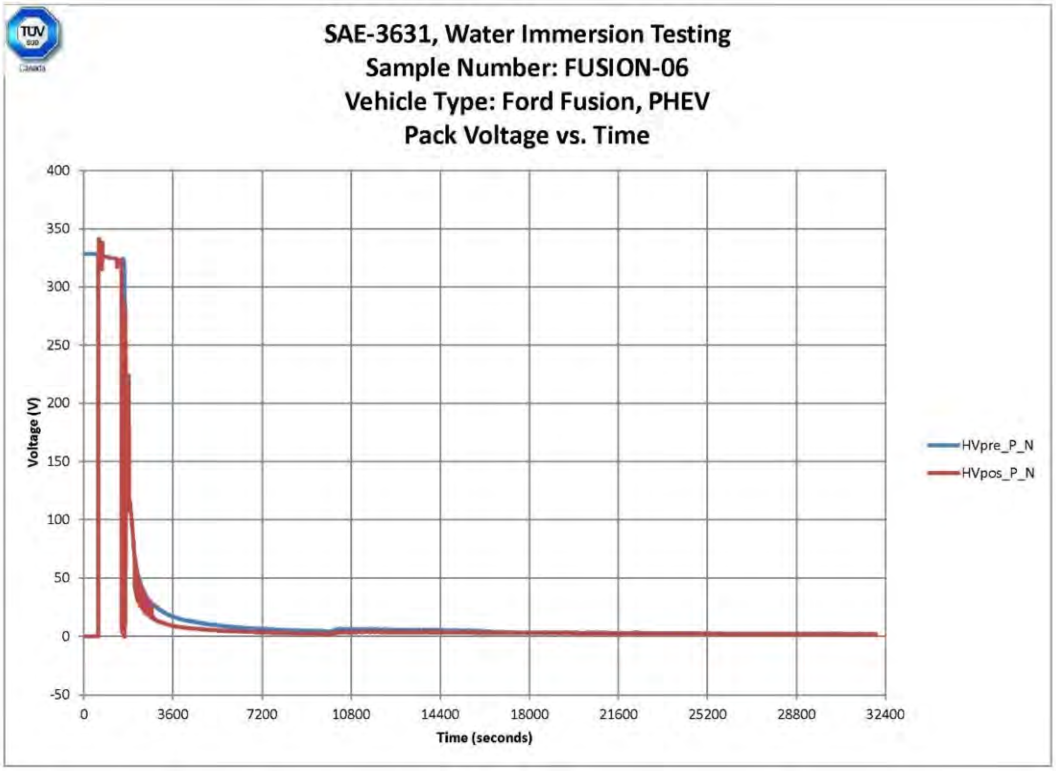


Figure 109 - Ford Fusion-2 PHEV RESS voltage for the first 9 hours of testing.

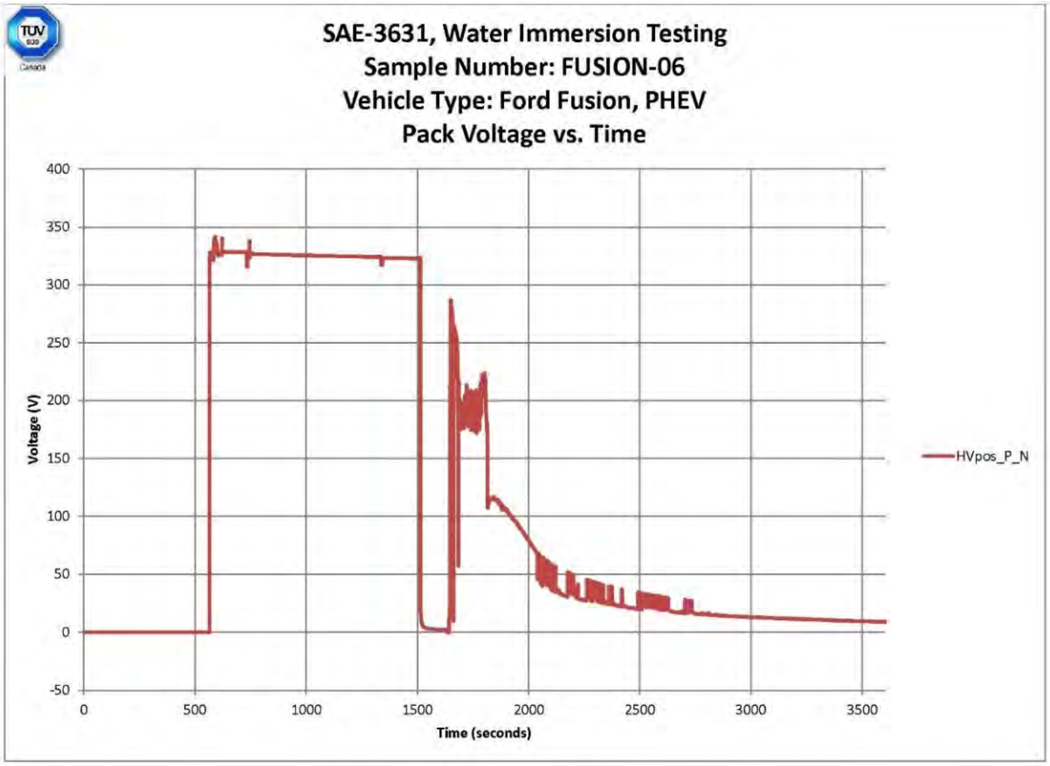


Figure 110 - Ford Fusion-2 PHEV HV post-contactor voltage for the first 1 hour of testing.

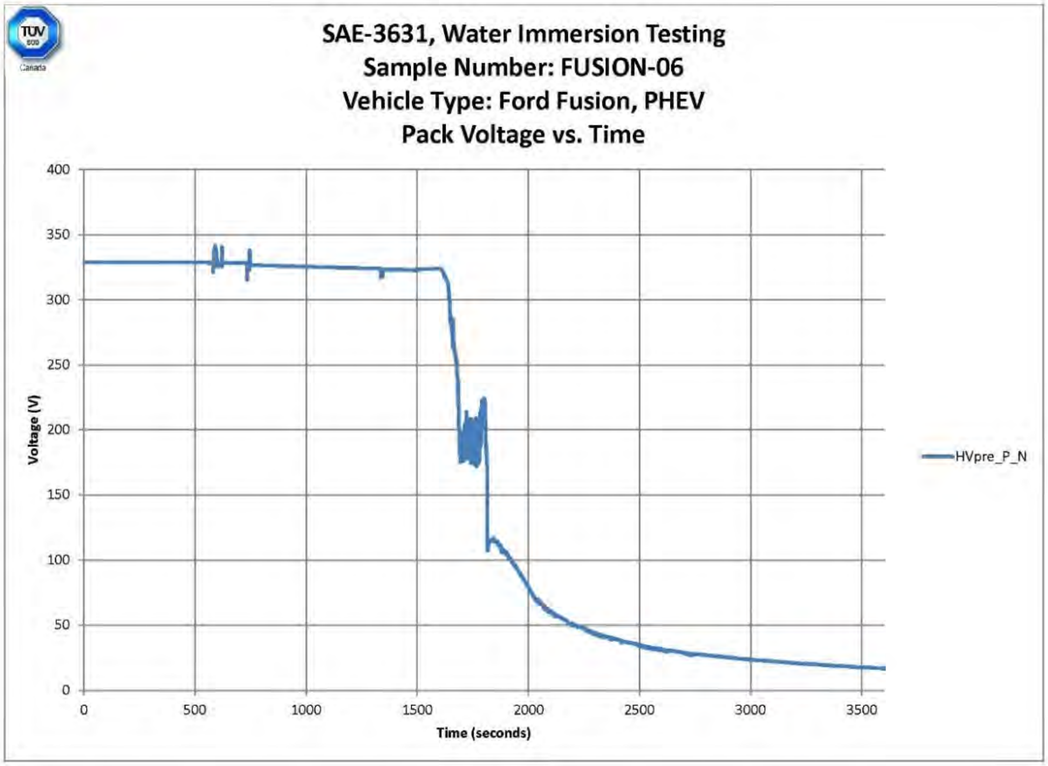


Figure 111 - Ford Fusion-2 PHEV HV pre-contactor voltage for the first 1 hour of testing.

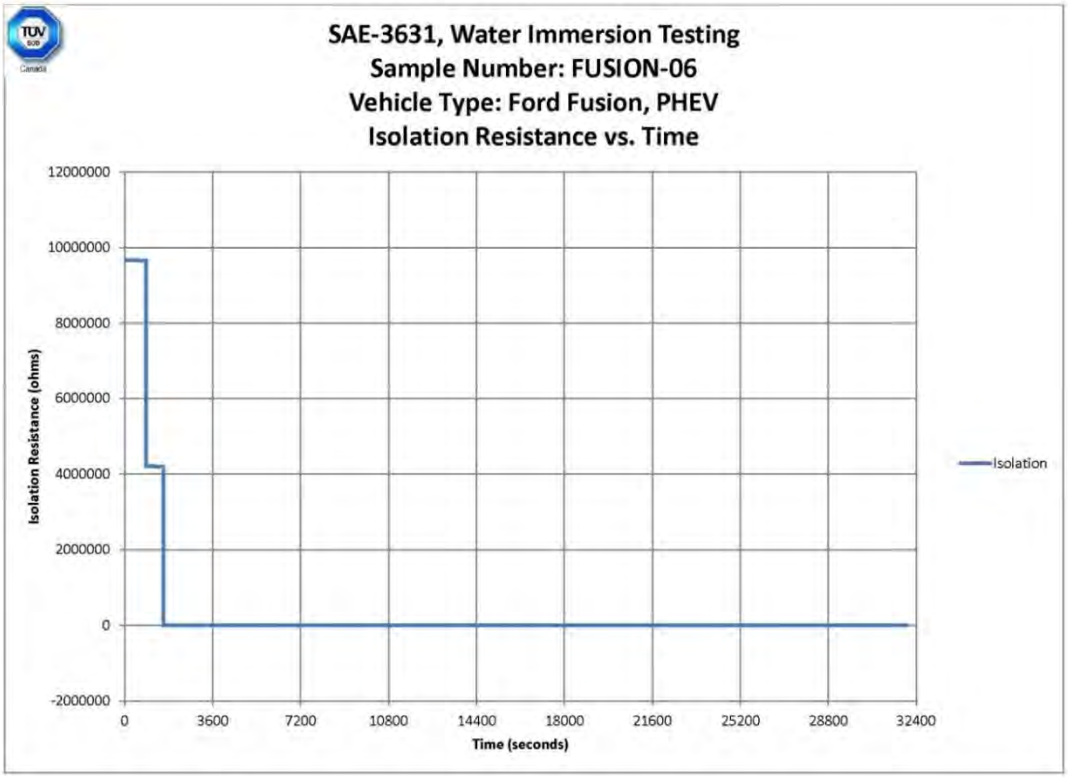


Figure 112 - Ford Fusion-2 PHEV isolation resistance for the first 9 hours of testing.

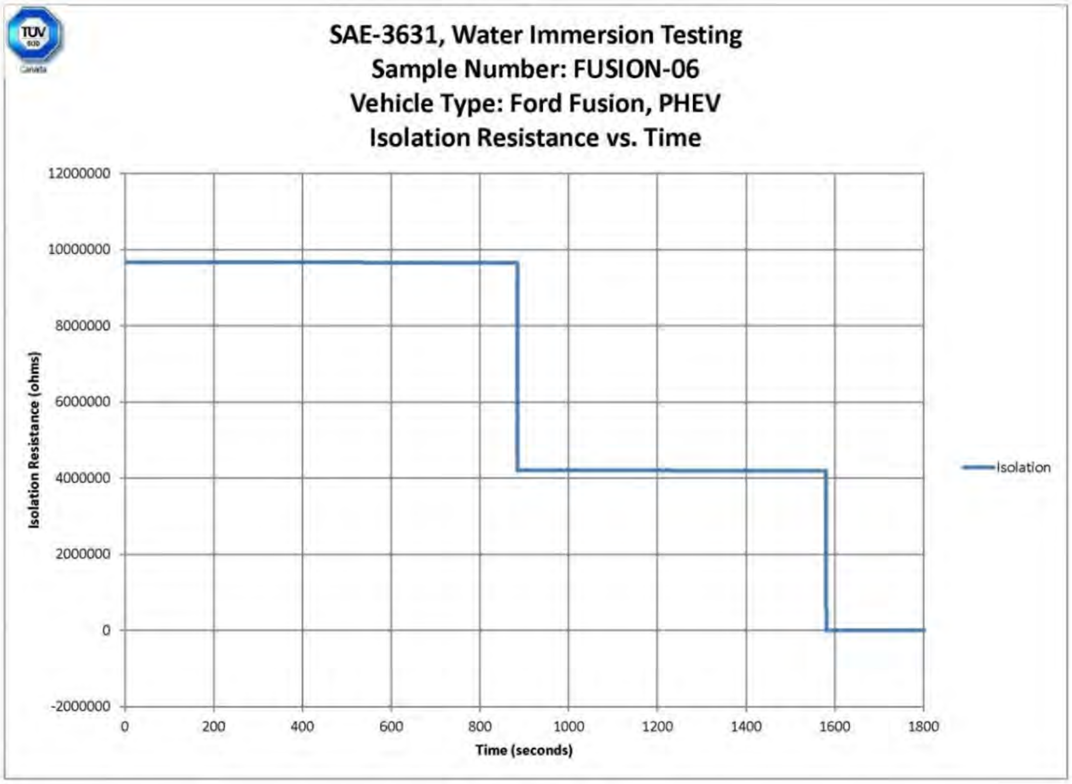


Figure 113 - Ford Fusion-2 PHEV isolation resistance for the first 30 minutes of testing.

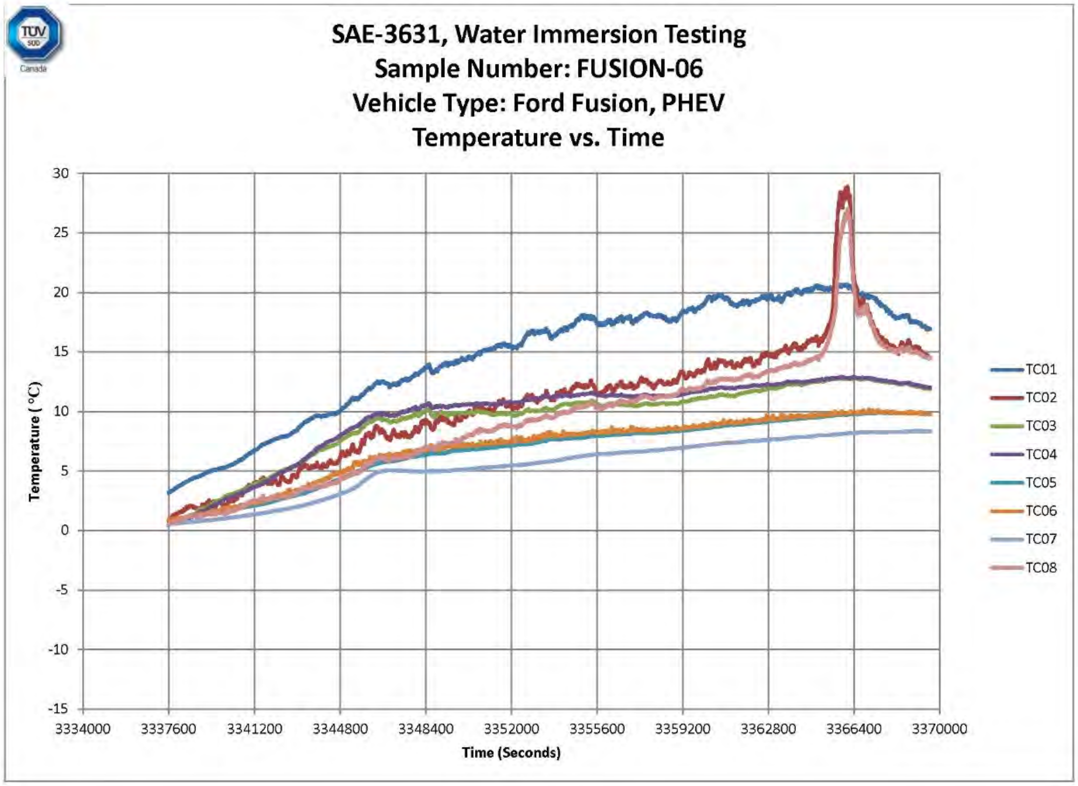


Figure 114 - Ford Fusion-2 PHEV temperature profile for the last 10 hours of testing.

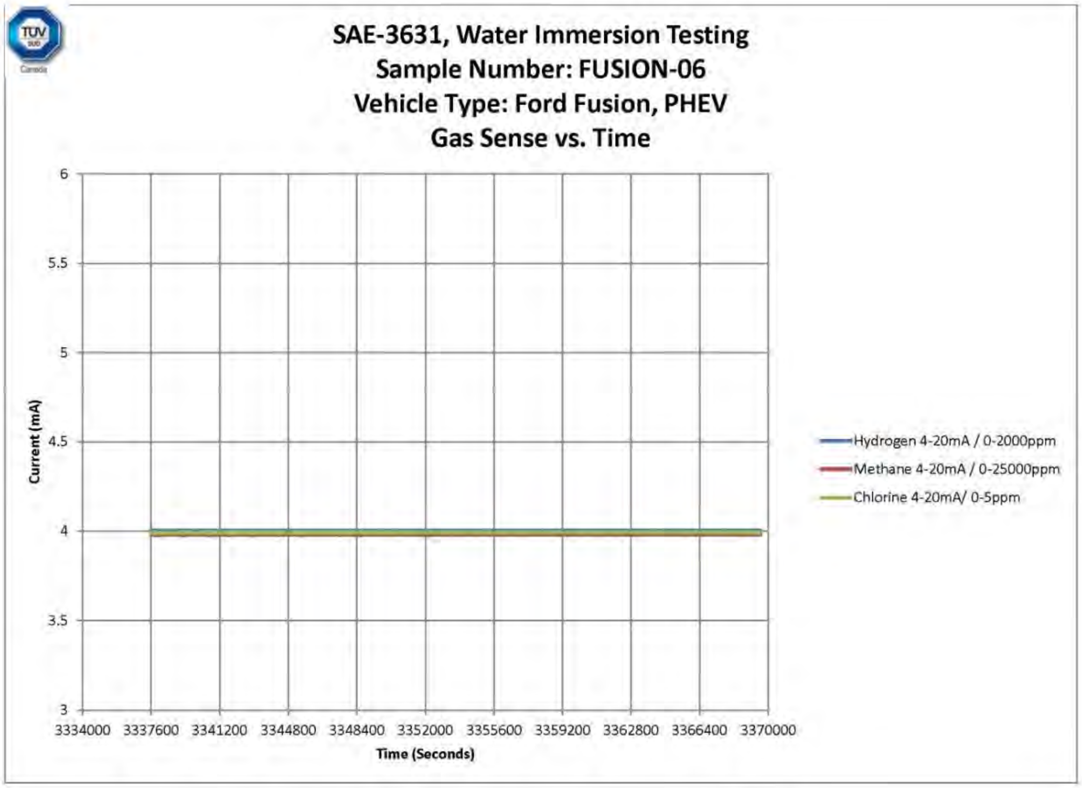


Figure 115- Ford Fusion-2 PHEV gas sensing current for the last 10 hours of testing.

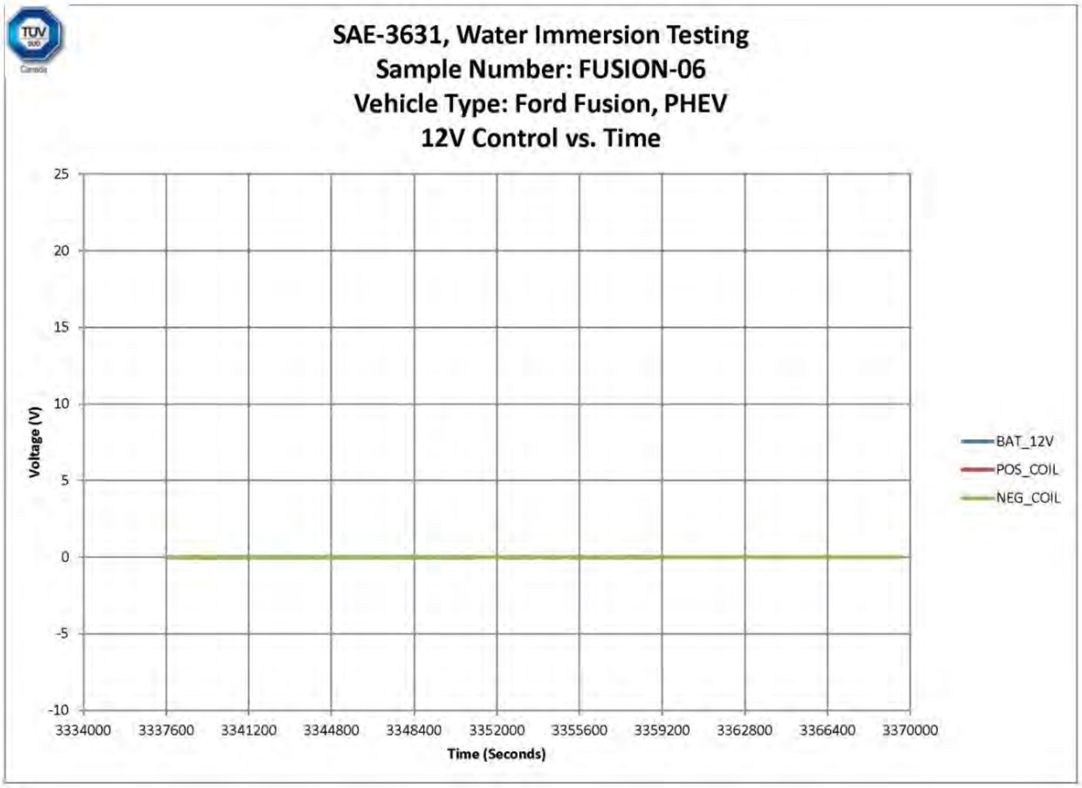


Figure 116 - Ford Fusion-2 PHEV 12 V control voltage for the last 10 hours of testing.

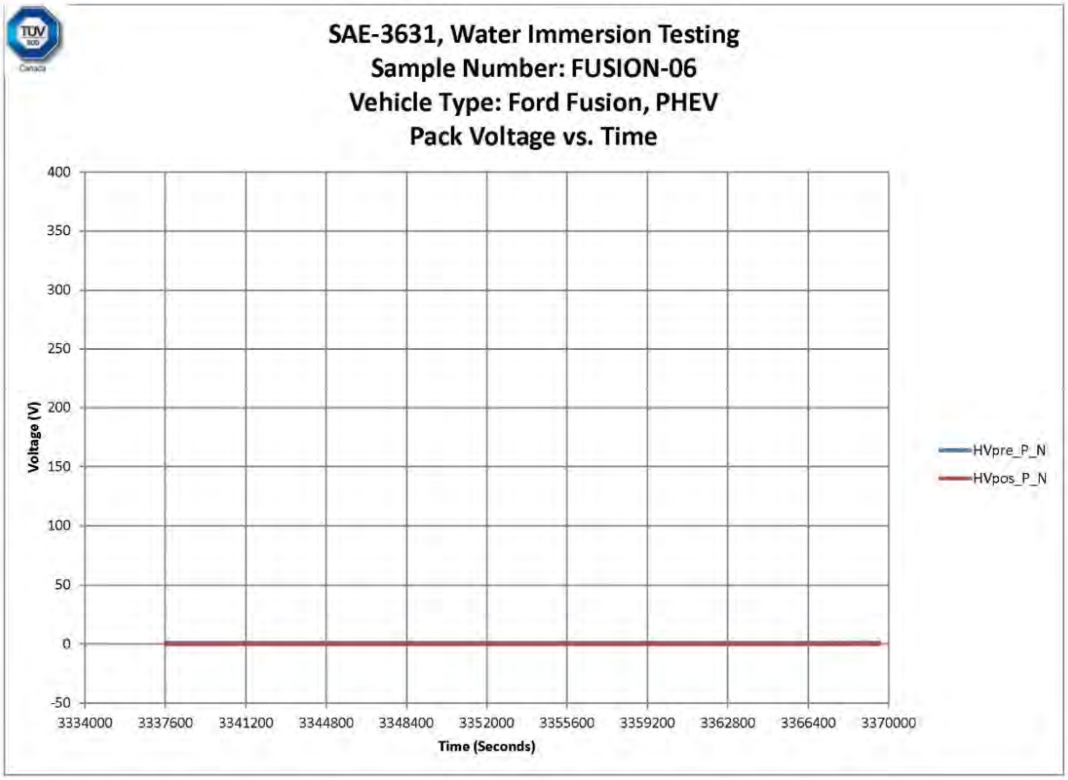


Figure 117 - Ford Fusion-2 PHEV RESS voltage for the last 10 hours of testing.

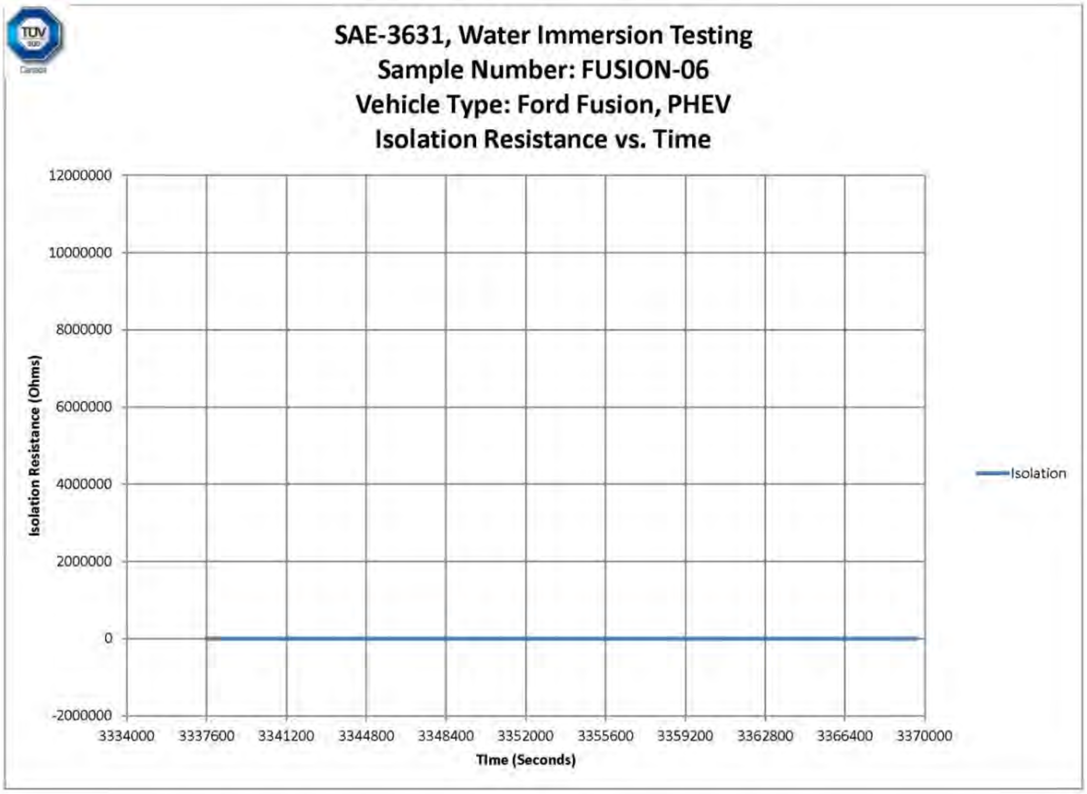


Figure 118 - Ford Fusion-2 PHEV isolation resistance for the last 10 hours of testing.

8.2.6.4 Seawater Analysis Results

Seawater samples were taken before and after immersion. They were measured on-site for pH, density and conductivity; the results are summarized in Table 35. Table 36 shows the VOCs that were above the reportable detection limit, as determined from Maxxam Analytics, Inc. Note that the samples were also analyzed for other VOCs that were below the reportable limit. Table 37 shows the total oil and grease content from the samples.

Table 35 - Ford Fusion-2 PHEV Conductivity, Salinity, Density, and pH

Time	Conductivity (mS/cm)	Salinity (wt%)	Density (g/cm³)	pH
Pre-immersion	45.2	2.63	1.020	7.2
Post-immersion	45.6	2.67	1.020	7.3

Table 36 - Ford Fusion-2 PHEV VOCs above Reportable Detection Limit

Volatile Organics	Units	Pre-Immersion	Post-Immersion	RDL*
Benzene	µg/L	<0.50	1.4	0.50

*RDL=Reportable Detection Limit

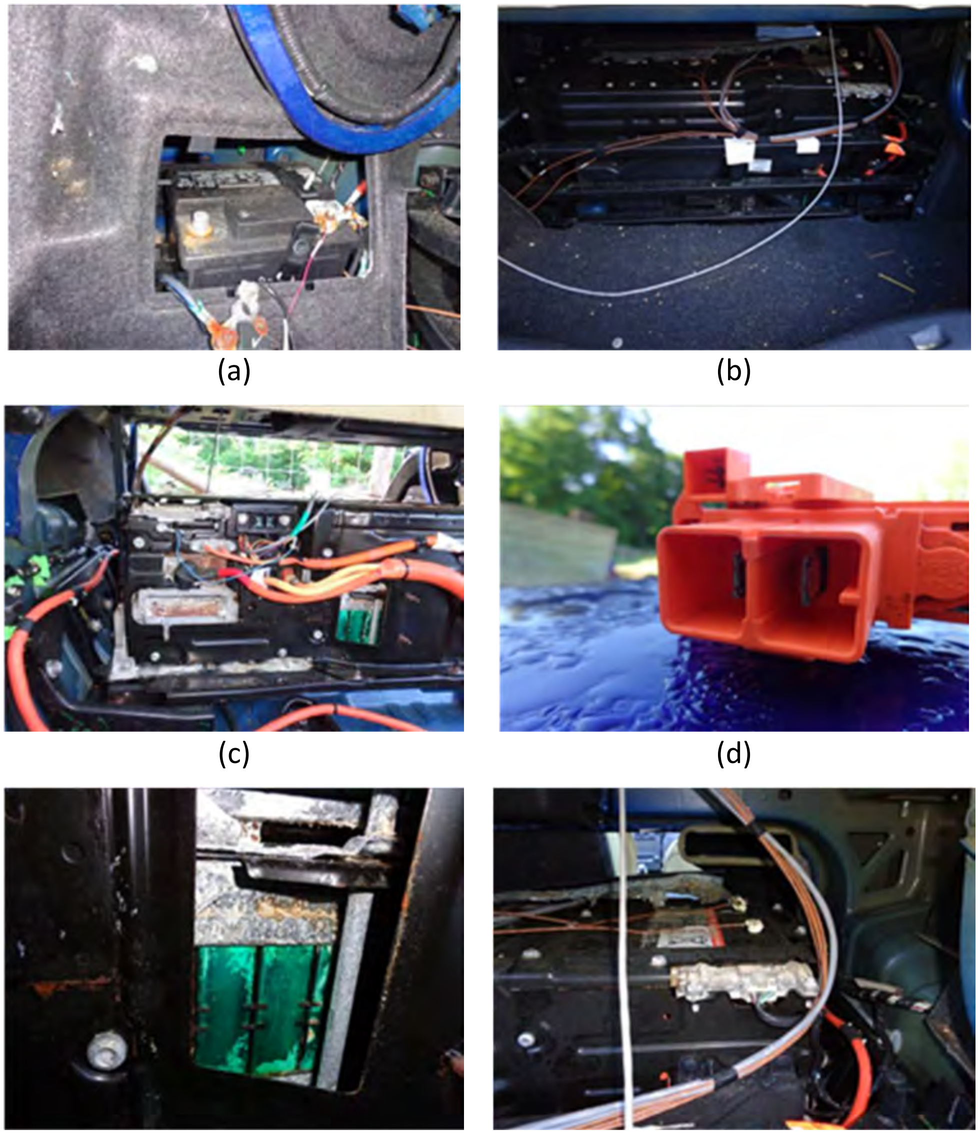
Table 37 - Ford Fusion-2 PHEV Total Oil and Grease Content

Petroleum Hydrocarbons	Units	Pre-Immersion	Post-Immersion	RDL*
Total oil and grease	mg/L	<0.50	0.60	0.50

*RDL=Reportable Detection Limit

8.2.6.5 Post-Mortem Analysis

Figure 119 shows various vehicle components after testing was complete. Post-mortem analysis did not indicate any evidence of behaviors that could result in an HSL higher than 4 (i.e., no anticipated fires, ruptures, or explosions) based on EUCAR standards. Although the temperature increased inside the RESS during immersion from -5°C to 21°C, it quickly declined to ambient levels at the end of immersion and followed the diurnal ambient values until the end of the test. Additionally, the water immersion caused the RESS voltage to drop from 328 V to 8 V within the first hour of immersion; it then went down to 0 V until the end of the test. Therefore, no post-mortem analysis was conducted on the battery pack.



(a) (b)

(c) (d)

(e) (f)

Figure 119 - Ford Fusion-2 PHEV post-test vehicle condition: a) 12 V battery, b) interior trunk, c) HV charging cables, d) manual service disconnect, e) cell close-up, and f) voltage sense control unit.

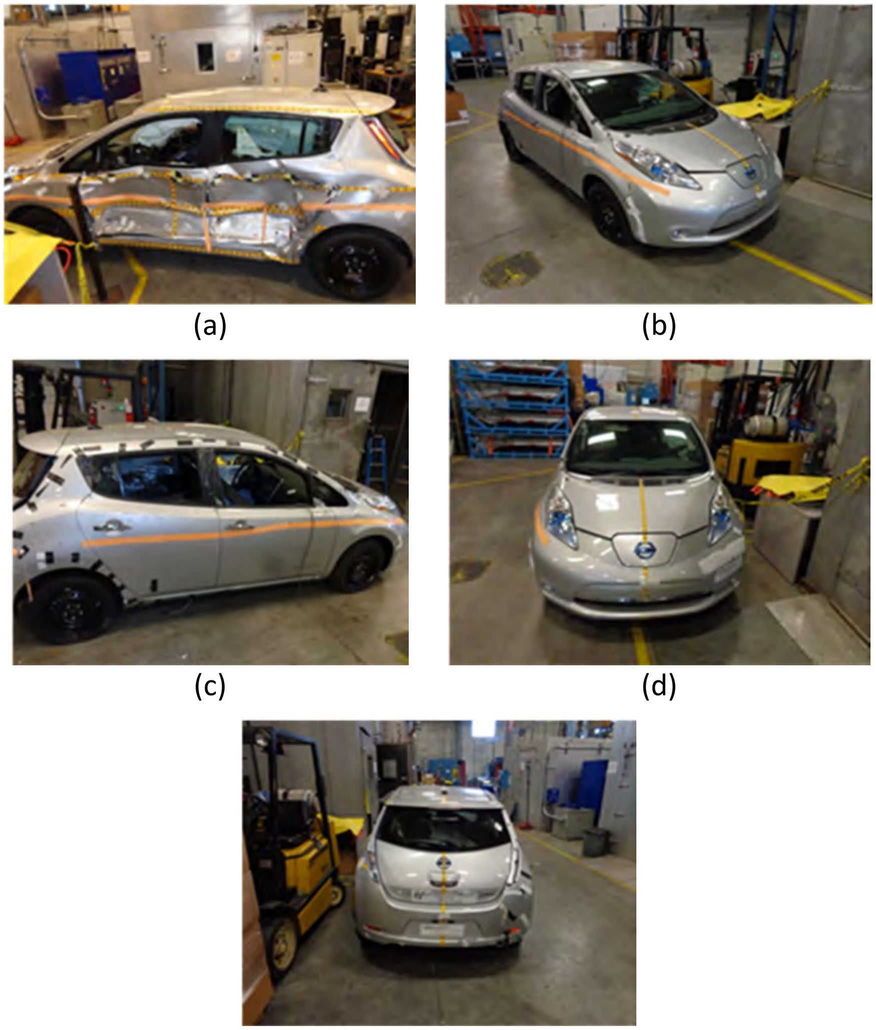
8.3 Water Immersion in Summer Conditions

8.3.1 Nissan Leaf EV

The Nissan Leaf (Leaf-3) was a new production EV previously used for side impact testing, see Table 38. Figure 120 shows the as-received vehicle from multiple angles. Figure 121 shows the vehicle in its immersion tank.

Table 38 - Nissan Leaf-3 EV Details

Vehicle Class	Passenger Car
Manufacturer	Nissan
Make	Leaf
Model	Unknown (S/SV/SL)
Date of Manufacture	Jan-2013
VIN	1N4AZ0CP5DC400553
Condition	Damaged (side impact)
Vehicle Type	EV



(a) (b) (c) (d) (e)

Figure 120 - Nissan Leaf-3 EV initial vehicle condition: a) left view, b) front ¾ view, c) right view, d) front view, and e) rear view.

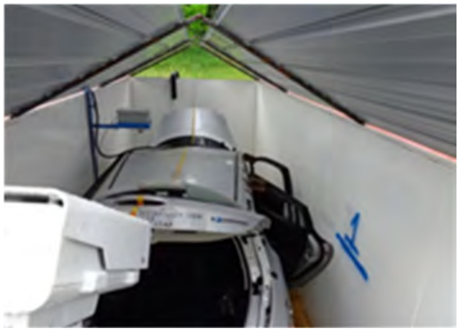


Figure 121 - Nissan Leaf-3 EV in its immersion container.

8.3.1.1 Sample Preparation

As received, the vehicle was damaged from side impact testing and not operational due to a missing MSD. An MSD was purchased and installed. The 12 V battery was also restored to health. After it was charged, the vehicle would power on and shift gears. However, it would not further operate since the RESS was at 0% SOC and no charger was provided to charge the pack. The RESS was visually inspected and no damage from the side impact test was observed. All the loose interior parts were tagged and removed from the cabin.

For HV and isolation measurements, the RESS was removed from the vehicle (see Figure 122). The perimeter bolts were removed and the silicone seal was cut to remove the lid. Isolation measurements were taken and HV measurement wires were tightly bolted to the contactor terminals. The coil sense wires were soldered into place. The RESS was then sealed to prevent water intrusion through the sense leads exiting the pack (see Section 8.1.2). Thermocouple wires, HV measurement wires, and coil wires were passed through a bolt hole on the RESS case, then epoxy was applied to hold the wires in place followed by silicone caulk to seal the hole. Silicone caulk was then replaced on the perimeter of the case lid; the case lid was bolted back onto the RESS and re-installed into the vehicle. Voltage sense wires were then attached to the positive and negative terminals of the 12 V battery (LV). All thermocouples, gas sense wires, and voltage sense wires were then wired into the DAQ system and the vehicle was loaded into the immersion container.

A total of eight thermocouples were installed as specified in test procedure (see Section 6.5.1.13), including the RESS enclosure, near contactors, the control unit, and the 12 V battery. Thermocouple locations are provided in Table 39 and shown in Figure 123. The thermocouples were held in position using epoxy adhesive.

Three gas sensors were also mounted above the driver window (see Section 7.2).

Table 39 - Nissan Leaf-3 EV Thermocouple Placement

Number	**Location**
TC1, TC2	Contactor
TC3, TC4, TC5, TC6	RESS enclosure
TC7	Control module
TC8	12 V battery

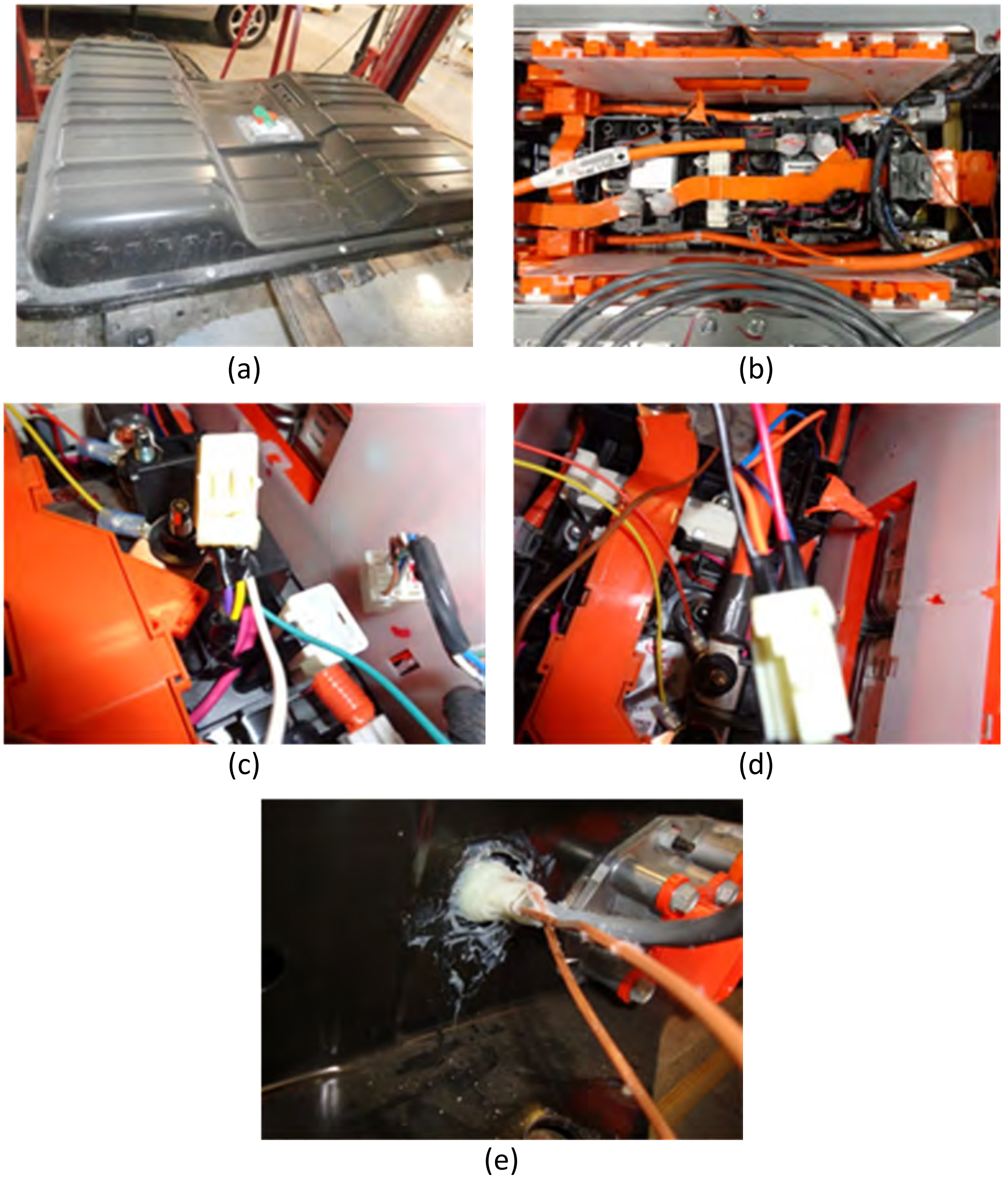
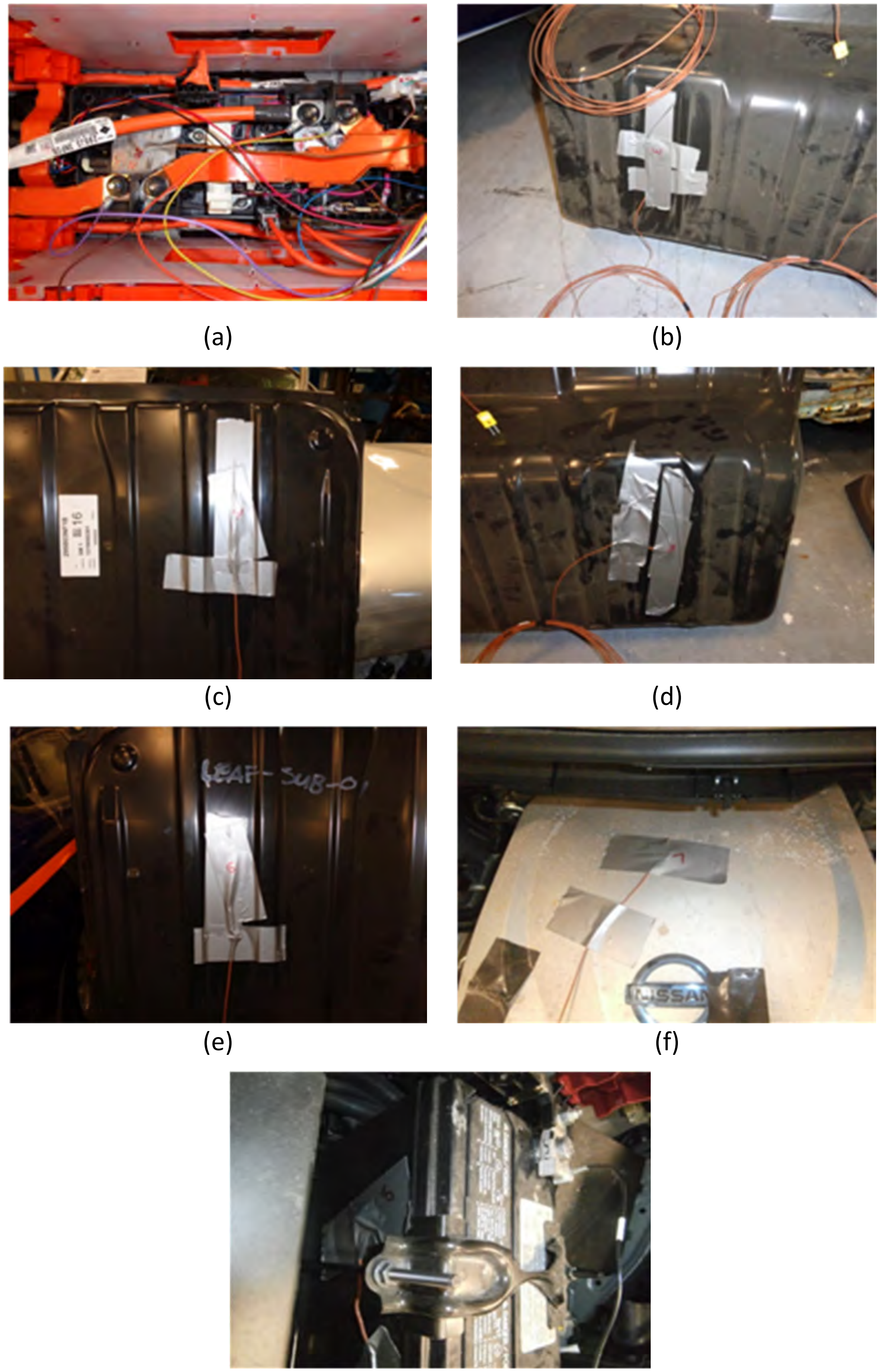

(a) (b) (c) (d) (e)

Figure 122 - Nissan Leaf-3 EV HV connections: a) RESS removed from vehicle, b) contactor assembly, c) coil wires, d) second image of coil wires, and d) wires sealed at case wall.



(a) (b)

(c) (d)

(e) (f)

(g)

Figure 123 - Nissan Leaf-3 EV HV thermocouple placement: a) TC1 and TC2 on the contactor, b) TC3 on the RESS case, c) TC4 on the RESS case, d) TC5 on the RESS case, e) TC6 on the RESS case, f) TC7 on the control module, and g) TC8 on the 12 V battery.

8.3.1.2 Test Conditions

Testing was performed outdoors in ambient temperatures of approximately 13°C. There was precipitation on the day the vehicle was immersed. The vehicle remained in the immersion container during the post-extraction observation period.

8.3.1.3 Immersion Test Results

The test event log is summarized in Table 40. Figures 124 through 129 show measured data for the initial 9 hours of the test as follows:

- Figure 124 - Temperature profile for the first 9 hours of testing
- Figure 125 - Gas sensing current for the first 9 hours of testing
- Figure 126 - 12 V control voltage for the first 9 hours of testing
- Figure 127 - Electrode to chassis voltage for the first 9 hours of testing
- Figure 128 - RESS voltage for the first 9 hours of testing
- Figure 129 - Isolation resistance for the first 9 hours of testing

Figures 130 through 134 show measured data for the final 10 hours of the test as follows:

- Figure 130 - Temperature profile for the last 10 hours of testing
- Figure 131 - Gas sensing current for the last 10 hours of testing
- Figure 132 - 12 V control voltage for the last 10 hours of testing
- Figure 133 - RESS voltage for the last 10 hours of testing
- Figure 134 - Isolation resistance for the last 10 hours of testing

Table 40 - Nissan Leaf-3 EV Test Event Log

Event	**Time**	**Temperature**	**Primary Source**	**Secondary Source**
Start of immersion	2:45 PM		Test field notes	
Start of self-heating in observation period (if any)	5:10 PM		graphs	Test Field Notes
Time at first flames	N/A		video	IR Camera
Highest recorded HV battery temperature at time of first flames		N/A	graphs	
Time of first bang, explosion or pressure wave captured on video	N/A		video	
Time of first smoke/gases/vapor	N/A		video	IR camera
Time of RESS case maximum temperature	7:17 PM		graphs	
Maximum RESS case temperature		28°C	logged data	
Time when RESS pre-contactor voltage is more than $V_{initial} \pm 2\%$	4:24 PM		graphs	logged data
Time when the LV battery voltage is more than $V_{initial} \pm 2\%$	N/A		graphs	logged data
Time to first measurement of sustained (>110% of initial reading) CH_4 presence (>5 s)	N/A		logged data	
Time to first measurement of sustained (>110% of initial reading) CL_2 presence (>5 s)	N/A		logged data	
Time to first measurement of sustained (>110% of initial reading) H_2 presence (>5 s)	N/A		logged data	

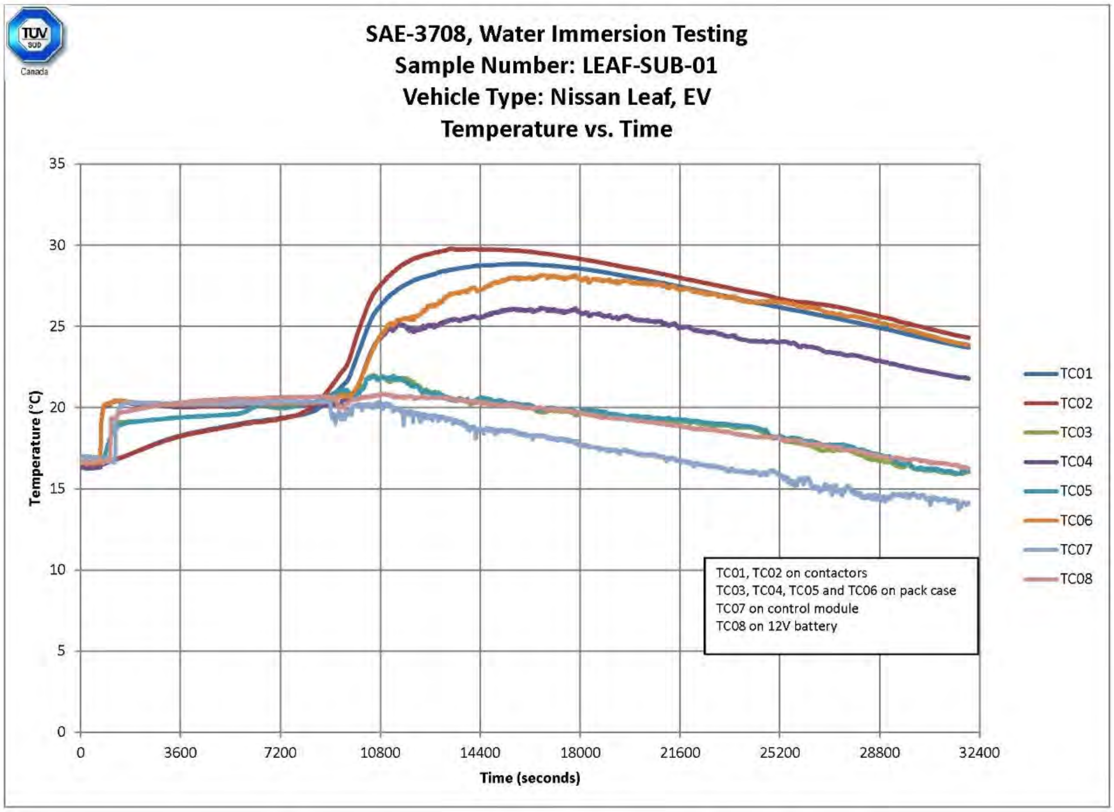


Figure 124 - Nissan Leaf-3 EV temperature profile for the first 9 hours of testing.

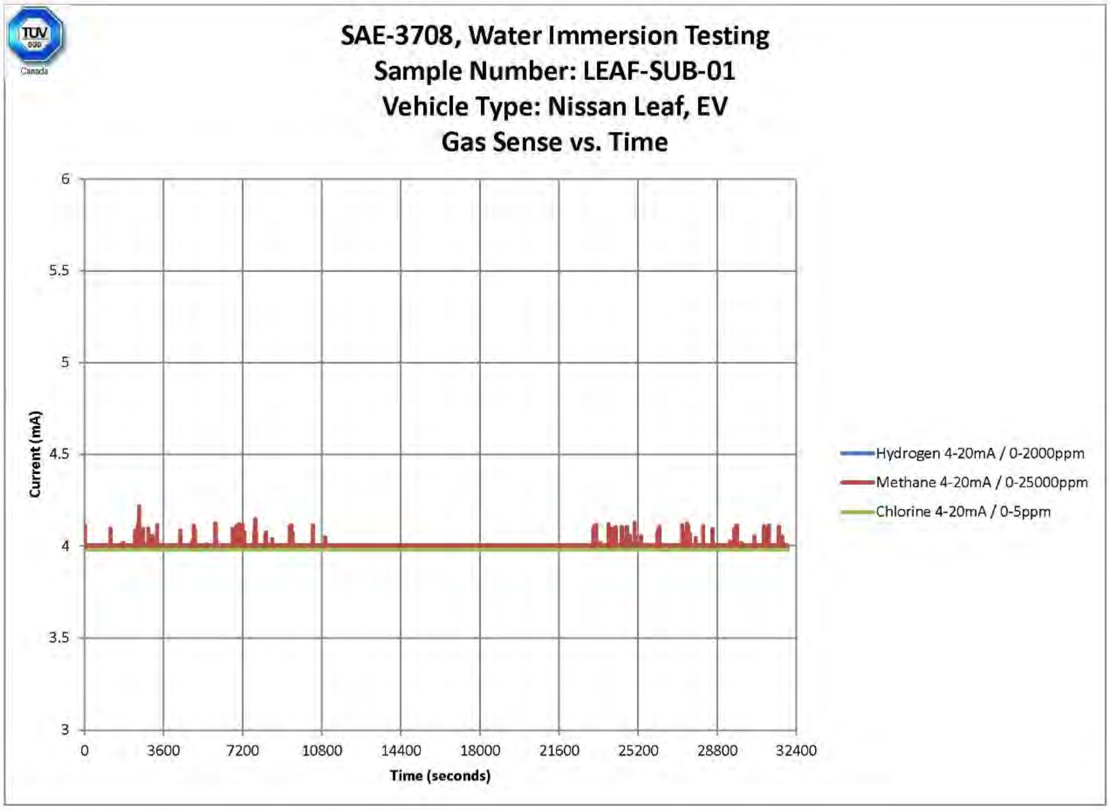


Figure 125 - Nissan Leaf-3 EV gas sensing current for the first 9 hours of testing.

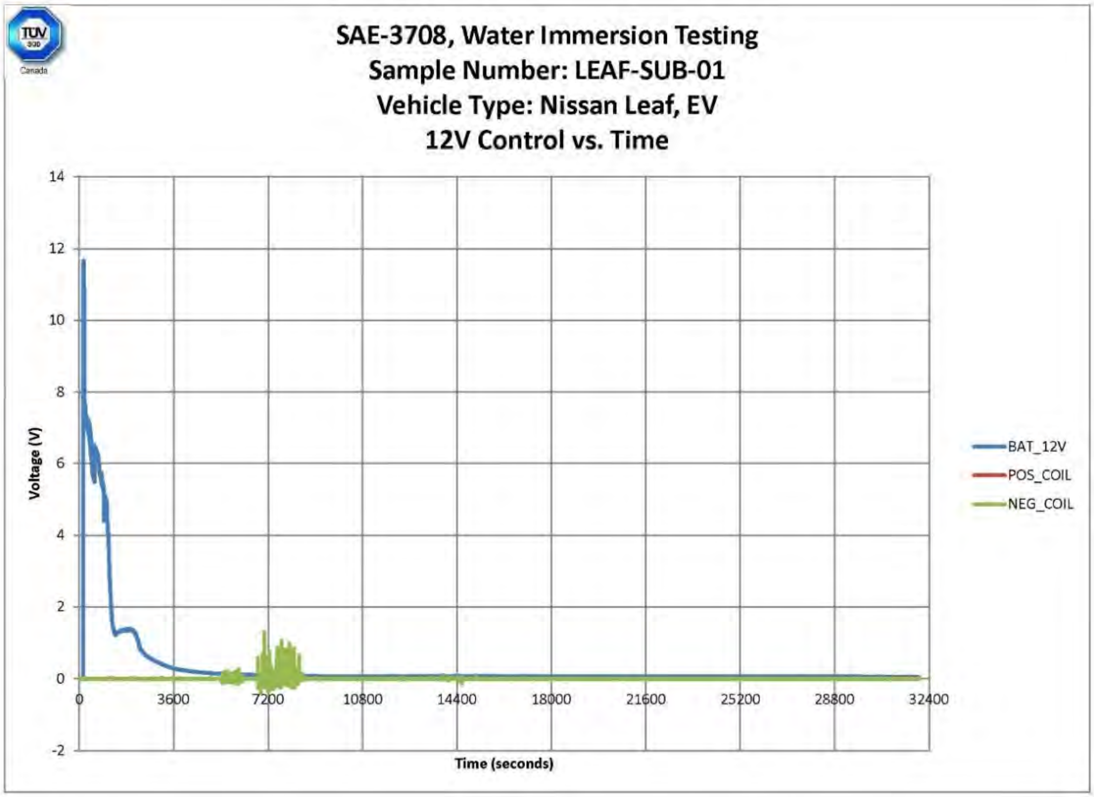


Figure 126 - Nissan Leaf-3 EV 12 V control voltage for the first 9 hours of testing.

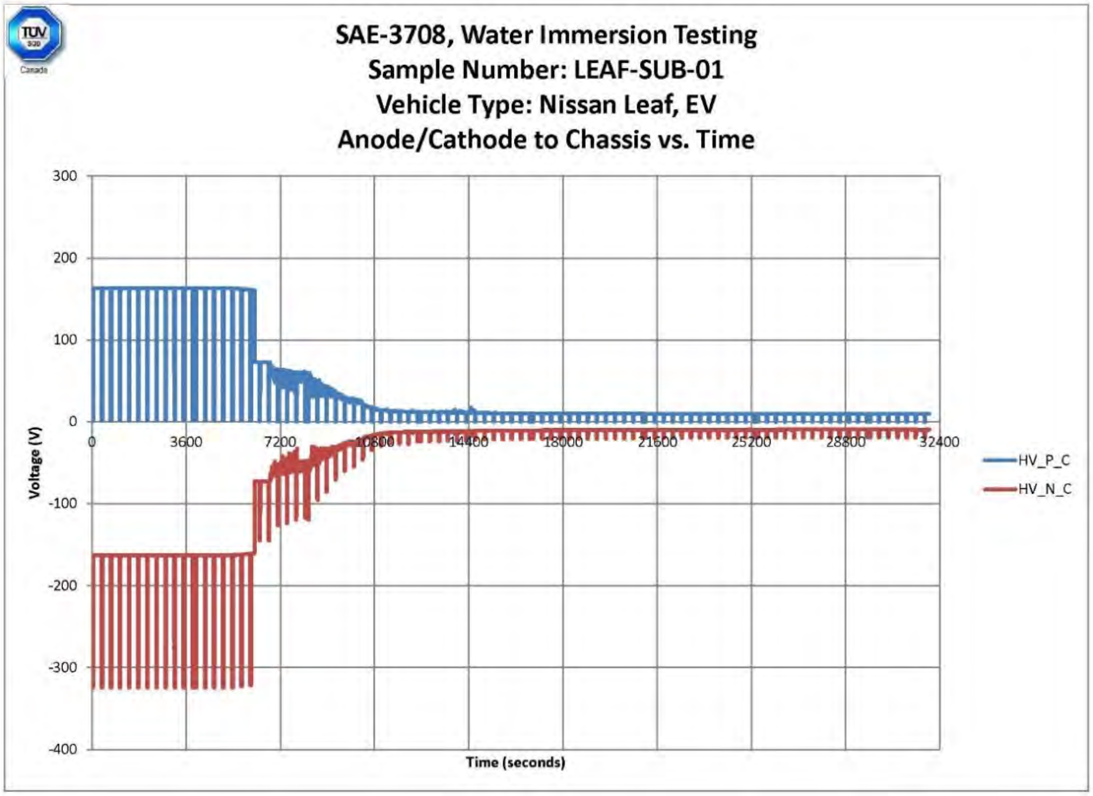


Figure 127 - Nissan Leaf-3 EV electrode to chassis voltage for the first 9 hours of testing.

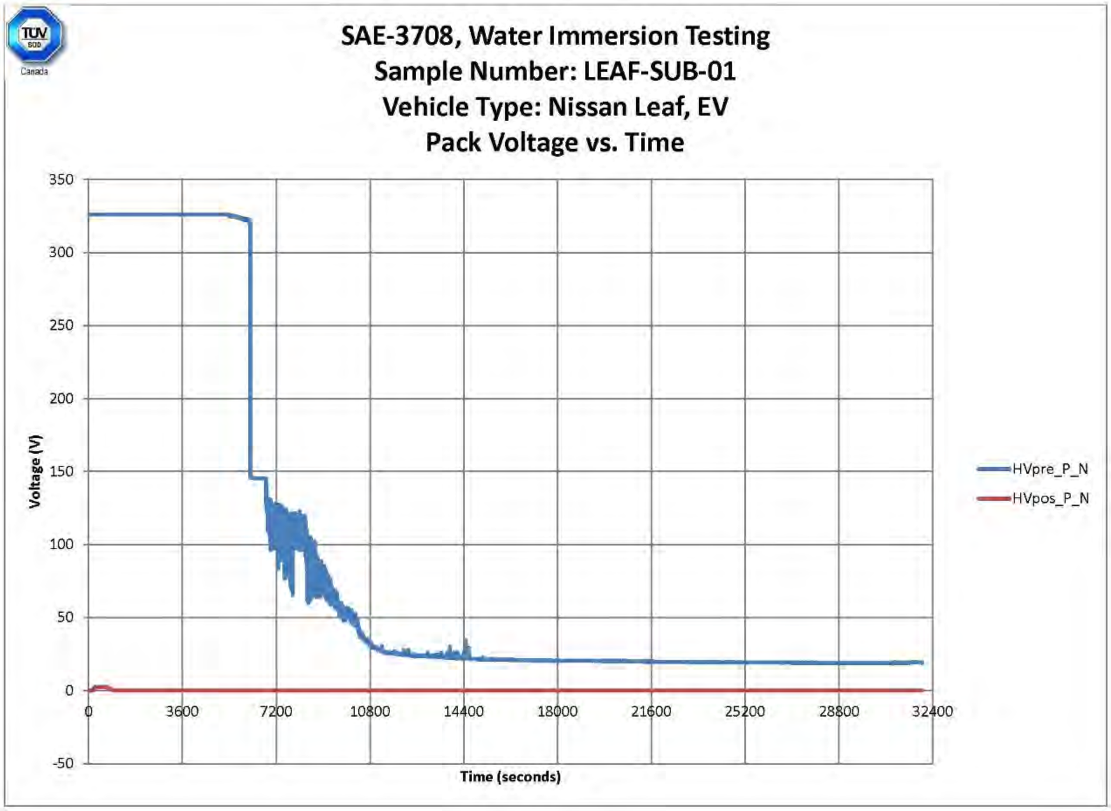


Figure 128 - Nissan Leaf-3 EV RESS voltage for the first 9 hours of testing.

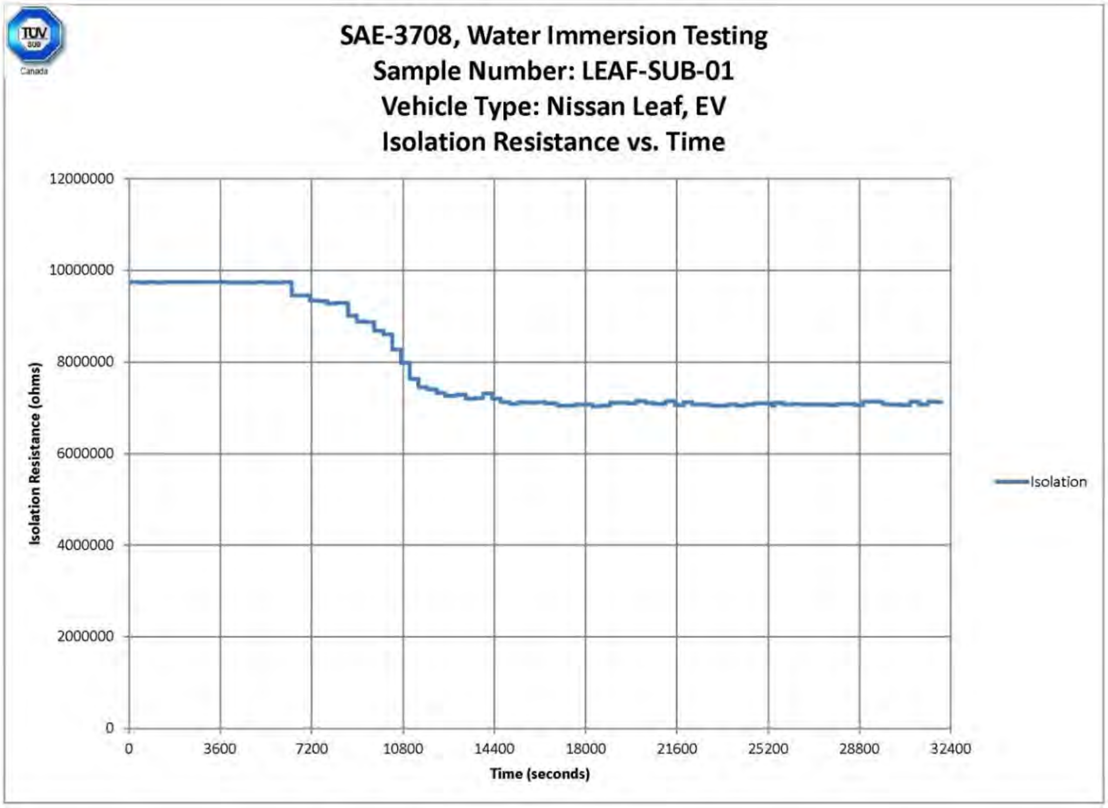


Figure 129 - Nissan Leaf-3 EV isolation resistance for the first 9 hours of testing.

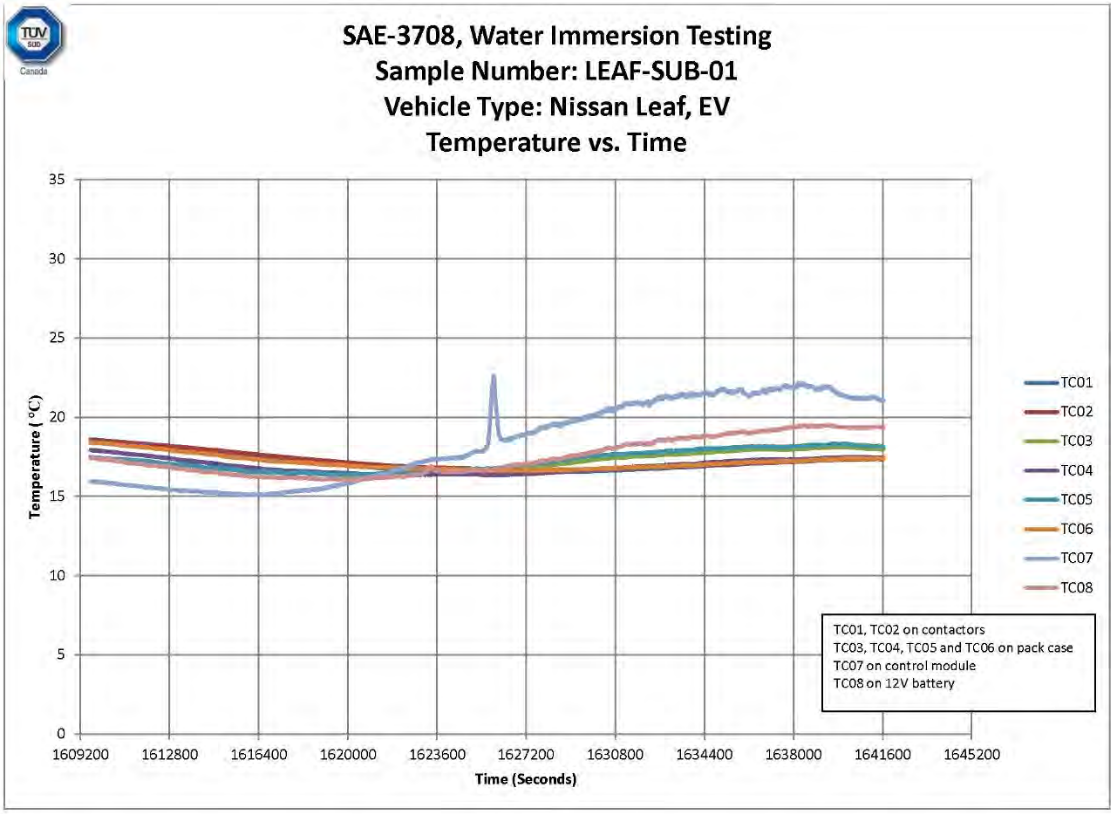


Figure 130 - Nissan Leaf-3 EV temperature profile for the last 10 hours of testing.

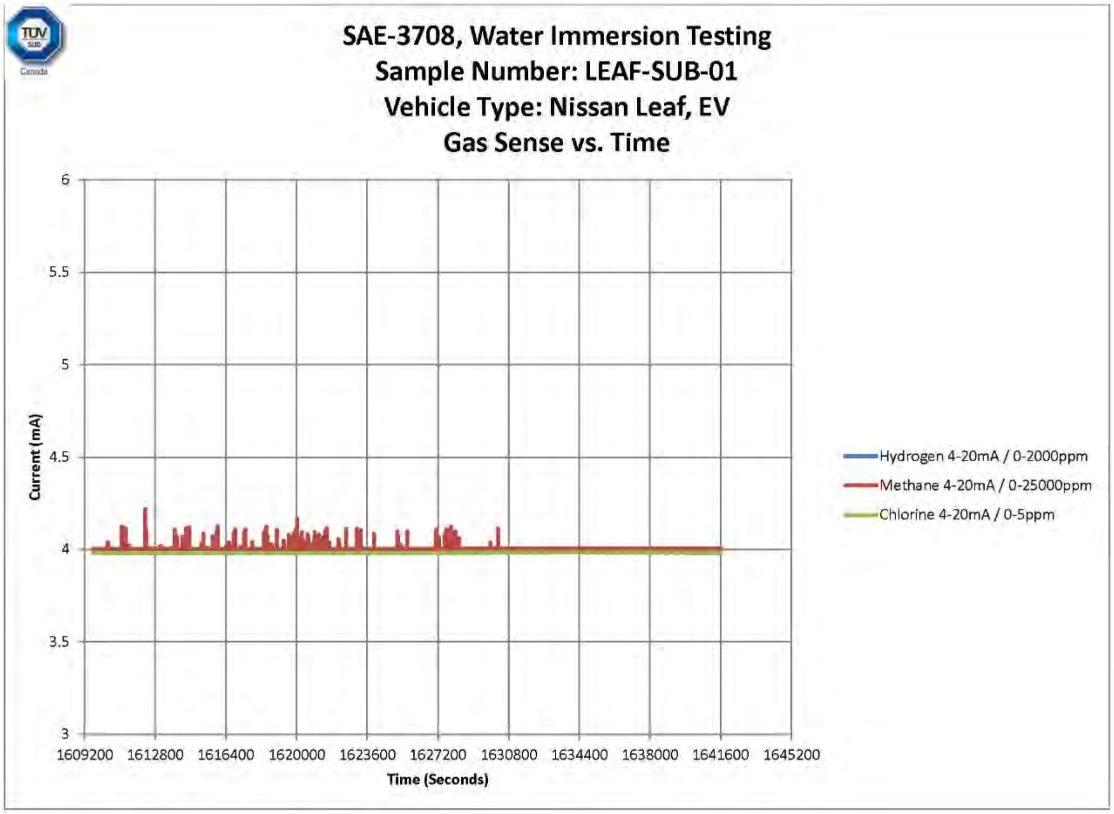


Figure 131 - Nissan Leaf-3 EV gas sensing current for the last 10 hours of testing.

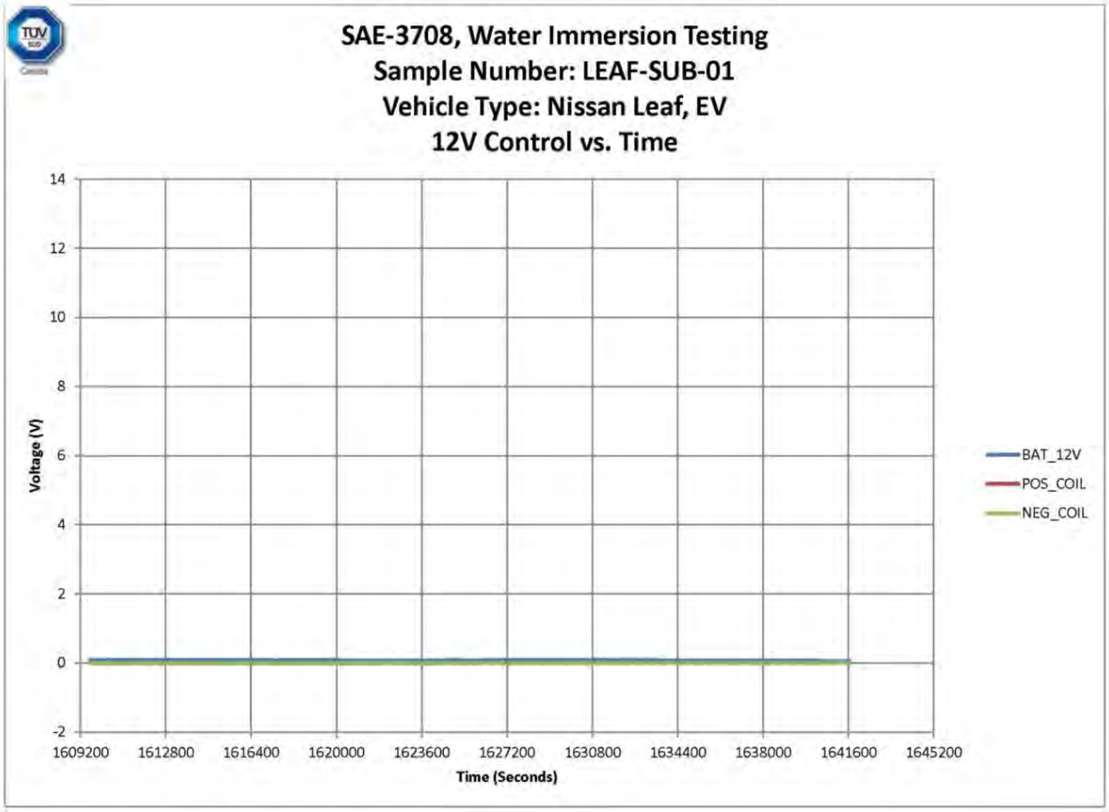


Figure 132 - Nissan Leaf-3 EV 12 V control voltage for the last 10 hours of testing.

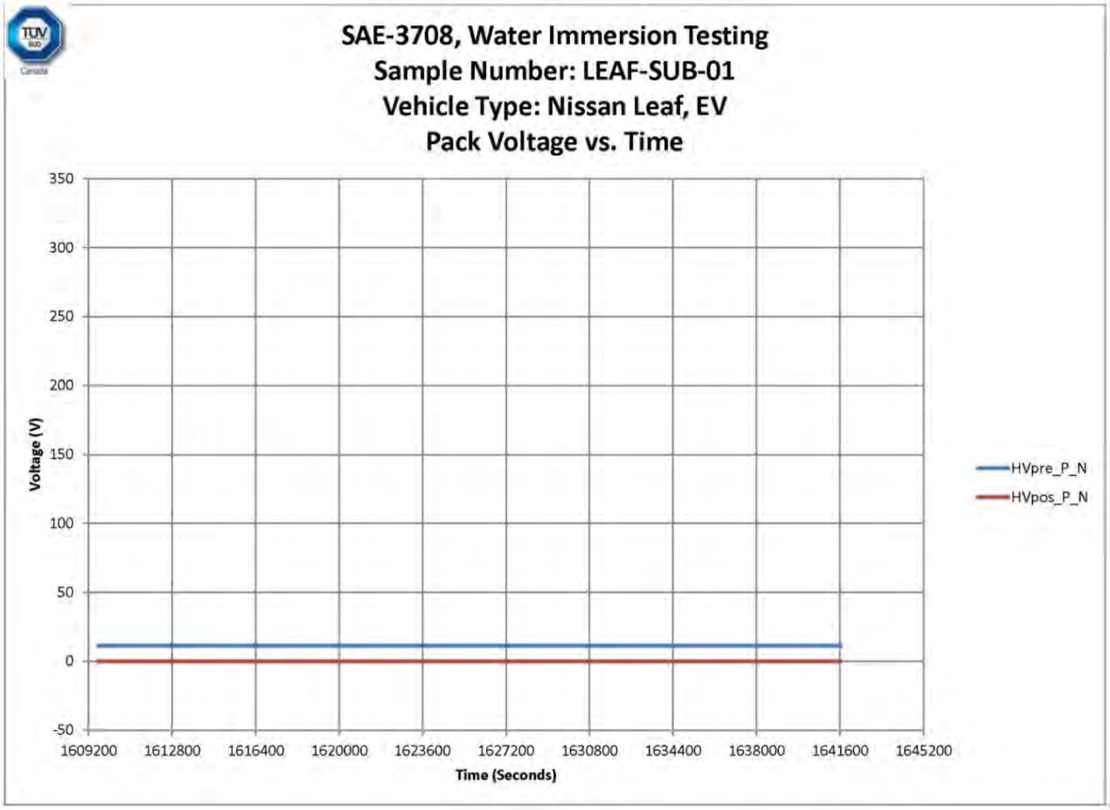


Figure 133 - Nissan Leaf-3 EV RESS voltage for the last 10 hours of testing.

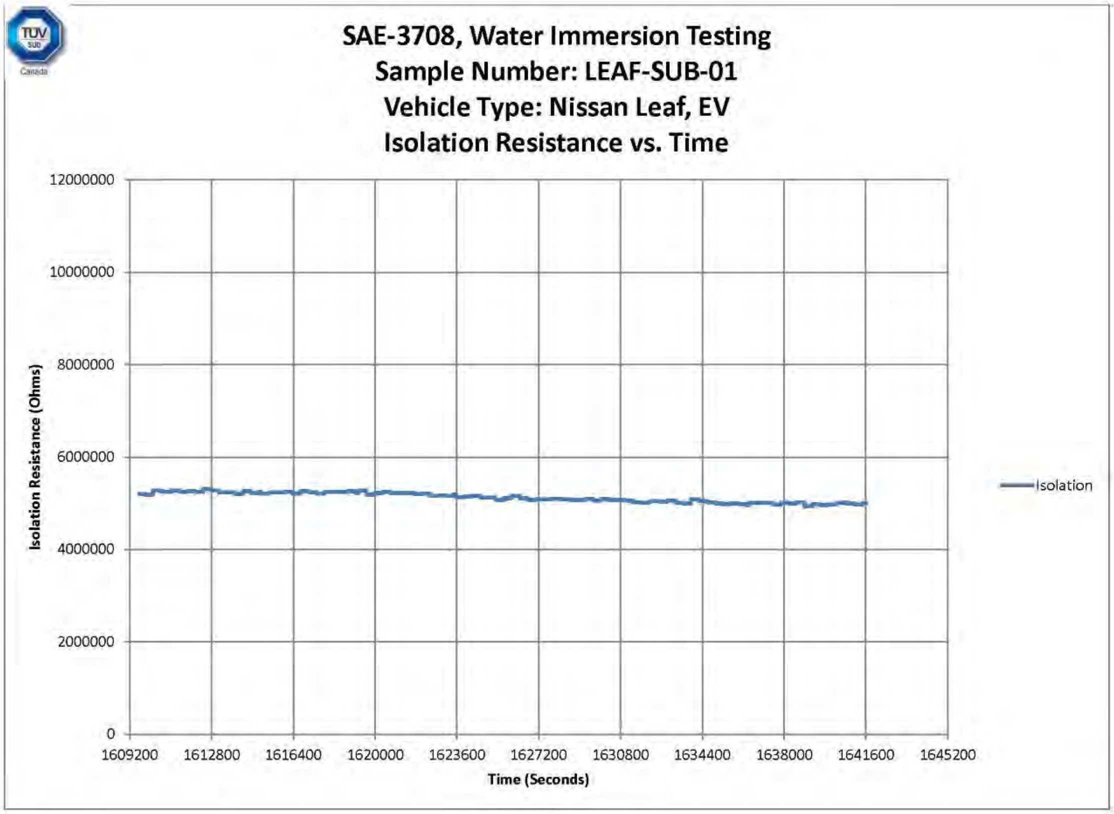


Figure 134 - Nissan Leaf-3 EV isolation resistance for the last 10 hours of testing.

8.3.1.4 Seawater Analysis Results

Seawater samples were taken before and after immersion. They were measured on-site for pH, density and conductivity; the results are summarized in Table 41. Table 42 shows the VOCs that were above the reportable detection limit, as determined from Maxxam Analytics, Inc. Note that the samples were also analyzed for other VOCs that were below the reportable limit. Table 43 shows the total oil and grease content from the samples.

Table 41 - Nissan Leaf-3 EV Conductivity, Salinity, Density, and pH

Time	Conductivity (mS/cm)	Salinity (wt%)	Density (g/cm³)	pH
Pre-immersion	57.3	3.51	1.026	7.4
Post-immersion	56.4	3.46	1.025	7.3

Table 42 - Nissan Leaf-3 EV VOCs above Reportable Detection Limit

Volatile Organics	Units	Pre-Immersion	Post-Immersion	RDL*
Acetone (2-Propanone)	µg/L	12	12	10

*RDL=Reportable Detection Limit

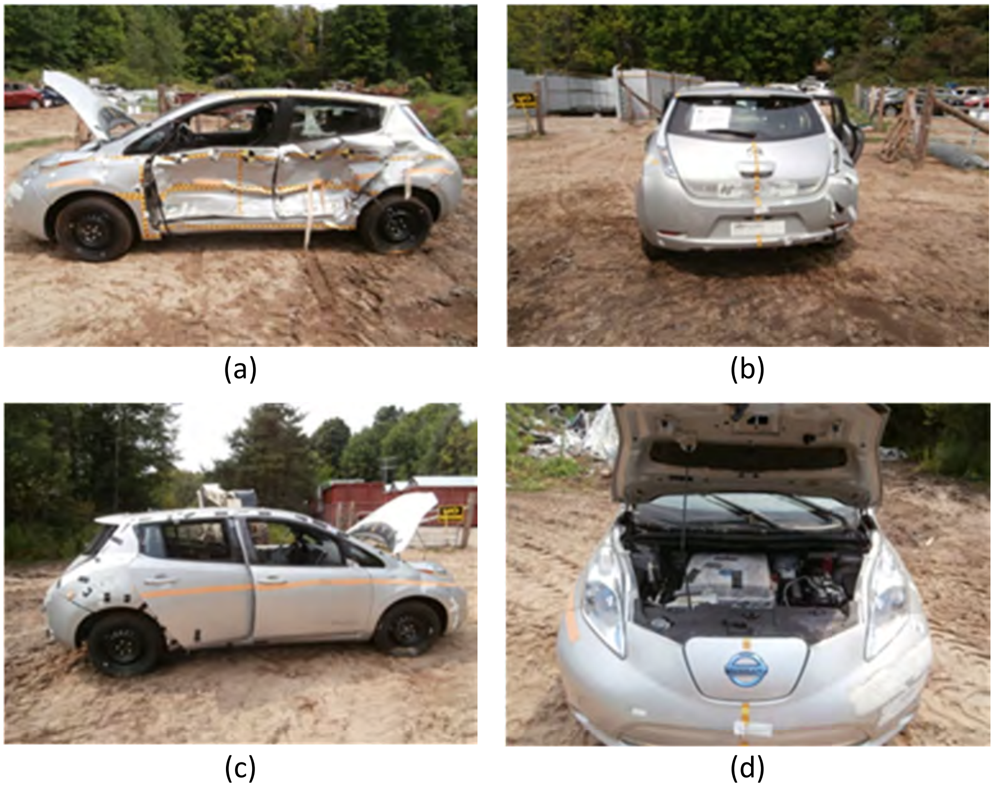
Table 43 - Nissan Leaf-3 EV Total Oil and Grease Content

Petroleum Hydrocarbons	Units	Pre-Immersion	Post-Immersion	RDL
Total oil and grease	mg/L	ND*	ND*	0.50

*ND=Not Detected

8.3.1.5 Post-Mortem Analysis

Figure 135 shows the vehicle from multiple angles after testing was complete. Post-mortem analysis did not indicate any evidence of behaviors that could result in an HSL higher than 4 (i.e., no anticipated fires, ruptures, or explosions) based on EUCAR standards. Although the RESS temperature increased during immersion, it quickly declined to ambient levels after 4 hours and followed the diurnal ambient values until the end of the test. In addition, the water immersion caused the RESS voltage to drop from 326 V to 24.5 V within the first hour of the test and was at 11.2 V at end of test. Therefore, no post-mortem analysis was conducted on the battery pack.


(a) (b)

(c) (d)

Figure 135 - Nissan Leaf-3 EV post-test vehicle condition: a) driver side view, b) rear view, c) passenger side view, and d) front side view with hood up.

8.3.2 Mitsubishi iMiev EV

The Mitsubishi iMiev was a new production EV previously used for side impact testing, see Table 44. Figure 136 shows the as-received vehicle from multiple angles. Figure 137 shows the vehicle in its immersion tank.

Table 44 - Mitsubishi iMiev EV Details

Vehicle Class	Passenger Car
Manufacturer	Mitsubishi
Make	iMiev
Model	Unknown
Date of Manufacture	Dec-2011
VIN	JA3215H17CU016563
Condition	Damaged (side impact)
Vehicle Type	EV

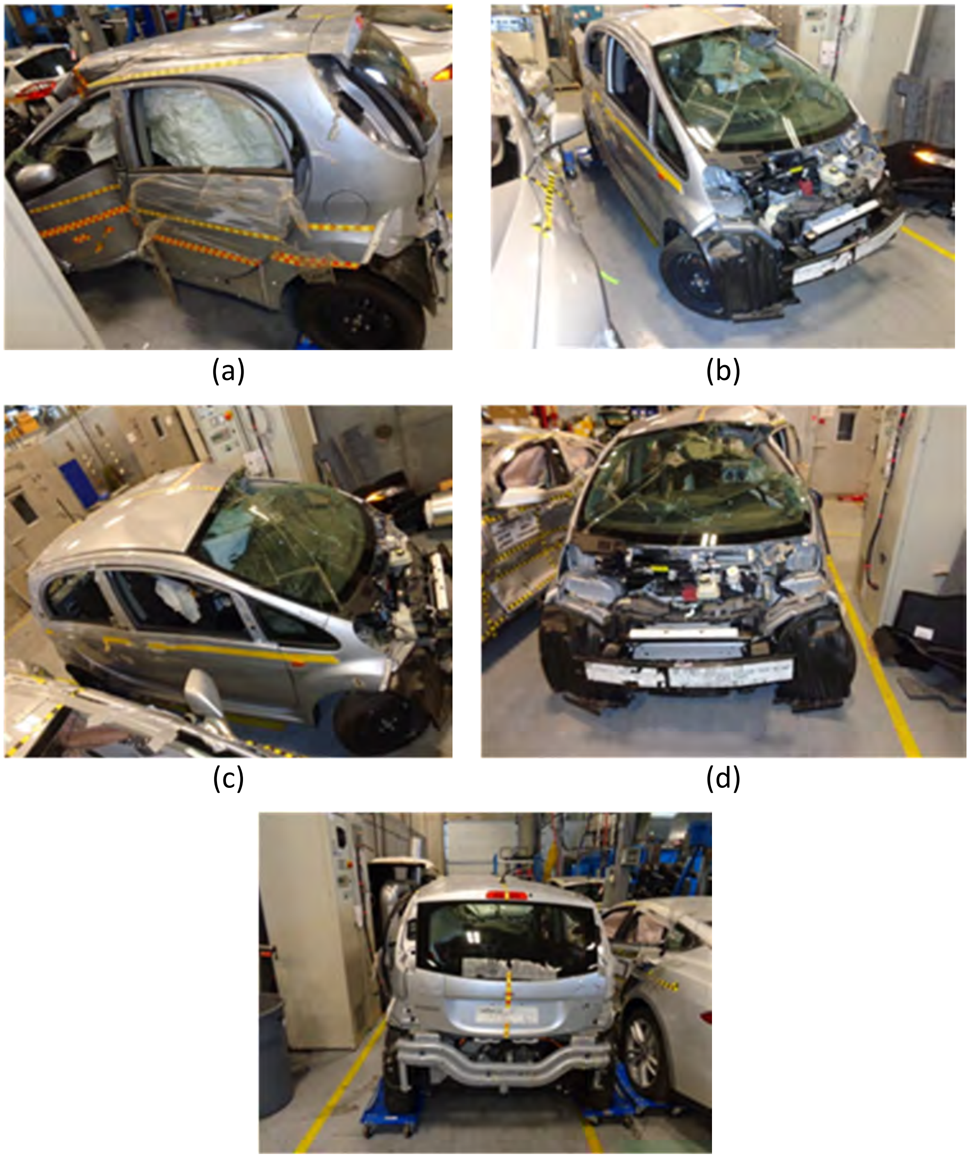

(a) (b) (c) (d) (e)

Figure 136 - Mitsubishi iMiev EV initial vehicle condition: a) left view, b) front ¾ view, c) right view, d) front view, and e) rear view.

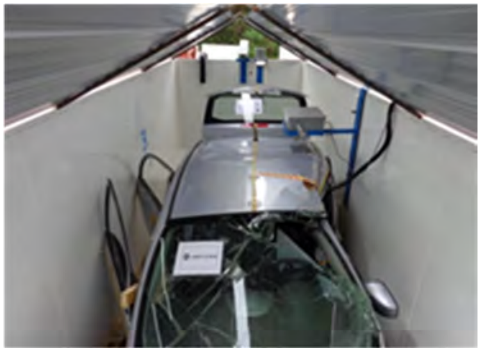


Figure 137 - Mitsubishi iMiev EV in its immersion container.

8.3.2.1 Sample Preparation

As received, the vehicle was damaged from side impact testing and not operational due to a missing MSD. An MSD was purchased and installed. After the 12 V battery was replaced, the vehicle would power on. However, no charger was provided to charge the pack. The RESS was visually inspected and it was noted that the lid was damaged from the side impact test. All the loose interior parts were tagged and removed from the cabin.

For HV and isolation measurements, the RESS was removed from the vehicle (see Figure 138). The perimeter bolts and lid were then removed. Isolation measurements were taken and HV measurement wires were tightly bolted to the contactor terminals. The coil sense wires were soldered into place. The RESS was sealed to prevent water intrusion through the sense leads exiting the pack (see Section 8.1.2). Thermocouple wires, HV measurement wires, and coil wires were passed through a hole on the RESS case and epoxy was then applied to hold the wires in place followed by silicone caulk to seal the hole. The case lid was bolted back on and the RESS was re-installed into the vehicle. Voltage sense wires were then attached to the positive and negative terminals of the 12 V battery (LV). All thermocouples, gas sense wires, and voltage sense wires were wired into the DAQ system and the vehicle was loaded into the immersion container.

A total of eight thermocouples were installed as specified in test procedure (see Section 6.5.1.13), including the RESS enclosure, near contactors, the control unit, and the 12 V battery. Thermocouple locations are provided in Table 45 and shown in Figure 139. The thermocouples were held in position using epoxy adhesive.

Three gas sensors were also mounted above the driver window (see Section 7.2).

Table 45 - Mitsubishi iMiev EV Thermocouple Placement

Number	Location
TC1, TC2	Contactor
TC3, TC4, TC5, TC6	RESS enclosure
TC7	Control module
TC8	12 V battery

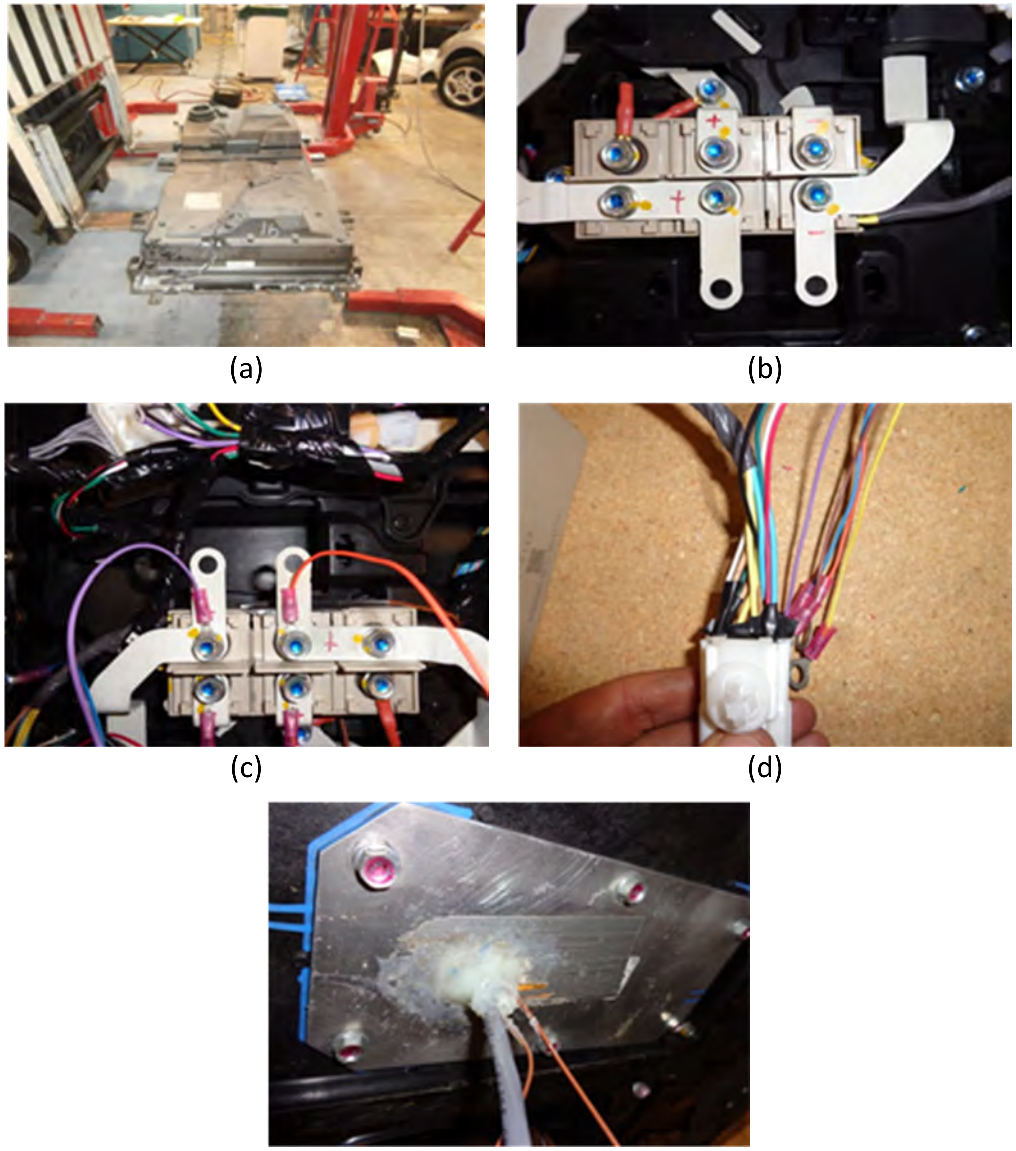
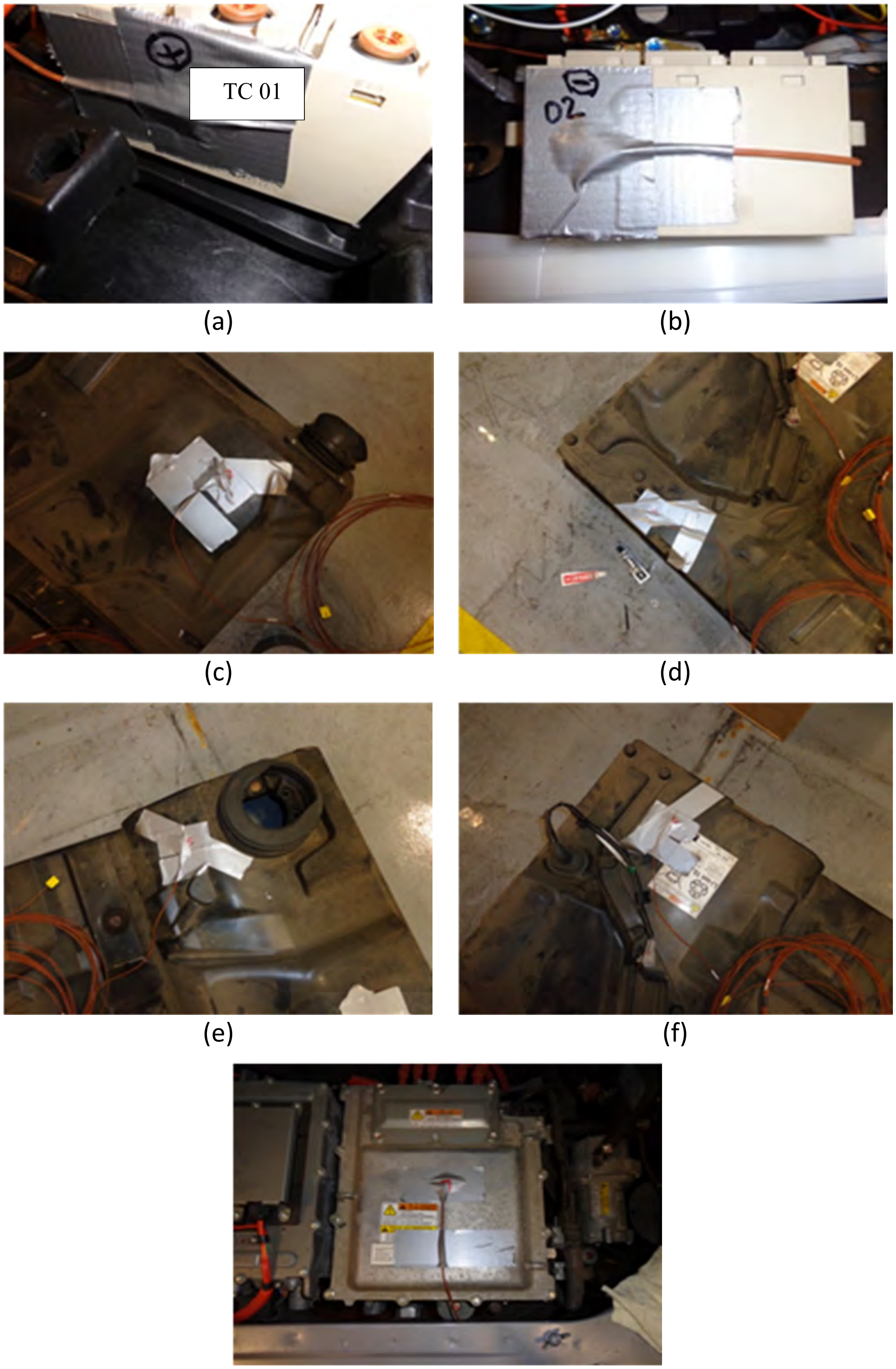

(a)
(b)
(c)
(d)
(e)

Figure 138 - Mitsubishi iMiev EV HV connections: a) RESS removed from vehicle, b) contactor assembly, c) measurement wires, d) coil wires, and e) wires sealed at case wall.



(a) (b) (c) (d) (e) (f) (g)

Figure 139 - Mitsubishi iMiev EV HV thermocouple placement: a) TC1 on the contactor, b) TC2 on the contactor, c) TC3 on the RESS case, d) TC4 on the RESS case, e) TC5 on the RESS case f) TC6 on the RESS case, and g) TC7 on the control module.

8.3.2.2 Test Conditions

Testing was performed outdoors in ambient temperatures of approximately 13°C. There was precipitation on the day the vehicle was immersed. The vehicle remained in the immersion container during the post-extraction observation period.

8.3.2.3 Immersion Test Results

The test event log is summarized in Table 46. Figures 140 through 145 show measured data for the initial 9 hours of the test as follows:

- Figure 140 - Temperature profile for the first 9 hours of testing
- Figure 141 - Gas sensing current for the first 9 hours of testing
- Figure 142 - 12 V control voltage for the first 9 hours of testing
- Figure 143 - Electrode to chassis voltage for the first 9 hours of testing
- Figure 144 - RESS voltage for the first 9 hours of testing
- Figure 145 - Isolation resistance for the first 9 hours of testing

Figures 146 through 150 show measured data for the final 10 hours of the test as follows:

- Figure 146 - Temperature profile for the last 10 hours of testing
- Figure 147 - Gas sensing current for the last 10 hours of testing
- Figure 148 - 12 V control voltage for the last 10 hours of testing
- Figure 149 - RESS voltage for the last 10 hours of testing
- Figure 150 - Isolation resistance for the last 10 hours of testing

Table 46 - Mitsubishi iMiev EV Test Event Log

Event	**Time**	**Temperature**	**Primary Source**	**Secondary Source**
Start of immersion	11:55 AM		Test field notes	
Start of self-heating in observation period (if any)	12:00 PM		graphs	Test field notes
Time at first flames	N/A		video	IR Camera
Highest recorded HV battery temperature at time of first flames		N/A	graphs	
Time of first bang, explosion or pressure wave captured on video	N/A		video	
Time of first smoke/gases/vapor	N/A		video	IR camera
Time of RESS case maximum temperature	12:04 PM		graphs	
Maximum RESS case temperature		24°C	logged data	
Time when RESS pre-contactor voltage is more than $V_{initial}$ ± 2%	12:00 PM		graphs	logged data
Time when the LV battery voltage is more than $V_{initial}$ ± 2%	12:00 PM		graphs	logged data
Time to first measurement of sustained (>110% of initial reading) CH_4 presence (>5 s)	N/A		logged data	
Time to first measurement of sustained (>110% of initial reading) CL_2 presence (>5 s)	N/A		logged data	
Time to first measurement of sustained (>110% of initial reading) H_2 presence (>5 s)	N/A		logged data	

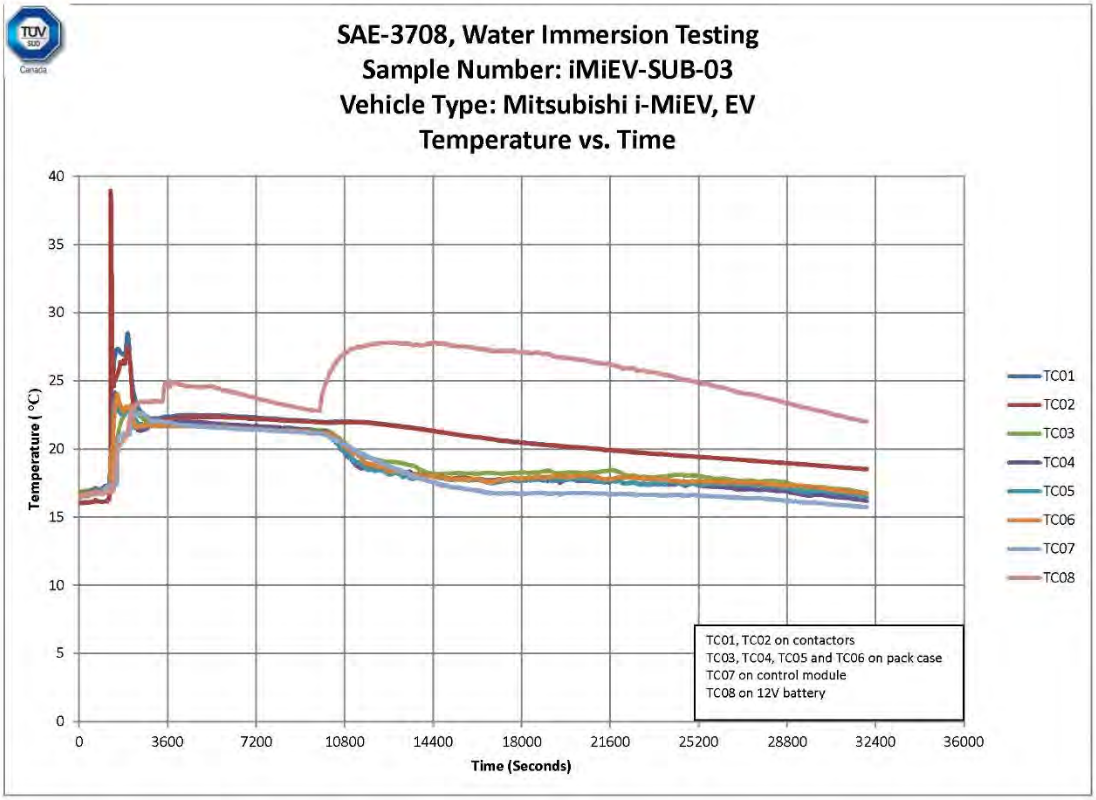


Figure 140 - Mitsubishi iMiev EV temperature profile for the first 9 hours of testing.

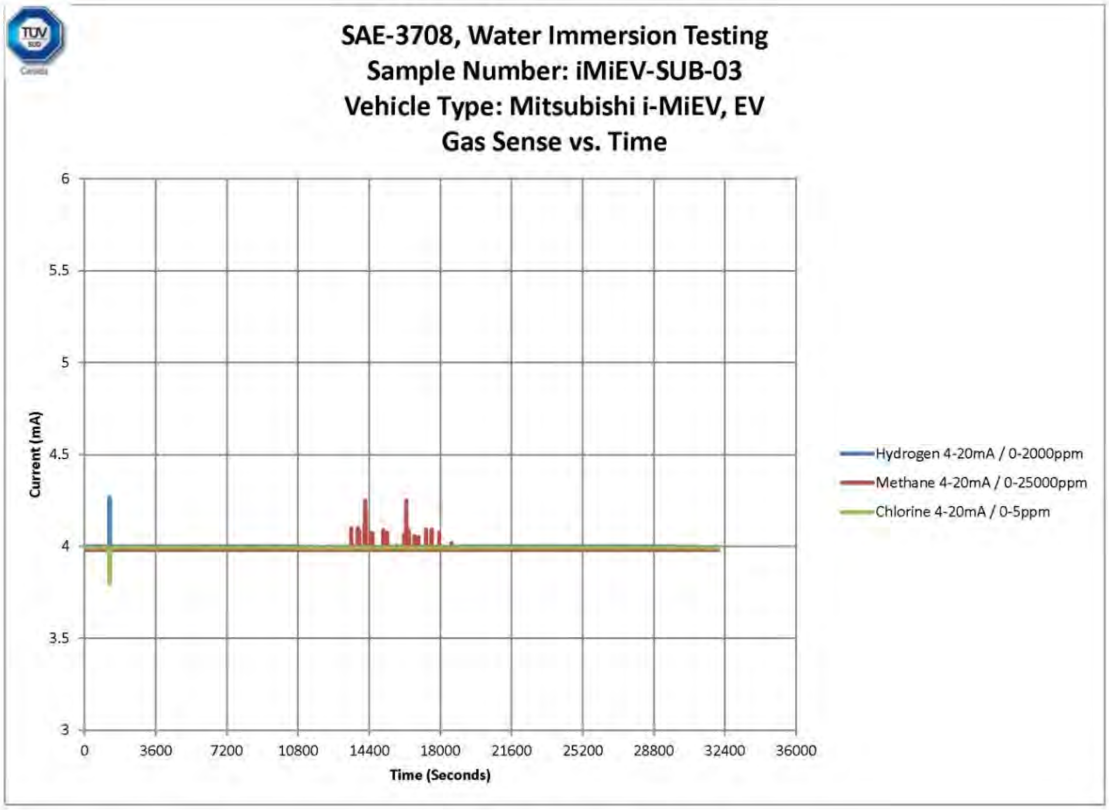


Figure 141 - Mitsubishi iMiev EV gas sensing current for the first 9 hours of testing.

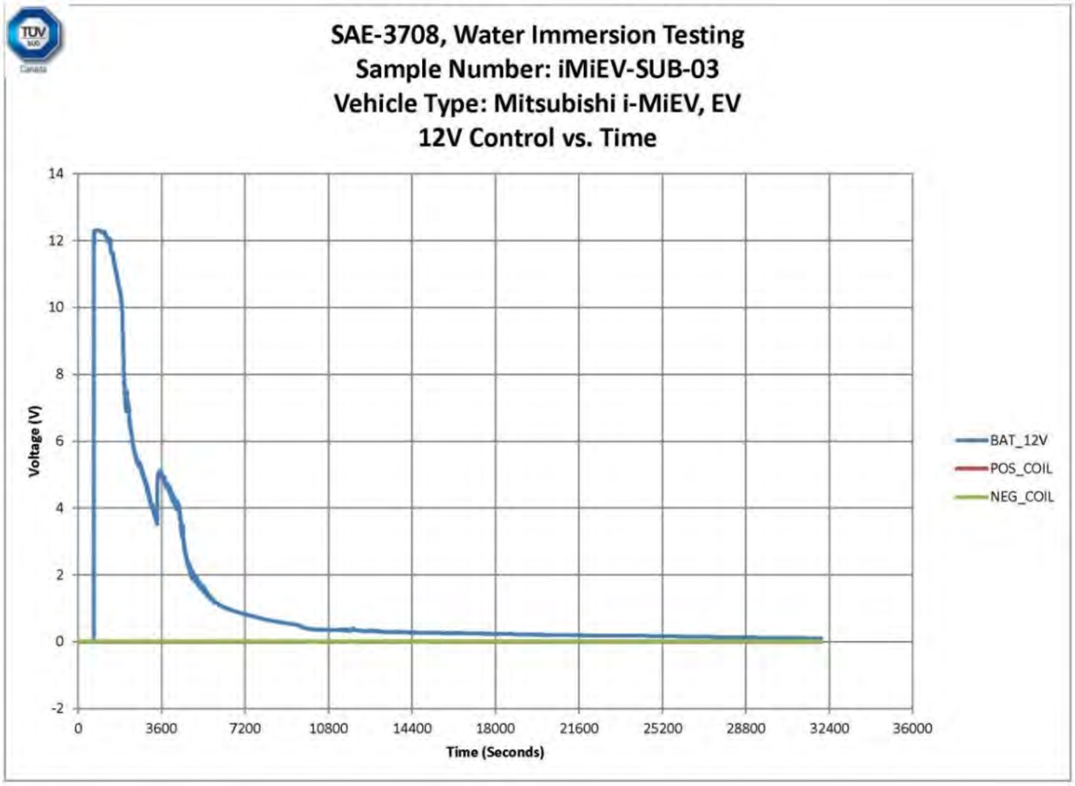


Figure 142 - Mitsubishi iMiev EV 12 V control voltage for the first 9 hours of testing.

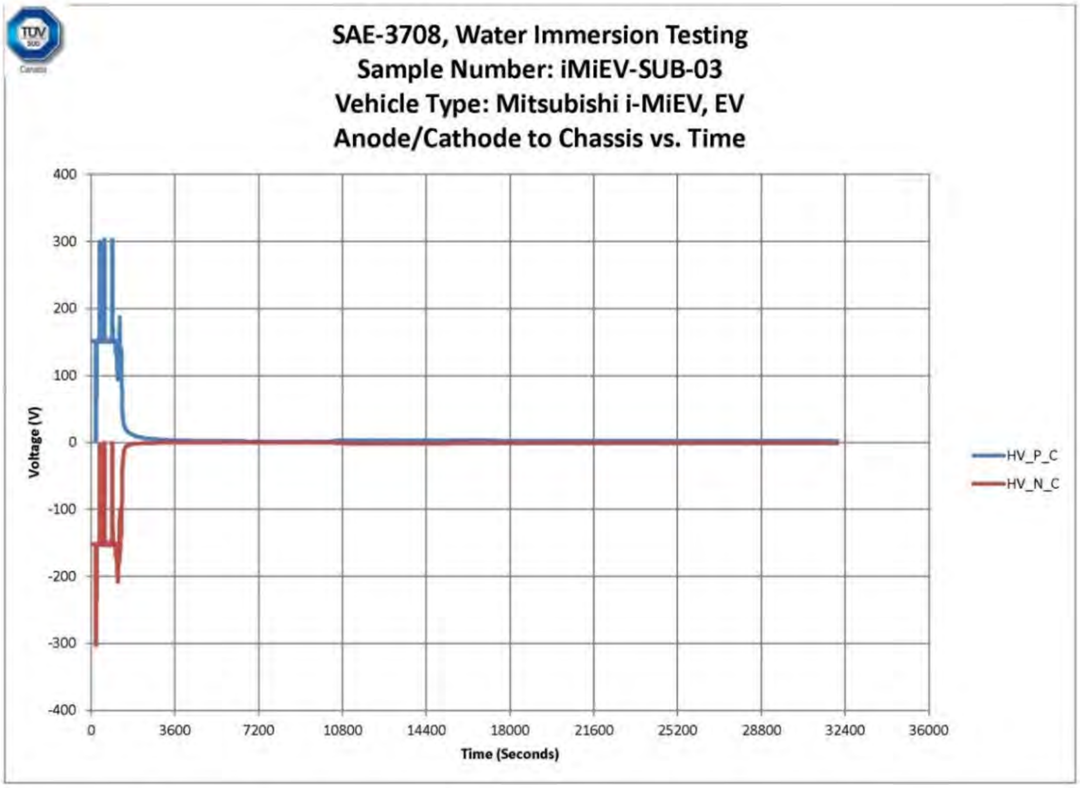


Figure 143 - Mitsubishi iMiev EV electrode to chassis voltage for the first 9 hours of testing.

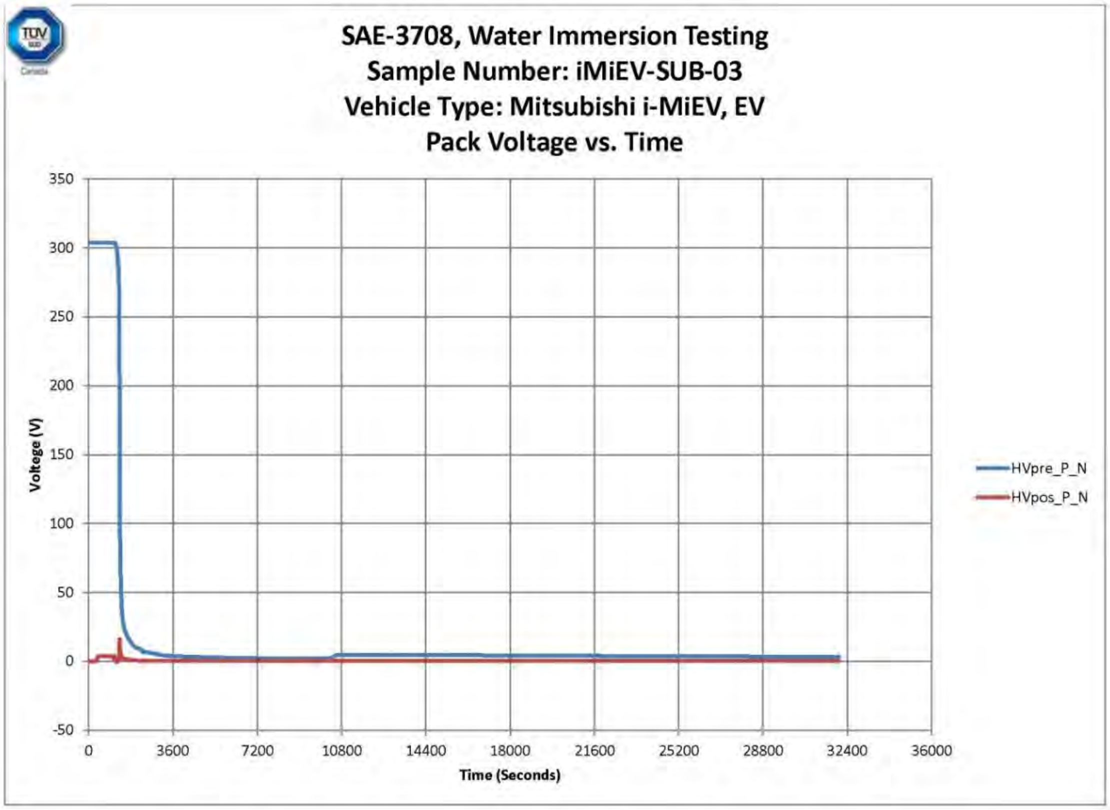


Figure 144 - Mitsubishi iMiev EV RESS voltage for the first 9 hours of testing.

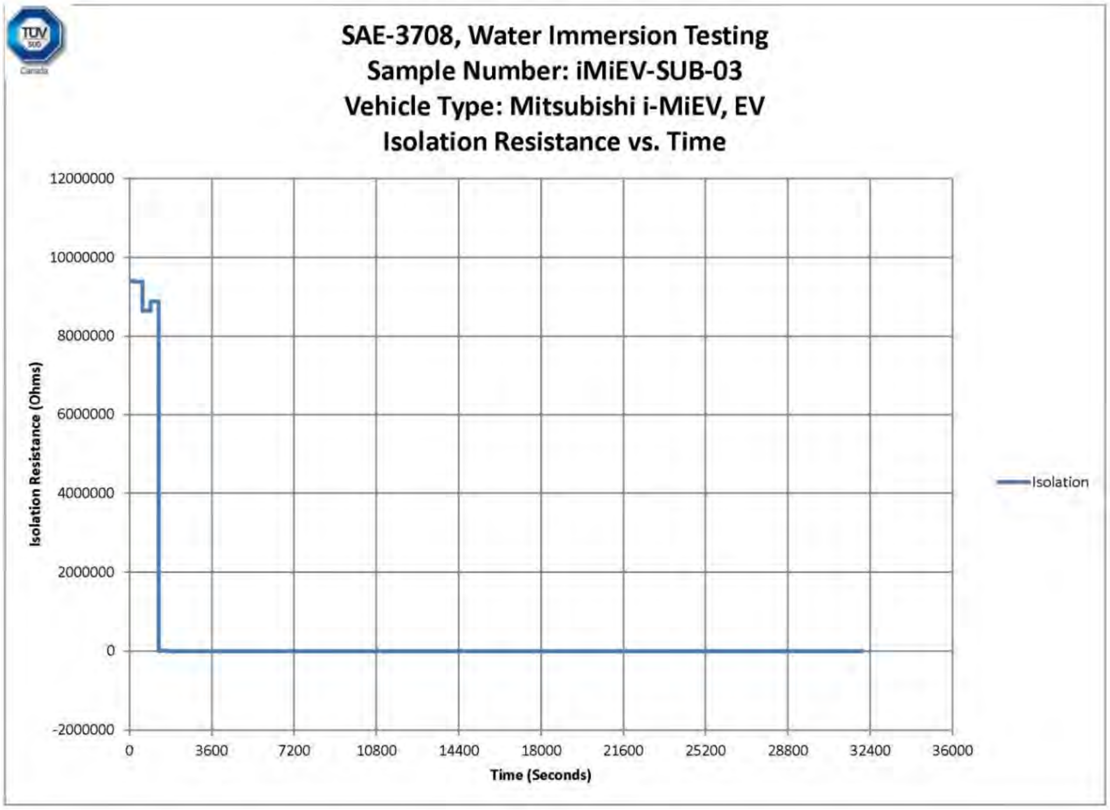


Figure 145 - Mitsubishi iMiev EV isolation resistance for the first 9 hours of testing.

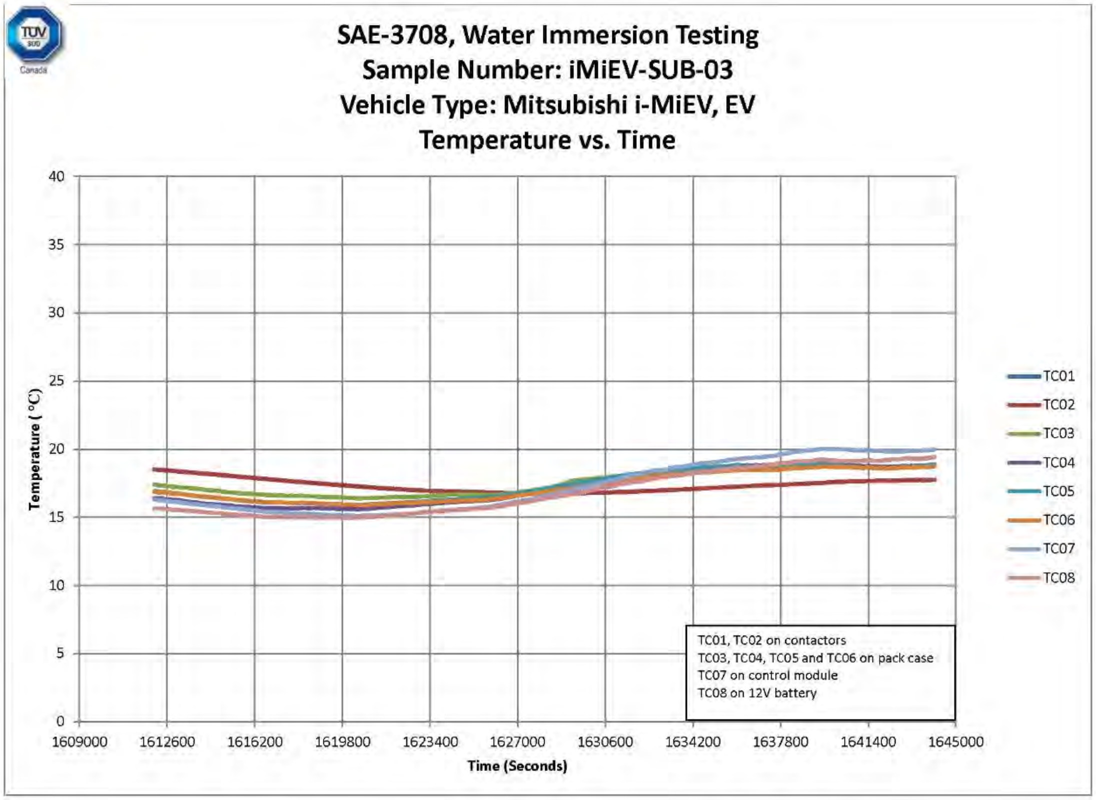


Figure 146 - Mitsubishi iMiev EV temperature profile for the last 10 hours of testing.

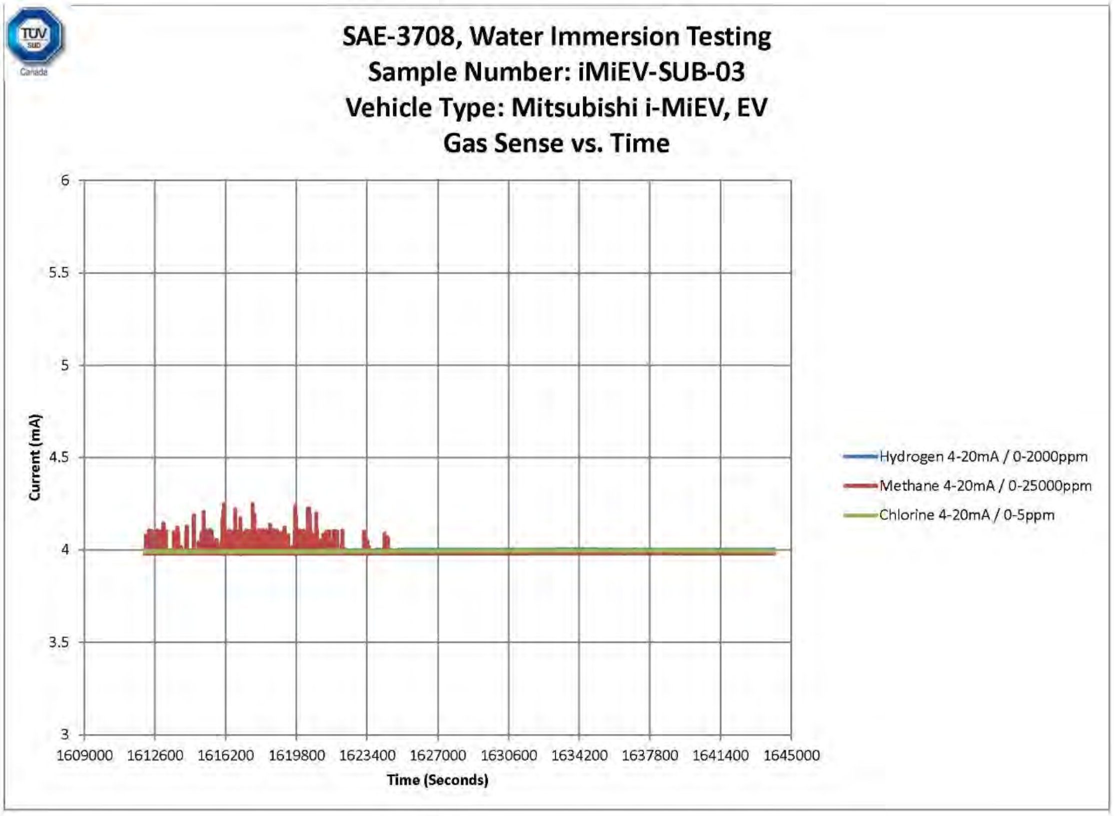


Figure 147 - Mitsubishi iMiev EV gas sensing current for the last 10 hours of testing.

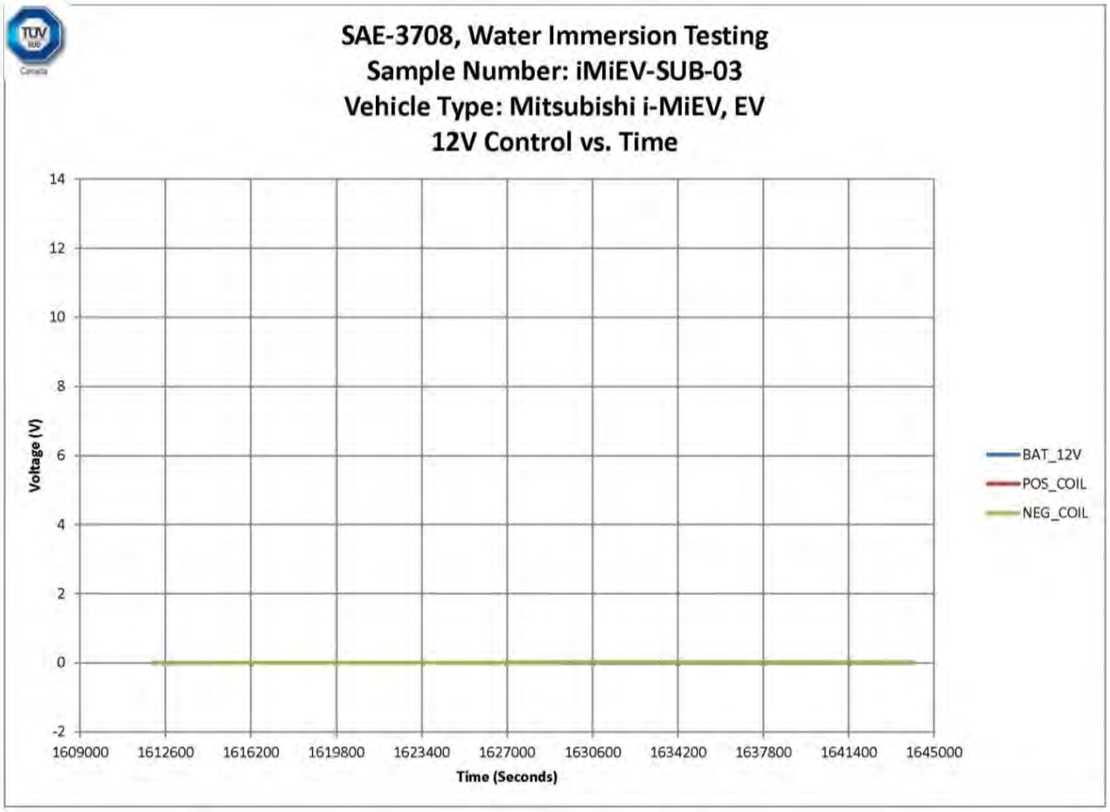


Figure 148 - Mitsubishi iMiev EV 12 V control voltage for the last 10 hours of testing.

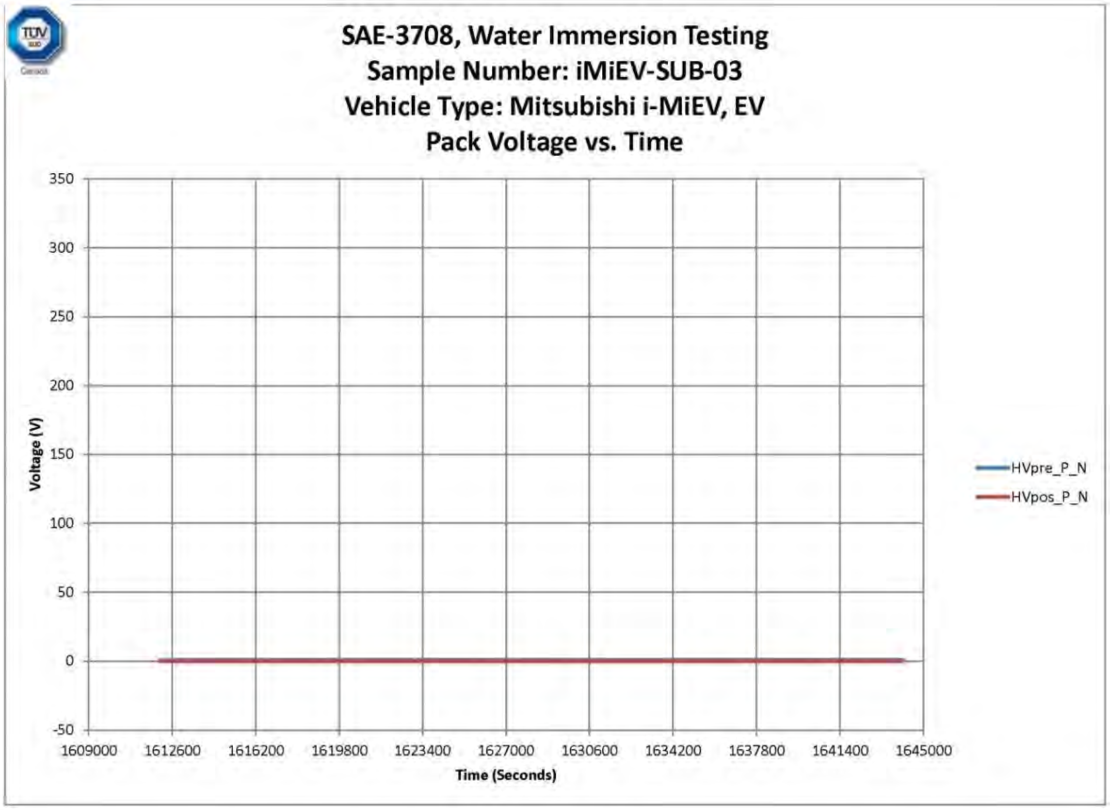


Figure 149 - Mitsubishi iMiev EV RESS voltage for the last 10 hours of testing.

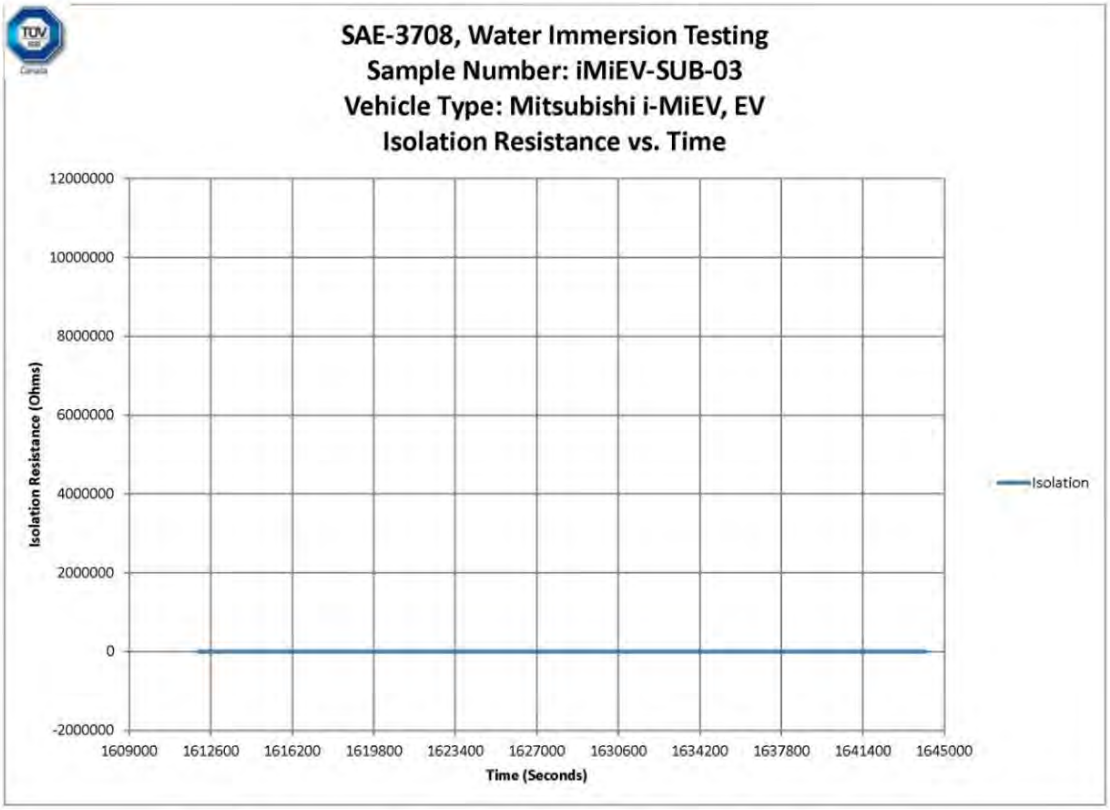


Figure 150 - Mitsubishi iMiev EV isolation resistance for the last 10 hours of testing.

8.3.2.4 Seawater Analysis Results

Seawater samples were taken before and after immersion. They were measured on-site for pH, density and conductivity; the results are summarized in Table 47. Table 48 shows the VOCs that were above the reportable detection limit, as determined from Maxxam Analytics, Inc. Note that the samples were also analyzed for other VOCs that were below the reportable limit. Table 49 shows the total oil and grease content from the samples.

Table 47 - Mitsubishi iMiev EV Conductivity, Salinity, Density, and pH

Time	Conductivity (mS/cm)	Salinity (wt%)	Density (g/cm^3)	pH
Pre-immersion	55.3	3.39	1.025	7.4
Post-immersion	56.2	3.44	1.025	7.4

Table 48 - Mitsubishi iMiev EV VOCs above Reportable Detection Limit

Volatile Organics	Units	Pre-Immersion	Post-Immersion	RDL*
Acetone (2-Propanone)	µg/L	12	12	10

*RDL=Reportable Detection Limit

Table 49 - Mitsubishi iMiev EV Total Oil and Grease Content

Petroleum Hydrocarbons	Units	Pre-Immersion	Post-Immersion	RDL
Total oil and grease	mg/L	ND*	ND*	0.50

*ND=Not Detected

8.3.2.5 Post-Mortem Analysis

Figure 151 shows the vehicle from multiple angles after testing was complete. Post-mortem analysis did not indicate any evidence of behaviors that could result in an HSL higher than 4 (i.e., no anticipated fires, ruptures, or explosions) based on EUCAR standards. Although the RESS temperature increased during immersion, it quickly declined to ambient levels after 4 hours and followed the diurnal ambient values until the end of the test. In addition, the water immersion caused the RESS voltage to drop from 304 V to 4.5 V within the first hour of the test and was at 0 V at end of test. Therefore, no post-mortem analysis was conducted on the battery pack.

(a) (b) (c) (d) (e) (f)

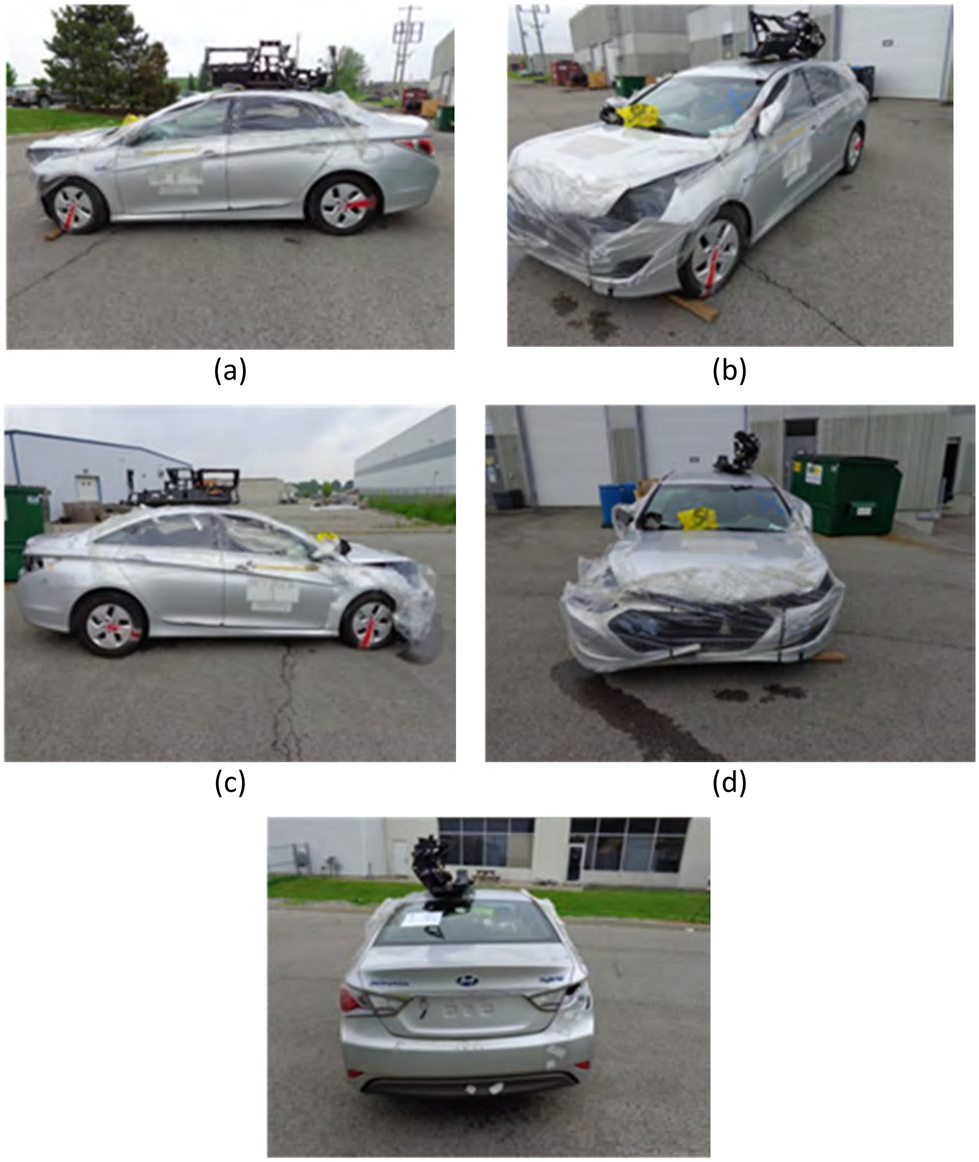
Figure 151 - Mitsubishi iMiev EV post-test vehicle condition: a) front view, b) rear view, c) passenger side view, d) driver's side, e) interior cabin (front), and f) interior cabin (rear).

8.3.3 Hyundai Sonata HEV

The Hyundai Sonata was a new production HEV previously used for front impact testing, see Table 50. Figure 152 shows the as-received vehicle from multiple angles. Figure 153 shows the vehicle in its immersion tank as well as the video camera setup.

Table 50 - Hyundai Sonata HEV Details

Vehicle Class	Passenger Car
Manufacturer	Hyundai
Make	Sonata
Model	Hybrid
Date of Manufacture	Jan-2011
VIN	KMHEC4A42BA002136
Condition	Damaged (Front impact)
Vehicle Type	HEV



(a) (b)

(c) (d)

(e)

Figure 152 - Hyundai Sonata HEV initial vehicle condition: a) left view, b) front ¾ view, c) right view, d) front view, and e) rear view.


(a) (b)

Figure 153 - Hyundai Sonata HEV setup: a) video camera, and b) the vehicle in its immersion container.

8.3.3.1 Sample Preparation

As received, the vehicle was damaged from front impact testing and not operational. The gauge was warning of low fuel level and the RESS was at approximately 25% SOC based on the dashboard display. The 12 V battery was removed followed by the MSD and the HV cables. The rear seat back was already removed along with the trunk interior upon arrival. All the loose interior parts were tagged and removed from the cabin.

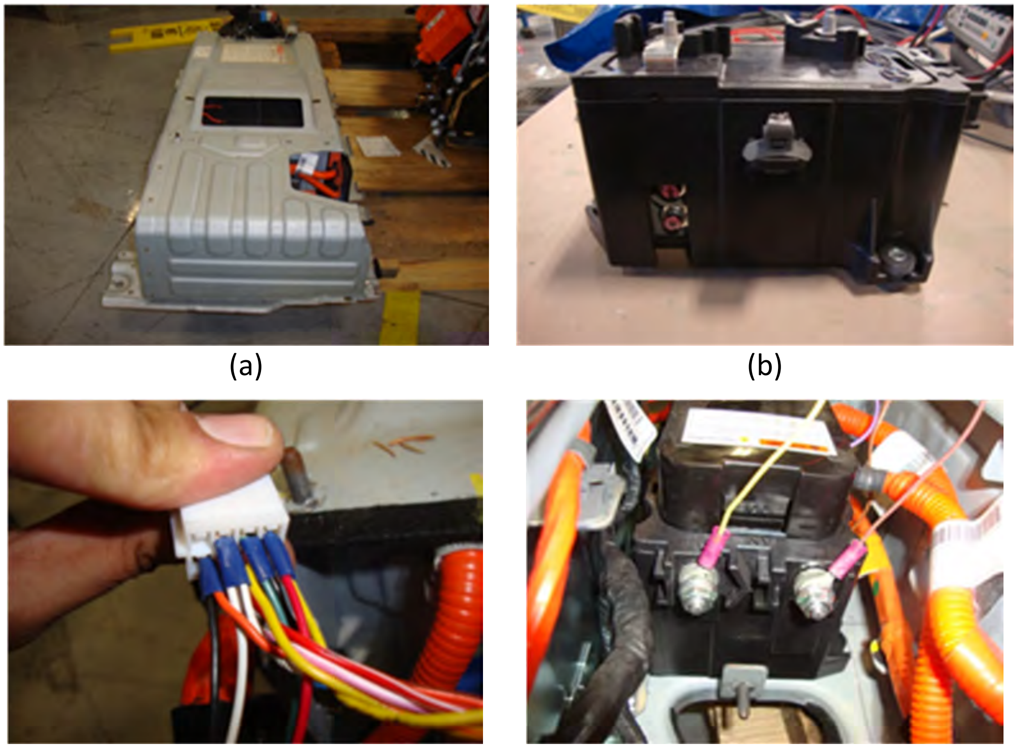
For HV and isolation measurements, the RESS was removed from the vehicle (see Figure 154). The cover was removed from the contactors and then the contactors were removed. The contactor assembly was then taken apart. The measurement wires were tightly bolted to the bus bars of the assembly. The coil wires were soldered to the pins of the electrical connectors. The contactor was reassembled and re-installed; the RESS was then placed back into the vehicle. The rear seat was re-installed but there was no trunk interior provided. Voltage sense cables were installed on the 12 V battery.

A total of eight thermocouples were installed as specified in test procedure (see Section 6.5.1.13), including the RESS enclosure, near contactors, the control unit, and the 12 V battery. Thermocouple locations are provided in Table 51 and shown in Figure 155. The thermocouples were held in position using epoxy adhesive.

Three gas sensors were also mounted above the driver window (see Section 7.2).

Table 51 - Hyundai Sonata HEV Thermocouple Placement

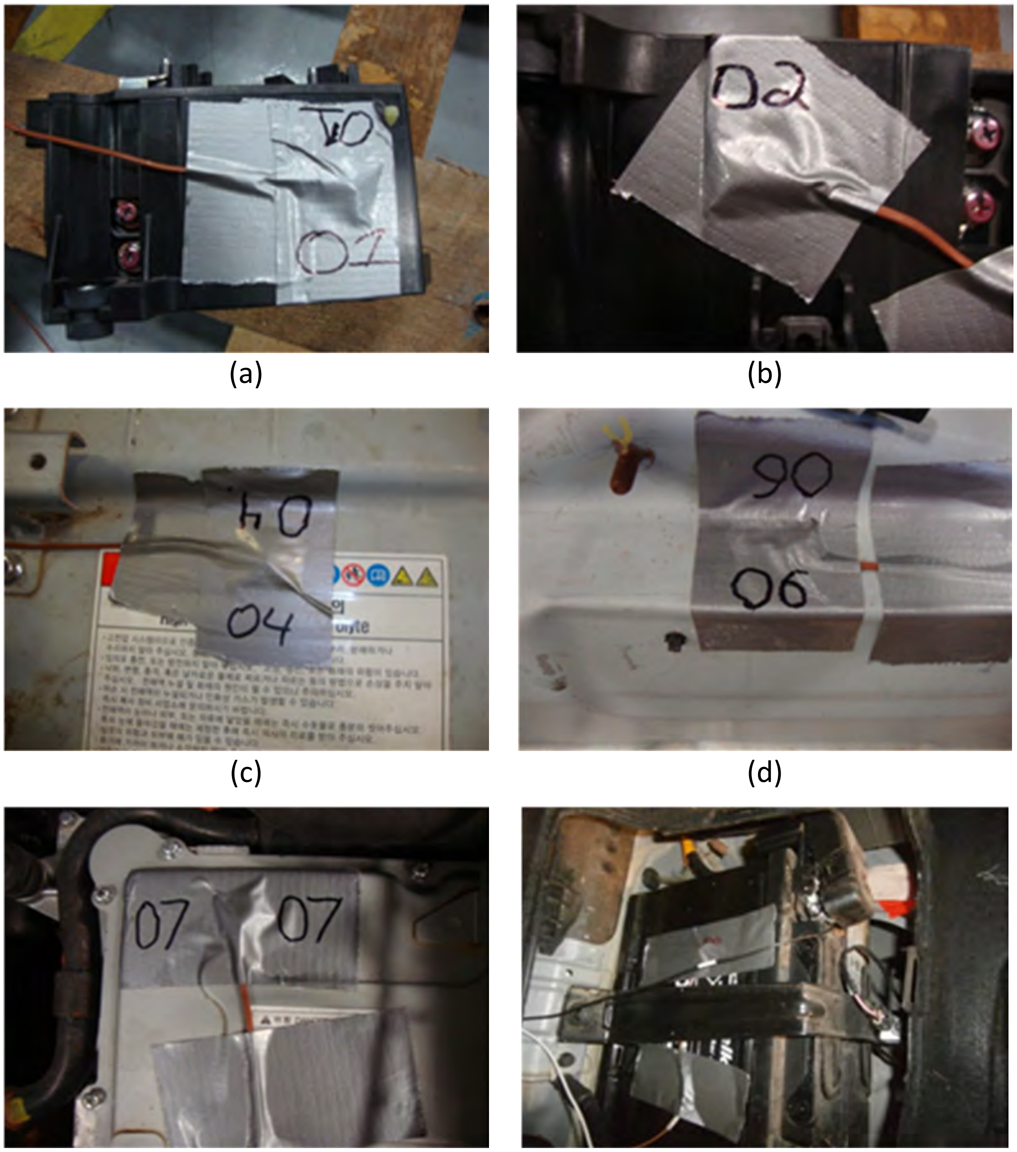
Number	Location
TC1, TC2	Contactor
TC3, TC4, TC5, TC6	Pack case
TC7	Control module
TC8	12V battery



(a) (b)

(c) (d)

Figure 154 - Hyundai Sonata HEV HV connections: a) RESS removed from vehicle, b) contactor assembly, c) coil wires, and d) measurement wires.



(a) (b)

(c) (d)

(e) (f)

Figure 155 - Hyundai Sonata HEV HV thermocouple placement: a) TC1 on the contactor, b) TC2 on the contactor, c) TC4 on the RESS case, d) TC6 on the RESS case, e) TC7 on the control module, and f) TC8 on the 12 V battery.

8.3.3.2 Test Conditions

Testing was performed outdoors in ambient temperatures of approximately 16°C. There was precipitation on the day the vehicle was immersed. The vehicle remained in the immersion container during the post-extraction observation period.

8.3.3.3 Immersion Test Results

The test event log is summarized in Table 52. Figures 156 through 161 show measured data for the initial 9 hours of the test as follows:

- Figure 156 - Temperature profile for the first 9 hours of testing
- Figure 157 - Gas sensing current for the first 9 hours of testing
- Figure 158 - 12 V control voltage for the first 9 hours of testing
- Figure 159 - Electrode to chassis voltage for the first 9 hours of testing
- Figure 160 - HV pack voltage for the first 9 hours of testing
- Figure 161 - Isolation resistance for the first 9 hours of testing

Figures 162 through 166 show measured data for the final 10 hours of the test as follows:

- Figure 162 - Temperature profile for the last 10 hours of testing
- Figure 163 - Gas sensing current for the last 10 hours of testing
- Figure 164 - 12 V control voltage for the last 10 hours of testing
- Figure 165 - HV pack voltage for the last 10 hours of testing
- Figure 166 - Isolation resistance for the last 10 hours of testing

Table 52 - Hyundai Sonata HEV Test Event Log

Event	**Time**	**Temperature**	**Primary Source**	**Secondary Source**
Start of immersion	8:51 AM		Test field Notes	
Start of self-heating in observation period (if any)	N/A		graphs	Test field Notes
Time at first flames	N/A		video	IR Camera
Highest recorded HV battery temperature at time of first flames		N/A	graphs	
Time of first bang, explosion or pressure wave captured on video	N/A		video	
Time of first smoke/gases/vapor	N/A		video	IR camera
Time of RESS case maximum temperature	9:31 AM		graphs	
Maximum RESS case temperature		22°C	logged data	
Time when pre-contactor HV pack voltage is more than $V_{initial}$ ± 2%	9:04 AM		graphs	logged data
Time when the LV battery voltage is more than $V_{initial}$ ± 2%	9:00 AM		graphs	logged data
Time to first measurement of sustained (>110% of initial reading) CH_4 presence (>5 s)	N/A		logged data	
Time to first measurement of sustained (>110% of initial reading) CL_2 presence (>5 s)	N/A		logged data	
Time to first measurement of sustained (>110% of initial reading) H_2 presence (>5 s)	N/A		logged data	

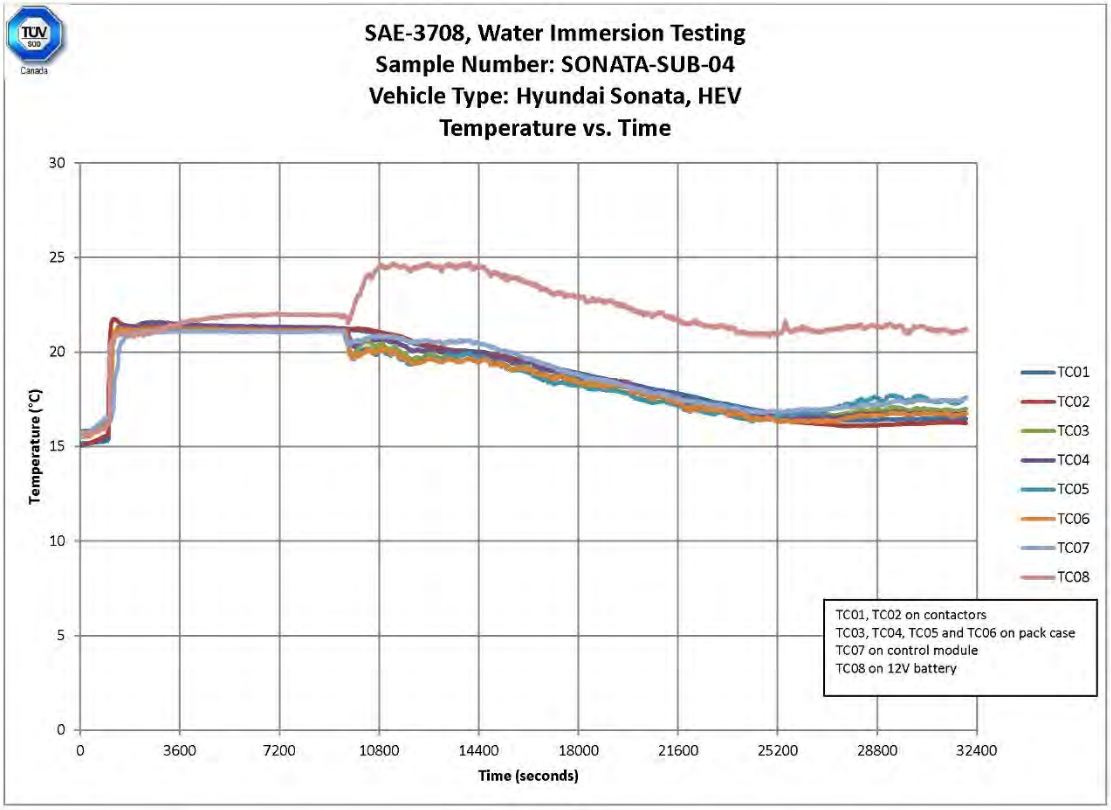


Figure 156 - Hyundai Sonata HEV temperature profile for the first 9 hours of testing.

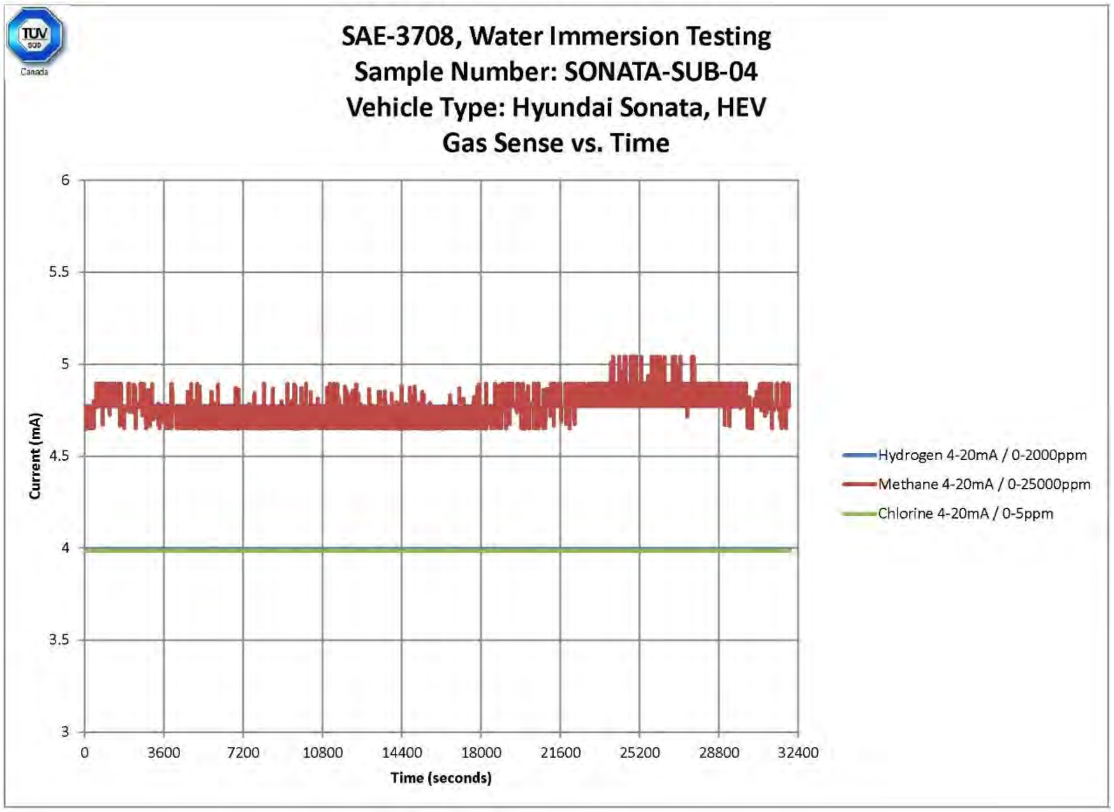


Figure 157 - Hyundai Sonata HEV gas sensing current for the first 9 hours of testing.

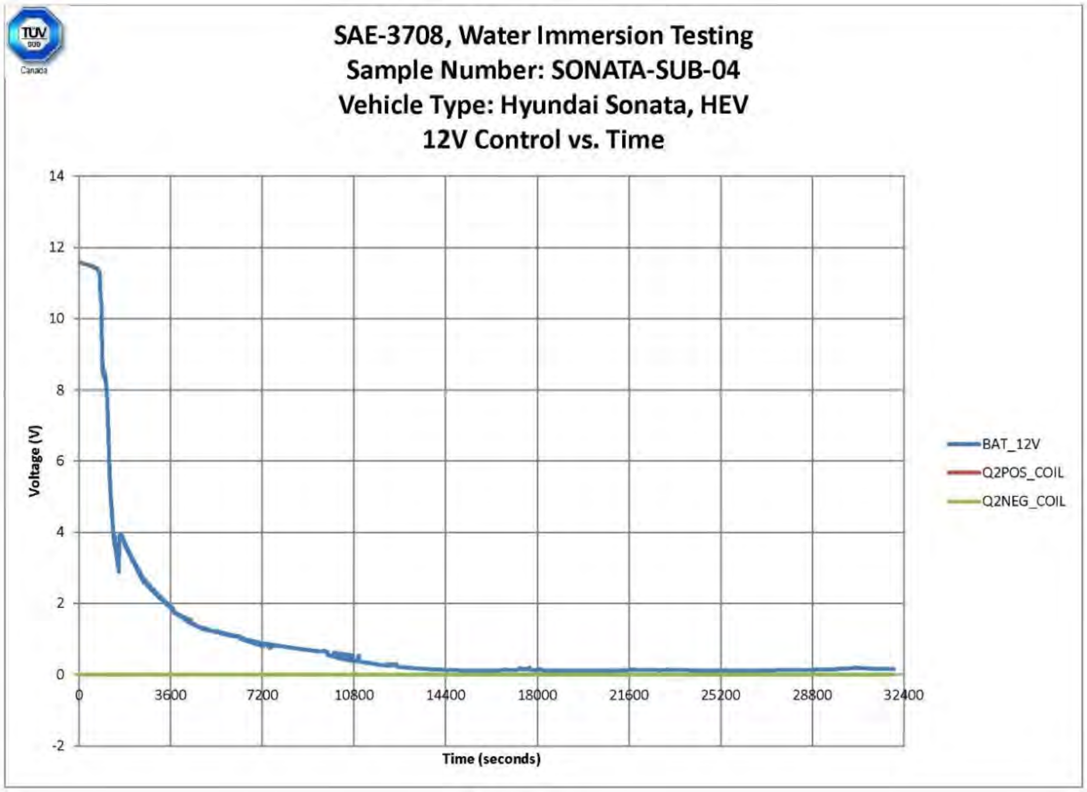


Figure 158 - Hyundai Sonata HEV 12 V control voltage for the first 9 hours of testing.

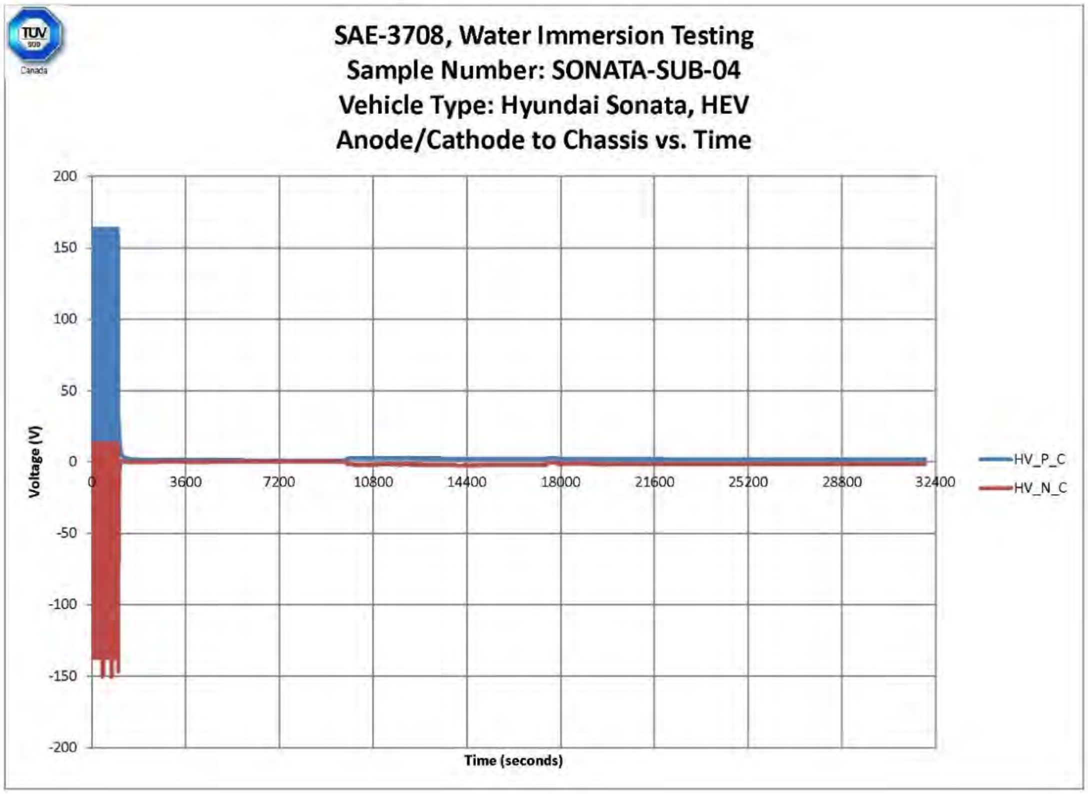


Figure 159 - Hyundai Sonata HEV electrode to chassis voltage for the first 9 hours of testing.

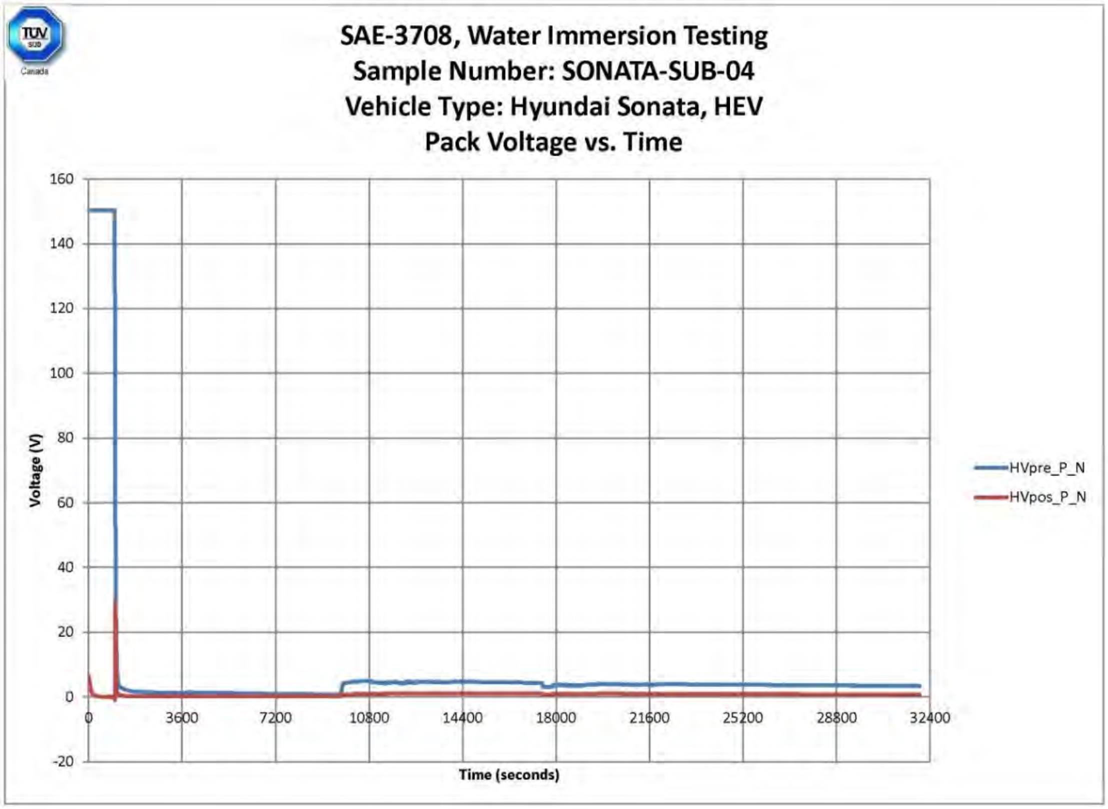


Figure 160 - Hyundai Sonata HEV HV pack voltage for the first 9 hours of testing.

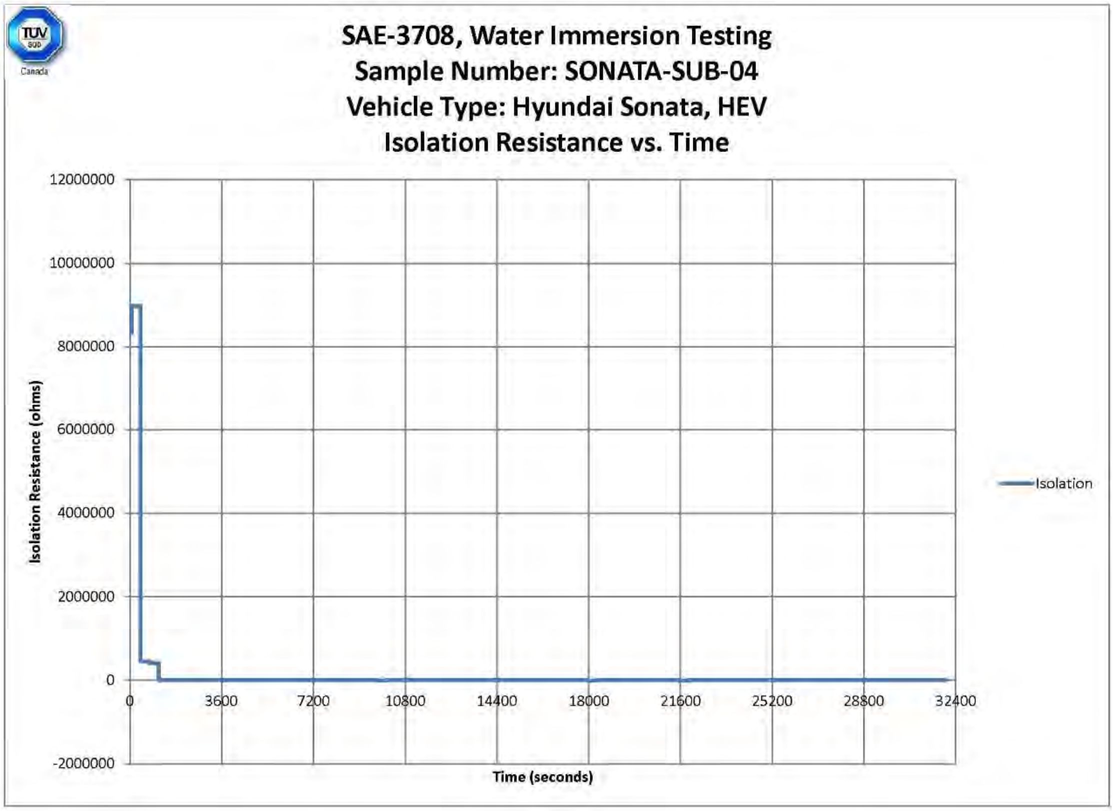


Figure 161 - Hyundai Sonata HEV isolation resistance for the first 9 hours of testing.

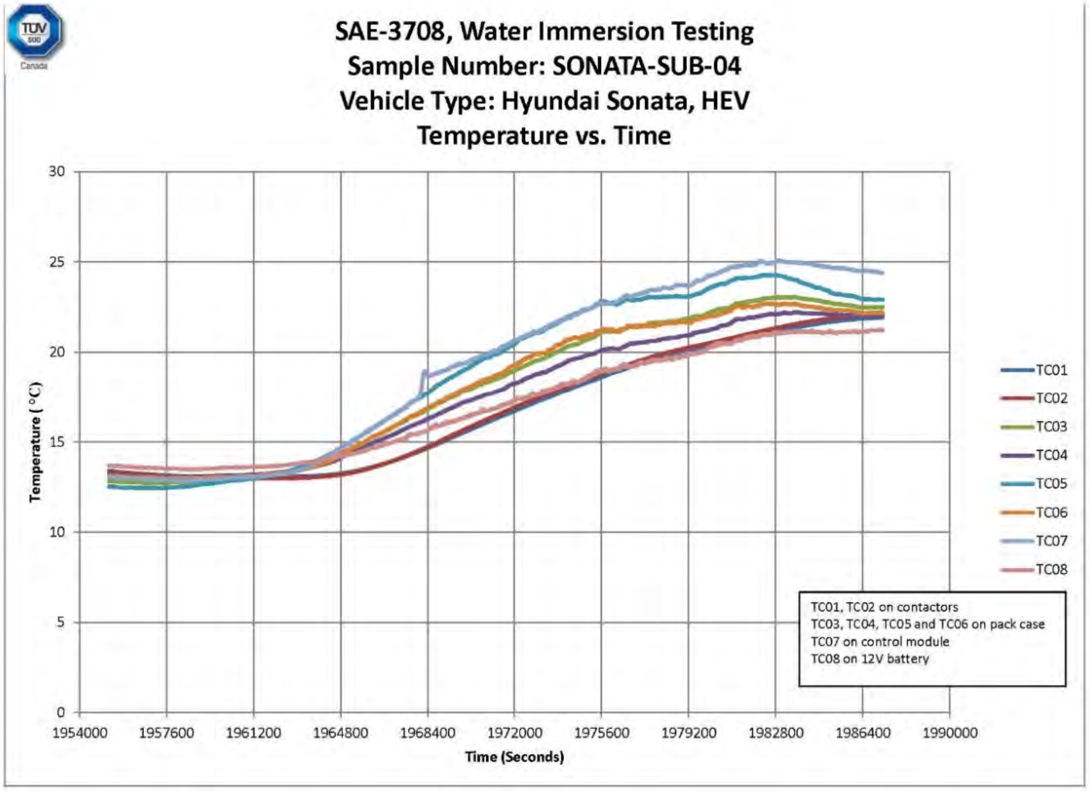


Figure 162 - Hyundai Sonata HEV temperature profile for the last 10 hours of testing.

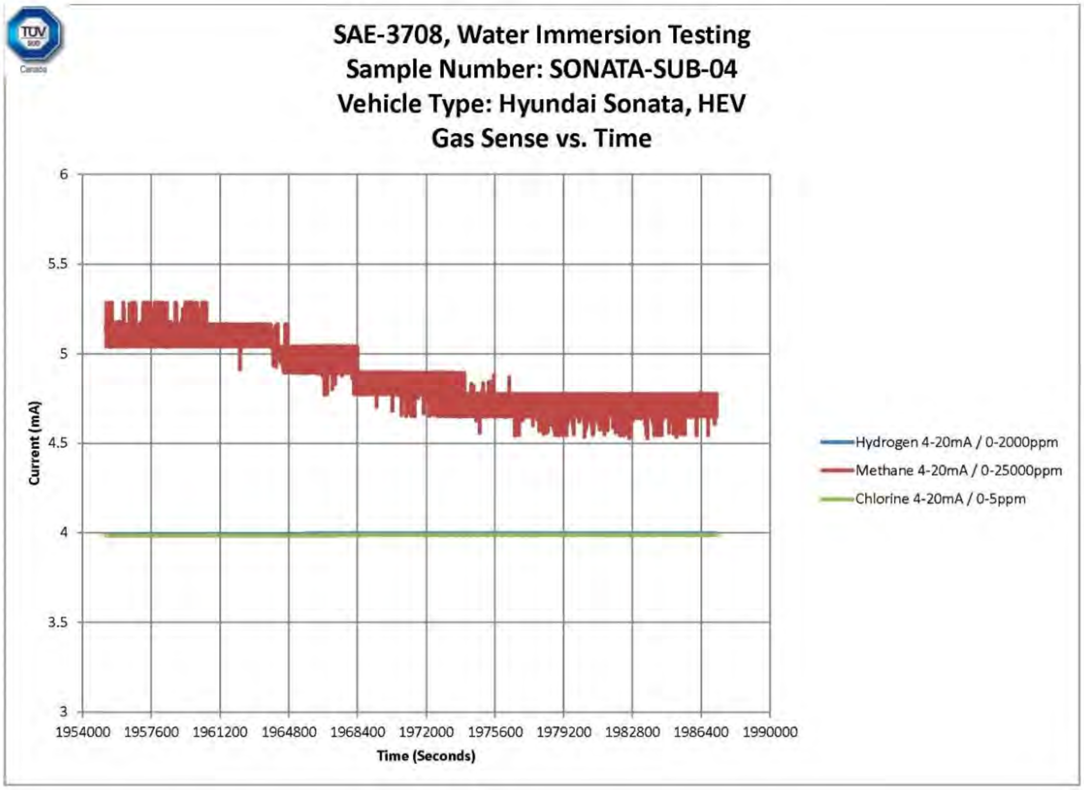


Figure 163 - Hyundai Sonata HEV gas sensing current for the last 10 hours of testing.

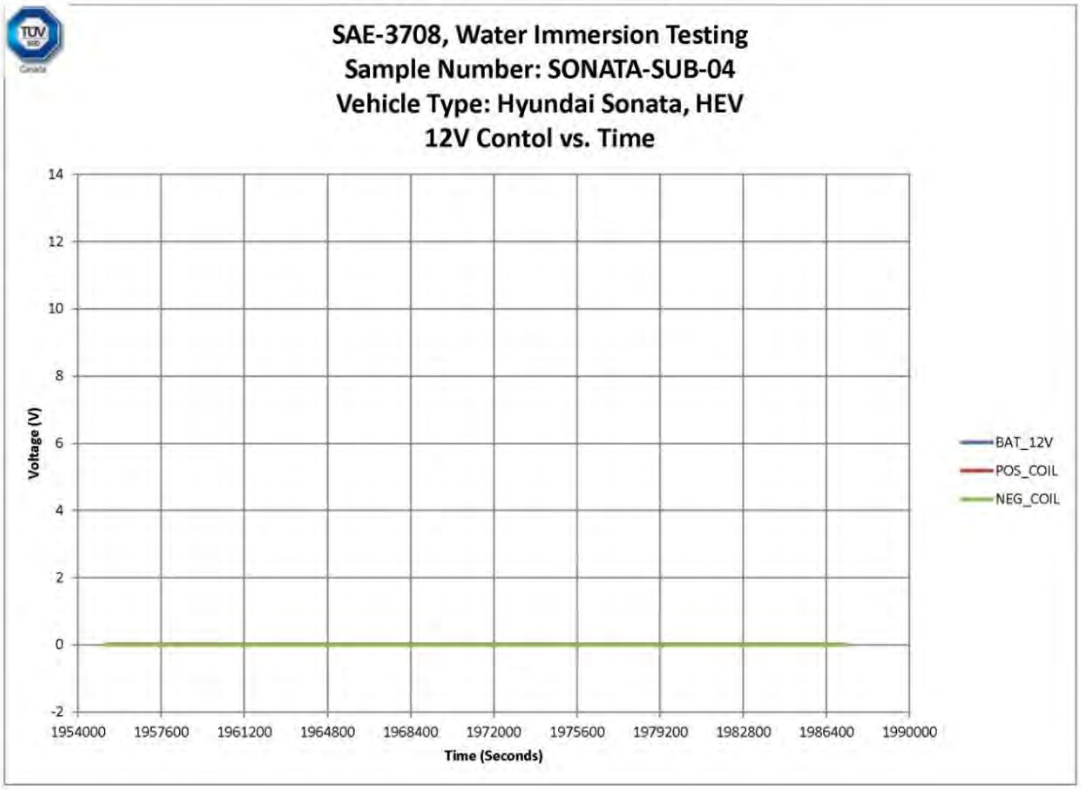


Figure 164 - Hyundai Sonata HEV 12 V control voltage for the last 10 hours of testing.

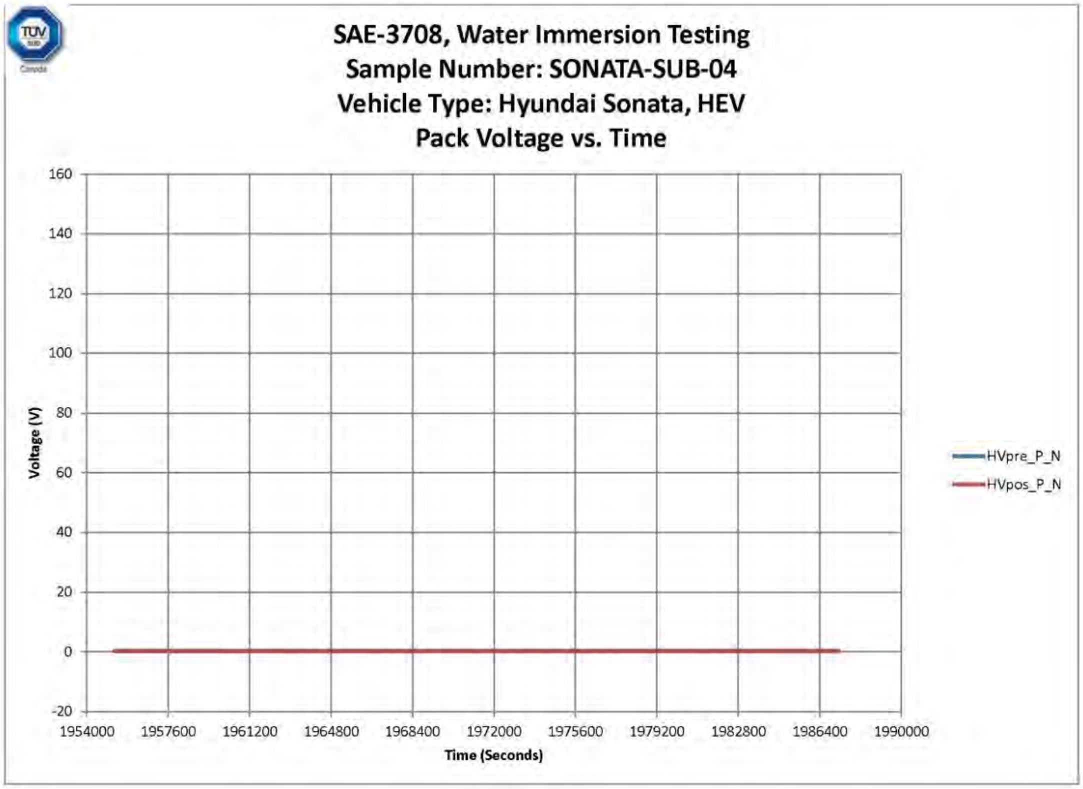


Figure 165 - Hyundai Sonata HEV HV pack voltage for the last 10 hours of testing.

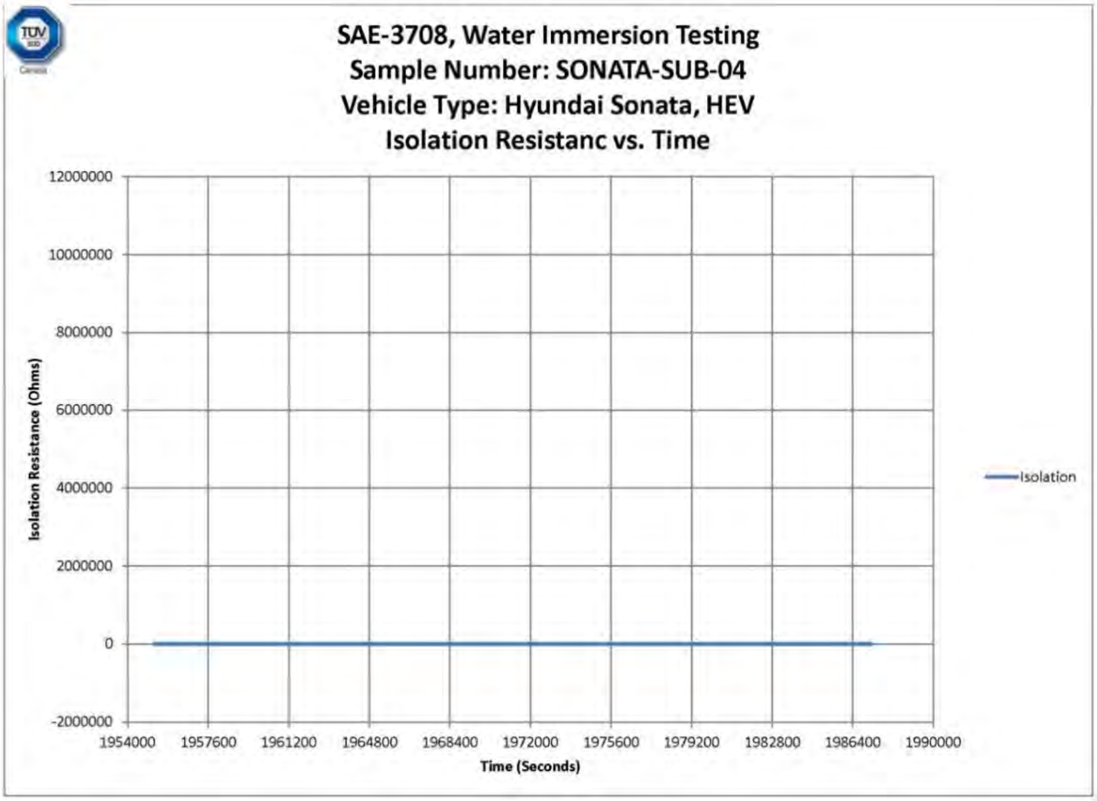


Figure 166 - Hyundai Sonata HEV isolation resistance for the last 10 hours of testing.

8.3.3.4 Seawater Analysis Results

Seawater samples were taken before and after immersion. They were measured on-site for pH, density and conductivity; the results are summarized in Table 53 Table 54 shows the VOCs that were above the reportable detection limit, as determined from Maxxam Analytics, Inc. Note that the samples were also analyzed for other VOCs that were below the reportable limit. Table 55 shows the total oil and grease content from the samples.

Table 53 - Hyundai Sonata HEV Conductivity, Salinity, Density, and pH

Time	Conductivity (mS/cm)	Salinity (wt%)	Density (g/cm³)	pH
Pre-immersion	53.8	3.30	1.025	7.4
Post-immersion	55.1	3.36	1.025	7.5

Table 54 - Hyundai Sonata HEV VOCs above Reportable Detection Limit

Volatile Organics	Units	Pre-Immersion	Post-Immersion	RDL*
Acetone (2-Propanone)	µg/L	ND**	14	10
Chloroform	µg/L	0.11	0.10	0.10
p+m-Xylene	µg/L	ND**	0.11	0.10
Xylene (Total)	µg/L	ND**	0.11	0.10

*RDL=Reportable Detection Limit
**ND=Not Detectable

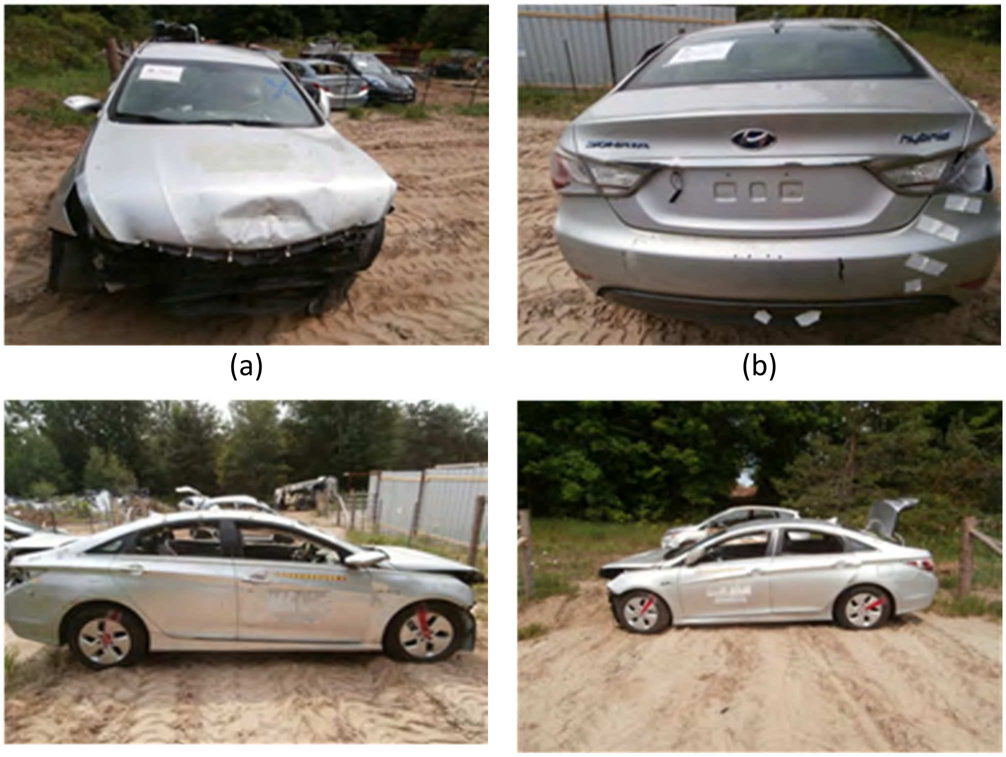
Table 55 - Hyundai Sonata HEV Total Oil and Grease Content

Petroleum Hydrocarbons	Units	Pre-Immersion	Post-Immersion	RDL
Total oil and grease	mg/L	ND*	ND*	0.50

*ND=Not Detected

8.3.3.5 Post-Mortem Analysis

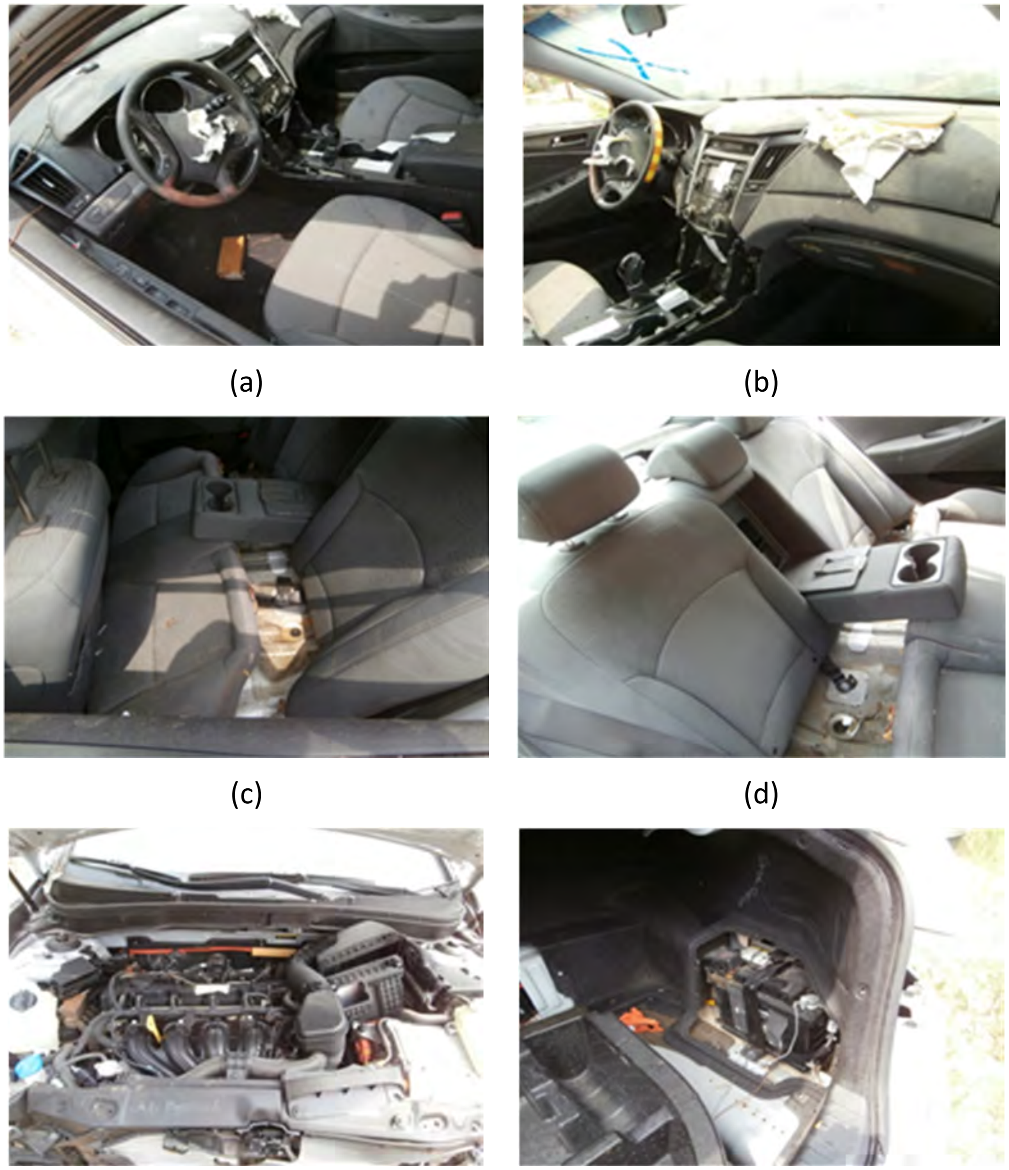
Figures 167 and 168 show the vehicle from multiple angles after testing was complete. Post-mortem analysis did not indicate any evidence of behaviors that could result in an HSL higher than 4 (i.e., no anticipated fires, ruptures, or explosions) based on EUCAR standards. Although the RESS temperature increased during immersion, it quickly declined to ambient levels after 3 hours and followed the diurnal ambient values until the end of the test. In addition, the water immersion caused the RESS voltage to drop from 150 V to 2 V within the first hour of the test and was at 0.5 V at end of test. Therefore, no post-mortem analysis was conducted on the battery pack.



(a) (b)

(c) (d)

Figure 167 - Hyundai Sonata HEV post-test external vehicle condition: a) front view, b) rear view, c) passenger side, and d) driver's side.



(a) (b) (c) (d) (e) (f)

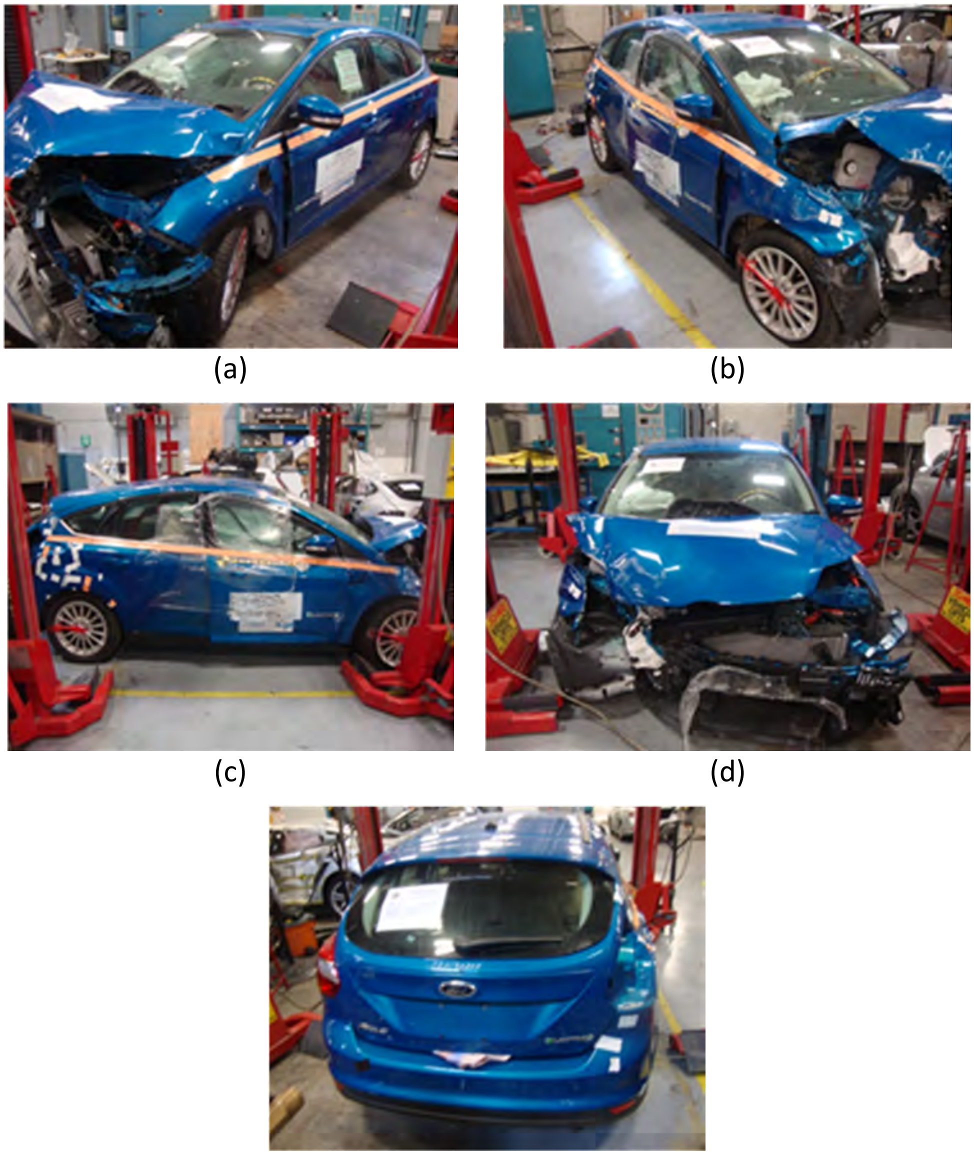
Figure 168 - Hyundai Sonata HEV post-test internal vehicle condition: a) interior cabin view, b) another interior cabin view, c) interior rear cabin view, d) another interior rear cabin view, e) engine bay, and f) trunk and 12 V battery.

8.3.4 Ford Focus LP EV

The Ford Focus was a new production EV previously used for front impact testing, see Table 56. Figure 169 shows the as-received vehicle from multiple angles. Figure 170 shows the vehicle in its immersion tank as well as the video camera setup. Note that the Ford Focus has two battery packs, so the testing was repeated twice. This report focuses on the lower pack (LP) RESS. The vehicle was immersed in brackish water made with sea salt crystals and fresh water formulated to be 17.5 g/kg for a duration of 1 hour.

Table 56 - Ford Focus LP EV Details

Vehicle Class	Passenger Car
Manufacturer	Ford
Make	Focus
Model	BEV
Date of Manufacture	Dec-2012
VIN	1FADP3R48DL217777
Condition	Damaged (Front impact)
Vehicle Type	EV


(a) (b)

(c) (d)

(e)

Figure 169 - Ford Focus LP EV initial vehicle condition: a) left view, b) front ¾ view, c) right view, d) front view, and e) rear view.

(a) (b)

Figure 170 - Ford Focus LP EV setup: a) video camera, and b) the vehicle in its immersion container.

8.3.4.1 Sample Preparation

As received, the vehicle was not operational and damaged from front impact testing. All the loose interior parts were tagged and removed from the cabin. The battery pack was showing fully charged based on dashboard display (this was a display of both packs, they could not be checked individually). The 12 V battery was removed, followed by the MSD's from both packs and the HV cables. The RESS cooling system was drained.

For HV and isolation measurements, the RESS was removed from the vehicle and the contactor assembly was taken apart (see Figure 171). The measurement wires were then tightly bolted to the bus bars. The RESS was sealed to prevent water intrusion through the sense leads exiting the pack (see Section 8.1.2). There was an additional hole that had been drilled by a previous test lab that was also sealed. The contactor was reassembled and re-installed in the RESS. Butyl tape was replaced where necessary to ensure sealing of the RESS enclosure. The RESS was placed back into the vehicle and the cooling system was re-filled. Voltage sense cables were installed on the 12 V battery.

A total of eight thermocouples were installed as specified in test procedure (see Section 6.5.1.13), including the RESS enclosure, near contactors, the control unit, and the 12 V battery. Thermocouple locations are provided in Table 57 and shown in Figure 172. The thermocouples were held in position using epoxy adhesive.

Three gas sensors were also mounted above the driver window (see Section 7.2).

Table 57 - Ford Focus LP EV Thermocouple Placement

Number	Location
TC7, TC8	Contactors
TC1, TC4, TC5, TC6	RESS enclosure
TC2	Control unit
TC3	12 V battery

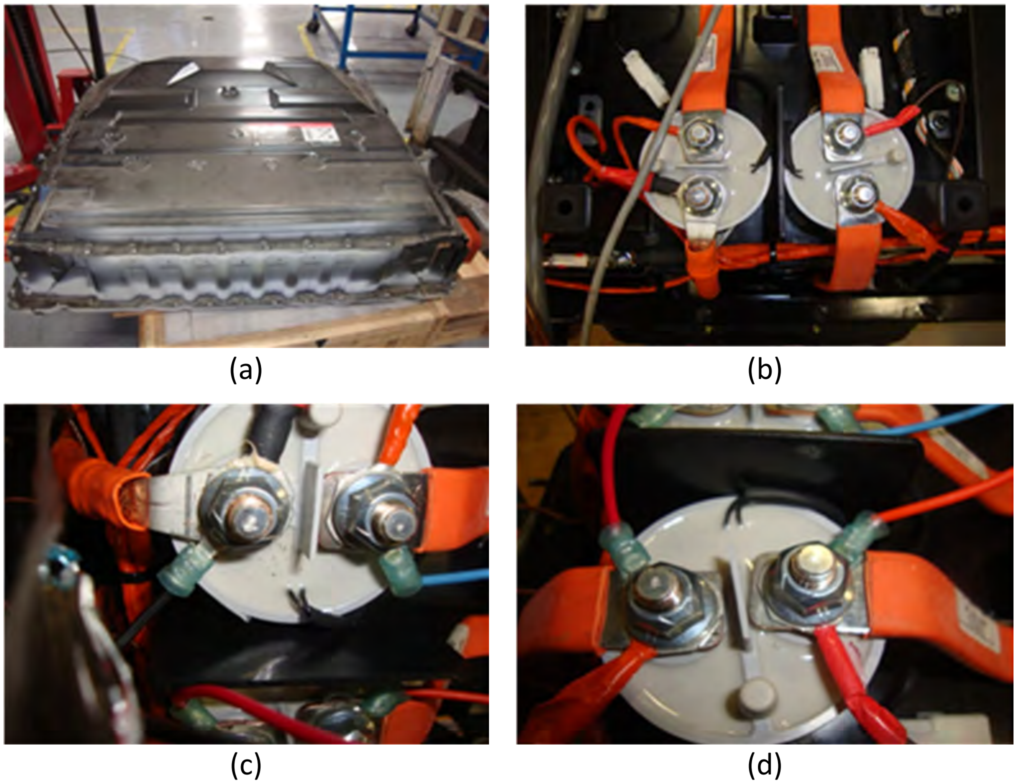

(a) (b) (c) (d)

Figure 171 - Ford Focus LP EV HV connections: a) RESS removed from vehicle, b) contactor assembly, c) leads connected a bus bar, and d) leads connected a bus bar.

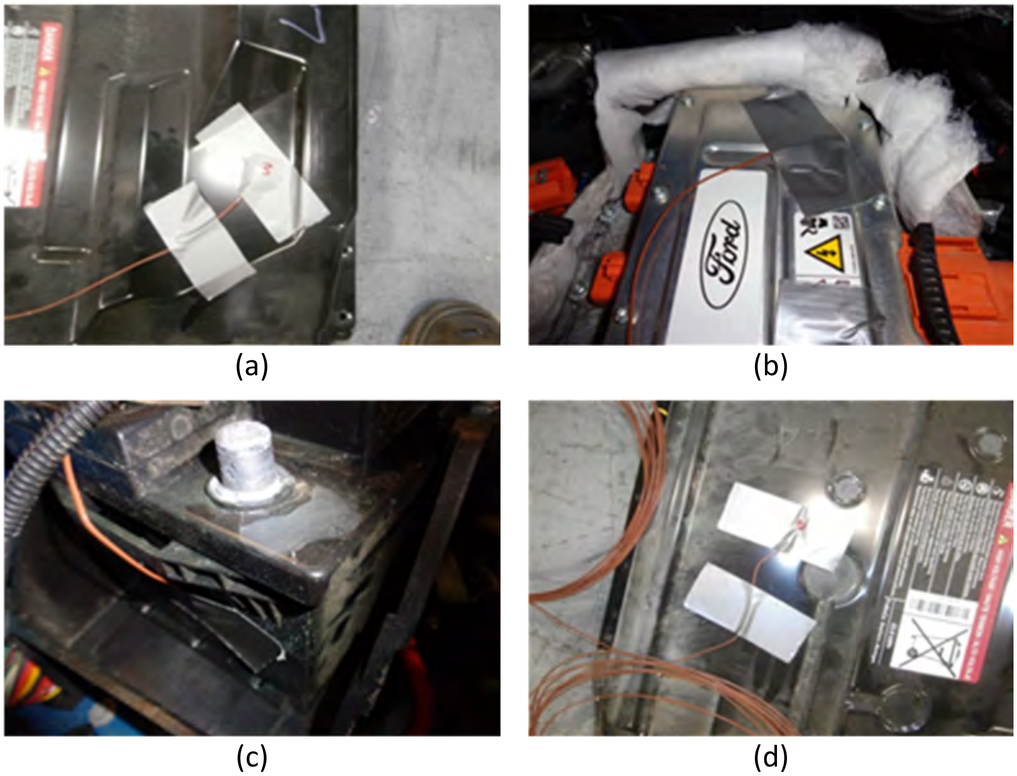

(a) (b) (c) (d)

Figure 172 - Ford Focus LP EV HV thermocouple placement: a) TC1 on the RESS case, b) TC2 on the control unit, c) TC3 on the 12 V battery, and d) TC6 on the RESS case.

8.3.4.2 Test Conditions

Testing was performed outdoors in ambient temperatures of approximately 24°C. There was no precipitation on the day the vehicle was immersed. The vehicle remained in the immersion container during the post-extraction observation period.

8.3.4.3 Immersion Test Results

The test event log is summarized in Table 58. Figures 173 through 178 show measured data for the initial 9 hours of the test as follows:

- Figure 173 - Temperature profile for the first 9 hours of testing
- Figure 174 - Gas sensing current for the first 9 hours of testing
- Figure 175 - 12 V control voltage for the first 9 hours of testing
- Figure 176 - Electrode to chassis voltage for the first 9 hours of testing
- Figure 177 - RESS voltage for the first 9 hours of testing
- Figure 178 - Isolation resistance for the first 9 hours of testing

Figures 179 through 183 show measured data for the final 10 hours of the test as follows:

- Figure 179 - Temperature profile for the last 10 hours of testing
- Figure 180 - Gas sensing current for the last 10 hours of testing
- Figure 181 - 12 V control voltage for the last 10 hours of testing
- Figure 182 - RESS voltage for the last 10 hours of testing
- Figure 183 - Isolation resistance for the last 10 hours of testing

Table 58 - Ford Focus LP EV Test Event Log

Event	**Time**	**Temperature**	**Primary Source**	**Secondary Source**
Start of immersion	11:40 AM		Test Field Notes	
Start of self-heating in observation period (if any)	12:30 PM		graphs	Test field Notes
Time at first flames	N/A		video	IR Camera
Highest recorded HV battery temperature at time of first flames		N/A	graphs	
Time of first bang, explosion or pressure wave captured on video	N/A		video	
Time of first smoke/gases/vapor	N/A		video	IR camera
Time of RESS case maximum temperature	1:34 PM		graphs	
Maximum RESS case temperature		79°C	logged data	
Time when RESS pre-contactor voltage is more than $V_{initial} \pm 2\%$	12:39 PM		graphs	logged data
Time when the LV battery voltage is more than $V_{initial} \pm 2\%$	11:50 AM		graphs	logged data
Time to first measurement of sustained (>110% of initial reading) CH_4 presence (>5 s)	N/A		logged data	
Time to first measurement of sustained (>110% of initial reading) CL_2 presence (>5 s)	N/A		logged data	
Time to first measurement of sustained (>110% of initial reading) H_2 presence (>5 s)	12:05 PM		logged data	

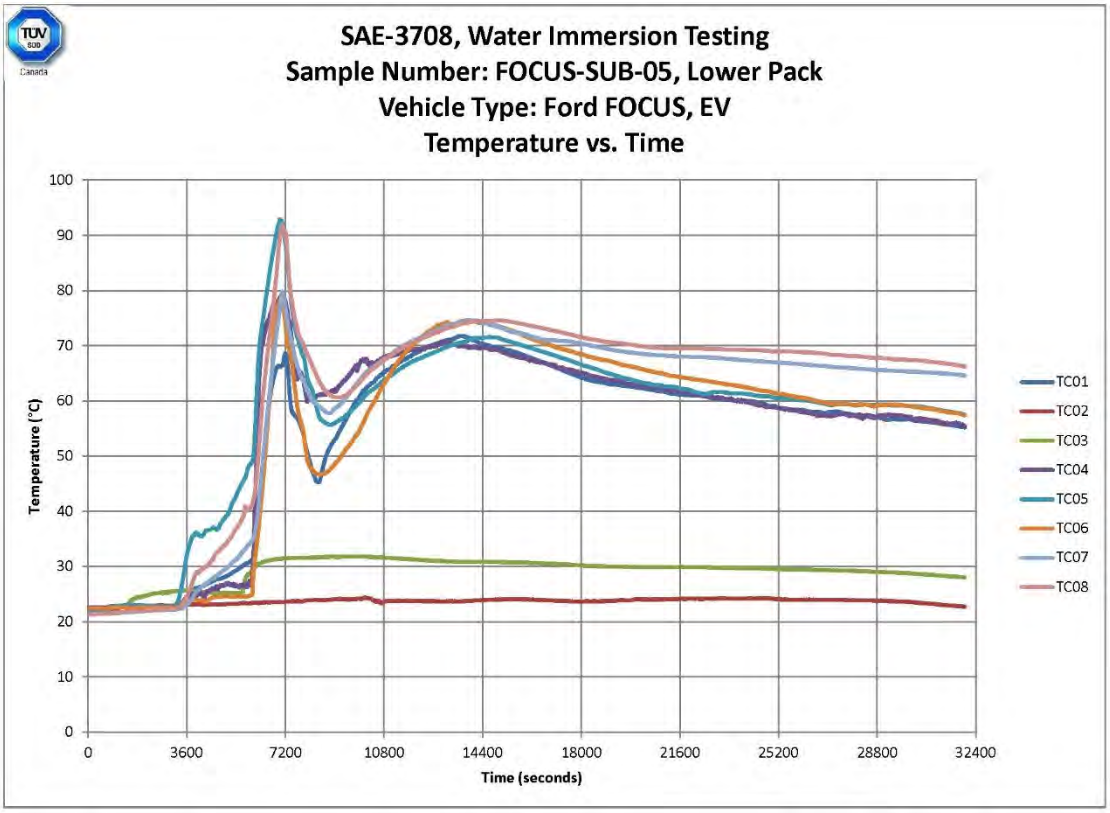


Figure 173 - Ford Focus LP EV temperature profile for the first 9 hours of testing.

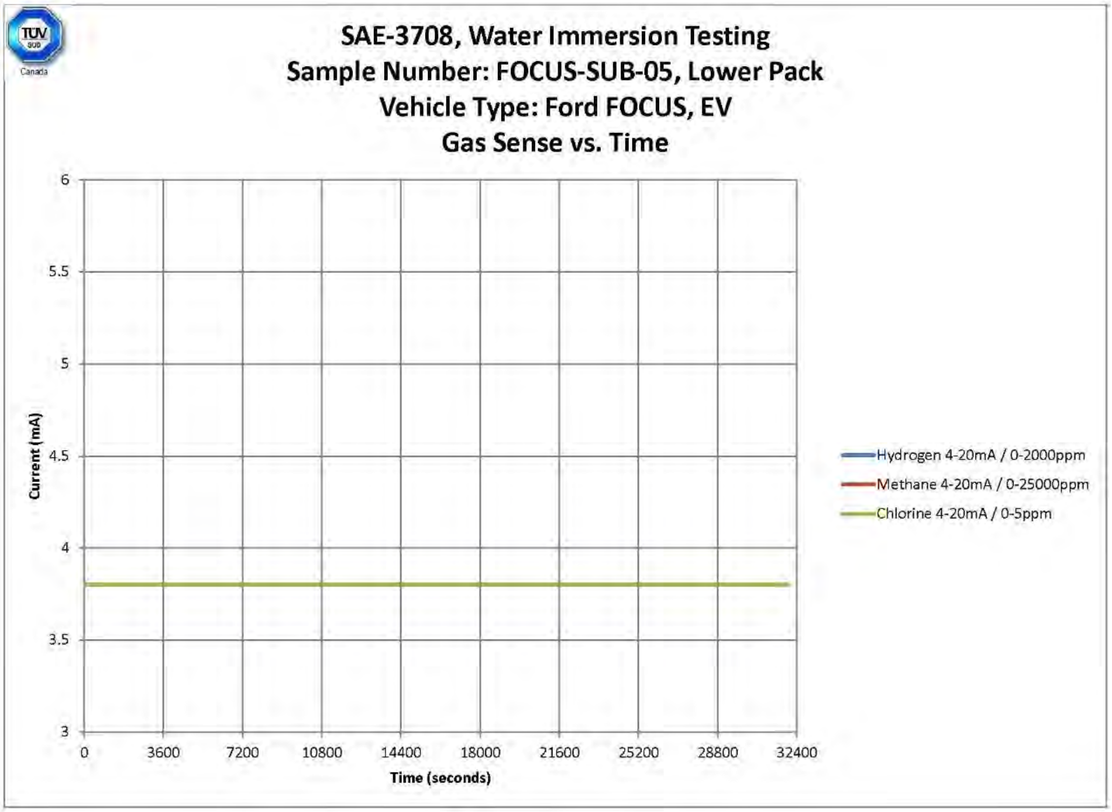


Figure 174 - Ford Focus LP EV gas sensing current for the first 9 hours of testing.

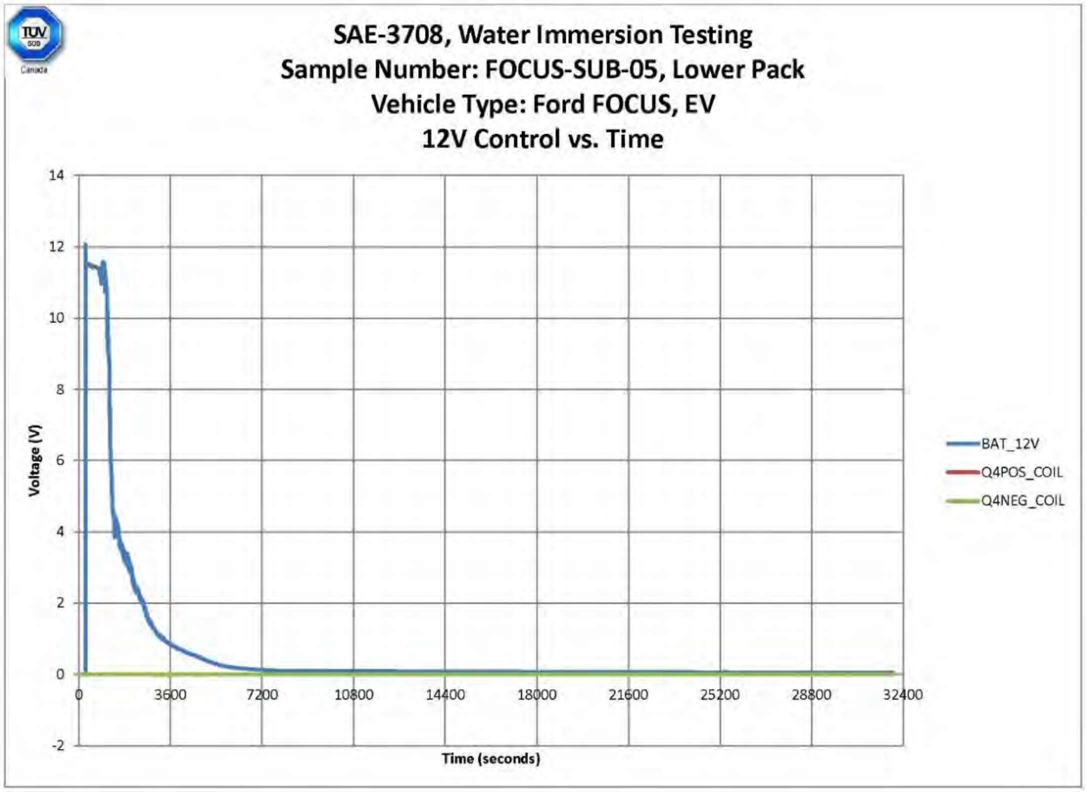


Figure 175 - Ford Focus LP EV 12 V control voltage for the first 9 hours of testing.

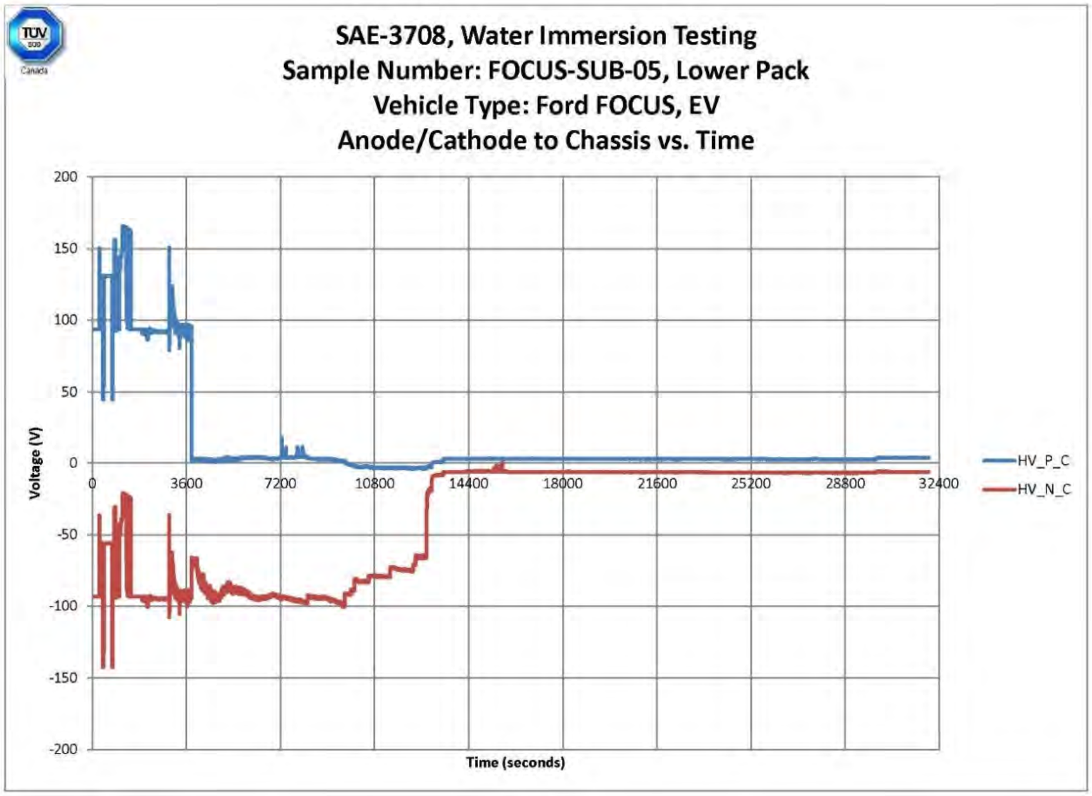


Figure 176 - Ford Focus LP EV electrode to chassis voltage for the first 9 hours of testing.

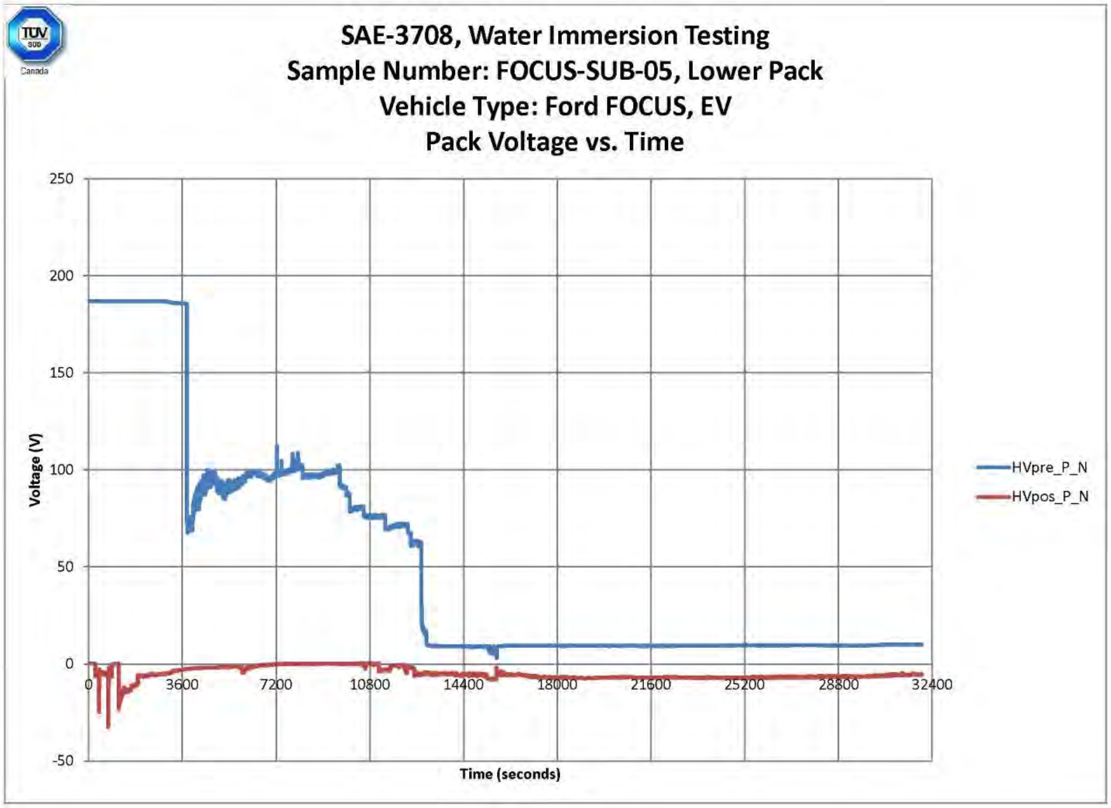


Figure 177 - Ford Focus LP EV RESS voltage for the first 9 hours of testing.

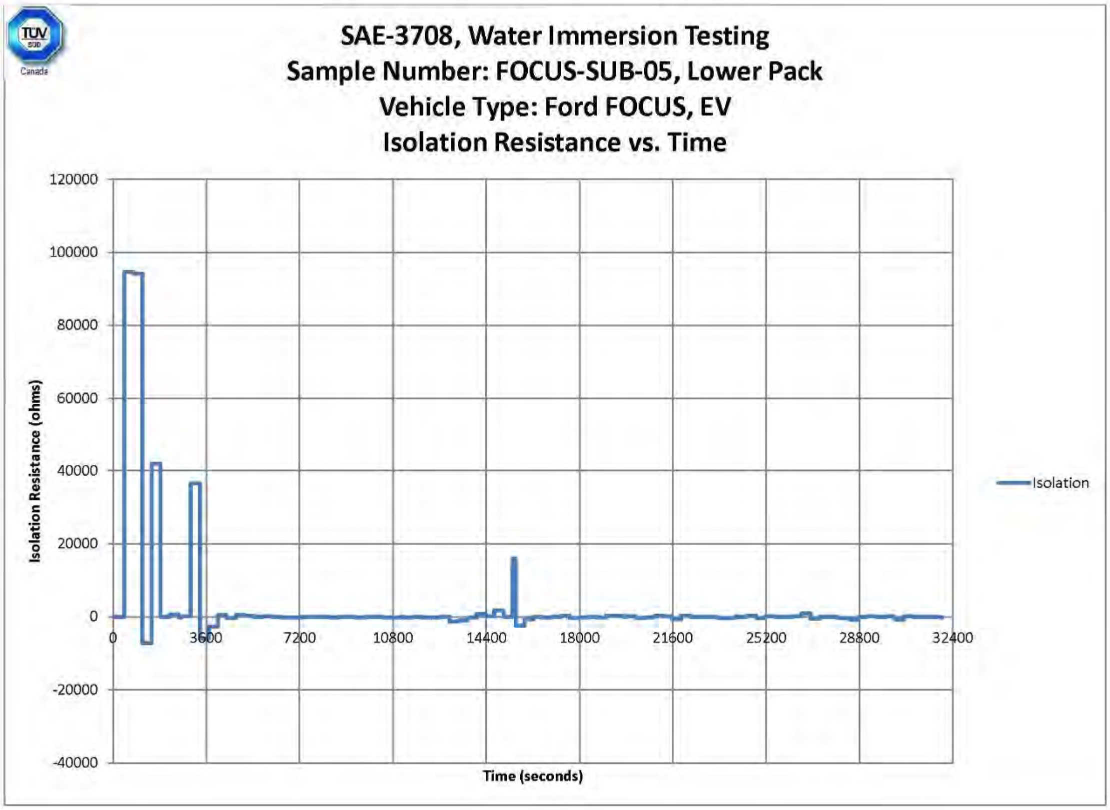


Figure 178 - Ford Focus LP EV isolation resistance for the first 9 hours of testing.

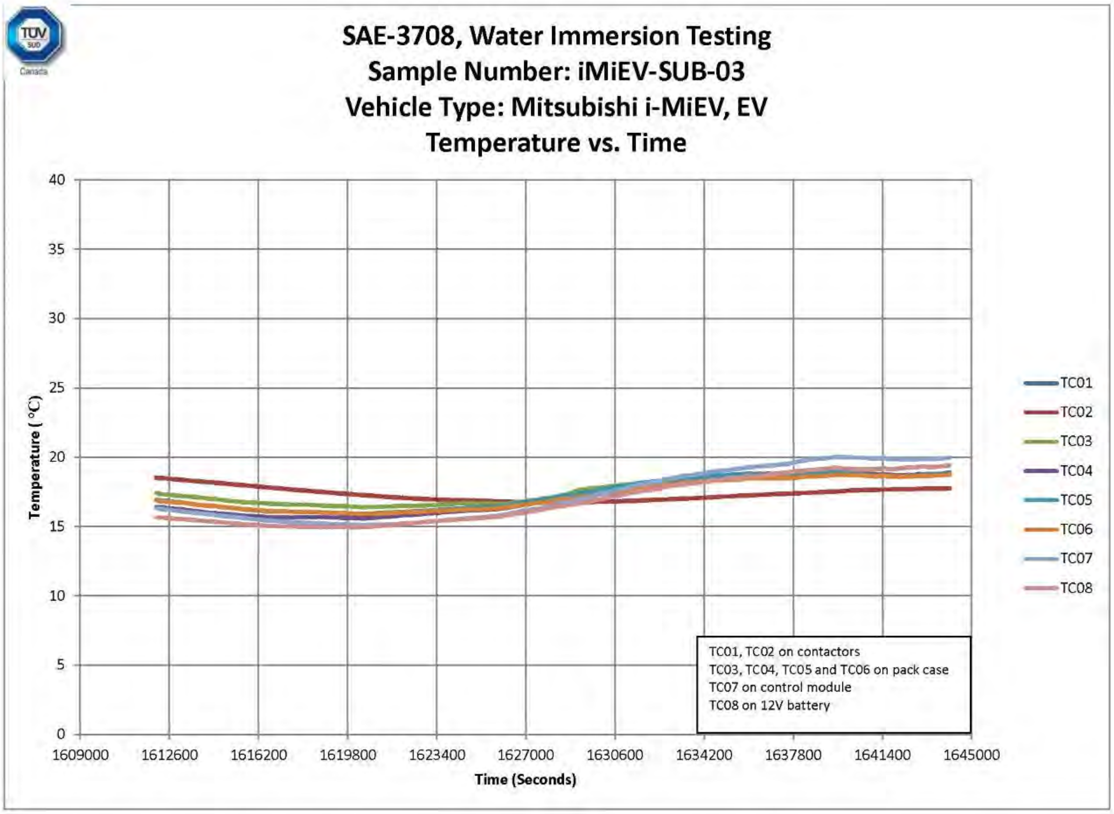


Figure 179 - Ford Focus LP EV temperature profile for the last 10 hours of testing.

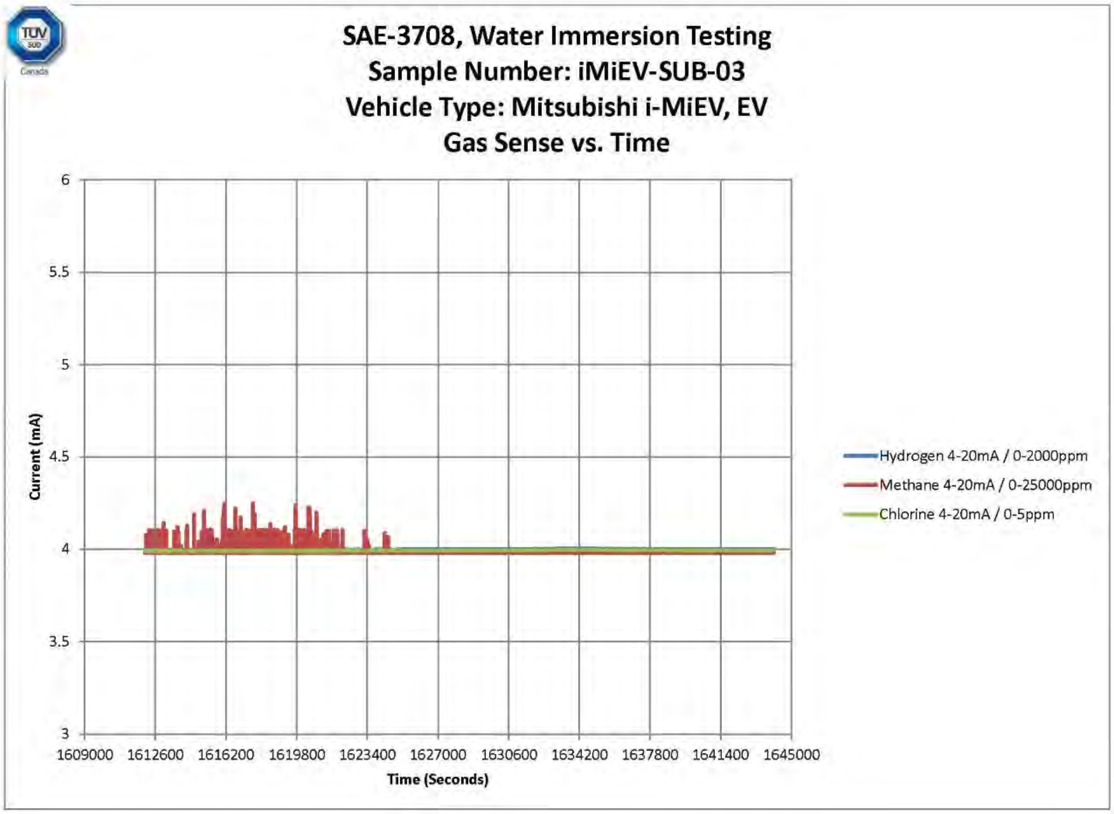


Figure 180 - Ford Focus LP EV gas sensing current for the last 10 hours of testing.

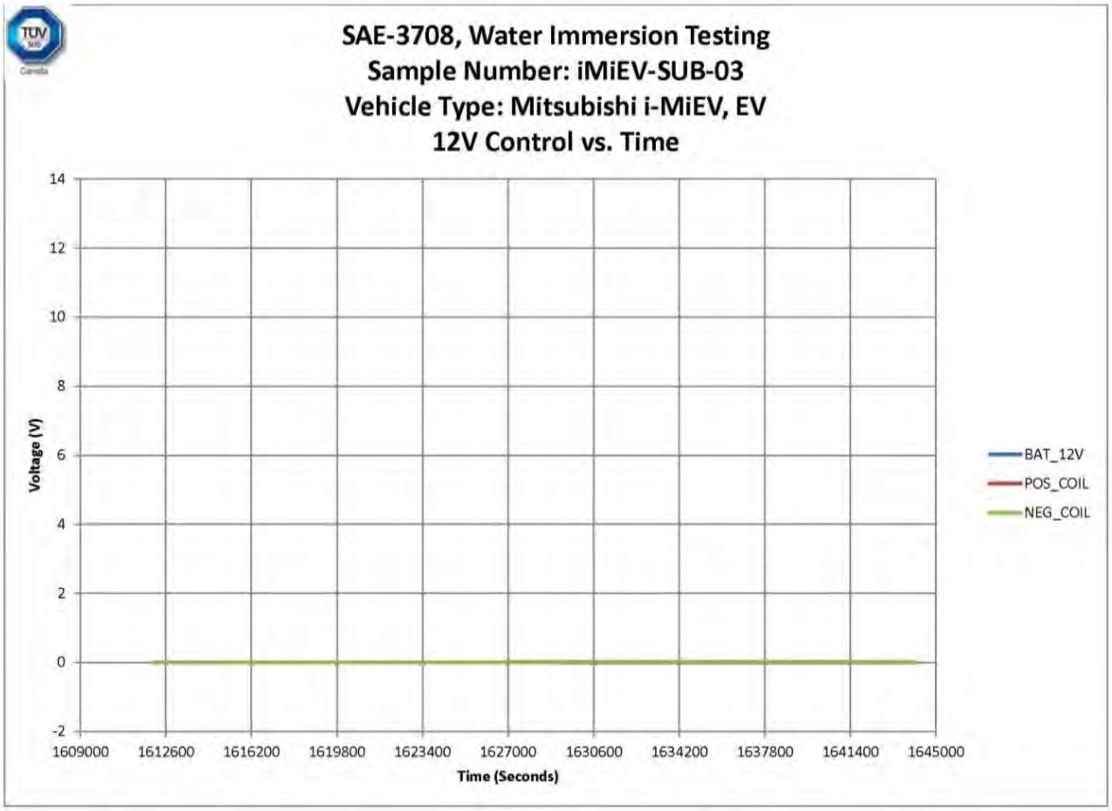


Figure 181 - Ford Focus LP EV 12 V control voltage for the last 10 hours of testing.

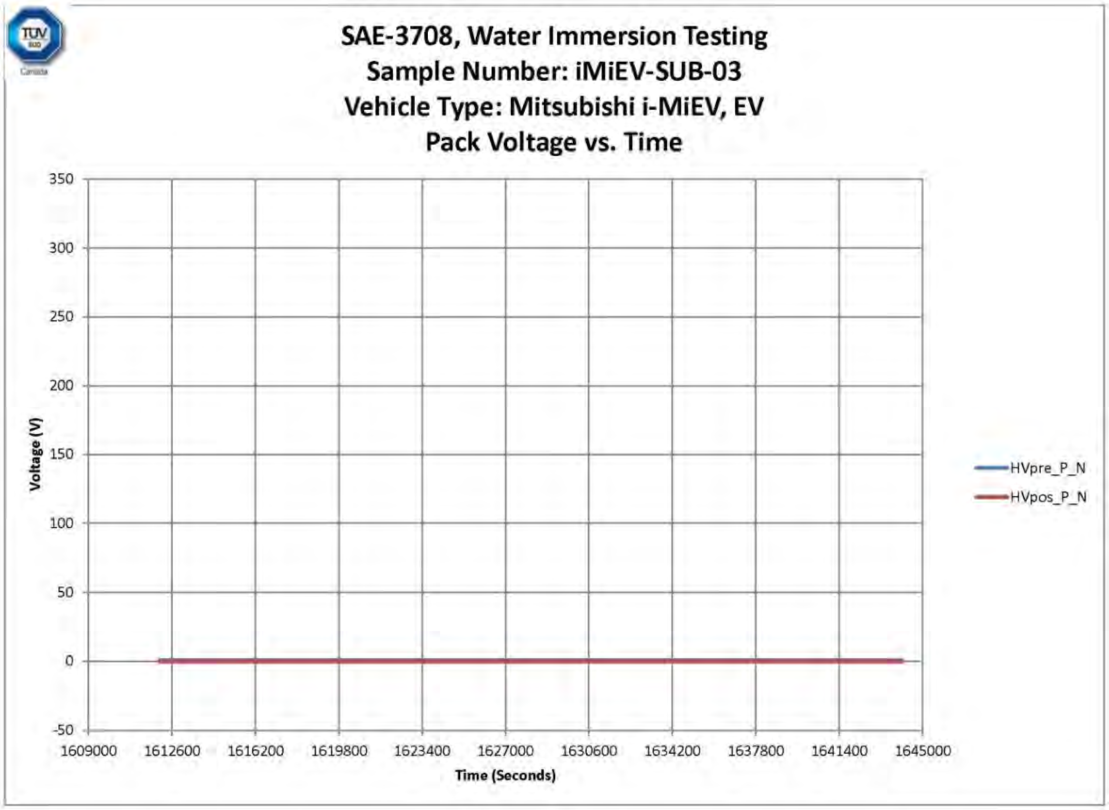


Figure 182 - Ford Focus LP EV RESS voltage for the last 10 hours of testing.

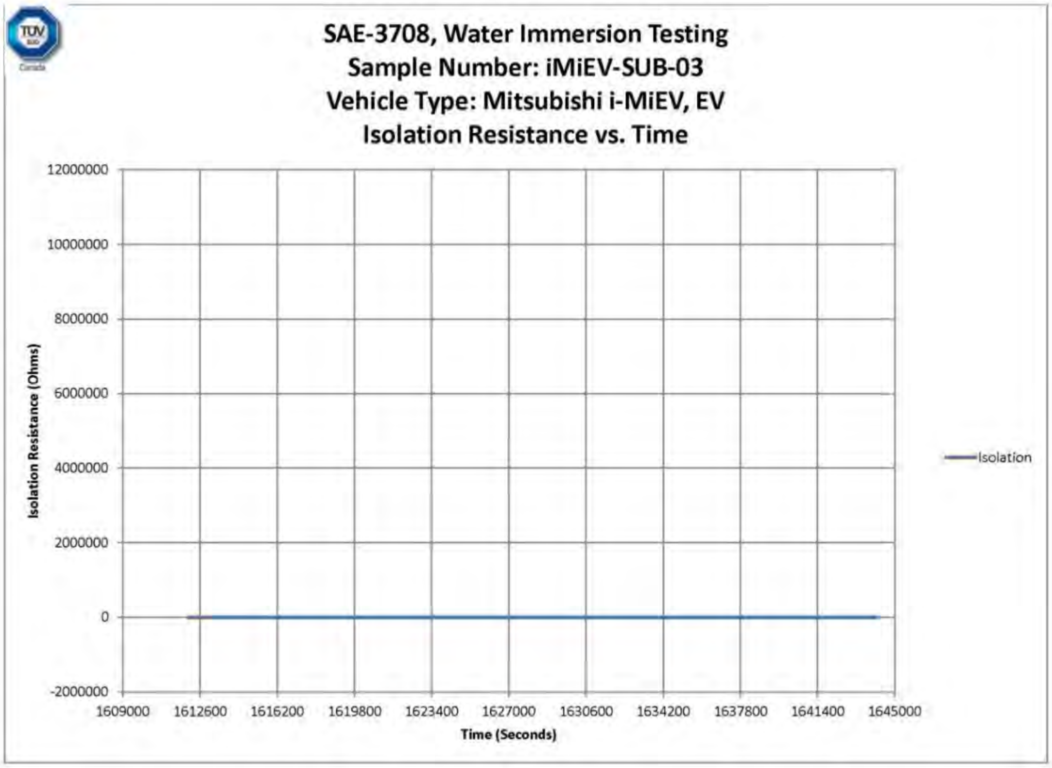


Figure 183 - Ford Focus LP EV isolation resistance for the last 10 hours of testing.

8.3.4.4 Seawater Analysis Results

Seawater samples were taken before and after immersion. They were measured on-site for pH, density and conductivity; the results are summarized in Table 59. Table 60 shows the VOCs that were above the reportable detection limit, as determined from Maxxam Analytics, Inc. Note that the samples were also analyzed for other VOCs that were below the reportable limit. Table 61 shows the total oil and grease content from the samples.

Table 59 - Ford Focus LP EV Conductivity, Salinity, Density, and pH

Time	Conductivity (mS/cm)	Salinity (wt%)	Density (g/cm³)	pH
Pre-immersion	30.5	1.72	1.011	7.6
Post-immersion	30.4	1.72	1.011	7.6

Table 60 - Ford Focus LP EV VOCs above Reportable Detection Limit

Volatile Organics	Units	Pre-Immersion	Post-Immersion	RDL*
Chloroform	μg/L	0.19	0.16	0.10

*RDL=Reportable Detection Limit

Table 61 - Ford Focus LP EV Total Oil and Grease Content

Petroleum Hydrocarbons	Units	Pre-Immersion	Post-Immersion	RDL
Total oil and grease	mg/L	ND*	ND*	0.50

*ND=Not Detected

8.3.4.5 Post-Mortem Analysis

The vehicle itself showed no evidence of any elevated thermal activity either on the interior or exterior. The temperatures increased inside the battery during immersion, and then they declined to ambient levels after 4 hours and then followed the diurnal ambient values until the end of the test. In addition, the water immersion caused the pack voltage to drop from 187 V to 67 V within the first hour of immersion. The voltage then dropped to 9.6 V and was at 8.6 V at the end of the test. Therefore, no post mortem analysis was conducted on this pack.

8.3.5 Ford Focus UP EV

The Ford Focus was a new production EV previously used for front impact testing, see Table 62. Figure 169 (above) shows the as-received vehicle from multiple angles. Figure 170 (above) shows the vehicle in its immersion tank as well as the video camera setup. Note that the Ford Focus has two battery packs, so the testing was repeated twice. This report focuses on the upper pack (UP) RESS. The vehicle was immersed in brackish water made with sea salt crystals and fresh water formulated to be 17.5 g/kg for a duration of 1 hour.

Table 62 - Ford Focus UP EV Details

Vehicle Class	Passenger Car
Manufacturer	Ford
Make	Focus
Model	BEV
Date of Manufacture	Dec-2012
VIN	1FADP3R48DL217777
Condition	Damaged (Front impact)
Vehicle Type	EV

8.3.5.1 Sample Preparation

As received, the vehicle was damaged from front impact testing and not operational. All the loose interior parts were tagged and removed from the cabin. The battery pack was showing fully charged based on dashboard display (this was a display of both packs, they could not be checked individually). The 12 V battery was removed, followed by the MSD's from both packs and the HV cables. The pack cooling system was drained.

For HV and isolation measurements, the RESS was removed from the vehicle and the contactor assembly was taken apart (see Figure 184). The measurement wires were then tightly bolted to the bus bars. The RESS was sealed to prevent water intrusion through the sense leads exiting the pack (see Section 8.1.2). The contactor was reassembled and re-installed in the pack. Butyl tape was replaced where necessary to ensure sealing of the RESS enclosure. The RESS was placed back into the car and the cooling system was re-filled. Voltage sense cables were installed on the 12 V battery.

A total of eight thermocouples were installed as specified in test procedure (see Section 6.5.1.13), including the RESS enclosure, near contactors, the control unit, and the 12 V battery. Thermocouple locations are provided in Table 63 and shown in Figure 185. The thermocouples were held in position using epoxy adhesive.

Three gas sensors were also mounted above the driver window (see Section 7.2).

Table 63 - Ford Focus UP EV Thermocouple Placement

Number	Location
TC6, TC5	Contactors
TC1, TC2, TC3, TC4	RESS enclosure
TC8	Control unit
TC7	12 V battery

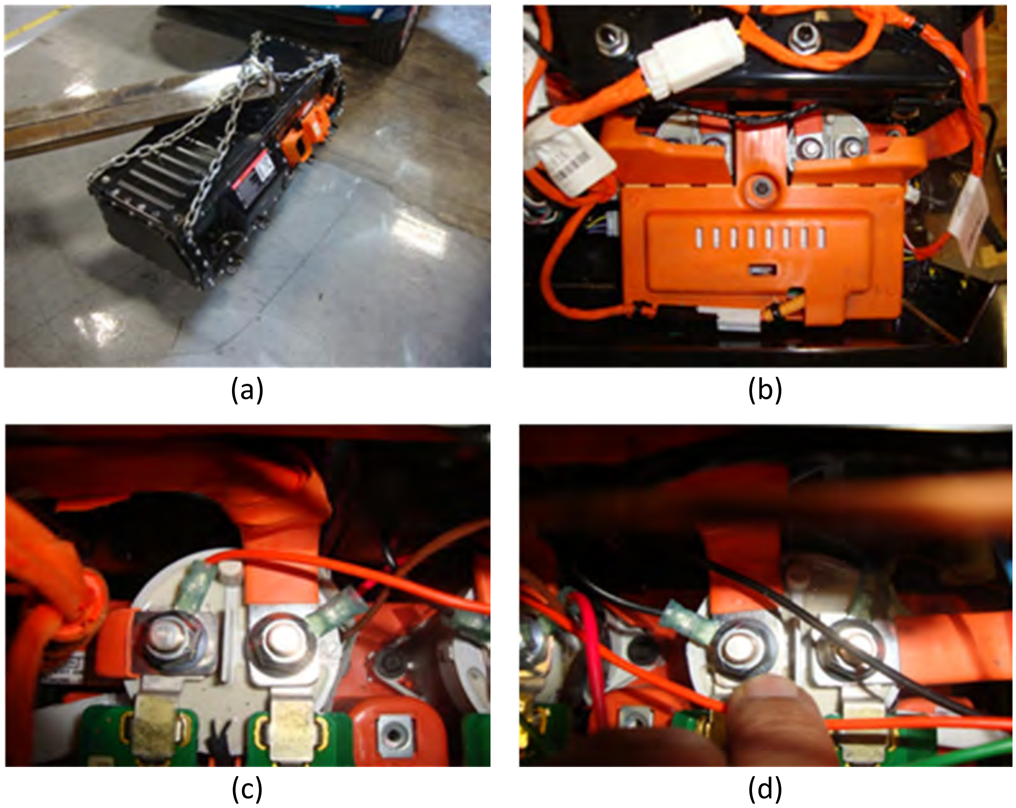
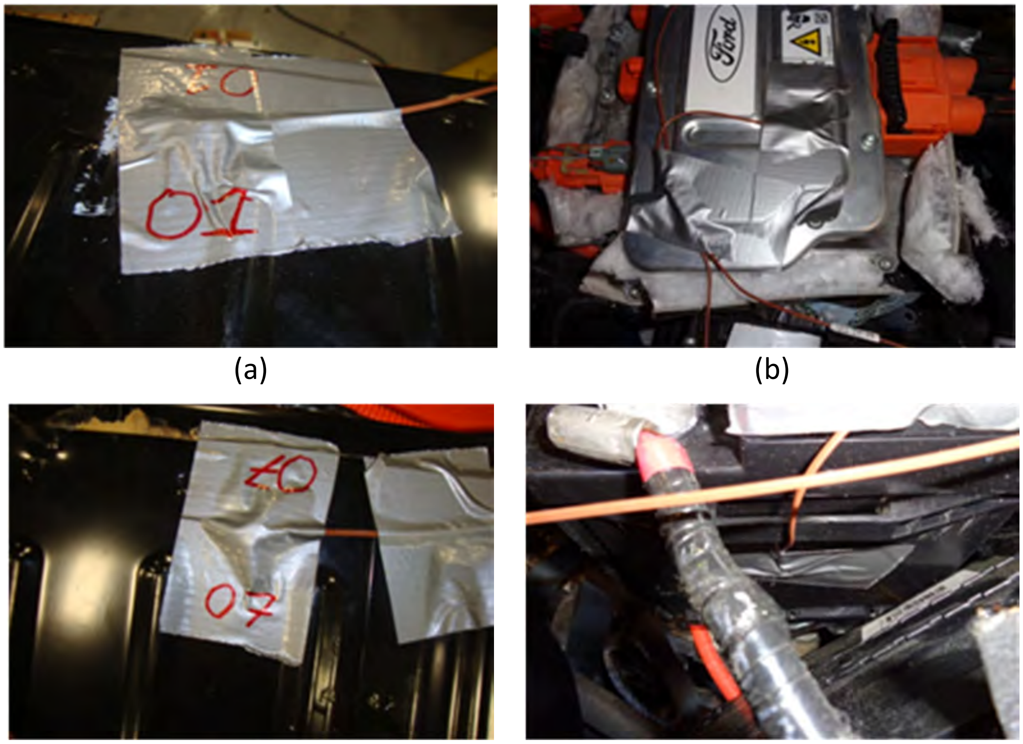

(a) (b) (c) (d)

Figure 184 - Ford Focus UP EV HV connections: a) RESS removed from vehicle, b) contactor assembly, c) sense leads bolted to bus bar, and d) sense leads bolted to bus bar.



(a) (b)

(c) (d)

Figure 185 - Ford Focus UP EV HV thermocouple placement: a) TC on the RESS case, b) TC on the control unit, c) TC RESS case, and d) TC on the 12 V battery.

8.3.5.2 Test Conditions

Testing was performed outdoors in ambient temperatures of approximately 24°C. There was no precipitation on the day the vehicle was immersed. The vehicle remained in the immersion container during the post-extraction observation period.

8.3.5.3 Immersion Test Results

The test event log is summarized in Table 64. Figures 186 through 191 show measured data for the initial 9 hours of the test as follows:

- Figure 186 - Temperature profile for the first 9 hours of testing
- Figure 187 - Gas sensing current for the first 9 hours of testing
- Figure 188 - 12 V control voltage for the first 9 hours of testing
- Figure 189 - Electrode to chassis voltage for the first 9 hours of testing
- Figure 190 - RESS voltage for the first 9 hours of testing
- Figure 191 - Isolation resistance for the first 9 hours of testing

Figures 192 through 196 show measured data for the final 10 hours of the test as follows:

- Figure 192 - Temperature profile for the last 10 hours of testing
- Figure 193 - Gas sensing current for the last 10 hours of testing
- Figure 194 - 12 V control voltage for the last 10 hours of testing
- Figure 195 - RESS voltage for the last 10 hours of testing
- Figure 196 - Isolation resistance for the last 10 hours of testing

Table 64 - Ford Focus UP EV Test Event Log

Event	Time	Temperature	Primary Source	Secondary Source
Start of immersion	11:40 AM		Test field notes	
Start of self-heating in observation period (if any)	N/A		graphs	Test field notes
Time at first flames	N/A		video	IR camera
Highest recorded HV battery temperature at time of first flames		N/A	graphs	
Time of first bang, explosion or pressure wave captured on video	N/A		video	
Time of first smoke/gases/vapor	N/A		video	IR camera
Time of RESS case maximum temperature	3:12 PM		graphs	
Maximum RESS case temperature		99°C	logged data	
Time when RESS pre-contactor voltage is more than $V_{initial}$ ± 2%	11:56 AM		graphs	logged data
Time when the LV battery voltage is more than $V_{initial}$ ± 2%	11:50 AM		graphs	logged data
Time to first measurement of sustained (>110% of initial reading) CH_4 presence (>5 s)	N/A		logged data	
Time to first measurement of sustained (>110% of initial reading) CL_2 presence (>5 s)	N/A		logged data	
Time to first measurement of sustained (>110% of initial reading) H_2 presence (>5 s)	12:05 PM		logged data	

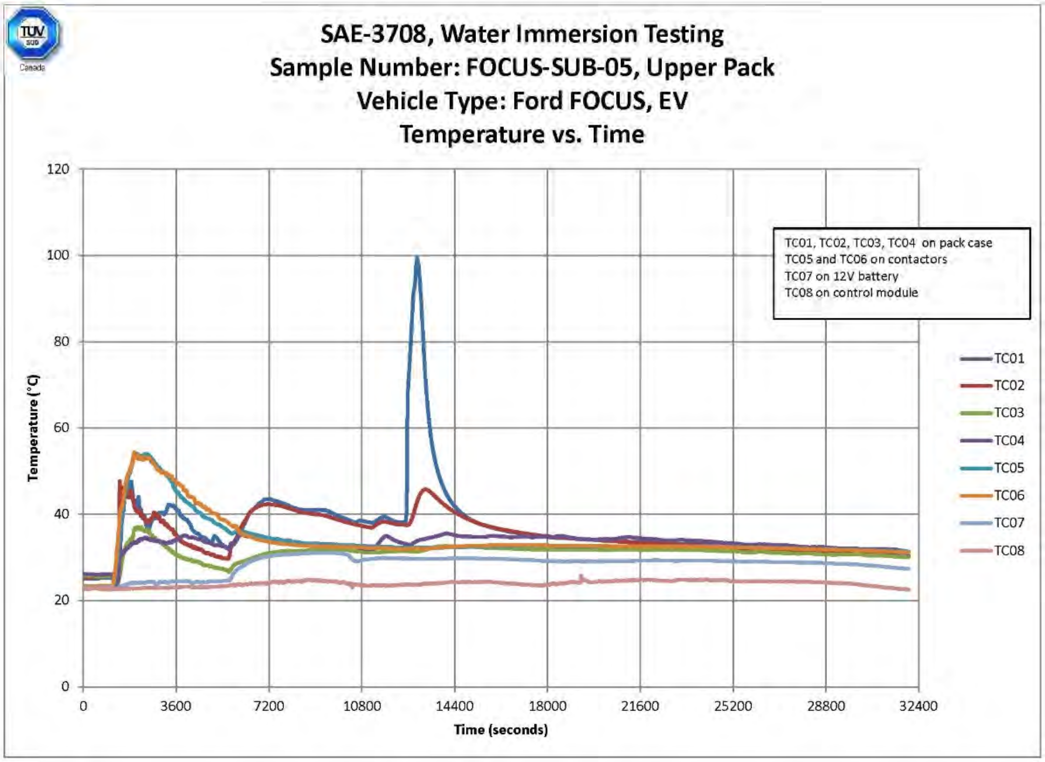


Figure 186 - Ford Focus UP EV temperature profile for the first 9 hours of testing.

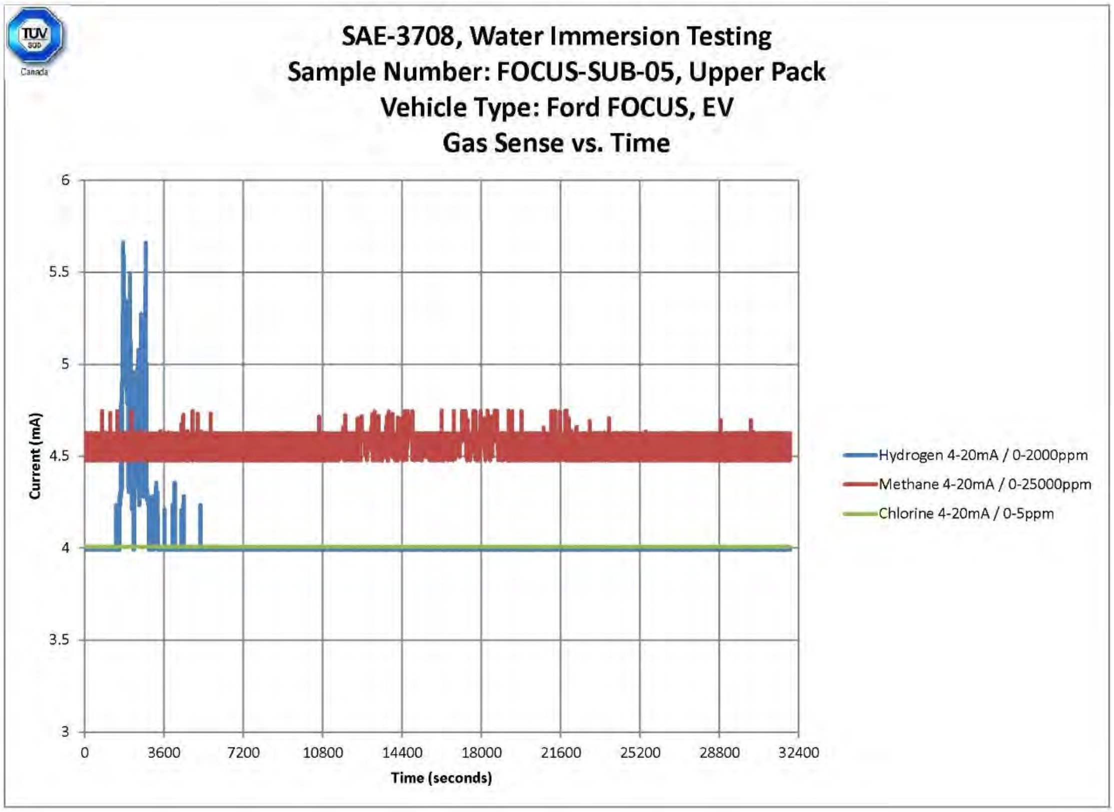


Figure 187 - Ford Focus UP EV gas sensing current for the first 9 hours of testing.

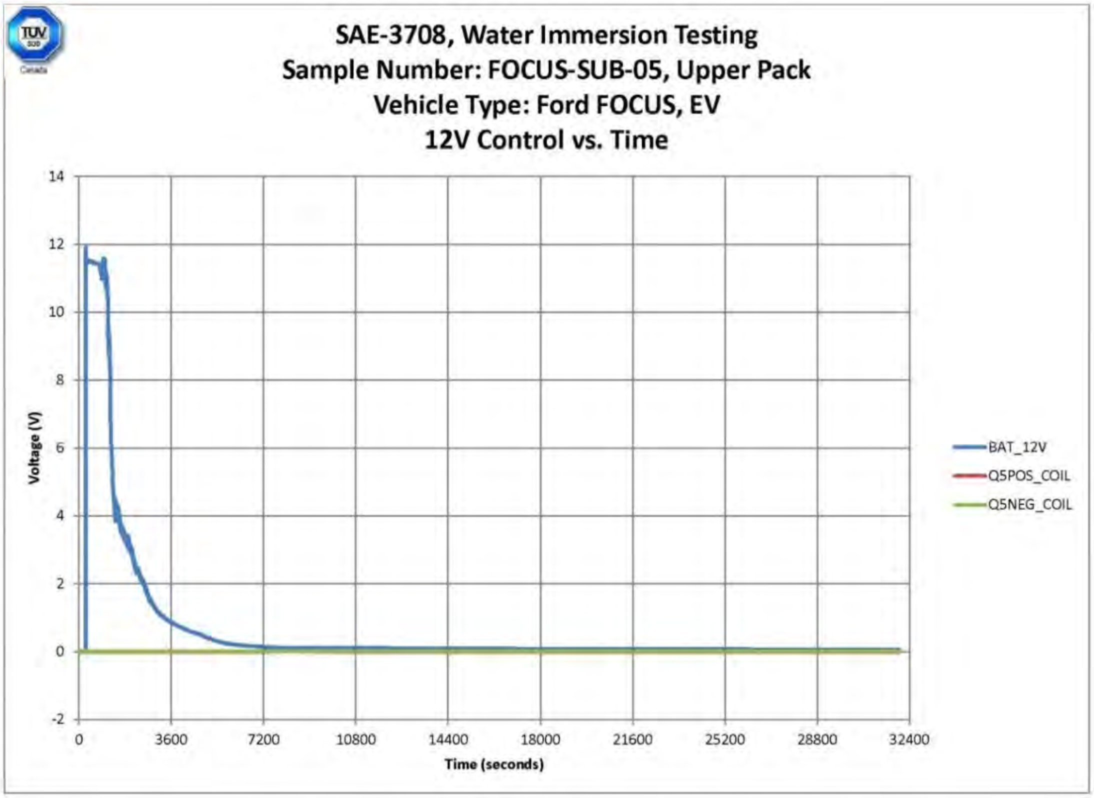


Figure 188 - Ford Focus UP EV 12 V control voltage for the first 9 hours of testing.

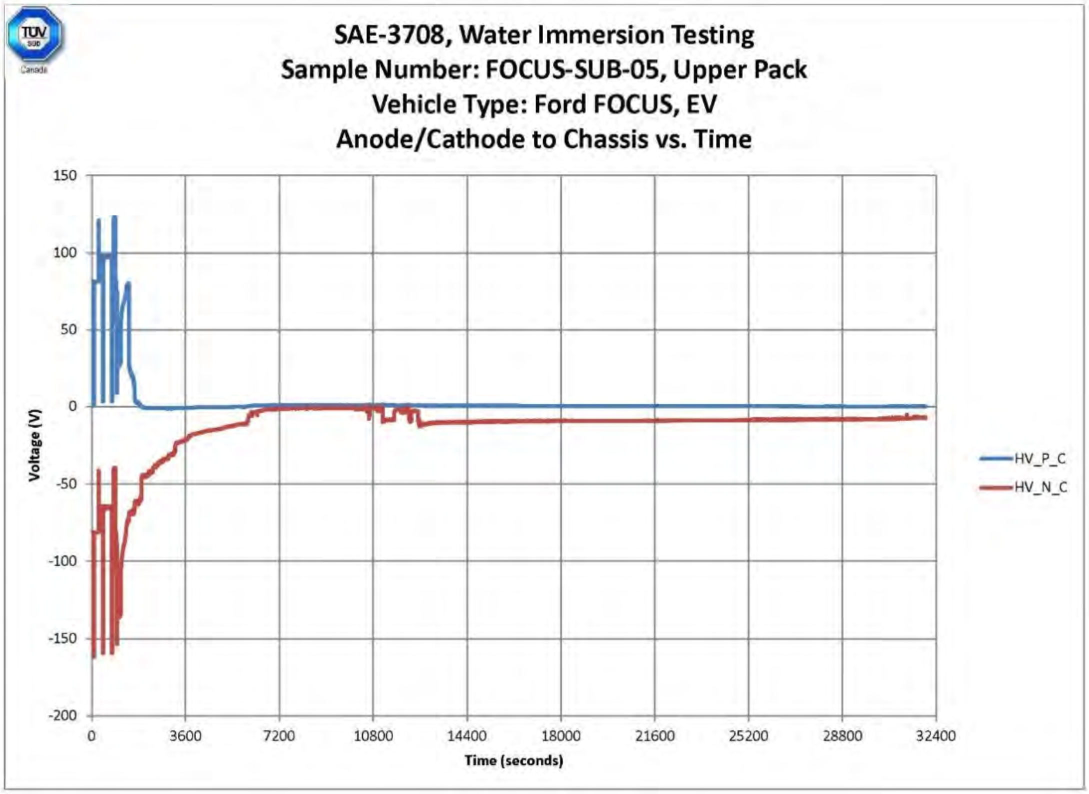


Figure 189 - Ford Focus UP EV electrode to chassis voltage for the first 9 hours of testing.

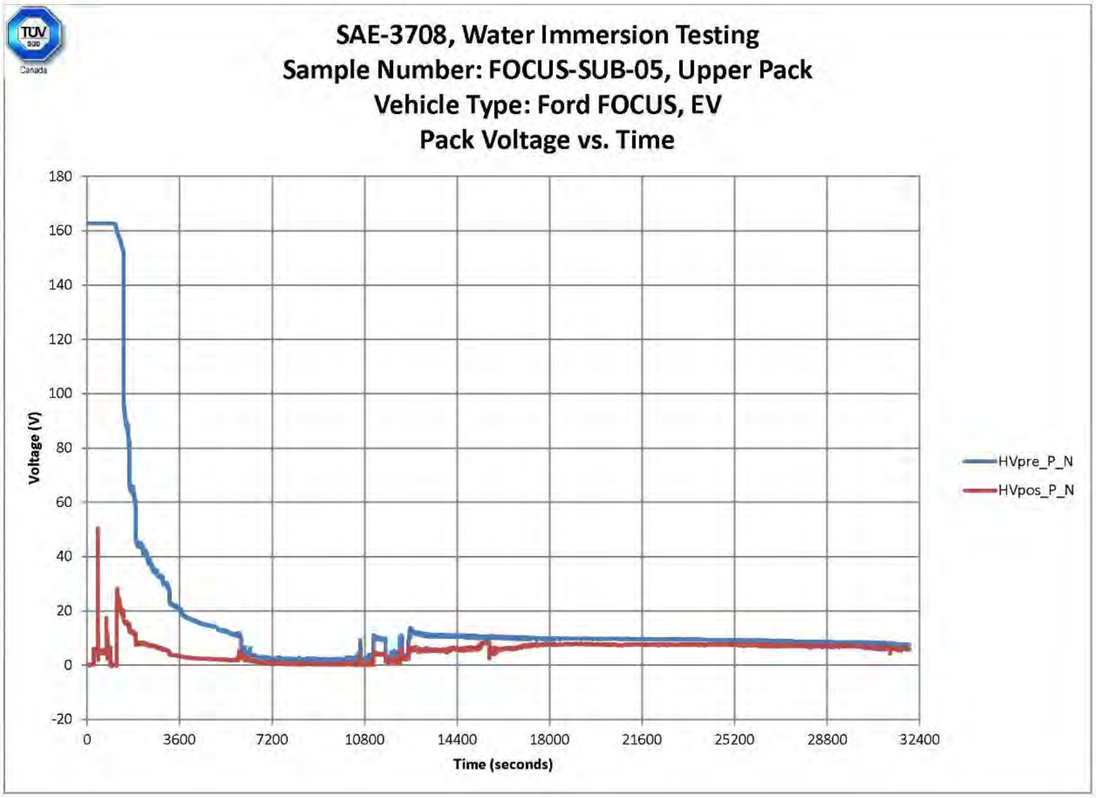


Figure 190 - Ford Focus UP EV RESS voltage for the first 9 hours of testing.

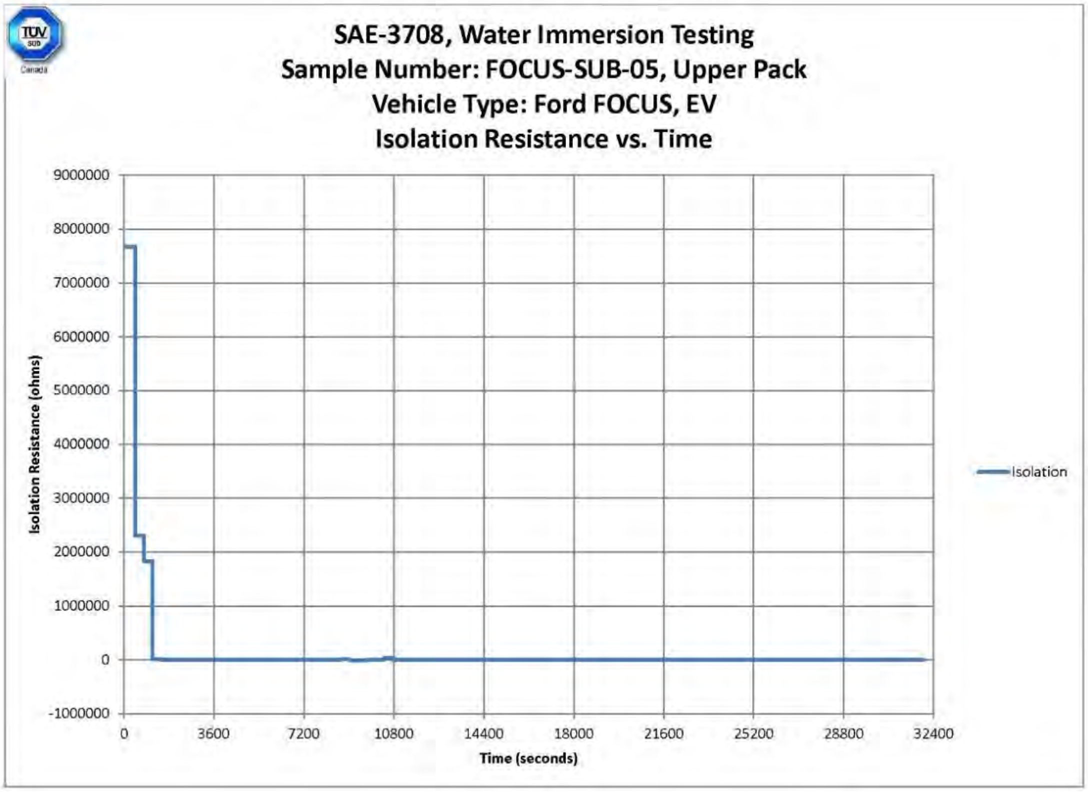


Figure 191 - Ford Focus UP EV isolation resistance for the first 9 hours of testing.

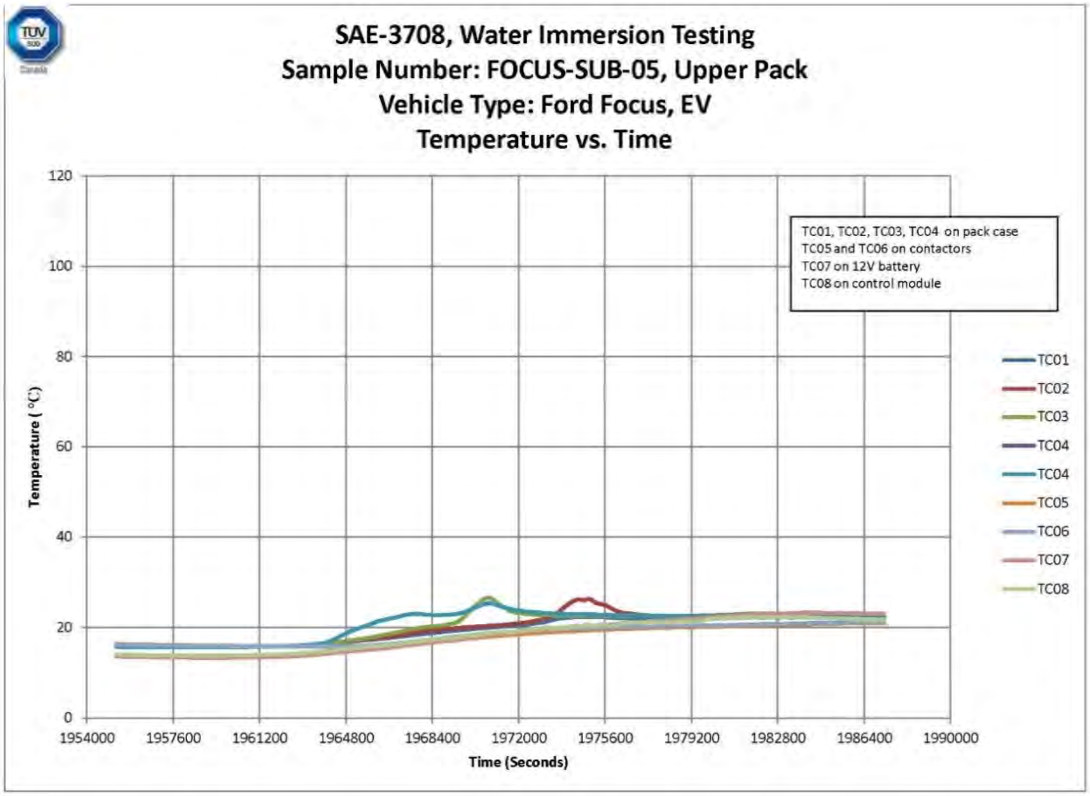


Figure 192 - Ford Focus UP EV temperature profile for the last 10 hours of testing.

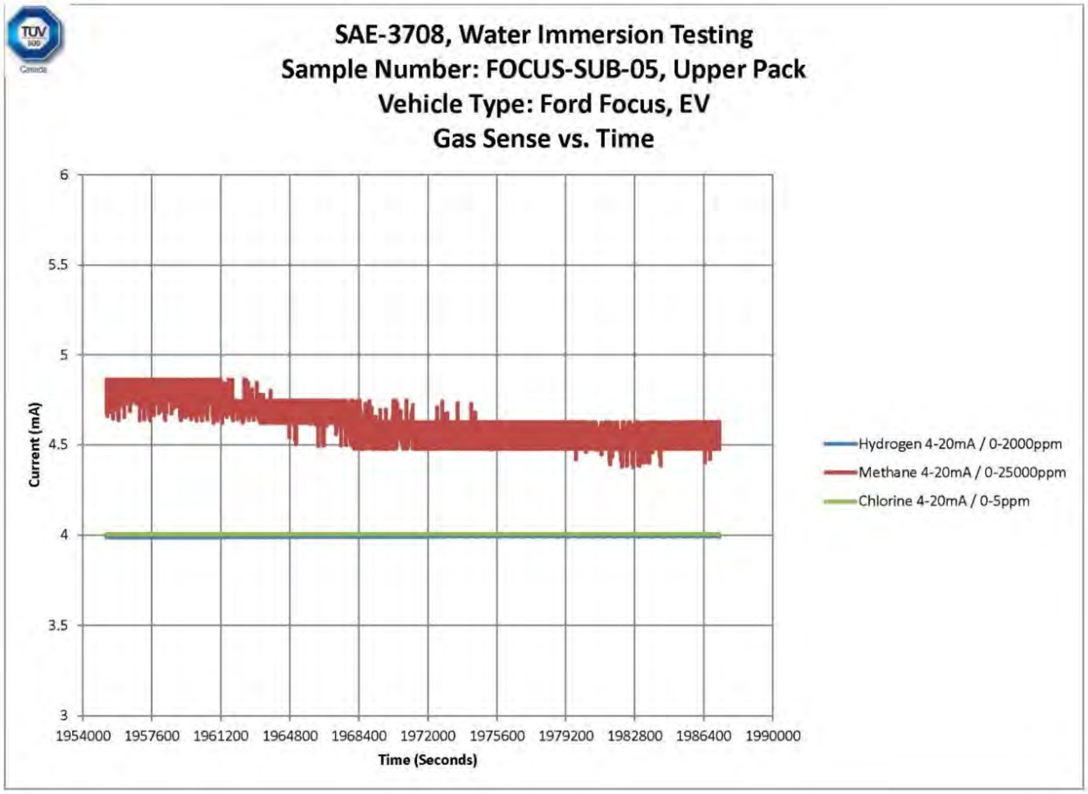


Figure 193 - Ford Focus UP EV gas sensing current for the last 10 hours of testing.

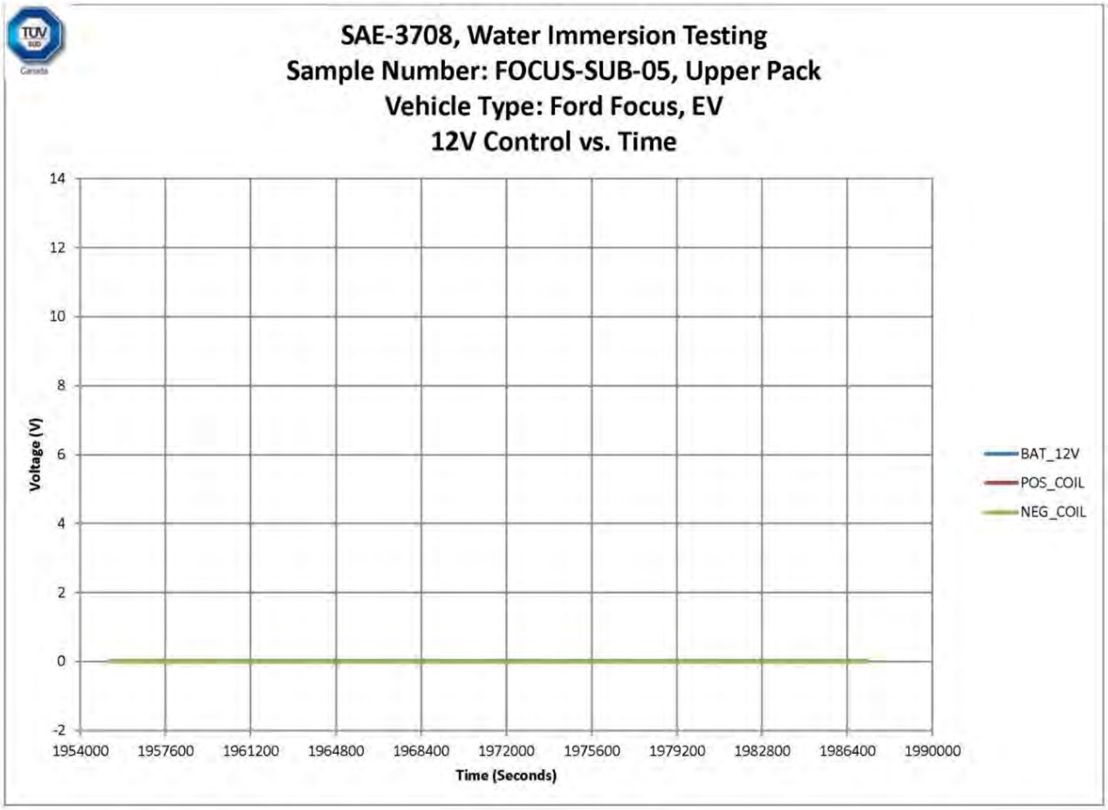


Figure 194 - Ford Focus UP EV 12 V control voltage for the last 10 hours of testing.

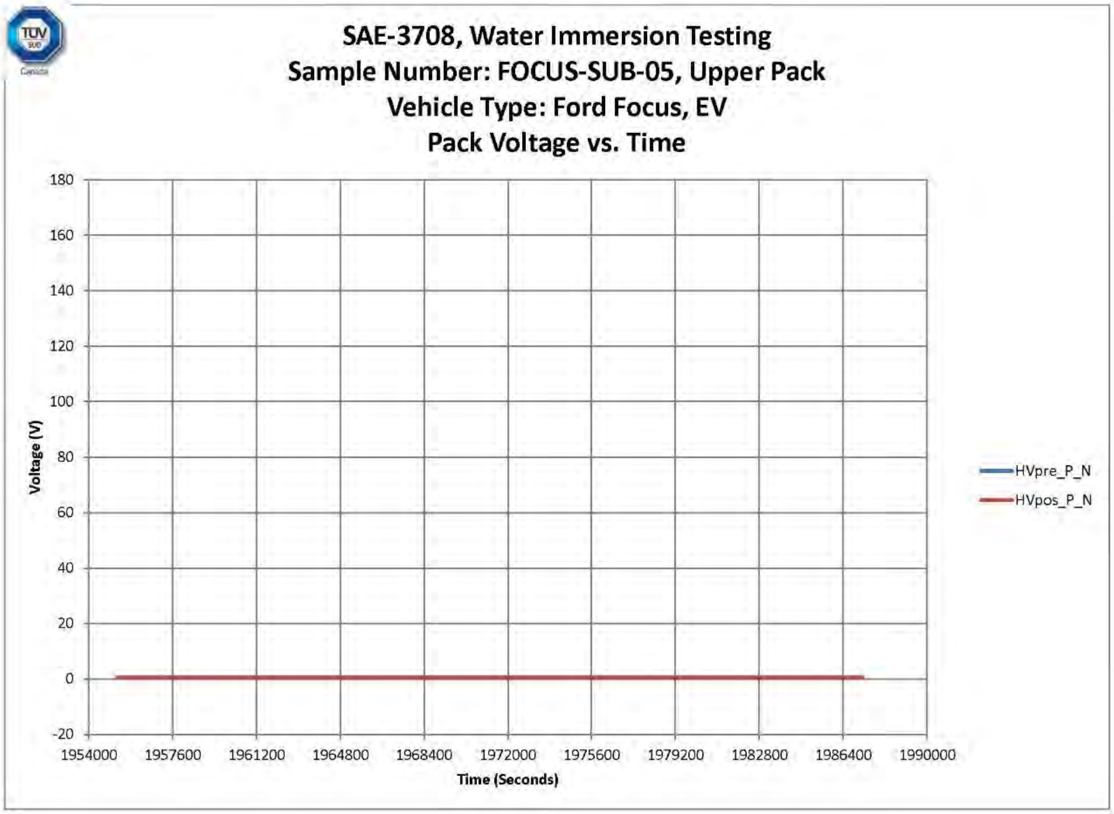


Figure 195 - Ford Focus UP EV RESS voltage for the last 10 hours of testing.

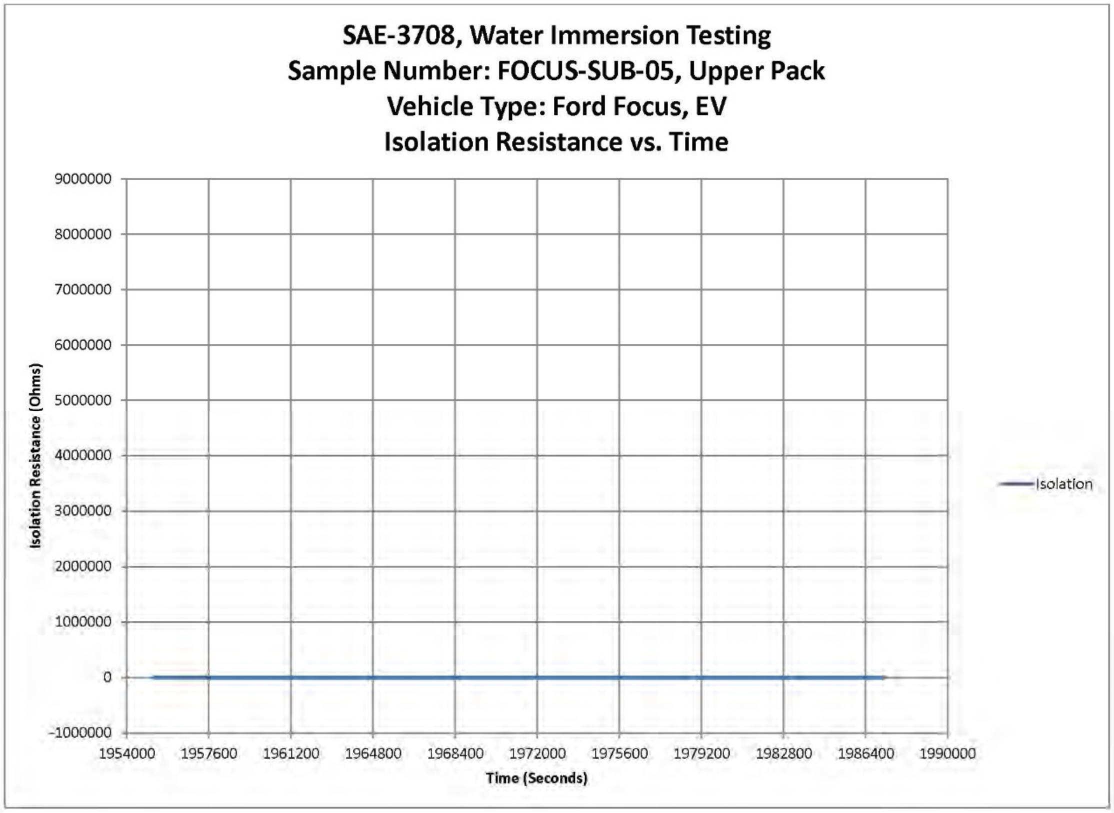


Figure 196 - Ford Focus UP EV isolation resistance for the last 10 hours of testing.

8.3.5.4 Seawater Analysis Results

Seawater samples were taken before and after immersion. They were measured on-site for pH, density and conductivity; the results are summarized in Table 65. Table 66 shows the VOCs that were above the reportable detection limit, as determined from Maxxam Analytics, Inc. Note that the samples were also analyzed for other VOCs that were below the reportable limit. Table 67 shows the total oil and grease content from the samples.

Table 65 - Ford Focus UP EV Conductivity, Salinity, Density, and pH

Time	Conductivity (mS/cm)	Salinity (wt%)	Density (g/cm³)	pH
Pre-immersion	30.5	1.72	1.011	7.6
Post-immersion	30.4	1.72	1.011	7.6

Table 66 - Ford Focus UP EV VOCs above Reportable Detection Limit

Volatile Organics	Units	Pre-Immersion	Post-Immersion	RDL*
Chloroform	µg/L	0.19	0.16	0.10

*RDL=Reportable Detection Limit

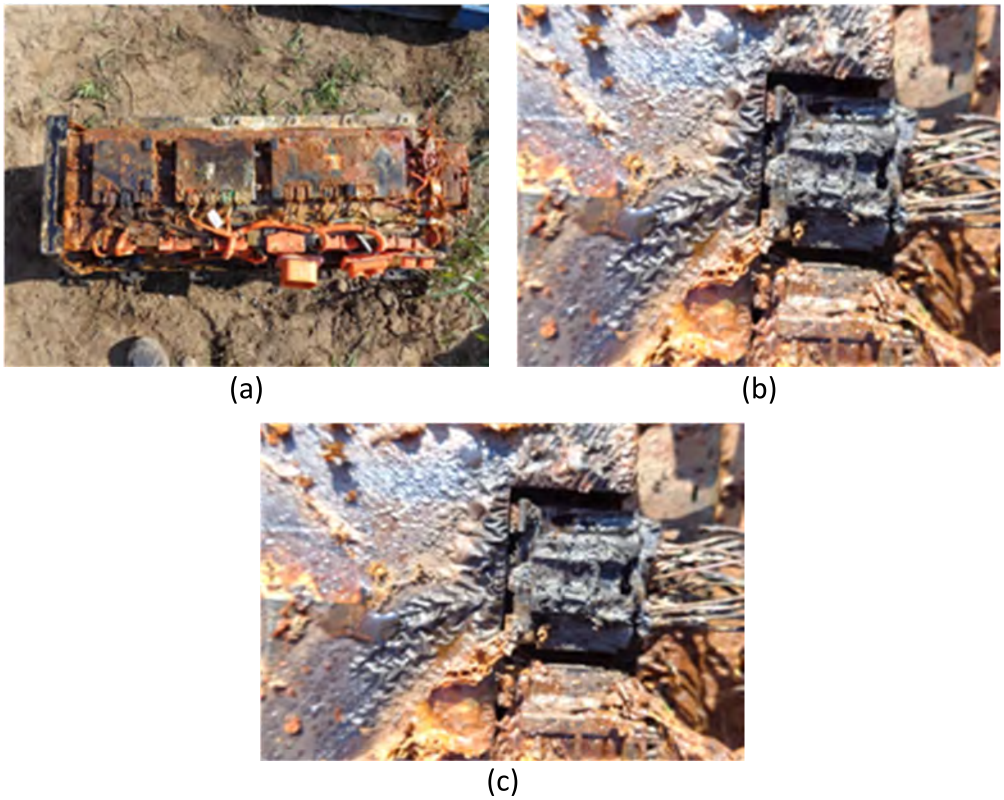
Table 67 - Ford Focus UP EV Total Oil and Grease Content

Petroleum Hydrocarbons	Units	Pre-Immersion	Post-Immersion	RDL
Total oil and grease	mg/L	ND*	ND*	0.50

*ND=Not Detected

8.3.5.5 Post-Mortem Analysis

This vehicle was selected for a post-mortem analysis based on evidence of overheating inside the upper pack. The vehicle itself showed no evidence of any elevated thermal activity either on the interior or exterior. The upper pack showed no signs of heat damage or smoke on its exterior. However, the interior of the pack did have heat damage on the wiring as shown in Figure 197. The DAQ RESS thermocouple records show an excursion as measured on the battery case reaching 99°C over a period of about 15 minutes. The voltage during this period was very low at about 10 V and stable. RESS isolation was very low, at about 150Ω.



(a) (b)

(c)

Figure 197 - Ford Focus UP EV post-mortem analysis: a) module with damaged wiring, b) module with damaged wiring close-up, and c) heat damaged paint close-up on elecronic module.

8.3.6 GM Volt PHEV

The GM Volt (Volt-2) was a new production PHEV, see Table 68. Figure 198 shows the as-received vehicle from multiple angles. Figure 199 shows the vehicle in its immersion tank as well as the video camera setup.

Table 68 - GM Volt-2 PHEV Details

Vehicle Class	Passenger Car
Manufacturer	GM
Make	Chevrolet
Model	Volt
Date of Manufacture	February 2014
VIN	1G1RA6E47EU153437
Condition	New
Vehicle Type	PHEV

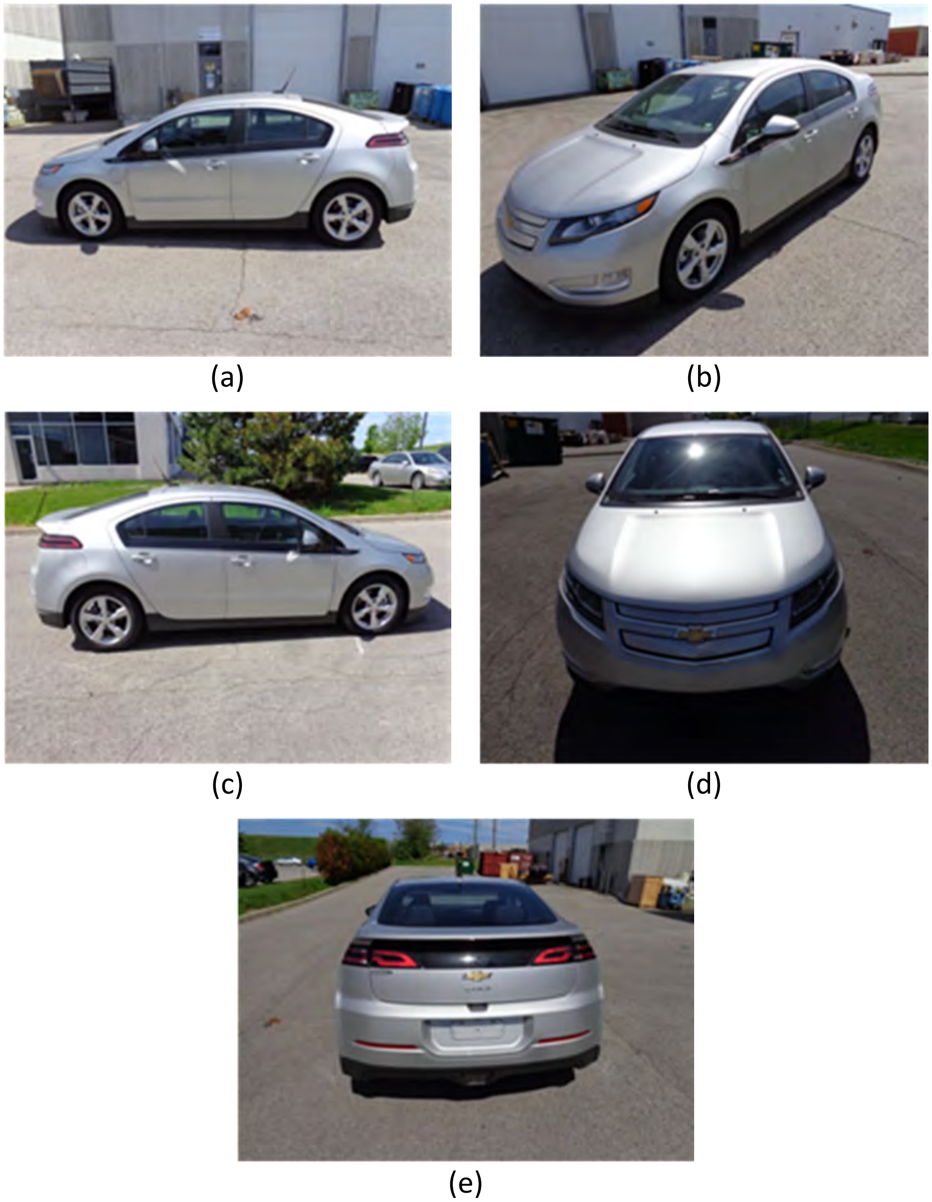

(a) (b) (c) (d) (e)

Figure 198 - GM Volt-2 PHEV initial vehicle condition: a) left view, b) front ¾ view, c) right view, d) front view, and e) rear view.

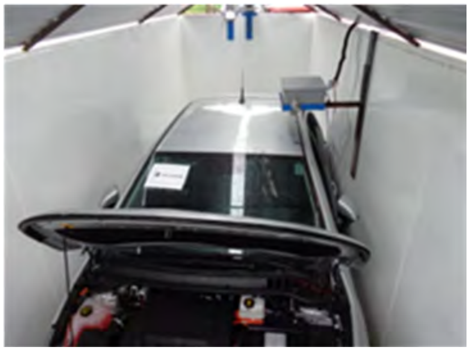


Figure 199 - GM Volt-2 PHEV in its immersion container.

8.3.6.1 Sample Preparation

As received, the vehicle was new and operational. The display showed near 0% SOC in the battery pack and the fuel tank was also near empty. All the loose interior parts were tagged and removed from the cabin.

For HV and isolation measurements, the RESS was removed from the vehicle and the contactor assembly was taken apart (see Figure 200). The HV measurement wires were tightly bolted to the bus bars of the assembly. The coil wires were soldered to the pins of the electrical connectors. The RESS was sealed to prevent water intrusion through the sense leads exiting the pack (see Section 8.1.2). The contactors were reassembled and re-installed in the pack. The RESS was then charged to approximately 70% SOC to mimic the state of charge in the previous test. From an empty tank, 5 L of fuel was added (see Section 6.4). Voltage sense cables were installed onto the 12 V battery.

A total of eight thermocouples were installed as specified in test procedure (see Section 6.5.1.13), including the RESS enclosure, near contactors, the control unit, and the 12 V battery. Thermocouple locations are provided in Table 69 and shown in Figure 201. The thermocouples were held in position using epoxy adhesive.

Three gas sensors were also mounted above the driver window (see Section 7.2).

Table 69 - GM Volt-2 PHEV Thermocouple Placement

Number	Location
TC1, TC2	Contactors
T3, TC4, TC5, TC6	RESS enclosure
TC7	Control module
TC8	12 V battery

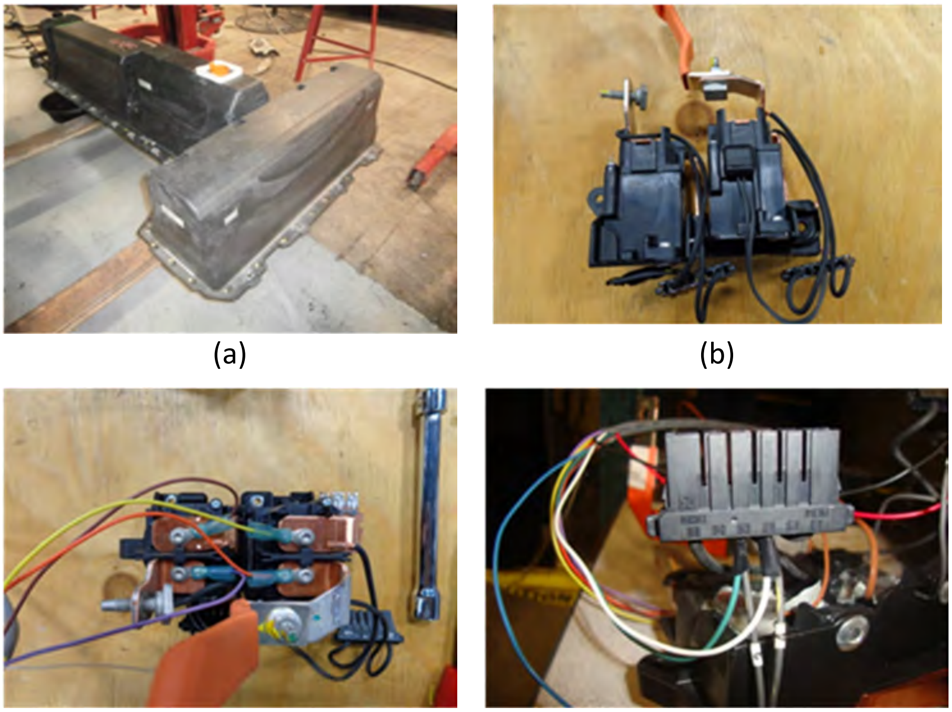
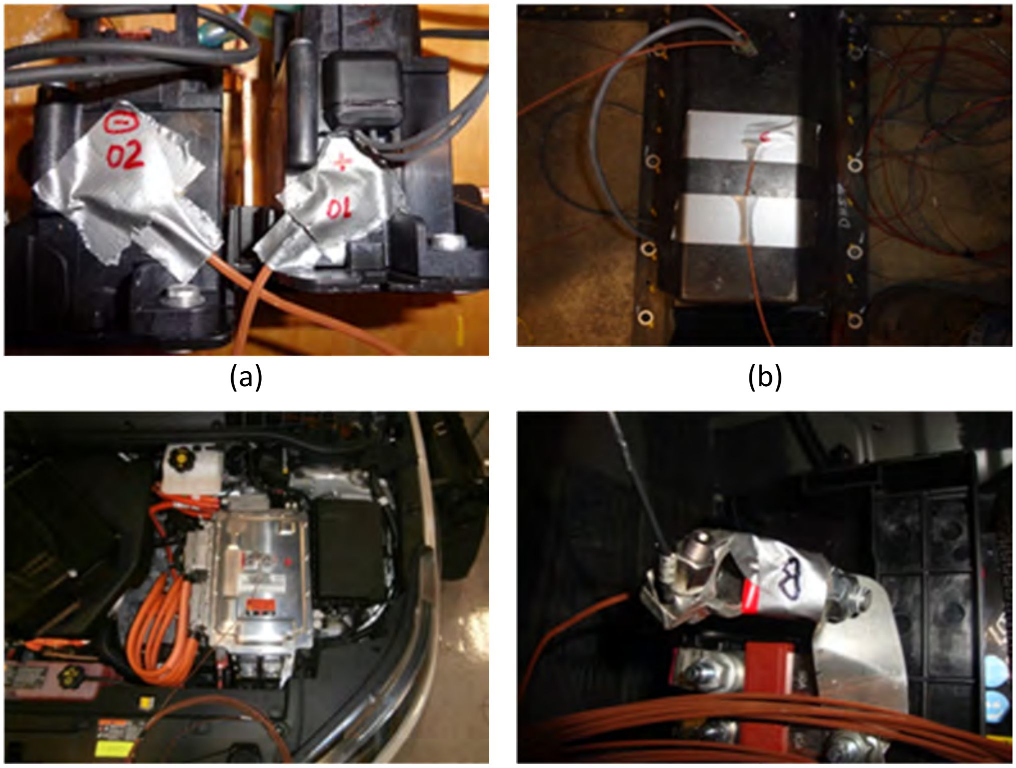

(a) (b) (c) (d)

Figure 200 - GM Volt-2 PHEV HV connections: a) RESS removed from vehicle, b) contactor assembly, c) measurement wires attached to bus bar, and d) coil wires.



(a) (b) (c) (d)

Figure 201 - GM Volt-2 PHEV HV thermocouple placement: a) TC1 and TC2 on the contactors, b) TC6 on the RESS case, c) TC7 on the control module, and d) TC8 on the 12 V battery.

8.3.6.2 Test Conditions

Testing was performed outdoors in ambient temperatures of approximately 23°C. There was no precipitation on the day the vehicle was immersed. The vehicle remained in the immersion container during the post-extraction observation period.

8.3.6.3 Immersion Test Results

The test event log is summarized in Table 70. Figures 202 through 207 show measured data for the initial 9 hours of the test as follows:

- Figure 202 - Temperature profile for the first 9 hours of testing
- Figure 203 - Gas sensing current for the first 9 hours of testing
- Figure 204 - 12 V control voltage for the first 9 hours of testing
- Figure 205 - Electrode to chassis voltage for the first 9 hours of testing
- Figure 206 - RESS voltage for the first 9 hours of testing
- Figure 207 - Isolation resistance for the first 9 hours of testing

Figures 208 through 212 show measured data for the final 10 hours of the test as follows:

- Figure 208 - Temperature profile for the last 10 hours of testing
- Figure 209 - Gas sensing current for the last 10 hours of testing
- Figure 210 - 12 V control voltage for the last 10 hours of testing
- Figure 211 - RESS voltage for the last 10 hours of testing
- Figure 212 - Isolation resistance for the last 10 hours of testing

Table 70 - GM Volt-2 PHEV Test Event Log

Event	**Time**	**Temperature**	**Primary Source**	**Secondary Source**
Start of immersion	3:25 PM		Test field notes	
Start of self-heating in observation period (if any)	3:21 PM		graphs	Test field notes
Time at first flames	N/A		video	IR Camera
Highest recorded HV battery temperature at time of first flames		N/A	graphs	
Time of first bang, explosion or pressure wave captured on video	N/A		video	
Time of first smoke/gases/vapor	N/A		video	IR camera
Time of RESS case maximum temperature	3:36 PM		graphs	
Maximum RESS case temperature		38°C	logged data	
Time when RESS pre-contactor voltage is more than $V_{initial}$ ± 2%	N/A		graphs	logged data
Time when the LV battery voltage is more than $V_{initial}$ ± 2%	3:34 PM		graphs	logged data
Time to first measurement of sustained (>110% of initial reading) CH_4 presence (>5 s)	N/A		logged data	
Time to first measurement of sustained (>110% of initial reading) CL_2 presence (>5 s)	N/A		logged data	
Time to first measurement of sustained (>110% of initial reading) H_2 presence (>5 s)	N/A		logged data	

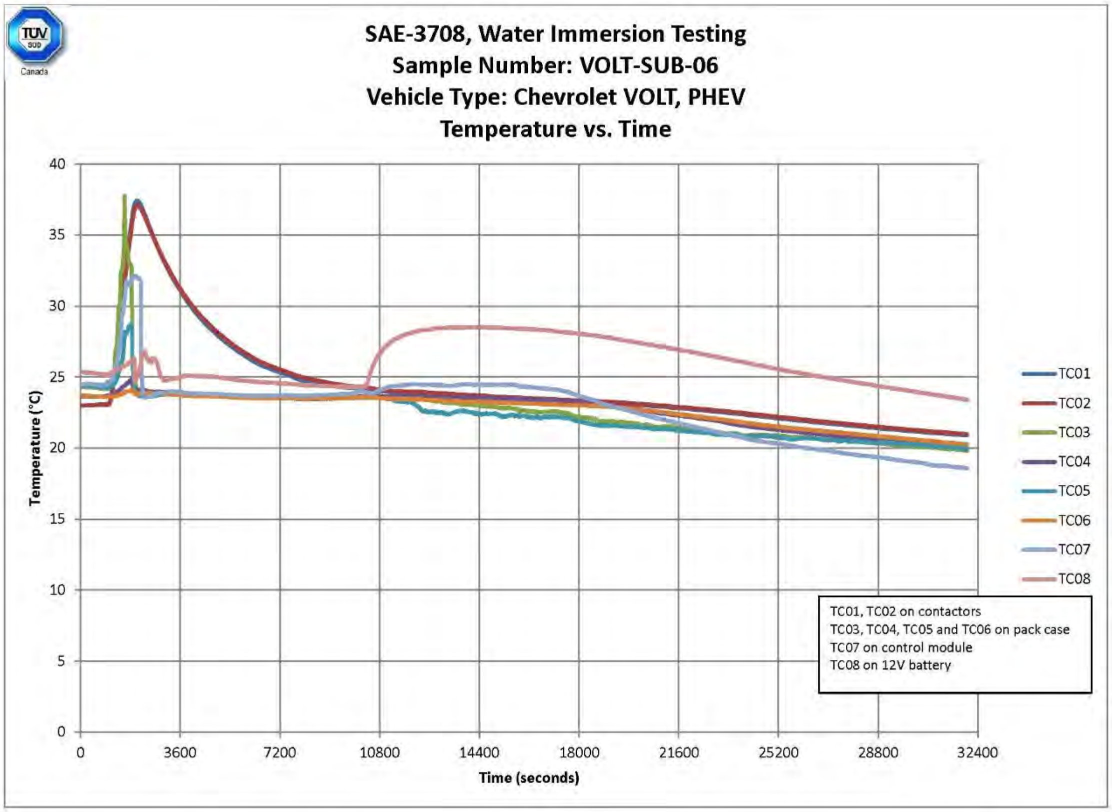


Figure 202 - GM Volt-2 PHEV temperature profile for the first 9 hours of testing.

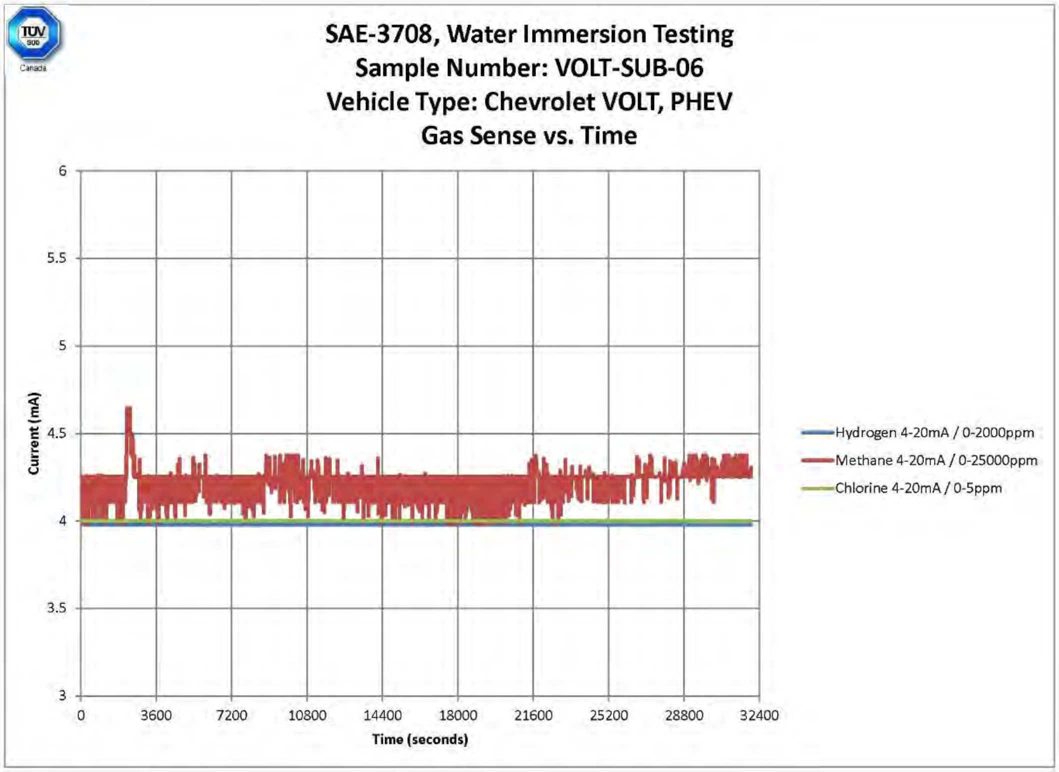


Figure 203 - GM Volt-2 PHEV gas sensing current for the first 9 hours of testing.

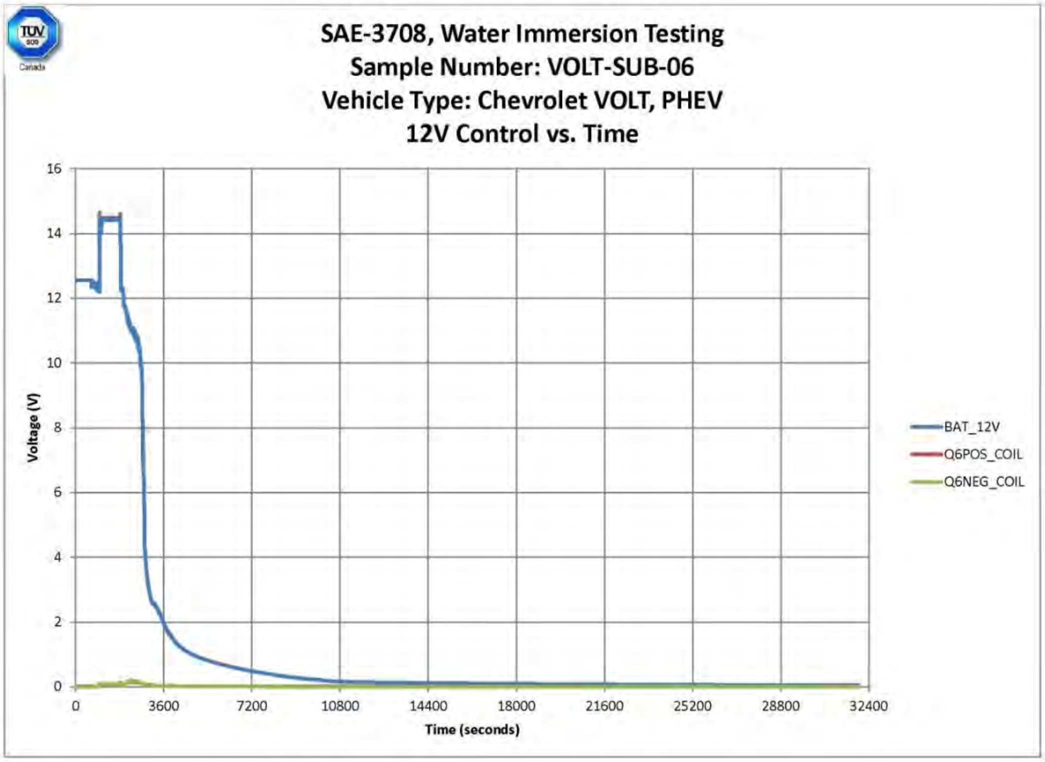


Figure 204 - GM Volt-2 PHEV 12 V control voltage for the first 9 hours of testing.

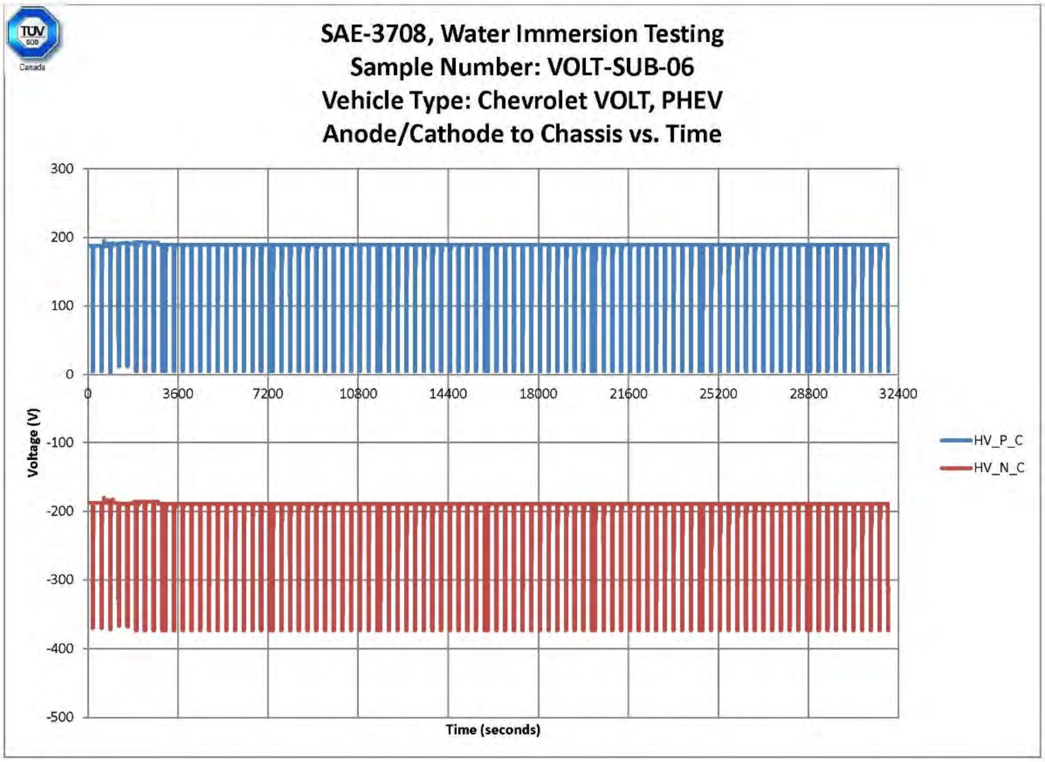


Figure 205 - GM Volt-2 PHEV electrode to chassis voltage for the first 9 hours of testing.

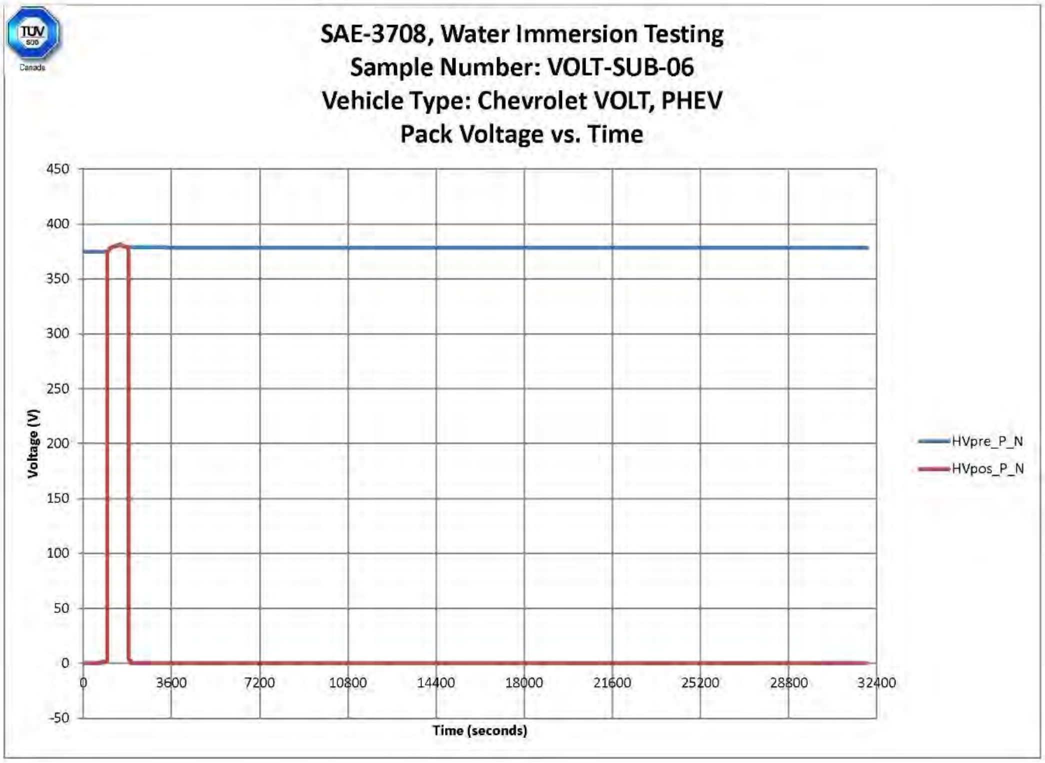


Figure 206 - GM Volt-2 PHEV RESS voltage for the first 9 hours of testing.

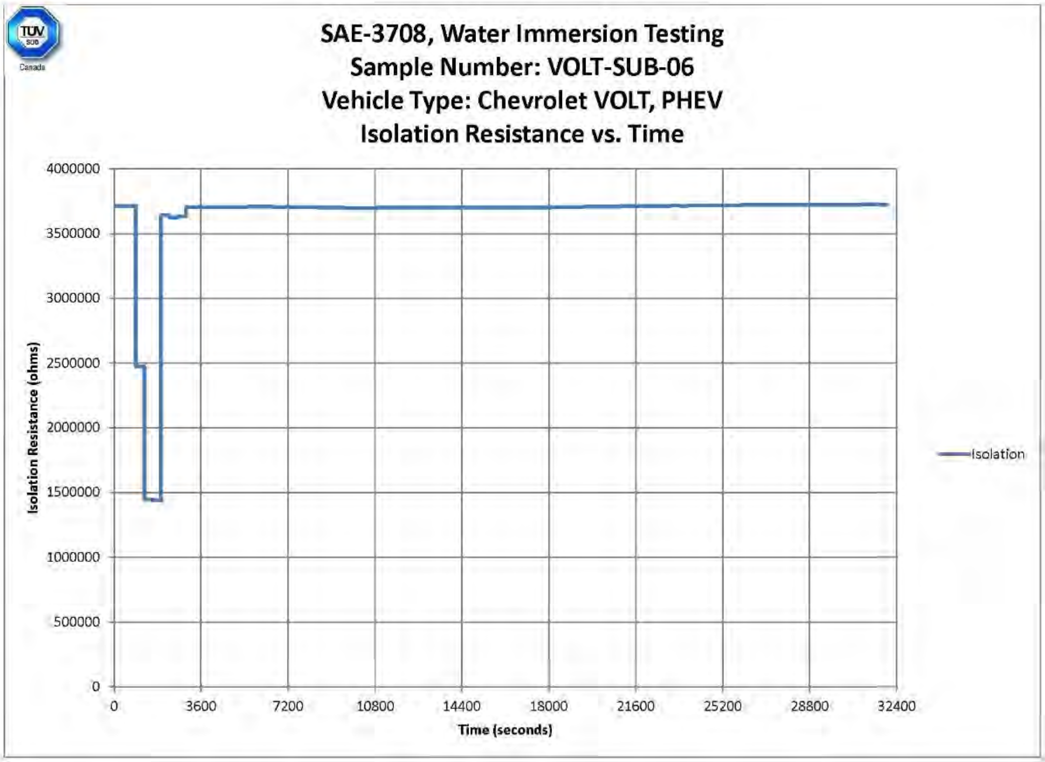


Figure 207 - GM Volt-2 PHEV isolation resistance for the first 9 hours of testing.

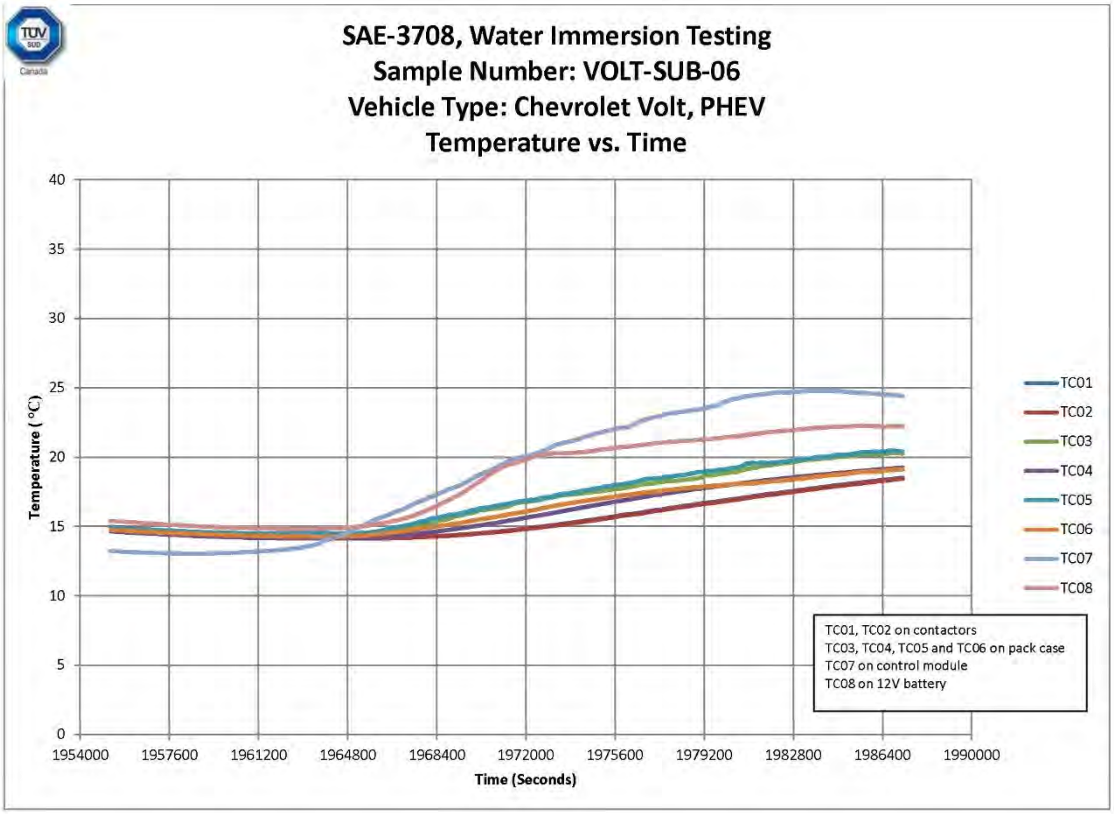


Figure 208 - GM Volt-2 PHEV temperature profile for the last 10 hours of testing.

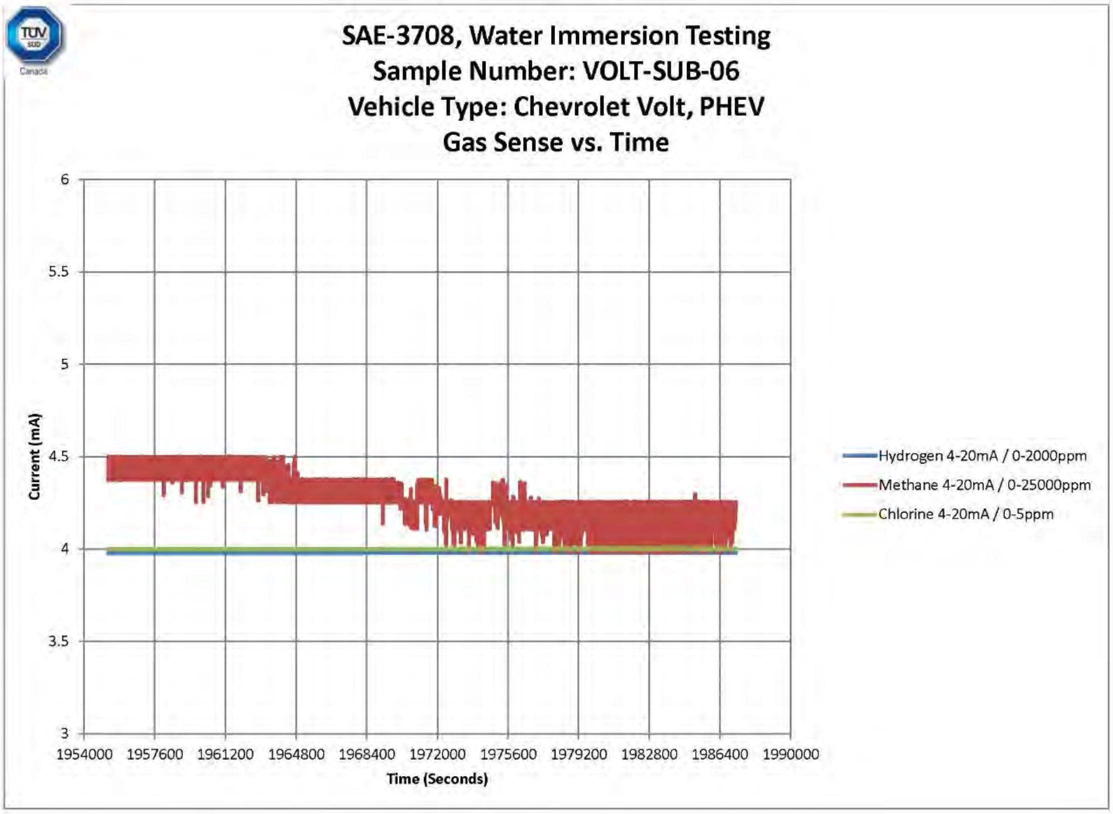


Figure 209 - GM Volt-2 PHEV gas sensing current for the last 10 hours of testing.

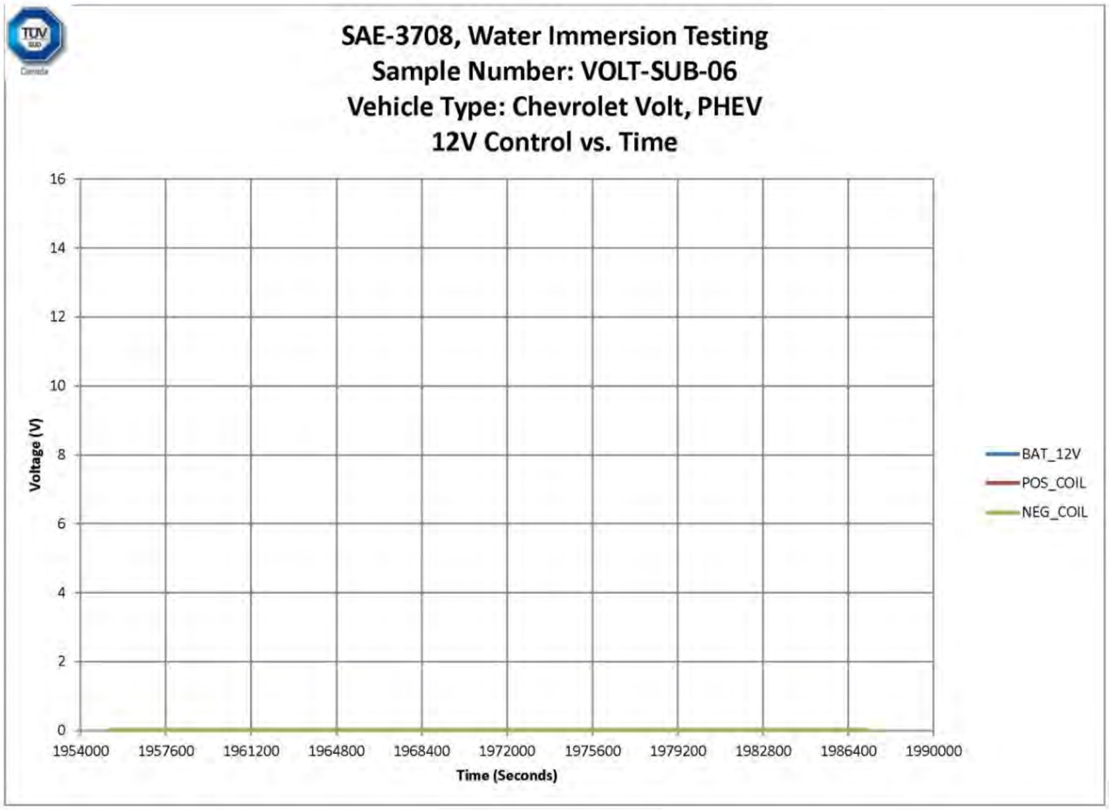


Figure 210 - GM Volt-2 PHEV 12 V control voltage for the last 10 hours of testing.

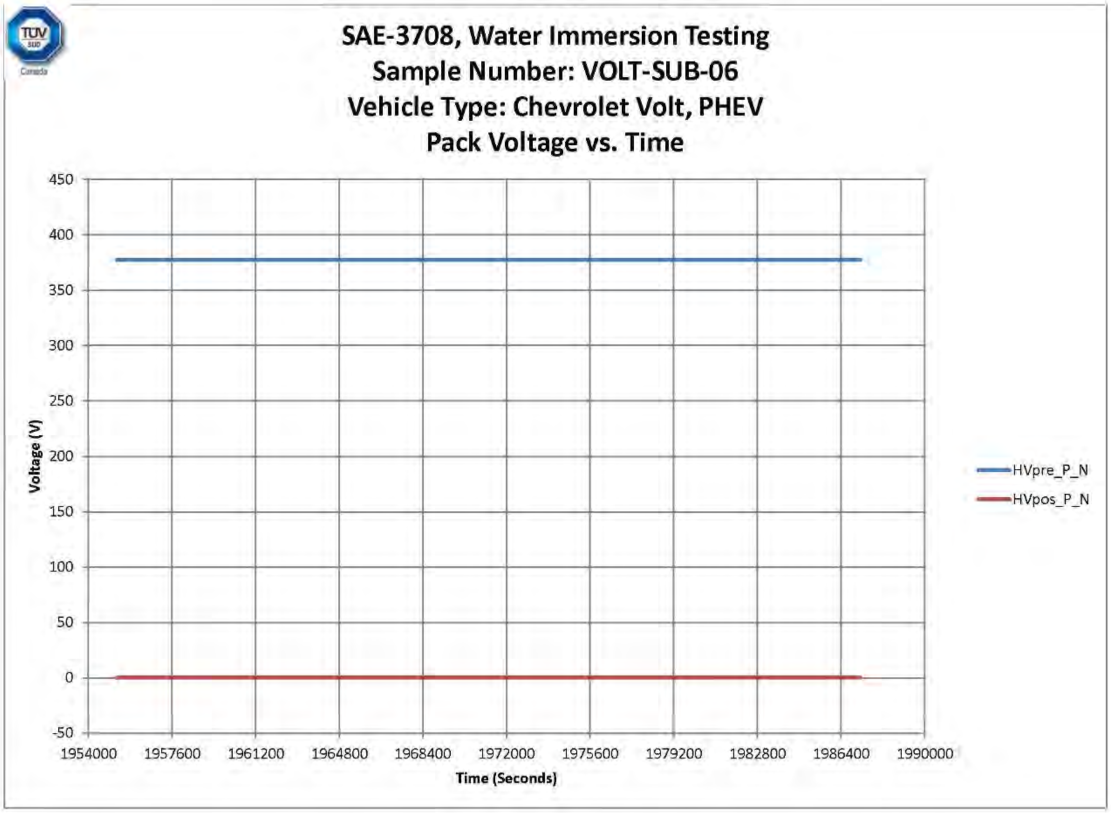


Figure 211 - GM Volt-2 PHEV RESS voltage for the last 10 hours of testing.

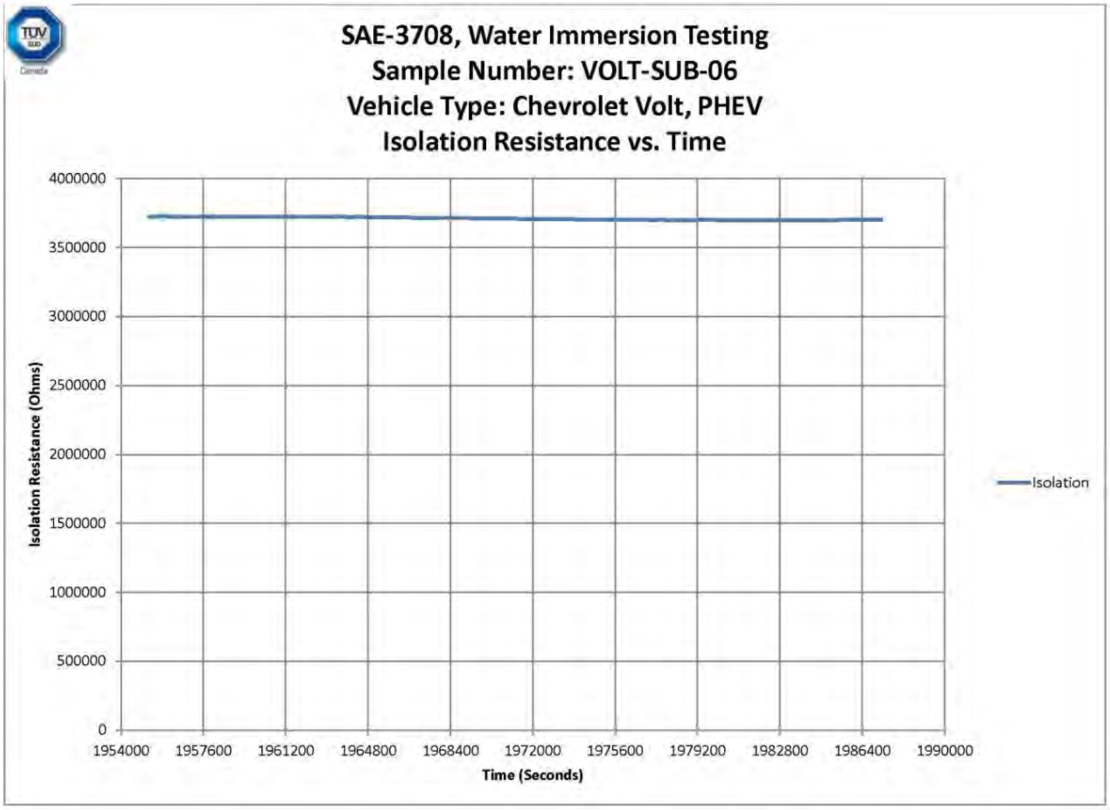


Figure 212 - GM Volt-2 PHEV isolation resistance for the last 10 hours of testing.

8.3.6.4 Seawater Analysis Results

Seawater samples were taken before and after immersion. They were measured on-site for pH, density and conductivity; the results are summarized in Table 71. Table 72 shows the VOCs that were above the reportable detection limit, as determined from Maxxam Analytics, Inc. Note that the samples were also analyzed for other VOCs that were below the reportable limit. Table 73 shows the total oil and grease content from the samples.

Table 71 - GM Volt-2 PHEV Conductivity, Salinity, Density, and pH

Time	**Conductivity (mS/cm)**	**Salinity (wt%)**	**Density (g/cm^3)**	**pH**
Pre-immersion	53.6	3.27	1.025	7.5
Post-immersion	53.4	3.25	1.025	7.4

Table 72 - GM Volt-2 PHEV VOCs above Reportable Detection Limit

Volatile Organics	**Units**	**Pre-Immersion**	**Post-Immersion**	**RDL***
Chloroform	µg/L	0.16	0.11	0.10
o-Xylene	µg/L	ND**	0.19	0.10
Xylene (Total)	µg/L	ND**	0.19	0.10

*RDL=Reportable Detection Limit

**ND=Not Detectable

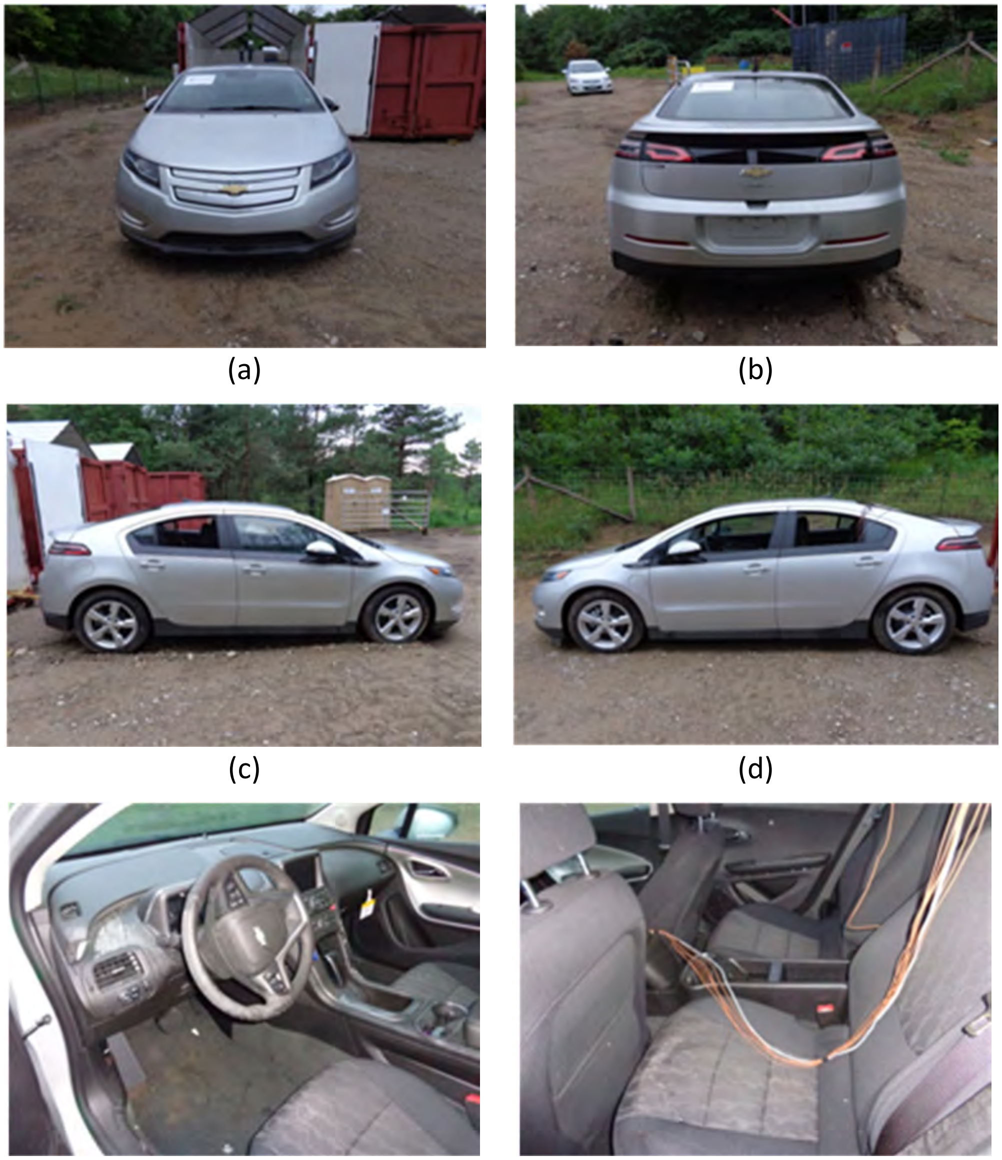
Table 73 - GM Volt-2 PHEV Total Oil and Grease Content

Petroleum Hydrocarbons	**Units**	**Pre-Immersion**	**Post-Immersion**	**RDL**
Total oil and grease	mg/L	ND*	ND*	0.50

*ND=Not Detected

8.3.6.5 Post-Mortem Analysis

Figure 213 shows the vehicle from multiple angles after testing was complete. Post-mortem analysis did not indicate any evidence of behaviors that could result in an HSL higher than 4 (i.e., no anticipated fires, ruptures, or explosions) based on EUCAR standards. Although the RESS temperature increased during immersion, it quickly declined to ambient levels after 3 hours and followed the diurnal ambient values until the end of the test. In addition, the water immersion caused the RESS voltage to increase from 375 V to 378 V within the first half-hour of the test and was at 377.5 V at end of test. Therefore, no post-mortem analysis was conducted on the battery pack.



(a) (b)

(c) (d)

(e) (f)

Figure 213 - GM Volt-2 PHEV post-test external vehicle condition: a) front view, b) rear view, c) passenger side, d) driver's side, e) front dash, and f) rear seats.

8.4 Water Immersion Observations

Testing was conducted for demonstration purposes with some test conditions that were outside the designated boundary (e.g., ambient temperature). Thus, this report is not intended to be a performance and safety evaluation for each manufacturer/vehicle. The observations provided herein are not conclusive or comparable.

8.4.1 General Observations

Immersion tests were run at opposite ends of the seasons (i.e., late winter and midsummer conditions). During winter testing, a GM Volt PHEV (Volt-1, see Section 8.2.4) became fully engaged in a vehicle fire about 5 hours after the 2-hour immersion period ended. The fire resulted in total destruction of the vehicle and nearby equipment (video camera, gas sensors), see Figure 214. While summer testing also tested a GM Volt (Volt-2, see Section 8.3.6), it did not undergo thermal runaway despite using the same immersion procedure.

Figure 214 -GM Volt PHEV post fire and salt water discharge.

During summer testing, a thermal excursion in the Ford Focus resulted in limited localized heat damage to an electronic module in the upper pack (see Section 8.3.5). The measured temperature of the RESS enclosure reached 99°C. However, the melted insulation on the affected connector indicated that the local temperature could have been higher. No cell damage was observed, see Figure 215 (this is the same as Figure 197(a)).

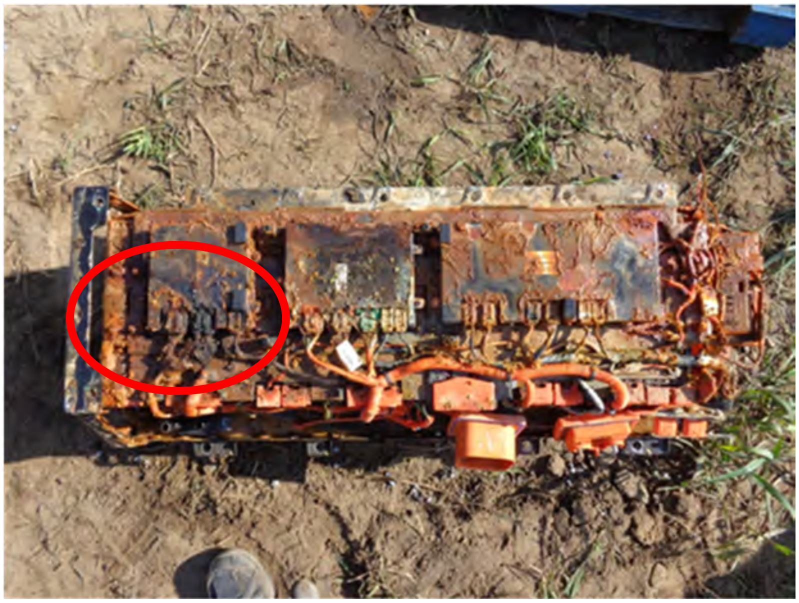


Figure 215 - Ford Focus UP EV post test electronic module connector heat damage.

Table 74 summarizes the time to loss for voltage and isolation resistance for all 12 water immersion tests. Table 75 shows the results of the water chemistry analyses from samples taken before and after the immersion. Conductivity, the parameter thought to be of most influence in this test, fluctuates between +2.5% and -3.5%. Salinity changes between +2.0% and -2.5%. The change in major organics is primarily from benzene and chloroform.

Table 74 - Time to Loss of HV and LV Values

Weather	Vehicle		Time to Loss (min)		
	OEM	Make	50% of HV	50% of LV	Isolation resistance to <500xVoc$_{start}$
Winter	Ford	C-Max	9	15	10
		Fusion-1	19	20	19
		Fusion-2	25	25	26
	Nissan	Leaf-1	228	36	21
		Leaf-2	No loss	No data*	No loss below target
	Chevy	Volt-1	430	25	22
Summer	Nissan	Leaf-3	103	7	No loss below target
	Mitsubishi	iMiev	22	38	21
	Hyundai	Sonata	20	17	7
	Ford	Focus UP	65	20	18
		Focus LP	65	20	18
	Chevy	Volt-2	No loss	46	No loss below target

* First 7 hours of data corrupted.

Table 75 - Water Chemistry Analysis

Weather	Vehicle		Conductivity		Salinity		Major VOCs
	OEM	Time	(mS/cm)	Δ	(wt%)	Δ	
Winter	Ford C-Max	Pre	45.6	UP 1.75%	2.67	UP 1.9%	DOWN>15% (benzene)
		Post	46.4		2.72		
	Ford Fusion-1	Pre	51.1	0%	3.10	UP 1.6%	UP>12% (benzene)
		Post	51.1		3.15		
	Ford Fusion-2	Pre	45.2	UP 0.9%	2.63	UP 1.5%	UP >180% (benzene)
		Post	45.6		2.67		
	Nissan Leaf-1	Pre	49.7	DOWN 3.4%	2.92	DOWN 2.4%	< RDL*
		Post	48.0		2.85		
	Nissan Leaf-2	Pre	50.5	UP 0.2%	3.08	0%	< RDL*
		Post	50.6		3.08		
	Chevy Volt-1	Pre	51.0	DOWN 0.6%	3.15	DOWN 0.6%	UP>40% (benzene)
		Post	50.7		3.13		
Summer	Nissan Leaf-3	Pre	57.3	DOWN 1.6%	3.51	DOWN 1.4%	0% (acetone)
		Post	56.4		3.46		
	Mitsubishi iMiev	Pre	55.3	UP 1.6%	3.39	UP 1.5%	0% (acetone)
		Post	56.2		3.44		
	Hyundai Sonata	Pre	53.8	UP 2.4%	3.3	UP 1.8%	DOWN<10% (chloroform)
		Post	55.1		3.36		
	Ford Focus (UP/LP)	Pre	30.5	DOWN 0.33%	1.72	0%	DOWN<20% (chloroform)
		Post	30.4		1.72		
	Chevy Volt-2	Pre	53.6	DOWN 0.37%	3.27	DOWN 0.6%	DOWN<35% (chloroform)
		Post	53.4		3.25		

*RDL=Reportable Detection Limit

One of the critical performance metrics for seawater immersion is the reaction of the HV isolation resistance. The two classes of RESS designs are 'closed' packs (i.e., fully sealed to the outside environment) and 'open' packs (i.e., not sealed). A fully and effectively sealed RESS can prevent the intrusion of any conductive seawater and maintain the design value of isolation. In these cases, there is no single point failure for a loss of isolation to the battery enclosure and or the vehicle conductive surfaces. If, however, the RESS is not sealed and seawater infiltrates the HV areas, new risks are introduced, including voltage leakage to the RESS case and/or internal unintended circulating currents that create excess heat which may, if high enough, lead to thermal runaway and potentially fire and explosion of the pack.

If the RESS is well engineered to stop seawater entry, it may have commercial value after the immersion event even though the rest of the vehicle will likely have little value. If the sealing design allows water entry, whether by design or omission, the failure mode has a good chance of removing the pack energy resulting in a benign immersion result. The RESS will likely be unusable afterwards due to conductive salts deposition.

8.4.2 Observations for Closed Packs

8.4.2.1 Volt

For the winter test, RESS removal and re-insertion was based on GM standard practices from the internet. Standard shop tools and commercially available sealing materials were used to make a feedthrough hole in the RESS enclosure for voltage and temperature sensor cabling. The leak tightness of the lab-fabricated feedthroughs sealing method using silicone RTV had been verified with shop air pressure drop tests before the immersion test. The RESS cover was reassembled using the original butyl rubber sealing at the front of the pack

For the summer test, GM provided more detailed standard practices and a special shop tool was made available from a local GM dealer to support the RESS mass uniformly during removal and re-insertion. A water leak test apparatus was also made available from the same local GM dealer to verify the RESS leak tightness. Although the same feedthrough fabrication method was used, verification that all of the seals (including the lab-fabricated seal) were leak tight was based on a GM-recommended smoke test. The RESS cover was reassembled using new butyl rubber sealing.

However, there is no evidence that the updated methods used during the summer had a measurable influence in the pretest outcome. Consequently, the variation between the summer and winter tests is not believed to have had an influence on the results.

The GM Volt test during summer conditions did not experience any significant abnormal behavior. The RESS voltage remained almost constant to the end of test. The 12 V battery did lose its open circuit voltage within 46 minutes, as could be expected with the terminals open to the seawater solution. The isolation resistance also remained well above the ISO 6469-1 thresholds and did not drop appreciably from the initial 3.7 MΩ level. However, there was a 14 minute period where the contactors effectively closed without the 12 V signal and full voltage was present at the contactors output (this happened at about 15 minutes from the start of immersion).

In summary, the significant difference in behavior between the two Volt test vehicles does not have an obvious cause, either from the data or the post-mortem examination.

8.4.2.2 Leaf

The three Leaf packs (see Sections 8.2.3, 8.2.5, and 8.3.1) performed well as a group. There were no abnormal reactions (e.g., fire or explosion) during the post-extraction period. As shown in Table 74, Leaf-2 (Section 8.2.5) and Leaf-3 (Section 8.3.1) only had minor loss of isolation. All three Leaf packs showed some of the longest time-to-loss periods at high voltage (Leaf-2 showed no loss at all). Only the Volt-1 showed longer time-to-loss at high voltage, but it caught fire soon after (see Section 8.4.1).

All the Leaf packs were submersed in sea water after the post-extraction period to help discharge any remaining stranded energy.

8.4.3 Observations for Open Packs

8.4.3.1 Ford Fusion, C-Max, and Focus

The five Ford packs primarily had ‘benign’ failure mode reactions to seawater immersion. As shown in Table 74, the RESS voltage dropped to discharged levels during the immersion period (the time to reach 50% of the initial capacity was used as a benchmark measurement to assess the degree of self discharge). The discharge time to 50% or more of the original open circuit voltage was from 9 to 65 minutes. For reference, the time-to-loss of 50% for LV ranged between 15 to 25 minutes.

The in-rush of seawater compromised the isolation resistance for all five packs. The loss of isolation resistance only required between 10 to 26 minutes. As shown in Table 74, there is a strong time correlation between the loss of HV and isolation resistance for the C-Max and Fusion vehicles. However, the correlation is not present for the two Focus packs. This may be related to the use of brackish water and/or cutting the immersion time in half.

8.4.3.2 Hyundai Sonata, Mitsubishi, i-Miev

The Hyundai Sonata and Mitsubishi iMiev behaved similarly to the Ford vehicles (see Section 8.4.3.1) with comparable times for HV loss, LV loss, and isolation loss. The failure mode reactions were also benign like the Ford RESSs.

VIBRATION AND THERMAL CYCLING TEST

Test Procedure

1. PURPOSE

Electric propulsion in a Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV) and Electric Vehicle (EV) platform relies on Rechargeable Energy Storage Systems (RESSs), commonly referred to as batteries. However, 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 that are different than those associated with an internal combustion engine. The purpose of this testing is to assess RESS safety and robustness from an electrical and mechanical standpoint based on various multi-axis vibration profiles and shock tests along with some thermal cycling. The tests are designed to verify that there are no safety issues arising from vibration and temperature excursions in real world applications. The devices subjected to the test procedure defined herein can be evaluated based on a safety star rating system, which is an improvement over the pass/fail criteria in existing standards. This standard applies to any new, production-ready battery that provides propulsion for electric vehicles; it does not apply to energy storage systems used for Starting, Lighting, Ignition (SLI) or other electrical accessory systems in the vehicle.

2. SCOPE

This test procedure describes vibration, thermal cycling, and shock testing of a single RESS. The RESS includes both control circuitry and the battery cells/modules that are integrated into a full-size pack to meet the vehicle power and energy demands. If the vehicle consists of mechanically separated RESSs, each battery pack sub-system shall be tested separately. If the control or monitoring circuit is required for RESS operation but not integral to the battery pack structure, it may be connected during testing to operate and/or monitor the RESS, but it should not be subjected to vibration or thermal stresses. For statistical purposes, multiple samples could be tested with the procedures described herein. Though outside the scope of this document, some samples may also be subjected to accelerated aging (either after or during vibration testing) to determine the effects of vibration on RESS life, performance, and electro-mechanical reliability.

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 DNV-GL Publications

Available from Det Norske Veritas – Germanischer Lloyd (DNV-GL): P.O Box 300, 1322 Høvik, Norway, Tel: +47-6757-9900, www.dnvgl.com.

- DNV-GL standard for certification Number 2.4 – Environmental Test Specification for Instrument and Automation Equipment

3.1.2 IEC Publications

Available from the International Electrotechnical Commission (IEC): 446 Main Street 16th Floor, Worcester, MA 01608, Tel: 508-755-5663, www.iec.ch.

- IEC 60068-2-64 Tests – Test Fh: Vibration, Broadband Random and Guidance
- IEC 60086-2-6 Tests – Test Fc: Vibration (Sinusoidal)
- IEC 60086-2-27 Tests – Test Ea and guidance: Shock

3.1.3 ISO Publications

Available from International Standards Organization (ISO) Central Secretariat: 1, ch. de la Voie-Creuse CP 56, CH-1211 Geneva 20 Switzerland, Tel.: +41-22-749-01-11, www.iso.org.

- ISO 16750-3 Environmental Conditions for Testing of Electrical and Electronic Equipment Volume 3: Mechanical Loads.
- ISO 13355:2001 Packaging - Complete, Filled Transport Packages and Unit Loads - Vertical Random Vibration Test
- ISO/DIN 12405-1 Electrically Propelled Road Vehicles - Test Specification for Lithium-Ion Traction Battery Packs and Systems Part 1: High Power Applications

3.1.4 SAE Publications

Available from the Society of Automotive Engineeres (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 J2380 - Vibration Testing of Electric Vehicle Batteries
- SAE J2464/2929 - Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing

4. DEFINITIONS

Abnormal Temperature Conditions

A deviation from the typical operating temperature range defined by the manufacturer.

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. It calculates and communicates battery status and state of function to the vehicle system for energy flow management. In the event of a system failure, the BMS can also open contactors and isolate the battery from the rest of the hybrid system.

Battery Module

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

Capacity

The total number of ampere-hours (Ah) that can be withdrawn from a fully charged battery under specified conditions.

Depth of Discharge (DOD)

The discharge capacity in ampere-hours that is withdrawn from a battery, expressed as a percentage of the battery ampere-hour capacity.

Discharge Rate

The rate of discharge current, often expressed as a C-rate relative to the rated capacity.

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).

EV: Electric Vehicle

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

HEV: Hybrid Electric Vehicle (HEV)

An automobile type vehicle, powered by an internal combustion engine and an electric motor that draws stored energy from a rechargeable energy storage device for power assist.

High Voltage (HV) Connector

The means by which high voltage power is supplied and removed from the RESS through positive and negative terminals.

Insulation Resistance Measurement

The result of an insulation resistance test, which is often conducted by an insulation tester that can apply a range of voltages to a test point and indicate the resistance at that voltage. Typically, resistances greater than 0.5 MΩ can be detected at 500 V_{DC}.

Low Voltage (LV) Connector

The means by which low voltage power is supplied and removed from the RESS through positive and negative terminals.

Material Safety Data Sheet (MSDS)

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

Negative Terminal

The terminal of a battery or other voltage source from which electrons flow through the external circuit to the positive terminal when under a discharge condition.

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.

Positive Terminal

The terminal of a battery or other voltage source toward which electrons flow through the external circuit when under a discharge condition.

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.

Relative Humidity

A ratio of the amount of water vapor actually present in the air to the greatest amount possible at the same temperature.

Resonance

The state of a system in which an abnormally large vibration is produced in response to an external stimulus. It occurs when the frequency of the stimulus is the same, or nearly the same, as the natural vibration frequency of the system.

Rated Capacity

The manufacturer's specification of the total number of ampere-hours (Ah) that can be withdrawn from a fully charged cell or battery for a specified set of test conditions such as discharge rate, temperature, discharge cutoff voltage, etc.

Safety Disconnects

The opening of the high voltage circuit through manual disconnects designed into the RESS, thus creating an open circuit condition.

Short-Circuit Current

The current delivered when the positive and negative battery terminals are directly connected with a low-resistance conductor.

Stabilization Time

The amount of time required to stabilize the temperature of the RESS to the ambient environment.

State of Charge (SOC)

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

Test Fixture

A support structure that is as similar as possible to the manufacturer's mounting and support characteristics.

Voltage Drift

A change in output voltage potential under rest conditions for a pre-specified time duration.

5. GENERAL TEST REQUIREMENTS

5.1 General Precautions

5.1.1 Conducting vibration and shock testing on any cell chemistry is potentially hazardous.

5.1.1.1 Prior to testing, the test facility should become familiar with the contents of a battery or cell and the related potential hazards; appropriate personal protective equipment (PPE) should also be assembled. A Material Safety Data Sheet (MSDS) or Emergency Response Guide (ERG) may provide relevant information.

5.1.1.2 Testing should be conducted in a well-ventilated environment with provisions to mitigate smoke, flammable vapors, or toxic vapors.

5.1.1.3 Personnel conducting testing should be equipped with appropriate PPE such as eye protection (safety glasses, googles, or face shield), high voltage resistant gloves, and high temperature resistant gloves. The testing agency should determine appropriate PPE prior to beginning of testing.

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

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

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

5.1.2.1 Systems are heavy and must be mounted and removed from a test fixture.

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

5.1.2.3 Modifying and working with potentially energized RESS elements can also expose personnel to high voltages and arc flash hazards. An element that may carry a voltage above 40 V should be considered a lethal shock hazard and treated accordingly. All such elements should be probed using an isolated meter before any contact is made with them, even while using high voltage gloves. Testing personnel should not assume that high voltage elements are safe and should confirm the absence of voltage using an isolated meter before touching the exposed elements.

5.2 Test-Specific Precautions

5.2.1 Prior to testing, the RESS shall be visually inspected for any defects or abnormalities.

5.2.2 The RESS shall be instrumented with appropriate sensors to monitor voltage, SOC, temperature, and resonances. It shall also be instrumented to measure any loss of electrical isolation for both the battery positive and negative connection to the case and/or equipment ground.

5.2.3 Hazards associated with vibration and shock tests can include:

5.2.3.1 Loss of electrical isolation between the battery positive/negative connection and the RESS enclosure and/or test equipment ground. The isolation resistance shall be verified between each step of vibration or shock testing, and periodically during extended rest intervals (e.g., once every 8 hours or as instructed in a device-specific test plan). The isolation shall be 0.5 MΩ or greater (1.0 mA or less leakage at 500 V_{DC}). Isolation shall be measured by verifying the resistance level between both the battery positive connection and the device housing, as well as the battery negative connection and the device housing.

5.2.3.2 Abnormal battery voltages indicating the presence of open- or short-circuit conditions.

5.2.3.3 Unexpected resonance conditions within the battery, indicating failure of mechanical tie-down components.

5.2.3.4 Abnormal temperature conditions indicating possible damage to battery cells or thermal management system components.

5.2.3.5 A change in the RESS state of charge (SOC) indicating possible loss of isolation between internal components of the device.

5.2.4 The RESS shall be visually inspected between each step of vibration testing, or periodically (e.g., once every 8 hours or as specified in a device-specific test plan) during extended rest intervals.

5.2.5 Detection of any of the conditions listed in Section 5.2.3 (or any observable anomalies during a visual inspection) shall cause testing to be suspended until the condition has been evaluated and a determination has been made that either it is safe to proceed or the testing should be terminated.

5.3 Safety Recommendations

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

5.3.2 The testing facility shall maintain appropriate standard operating procedures for laboratory and personnel safety. These procedures should include the following:

5.3.2.1 Proper and applicable protective equipment shall be worn at all times (including, but not limited to, safety glasses and Class 0 electrical gloves) during testing and while handling or examining the RESS.

5.3.2.2 Proper local exhaust ventilation is required around the test area, which includes the RESS and vibration test equipment. The test area shall be isolated from the rest of the facility to the extent possible. The ventilation must be capable of removing any smoke or gas released from the RESS, provide sufficient make-up air to eliminate any buildup of pressure in the test area, and limit exposure of personnel to any such smoke (e.g., a roof mounted exhaust fan with ducting extending into the test area and a separate air inlet from the outside of the building). The facility may consider additional filtering or scrubber systems based on local regulations.

5.3.2.3 Class D or other appropriate fire extinguishers must be available near the test stand during testing. Considerations should be made for any electrical fires or flammable metals, such as magnesium components of the vibration table.

5.3.2.4 Unnecessary combustibles and debris in the test area shall be removed.

5.4 Test Facility/ Equipment Requirements

5.4.1 Facility and equipment requirements for vibration, shock, and thermal cycle testing:

5.4.1.1 The facility must have a one- to three-axis vibration table capable of producing accelerations up to 10 gn over a frequency range of 10 to 1000 Hz (see Section 6.7). If the RESS can only be vibrated while in a particular physical orientation, a multi-axis table will be required. If a single axis shaker is used, it must be equipped with a means of operating in both the vertical and horizontal planes to ensure the RESS will remain in a vehicle orientation with respect to gravity (i.e., through the use of a slip table to support the RESS during inputs in the horizontal axes).

5.4.1.2 The RESS mounting and support structure (fixture) shall be as similar as possible to the manufacturer’s recommended installation requirements for all vibration and mechanical shock tests. The fixture shall keep the RESS from direct contact with any point of the vibration exciter. At a minimum, the fixture shall hold the RESS with the same level of rigidity as the vehicle. The fixture shall not have any resonances below 50 Hz (see Section 7.2). It shall be designed and built to allow removal from the vibration exciter for repositioning the RESS in each of the three orthogonal axes without having to remove the RESS from the fixture itself.

5.4.1.3 The vibration table must be equipped with a thermal chamber capable of sustaining temperatures between -40°C and 85°C as well as control relative humidity levels up to 85%. The default ambient temperature shall be 23±5°C. The vibration and thermal requirements must be performed concurrently.

5.4.1.4 The facility must have mechanical shock equipment capable of applying half-sine pulses at a 25 gn acceleration for 15 ms on all three axes.

5.4.1.5 During testing, the vibration and shock excitation shall be monitored through the use of accelerometers. The size and type of accelerometer can be determined by the test facility based on size of the RESS or general availability. Temperature compensated accelerometers are recommended. However, at a minimum, the accelerometers shall have a suitable operating range to guarantee the accuracy of the sensor. For all outlined tests, a minimum of four accelerometers shall be used per RESS and placed in the following manner:

- Two accelerometers shall be placed on the upper rigid corners diagonally across from one another in opposite corners.
- One accelerometers shall be placed on the fixture mounting support as far from exciter as possible.
- One accelerometers shall be placed on the centerline axis of the test mounting plate or shaker slip table where applicable.

The accelerometers on the mounting support and the centerline of the mounting plate or slip table shall be used as the control accelerometers, controlled as an average of the two locations. The two sensors placed on the upper rigid corners diagonally across from one another are used to measure resonances.

The locations of the accelerometers shall be recorded and photographed to facilitate test repeatability. If it is unfeasible to place accelerometers in these positions, alternate locations maybe selected, recorded, and explained as to why the original locations were not utilized.

See Section 6.5 for guidelines on the accelerometer parameters and setup.

5.4.1.6 The facility must have recording and measuring equipment to properly record the data described in Section 6.8, with the capability to meet the accuracy levels described in Section 6.5.

5.4.1.7 The facility must have recording and acquisition equipment capable of communicating with the RESS Battery Management System, if the RESS is so equipped.

5.5 Test Equipment Calibration

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

- Type of equipment, manufacturer, model number, etc.
- Measurement range
- Accuracy
- Calibration interval
- Type of standard used (calibration traceability of the standard must be evident)

6. TEST PROCEDURE

6.1 Test Type

6.1.1 Vibration, shock, and thermal cycling are generally non-destructive tests that subject a RESS to stresses that are typical of real world environmental conditions. The RESS is rated for safety based on isolation resistance, temperature rise, voltage drift, structural damage, and capacity loss.

6.2 Device Under Test

6.2.1 The device under test (DUT) shall be a production-ready RESS that is intended for in-vehicle use.

6.2.2 The RESS used for testing should be as new and uncycled as practical.

6.3 DUT Preconditioning

6.3.1 Prior to vibration and shock testing, the RESS shall be subjected to thermal characterization, a full charge/discharge cycle, and a full charge to 100% SOC (see Section 6.4).

6.4 Test Sequence

6.4.1 The thermal cycle profile must first be developed. The procedure for this development is detailed in Section 6.6.

6.4.2 Once the thermal cycle development procedure is complete, a full charge/discharge cycle shall be performed on the RESS at 23±5°C using the manufacturer-recommended procedure. The RESS shall be fully charged to 100% SOC at the end of this cycle for vibration and shock testing (see Section 7.3).

6.4.3 The vibration and shock test is separated into five sequential steps as shown in Table 1.

Table 1 - Test Sequence Summary

Step	Test
1	Sine Sweep
2	Mechanical Shock
3	Sine Sweep (repeated)
4	Random Vibration
5	Sine Sweep (repeated)

6.4.3.1 <u>Step 1 - Sine Sweep:</u> The purpose of this test is to find any resonances in the RESS which could lead to potential mechanical failure under normal operating vibration conditions. As found in IEC 60068 2-64, a resonance point is any excitation of the RESS over two times the input excitation from the vibration stand. The sine sweep profile shall be conducted in three orthogonal axes, referred to as X, Y, Z. The vibration controller setup is described in Section 6.5.4. Resolution requirements should be included in a device-specific test plan; Table 2 shows some suggested tolerance limits. See Section 6.7.3 for additional discussion on the sine sweep profile.

6.4.3.2 Step 2 - Mechanical Shock: The purpose of this test is to ensure proper isolation between the energy cells, RESS enclosure, and any other devices placed within RESS. The mechanical shock profile shall be run in three orthogonal axes, referred to as X, Y, Z. Allow a 30 to 90 second dwell period between shock pulses so the RESS can return to a steady state condition. See Section 6.7.6 for additional discussion on the mechanical shock profile.

6.4.3.3 Step 3 - Sine Sweep (repeated): The purpose of this test is to ensure that resonances in the RESS (documented during Step 1) have not changed as a result of the mechanical shock test. Resonance changes indicate a potential mechanical change or damage within the RESS. The test profile is the same as in Step 1. The RESS condition shall be evaluated based on the sequence detailed in Section 6.8. If it is deemed safe (i.e., no damage due to the shock test), testing can proceed to the next step.

6.4.3.4 Step 4 - Random Vibration: The purpose of this test is to ensure that the RESS can be considered safe for use in a typical light vehicle transportation scenario. The random vibration profile shall be run in three orthogonal axes, referred to as X, Y, Z. This test is run in conjunction with the temperature profile specified in Section 6.7.5. See Section 6.7.4 for additional discussion on the random vibration profile. The duration of the random vibration test will depend on the stabilization time of the RESS, which is found through the use of the thermal cycle profile development procedure detailed in Section 6.6.

6.4.3.5 Step 5 - Sine Sweep (repeated): The purpose of this test is to ensure that resonances in the RESS (documented during the Step 1) have not changed as a result of the random vibration test. Resonance changes indicate a potential mechanical change or damage within the RESS. The test profile is the same as in Step 1.

6.5 Test Guidelines

6.5.1 Testing is intended to be performed on one RESS. It should be secured to the vibration stand using the standard RESS mounting locations per normal in-use applications.

6.5.2 The RESS shall be unpowered with all safety disconnects in place during testing. The HV (high voltage) and LV (low voltage) mating connectors shall be attached to the RESS for test monitoring as specified in Section 6.8.

6.5.3 For all measured data (Section 6.8), unless more specific requirements are provided in a device-specific test plan, the measurement tolerances in Table 2 shall be considered acceptable.

Table 2 - Measurement Tolerances

Temperature	±2°C or ±5% of reading
Voltage, Current	±1% of reading
Vibration	±4% of reading

6.5.4 Guidelines for the accelerometer and vibration controller parameters are detailed in Table 3.

Table 3 - Vibration Controller Parameters

Parameter	**Value**
System Startup Rate	20%
Filtering Window	Hanning
Slew Rate	200 V/μs
Signal Clipping	None
Data Recording Rate	1 / minute

6.6 Thermal Cycle Profile Development

6.6.1 The RESS response to changes in temperature shall be evaluated to ensure proper thermal loading (independent of device mass). The thermal cycle profile development test shall be performed on the RESS prior to the start of the vibration test sequence. A "stabilization time" will be determined and used to dictate the time required for Step 4 (Random Vibration).

6.6.2 Place the RESS in the center of a thermal chamber capable of the temperature extremes listed herein. The RESS placement shall be the same as the in-use orientation. The vibration fixture should be used if space allows. Document and photograph this setup.

6.6.3 Thermocouple placement shall be as follows:

6.6.3.1 If applicable, use the internal temperature monitoring information provided by the RESS management system. If unavailable, attach a minimum of one thermocouple internal to device if possible. The location of the thermocouple placement shall be recorded.

6.6.3.2 Place a minimum of two additional thermocouples on the RESS enclosure. This provides at least three total RESS measurement points (including the internal thermocouple from Section 6.6.3.1).

6.6.3.3 Place at minimum two additional thermocouples within the chamber at a distance of no more than 10 inches from the RESS.

6.6.4 Stabilization time at each temperature condition is determined as follows:

6.6.4.1 Bring the RESS to 23±5°C in the chamber once the thermocouples have been installed. Ensure thermal equilibrium is achieved.

6.6.4.2 Drop the chamber temperature to -40°C using a 1 hour thermal ramp rate.

6.6.4.3 When the chamber reaches -40°C, record the time when the two external thermocouples (Section 6.6.3.3) match the chamber temperature within ±2°C.

6.6.4.4 Continue soaking the RESS and record the time when the RESS thermocouples (Sections 6.6.3.1 and 6.6.3.2) are within ±2°C of the designated chamber temperature. If multiple internal sensors are accessible by the RESS management system, at least 90% of them should be within ±2°C.

6.6.4.5 Stabilization time is the difference between the stabilized RESS temperature (Section 6.6.4.4) and the stabilized external temperature (Section 6.6.4.3).

6.6.4.6 Repeat this process (Sections 6.6.4.2 through 6.6.4.5) for chamber temperatures of 50°C, 85°C, and 25°C.

6.6.5 The total random vibration duration at each temperature condition shall be the identified stabilization time from Section 6.6.4 plus 1 hour. Random vibration is also conducted during the 1-hour thermal ramps. The rationale for these levels and tolerances is discussed in Section 7.1.

6.7 Test Parameters

6.7.1 Except for thermal cycling during random vibration, testing shall be conducted at a laboratory ambient temperature of 23±5°C.

6.7.2 The SOC shall be set to 100% for the duration of the testing described herein (see Section 7.3). The SOC shall be measured as defined in Section 6.8.

6.7.3 Sine Sweep Profile

6.7.3.1 The sine sweep profile is shown in Table 4. It consists of a 1 gn constant acceleration value applied over a frequency range of 10 to 1000 Hz with a sweep rate of 1 octave/min. The profile shall be conducted three orthogonal axes, referred to as X, Y, Z.

6.7.3.2 The control tolerance band shall be ± 6 dB for a test abort condition. An alarm limit can be set at ± 3 dB.

6.7.3.3 A RESS excitation factor of two or more beyond the input level will be considered a resonance node.

Table 4 - Sine Sweep Profile

Amplitude	1 gn
Frequency Range	10-1000 Hz
Sweep Rate	1 octave/minute

6.7.4 Random Vibration Profile

6.7.4.1 The random vibration profile is shown in Table 5 and Figure 1. The frequencies range between 10 and 1000 Hz with at least eight steps at various levels of acceleration. The Gn_{RMS} is 1.7 for the X- and Y-axes and 2.0 for the Z-axis.

6.7.4.2 The identified frequencies are randomly applied throughout the duration of the thermal cycle, including the 1-hour temperature transitions.

6.7.4.3 The control tolerance band shall be ± 6 dB for a test abort condition. An alarm limit can be set at ± 3 dB.

Table 5 - Random Vibration Profiles

X-Axis		**Y-Axis**		**Z-Axis**	
Hz.	**gn²/Hz**	**Hz.**	**gn²/Hz**	**Hz.**	**gn²/Hz**
10	0.065	10	0.065	10	0.07
15	0.065	15	0.065	20	0.08
25	0.029	25	0.029	35	0.037
80	0.012	80	0.012	45	0.037
130	0.006	130	0.006	80	0.02
200	0.006	200	0.006	170	0.005
250	0.001	250	0.001	200	0.005
1000	0.00003	1000	0.00003	250	0.0007
				1000	0.0001
Gn_{rms}: 1.7		Gn_{rms}: 1.7		Gn_{rms}: 2.0	

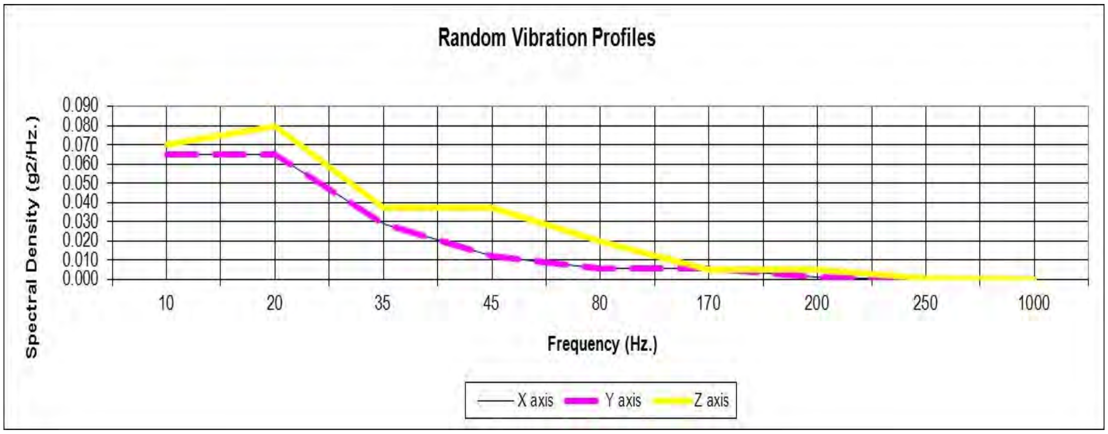


Figure 1 - Random vibration profile.

6.7.5 Temperature Profile

6.7.5.1 The temperature profile is shown in Table 6 and Figure 2; it is run in conjunction with random vibration. The total duration is 7 hours plus stabilization time (ST), which is determined from the thermal cycle profile development (Section 6.6).

6.7.5.2 The test temperature ranges from -40 to 85°C. The relative humidity (RH) at 85°C shall be 45±3%; the relative humidity at 50°C shall be 85±3%.

Table 6 - Temperature Profile

Segment Length	Elapsed Time	Temperature	Humidity
0	0	25°C	N/A
1 hour	1 hour	-40°C	N/A
ST+1 hour	2+ hours	-40°C	N/A
1 hour	3+ hours	85°C	45% RH
ST+1 hour	4+ hours	85°C	45% RH
1 hour	5+ hours	50°C	85% RH
ST+1 hour	6+ hours	50°C	85% RH
1 hour	7+ hours	25°C	N/A

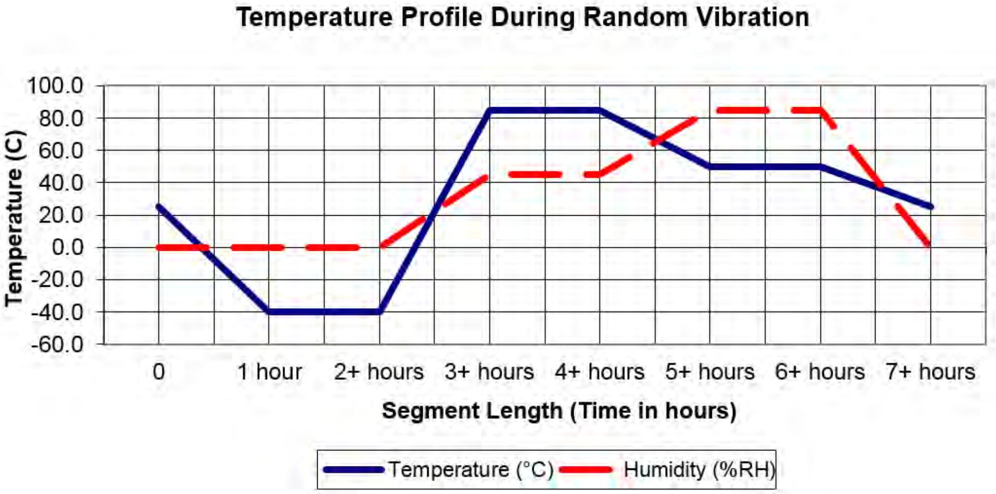


Figure 2 - Temperature during random vibration.

6.7.6 Mechanical Shock Profile

6.7.6.1 The mechanical shock profile is shown in Table 7. The half-sine pulse is applied at a 25 gn acceleration for 15 ms. The shock test is performed three times per axis (X, Y, Z) on both the positive and negative directions for a total of 18 tests.

6.7.6.2 The tolerance shall be ±5 gn (i.e., 20% of peak acceleration) within the 15 ms nominal pulse duration.

Table 7 - Mechanical Shock Profile

Acceleration	Duration	Pulse Type	Number of Pulses
25 gn	15 ms	Half-Sine	3/axis; both positive and negative directions for a total of 18 pulses

6.8 Measured Data

6.8.1 Data acquisition requirements and associated measurement rates during performance testing shall be included in a device-specific test plan.

6.8.2 The following data shall be recorded prior to each test step and at end of test (the rationale for these data are discussed in Section 7.4):

6.8.2.1 Isolation resistance shall be measured between the battery positive/negative connection and the RESS enclosure and/or test equipment ground.

6.8.2.2 Loss of voltage potential shall be measured between the positive and negative battery terminals. Additionally, this parameter shall be monitored continuously during Step 4 (random vibration) with a minimum measurement rate of one sample per minute.

6.8.2.3 Mechanical resonances of the RESS shall be measured with respect to frequency and amplitude level. Note any difference between sine sweep results in Steps 1, 3 and 5.

6.8.2.4 Temperature shall be recorded at several external and internal (where applicable) locations as a function of time. Ideally, it should be captured through the RESS management system. If this is not available, a minimum of two thermocouples should be placed directly on the RESS enclosure and one thermocouple placed internal to the RESS. Thermistors and or RTDs may also be used, provided the accuracy levels defined in Table 2 are met.

6.8.2.5 Voltage drift shall be measured to determine changes in the RESS SOC (if any). Additionally, the voltage drift shall be monitored continuously during Step 4 (random vibration) with a minimum measurement rate of one sample per minute.

6.8.2.6 Structural damage shall be evaluated with visual examination.

6.8.3 A report shall be prepared detailing the applied vibration level, followed by a compilation and interpretation of all acquired data. The report shall also include a safety performance ranking as defined in Section 6.11.

6.9 Inspection Method

6.9.1 The RESS shall be visually inspected between each test step.

6.9.2 The RESS shall not be removed from its fixture or the test stand between test steps.

6.10 Post-Test Requirements

6.10.1 After testing is completed, the RESS shall be removed from the test stand. The fixture, mounting apparatus and hardware shall also be removed. The RESS shall undergo a complete visual inspection.

6.10.2 The RESS SOC shall be measured and verified, as well as the isolation resistance between the positive/negative connection and the RESS enclosure.

6.10.3 The RESS shall also undergo a complete functional charge/discharge sequence per Section 6.3.

6.11 Potential Assessment Criteria

6.11.1 Based on the measured data from Section 6.8, the RESS should be deemed unsafe if any of the following conditions are met:

6.11.1.1 Isolation resistance is less than 0.5 MΩ.

6.11.1.2 Mechanical resonances of the RESS greater than 10% in frequency or amplitude level of the identified resonance points from the initial sine sweep test. This shall require an internal inspection of the RESS. Shifts in mechanical resonances may also indicate structural damage.

6.11.1.3 Temperature rise is greater than 10°C.

6.11.1.4 Voltage drift results in a more than a 5% change in the SOC. This can be up to complete loss of potential.

6.11.1.5 Structural damage, including any abnormal deformations, cracks, or other signs of physical damage to the RESS that can be found through visual examination methods.

6.11.2 Additionally, the RESS has failed to meet the test criteria if a change in capacity, discharge duration, or charging duration greater than 5% is observed when compared to pre-test values.

6.11.3 Safety Rating System

6.11.3.1 The RESS performance for the above criteria can be categorized based on a color coding and star system. The RESS is assigned a certain color for each measurable data point as follows:

- Red: the evaluation tolerance was not met (any red evaluation means that the RESS does not meet the acceptance criteria and is deemed unsafe).

- Yellow: the evaluation tolerance was within acceptance criteria but a deviation was recorded.

- Green: the evaluation tolerance was within acceptance criteria.

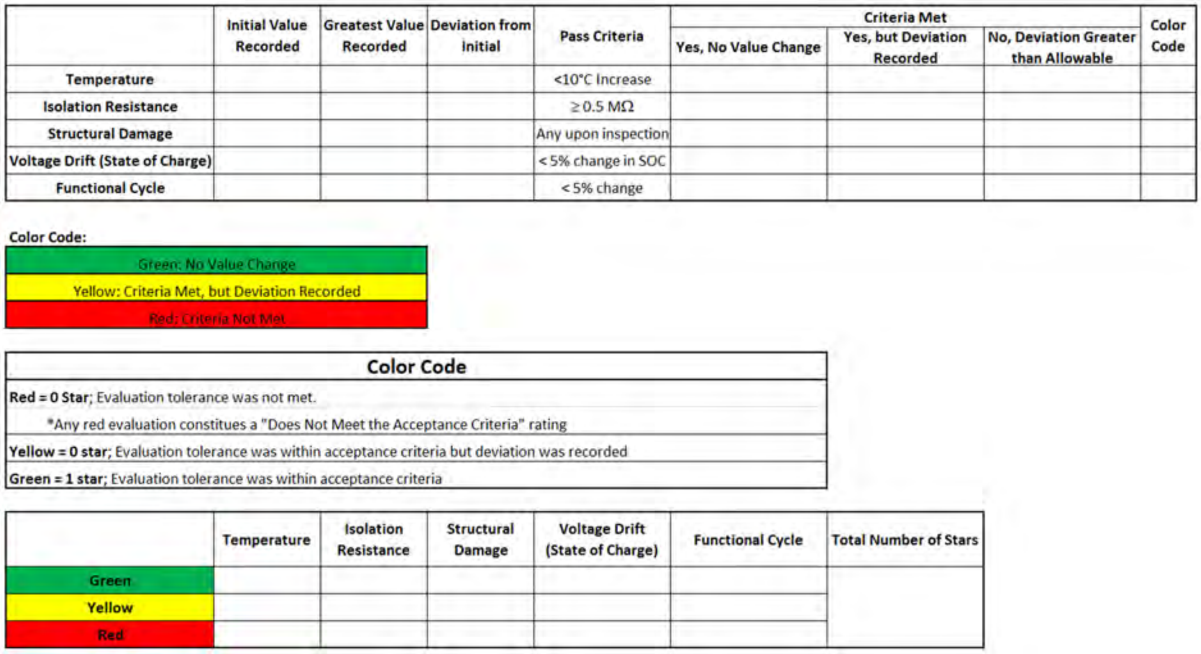
6.11.3.2 Based on the color code given to each measurable data point, a star rating for the given RESS can be derived. The star rating is calculated with the following method:

- If a green color code is assigned, then the RESS receives one star for that met criterion.

- If a yellow color code is assigned, then the RESS does not receive a star for that criterion.

- If a red color code is assigned for any measured data point, the RESS is deemed unsafe.

6.11.3.3 An example color coding and star rating worksheet is shown in Figure 3. The rationale for this rating system is provided in Section 7.4.



	Initial Value Recorded	**Greatest Value Recorded**	**Deviation from Initial**	**Pass Criteria**	**Criteria Met**			**Color Code**
					Yes, No Value Change	**Yes, but Deviation Recorded**	**No, Deviation Greater than Allowable**	
Temperature				<10°C Increase				
Isolation Resistance				≥ 0.5 MΩ				
Structural Damage				Any upon inspection				
Voltage Drift (State of Charge)				< 5% change in SOC				
Functional Cycle				< 5% change				

Color Code:

🟩 Green: No Value Change

🟨 Yellow: Criteria Met, but Deviation Recorded

🟥 Red: Criteria Not Met

Color Code
Red = 0 Star; Evaluation tolerance was not met. *Any red evaluation constitues a "Does Not Meet the Acceptance Criteria" rating
Yellow = 0 star; Evaluation tolerance was within acceptance criteria but deviation was recorded
Green = 1 star; Evaluation tolerance was within acceptance criteria

	Temperature	**Isolation Resistance**	**Structural Damage**	**Voltage Drift (State of Charge)**	**Functional Cycle**	**Total Number of Stars**
🟩 **Green**						
🟨 **Yellow**						
🟥 **Red**						

Figure 3 - Example color code and star rating worksheet.

7. TEST PROCEDURE RATIONALE

Vibration and shock tests are highly relevant to the new fleet of electric or hybrid electric vehicles that are being developed with advanced RESS technology. This document provides a test procedure for characterizing any safety-related problems that may occur during long-term vibration and shock. The intent of the procedure is to qualify the overall safety of mature, production-ready batteries and categorize them with a standardized safety rating system. The vibration spectra developed herein have been synthesized from a combination of other test specifications currently in practice. The procedure is designed to be repeatable.

The available standards that have been assembled for guidance are listed in Table 8.

Table 8 - Standards Used for Guidance

Test Specification	Vibration Profile	Description
DNV 2.4 Section 3.6	Sine Sweep	Transportation specification dealing with low frequency, high displacement movements (typically seen in over sea travel).
	Random Spectrum	
GMW 3172	Sine Sweep	Specification providing rationale for test methods common to the automotive industry.
	Random Spectrum	
	Mechanical Shock	
ISO 16750-3:2003	Sine Sweep	Common test specification/guideline for vehicle transportation.
	Random Spectrum	
ISO 13355:2001	Random Spectrum	Specification intended for packing testing/shipping.
ISO/DIN 12405-1	Random Spectrum	Specification that is directed towards Li-ion battery pack testing.
IEC 60068-2-64:2008	Random Spectrum	Guidelines for broadband random vibration.
SAE J2380	Random Spectrum	SAE's current durability vibration profile for energy storage products.
SAE J2464/2929	Sine Sweep/Shock	A more recent SAE revision directed towards energy storage product safety.
UN DOT Manual S.38.3	Sine Sweep	Specification that is intended for packing testing/ shipping safety as it pertains to energy storage products; used for verification that a product does not need to be shipped as hazardous material.
	Mechanical Shock	

7.1 Test Temperature and Humidity Rationale

The purpose of temperature and humidity stress is to create accelerated degradation and thermal fatigue. It further exposes potential problem areas with the RESS and better evaluates its resistance to the imposed vibration profile. Vehicle vibration stress can occur together with extremely low or high temperatures, thus it is reasonable to include this stress type when evaluating the safety of the device.

GMW 3172 addresses the use of temperature in conjunction with vibration testing; it is based on ISO 16750-3, but the levels were developed for automotive applications. The three temperatures of -40°C , 50°C , and 85°C, along with the corresponding humidity levels of 45% and 85% (with a 3% tolerance), were selected for this test procedure based on GMW 3172. It references these temperatures for devices that would be anywhere in/on the vehicle (shielded from conventional engine heat, if applicable). If the maximum operating limit of the RESS is less than 85°C, the maximum RESS limit should be used instead.

To ensure proper thermal loading during random vibration (independent of RESS mass and shielding), the temperature cycle profile in Figure 2 has been developed with guidance from ISO 16750-4 and GMW 3172. A stabilization temperature tolerance of ±2°C was used based on the tolerances found in these specifications. A RESS with smaller mass exhibits faster temperature transitions, so the thermal shock will be higher and vibration duration will be shorter. A larger RESS, however, exhibits slower temperature transitions, thus a longer vibration duration. This trade-off allows for any size RESS exposure to vibration throughout the temperature transitions, with a minimum guaranteed duration at each temperature extreme.

7.2 Vibration Types and Profile Rationale

The purpose of this test procedure is to evaluate the effect of vibration and shock on a RESS. The tests are primary based on DNV 2.4 Section 3.6, ISO 16750-2:3:2003, and GMW 3172. DNV 2.4 Section 3.6 is useful since it incorporates energies found in the lower end of the frequency spectrum, thus enabling a broad vibration bandwidth. ISO 16750-2:3:2003 describes the mechanical loads that can affect electric and electronic systems and components with respect to their mounting on vehicles. GMW 3172 emulates ISO 16750-3 from a vibration and shock standpoint, but is more focused on automotive applications. Other test specifications were considered, but ultimately not referenced for the vibration parameters in this test procedure. For example, SAE J2380 was not used since it is focused on durability and is slightly more severe than needed. This test procedure is focused on evaluating the level of safety to a given device, not the durability limit.

The test fixture must be free of any resonances below 50 Hz to eliminate unintended excessive mechanical stress to the RESS. This level was selected based on SAE J2464, which uses the same type of devices.

The specified placement of accelerometers in Section 5.4.1.5 was included to create common parameters and reduce variances in the test methods. This gives a higher probability of similar results for identical RESSs tested by different facilities. Commercially available vibration controllers typically provide four control and measurement channels. Therefore, it was selected as a minimum for these tests.

The specified vibration controller setup in Section 6.5.4 was included to create common parameters and reduce variances in the test methods. This gives a higher probability of similar results for identical RESSs tested by different facilities. The parameters are standard settings for all vibration tests.

7.2.1 Sine Sweep

A sine sweep is common in automotive testing to quickly determine resonances within a DUT. Mechanical resonances are the tendency of a system to absorb more energy when the vibration frequency matches the system's natural frequency. It may cause violent swaying motions and even catastrophic failure in improperly constructed RESSs, resulting in very dangerous and life threatening situations.

The parameters listed in Section 6.7.3 were selected based on guidance from ISO 16750-3 and IEC60068 2-64:2008. ISO 16750-3 describes the mechanical loads that can affect the electric and electronic systems and components of a RESS. From IEC 60068 2-64:2008, a resonance point is defined as any excitation of the RESS over two times the input excitation from the vibration stand.

The sine sweep profile is repeated after the random vibration and mechanical shock tests for comparisons with the initial test to assess RESS condition. This allows for changes in the mechanical resonances (if any) to be measured. Thus, it is possible to identify changes to the structure of the RESS that cannot be visually identified.

7.2.2 Mechanical Shock

The parameters for mechanical shock were selected based on the standards defined in Table 8 (specifically, GMW 3172, ISO 16750-3:2003, and SAE J2464). GMW 3172 emulates ISO 16750-3 for vibration and shock, but from an automotive perspective. The shock parameters used herein (25 gn at 15 ms and 18 total pulses) are based on the common industry standard, as defined in GMW 3172 and SAE J2464. The purpose of this test is to simulate potential degradation from in-vehicle use. There are also higher shock levels within GMW 3172, but they are used to simulate collision shock; this was considered unreasonable for testing the long term effects of vibration and shock on the RESSs.

7.2.3 Random Vibration

The purpose of the random vibration profile is to simulate what would be reasonably considered long term degradation effects. The parameters were selected based on ISO 16750-3, GMW 3172, and ISO 12405-1.

7.3 Condition of RESS

This test procedure is applicable to a new RESS. Although the intended sample size is one RESS, additional samples could be included for statistical assessments. The intent is to stress the RESS from a mechanical and thermal standpoint. Including a power profile during testing incorporates a level of complexity that does not to provide additional value.

The basic RESS preconditioning requirements were selected to ensure general safety within the test site and allow for certain data to be recorded. Although the SAE J2380 specification is a durability-based recommendation, the test article is the same as this procedure and thus, it is reasonable to emulate the conditions. The first condition is the verification of the isolation resistance of the battery; the levels are set to allow for the RESS to be handled safely. The next condition is the RESS SOC; although SAE J2380 recommends 80% DOD (i.e., approximately 20% SOC), this procedure uses 100% SOC to maximize potential failure mechanisms.

7.4 Measurement Data Rationale

Previous specifications and the ECE R100-R2 regulation rely only on pass/fail criteria for safety assessments. This standard provides enhanced metrics with a safety performance ranking system. The star rating (Section 6.11.3) was developed to create a system in which the RESSs subjected to this test procedure could be compared. The tolerances selected for each data point were developed based on experience with previous testing.

The measurement data described in Section 6.8 (as well as Section 5.2.3) were derived from SAE J2380 since it uses similar RESS types. The specific data requirements were selected from SAE J2380 (for isolation resistance and change in SOC) and SAE J2464 Version 002 (for temperature, resonance, and structural damage). These were determined to be the parameters of interest for categorizing the safety of the RESS due to previous experience in electric vehicle/energy storage device testing. The measurement accuracies (Section 6.5) were also extracted from SAE J2464.

VIBRATION AND THERMAL CYCLING TEST

Warwick Vibration Test with Thermal Cycling Test Peer Review

1. EXECUTIVE SUMMARY

The following document is a critical review of the draft Society of Automotive Engineers (SAE) test procedure “Vibration with Thermal Cycling - Version 6” developed on behalf of the National Highway Traffic Safety Administration (NHTSA).

It is our recommendation that the following key items are considered within future revisions:

- A list of specific Rechargeable Energy Storage Systems (RESS) and subsystems that this testing is applicable to is included in the introduction of the Standard.

- Additional facility safety requirements such as the identification of specific types of class D fire extinguisher, poisonous gas detection tailored to test item chemistry, air extraction and processing and shaker table thermal barriers, as well as an increase in regular instrumentation and visual inspections of the test item.

- The use of a shaker table with a slip table or a multi-axis table to be specified to ensure the device under test (DUT) is evaluated in its design intent orientation and with respect to gravity.

- Additional fixture requirements which are in-line with vibration testing “good practice”.

- Replacement of the two proposed sine profiles with a single test profile that is better suited to identification and evaluation of resonances (e.g. a constant 1gn sine sweep within the full frequency range of the vibration profile - 10 to 1000Hz).

- A specified delay between shock test pulses of 30 to 90 seconds to allow the DUT to stabilise as well as periods of observation between shock and vibration tests.

- The inclusion of an additional resonance search via a sine sweep between the shock and vibration test to evaluate the mechanical integrity of the DUT.

- Revisions to the random profiles to include a constant Power Spectral Density (PSD) level from 10 to 30Hz within the Z-axis profile, and testing commencing from 5Hz upwards as opposed to the specified 10Hz.

- The inclusion of tolerance bands for all vibration test profiles.

- Specify the use of temperature compensated accelerometers. The total accelerometer weight must be no greater than 5% of the total weight of the DUT or the weight of the component that it is attached to on/within the DUT.

- Test thermal cycle should be revised so that a constant amount of vibration is applied regardless of the thermal mass of the DUT.

2. NOMENCLATURE

Abbreviation Nomenclature Term

BEV	Battery Electric Vehicle
BMS	Battery Management System
DUT	Device Under Test
ECE	Economic Commission for Europe
ED	Electric Drive
EV	Electric Vehicle
FSD	Full Scale Deflection
GMW	General Motors Worldwide
HEV	Hybrid Electric Vehicle
HV	High Voltage
IEC	International Electrotechnical Commission
iMiEV	Innovative Mitsubishi Electric Vehicle
ISO	International Organization for Standardisation
LV	Low Voltage
NHSTA	National Highways Safety Traffic Administration
PSD	Power Spectral Density
RESS	Rechargeable Energy Storage System
SAE	Society of Automotive Engineers
SOC	State Of Charge
SRS	Shock Response Spectrum
UN	United Nations

3. INTRODUCTION

This document is a critical review of Version 6 of the SAE draft test procedure - "Vibration with Thermal Cycling". The stated aim of this procedure is to validate the mechanical integrity of a Rechargeable Energy Storage System (RESS) via the application of vibration energy in all three axes of the Device Under Test (DUT) whilst simultaneously applying climatic conditioning. This critical review evaluates Sections 1 to 6 of this draft procedure. Test profiles discussed within this review use the vehicle axis convention shown in Figure 1.

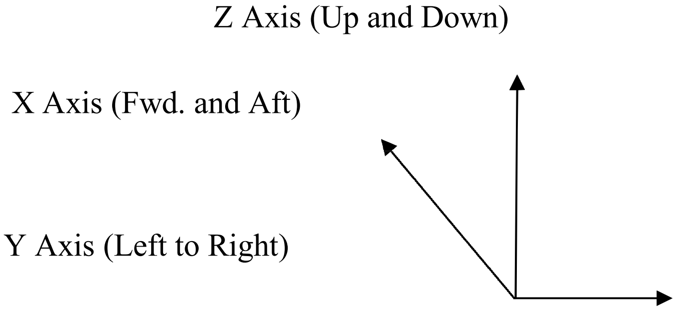


Figure 1 - Vehicle Axis Convention [1].

3.1 Report Aim

To critically assess Version 6 of the SAE document "Vibration with Thermal Cycling Test Procedure" derived for validating the vibration performance of battery packs within the context of vehicle safety, via comparisons to existing academic research and industry practice.

3.2 Report Scope

The scope of this report is to highlight perceived weaknesses within the draft Standard and, where appropriate, make recommendations for its improvement. The responsibility for authorship and quality assurance of the Standard resides with the SAE.

4. ASSESSMENT OF SPECIFICATION BY SECTION

4.1 Section 1: Purpose and 2 Scope

The content of the Standard implies its application for testing large multi-cell battery systems. However, the term RESS is largely undefined and would benefit from a more formal definition. The term RESS is widely employed to describe other technology solutions (flywheels, ultra capacitors, and hydraulic accumulators). Further, it is undefined as to whether the applicability of the Standard covers single cells, battery modules (typically circa: 60V nominal voltage) or full vehicle battery installations.

It would be beneficial to state in the introduction that this test applies vibration and climatic condition simultaneously to the DUT to avoid confusion.

Within section 2, the Standard makes reference to life cycle testing either before or after testing to determine the effects of vibration on the life of the DUT. It is recommended that this is changed to identify a specific type of life cycle testing, as this term is applied to multiple types of life cycle tests such as electrical, fatigue, storage, temperature aging etc.

4.2 Section 3: References

These have not been evaluated.

4.3 Section 4: Definitions

It is recommended that definitions for C-rate and resonance are added.

4.4 Section 5: General Test Requirements

4.4.1 Evaluation of Section 5.1: General Test Precautions and Section 5.2: Test-Specific Precautions

The procedure uses different terminology throughout to describe the DUT. Within sections 5.1 and 5.2, it is referred to as a test unit, then later it is described as a DUT, test article and test device. It is recommended that a single term is used throughout.

Within section 5.1, the statement of “unless otherwise stated, testing shall be conducted at an ambient temperature of 23°C +/- 5°C” adds confusion. It is unclear as to whether it relates to the whole Standard or just pre-test instrumentation and storage. It is recommended that this requirement is either removed or reworded so that it specifically relates to a defined stage.

If the Standard recommends opening the DUT (assuming a multi-cell device for instrumentation or inspection) it is recommended that the Standard advices caution and the adoption of suitable Health and Safety procedures.

It may be appropriate that temperature and humidity requirements be included when discussing instrumentation of the DUT. This should be in-line with manufacturer’s guidelines. This is to ensure that no excess moisture is introduced to the DUT. The DUT should also be resealed in line with production tolerances to minimises moisture ingress (e.g. during the high humidity soak phase of the test profile).

It is recommended that for both test accuracy and safety the DUT is visually inspected and that measurements from instrumentation are reviewed by the staff conducting the tests more than the prescribed “once per day” so that voltage, thermal or mechanical issues are closely monitored and mitigating actions taken. Further precautions may include, but are not constrained to, the use of a data logging system capable of emitting an audible and/or visual alarm in the event of measurements exceeding predefined thresholds.

4.4.2 Evaluation of Section 5.3: Safety Requirements

The draft procedure states that "Class D extinguishers are located near the test stand". Suggested rewording would be: "suitable Class D extinguisher applicable to the chemistry of the battery under evaluation is selected" as Class D "M28" powder is known to be unsuitable for lithium fires [2]. Equally a liquid based extinguishing system would be undesirable given that both the test item and the majority of shaker table test facilities contain high voltage electronics.

An alternative strategy could be to smother the DUT in kiln dried silica sand via an automated means and quarantine the DUT and test facility until it is deemed safe (via instrumentation, thermal imaging and gas detection measurements). The benefit of sand, unlike graphite based class D extinguishers, is that it presents a lower risk for damaging the coils within electromagnetic shaker tables during thermal events - reduced risk of a secondary facility event and subsequently shorter facility repair time following a battery fire.

It is recommended that hydrofluoric and other poisonous gas detection (which can change depending on battery chemistry) is integrated into the facility which would alert personnel to venting of the DUT. Requirements for the air extraction system must also be capable of processing/ capturing contaminates that may be an environmental hazard or harmful to local personnel.

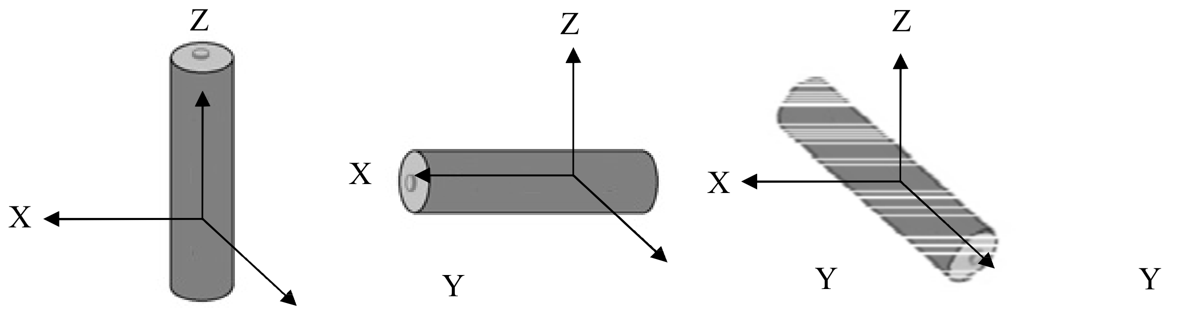
It is recommended that a thermal barrier is placed between the head expander and slip table of the shaker table. Typically shaker tables are constructed using large magnesium alloy castings [3]. A thermal barrier is recommended to reduce the risk of a magnesium alloy fire as a result of a thermal event (battery temperature emissions can achieve temperatures in excess of 800°C [4]) that is within the ignition range of some magnesium alloys [5].

4.4.3 Evaluation of Section 5.4: Test Facility Requirements:

It is recommended that either a multi-axis shaker table or a single axis shaker table combined with a slip table are used for testing items at a pack level so the DUT is held in its design intent orientation during testing in any of its three axis, so that internal components of the DUT are not stressed in an unrealistic manner. This is often referred to as testing an item "with respect to gravity".

If the scope of the proposed Standard is to include individual cells or battery modules, then testing with respect to gravity may dictate multiple testing of a single cell/module (i.e. the Nissan Leaf pack contains battery modules packaged with different orientations[6]). It would be necessary to evaluate three samples to ensure that they were sufficiently robust. An illustration of such a test set up is shown in Figure 2.

For shaker table performance requirements, upon reviewing the current vibration profiles, the shaker table would needed to be capable of testing within the frequency range of the test specification (5 to 1000 Hz) as opposed to the current minimum frequency range that is stated is (5 to 500 Hz).



Test Orientation of Sample 1 Test Orientation of Sample 2 Test Orientation of Sample 3

Figure 2 - Test Orientation for Samples which could be Installed into a Battery Assembly in any Orientation [7].

4.5 Section 6: Test Procedure

4.5.1 Section 6.1: Test Sequence

4.5.1.1 Thermal Cycle

The test definition does not consider or give the user direction regarding the test parameters required for the RESS that have a thermal management system.

4.5.1.2 Fixture Development

It is advised that the fixture requirements are reassessed to consider good industry practice.

- The fixture needs to be stronger than the DUT to ensure that it does not fatigue during the test or transmit any unrealistic vibration energy to the test item [8].
- Any accelerometer control or monitor mounting locations on the fixture should be integrated into the rigs design so that accelerometer locations do not change for each test or during assessment[8].
- The first resonant frequency of the rig should be kept above the highest vibration frequency specified within the procedure to ensure isolation of the test and rig resonance [8, 9].
- Fixtures need to be extremely flat to offer good mechanical compliance and to ensure good transmissibility of vibration energy to the test item and that any slip table bed remains unstressed during the test [8].
- Fixture should be assessed for cross-axial performance prior to testing to ensure that the fixture is stiff in all transverse axes and that no unrealistic vibration loads are transmitted to the DUT during the evaluation [8, 9].

We strongly endorse the requirement: “Test Fixture is to be designed and built in a manner as to allow it to be removed from the vibration exciter in order to reposition the DUT in each of the three orthogonal axes, without having to remove the DUT from the fixture itself.” It is also recommended to extend the requirement, such that the fixture is designed to allow visual inspections of the DUT (without limiting its vibration response performance).

4.5.1.3 Assessment of test sequence

The current proposed test sequence within the draft test procedure is as follows:

- Step 1 Sine Sweep Test
- Step 2 Mechanical Shock Test
- Step 3 Random Vibration Test
- Step 4 Sine Sweep Test (repeated)

The Standard does not specify any rest duration between tests for observation. This is common in other Electric Vehicle (EV) battery vibration test procedures such as Economic Commission for Europe (ECE) R100 [10] where an hour observation and monitoring time is allowed between evaluations to monitor for thermal rises or changes in cell voltage [10].

Given that the purpose of including shock tests is to replicate mishandling during transporting, installation or abusive vehicle inputs [11], it would be preferable to conduct an additional sine sweep resonance search post the mechanical shock testing to determine if the shock loads have changed the mechanical properties of the DUT.

With regard to the location of the mechanical shock test within the test sequence, it is typically dependant on what the shock is designed to represent. Given the scope and purpose of this Standard (an assessment of the safety and robustness of a RESS), it may be prudent to have a typical packaging transport shock test at the start of the test specification that is of a peak saw tooth shape and apply a body mounted sine shock profile as proposed at end of the random vibration profile, so that a “worst case” scenario is applied to the DUT.

It is recommended that the test sequence is summarised in a single table, which includes, but not constrained to: test parameters, details of the climatic conditions of the test, device State of Charge (SOC), the powered/unpowered state of ancillaries etc.

The proposed shock test does not stipulate the control tolerance band for the evaluation. It also does not stipulate the pre and post pulse compensation tolerance. To produce a pulse on a shaker, the end velocity and displacement must be zero[11]. Therefore the drive signal must be conditioned so that the initial and ending acceleration, velocity and displacement values are zero[11]. This is generally done by adding compensating waveforms before and after the main pulse. If these pulses are made too large they will alter the severity of the test pulse. A typical 10% allowance is considered acceptable as a defined pre and post-pulse compensation value [11, 12].

Whilst it is not standard convention within the majority of shock testing procedures, it may be within the interest of this Standard to acknowledge that some shaker tables require pre-test shocks to be performed on the test item in both positive and negative directions in each axis and during each batch of shocks in each axis, for control loop characterisation. Typically the control signal (shock pulse) is slowly built up to a maximum level of 100% by performing 2 control loop characterisation shocks at 25%, 50% and 75% level of the maximum shock pulse respectively prior to the undertaking the desired test pulses [12].

It is recommended that the standard should define the actions to be taken by the test engineers if any mechanical damage, cracking, buckling or change in temperature or voltage is observed as currently there is little guidance within the Standard.

4.5.1.4 Assessment of Step 1 and Step 4 – Sine Sweep

The aim of the swept sine test is "to find any potential resonances in the DUT which could cause failure under normal operating vibration conditions. As found in International Electrotechnical Commission (IEC) 60068 2-64, it is determined that a resonance point is any excitation of the test article over two times the input excitation from the Vibration stand."

It is our considered view that the proposed sine profiles are unsuitable for this assessment. Firstly, the sine profiles have been developed from an amalgamation of durability or robustness testing profiles that are unsuitable given that the purpose of this evaluation is to not stress the component, but merely characterise its vibration behaviour. Consequently they are deemed to be too aggressive for a resonance characterisation test. Typically a sine profile with a constant acceleration value between 0.5 gn to 2 gn (typically 1gn) within the frequency range of the vibration test is used to determine the resonant frequencies of components[13].

Also the proposed sine profiles do not cover the same frequency range as that of the random profile as they are clipped at 440 Hz, which is not desirable as it is good test practice to conduct a resonance search within the same frequency range as the vibration test.

For a resonance search it is unnecessary to have two different swept sine profiles based on the weight of the component. The supplied justification within the test proposal for two different sine profiles comes from a study whose results do not directly apply to the application of a sine profile for a resonance search evaluation and are scoped for robustness testing of battery assemblies when in an unrestrained cargo environment and are from a revised version of a requirement from the latest release of the "United Nations (UN) Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria (Revision 5 Amendment1) – Section 38.3 – Test 3 "Vibration". Appendix A provides further information on why this requirement was applied to UN 38.3.

The proposed sine sweep asks for 10 sweeps in each of the three axis to be applied to DUT. Given that the purpose of a resonance search test is to measure the vibration response of the test item, it is recommended that this is reduced to a single sweep to the peak frequency with a return sweep to the start frequency for each axis of the DUT. 10 sweeps will stress the component prior to the application of the random vibration profile and will impact the quality of the resonance search data.

The proposed Standard does not state the sweep convention. It is common place that a single sweep is either an upward or downward sweep of the specified sine profile frequency band. A sweep of one octave a minute should be used for this type of evaluation so the device under test is subjected to the same number of sinusoidal cycles at the lower frequencies as that at the higher frequency [14].

4.5.1.5 Assessment of Step 2 – Mechanical Shock Test

The half sine profile of the mechanical shock test specified is a typical shock pulse that would be applied to a body mounted component. It is noted that the test guidelines for the shock test do not stipulate the minimum duration required between each shock pulse. It is desirable for test measurement accuracy and also to ensure a realistic test that the DUT is allowed to return to a steady state condition before the next shock pulse is applied. It is recommended that a delay between pulses of circa: 30 – 90 seconds is defined.

It may also be desirable to scope the test to allow for visual inspections to be conducted between pulses. This test should also be conducted with respect to gravity (as defined in Section 2.4.3).

4.5.1.6 Assessment of Step 3 – Random Profile

The random test profile proposed by this standard is shown in Table 1

Table 1 - Proposed Random Vibration Test Profiles for X, Y and Z Axis of DUT

X axis		Y axis		Z axis	
Hz.	g2/Hz.	Hz.	g2/Hz.	Hz.	g2/Hz.
10	0.065	10	0.065	10	0.07
15	0.065	15	0.065	20	0.08
25	0.029	25	0.029	35	0.037
80	0.012	80	0.012	45	0.037
130	0.006	130	0.006	80	0.02
200	0.006	200	0.006	170	0.005
250	0.001	250	0.001	200	0.005
1000	0.00003	1000	0.00003	250	0.0007
				1000	0.0001
G rms:1.7		G rms: 1.7		Grms: 2.0	

As outlined in the test profile rationale, these random profiles were created using International Organization for Standardisation (ISO) 16750-3, General Motors Worldwide (GMW) 3172, and ISO 12405-1,as guidance in order to simulate what would reasonably be considered long term degradation.

The test duration is dependent on the length of the thermal cycle that will in turn vary as a function of the thermal mass of the DUT. From both a vibration robustness and test consistency perspective this is undesirable as comparisons cannot be made between different devices as the test parameters will not be consistent. Within this specification, a device of a lower thermal mass will be subjected to less vibration energy than an item which has a larger thermal mass, which in practice would not happen (e.g. two different sizes or masses of RESS installed within the same vehicle). It is desirable to have a fixed temperature stabilisation, soak and vibration time so that any RESS regardless of size, shape or mass is subjected to the same test conditions. It would also potentially eliminate any perception of bias in the Standard towards smaller RESS.

The test does not specify any control tolerances for the random profile. Typically control tolerances for a random profile are +/- 3 dB of the specified value measured at the reference point for an alarm limit and +/-6 dB of the specified value for a test abort condition [14]. Because the random vibration profile is controlled via a probability distribution function the DUT will be excited to the specified profile, it is common to state the "sigma value" (standard deviation (SD)). 3 sigma or 3SD equates to a 93.3% certainty the DUT will be exposed to the values within the specified test PSD and is a commonly adopted control value with random vibration tests.

The proposed random profile uses the same vibration profile for the X and Y axis. Whilst the X and Y axis have similar energy content, the frequencies and associated energy levels differ between these two axis. An example of this is illustrated in Figure 3. It is recommended that a separate X and Y axis profile is developed.

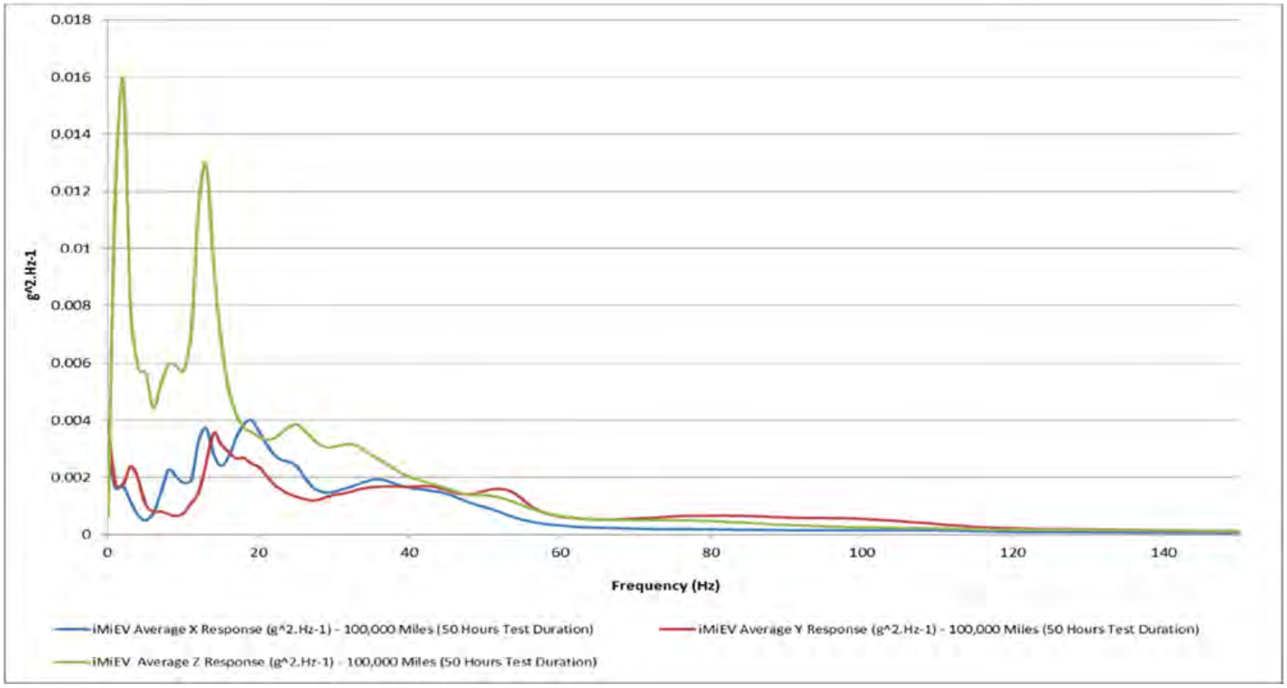


Figure 3 - PSD Data from Mitsubishi iMiEV Sequenced to 100,000 Miles of Durability Illustrating Vibration Behaviour for Each Axis of Vehicle[1].

Report [1] has compared the profiles to data recorded from the RESS of a Nissan Leaf, Mitsubishi Innovative Mitsubishi Electric Vehicle (iMiEV) and a Smart Electric Drive (ED) when driven over repeatable durability surfaces at Millbrook Proving Ground and sequenced to 100,000 miles durability, representative of typical European passenger vehicle usage. It must be noted that specified design lives for automotive component validation are usually between 100,000 to 180,000 miles of customer usage [15-17].

The profiles generated are based on random vibration test duration of 16 hours per axis using the assumption that the stabilisation time is be approximately 2 hours per temperature in the test profile, and a ramp time of 1 hour between temperatures. The results are shown in Figure 4 to Figure 6.

It is noteworthy that the data that the profiles are compared to are an approximation of the vibration Power Spectral Density (PSD) energy required to replicate 100,000 miles driving. The results relate to only these vehicles and do not include within its synthesis off road surfaces or non- passenger vehicle data.

Reviewing the Z axis profile compared to 100,000 miles of sequenced vibration data from the Battery Electric Vehicle (BEV) products as shown in Figure 4, vibration energy below 10Hz can be observed within the figure. It is recommended that the test profile should be adjusted to include vibration inputs below 10Hz. However it is recommended not to specify test frequencies below 5Hz as the displacement required to replicate these frequencies and desired PSD levels will be outside the equipment capabilities of the majority of commercially available electromagnetic shaker tables and some hydraulically actuated shaker tables.

In terms of the profile PSD levels there is some correlation in curve shape between the synthesised data and the Z-axis profile. However, given that these profiles will be applied to RESS destined for a wide range of automotive products, it would be desirable to remove the peak at 20 Hz in the proposed Z axis PSD and apply a constant PSD level from 10 to 30 Hz as from the three vehicles assessed the peaks in the battery vibration energy are witnessed at different points during this frequency band, as these peaks will change depending on the RESS construction and the vehicle response. As a result it may be desirable from a safety and robustness perspective to test using a flat PSD from 10 to 30 Hz to guarantee the DUT is excited at a representative “in-service” PSD energy.

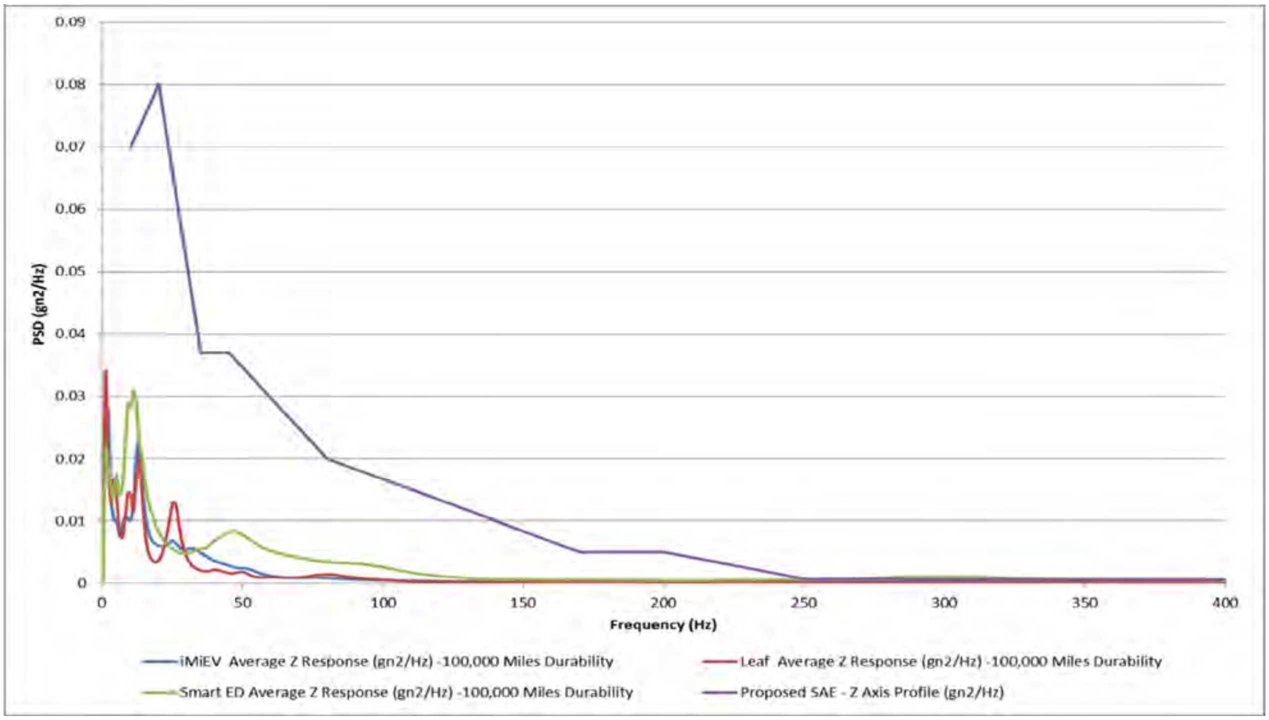


Figure 4 - Mitsubishi iMiEV, Nissan Leaf and Smart ED Battery Vibration Data from Proving Ground Inputs Sequenced to 100,000 Miles Durability and Compared to Proposed Z Axis Test Profile – 16Hrs Test Duration [1].

Another recommendation with regard to the suitability of this profile, relates to the reduction in PSD level above 30Hz. The current gradient is gradual in comparison to the measured data. It may be more realistic to adjust the proposed profile so that it is more representative of the trend witnessed in the measured data shown in Figure 454.

Reviewing both the X and Y axis profiles (Figure 455 and Figure 456) it is noticeable that the Y axis PSD energy is significantly less than that proposed by the Standard which is the same for both the X and Y axis. The proposed X axis PSD levels are also significant in comparison to the vehicle’s battery response. It is recommended that the levels proposed for the X and Y axis are adjusted to be more representative without sacrificing the objective of determining safety and robustness.

It is recommended that an inspection is undertaken at the end of each axis evaluation prior to the DUT being moved to the next test orientation to ensure it is safe for it to be moved.

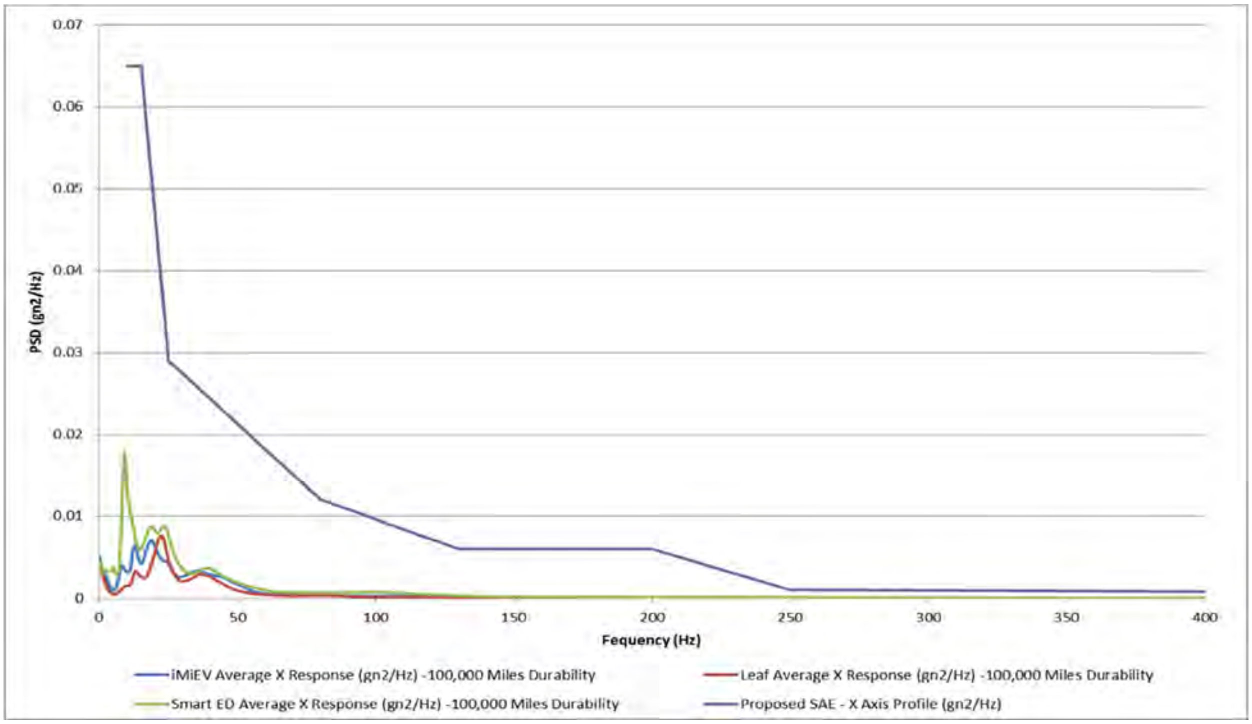


Figure 5 - Mitsubishi iMiEV, Nissan Leaf and Smart ED Battery Vibration Data from Proving Ground Inputs Sequenced to 100,000 Miles Durability and Compared to Proposed X Axis Test Profile – 16Hrs Test Duration[1].

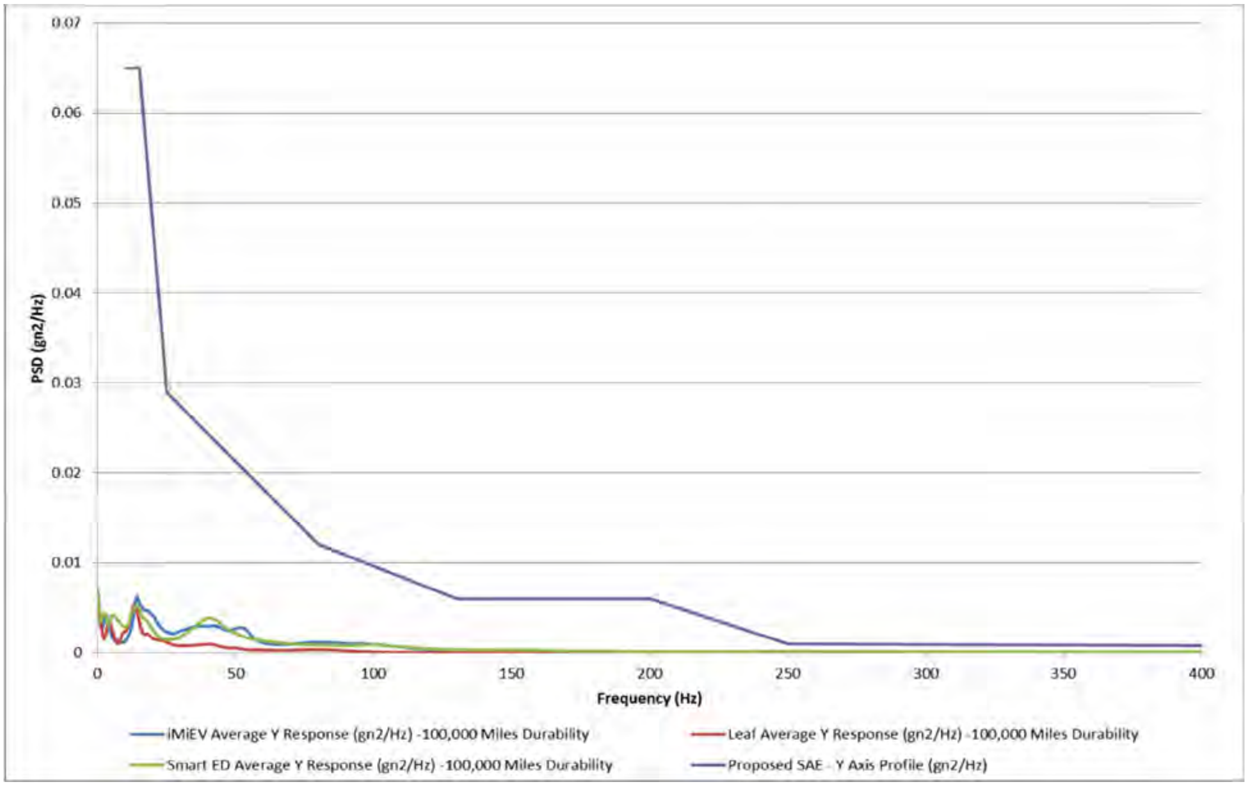


Figure 6 - Mitsubishi iMiEV, Nissan Leaf and Smart ED Battery Vibration Data from Proving Ground Inputs Sequenced to 100,000 Miles Durability and Compared to Proposed Y Axis Test Profile – 16Hrs Test Duration [1].

4.5.1.7 Accelerometer Types and Locations for Testing

For the accelerometer types and their location on the DUT, the Standard suggests that the "Size and type of accelerometer can be determined by test facility based on the size of the test article or general availability." Whilst this allows for engineering judgement, it is recommended that some requirements on accelerometer types and sizes are included. It is recommended that the combined weight of the accelerometers attached to the DUT are no greater than 5% of the total sample weight or 5% of the weight of the component that it is attached to (this point is particularly pertinent for the testing of individual cells). As an example, 18650 cells, comparable to the Tesla battery assemblies[18, 19], typically have a weight of 40 grams +/-10 grams whilst the majority of accelerometers suitable for this kind of testing weigh between 4 to10 grams [20].

It is recommended that the Standard specifies that accelerometers are of the "temperature compensated" type, so that any risk of measurement inaccuracy or sensor failure is minimised during climatic conditioning.

The Standard proposes a minimum of four accelerometers are to be used per test article and placed in the following manner:

- Two (2) accelerometers to be placed on the upper rigid corners diagonally across from one another in opposite corners
- One (1) on mounting support as far from exciter as possible
- One (1) on test mounting plate or shaker slip table were applicable

For the swept sine it is recommended that the Standard specifies the locations where the DUT shall be measured for resonances. This could be the upper rigid corners diagonally across from one another on the DUT. The standard needs to define the control accelerometer location(s). This could be an averaged or maximum control strategy employing the accelerometer mounted on the support structure (which is assumed to be the fixture in this review) and the one on the test mounting plate / slip table. It is recommended that one of the control accelerometers is placed near one of the fasteners going into the shaker tables armature (in the case of a head expander for Z axis testing) or in the centre on the non-driven end of a slip table, as these locations typically offer good vibration transmissibility, thus improving control accuracy.

The random vibration test proposes a minimum of three (3) accelerometers are to be used per test article and should be placed in the following manner:

- One (1) on test article as far from the exciter as possible
- One (1) on mounting support as far from the exciter as possible
- One (1) on test mounting plate or shaker slip table were applicable

The random profile requirements do not outline which is the control and which are monitor accelerometers. In the case of the random test, it would be advisable to have the items on the fixture and slip table and mounting plates as the control accelerometers. The current accelerometers description does not define that the same consideration must be given towards accelerometer positioning for the X and Y axis locations.

4.5.2 Section 6.2: Device Under Test

It is recommended that this section is placed at the start of the Standard and highlights the specific types of RESS applicable to this Standard.

4.5.3 Section 6.3: Test Guidelines

The conditions for each of the test steps are defined as:

- Step 1: The DUT is to be unpowered, with all safety disconnects in place.
- Step 2: The DUT is to be unpowered, with all safety disconnects in place.
- Step 3: The DUT is to be unpowered, while High Voltage (HV) and Low Voltage (LV) mating connectors are to be attached to the DUT. The DUT is to be monitored during testing.
- Step 4: The DUT is to be unpowered, with all safety disconnects in place.

It is recommended that this information be summarised within a single table and perhaps combined with a table defining the test steps.

The guidelines do not give the user clear guidance on whether the battery management system should be installed and validated during the test, however it implies it as “safety disconnects are to be in place”. The purpose of this Standard is to assess a RESS to an aggressive vibration environment and its ability to survive the test conditions with minimal degradation, or to fail in a safe manner. It is the recommendation of this review that guidance with regard to the fitment and validation of the battery management system and associated ancillaries are included.

The Standard does not consider that within some RESS the HV and/or LV systems will need to be activated to allow the activation of safety disconnects and component monitoring.

It is also recommended that a humidity measurement and control tolerance is introduced to the Standard to ensure test consistency and repeatability.

4.5.4 Section 6.4: Thermal Cycle Profile Development

The proposed thermal cycle profile (Figure 7) compensates for the stabilisation time of different masses for the RESS. However, as a result of this methodology, different durations of vibration energy will be applied to different masses of RESS. This is not desirable as a RESS with a lower thermal mass will be subjected to a lower quantity of vibration energy. It is recommended that the stabilisation time within the specification be changed so that no vibration occurs during this period, or the stabilisation time is pre-set.

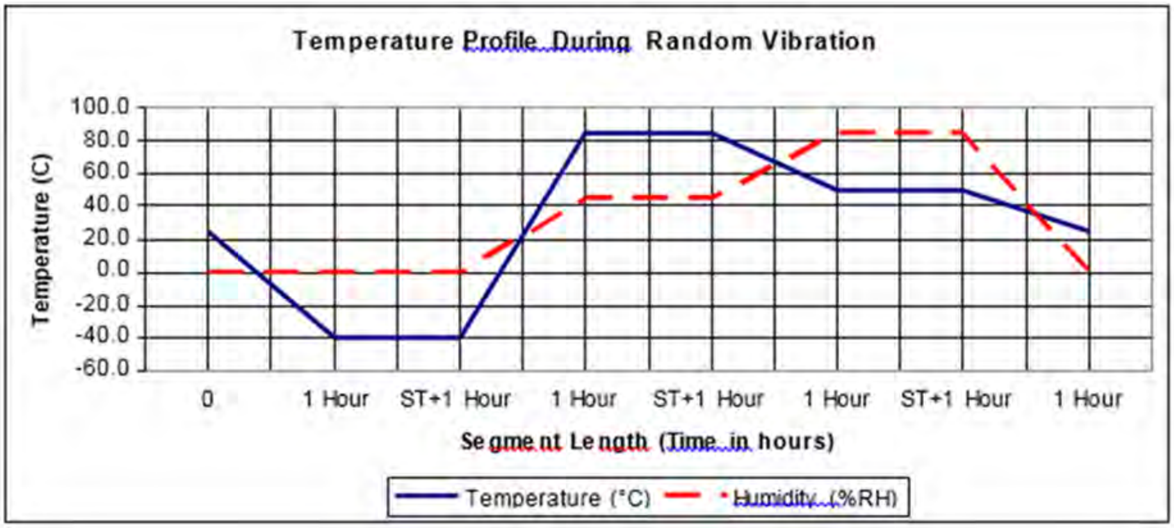


Figure 7 - Proposed Temperature and Humidity Cycle for Random Vibration Testing.

The Standard does not offer the user any guidance on how the test should be adjusted for different thermal management methods employed by BEV manufacturers. For example the Chevrolet Volt uses a traditional automotive liquid cooling system, whilst the Nissan Leaf uses a combination of resistive energy and air cooling. The thermal cycle does not currently define control tolerances for temperature and humidity. It is recommended that the SAE agree upon a set of control tolerances for the proposed thermal cycle.

4.5.5 Section 6.5: Test Parameters

Recommendations on changes to the test parameters are discussed in the other relevant Sections within this document.

4.5.6 Section 6.6: DUT Preconditioning

The DUT preconditioning section should be brought forward to the start of the Standard so that the testing is defined in a chronological order.

The preconditioning of the battery should define the charge and discharge cycle parameters such as the C-rate desired to adjust the SOC and also the climatic conditions and the subsequent tolerances for this preconditioning. It is recommended that the preconditioning phase defines pre- test measurements and the process to characterise the DUT (e.g. weight, dimensions including photographs where applicable). It is recommended that the same test characterisation is repeated at the end of the procedure to identify any change in the mechanical integrity of the RESS.

4.5.7 Section 6.7: Measured Data

It is recommended that a temperature and humidity trace of the test environment is recorded to ensure that the DUT is exposed to the desired test profile and that this profile is within test tolerance.

Weight is also a measurement often recorded at the start and end of testing within the mechanical validation of RESS and cells as this allows the engineer to quantify the loss of mass associated with electrolyte, structural material or coolant leakage.

With regard to loss of voltage potential, it is assumed that this test is to identify an internal electrical short-circuit within the module. A sampling interval of one minute would be inadequate to identify this failure mode and take corrective action without first turning the shaker table-off. It is unclear how this test case may interact with the "isolation resistance" evaluation or the test guidelines defined in Section 2.5.1. Depending on the functionality of the BMS (if powered) it is conceivable that a loss of isolation resistance could be identified as an internal short-circuit triggering a further test failure (loss of voltage potential).

Reviewing the voltage drift requirement, it would appear that this evaluation would be a duplication of the above "loss of voltage potential", in that both define the same measurement at the same sample rate. It is unclear as to the justification for continually measuring open circuit voltage during the test. There is no evidence within the literature that quantifies the impact of RESS vibration on SOC and hence if any stabilisation time is required before an accurate SOC measurement may be made.

The 10% change in resonances should also be widened to include the investigation of causes of entirely new resonances observed between the start and end of testing. This would potentially indicate a loss of mechanical integrity of a sub component within the assembly. This requirement also needs to define the meaning of the stated 10% change – whether this relates to 10% of the measured value or to 10% of the full measurement range (e.g. Full Scale Deflection).

A logging frequency for the RESS internal temperature should be sufficiently high to identify the onset of a thermal event. It is recommended that sampling is not greater than 1 sample a second.

For structural damage, it is advisable to stipulate that this also includes an assessment of the sub components of the RESS. This is discussed further in Section 2.5.8.

4.5.8 Section 6.8: Inspection Method

It is recommended that the DUT is constantly monitored during testing with an inspection performed at the start and end of testing and as outlined in chapter 2.5.1.3 additional resonance search and visual inspections included at the end of the shock testing.

4.5.9 Section 6.9: Post Test Requirements

Given that the proposed RESS, are an assembly of cells, bus-bars and cooling circuits, it would be beneficial to determine the effect that this test has had on the mechanical integration of these components. It is recommended that a strip-down and inspection of the subcomponents is conducted to ensure no cracking, deformation, fretting, dusting, buckling or material delamination is observed at a sub assembly and component level as the current assessment will only capture the effect of the test on the casing.

4.5.10 Section 6.10: Acceptance Criteria

The acceptance criterion is not clearly defined. It does not outline robustly, when the DUT is to be assessed for the acceptance criteria or at what stage of the evaluation they apply. A refined version of the table outlined in Appendix B of the specification would assist to explain the desired acceptance criteria.

If the temperature requirement is applicable for any stage within the test process, it is recommended that the change in RESS temperature is in relationship to the ambient temperature so that a failure criterion is not met due to the chamber changing the temperature set point. Also a rise in temperature should also be achieved over a given time frame (e.g. $4°Cs^{-1}$). When setting a temperature change requirement, the specification should be mindful that someone entering the test cell to inspect the item may cause a temperature deviation in the DUT measurement (it is noted that it would be potentially unsafe for someone to enter the facility mid test with a live battery).

4.6 Other Observations within the Standard

Gravity should be defined within the procedure as “gn” so that the term is not confused with gram which is defined by g.

4.7 Questions Posed by SAE Project Team

4.7.1 Difference in Vibration Energy Subjected to Pack Mounted in Different Locations of the Vehicle

Within research conducted by Kjell et al on a Volvo C30 Electric, the vibration response was measured from multiple positions on the vehicle to determine the variance in acceleration at different possible RESS installation locations. This data was obtained by instrumenting the vehicle with tri-axial accelerometers and driving the test vehicle at a steady state speed over a track of cobble stones[21]. The locations measured were the trunk floor, one of the suspension towers (or legs), the centre of the vehicle (from the floor) and the front of the vehicles floor (from the front of C30’s RESS). This study found there was a correlation in acceleration witnessed between the shock tower location, centre and front floor accelerometer positions from 5 to 100Hz, however the trunk floor accelerometer witnessed a significant amount of acceleration within this study[21]. This trend is illustrated below in the Shock Response Spectrum (SRS calculated for the Z axis accelerations from each of the measurement locations.

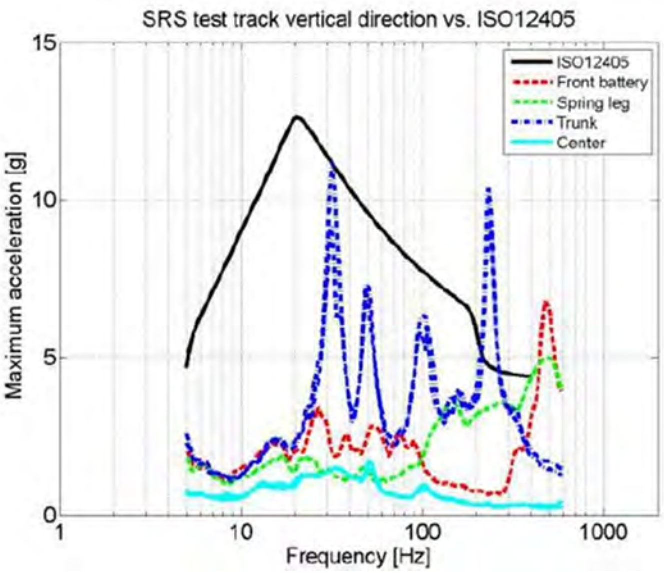


Figure 8 - SRS for the Measured Signal for Z axis Motion, Compared to Calculated SRS from ISO12405 [21].

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6. APPENDIX A

6.1 The Origin of the Mass Requirement with UN38.3

UN38.3 was originally developed as a robustness test to determine the airworthiness via air freight for battery cells and assemblies destined for consumer electronics. The standard was developed as a response to a significant li-ion battery fire at Los Angeles International Airport on 28th April 1999 [22, 23]. In this incident a shipment of two pallets of 120,000, small lithium 10280 type batteries caught fire at the Northwest Airlines cargo storage area when they were inadvertently dropped whilst being removed from the aircraft by a fork lift operator [24, 25]. Approximately four hours after the mishandling incident, the impacted pallet of battery cells started to smoke prior to catching fire [24]. The fire spread to the second pallet resulting in a significant fire safety incident which caused property and equipment damages in excess of $500,000 [24, 25]. The Los Angeles Airport fire of April 1999, as well as other serious lithium battery incidents within the field of aviation, escalated calls for tighter measures to ensure greater safety in lithium battery transportation and to tighten existing measures already in place [22, 25]. Within 20 months of the Los Angeles fire, the Economic and Social Council's Committee of Experts on the Transport of Dangerous Goods presented the test methods and procedures – "Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria", which outlined a series of legislative tests that battery cells have to be subjected to before being allowed to be sent by air cargo. Within this suite of tests, a specific vibration test; "Section 38.3 – Test 3 Vibration" is mandated.

In 2008 the fourth edition of UN38.3 was released. The vibration profile specified by this edition of the standard was as follows:

Table 2 - Summary of a Single Cycle of UN38.3 Test 3 – As Defined in forth revision of "Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria" [26]

Frequency [Hz]	**Acceleration [m/s^2]**	**Acceleration [gn]**	**Peak to Peak Amplitude [mm]**
7 - 18	9.81	1	Amplitude decreasing
18 - 50	Gradually increased from 9.81 to 78.5	Gradually increased from 1 to 8	0.8
50 - 200	78.5	8	Amplitude decreasing
200 - 50	78.5	8	Amplitude increasing
50 - 18	Gradually decreased from 78.5 to 9.81	Gradually decreased from 8 to 1	0.8
18 - 7	9.81	1	Amplitude increasing

Within the late 2000's several large and new automotive vehicle manufacturers, such as Nissan, Fisker, Tesla and GM, embarked on EV projects all of which had large battery packs in excess of 50Kg, which had to be validated to this legislative standard.

Whilst the intention of UN38.3 Test 3 is to ensure the safety and stability of a particular li-on battery during multiple transport conditions, it was scoped with "solid" consumer electronic batteries in mind, such as those involved in the April 1999 LA Airport fire[1, 27]. As a result the fourth edition of UN38.3 and its earlier releases, were made mandatory for large HEV and BEV Li-Ion automotive RESS "without any consideration for the design of these products" [1]. Subsequently this standard did not take into account the size, weight or lithium content of the RESS under evaluation and subjected all devices to the same vibration profile. The reason why the 8 gn requirement was deemed unrealistic [27], for HEV and BEV battery assemblies is because the vibration mode is reduced by the mass of the pack and therefore would be typically, according to Moore et al, 2 gn for battery packs greater than 12kg in weight [1, 27]. Also, HEV and BEV battery pack assemblies are typically a system of electronic controllers, sensors, cooling infrastructure, cabling, bus bars, cells, covers and attachment brackets and, unlike small consumer electronic batteries will have several resonant frequencies under 200Hz [27] which at the unrealistic gn levels required by the fourth edition of UN38.3, is likely to result in a battery pack becoming over engineered to meet the arduous requirement of this vibration profile [1, 27].

In response to these short comings the current "fifth revision - amendment one" of UN38.3 has several significant changes. Firstly the standard now offers two different vibration profiles. One is targeted at the validation of large battery packs, whilst the other is used for the validation of cells and smaller battery assemblies such as those used in non-automotive applications such as computer servers. The classification criteria of small or large cells and battery assemblies are defined in Table 2, whilst the vibration profile for this standard is outlined in Table 3.

Table 3 - Classification of Cells and Batteries According to UN38.3 Revision 5 Amendment 1 [22, 28]

Classification	**Description of Classification Criteria**
Small Cells	Up to 12 grams lithium content, or up to 150 Wh for lithium cells
Large Cell	Over 12 grams lithium content, or over 150 Wh for lithium cells
Small Battery	Gross mass not more than 12 kg
Large Battery	Gross mass more than 12 kg

Table 4 - Summary of a Single Cycle of UN38.3 Test 3 – As Defined in Revision 5 Amendment 1 of "Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria" [28]

Frequency [Hz]	**Acceleration [gn] for a Either Large or Small Cells Small or Battery Assemblies**	**Frequency [Hz]**	**Acceleration [gn] for a Large Battery Assemblies**
7 - 18	1	7 - 18	1
18 - 50	Gradually increased from 1 to 8	18 - 25	Gradually increased from 1 to 2
50 - 200	8	25 - 200	2
200 - 50	8	200 - 25	2
50 - 18	Gradually decreased from 8 to 1	25 - 18	Gradually decreased from 2 to 1
18 - 7	1	18 - 7	1

VIBRATION AND THERMAL CYCLING TEST

Response to Warwick Vibration with Thermal Cycling Test Peer Review

Peer review response letter for RESS Vibration with thermal Cycling procedure

The following document outlines the direct responses to the critical review of the draft Society of Automotive Engineers (SAE) test procedure "Vibration with Thermal Cycling - Version 6" developed on behalf of the National Highway Traffic Safety Administration (NHTSA).

Below is the list of recommendations by Warwick University to be considered along with the corresponding response to each of those recommendations.

1. Recommendation:

Add a list of specific Rechargeable Energy Storage Systems (RESS) and subsystems that this testing is applicable to is included in the introduction of the Standard.

Response:

The Addition of a specific list may inadvertently exclude RESS types now and in the future as these devices specifics change. We have added a definition as to what constitutes a RESS, allowing for a broader range of devices to be encompassed by this procedure. Additionally, in the scope, we address split-systems and RESS with separate control/monitoring circuits which are not mechanically part of the same RESS structure.

As also recommended, undefined terms such as "test article," "device", etc have been changed to use "DUT" consistently.

2. Recommendation:

Add facility safety requirements such as the identification of specific types of class D fire extinguisher, poisonous gas detection tailored to test item chemistry, air extraction and

processing and shaker table thermal barriers, as well as an increase in regular instrumentation and visual inspections of the test item.

Response:

This information would be too specific for a procedure to be used on multiple RESS types. The general facility precautions are listed in Section 4.3 along with recommended considerations.

3. Recommendation:

The use of a shaker table with a slip table or a multi-axis table to be specified to ensure the device under test (DUT) is evaluated in its design intent orientation and with respect to gravity.

Response:

Concur with this recommendation, and this explanation has been added to Section 4.4.

4. Recommendation:

Add fixture requirements which are in-line with vibration testing "good practice".

Response:

The good practices explained in the procedure are sufficient in terms of fixture development for a document such as this. Based on the review of other similar procedures already used in industry it is not common to add this information to this type of document. References that these good practices recommended are to be adhered to have been added.

5. Recommendation:

Consider the replacement of the two proposed sine profiles with a single test profile that is better suited to Identification and evaluation of resonances (e.g. a constant 1gn sine sweep within the full frequency range of the vibration profile - 10 to 1000Hz).

Response:

The original test procedure was to use the Sine sweep portion of the vibration as durability cycle itself as opposed to it only being a check as to the vitality of the device. This scope changed, but the procedure did not. Concur with the recommendation and changed the procedure in section 5.

6. Recommendation:

Add a specified delay between shock test pulses of 30 to 90 seconds to allow the DUT to stabilize as well as periods of observation between shock and vibration tests.

Response:

Concur with the recommendation and this delay requirement has been added to section 5.1.

7. Recommendation:

Include an additional resonance search via a sine sweep between the shock and vibration test to evaluate the mechanical integrity of the DUT.

Response:

Concur with the recommendation and the additional resonance sweep requirement has been added to section 5.1.

8. Recommendation:

Revise the random profiles to include a constant Power Spectral Density (PSD) level from 10 to 30Hz within the Z-axis profile, and testing commencing from 5Hz upwards as opposed to the specified 10Hz.

Response:

After further review of current industry specification listed within the test procedure, the lower end of the frequency domain should remain 10Hz, further justification can be found in section 6.3.

9. Recommendation:

Include tolerance bands for all vibration test profiles.

Response:

Concur with the recommendation and this tolerance band requirement has been added to section 5.

10. Recommendation:

Specify the use of temperature compensated accelerometers. The total accelerometer weight must be no greater than 5% of the total weight of the DUT or the weight of the component that it is attached to on/within the DUT.

Response:

Concur with the recommendation and the accelerometer requirement has been added to section 5.1.

11. Recommendation:

Test thermal cycle should be revised so that a constant amount of vibration is applied regardless of the thermal mass of the DUT.

Response:

The temperature profiling as stated is viable, As a sample with smaller mass will exhibit faster temperature transitions, the thermal shock will be higher the smaller the thermal load of the DUT. A larger sample however, will exhibit slower temperature transitions, thus will experience a longer vibration duration. This trade-off allows for any size sample exposure to vibration throughout the temperature transitions, with a minimum guaranteed duration at each temperature extreme. This is also explained in section 6.1.

APPENDIX

Failure Mode & Effects Analysis (FMEA)

Issue	Item	Function	Requirement	Type: Hybrid Plug-in Hybrid Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
1	**LI-ION Battery System**												0									0
2	F1	F1. Retain pack/system to vehicle	During normal customer use (driving, charging, parking)	All	F1.1 System not retained during driving	Hazardous (projectile, dragging on ground--penetration)	Attachment design not adequate for driving duty cycle (vibration, fatigue, shock loads)		Vehicle durability, J2929 (UN T3, J2380)	10	1	4	40	10	None - OEM's have stringent durability schedules							0
3	F1	F1. Retain pack/system to vehicle	During normal customer use (driving, charging, parking)	All	F1.1 System not retained during driving	Hazardous (projectile, dragging on ground--penetration)	Corrosion and exposure to harsh chemicals		Vehicle durability	10	1	7	70	10	None - OEM's have stringent durability schedules							0
4	F1	F1. Retain pack/system to vehicle	During normal customer use (driving, charging, parking)	P, E	F1.2 System not retained during charging	Annoyance	Low priority - not analyzed			4	0	0	0	0	None - Annoyance impact low priority							0
5	F1	F1. Retain pack/system to vehicle	During normal customer use (driving, charging, parking)	All	F1.3 System not retained while parked	Annoyance	Low priority - not analyzed			4	0	0	0	0	None - Annoyance impact low priority							0
6	F1	F1. Retain pack/system to vehicle	During normal customer use (driving, charging, parking)	All	F1.4 System partially retained during driving	Hazardous (dragging on ground--penetration, lead to fully disengaged, damage to other systems such as hydraulic system, damage to battery system cable leading to insulation failure, damage to battery cooling system)	Attachment design not adequate for driving duty cycle (vibration, fatigue, shock loads)		Vehicle durability, J2929 (UN T3, J2380)	10	4	4	160	40	None - OEM's have stringent durability schedules							0
7	F1	F1. Retain pack/system to vehicle	During normal customer use (driving, charging, parking)	P, E	F1.5 System partially during charging	Annoyance	Low priority - not analyzed			4	0	0	0	0	None - Annoyance impact low priority							0
8	F1	F1. Retain pack/system to vehicle	During normal customer use (driving, charging, parking)	All	F1.6 System partially retained while parked	Annoyance	Low priority - not analyzed			4	0	0	0	0	None - Annoyance impact low priority							0
9	F1	F1. Retain pack/system to vehicle	During crash and post-crash	All	F1.7 System not retained during crash	Hazardous	Crash force exceeds design limits (Shock loads)	305 retained at single attachment minimum	FMVSS 305 (Crash Testing & Retension)	10	7	4	280	70	None - OEM's required to meet FMVSS 305 (front, side and rear impacts)							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-in Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
10	F1	F1. Retain pack/system to vehicle	During crash and post-crash	All	F1.8 System not retained post-crash	Hazardous (first responders, towing)	Crash force exceeds design (Shock loads)	305 retained at single attachment minimum	FMVSS 305 (post test roll and visual inspection)	10	4	4	160	40	Assess potential for supplemental test procedure to simulate 2nd responder conditions (i.e, tow truck, salvage yard, etc.)							0
11	F1	F1. Retain pack/system to vehicle	During crash and post-crash	All	System partially retained during crash	Hazardous (first responders, towing)	Crash force exceeds design (Shock loads)	305 retained at single attachment minimum	FMVSS 305 (post test roll and visual inspection)	10	4	4	160	40	Assess potential for supplemental test procedure to simulate 2nd responder conditions (i.e, tow truck, salvage yard, etc.)							0
12	F1	F1. Retain pack/system to vehicle	During other events (service and maintenance, transport, vehicle recycling & disposal)	All	F1.9 System not retained during service, maintenance and transport	Performance (loss of mounting hits bed of tow truck)	Tow-incorrect vehicle hookup to pack	Design considerations. Tow instructions (verification by OEM)	OEM-specific techniques	7	4	7	196	28	Assess the need to develop design guideleines / recommended practices to prevent inadvertant tow hook attachment. Assure that proper towing instructions are provided by OEM. Refer to SAE TEVHYB12 1st/2nd responder committee no further action required			OEM tow / hoist / service instructions exist - no further action required				0
13	F2	F2. Prevent or minimize mechanical damage during usage	During normal customer use (driving, charging, parking) and foreseeable misuse	All	F2.1 System damaged during normal use	Hazardous	Pack design inadequate for driving duty cycle		Vehicle durability	10	4	7	280	40	None - OEM's have stringent durability schedules							0
14	F2	F2. Prevent or minimize mechanical damage during usage	During normal customer use (driving, charging, parking) and foreseeable misuse	All	F2.1 System damaged	Hazardous	Customer misuse		Vehicle durability	10	4	7	280	40	Verify vehicle durability includes misuse no further action required	Each OEM		OEM's have stringent durability schedules / validation profiles - no further action required				0
15	F2	F2. Prevent or minimize mechanical damage during usage	During normal customer use (driving, charging, parking) and foreseeable misuse	All	F2.2 System damaged during crash (vehicle totalled)	Hazardous	Vehicle/pack design inadequate for crash force		FMVSS 305 (retention), J2929 crash, NCAP	10	4	4	160	40	Is combination of FMVSS 305 and J2929 adequate?							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-in Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
16	F2	F2. Prevent or minimize mechanical damage during usage	During normal customer use (driving, charging, parking) and foreseeable misuse	All	F2.3 System damaged during minor crash (vehicle repairable)	Hazardous (damage initiation resulting in further failure over time)	Vehicle/pack packaging inadequate	Design considerations	None	10	4	7	280	40	Discuss testing method and rating Determine if OEM-specific internal standards are comprehensive enough. Determine if industry standard testing is needed. Diagnostics and associated repair / inspection procedures are sufficient **consider extended time exposure in test methods developed**			Subsequent discussion indicates that OEM specific diagnostics would be able to identify if any damage exists.				0
17	F2	F2. Prevent or minimize mechanical damage during usage	During normal customer use (driving, charging, parking) and foreseeable misuse	All	F2.3 System damaged during crash (vehicle repairable)	Hazardous (damage initiation resulting in further failure over time)	Pack strength inadequate		J2929 (Crush, drop, etc.)	10	4	4	160	40	Action TBD							0
18	F2	F2. Prevent or minimize mechanical damage during usage	During other events (service, transport, vehicle recycling & disposal)	All	F2.4 System damaged during service, transport, recycling and storage	Hazardous (damage initiation resulting in further failure over time)	Vehicle hoisted at pack (misuse)	Documented procedure (established practice)	OEM-specific techniques & instructions	10	1	7	70	10	Discuss testing method and rating Do established practices need to change? Refer to SAE TEVHYB12 1st/2nd responder committee **No further action required**			OEM tow / hoist / service instructions exist - no further action required				0
19	F2	F2. Prevent or minimize mechanical damage during usage	During other events (service, transport, vehicle recycling & disposal)	All	F2.4 System damaged during service, transport, recycling and storage	Hazardous (damage initiation resulting in further failure over time)	Vehicle towed at pack (misuse)	Documented procedure, design considerations, training, proper tools	OEM-specific techniques & instructions	10	4	7	280	40	Discuss testing method and rating Do established practices need to change? Refer to SAE TEVHYB12 1st/2nd responder committee **No further action required**			OEM tow / hoist / service instructions exist - no further action required				0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-in Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
20	F3	F3. Provide means for keeping foreign materials (water, dust, etc.) out of battery system	During normal customer use (driving, charging, parking)	All	F3.1 System contamination from water (conductive liquid)	Hazardous over time	Inadequate enclosure design - prevent intrusion - allow expel		Vehicle durability; battery system (J2929) / vehicle immersion (J2344) test	9	4	4	144	36	None required							0
21	F3	F3. Provide means for keeping foreign materials (water, dust, etc.) out of battery system	During normal customer use (driving, charging, parking)	All	F3.1 System contamination from water (conductive liquid)	Hazardous over time	Enclosure compromised by aggressive chemical source (e.g., corrosion)		J2579 Technical...Fuel Systems and Fuel Cell and other Hydrogen Vehicles (exposure to standard chemical substance)	9	4	7	252	36	Review J2579 to determine if it is transferrable (both LIB and fuel cells must be robust against chemical sources) Review J2929 for addition/change based on J2579 consider whether common minimum standard needed - major OEM durability/corrosion assessments sufficient; uncertain regarding new entry mfrs			OEM's have stringent durability schedules / validation profiles - no further action required				0
22	F3	F3. Provide means for keeping foreign materials (water, dust, etc.) out of battery system	During normal customer use (driving, charging, parking)	All	F3.2 System contamination from road debris (including dust and salt)	Hazardous over time	Inadequate enclosure design - prevent intrusion - allow expel		Vehicle durability	9	4	7	252	36	None - OEM's have stringent durability schedules / validation profiles Consider "large debris" damage							0
23	F3	F3. Provide means for keeping foreign materials (water, dust, etc.) out of battery system	During normal customer use (driving, charging, parking)	All	F3.2 System contamination from road debris (including dust and salt)	Hazardous over time	Enclosure compromised by aggressive chemical source (e.g., corrosion)		J2579 (exposure to standard chemical substance)	9	4	7	252	36	Review J2579 to determine if it is transferrable (both LIB and fuel cells must be robust against chemical sources) Review J2929 for addition/change based on J2579 See item 21 above	Phil Horton Galen Ressler		OEM's have stringent durability schedules / validation profiles - no further action required				0
24	F3	F3. Provide means for keeping foreign materials (water, dust, etc.) out of battery system	During crash and post-crash	All	F3.4 System contamination during crash or post-crash	Hazardous	Pack enclosure compromised due to crash force		J2929 (4.5 and 4.6)	10	4	7	280	40	Post-crash protocol needs to be developed Consider need for additional post-crash criteria; need for battery-centric test conditions?							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-In Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
25	F3	F3. Provide means for keeping foreign materials (water, dust, etc.) out of battery system	During other events (service, transport, vehicle recycling & disposal)	All	F3.5 System contamination during service	Hazardous	Tow, hoist or service procedure compromises pack	OEM-specific instructions	OEM-specific	10	4	7	280	40	Assess the need to develop design guideleines / recommended practices to prevent inadvertant tow hook attachment. Assure that proper towing instructions are provided by OEM. Refer to SAE TEVHYB12 1st/2nd responder committee no further action required			OEM tow / hoist / service instructions exist - no further action required				0
26	F3	F3. Provide means for keeping foreign materials (water, dust, etc.) out of battery system	During other events (service, transport, vehicle recycling & disposal)	All	F3.5 System contamination during service	Hazardous	Contamination during service		None	10	4	7	280	40	Assess the need to develop design guideleines / recommended practices to protect the battery pack during repair Determine what OEM procedures exist currently no further action required			OEM towing/ instructions exist				0
27	F3	F3. Provide means for keeping foreign materials (water, dust, etc.) out of battery system	During other events (vehicle recycling & disposal)	All	F3.5 System contamination during service	Hazardous	Contamination at recycling center		None	10	4	10	400	40	No further action by this task force. Refer to SAE Committee TEVVBC10 for battery recycling J2974 TIR battery recycling, J2984 recommended practice for transportation of battery systems for recycling							0
28	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.1 Normal status not reported	Hazardous (loss of propulsion), Performance (may affect ability to charge, vehicle shut down), Annoyance for service	Loss of communication - battery to vehicle	Vehicle fault strategy	Electrical validation (e.g. open, short), software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles need to evaluate vehicle behavior during this event							0
29	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.1 Normal status not reported	Hazardous (loss of propulsion), Performance (may affect ability to charge, vehicle shut down), Annoyance for service	Loss of communication - battery internal	Vehicle fault strategy/RESS fault strategy	J2929 Overcharged 4.9, over discharged 4.10 4.12 fault analysis , software testing	10	4	4	160	40	None - OEM's have stringent durability schedules / validation profiles							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-in Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
30	F4	F4, Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.1 Normal status not reported	Hazardous (loss of propulsion), Performance (may affect ability to charge, vehicle shut down), Annoyance for service	Loss of power to electronic modules	Vehicle fault strategy	Standard voltage check, software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles need to evaluate vehicle behavior during this event							0
31	F4	F4, Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.1 Normal status not reported	Hazardous (loss of propulsion), Performance (may affect ability to charge, vehicle shut down), Annoyance for service	Loss of sensor	Vehicle fault strategy/RESS fault strategy	EMC testing ECER10, J1113), vehicle durability, software testing	10	4	4	160	40	None - OEM's have stringent durability schedules / validation profiles							0
32	F4	F4, Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.1 Normal status not reported	Hazardous	Corrupt communication (wrong data communicated)	Serial data communication strategies	EMC, J1113, Durability	10	1	4	40	10	None - signal quality beyond scope of task force							0
33	F4	F4, Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.2 Normal status reported intermittently	Hazardous (loss of propulsion), Performance (may affect ability to charge, vehicle shut down), Annoyance for service	Intermittent loss of communication - battery to vehicle	Vehicle fault strategy	Electrical validation (e.g. open, short), software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles integrate with item 28 above							0
34	F4	F4, Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.2 Normal status reported intermittently	Hazardous (loss of propulsion), Performance (may affect ability to charge, vehicle shut down), Annoyance for service	Intermittent loss of communication - battery internal	Vehicle fault strategy/RESS fault strategy	J2929 Overcharged 4.9, over discharged 4.10 4.12 fault analysis , software testing	10	4	4	160	40	None - OEM's have stringent durability schedules / validation profiles							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-in Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
35	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.2 Normal status reported intermittently	Hazardous (loss of propulsion), Performance (may affect ability to charge, vehicle shut down), Annoyance for service	Intermittent loss of power	Vehicle fault strategy	Standard voltage check, software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles Integrate with item 30 above							0
36	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.2 Normal status reported intermittently	Hazardous (loss of propulsion), Performance (may affect ability to charge, vehicle shut down), Annoyance for service	Loss of sensor	Vehicle fault strategy/RESS fault strategy	EMC testing ECER10, J1113), vehicle durability, software testing	10	4	4	160	40	None - OEM's have stringent durability schedules / validation profiles							0
37	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.2 Normal status reported intermittently	Hazardous	Corrupt communication (wrong data communicated)	Serial data communication strategies	EMC, J1113, Durability	10	1	4	40	10	None - signal quality beyond scope of task force							0
38	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging,	All	F4.3 Normal status reported instead of failure (Unintended)	Hazardous	Microprocessor failure	Vehicle fault strategy/RESS fault strategy	Microprocessor validation, software testing	10	1	7	70	10	None Integrate with item 41 below							0
39	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.3 Normal status reported instead of failure (Unintended) (including service)	Hazardous	Error from sensor(s)	Sensor redundancy	EMC, J1113, Durability	10	4	4	160	40	None - OEM's have stringent durability schedules / validation profiles							0
40	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.3 Normal status reported instead of failure (Unintended) (including service)	Hazardous	Corrupt communication (wrong data communicated)	Serial data communication strategies	EMC, J1113, Durability	10	1	4	40	10	None - signal quality beyond scope of task force							0
41	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.3 Normal status reported instead of failure (Unintended) (including service)	Hazardous	Loss of communication - battery to vehicle	Vehicle fault strategy	Electrical validation (e.g. open, short), software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles need to evaluate vehicle behavior during this event							0

Issue	Item	Function	Requirement	Type Hybrid, Plug-In Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
42	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.3 Normal status reported instead of failure (Unintended) (Including service)	Hazardous	Loss of communication - battery internal	Vehicle fault strategy/RESS fault strategy	J2929 Overcharged 4.9, over discharged 4.10 4.12 fault analysis , software testing	10	4	4	160	40	None - OEM's have stringent durability schedules / validation profiles							0
43	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.3 Normal status reported instead of failure (Unintended) (Including service)	Hazardous	Loss of power	Vehicle fault strategy	Standard voltage check, software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles need to evaluate vehicle behavior during this event							0
44	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.5 Failure status reported intermittently (including service)	Hazardous	Intermittent loss of communication - battery to vehicle	Vehicle fault strategy	Electrical validation (e.g. open, short), software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles integrate with item 33							0
45	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.5 Failure status reported intermittently (including service)	Hazardous	Intermittent loss of communication - battery internal	Vehicle fault strategy/RESS fault strategy	J2929 Overcharged 4,9, over discharged 4.10 4.12 fault analysis , software testing	10	4	4	160	40	None - OEM's have stringent durability schedules / validation profiles							0
46	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.5 Failure status reported intermittently (including service)	Hazardous	Intermittent loss of power	Vehicle fault strategy	Standard voltage check, software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles integrate with item 35							0
47	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.5 Failure status reported intermittently (including service)	Hazardous	Intermitted loss of sensor	Vehicle fault strategy/RESS fault strategy	EMC testing ECER10, J1113), vehicle durability, software testing	10	4	4	160	40	None - OEM's have stringent durability schedules / validation profiles							0
48	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.5 Failure status reported intermittently (including service)	Hazardous	Corrupt communication (wrong data communicated)	Serial data communication strategies	EMC, J1113, Durability	10	1	4	40	10	None - OEM's have stringent durability schedules / validation profiles and signal quality beyond scope of task force							0
49	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging,	All	F4.6 Failure status reported when normal (Unintended)	Hazardous (loss of propulsion)	Microprocessor failure	Vehicle fault strategy/RESS fault strategy	Microprocessor validation, software testing	10	1	7	70	10	None integrate with item 83 below							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-In Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
50	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.6 Failure status reported when normal (Unintended)	Hazardous	Error from sensor(s)	Sensor redundancy	EMC, J1113, Durability	10	4	4	160	40	None - OEM's have stringent durability schedules / validation profiles							0
51	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.6 Failure status reported when normal (Unintended)	Hazardous	Corrupt communication (wrong data communicated)	Serial data communication strategies	EMC, J1113, Durability	10	1	4	40	10	None - signal quality beyond scope of task force							0
52	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.6 Failure status reported when normal (Unintended)	Hazardous (loss of propulsion)	Loss of communication - battery to vehicle	Vehicle fault strategy	Electrical validation (e.g. open, short), software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles Integrate with item #1							0
53	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.6 Failure status reported when normal (Unintended)	Hazardous	Loss of communication - battery internal	Vehicle fault strategy/RESS fault strategy	J2929 Overcharged 4.9, over discharged 4.10 4.12 fault analysis , software testing	10	4	4	160	40	None - OEM's have stringent durability schedules / validation profiles							0
54	F4	F4. Report status of battery unit to vehicle system	During normal customer use (driving, charging, parking) and service	All	F4.6 Failure status reported when normal (Unintended)	Hazardous (loss of propulsion)	Loss of power	Vehicle fault strategy	Standard voltage check, software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles Integrate with item #3							0
55	F4	F4. Report status of battery unit to vehicle system	Post-crash	All	F4.7 Status wrong or not reported (reports normal when battery failure exists)	Hazardous (first responders, towing)	Loss of communication (e.g. battery damaged, wire damaged, etc.)	Battery system location and structure	Crash testing, FMVSS 305, J2929 (4.5, 4.6)	10	4	4	160	40	Task force to consider testing methods needed for post-crash							0
56	F4	F4. Report status of battery unit to vehicle system	Post-crash	All	F4.7 Status wrong or not reported (reports normal when battery failure exists)	Hazardous (first responders, towing)	Microprocessor failure	Battery system location and structure	Crash testing, FMVSS 305, J2929 (4.5, 4.6)	10	1	4	40	10	Task force to consider testing methods needed for post-crash							0
57	F4	F4. Report status of battery unit to vehicle system	Post-crash	All	F4.7 Status wrong or not reported (reports normal when battery failure exists)	Hazardous (first responders, towing)	Loss of senosr	Battery system location and structure	Crash testing, FMVSS 305, J2929 (4.5, 4.6)	10	7	4	280	70	Task force to consider testing methods needed for post-crash							0
58	F4	F4. Report status of battery unit to vehicle system	Post-crash	All	F4.7 Status wrong or not reported (reports normal when battery failure exists)	Hazardous (first responders, towing)	Sensor accuracy bad	Battery system location and structure	Crash testing, FMVSS 305, J2929 (4.5, 4.6)	10	4	4	160	40	Task force to consider testing methods needed for post-crash							0
59	F4	F4. Report status of battery unit to vehicle system	Post-crash	All	F4.8 Status wrong (reports failure when OK)	Annoyance	Low priority - not analyzed			4			0	0	None - Annoyance impact low priority							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-in Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
60	F5	F5. Provide control and management of cells within battery system	Maintain State of Charge (SOC) within operating range	All	F5.1 SOC over charged (outside range) Note: less applicable to HEV)	Hazardous	Error from sensor(s) Sensor wire - ground short - 12v short - open - EMC	Sensor redundancy, RESS fault strategy	OEM-specific test methods, software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles need to consider this - not clear how this can be assessed at vehicle level							0
61	F5	F5. Provide control and management of cells within	Maintain State of Charge (SOC) within operating range	All	F5.1 SOC over charged (outside range) Note: less	Hazardous	Microprocessor failure	Vehicle fault strategy/RESS fault strategy	Microprocess or validation, software testing	10	1	7	70	10	None integrate with item 60 above							0
62	F5	F5. Provide control and management of cells within battery system	Maintain State of Charge (SOC) within operating range	All	F5.1 SOC over charged (outside range) Note: less applicable to HEV)	Hazardous	Bad algorithm		HIL/Bench	10	4	7	280	40	None - algorithm out of scope integrate with item 60 above							0
63	F5	F5. Provide control and management of cells within battery system	Maintain State of Charge (SOC) within operating range	All	F5.1 SOC over charged (outside range) Note: less applicable to HEV)	Hazardous	Corrupt communication (wrong data communicated: data wrong or old data)	Serial data communication strategies	EMC, J1113, Durability, J2929 4.9, 4.10, 4.12	10	1	4	40	10	None - OEM's have stringent durability schedules / validation profiles							0
64	F5	F5. Provide control and management of cells within battery system	Maintain State of Charge (SOC) within operating range	All	F5.2 SOC over discharged Note: less applicable to HEV)	Hazardous	Error from sensor(s) Sensor wire - ground short - 12v short - open - EMC	Sensor redundancy, RESS fault strategy	OEM-specific test methods, software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles need to consider this - not clear how this can be assessed at vehicle level							0
65	F5	F5. Provide control and management of cells within	Maintain State of Charge (SOC) within operating range	All	F5.2 SOC over discharged Note: less applicable to HEV)	Hazardous	Microprocessor failure	Vehicle fault strategy/RESS fault strategy	Microprocess or validation, software testing	10	1	7	70	10	None integrate with item 64 above							0
66	F5	F5. Provide control and management of cells within battery system	Maintain State of Charge (SOC) within operating range	All	F5.2 SOC over discharged Note: less applicable to HEV)	Hazardous	Bad algorithm		HIL/Bench	10	4	7	280	40	None - algorithm out of scope integrate with item 64 above							0
67	F5	F5. Provide control and management of cells within battery system	Maintain State of Charge (SOC) within operating range	All	F5.2 SOC over discharged Note: less applicable to HEV)	Hazardous	Corrupt communication (wrong data communicated: data wrong or old data)	Serial data communication strategies	EMC, J1113, Durability, J2929 4.9, 4.10, 4.12	10	1	4	40	10	None - OEM's have stringent durability schedules / validation profiles							0
68	F5	F5. Provide control and management of cells within battery system	Temperature controlled within operating limits.	All	F5.3 Temperature too high (above safety level)	Hazardous	Insufficient cooling capacity (design)	Battery thermal management system	Vehicle durability, J2929 (4.11)	10	4	4	160	40	None							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-In Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
69	F5	F5. Provide control and management of cells within battery system	Temperature controlled within operating limits	All	F5.3 Temperature too high	Hazardous	Loss of thermocouple / temperature sensor, bad sensor, Sensor wire - ground short - 12v short - open	Battery termal management system, RESS fault strategy, Sensor redundancy	OEM testing methods, software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles need to consider this - not clear how this can be assessed at vehicle level							0
70	F5	F5. Provide control and management of cells within battery system	Temperature controlled within operating limits	All	F5.3 Temperature too high	Hazardous	High battery resistance		Vehicle durability, J2929 (4.11)	10	4	4	160	40	None - high battery resistance out of scope							0
71	F5	F5. Provide control and management of cells within	Temperature controlled within operating limits	All	F5.3 Temperature too high	Hazardous	Excessive heat exposure (exhaust)	Battery system location and structure	OEM testing methods	10	1	7	70	10	None need to consider this							0
72	F5	F5. Provide control and management of cells within battery system	Temperature controlled within operating limits	All	F5.3 Temperature too high	Hazardous	External heating	Battery system location and structure	OEM testing methods, J2929 (4.7)	10	1	4	40	10	J2929 includes section 4.7. Task force to review and determine if further action needed to verify 4.7 and publish data for industry agreement							0
73	F5	F5. Provide control and management of cells within battery system	Temperature controlled within operating limits	All	F5.4 Temperature too low during charging	Hazardous under charging conditions	External cooling	RESS and vehicle control strategies	OEM testing methods, software testing	10	4	7	280	40	Note: Severity 9 or 10 depending on cell design None - OEM's have stringent durability schedules / validation profiles Multiple failure (temperature and voltage control/diagnostics) required for hazard to occur. Consider for dual failure / loss of control situation							0

Issue	Item	Function	Requirement	Type: Hybrid Plug-in Hybrid Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
74	F5	F5. Provide control and management of cells within battery system	Temperature controlled within operating limits	All	F5.4 Temperature too low during charging	Hazardous under charging conditions	Loss of thermocouple / temperature sensor, bad sensor; Sensor wire - ground short - 12v short - open	Battery termal management system, RESS fault strategy, Sensor redundancy	OEM testing methods, software testing	10	4	7	280	40	Note: Severity 9 or 10 depending on cell design None - OEM's have stringent durability schedules / validation profiles Multiple failure (temperature and voltage control/diagnostics) required for hazard to occur. **Consider for dual failure / loss of control situation**							0
75	F5	F5. Provide control and management of cells within battery system	Maintain appropriate voltage consistency across all cells	All	F5.5 Voltage consistency not maintained	Performance	Processing failure, bad sensor, sensor wire (ground short, 12v short: open), wrong limit selected, corruption), high cell R, design specific - loss of parallel cell		OEM testing methods	7	4	7	196	28	None - Performance impact low priority							0
76	F5	F5. Provide control and management of cells within battery system	Maintain appropriate voltage levels for each cells	All	F5.6 Cell voltage level too high	Hazardous	Design specific - Loss of parallel cell	RESS fault strategy	Vehicle durability, OEM testing methods, software testing	10	4	7	280	40	Is this a multi-point failure leading to a hazardous effect? None - OEM's have stringent durability schedules / validation profiles **covered above - Item 60**							0
77	F5	F5. Provide control and management of cells within battery system	Maintain appropriate voltage levels for each cells	All	F5.6 Cell voltage level too high	Hazardous	High cell R	RESS fault strategy	OEM testing methods, software testing	10	4	7	280	40	Is this a multi-point failure leading to a hazardous effect? Action: None - OEM's have stringent durability schedules / validation profiles **covered above - Item 60**							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-in Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
78	F5	F5. Provide control and management of cells within battery system	Maintain appropriate voltage levels for each cells	All	F5.6 Cell voltage level too high	Hazardous	Processing failure, bad sensor, sensor wire (ground short, 12v short, open), wrong limit selected, corruption)	RESS fault strategy	OEM testing methods, software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles covered above - item 60							0
79	F5	F5. Provide control and management of cells within battery system	Maintain charge and discharge currents within appropriate limits	All	F5.6 Cell voltage level too high	Hazardous	Charger failure	Vehicle/RESS fault strategy	J1772? Validated based on discharge current testing, software	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles covered above - item 60							0
80	F5	F5. Provide control and management of cells within battery system	Maintain appropriate tempature levels	All	F5.6A Measured Cell voltage level too high	Hazardous	High contact resistance at cell connections leading to local high temperatures at terminals.		OEM testing methods	10	7	7	490	70	None - OEM's have stringent durability schedules / validation profiles need to consider this condition							0
81	F5	F5. Provide control and management of cells within battery system	Maintain appropriate voltage levels for each cells	All	F5.7 Voltage level too low	Hazardous	Error from senser(s) Sensor wire - ground short - 12v short - open - EMC	Serial data communication strategies	EMC, J1113, Durability, J2929 4.9, 4.10, 4.12	10	1	4	40	10	None - OEM's have stringent durability schedules / validation profiles							0
82	F5	F5. Provide control and management of cells within battery system	Maintain appropriate voltage levels for each cells	All	F5.7 Voltage level too low	Hazardous	Corruption of stored data, Corrupt communication (wrong data communicated data wrong or old data)	RESS fault strategy	OEM testing methods, software testing	10	1	7	70	10	None covered above - item 84							0
83	F5	F5. Provide control and management of cells within battery system	Maintain appropriate voltage levels for each cells	All	F5.7 Voltage level too low	Hazardous	Main contactors can't disconnect	Vehicle fault strategy/RESS fault strategy	OEM testing methods, software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles covered above - item 84							0
84	F5	F5. Provide control and management of cells within battery system	Maintain appropriate voltage levels for each cells.	All	F5.7 Voltage level too low	Hazardous	Short circuit of HV outside battery pack.	Use of fuse	J2929 (4.8)	10	1	4	40	10	None							0
85	F5	F5. Provide control and management of cells within battery system	Maintain charge and discharge currents within appropriate limits	EV, PHEV	F5.8 Current (over limit)	Hazardous	Charger failure	Vehicle/RESS fault strategy, Use of fuse	J1772? Validated based on discharge current testing, software testing	10	4	7	280	40	None - OEM's have stringent durability schedules / validation profiles covered by short circuit requirements							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-In Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
86	F5	F5. Provide control and management of cells within battery system	Maintain charge and discharge currents within appropriate limits	All	F5.8 Current (over limit)	Hazardous	Fuse failure	Proper fuse selection	J2929 (4.8)	10	1	4	40	10	None							0
87	F5	F5. Provide control and management of cells within battery system	Maintain charge and discharge currents within appropriate limits	All	F5.8 Current (over limit)	Hazardous	External to pack short	Use of fuse	J2929 (4.8), J2464	10	4	4	160	40	None							0
88	F5	F5. Provide control and management of cells within battery system	Maintain charge and discharge currents within appropriate limits	All	F5.9 Charge current (under limit)	Performance				7			0	0	None - Performance impact low priority							0
89	F5	F5. Provide control and management of cells within battery system	Maintain charge and discharge currents within appropriate limits	All	F5.11 Discharge current (under limit)	Performance				7			0	0	None - Performance impact low priority							0
90	F6	F6a. Provide for temperature management	Temperature range	All	Loss of flow / partial loss of flow	Performance				7			0	0	None - Performance impact low priority							0
91	F6	F6a. Provide for temperature management	Temperature range	All	Loss of flow / partial loss of flow	Performance				7			0	0	None - Performance impact low priority							0
92	F6	F6a. Provide for temperature management	Temperature range	All	Loss of flow / partial loss of flow	Performance				7			0	0	None - Performance impact low priority							0
93	F6	F6a. Provide for temperature management	Temperature range	All	Loss of flow / partial loss of flow	Performance				7			0	0	None - Performance impact low priority							0
94	F6	F6a. Provide for temperature management	Temperature range	All	Loss of flow / partial loss of flow	Performance				7			0	0	None - Performance impact low priority							0
95	F6	F6a. Provide for temperature management	Temperature range	All	Loss of flow / partial loss of flow	Performance				7			0	0	None - Performance impact low priority							0
96	F6	F6a. Provide for temperature management	Temperature range	All	Intermittent flow	Performance				7			0	0	None - Performance impact low priority							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-in Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
97	F6	F6a. Provide for temperature management	Temperature	All	F6a 1 and 2 Loss of liquid (leak) and partial loss of liquid (leak)	Hazardous	System over pressure	OEM-specific design guidelines, RESS fault strategies	OEM testing methods	10	4	7	280	40	No current industry standard for cooling strategy (liquid, air, refrigerant or nothing) Consider impacts of long-term exposure (loss of liquid) No action required - OEM's have stringent durability schedules / validation profiles multiple failure event (loss of cooling system and loss of temperature monitor) what about system without one or other of these capabilities							0
98	F6	F6a. Provide for temperature management	Temperature	All	F6a 1 and 2 Loss of liquid (leak) and partial loss of liquid (leak)	Hazardous	Broken line (durability	OEM-specific design guidelines, RESS fault strategies	OEM testing methods	10	4	7	280	40	No current industry standard for cooling strategy (liquid, air, refrigerant or nothing) Consider impacts of long-term exposure (loss of liquid) No action required - OEM's have stringent durability schedules / validation profiles multiple failure event (loss of cooling system and loss of temperature monitor) what about system without one or other of these capabilities							0
99	F6	F6a. Provide for temperature management	Temperature	All	F6a 1 and 2 Loss of liquid (leak) and partial loss of liquid (leak)	Hazardous	Pack impingement (crush)	OEM-specific design guidelines	Crush test J2929 (4.5)	10	4	4	160	40	Consider impacts of long-term exposure (post-crash)							0
100	F6	F6a. Provide for temperature management	Temperature	All	F6a 1 and 2 Loss of liquid (leak) and partial loss of liquid (leak)	Hazardous	Material compatibility - w/ Cooling liquid	OEM-specific design guidelines, RESS fault strategies	OEM-specific test methods, vehicle durability	10	4	7	280	40	Verify material standard (HVAC standards) **Multiple Failure Event**							0
101	F6	F6a. Provide for temperature management	Temperature	All	F6a 1 and 2 Loss of liquid (leak) and partial loss of liquid (leak)	Hazardous	Seal design	OEM-specific design guidelines, RESS fault strategies	OEM testing methods, vehicle durability	10	4	7	280	40	HVAC standard for seal information - **Multiple Failure Event**							0

Issue	Item	Function	Requirement	Type: Hybrid Plug In Hybrid Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color Key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
102	F6	F6b. Provide for vent gas management	Vent gas management - Design 1 (system design allows gas to escape) - gas escapes	All	F6b.3 and 4 Loss of gas vent management and partial loss	Hazardous	Blockage (design specific)	OEM-specific design, RESS fault strategy (when vent gas mgmt and cooling same system)	Vehicle durability, post durability flow check, software testing	10	4	7	280	40	No current industry standard for vent gas management - Multiple failure event							0
103	F6	F6b. Provide for vent gas management	Vent gas management - Design 1 (system design allows gas to escape) - gas escapes	All	F6b.3 and 4 Loss of gas vent management and partial loss: Gas vents outside of normally controlled system design	Hazardous	Corrosion -	OEM-specific design, RESS fault strategy (when vent gas mgmt and cooling same system), material compatibility evaluation	Vehicle durability, post durability flow check, software testing	10	4	7	280	40	No current industry standard for vent gas management - Multiple failure event							0
104	F6	F6b. Provide for vent gas management	Vent gas management - Design 1 (system design allows gas to escape) - gas escapes	All	F6b.3 and 4 Loss of gas vent management and partial loss	Hazardous	Flow failure (fans stop)	OEM-specific design, RESS fault strategy (when vent gas mgmt and cooling same system)	Vehicle durability, post durability flow check, software testing	10	4	7	280	40	No current industry standard for vent gas management - Multiple failure event							0
105	F6	F6b. Provide for vent gas management	Vent gas management - Design 2 (system design that keeps gas within enclosure) - gas retained	All	F6b.3 and 4 Loss of gas vent management and partial loss	Hazardous	Retaining enclosure opens	OEM-specific design, RESS fault strategy, material compatibility evaluation	Vehicle durability, post durability pressure check, software testing	10	4	7	280	40	No current industry standard for vent gas management Consider impacts of long-term exposure to vent gas- Multiple Failure event							0
106	F6	F6b. Provide for vent gas management	Vent gas management - Design 2 (system design that keeps gas within enclosure) - gas retained	All	F6b.3 and 4 Loss of gas vent management and partial loss	Hazardous	Too much gas	OEM-specific design, RESS fault strategy	OEM-specific battery venting verification, software testing	10	4	7	280	40	No current industry standard for vent gas management Consider impacts of long-term exposure Multiple Failure event							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-In Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see "Column Definitions" tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
107	F6	F6b. Provide for vent gas management	Vent gas management - Design 2 (system design that keeps gas within enclosure) - gas retained	All	F6.5 Unintended (open when should be closed)	Hazardous - allows contamination (design specific)	Check valve failure	OEM-specific design, material compatibility evaluation	OEM testing methods	10	4	7	280	40	No current industry standard for vent gas management Consider impacts of long-term exposure -**Multiple Failure event**							0
108	F7	F7. Limit propagation of cell/module event to vehicle level involvement		All	F7.1 System does not limit propagation of cell/module event to vehicle level involvement during normal vehicle usage	Hazardous	Heat generation of battery internal exceeds isolation properties of the enclosure For Example: - over charge - undetected cell internal fault (debris from production) - out of spec mechanical connection - cell mechanical damage (penetration) - extended over current - exposed to external fire - misapplication of battery pack (i.e. non-OEM aftermarket replacement) - improper reuse of battery pack - improper handling of battery pack	OEM-specific designs	No current testing method. (J2464 Section 4.4.5 includes an example of how to test for propagation). J2929 Section 4.12 requires fault analysis for cell failure leading to propagation)	10	10	10	1000	100	1. Measure heat generation profile of battery during a propagation event (including time to reach certain temps, how long before it dissipates, how long before it reaches vehicle, etc.) with goal to identify worst case profile that comprehends reasonable usage 2. Test with artificial generation of that function 3. Develop acceptance criteria for "limit" propagation of cell/module event to vehicle level 4. Consider both single level and dual level potential failure modes (e.g. loss of battery management system) Note, Definition of "limit propagation" is required as part of test method development							0
109	F7	F7. Item removed (covered above)																				0
110	F7	F7. Item removed (covered above)																				0
111	F7	F7. Item removed (covered above)																				0
112	F7	F7. Item removed (covered above)																				0
113	F7	F7. Item removed (covered above)																				0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-in Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
114	F7	F7. Item removed (covered above)																				0
115	F7	F7. Item removed (covered above)																				0
116	F7	F7. Item removed (covered above)																				0
117	F8	F8. Maintain electrical isolation of high voltage (HV) circuit		All	F8.1 HV circuit not isolated or isolated intermittently	Hazardous (service, post-crash) Performance (plug-in charging) Annoyance (normal driving conditions, parked, transport)	Material breakdown insulated material breaks down and becomes conductive over time (material selection, creepage distance)	OEM service procedure for protecting service technician, OEM design-specific, OEM modelling, RESS fault strategy, vehicle fault strategy	Life cycle aging, isolation test, J2578 HV withstand test Section 4.4.4, software testing	10	1	7	70	10	Verify ISO standard for aging requirement, review J2578 work in progress (document change regarding HV withstand test being considered by working group). Curent International standards may not address aging factors. Current International standards define the requirements to mitigate single point failures (specifically ISO 6469-3) **note: aging test method needed** **(2/13/12: ISO 6722 proposed for aging, need copy for team review)**	review if F8 items are a subset of F9						0
118	F8	F8. Maintain electrical isolation of high voltage (HV) circuit		All	F8.1 HV circuit not isolated or isolated intermittently	Hazardous (service, post-crash) Performance (plug-in charging) Annoyance (normal driving conditions, parked, transport)	Foreign material conductance (dust, conductive liquid, larger debris, humidity)	OEM service procedure for protecting service technician, OEM enclosure design, OEM modelling, RESS fault strategy, vehicle fault strategy	Environmental testing, ISO20653 conditions for enclosure design, IEC60529 conditions for enclosure design, Life cycle aging, software testing	10	4	4	160	40	Review ISO and IEC to determine if performance testing from these documents should be integrated into the task force test plan (aging followed by HV withstand test does not seem to be covered). Curent International standards do not address aging factors. Current international standards define the requirements to mitigate single point failures	review if F8 items are a subset of F9						0

Issue	Item	Function	Requirement	Type Hybrid Plug-in Hybrid Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
119	F8	F8. Maintain electrical isolation of high voltage (HV) circuit		All	F8.1 HV circuit not isolated or isolated intermittently	Hazardous (service, post-crash) Performance (plug-in charging) Annoyance (normal driving conditions, parked, transport)	Deformation of barriers/enclosures [indirect contact]	OEM enclosure design, OEM modelling, RESS fault strategy, vehicle fault strategy	Vehicle durability for non-crash related deformation, FMVSS 305 (applies only if contactors are outside of pack enclosure), J2929 Section 4.2.2, 4.5, software testing	10	4	7	280	40	Consider developing testing method that tests loss of internal battery isolation due to deformation as a result of crash. Curent International standards do not address aging factors. Current international standards define the requirements to mitigate single point failures (specifically ISO 6469-3).	review if F8 items are a subset of F9						0
120	F8	F8. Maintain electrical isolation of high voltage (HV) circuit		All	F8.1 HV circuit not isolated or isolated intermittently	Hazardous (service, post-crash) Performance (plug-in charging) Annoyance (normal driving conditions, parked, transport)	Internal components and materials contact HV conductors (e.g. coolant leakage)	OEM system design, OEM modelling, RESS fault strategy, vehicle fault strategy, OEM service procedure to avoid electric shock	Vehicle durability, FMVSS 305 (applies only if contactors are outside of pack enclosure), J2929 Section 4.2.2, 4.5, software testing	10	4	4	160	40	Consider developing a study for long-term effects of various causes that contribute to HV circuit not isolated Consider developing testing method that tests loss of internal battery isolation due to internal component contact. Curent International standards do not address aging factors. Current international standards define the requirements to mitigate single point failures (specifically ISO 6469-3).	review if F8 items are a subset of F9						0
121	F8	F8. Maintain electrical isolation of HV circuit		All	F8.2 HV circuit partially isolated	Annoyance (under target above acceptable)	Material breakdown	OEM service procedure	Life cycle aging, isolation test	4	4	4	64	16	None - Annoyance impact low priority							0
122	F8	F8. Maintain electrical isolation of HV circuit		All	F8.2 HV circuit partially isolated	Annoyance (under target above acceptable)	Foreign material conductance	OEM service procedure	Environmental testing	4	4	4	64	16	None - Annoyance impact low priority							0
123	F9	F9. Prevent risk of electric shock (above 60v DC)		All	F9.1a Does not prevent electric shock during service and post-crash	Hazardous	Lack of finger proof connectors (without HVIL)	J2344 guidelines for electric vehicle safety, OEM-specific design	OEM-specific test methods	10	1	7	70	10	Consider developing a common test method Covered by existing standards (ISO 20653, J2929, WP29, J2578, UL)							0
124	F9	F9. Prevent risk of electric shock (above 60v DC)		All	F9.1b Does not prevent electric shock during service and post-crash (or intermittent)	Hazardous	Loss of isolation	Bonding (external case grounding), J2344 guidelines for electric vehicle safety	Isolation testing and Mega-Ohm measurement after test, See Function 8	10	4	4	160	40	Refer to Function 8 Prevent risk of electric shock							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-In Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
125	F9	F9. Prevent risk of electric shock (above 60v DC)		All	F9.1c Does not prevent electric shock	Hazardous	Exposed conductors	OEM-specific enclosure design	ISO20653 conditions for enclosure design, IEC60529 conditions for enclosure design, vehicle durability testing	10	1	4	40	10	Review ISO and IEC to determine if performance testing from these documents should be integrated into the task force test plan (veh durability followed by check for exposed conductors)			OEM's have stringent durability schedules / validation - No further action required				0
126	F9	F9. Prevent risk of electric shock (above 60v DC)		All	F9.1b Does not prevent electric shock during service and post-crash (or intermittent)	Hazardous	HVIL failure	J2344 guidelines for electric vehicle safety, OEM-specific design	OEM-specific test methods	10	1	7	70	10	Consider developing a common test method							0
127	F9	F9. Prevent risk of electric shock (above 60v DC)		All	F9.1a Does not prevent electric shock during service and post-crash	Hazardous	Welded contactors	OEM-specific contactor selection and sequencing; RESS faults strategy (welded contactor check, buss metering)	Vehicle durability, OEM-specific testing	10	1	7	70	10	Consider developing a common test method							0
128	F10	F10. Provides means for safety disconnect from vehicle HV system (above 60v DC)		All	F10.1 Loss of safety disconnect from vehicle HV system during normal operation	Hazardous	Unable to disconnect MSD due to mechanical damage	OEM-specific designs, MSD selection, J2929 Section 4.13.2 options	OEM Bench test, voltage sensor	10	1	7	70	10	None - OEM's have stringent durability schedules / validation profiles Consider need for industry standard							0
128a	F10	F10. Provides means for safety disconnect from vehicle HV system (above 60v DC)		All	F10.1 Loss of safety disconnect from vehicle HV system following crash	Hazardous	Auto-disconnect non-functional due to electrical or mechanical damage	OEM-specific designs, MSD selection, J2929 Section 4.13.2 options	FMVSS 305	10	1	7	70	10	None - covered by FMVSS-305							0
129	F10	F10. Provides means for safety disconnect from vehicle HV system (above 60v DC)		All	F10.1 Loss of safety disconnect from vehicle HV system during normal operation (required due to detected fault – Failure #1)	Hazardous	Malfunction of HV contactors due to external 12v short (harness) – Failure #2	OEM-specific designs, RESS fault strategies	OEM Bench test, voltage sensor, software testing	10	1	7	70	10	None - OEM's have stringent durability schedules / validation profiles 2/13/12: Consider developing Test Methodology							0
129a	F10	F10. Provides means for safety disconnect from vehicle HV system (above 60v DC)		All	F10.1 Loss of safety disconnect from vehicle HV system following crash	Hazardous	Malfunction of HV contactors due to external 12v short (harness)	OEM-specific designs, RESS fault strategies	FMVSS 305	10	1	7	70	10	None - covered by FMVSS-305							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-in Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
130	F10	F10. Provides means for safety disconnect from vehicle HV system (above 60v DC)		All	F10.1 Loss of HV disconnect during normal operation (e.g., fail to open HV contactors at shut down)	Hazardous	Malfunction of HV contactors due to high current welding	OEM-specific contactor selection and sequencing, RESS faults strategy (welded contactor check, buss metering)	Vehicle durability, OEM-specific testing (bench test)	10	1	7	70	10	None - OEM's have stringent durability schedules / validation profiles 2/13/12: Consensus developing Test Methodology							0
130a	F10	F10. Provides means for safety disconnect from vehicle HV system (above 60v DC)		All	F10.1 Loss of safety disconnect from vehicle HV system following crash	Hazardous	Malfunction of HV contactors due to high current welding	OEM-specific contactor selection and sequencing, RESS faults strategy (welded contactor check, buss metering)	FMVSS 305	10	1	7	70	10	None- covered by FMVSS-305							0
131	F10	F10. Provides means for safety disconnect from vehicle HV system		All	F10.3 Intermittent	Performance	Bad connection			7			0	0	None - Performance impact low priority							0
132	F10	F10. Provides means for safety disconnect from vehicle HV system		All	F10.3 Intermittent	Performance	Electric shock		Bench test, voltage sensor	7	1	7	49	7	None - Performance impact low priority							0
133	F10	F10. Provides means for safety disconnect from vehicle HV system		All	F10.3 Intermittent	Performance	External short (harness)		Bench test, voltage sensor	7	1	7	49	7	None - Performance impact low priority							0
134	F10	F10. Provides means for safety disconnect from vehicle HV system		All	F10.3 Intermittent	Performance	High current welding		Bench test	7	1	7	49	7	None - Performance impact low priority							0
135	F10	F10. Provides means for safety disconnect from vehicle HV system		All	F10.4 Unintended (disconnects from vehicle when not intended)	Performance	Broken circuit		Bench test, voltage sensor, controller logic	7	1	7	49	7	None - Performance impact low priority							0
136	F11	F11. Provide electrical power to vehicle		All	F11.1 Loss of electric power to vehicle	Hazardous (loss of propulsion)	HV harness (open circuit)	OEM-specific wire routing, bundle protection, vehicle fault strategies	OEM-specific (design reviews, bench test, vehicle durability, software testing	10	1	7	70	10	None - OEM design and process & durability testing							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-in Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
137	F11	F11. Provide electrical power to vehicle		All	F11.1 Loss of electric power to vehicle	Hazardous (loss of propulsion)	HV Connector	Locking connectors,vehicle fault strategies	OEM-specific (design reviews, bench test software testing), vehicle durability	10	1	7	70	10	None - OEM design and process & durability testing							0
138	F11	F11. Provide electrical power to vehicle		All	F11.1 Loss of electric power to vehicle	Hazardous (loss of propulsion)	LV harness/connector (shorts or open resulting in contactor open when commanded closed)	OEM-specific wire routing, bundle protection, Locking connectors,vehicle fault strategies	OEM-specific (design reviews, bench test, software testing), vehicle durability	10	1	7	70	10	None - OEM design and process & durability testing							0
139	F11	F11. Provide electrical power to vehicle		All	F11.1 Loss of electric power to vehicle	Hazardous (loss of propulsion)	ECU failure (Printed circuit board (PCB), ECU power failure 12v B+/Harness)	OEM-specific ECU designs, vehicle and RESS fault strategies	OEM-specific (design reviews, bench test, software testing), vehicle durability	10	1	7	70	10	None - OEM design and process & durability testing							0
140	F11	F11. Provide electrical power to vehicle		All	F11.1 Loss of electric power to vehicle	Hazardous (loss of propulsion)	Motor failure	OEM-specific designs, vehicle and RESS fault strategies	OEM-specific vehicle durability, software testing	10	1	7	70	10	None - OEM design and process (motor out of scope)							0
141	F11	F11. Provide electrical power to vehicle		All	F11.2 Reduced level of electric power to vehicle	Performance	Inverter failure		Temperature	7	1	7	49	7	None - Performance impact low priority							0
142	F11	F11. Provide electrical power to vehicle		All	F11.2 Reduced level of electric power to vehicle	Performance	Battery		Temperature	7	1	7	49	7	None - Performance impact low priority							0
143	F11	F11. Provide electrical power to vehicle		All	F11.2 Reduced level of electric power to vehicle	Performance	Stack reduction		V, I sensor	7	1	7	49	7	None - Performance impact low priority							0
144	F11	F11. Provide electrical power to vehicle		All	F11.3 Too much electric power to vehicle (High current output greater than expected limit)	Hazardous	Inverter failure	OEM-specific designs, RESS fault strategies (current measurement)	OEM-specific testing (inverter/ system testing), software testing	10	1	7	70	10	None - Out of Scope							0
145	F11	F11. Provide electrical power to vehicle		All	F11.3 Too much electric power to vehicle (High current output greater than expected limit)	Hazardous	Resistance short (high sustained current below fuse limit)	OEM-specific designs, RESS fault strategies (current measurement)	OEM-specific testing (system testing), software testing	10	1	7	70	10	None - Also see Function 5.8 control and management of cells within battery system							0

Issue	Item	Function	Requirement	Type Hybrid, Plug-in Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
146	F11	F11. Provide electrical power to vehicle		All	F11.3 Too much electric power to vehicle (High current output greater than expected limit)	Hazardous	HV system failure (high voltage user devices - other systems such as electric HVAC, aux power, power steering, AC power outlet)	OEM-specific designs, RESS fault strategies (current measurement)	OEM-specific testing (system testing), software testing	10	1	7	70	10	None - requires dual failure mode to be hazardous. Also see Function 5.8 control and management of cells within battery system							0
147	F11	F11. Provide electrical power to vehicle		All	F11.3 Too much electric power to vehicle (High current output greater than expected limit)	Hazardous	HV cable failure		Fuse OEM diagnostic tool	10	1	7	70	10	None - OEM's have stringent durability schedules / validation profiles							0
148	F11	F11. Provide electrical power to vehicle		All	F11.4 Intermittent loss of electric power to vehicle	Hazardous (loss of propulsion)	Electrical stress due to damage to in-line contactors or defective contactor	OEM-specific design, RESS fault strategy, vehicle fault strategy	OEM-specific Bench test, vehicle durability, software testing	10	1	7	70	10	None - OEM design and process & durability testing							0
149	F11	F11. Provide electrical power to vehicle		All	F11.4 Intermittent loss of electric power to vehicle	Hazardous (loss of propulsion)	External 12v short (harness) (resulting in intermittent contactor opening when commanded closed)	OEM-specific wire routing, bundle protection, Locking connectors, vehicle fault strategies	OEM-specific (design reviews, bench test, software testing), vehicle durability	10	1	7	70	10	None - OEM design and process & durability testing							0
150	F11	F11. Provide electrical power to vehicle		All	F11.5 Unintended electric power to vehicle (HV output energized unexpectantly)	Hazardous	Harness short to B+ (12v) (resulting in contactor closing when commanded open)	OEM-specific wire routing, bundle protection, Locking connectors, vehicle fault strategies	OEM-specific (design reviews, bench test, software testing), vehicle durability	10	1	7	70	10	None - OEM's have stringent durability schedules / validation profiles 2/13/12: Consider developing Test Methodology (consider whether covered in item #130)							0
151	F12	F12. Accept charge from vehicle and/or external charging source	From vehicle	All	F12.1 Does not accept charge from vehicle	Performance (loss is gradual)			OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - Performance impact low priority							0
152	F12	F12. Accept charge from vehicle and/or external charging source	From vehicle	All	F12.1 Does not accept charge from vehicle	Performance (loss is gradual)	Voltage sensor failure		OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - Performance impact low priority							0
153	F12	F12. Accept charge from vehicle and/or external charging source	From vehicle	All	F12.1 Does not accept charge from vehicle	Performance (loss is gradual)	Temperature (hot)		OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - Performance impact low priority							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-in Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
154	F12	F12. Accept charge from vehicle and/or external charging source	From vehicle	All	F12.1 Does not accept charge from vehicle	Performance (loss is gradual)	Temperature (cold)		OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - Performance impact low priority							0
155	F12	F12. Accept charge from vehicle and/or external charging source	From vehicle	All	F12.1 Does not accept charge from vehicle	Performance (loss is gradual)	Battery cell failure		OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - Performance impact low priority							0
156	F12	F12. Accept charge from vehicle and/or external charging source	From vehicle	All	F12.1 Does not accept charge from vehicle	Performance (loss is gradual)	contactor failure		OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - Performance impact low priority							0
157	F12	F12. Accept charge from vehicle and/or external charging source	From vehicle	All	F12.1 Does not accept charge from vehicle	Performance (loss is gradual)	Harness failure		OEM tool voltage sensor, temperature sensor	7	1	7	49	7	None - Performance impact low priority							0
158	F12	F12. Accept charge from vehicle and/or external charging source	From vehicle	All	F12.1 Does not accept charge from vehicle	Performance (loss is gradual)	Fuse failure		OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - OEM's have stringent durability schedules / validation profiles							0
159	F12	F12. Accept charge from vehicle and/or external charging source	From vehicle	All	F12.2 Partial charge accepted from vehicle	Performance (loss is gradual)	Cell or monitoring system failure	OBD, BMS error set	Software testing	7	1	7	49	7	None - OEM's have stringent durability schedules / validation profiles							0
160	F12	F12. Accept charge from vehicle and/or external charging source	From vehicle	All	F12.3 Intermittent charging from vehicle	Performance (loss is gradual)	Cell or monitoring system failure	OBD, BMS error set	Software testing	7	1	7	49	7	None - OEM's have stringent durability schedules / validation profiles							0
161	F12	F12. Accept charge from vehicle and/or external charging source	From vehicle	All	F12.3 Intermittent charging from vehicle	Performance (loss is gradual)	Voltage sensor failure	OBD, BMS error set	Software testing	7	1	7	49	7	None - OEM's have stringent durability schedules / validation profiles							0
162	F12	F12. Accept charge from vehicle and/or external charging source	From vehicle	All	F12.4 Unintended charge	Hazardous (due to over charge)	Regenerative braking charge system failure by poor design limits	Vehicle fault strategy, OEM-specific system design	OEM-specific software testing, J2929 (Section 4.9 single pt over charge), vehicle durability	10	1	4	40	10	None - OEM's have stringent durability schedules / validation profiles							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-in Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
153	F12	F12. Accept charge from vehicle and/or external charging source	From external charging source	P, E	F12.5 Does not accept charge from external source	Performance (unable to charge)	J1772 - insufficient definitions of charging states (charging software not working on all OEM vehicles)	OEM sanctions certain chargers	Unknown	7	7	10	490	49	None - UL and SAE J1772 being revised for 3rd party chargers							0
154	F12	F12. Accept charge from vehicle and/or external charging source	From external charging source	P, E	F12.5 Does not accept charge from external source	Performance (unable to charge)	Voltage sensor failure		OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - Performance impact low priority Refer to Function 5 for potentially hazardous causes							0
155	F12	F12. Accept charge from vehicle and/or external charging source	From external charging source	P, E	F12.5 Does not accept charge from external source	Performance (unable to charge)	Temperature (hot)		OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - Performance impact low priority Refer to Function 5 for potentially hazardous causes							0
156	F12	F12. Accept charge from vehicle and/or external charging source	From external charging source	P, E	F12.5 Does not accept charge from external source	Performance (unable to charge)	Temperature (cold)		OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - Performance impact low priority Refer to Function 5 for potentially hazardous causes							0
157	F12	F12. Accept charge from vehicle and/or external charging source	From external charging source	P, E	F12.5 Does not accept charge from external source	Performance (unable to charge)	Battery cell failure (voltage too low)		OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - Performance impact low priority Refer to Function 5 for potentially hazardous causes							0
158	F12	F12. Accept charge from vehicle and/or external charging source	From external charging source	P, E	F12.5 Does not accept charge from external source	Performance (unable to charge)	Contactor failure		OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - Performance impact low priority							0
159	F12	F12. Accept charge from vehicle and/or external charging source	From external charging source	P, E	F12.5 Does not accept charge from external source	Performance (unable to charge)	Harness failure		OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - Performance impact low priority							0
170	F12	F12. Accept charge from vehicle and/or external charging source	From external charging source	P, E	F12.5 Does not accept charge from external source	Performance (unable to charge)	Fuse failure		OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - Performance impact low priority							0
171	F12	F12. Accept charge from vehicle and/or external charging source	From external charging source	P, E	F12.6 Partial charge accepted from external source	Performance (unable to charge)	Cell or monitoring system failure		OBC, Batt, temperature sensor, BMS error set	7	1	7	49	7	None - Performance impact low priority Refer to Function 5 for potentially hazardous causes							0
172	F12	F12. Accept charge from vehicle and/or external charging source	From external charging source	P, E	F12.7 Intermittent charging from external source	Performance (unable to charge)	J1772		OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - Refer to F12.5							0

Issue	Item	Function	Requirement	Type: Hybrid, Plug-in Hybrid, Electric	Potential Failure Mode	Potential Effect(s) of Failure Mode	Potential Cause(s) for the Failure Mode	Prevention of Cause or Failure Mode	Detection of Cause or Failure Mode	Severity	Occurrence	Detection	RPN	SO	Recommended Action(s) (see 'Column Definitions' tab for color key)	Responsibility	Target Completion Date	Actions Taken	Severity	Occurrence	Detection	RPN
173	F12	F12. Accept charge from vehicle and/or external charging source	From external charging source	P, E	F12.7 Intermittent charging from external source	Performance (unable to charge)	Voltage sensor failure		OEM tool, voltage sensor, temperature sensor	7	1	7	49	7	None - Performance impact low priority Refer to Function 5 for potentially hazardous causes							0
174	F12	F12. Accept charge from vehicle and/or external charging source	From external charging source	P, E	F12.8 Unintended charge	Hazardous (over current or over charge only)	Battery control system failure	OEM-specific design, RESS fault strategy	J2929 Section 4.9, software testing	10	1	4	40	10	1. Evaluate J2929 to determine if it is sufficient for this potential cause 2. Propose charging security to the electronic vehicle systems security SAE committee			OEM's have stringent durability schedules / validation profiles - no further action required				0
175	F13	F13. Protect battery from extreme environmental conditions	Extreme high temperature over normal operating range (e.g. aftermarket or rework paint oven)		F13.1 Exposure to high external temperature resulting in material degradation	Hazardous	External heating	OEM-specific designs	KMVSS 18.3 to 80 degrees C, China QCT743 85 degrees C, UL STD 1642 130 degrees C	10	10	7	700	100	Evaluate latent fault potential for intermediate over-heating (80-120 degrees C) Evaluate frequency of exposure to artificial high temperature environments Research standards for more information regarding high temperature testing							0
176	F13	F13. Protect battery from extreme environmental conditions	Extreme low temperature below normal operating range (e.g. arctic)		F13.2 Exposure to extreme low temperature resulting in hardware failures	Hazardous	External cooling	OEM-specific designs (maintain heating functionality)	Uknown	10	4	7	280	40	Investigate failure mode further to determine what migh occur (verify severity) May be multiple failure event			OEM's have stringent durability schedules / validation profiles - mp further action required				0
177	F13	F13. Protect battery from extreme environmental conditions	Extreme humidity/salt fog		F13.3 Exposure to humidity/salt fog resulting in corrosion	Hazardous	Insufficient enclosure protection (sealing)	OEM-specific designs	J2929 Section 4.2.4	10	4	4	160	40	None - OEM's have stringent durability schedules / validation profiles							0
178	F13	F13. Protect battery from extreme environmental conditions	Extreme high altitudes		F13.4 Exposure to extreme high altitudes resulting in hardware failures	Hazardous	Internal pressure differences at cell level or pack level	OEM-specific designs	UN transp of dangerous goods (section 38.3 test T.1)	10	1	4	40	10	None - part of UN transportation approval process and OEM's have stringent durability schedules / validation profiles							0

Ranking

RESS System FMEA Ranking Criteria

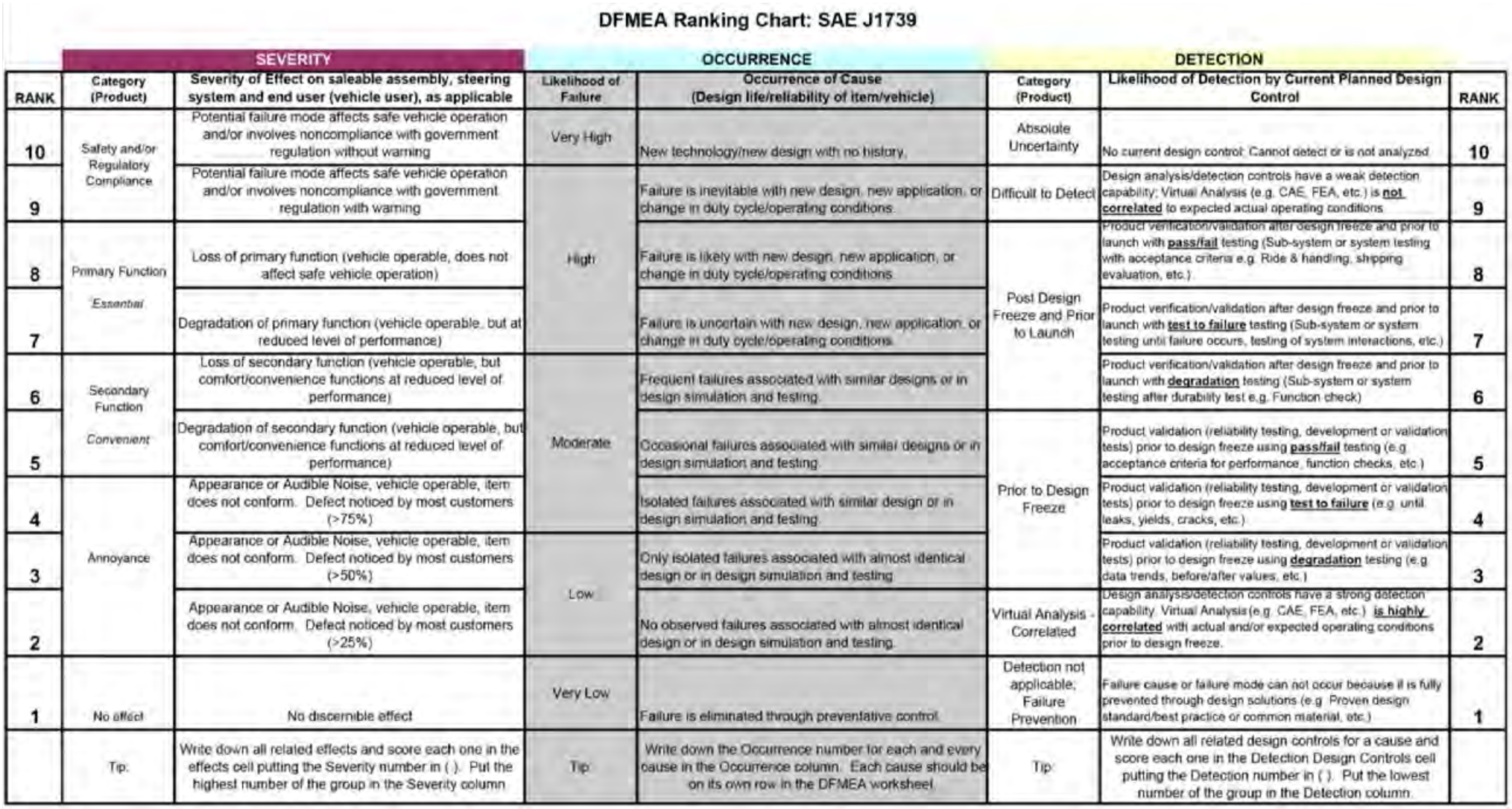
Ranking	Severity	Occurrence	Detection
10	Hazardous	High probability - No history	No current testing method
9	Hazardous over extended time	Not used	Not used
7	Performance	Medium probability - Frequent problem history	Moderate ability to detect (OEM specific)
4	Annoyance	Low probability - Isolated problems	High ability to detect (industry standard)
1	No effect	Very low probability - established practices	Detection not required

Consider overall industry, not only major OEM's

SEV x OCC x DET = RPN 1 - 1000

SEV x OCC = SO 1 - 100

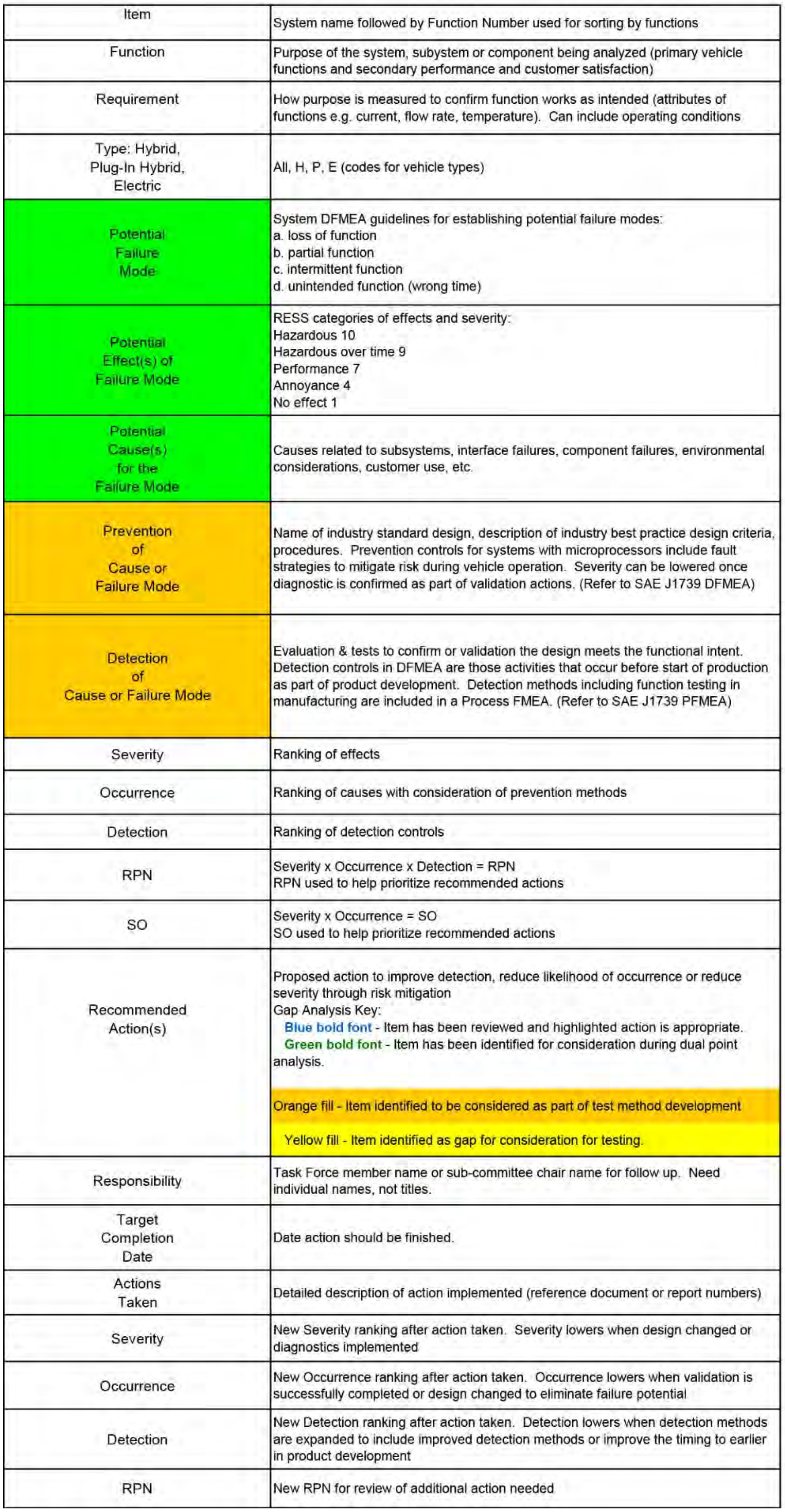
J1739 Ranking



DFMEA Ranking Chart: SAE J1739

	SEVERITY		OCCURRENCE		DETECTION		
RANK	**Category (Product)**	**Severity of Effect on saleable assembly, steering system and end user (vehicle user), as applicable**	**Likelihood of Failure**	**Occurrence of Cause (Design life/reliability of item/vehicle)**	**Category (Product)**	**Likelihood of Detection by Current Planned Design Control**	**RANK**
10	Safety and/or Regulatory Compliance	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning	Very High	New technology/new design with no history.	Absolute Uncertainty	No current design control; Cannot detect or is not analyzed	**10**
9		Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning	High	Failure is inevitable with new design, new application, or change in duty cycle/operating conditions.	Difficult to Detect	Design analysis/detection controls have a weak detection capability; Virtual Analysis (e.g. CAE, FEA, etc.) is **not correlated** to expected actual operating conditions	**9**
8	Primary Function	Loss of primary function (vehicle operable, does not affect safe vehicle operation)		Failure is likely with new design, new application, or change in duty cycle/operating conditions.	Post Design Freeze and Prior to Launch	Product verification/validation after design freeze and prior to launch with **pass/fail** testing (Sub-system or system testing with acceptance criteria e.g. Ride & handling, shipping evaluation, etc.)	**8**
7	*Essential*	Degradation of primary function (vehicle operable, but at reduced level of performance)		Failure is uncertain with new design, new application, or change in duty cycle/operating conditions.		Product verification/validation after design freeze and prior to launch with **test to failure** testing (Sub-system or system testing until failure occurs, testing of system interactions, etc.)	**7**
6	Secondary Function	Loss of secondary function (vehicle operable, but comfort/convenience functions at reduced level of performance)	Moderate	Frequent failures associated with similar designs or in design simulation and testing.		Product verification/validation after design freeze and prior to launch with **degradation** testing (Sub-system or system testing after durability test e.g. Function check)	**6**
5	*Convenient*	Degradation of secondary function (vehicle operable, but comfort/convenience functions at reduced level of performance)		Occasional failures associated with similar designs or in design simulation and testing.	Prior to Design Freeze	Product validation (reliability testing, development or validation tests) prior to design freeze using **pass/fail** testing (e.g. acceptance criteria for performance, function checks, etc.)	**5**
4	Annoyance	Appearance or Audible Noise, vehicle operable, item does not conform. Defect noticed by most customers (>75%)		Isolated failures associated with similar design or in design simulation and testing.		Product validation (reliability testing, development or validation tests) prior to design freeze using **test to failure** (e.g. until leaks, yields, cracks, etc.)	**4**
3		Appearance or Audible Noise, vehicle operable, item does not conform. Defect noticed by most customers (>50%)	Low	Only isolated failures associated with almost identical design or in design simulation and testing.		Product validation (reliability testing, development or validation tests) prior to design freeze using **degradation** testing (e.g. data trends, before/after values, etc.)	**3**
2		Appearance or Audible Noise, vehicle operable, item does not conform. Defect noticed by most customers (>25%)		No observed failures associated with almost identical design or in design simulation and testing.	Virtual Analysis - Correlated	Design analysis/detection controls have a strong detection capability. Virtual Analysis (e.g. CAE, FEA, etc.) **is highly correlated** with actual and/or expected operating conditions prior to design freeze.	**2**
1	No effect	No discernible effect	Very Low	Failure is eliminated through preventative control.	Detection not applicable; Failure Prevention	Failure cause or failure mode can not occur because it is fully prevented through design solutions (e.g. Proven design standard/best practice or common material, etc.)	**1**
	Tip:	Write down all related effects and score each one in the effects cell putting the Severity number in ( ). Put the highest number of the group in the Severity column.	Tip:	Write down the Occurrence number for each and every cause in the Occurrence column. Each cause should be on its own row in the DFMEA worksheet.	Tip:	Write down all related design controls for a cause and score each one in the Detection Design Controls cell putting the Detection number in ( ). Put the lowest number of the group in the Detection column.	

Column Definitions



Item	System name followed by Function Number used for sorting by functions
Function	Purpose of the system, subystem or component being analyzed (primary vehicle functions and secondary performance and customer satisfaction)
Requirement	How purpose is measured to confirm function works as intended (attributes of functions e.g. current, flow rate, temperature). Can include operating conditions
Type: Hybrid, Plug-In Hybrid, Electric	All, H, P, E (codes for vehicle types)
Potential Failure Mode	System DFMEA guidelines for establishing potential failure modes: a. loss of function b. partial function c. intermittent function d. unintended function (wrong time)
Potential Effect(s) of Failure Mode	RESS categories of effects and severity: Hazardous 10 Hazardous over time 9 Performance 7 Annoyance 4 No effect 1
Potential Cause(s) for the Failure Mode	Causes related to subsystems, interface failures, component failures, environmental considerations, customer use, etc.
Prevention of Cause or Failure Mode	Name of industry standard design, description of industry best practice design criteria, procedures. Prevention controls for systems with microprocessors include fault strategies to mitigate risk during vehicle operation. Severity can be lowered once diagnostic is confirmed as part of validation actions. (Refer to SAE J1739 DFMEA)
Detection of Cause or Failure Mode	Evaluation & tests to confirm or validation the design meets the functional intent. Detection controls in DFMEA are those activities that occur before start of production as part of product development. Detection methods including function testing in manufacturing are included in a Process FMEA. (Refer to SAE J1739 PFMEA)
Severity	Ranking of effects
Occurrence	Ranking of causes with consideration of prevention methods
Detection	Ranking of detection controls
RPN	Severity x Occurrence x Detection = RPN RPN used to help prioritize recommended actions
SO	Severity x Occurrence = SO SO used to help prioritize recommended actions
Recommended Action(s)	Proposed action to improve detection, reduce likelihood of occurrence or reduce severity through risk mitigation Gap Analysis Key: **Blue bold font** - Item has been reviewed and highlighted action is appropriate. **Green bold font** - Item has been identified for consideration during dual point analysis. Orange fill - Item identified to be considered as part of test method development Yellow fill - Item identified as gap for consideration for testing.
Responsibility	Task Force member name or sub-committee chair name for follow up. Need individual names, not titles.
Target Completion Date	Date action should be finished.
Actions Taken	Detailed description of action implemented (reference document or report numbers)
Severity	New Severity ranking after action taken. Severity lowers when design changed or diagnostics implemented
Occurrence	New Occurrence ranking after action taken. Occurrence lowers when validation is successfully completed or design changed to eliminate failure potential
Detection	New Detection ranking after action taken. Detection lowers when detection methods are expanded to include improved detection methods or improve the timing to earlier in product development
RPN	New RPN for review of additional action needed

Global Battery Test Procedure Standards

Fire Resistance Test Procedure (Pack Level):

Test Specification	SOC	Exposure Area	Flame Distance from DUT	Fuel Type	Heat Source Temperature	Exposure Duration	Explosion Determination
UNECE R100 - Draft	50%	20cm larger than DUT	Design height of RESS lowest surface above road surface	Commercial Fuel	Approx. 700°C	130 seconds	
UL 2580 External Fire Exposure Test	100%	Length of DUT	TCs placed 25 mm from bottom surface	Any Hydrocarbon Fuel	≥ 590°C	20 Min	Projectiles found beyond 1 m perimeter around DUT
USABC Battery Abuse Manual - Radiant Heat Test	80%		DUT does not contact cylindrical surface	Cylindrical Radiant surface, Furnace	890°C	10 Min.	
Freedom Car Battery Abuse Manual - Simulated Fuel Fire	100%		DUT does not contact cylindrical surface	Cylindrical Radiant surface, Furnace	890°C	10 Min.	
ISO 12405-3	50%	200 mm - 500 mm larger than DUT	Design height of RESS lowest surface above road surface	Commercial Fuel	Approx. 700°C	60 seconds direct exposure and 70 seconds indirect exposure	Explosion projectiles not quantified
SAE J2464 High Temperature Hazard Test	100%		DUT does not contact cylindrical surface	Cylindrical Radiant surface, Furnace	890°C	10 Min.	Explosion projectiles not quantified
SAE J2929 Exposure to Simulated Vehicle Fire	100%	*	*	*	*	Until battery system is involved in the fire	Wire Test Cage
KMVSS (Annex 1 - Part 48) 48.6.7 Combustion safety test	80%	Single burner		Any Fuel	890°C-900°C	120 Seconds	
KMVSS Article 18-3 Draft October, 2012	80% to 100%	Array of burners		LPG	800°C -900°C	120 Seconds	

* - multiple methods allowed

Water Immersion Test Procedure:

Test Specification	SOC	Immersion Solution	Immersion Depth	Test Duration	System State	Scale
SAE J2464	100%	5% NaCl	Cover DUT	2 Hr.	Normal orientation, passive protection devices integral to the RESS shall remain operational throughout the test. All active protective devices shall be disabled prior to the test.	Pack, Module
SAE J2929	100%	Salt water	Fully Submerged	2 Hr.	Operational & On	Pack
Freedom Car Battery Abuse Manual	100%	Salt water	Completely Submerge	2 Hr.		Pack
UL 2580	MOSOC##	5% NaCl	Cover DUT	1 Hr.	Operational & Active, connections made as intended in end use vehicle application	Pack, Module
UL 2271	100%	5% NaCl	Cover DUT	2 Hr.	Operational & Active	Pack, Module
QC/T 743-201x	100%	3.5% NaCl	Cover DUT	2 Hr.	Protective circuits removed	Pack or Cells
KMVSS (Annex 1 - Part 48)	80%	3.5% NaCl	Cover DUT to depth of 0.6 meter	1 Hr.	Test may be conducted without the Battery management module BMM and safety devices installed.	Pack
ISO 12405-3*						

* - Immersion test identified in this standard but essentially waived due to short circuit testing.
However, any method for immersion can be done if not waived.

- MOSOC is maximum operating state of charge (may or may not be 100% SOC)

External Short Circuit Test Procedures

Test Specification	Conductor Impedance	Hard Short Duration	Passive Short Circuit Protection Device Condition	Non-Passive Protective Device Condition	Observation Period	SOC
Freedom Car Battery Abuse Manual	≤5 mΩ	10 Min.	Operational	Disable	2 Hrs.	100%
USABC Abuse Test Manual	≤5 mΩ	10 Min.	Operational	Disable	2 Hrs.	100%
ISO 12405-1	100 (+0/-40) mΩ	10 Min.	Operational	Operational	2 Hrs.	100%
ISO 12405-2	20 (+0/-10) mΩ	10 min.	Operational	Operational	2 Hrs.	100%
ISO 12405-3	100 (+0/-40) mΩ or 20 (+0/-10) mΩ	10 Min.	Operational	Operational	2 Hrs.	100%
SAE J2464	≤5 mΩ	60 Min.	Disabled	Operational, Disabled & Bypassed	1 Hr.	
SAE J2929	≤5 mΩ	60 Min.	Operational	Operational	1 Hr.	
UL 2580#	≤ 20 mΩ	7 Hrs.	Operational	Operational but single fault condition	Cycle + 1 Hr.	MOSOC
UN 38.3	10 mΩ	60 Min.	*	*	6 Hrs.	100%
UN ECE R100	≤5 mΩ	60 Min.	Operational	Operational	1 Hr.	50%
QC/T 743-2006	≤5 mΩ	10 Min.			1 Hr.	100%
KMVSS (Annex 1 - Part 48)	50mΩ	60 Min.	Operational	Operational	NA	80%
Indian AIS-048 "Battery Operated Vehicles - Safety Requirements of Traction Batteries	≤5 mΩ	10 Min.	Operational	Disable	NA	100%

* - Test can be conducted per UN, or SAE J4646 or ISO 12405-1 or -2

\# - Test is repeated at current below trip point of protection (i.e. soft short)

** - Protection remains in the circuit when testing. However, this test can be waived on battery assemblies that are more than 6200 Wh rating and provided with a BMS system short circuits, overdiscaharge, overheating or overcharging of the system.

Overcharge Test Procedure (Pack Level):

Test Specification	Charge Current	Charge Voltage	Max. Overcharge Level	Cooling System	Passive Short Circuit Protection Device Condition	Non-Passive Protective Device Condition	Post Test Monitor Period
USABC Abuse Test Manual	32 Adc	450 Vdc	200% SOC or 4 Hours	Operational	Operational	Disabled	
Freedom Car Abuse Manual	32 Adc	450 Vdc	200% SOC or 4 Hours	Operational	Operational	Disabled	2 Hrs.
UN ECE R100	C/3		2 X Rated Charge Capacity	Operational	Operational	Operational	Charge Cycle + 1 Hr.
ISO 12405-1	C/5	20% of Max.	130% of SOC or cell temp above 55°C	Operational	Operational	Disabled	1 Hr.
ISO 12405-2	2C	20% of Max.	130% of SOC or cell temp above 55°C or autodisconnect activates	Operational	Operational	Disabled	1 Hr.
ISO 12405-3 #	C/5 or 2C	20% of Max.	130% of SOC or cell temp above 55°C or autodisconnect activates	Operational	Operational	Disabled	1 Hr.
SAE J2464	C/1	1.2 X Max. Charge Voltage	200% SOC		Operational	Disabled	1 Hr.
SAE J2464	C/1		200% SOC	Operational	Operational	Disabled	1 Hr.
SAE J2929	Icmax##	Vcmaxlimit#	VCmaxlimit	Operational	Operational	Disabled	1 Hr.
UL 2580	Icmax##		110% SOC or protection interrupts	Operational	Operational	Single fault in charging circuit controls	cycle + 1 Hr.
UN 38.3	2 X Max. Current	1.2 X Max. Charge Voltage	24 Hours	**	**	**	
QC/T 743-2006	1 *I*t A *		2 X Max. Charge Voltage or 100% SOC				1 Hr.
KMVSS (Annex 1 - Part 48)	32 Adc	1.5 X Max. Charge Voltage	150% SOC or 2.5 Hours	Operational	Operational	Disabled	2 Hrs.
Indian AIS-048	C/10		200% SOC				

- Either ISO 12405-1 or 12405-2 method depending if high power or high energy application

- Maximum specific charging rate

** - Protection remains in the circuit when testing. However, this test can be waived on battery assemblies that are more than 6200 Wh rating and provided with a BMS system short circuits, overdiscaharge, overheating or overcharging of the system. The individual modules would need to have been tested and passed.

Over Discharge Test Procedure (Pack Level):

Test Specification	Discharge Rate	Discharge Time Period	Max. Over Discharge Level	Cooling System	Passive Short Circuit Protection Device Condition	Non-Passive Protective Device Condition	Post Test Monitor Period
USABC Abuse Test Manual	C/1	90 Min.	All cells reversed for 15 Min.	Operational	Operational	Disabled	
Freedom Car Abuse Manual	C/1	90 Min. (Begins at 100% SOC)	-50% SOC or 50% of cells reversed for 15 Min.	Operational	Operational	Disabled	2 Hrs.
UN ECE R100	C/3	NA	25% recommended operating voltage	Operational	Operational	Disabled	Charge Cycle + 1 Hr.
ISO 12405-1	C/1	30 Min.	25% recommended operating voltage	Operational	Operational	Disabled	1 Hr.
ISO 12405-2	C/3	30 Min.	25% recommended operating voltage	Operational	Operational	Disabled	1 Hr.
ISO 12405-3	C/1 or C/3	30 Min.	25% recommended operating voltage	Operational	Operational	Disabled	1 Hr.
SAE J2464	Max. current	30 Min.	Module voltage reaches 0 ± 0.2 volts	Operational	Operational	Disabled	1 Hr.
SAE J2929	C/3 or 1C	NA	voltage reaches 0.0 V ± 0.2 V.	Operational	Operational	Disabled	cycle + 1 Hr.
UL 2580	IDmax	30 min after EODV or protection operates	NA	Operational	Operational	Operational but may be single faulted	1 Hr.
QC/T 743-2006	1 *I*t A *	30 Min. after voltage reaches 0	Module voltage reaches 0.0				
KMVSS (Annex 1 - Part 48)	C/1	90 Min. (Begins at 0% SOC)	-50% SOC				

* reference test current It current in amperes which is expressed as It (A) = Cn (Ah)/ 1 (h) where Cn is the rated capacity of the cell ; n is the time base (hours).

Icmax - maximum charge current;

Idmax - maximum discharge current

VCmaxlimit - maximum charging device output limit

Thermal Shock Test Specifications Used as Reference

Test Specification	Upper Temp	Lower Temp	Time to Reach Temp.	Soak Time	Number of Cycles	State of Charge	Post-Thermal Cycles @ Ambient Temp.	Scope
Freedom Car Abuse Manual	80°C	-40°C	30 Min.	6 Hrs.	5	50%	3	Tests intended to simulate actual use and abuse conditions
USABC Battery Test Procedure Manual	80°C	-40°C	15 Min.	6 Hrs.	5	50%	3	
UL 2580 and UL 2271	85°C	-40°C	15 Min.	6 Hrs.	5	MOSOC*	3	References J2462
UN 38.3	75°C	-40°C	30 Min.	6 Hrs./12 Hrs.	10		0	This test specification is intended for packing testing/shipping safety
UN ECE R100	60°C	-40°C	30 Min.	6 Hrs.	5	50%	1	
ISO 12405-1	85°C	-40°C	30 Min.	1 Hr.	5	50%	2	Test specification for High Power lithium-ion traction battery packs and systems
ISO 12405-3	85°C/60°C	-40°C	30 Min.	6 h	5	50% or 80% SOC	2	references ISO 12405-1 and -2
ISO 16750-4	95°C	-40°C		Varies from 10 to 90 Min.	30		0	References IEC 60068-2-14
SAE J2464	70°C	-40°C	15 Min.	6 Hrs.	5	100%	3	
SAE J2929						95-100% of the maximum which is possible during normal vehicle operation	0 or 3	References either Un 38.3 test or UL 24646 test
QC/T 743-2006	85°C	-40°C		Varies from 60 to 110 Min.	30		0	Standards for Vehicle Industry in the People's Republic of China

* - MOSOC is maximum operating state of charge and may not necessarily be 100% SOC

Vibration Test specifications used as reference

Test Specification	Vibration Profile	Axis	Duration per axis	Max. Freq.	State of charge	Scope
UNECE R100	Sine Sweep	Vertical	3 Hrs.	50 Hz	50% SOC	European ES product safety test standard
ISO 16750-3:2003	Sine Sweep	3	22 Hrs.	440 Hz	Not Specified	This is a common Test specification/guideline for vehicle transportation - testing for electrical and electronic equipment. Powertrain mounted equip. - Sine & Random / Body mounted equip. - Random
ISO 16750-3:2003	Random Spectrum	3	22 Hrs.	2,000 Hz	Not Specified	
ISO 12405-1#	Random Spectrum	3	21 Hrs.	200 Hz	50% SOC	Safety requirements with respect to the Rechargeable Energy Storage Systems (RESS) of road vehicles
ISO 12405-2#	Random Spectrum	3	21 Hrs.	200 Hz	50% SOC	Safety requirements with respect to the Rechargeable Energy Storage Systems (RESS) of road vehicles
ISO 12405-3#	Random Spectrum	3	21 Hrs.	200 Hz	50% SOC	Safety requirements with respect to the Rechargeable Energy Storage Systems (RESS) of road vehicles
SAE J2380	Random Spectrum	3	16/38/38 Hrs.	190 Hz	100% SOC	SAE's current durability vibration profile for ES products
SAE J2929	Random Spectrum	3	16/38/38 Hrs.	190 Hz	100% SOC	References J2380 & UN 38.3 - A more recent revision directed toward ES product safety
UN 38.3	Sine Sweep	3	3 Hrs.	200 Hz.	Not Specified	This test specification is intended for packing testing/shipping safety as it pertains to ES products for verification that a product does not need to be shipped as Hazardous material
UL 2271	Random Spectrum	3	55 Min.	500 Hz	MOSOC	References IEC 61959, Batteries For Use in Light Electric Vehicle Applications
UL 2580	Random Spectrum	3	16/38/38 Hrs.	500 Hz	MOSOC*	References J2380
QC/T 743-2006	Sine Sweep	Vertical	1 Hr.	55 Hz	100% SOC	Standards for Vehicle Industry in the People's Republic of China
DIN VDE V 0510-11	Random Spectrum			1,000 Hz	80%	Safety requirements for secondary lithium batteries for hybrid vehicles and mobile applications
USABC Manual	Random Spectrum	3	16/38/38 Hrs.	190 Hz	100% SOC	Procedure has been synthesized from actual rough-road measurements at locations appropriate for mounting of traction batteries in electric vehicles
USABC Manual	Sine Sweep	3	24 Hrs.	190 Hz	100% SOC	

- Also includes temperature variation during testing from -40C to 75C

* - Maximum Operating State of Charge

Over Temperature Test Procedure (Pack Level):

This test comparison is difficult since the tests are addressing different failure modes.

(such as hot or cold soak, extreme hot or cold exposure, restricted ability to charge at extreme hot or cold temps, etc.)

Test Specification	Charge Rate	No. of Charge/Discharge Cycles	Upper Limit Charge Temperature	Cooling System	Protection Deveices	SOC
UN ECE R100	Defined by the manufacturer	Continual	Defined by the manufacturer	Deactivated	Operational	
Freedom Car Abuse Manual	Use manufacturer's recommended charge algorithm and a discharge rate comparable to a 3-kW constant power rate	20	Defined by the manufacturer	Deactivated	Operational	
KMVSS (Annex 1 - Part 48)	NA	NA	80°C for 4 hours			80%

Under Temperature Test Procedure (Pack Level):

This test comparison is difficult since the tests are addressing different failure modes.

(such as hot or cold soak, extreme hot or cold exposure, restricted ability to charge at extreme hot or cold temps, etc.)

Test Specification	Charge Rate	No. of Charge/Discharge Cycles	Temperature	Soak Period	Protection Deveices	SOC
UN ECE R100	Defined by the manufacturer	Continual	0-5% of minimum normal operating SOC	24 Hrs.	Operational	0-5% of the minimum normal operating SOC

DOT HS 812 717
May 2019

U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**

NHTSA

14040-052119-v3b