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System-Level RESS Safety and Protection Test Procedure Development, Validation, and Assessment–Final Report

Disclaimer

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1 Introduction

The automotive application of electric propulsion in Hybrid Electric Vehicles (HEV), Plug-in Hybrid Electric Vehicles (PHEV) and Electric Vehicles (EV) relies on the application of a Rechargeable Energy Storage System (RESS) commonly referred to as a battery. In addition to the RESS itself, a Battery Management System (BMS) is an integral component of a vehicle's overall energy storage system. The BMS serves a variety of functions to incorporate a RESS into the larger system, but its primary function is to monitor and protect the RESS while communicating battery relevant system-level information to other parts of a vehicle's control system. With a specific focus on safety and RESS protection, the BMS is responsible monitoring the safety state of the battery system, while protecting the battery from operating outside its safe operating area. Under certain conditions, the BMS may need to actuate a switching device (typically referred to as contactors) to physically separate the RESS from conditions that are pushing the battery outside its normally safe operating conditions.

The automotive application and use of a RESS, such as a Lithium-ion (Li-ion) based battery system, poses certain potential risks to vehicle operators and occupants. These potential risks are different than those associated with internal combustion engine equipped vehicles. Many of these risks are associated with hazards and failure modes created when the battery exceeds its recommended operational limitations including those that are managed by active control algorithms programmed into the BMS.

The test procedures referenced in this report have been independently developed based on commonly accepted single point failure modes (1.3.4) and hazards related to battery technology and the ability of a BMS to effectively detect and mitigate certain safety relevant occurrences during operation. This report documents a research project to independently evaluate, refine and validate these test procedures for use within a vehicle-level set of tests that can be robustly applied to a wide range of vehicle technologies and battery configurations.

1.1 Scope

The test procedures developed within this document are applicable to all RESS-equipped HEVs, PHEVs and EVs. Specific guidance has been provided for application of the procedures to Li-ion based RESS systems as Li-ion cell chemistry is the dominant chemistry in RESS at the time of writing, however, the general approach provided could be applied to a range of other cell chemistries and battery systems.

1.2 Highlighted Cell, Module, and Pack Testing Procedures and Applicable Insights for System-level Procedure Development

As referenced in the introduction, this research project elaborates upon and builds from existing best-practices in the realms of battery cell, module, and pack testing. Based on this groundwork, the project identifies important concepts transferable to system-level evaluation as well as adjustments to create a system level test procedure that investigates core system-level safety concepts in alignment with existing battery test procedures, evaluation methodologies, and research across the spectrum of cell to pack-level. While a full list of relevant publications is provided in "Appendix A – Applicable Publications," this section highlights and cites some of the most relevant procedures, concepts, and failure modes used to generate the system-level procedures contained in this document.

Based on the examination of existing cell/module/pack literature, several key concepts, procedures, and failure modes arise across a range of safety evaluation procedures. These key concepts, procedures, and modes are used to form the core of the vehicle-level evaluation procedures in this document, supplemented with modifications to better highlight vehicle-level issues as well as facilitate more efficient and repeatable testing. While more rationale and discussion regarding specific tests and procedures is given in subsequent sections of this work, some the key evaluation tests and core concepts transferable to the vehicle-level testing include:

Key Evaluation Tests:

- Overcurrent protection
- Overcharge Protection System Single Point Failure
- Overdischarge Protection System Single Point Failure
- Thermal Control System Single Point Failure

Core Testing Concepts:

- **Functional safety** – A battery's control system should be able to actively detect and mitigate/avoid certain conditions, the escalation of which could lead to a safety issue.
- **Single fault tolerance** – A battery control system's response to an uncontrolled condition must be evaluated, therefore BMS provided charge/discharge control signals (i.e., charge/discharge power limits) should be disabled or ignored during over/under charge operation (while still remaining within a battery's maximum charge/discharge capacity)
- **Defined mitigation** – The proposed evaluation tests should have well-defined and observable mitigation responses as opposed to simply stating that a device must avoid thermal runaway or similar large-scale safety issue during testing.

The existing literature also provides some helpful insights into procedural issues related to some of the test procedures and while not summarized here, they are incorporated into the procedures discussed later in this documents.

More detailed highlights relating to 1) Key Evaluation Tests, 2) Core Testing Concepts, and 3) Procedural Notes from existing cell/module/pack literature is provided in the following three subsections.

1.2.1 Key Evaluation Tests- Failure Mode Protection

<u>ISO 6469-1: Electrically propelled road vehicles — Safety specifications — Part 1: On-board rechargeable energy storage system (RESS)</u>

> **Overheating** – *"Heat generation under any first-failure condition, which could form a hazard to persons, shall be prevented by appropriate measures, e.g., based on monitoring of current, voltage or temperature."*

<u>ISO 12405-1 : Electrically propelled road vehicles — Test specification for lithium-ion traction battery packs and systems - Part 1:High-power applications</u>

> **Overcharge** – "*The purpose of the overcharge protection test is to check the functionality of the overcharge protection function. This function shall interrupt the overcharge current in order to protect the DUT [Device Under Test] from any further related severe events caused by an overcharge current."*

> **Overdischarge** – *"The purpose of the overdischarge protection test is to check the functionality of the overdischarge protection function. This device shall interrupt the overdischarge current in order to protect the DUT from any further related severe events caused by an overdischarge current."*

ISO 12405-3 : Electrically propelled road vehicles — Test specification for lithium-ion traction battery packs and systems - Part 3: Safety performance requirements

Overheating (due to failed cooling system) – *"The purpose of this test is to verify the ability of the DUT to prevent internal overheating. This test considers also a failure of thermal control or cooling function."*

J2929 Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-based Rechargeable Cells

Single Point Overcharge Protection System Failure – *"This condition simulates the condition where the battery system charge device is no longer being controlled and the failure may allow the battery system to be overcharged."*

Single Point Overdischarge Protection System Failure – *"This condition simulates the condition where the battery system discharge load is no longer being controlled and the failure may allow the battery system to be over discharged."*

Single Point Thermal Control System Failure – *"This condition simulates the condition where the battery system temperature control is no longer operating and the failure may lead to a battery system over temperature condition."*

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

Overdischarge (Forced Discharge) and Overcharge Test (Cell and Module or Pack) – Note for these tests, *"All active protective devices shall be disabled prior to this test,"* which is more aggressive as compared to some of the other defined mitigation tests as discussed in other procedures (which allow for active mitigation mechanisms, typically via contactors).

UNR100 E/ECE/324/Rev.2/Add.99/Rev.2-E/ECE/TRANS/505/Rev.2/Add.99/Rev.2 – Annex 8G-I

Overcharge protection – *"The purpose of this test is to verify the performance of the overcharge protection."*

Overdischarge protection – *"The purpose of this test is to verify the performance of the overdischarge protection. This functionality, if implemented, shall interrupt or limit the discharge current to prevent the REESS [Rechargeable Energy Storage System] from any severe events caused by a too low SOC [State of Charge] as specified by the manufacturer."*

Over-temperature protection – *"The purpose of this test is to verify the performance of the protection measures of the REESS against internal overheating during the operation, even under the failure of the cooling function if applicable. In the case that no specific protection measures are necessary to prevent the REESS from reaching an unsafe state due to internal over-temperature, this safe operation must be demonstrated."*

1.2.2 Core Testing Concepts

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

Defined Mitigation - *"If a RESS system is not short-circuit proof in itself, a RESS over-current interruption device shall open the RESS circuit under conditions specified by the vehicle and/or RESS manufacturer, to prevent dangerous effects for persons, the vehicle and the environment."*

ISO 6469-2: Electrically propelled road vehicles —Safety specifications — Part 2: Vehicle operational safety means and protection against failures

Single Fault Tolerance - *"Measures shall be implemented to manage credible single-point failures."*

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

Single Fault Tolerance – *"Active charge control of the test equipment shall be disconnected."* (i.e., simply relying on a vehicle's control system to avoid overcharge is not sufficient single-fault tolerant behavior).

Defined Mitigation – *"BCU shall interrupt the overcharge current by an automatic disconnect of the main contactors to protect the DUT from further related severe effects."*

Concept: Defined Mitigation – *"The BCU shall interrupt the overdischarge current by an automatic disconnect of the main contactors in order to protect the DUT against further related severe effects."*

J2929 Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-based Rechargeable Cells

Single Fault Tolerance - *"Active charge control (i.e., Charge/Discharge Control Function) shall be disabled/disconnected from the charge device."*

Defined Mitigation - *"Continue charging until the charge device voltage is reached or the connection interface disconnects battery from charge device"*

UNR100 E/ECE/324/Rev.2/Add.99/Rev.2-E/ECE/TRANS/505/Rev.2/Add.99/Rev.2 – Annex 8G-I

Defined Mitigation – *"The charging shall be continued until the tested-device (automatically) interrupts or limits the charging."*

1.2.3 Procedural Notes and Highlights

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

SOC Based End-of-Test Condition – *"The overcharge test shall be terminated if the SOC level is above 130% or cell temperature levels are above… Limits for SOC and DUT cell temperature levels for terminating the overcharge protection test may be agreed between the supplier and customer."*

J2929 Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-based Rechargeable Cells

Implementation of Thermal Control Fault – "*The battery system is to be operated under normal operating conditions with the cooling system disabled.*"

UNR100 E/ECE/324/Rev.2/Add.99/Rev.2-E/ECE/TRANS/505/Rev.2/Add.99/Rev.2 – Annex 8G-I

Capacity Based End-of-Test Condition for Overcharge Testing – *"Where an automatic interrupt function fails to operate, or if there is no such function the charging shall be continued until the tested-device is charged to twice of its rated charge capacity."*

Battery Heating for Thermal Protection Evaluation – *"During the test, the tested-device shall be continuously charged and discharged with a steady current that will increase the temperature of cells as rapidly as possible within the range of normal operation as defined by the manufacturer."*

End-of-Test for Thermal Protection Testing – *"The temperature of the tested-device is stabilized, which means that the temperature varies by a gradient of less than 4 °C through 2 hours."*

1.3 System-Level Testing Concepts and Strategies

Building upon the accepted foundation of failure modes, concepts, and procedural highlights compiled in the literature review portion of this work, a range of additional and expanded concepts required for robust vehicle-level procedure development and application are detailed in the following subsections.

1.3.1 Vehicle-Level Procedure Development and Response Verification

Testing vehicle-level BMS and RESS system's response to uncontrolled and/or unexpected conditions at full system level validates real world safety functionality. Vehicle-level testing evaluates full-system production controls and behaviors and incorporates non-pack Electronic Control Units (ECUs) that may impact the battery in a full vehicle as compared to a pack-only test that does not necessarily include the vehicle's response to battery provided limits and issues. Similarly, since the evaluation procedures seek to evaluate BMS responses and behaviors in relation to unexpected conditions, it is reasonable that the full vehicle is more desirable in terms of a larger subset of possible unexpected behaviors and interactions. Using data from validation of the developed evaluation procedures, Figure 1 provides a simple example of how these unexpected vehicle behaviors may appear in the field. Despite a fully de-rated pack (unable to allow any recharge power), as indicated by a 0 kW reported recharge power limit and 100-percent reported SOC, the vehicle continues to charge the traction battery due to the application of uncontrolled charge current into the battery from an external power supply. While a RESS should theoretically end charging once the available charge power reported by the BMS drops to 0kW or 100-percent SOC is reported, this behavior (stopping charge via a broadcast charge limit) does not constitute an overcharge protection system single point failure tolerant system. Whether the uncontrolled charging is due to a regenerative braking fault, charging issue, or externally supplied power is not important. The vehicle's BMS should detect and mitigate the overcharge situation before it escalates into a much higher degree of overcharge and a possible thermal incident.

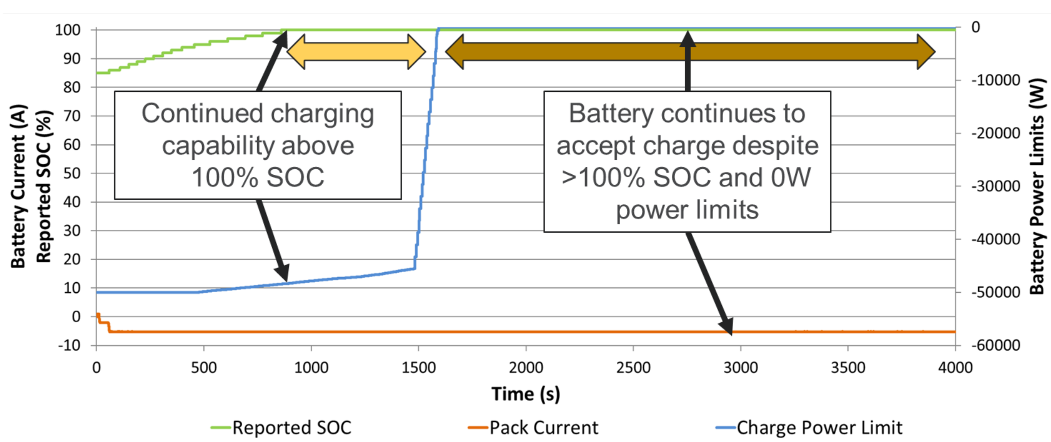

Figure 1: Unexpected charging due to uncontrolled operation

1.3.2 Safety via Actuation and Control Within the Overall RESS Safety Envelope

While the scope of this project is to develop, and validate test procedures to evaluate a vehicle's ability to robustly avoid escalating RESS safety issues due an initial hazard (single-point failure), a brief description of the various layers of RESS safety in a typical vehicle (HEV or PEV) battery application is necessary for continuity in rationale.

As illustrated in Figure 2, battery safety can be expressed in terms of optimization and integration of best-practices ranging from material selection to RESS/BMS system control, operation, and actuation. Highlighted in the figure, is a delineation of how the different layers described may approach safety. The material selection and pack design activities seek to reduce the severity or delay the onset of an incident should one occur, whereas the outer actuation and control layers seek to avoid and stop conditions that could escalate into a fault requiring the severity-reduction/onset delay based strategies implemented at the lower levels. Combining these strategies to avoid incidents while reducing the severity, or delaying the onset of an incident should one occur, have been very successful. While both approaches are important to overall battery safety, this project report focuses on the development and validation of a set of robust and repeatable procedures that can aid in determining the in-vehicle BMS/RESS system response to a suite of uncontrolled operating conditions that could lead to battery degradation or thermal runaway if not properly mitigated.

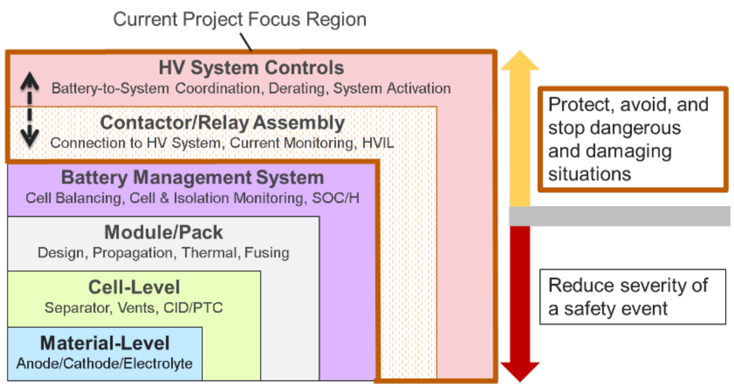

Figure 2: Highlighted layers of battery safety

This report will treat the concept of "functional" safety in the sense of active safety management via control and actuation (not to be confused with the more formal definition found in *ISO26262- Road vehicles – Functional Safety*. This concept definition will be strongly leveraged across this test development and validation work. Building off the discussion contained in [1], regarding the application of system safety engineering processes to battery safety, this detection and actuation based view seeks to identify hazards which are caused and mitigated by battery control systems. For example, battery pack overcharge due to uncontrolled charging operation would be considered a "functional" safety item. Hazards which are detected and mitigated by battery control systems are also considered functional safety conditions. An example of this type of condition is overheating due to usage. In both example cases, a BMS should detect the undesirable condition and seek to mitigate the condition(s) via an appropriate control response. Items that fall outside of "functional" safety include conditions which are detected and communicated by battery control systems, but not necessarily "actionable" via BMS controls. These are not "functional" safety conditions since the control system cannot take any mitigating actions. An example of a non-functional safety condition is excessive battery pack temperature caused by a source external to the battery.

1.3.3 Defined Mitigation Strategy

The preceding section introduces the concept of "mitigation.". Additional clarity in the context of RESS protection and battery safety use of mitigation is required for the report. Two primary mitigation strategies have been identified when seeking to protect its battery system:

1) **De-rating** – De-rating is the reduction of a battery's available power and is typically due to a state that indicates an undesirable condition such as rapidly increasing cell temperature, elevated temperatures, or very cold cell temperatures. By temporarily reducing a battery's ability to provide and/or absorb power, de-rating allows the battery to cool down (or at least stop increasing in temperature) in situations with elevated temperatures and reduces operation when the battery is so cold that certain usage levels could cause damage. While a battery can be de-rated to provide zero power capability, de-rating more frequently appears as a graduated enforcement that increases if the undesirable conditions persist. Figure 3 shows an example of de-rating for a vehicle operating at elevated battery temperatures. When considering de-rating in the context of battery safety evaluation procedures, some important considerations include: a) What conditions lead to de-rating, b) Does the vehicle respect the battery's de-rating conditions, and c) What is the de-rating ramp-out strategy.

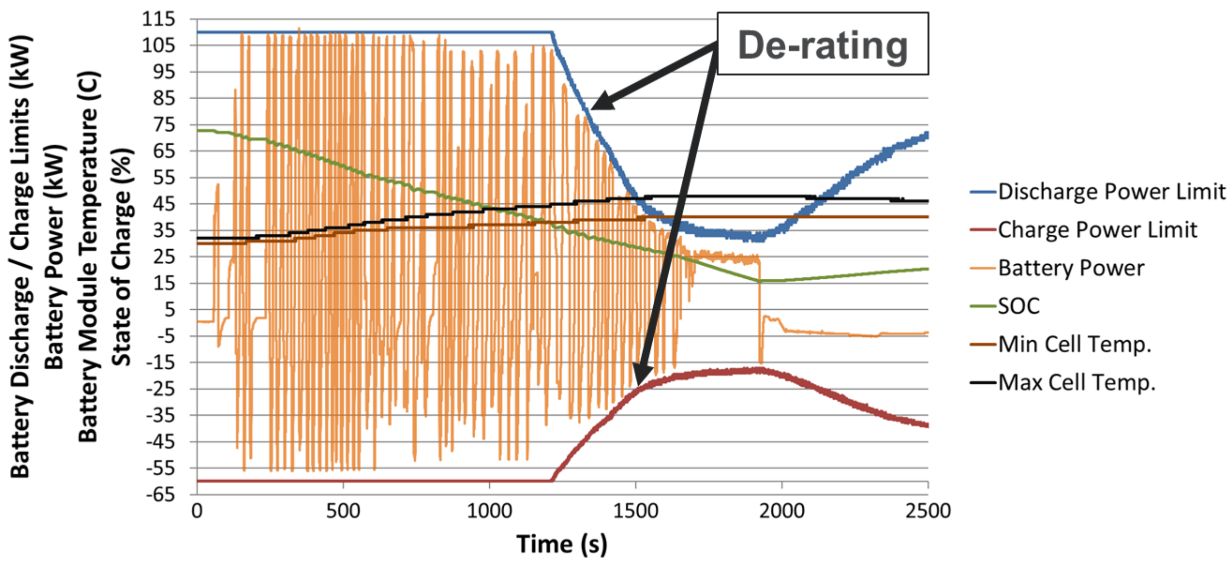

Figure 3: An example of battery de-rating at elevated cell temperatures

2) **System Disconnection** – Certain conditions and uncontrolled operational behaviors necessitate a more aggressive mitigation strategy from the battery control system. Namely, that the high-voltage (HV) RESS is physically isolated from the rest of the vehicle's HV system by opening the contactors between the battery and vehicle HV systems. In this situation, the battery will most likely be removed from the condition that is causing the undesirable state and thus escalation of a possible issue will be avoided. Figure 4 highlights a vehicle system disconnection in response to what the vehicle perceives as a possible overcharge situation. A vehicle's contactors may open for a wide variety of reasons, many of which are not directly RESS safety related, so when identifying test procedures to investigate system response it is important to consider: a) what conditions lead to contactor opening and b) Is a vehicle's protection strategy consistent.

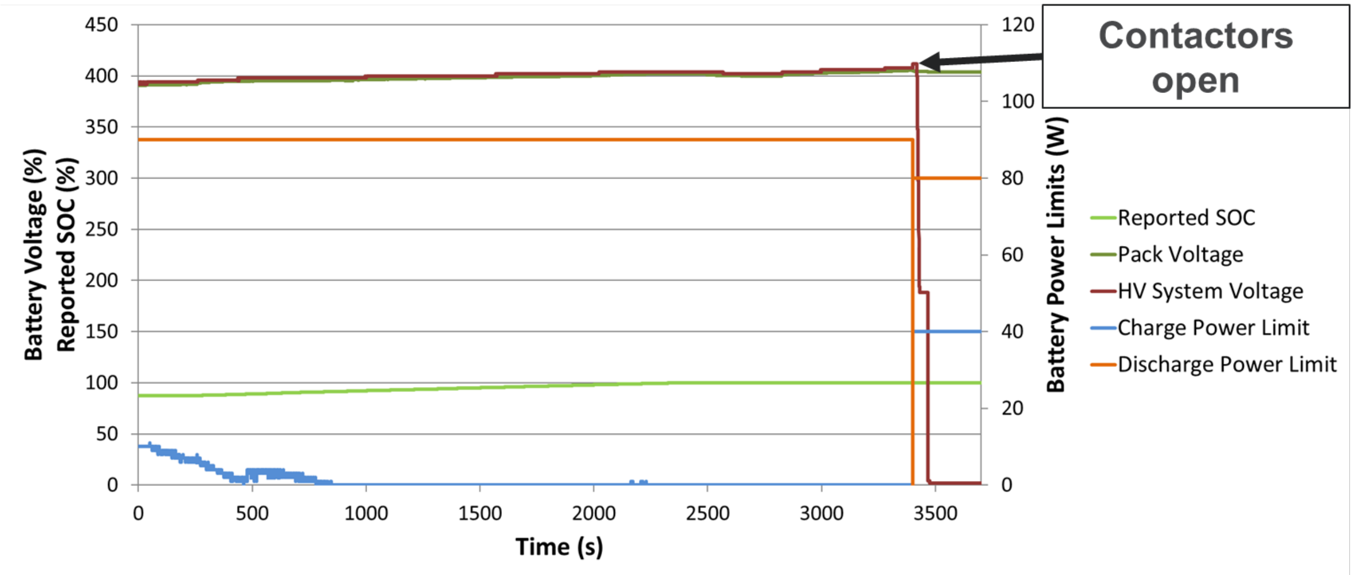

Figure 4: Example disconnection to avoid overcharge

1.3.4 Single-Fault Tolerance

Another important safety concept utilized frequently within this document is that of single-fault tolerance. The fundamental premise recognizes that faults of unknown and known origin will always happen, so a RESS should be robust and protected from escalating issues due to select single-point failures. For example, a failed cooling system should not lead to a thermal event due to continued battery usage and heating, rather the system should be able to detect the hazard and provide some form of mitigation such that more severe issues to not occur. This single-fault tolerance is relatively common-place when dealing with vehicle-level safety as well battery safety. For example, SAE J2929 (Electric and Hybrid Vehicle Propulsion Battery System Safety Standard-Lithium-based Rechargeable Cells) states: "[2929] is designed to assure that a single point fault will not result in fire, explosion, battery enclosure rupture or high voltage hazard" [2]. Figure 5 highlights a possible single-point failure evaluated during procedure validation: the vehicle communicates zero discharge capability to the overall control system, but the battery is still discharged due to uncontrolled operation. If a vehicle simply assumed that zero reported capability always leads to no discharging, this uncontrolled condition would likely lead to an over-depleted and damaged battery pack.

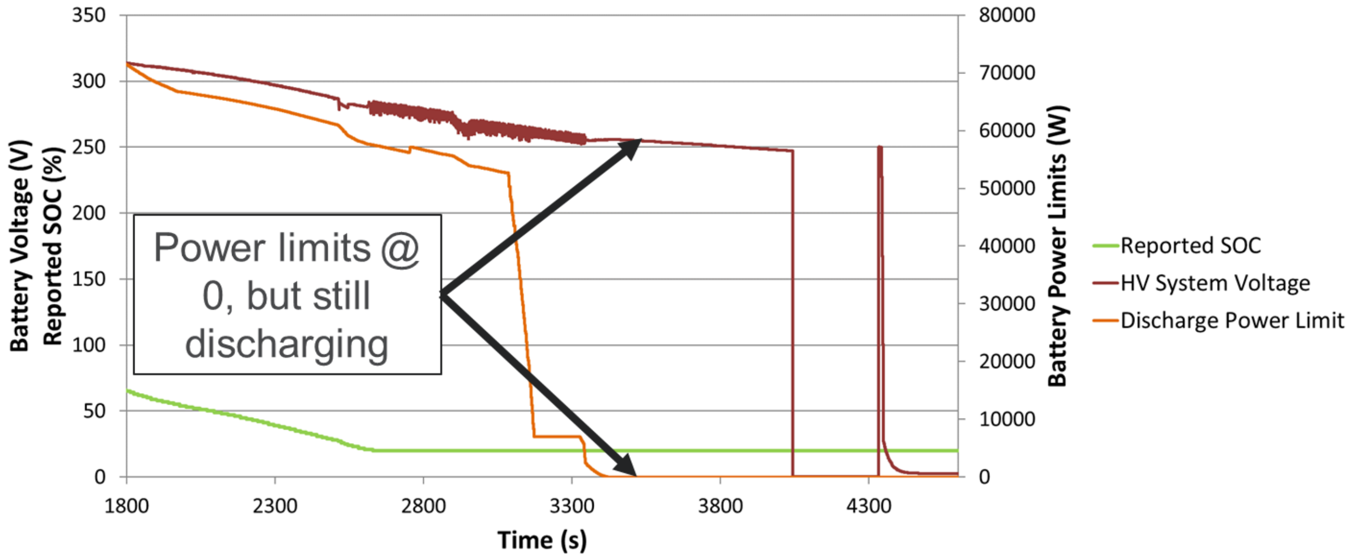

Figure 5: Uncontrolled discharging allows for discharge despite 0kW stated capability

2 Developed Test Procedures

2.1 Vehicle Preparation Procedure

Broadly speaking, preparation of the vehicle and RESS for BCU testing will include: documentation and characterization of the vehicle and its installed RESS, determining method of DC Link (2.4) connection to vehicle, and installation and documentation of monitoring sensors.

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

2.1.1.2 DC Link equipment shall be prepared per Section 2.4.

2.1.1.3 If the RESS must be opened to install any experimental equipment, it shall be photographed after opening and prior to the installation of any experimental equipment. An internal electrical isolation measurement should be performed prior to the installation of any experimental equipment. It is most convenient to obtain an isolation measurement while the RESS is installed in a vehicle. The RESS shall be closed in accordance to the manufacturer's specifications. Replacing a cover may require additional materials such as sealants or gaskets. The exterior of the RESS shall be photographed. If application of instrumentation has significantly diminished battery pack isolation, the instrumentation setup should be reviewed, and the cause of the loss of isolation should be found and if possible, eliminated.

2.1.1.4 Provisions shall be made to monitor and record at a minimum: 1) post-contactor (vehicle/charger side) HV system voltage (to detect contactor actuation), 2) battery terminal voltage, 3) RESS temperature (to identify thermal stability), and 4) SOC (to determine battery over/under/normal charge state). A data link with the vehicle CAN/diagnostic bus to allow logging of these and any additionally desired variables is the preferred implementation for logging. Depending upon RESS architecture, thermocouples may be placed on the RESS exterior to monitor RESS temperature and alternative sensor are allowable for voltage and other signals if a CAN data stream is unavailable. Post-contactor DC link voltage may also be provided by the DC load/power supply used during testing instead of a vehicle-based signal if this signal can be used to detect contactor actuation.

Recommended additional signals to be monitored and collected include: individual cell voltages, individual cell temperatures, contactor actuation states, battery current, and battery charge/discharge limits. These signals are also typically available from a vehicle's CAN/diagnostic bus and alternative sensors should not be used if they require significant additional internal instrumentation to the battery specifically for this testing.

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

2.1.1.6 The vehicle as prepared for testing shall be photographed.

2.2 Vehicle and Battery Preconditioning

While many testing standards related to cells and batteries require testing not only new un-cycled cells or battery packs, but also of cycled (aged) cells or battery packs, there is no-battery/vehicle preconditioning level required for this testing. Moreover, a vehicle's battery control system should be able to sufficiently detect and avoid any of the highlighted test scenarios at any point within its usable lifetime. If the fault detection threshold of a battery changes as it ages (i.e., voltage protection level for overcharge) the battery-condition appropriate information should be provided to the test operator.

2.3 Recommended Instrumentation and Instrumentation Used for Validation Testing

<u>Low Power Discharge</u>

HV Capable DC Programmable Load: *Equipment used – BK Precision 8522 - 500V, 2.4kW Capable*

Recommendations:

1) Must be HV capable to retain isolation.
2) Programmable load versus resistor bank is easier to use and more flexible (cycling load may be needed).
3) Voltage output needed/useful to verify contactor open externally.

Figure 6: HV capable programmable load

<u>High Power Charge (and discharge)</u>

HV Capable/High Power Bi-Directional Power Cycler: *Equipment used – AeroVironment ABC 170 - 445V, +125/-170kW Capable*

Recommendations:

1) Must be HV capable to retain isolation.
2) Programmable load versus resistor bank is easier to use and more flexible (cycling load may be needed in some cases).
3) Depending on assessment level (i.e., full regen) power levels may need to be fairly high (50kW and beyond).

Figure 7:HV Capable/High power bi-directional power cycler

<u>Climate Controlled Chassis Dynamometer</u>

Hot/Cold Ambient Capable Vehicle Dynamometer: *Equipment used – Argonne APRF Vehicle Dyno – (-17C) to (+35C) + & Solar Load*

Recommendations:

1) 4WD is helpful but not necessary (mfg. dyno mode or system bypass needed for 2WD).

Figure 8: Hot/Cold ambient capable vehicle dynamometer

<u>Supplemental Instrumentation</u>

Vehicle communications and diagnostic message logging: *Equipment used – Intrepid Control Systems neoVI Plasma + ANL decoded diagnostic messages (via OEM service tool), OEM Service tools for code resets and identification*

Recommendations:

1) Logging diagnostic messages provide the widest range of useful messages (individual Cell voltages, error states, etc.).
2) HS CAN also helpful, but not necessary if diagnostics available.
3) Some OEM service tools will log, but an additional tool is helpful when looking at multiple vehicles and manufacturers.
4) Vehicle service tool is very helpful for resetting codes and identifying fault causes (i.e., was it a battery directed fault?).

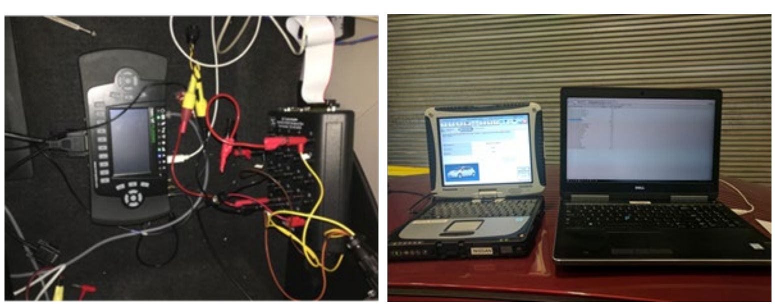

Figure 9: Vehicle communications and diagnostic message logging

2.4 DC Link Function and Installation

2.4.1 DC Link Rationale

To effectively perform the overcharge and overdischarge testing within the proposed suite of RESS safety evaluation tests, one must simulate an uncontrolled operational condition and thus there is a need to bypass the battery's controls relative to its charge and discharge limits. Two primary approaches can be used to simulate these uncontrolled conditions: 1) an OEM/manufacturer provided special override code or development ECU with the standard controls bypassed or 2) an external post-contactor DC link to the battery allowing for uncontrolled charge and discharge from the battery without requiring special software or alternative control versions. The external DC link is strongly preferred to the custom software case for several reasons. Given the desire for the most realistic set of vehicle responses possible, it is strongly preferred to utilize "stock" vehicle controls to evaluate a vehicle's mitigation response to overdischarge and over charge behaviors. Furthermore, external access allows for a wider range of researchers and engineers to perform the tests without the need to acquire special software or override codes from an OEM.

2.4.2 DC Link Installation Overview

A variety of devices can be connected to the DC Link to achieve the required electrical conditions for a test. A recommended configuration for the DC link interface with the vehicle is diagramed Figure 10. The figure shows the general connection location of the external DC Link at a post-contactor location between the vehicle RESS and the rest of the high-voltage components. Once installed, the DC link can be connected to either the discharge load or a bi-directional power supply depending on the required test conditions.

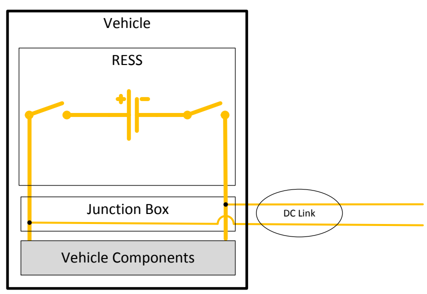

Figure 10: Basic Diagram of DC Link

Requirements for the DC Link include:

- The Vehicle OEM should provide the testing agency with documentation detailing how a DC Link can be installed with minimum disruption to the vehicle systems. Generally, vehicle high-voltage cables should be accessible adjacent to the RESS-to-vehicle high-voltage connection. For more discussion regarding the implementation methods used for the candidate vehicles, please refer to Section 3.2.1.

- It is recommended that appropriately sized fusing (capable of handling loads associated with testing without failing) be incorporated in the leads of the DC link to protect the connection cables from unexpectedly large current loads. Examples of DC Link installation points in a variety of vehicles are shown in Section 3.2.1.

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

- The DC Link shall be sufficiently isolated from all other parts of the vehicle. This isolation shall be capable of withstanding a voltage difference equal to U + 1695V.
- Joints or terminals shall be of a design capable of secure and low resistance connection such as a bolt secured lug.
- Cables used in the DC Link shall be rated to safely conduct the currents levels expected in all test procedures such that they do not become a failure point.
- Exposed high voltage should be minimized as part of the DC Link.
- Many functionally equivalent circuits are possible, but care should be taken to select components which are rated for the appropriate currents and voltages.
- Vehicle shall be able to charge and discharge normally with the DC Link connection installed.
- Once testing is complete, DC Link should be removed to avoid future issues related to the temporary installation of the DC Link for RESS protection purposes.

2.5 Vehicle RESS Over-Discharge

2.5.1 Test Procedure Rationale

Many battery chemistries can experience undesirable aging, electrolyte leakage, swelling, or even violent failure if overdischarged. As discussed in [3], deterioration ranging from SEI decomposition to severe internal shorting can be caused by overdischarge depending the depth of the overdischarge event (mild to severe overdischarge). Even though the initial over-discharge response of lithium-ion cells generally appears benign, it can cause damage to cell electrodes that can compromise cell stability and safety on subsequent recharge. A properly designed RESS will prevent cell over-discharge despite uncontrolled operation via opening the contactors once the overdischarge situation has been robustly detected.

During *typical* operation, a vehicle's control system will de-rate the available system power to avoid overdischarge while allowing for some driver response prior to zero available power. Once the system fully de-rates the available power to zero, the vehicle will not request or use power during typical controlled operation. For example, the DC-DC will not activate to power 12V accessories or recharge the 12V battery since the reported available power is zero. Recall, this work seeks to investigate an *uncontrolled* situation, during which the vehicle (or external load in this case) will still draw power despite the zero reported available power. This situation is the focus of the overdischarge test and is summarized below in Figure 11. Between roughly 2,225 and 2,250 seconds, the vehicle's reported discharge limit is 0 kW, yet discharging is still possible via the DC Link as evidenced by the continued drop in SOC. RESS discharge power de-rating can be seen between approximately 2,205 and 2,225 seconds. The intent of this test is to see if the vehicle opens its contactors once an overdischarge condition beyond a certain level is observed, thus avoiding further discharge, battery degradation, and failures associated with overdischarge.

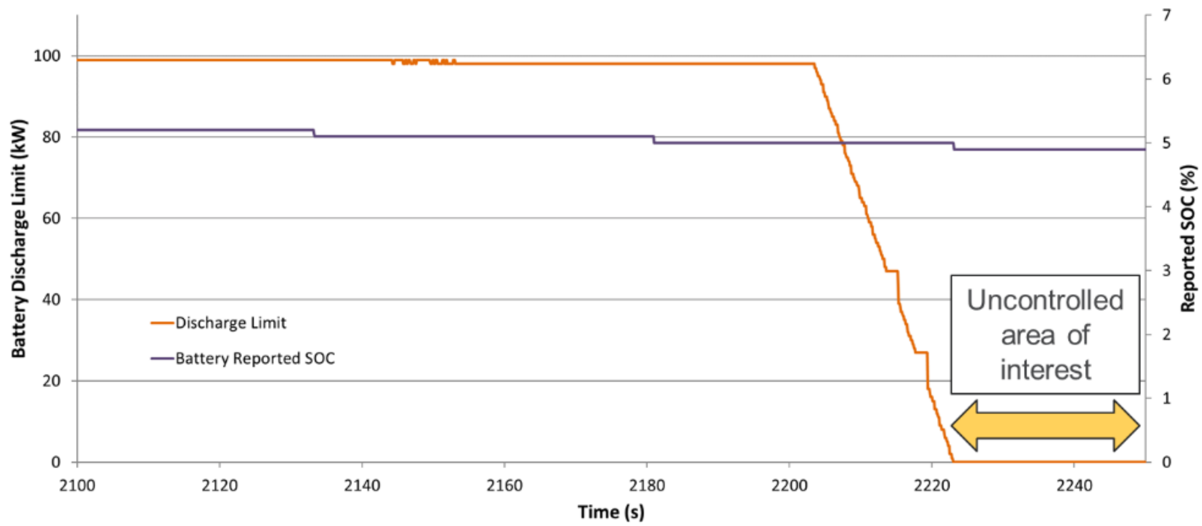

Figure 11: Typical battery de-rating and uncontrolled operating regime

Figure 12 provides an example validation test for one of the vehicles. Although the voltage and battery parameters may change from vehicle to vehicle, the general results is the same. At a particular voltage, the vehicle opens contactors, as indicated by an actuation command via CAN or a drop in reported vehicle-side voltage.

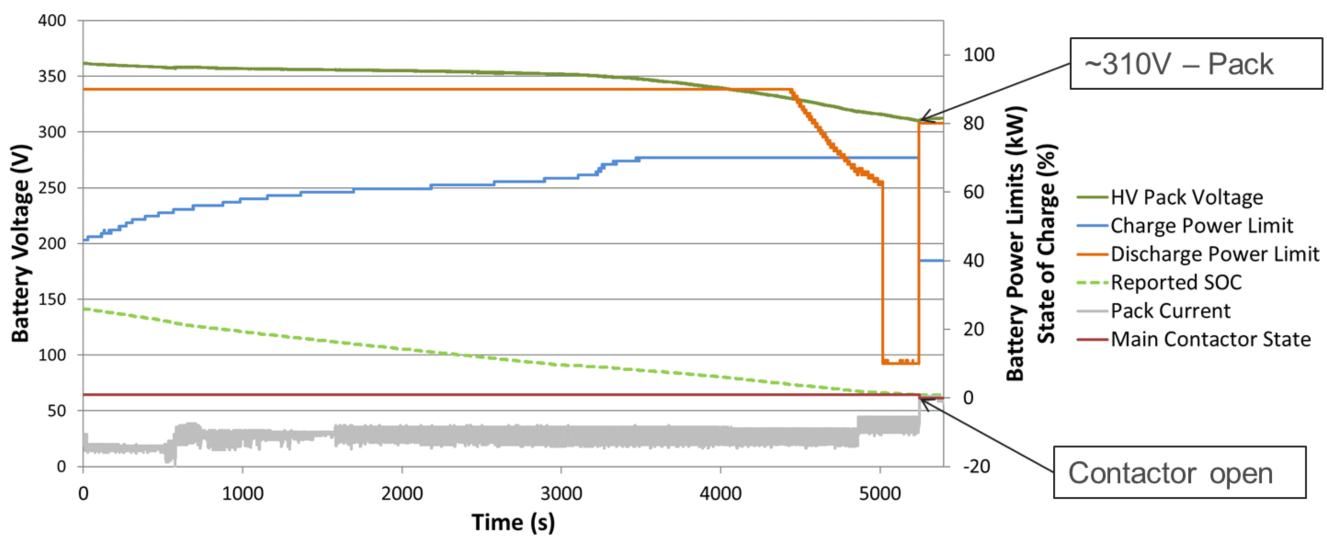

Figure 12: Example successful overdischarge test with contactors opening at ~5000s

2.5.2 RESS Overdischarge Test Procedure

2.5.2.1 Make the connection to the DC Link. See Section 2.4 for further discussion of DC Link installation. Installation may require that the RESS be removed from the vehicle, and subsequently re-installed.

2.5.2.2 Connect vehicle 12V battery to a vehicle charger to retain 12V power during testing (since vehicle DC-DC converter will be inactive during testing).

2.5.2.3 Discharge the vehicle RESS to approximately 10-percent SOC. For an HEV or PHEV, engine fueling shall be disabled to avoid engine restart. Methods by which to disable engine start include: 1) Remove fuel pump fuse or relay, 2) direct fuel-line cutoff via quick connect or similar, 3) remove all fuel from tank, 4) additional (non-software) method with input from DUT manufacturer. More discussion regarding disabling of the engine fueling system can be found in Section 3.3.1.

2.5.2.4 Chock the vehicle to prevent rolling or creep.

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

2.5.2.6 Initiate data recording: begin the test timer, start the video recording, and begin logging.

2.5.2.7 Connect the HV Capable Programmable Load or equivalent onto the terminals of the DC Link connection box, and power the load. Allow the RESS to discharge at the desired power load. While less than 1kW is typically suggested, for flexibility, the power value used for testing is ultimately at the discretion of the test operators or OEM as long as it is not so high as to induce a separate, unrelated fault condition.

2.5.2.8 Continue to discharge the RESS via this method until one of the following happens: 1) the vehicles opens its contactors due to the overdischarge condition as indicated by a large difference in DC Link Voltage and terminal voltage or a change in contactor actuation state or 2) 8 hours elapse.

Note: Care must be taken to ensure that the fault observed during testing is due to an overdischarge fault condition as opposed to a different condition related to the disabled engine fueling system. A repeatable fault level (typically voltage) during repeated discharge actuation events or a specific vehicle fault code should be used to confirm the nature of the vehicle fault. Refer to Section 3.3.1 for more detailed discussion regarding this issue.

2.5.2.9 Upon completion of testing, remove HV programmable DC load and return vehicle to normal operating condition, retaining DC link connections if required for subsequent overcharge testing.

2.6 Vehicle RESS Over-Charge

2.6.1 Test Procedure Rationale

Overcharge is generally considered the most dangerous uncontrolled condition for a li-ion battery and can lead to swelling, lithium plating, stability degradation, overheating, and ultimately thermal runaway. Moreover, most Li-Ion batteries are more reactive as SOC increases further exacerbating issues related to overcharge-induced events.

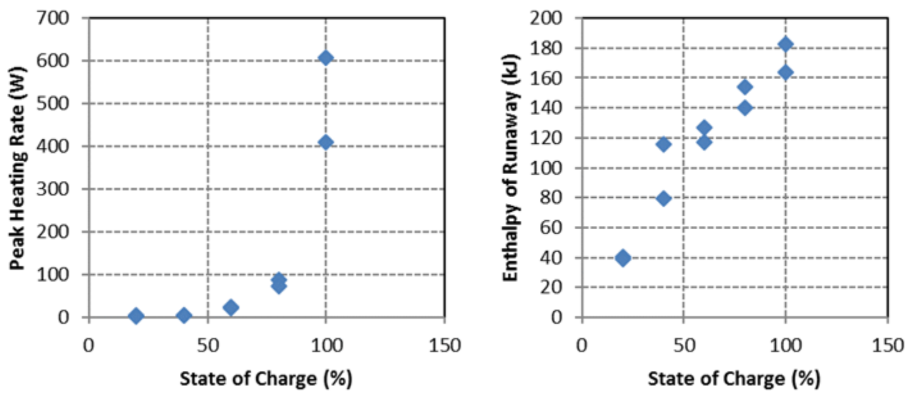

Figure 13: Increasing peak heating rate and enthalpy of runaway with increasing SOC

Figure 14 below shows a typical overcharge test, where the vehicle responds to the overcharge condition by opening contactors at roughly 4,000s. In support of the earlier discussion regarding single-fault tolerant systems, it can also be observed in the figure below that the charge limit for the entire duration of testing prior to contactors opening is 0kW despite the vehicle accepting offline power via the external overcharge setup.

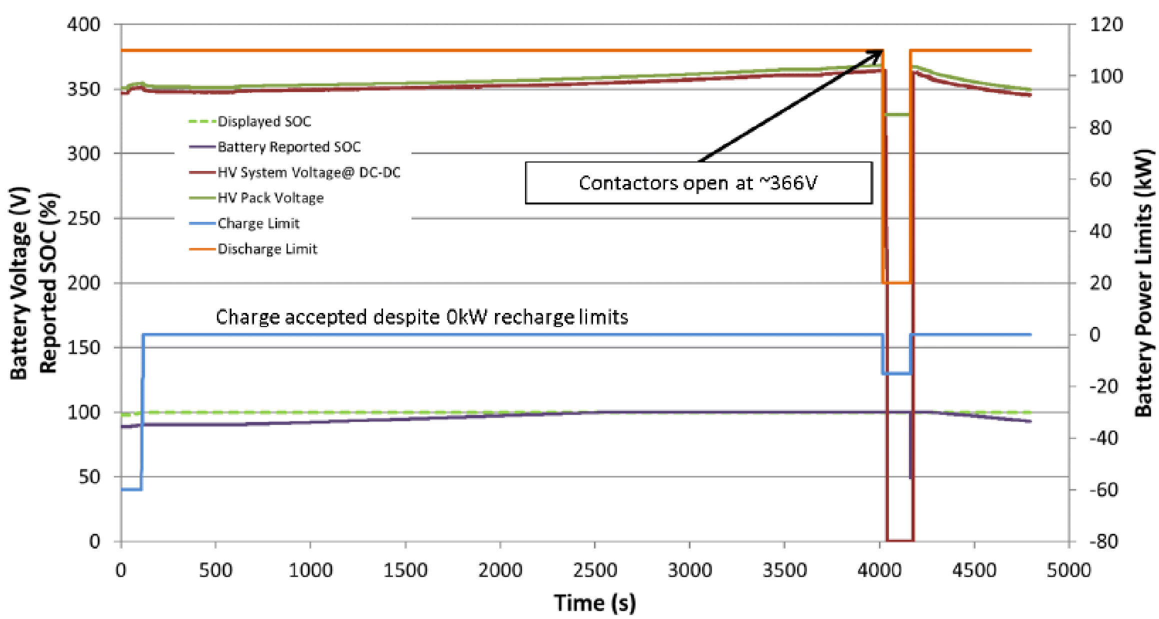

Figure 14: Example successful overcharge test with contactors opening at ~ 4,000s

2.6.2 RESS Overcharge Test Procedure

2.6.2.1 Discharge the RESS, until it is at approximately 95 percent. This may be accomplished by using the vehicle cabin heater, AC system, through driving, or an offline DC load.

2.6.2.2 Chock the vehicle to prevent rolling or creep.

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

2.6.2.4 Initiate data recording: begin the test timer, start the video recording, and begin logging.

2.6.2.5 Connect the HV capable power supply or equivalent onto the terminals of the DC Link connection box, and begin providing power to charge the battery at the desired power load. For flexibility, the power value used for testing is ultimately at the discretion of the test operators or OEM as long as it is not so high as to induce a separate, unrelated fault condition. Generally speaking, higher charge levels will lead to a faster test conclusion, but are more risky if a battery's fault mitigation strategy is unknown. In the absence of an OEM recommended charge power level, a recharge power of 3 kW is suggested as a value comparable to expected charging loads, yet not as large as possible charging loads the vehicle may see during regenerative braking events.

2.6.2.6 Continue to attempt to charge until one of the following occurs: 1) an automatic disconnect in the RESS opens, 2) the battery achieves an estimated pack SOC of 130 percent (refer to Section 3.3.1 for details on estimating SOC above 100%, or 3) 24 hours elapse from the beginning of testing.

2.6.2.7 Once the test has concluded, disconnect the overvoltage supply and return vehicle to normal operating condition or prepare for the next evaluation test.

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

2.7.1 Test Procedure Rationale

To avoid operation at elevated temperatures, many vehicle RESS employ a cooling system to ensure that the cells of the RESS are maintained within a desired temperature range during hot weather or under extended and/or aggressive operation. While the impacts of over-temperature operation vary by chemistry, most battery chemistries can be negatively affected if operation is attempted at high temperatures (per the limits of a specific chemistry) or if aggressive operation is attempted at high temperatures (high rate charging or discharging). For example, a vehicle with a failed cooling system without sufficient additional mitigation strategies can encounter elevated RESS temperatures during operation and allow 'hot spots' to develop within the RESS. A temperature imbalance or continued operation at elevated temperatures may even lead to thermal runaway of cells if appropriate counter measures, such as de-rating, are not taken. Taking these issues into account, a properly designed BMS and RESS will limit or prevent operation at temperatures above cell operating limitations despite a battery cooling system fault (failed cooling system). While either a non-operational vehicle or battery de-rating would be acceptable from a safety standpoint for this testing, it is expected that battery de-rating will be the vastly preferred response to a failed cooling system and is thus the primary confirmation focus of this testing. If a cooling system failed during normal driving, the immediate opening of contactors and resulting inoperability of the vehicle may itself create a larger safety issue than the lack of battery cooling. During procedure validation and despite their disabled cooling system, all of the candidate vehicles allowed for normal operation until the batteries reached a sufficiently elevated temperature and thus the primary intent should be to confirm thermal stability (or lack of continued, uncontrolled temperature increase) during aggressive operation despite a failed cooling system.

As discussed above and outlined in the procedure documentation, a successful test should show a vehicle's RESS temperature stabilizing despite continued operation. As with the other test, this behavior was successfully evaluated for all candidate vehicles, again validating the developed procedures. Figure 15 highlights a successful test (with procedure modifications to be discussed later in this section) with significant battery de-rating and stabilized cell temperatures observed at approximately 1,500s.

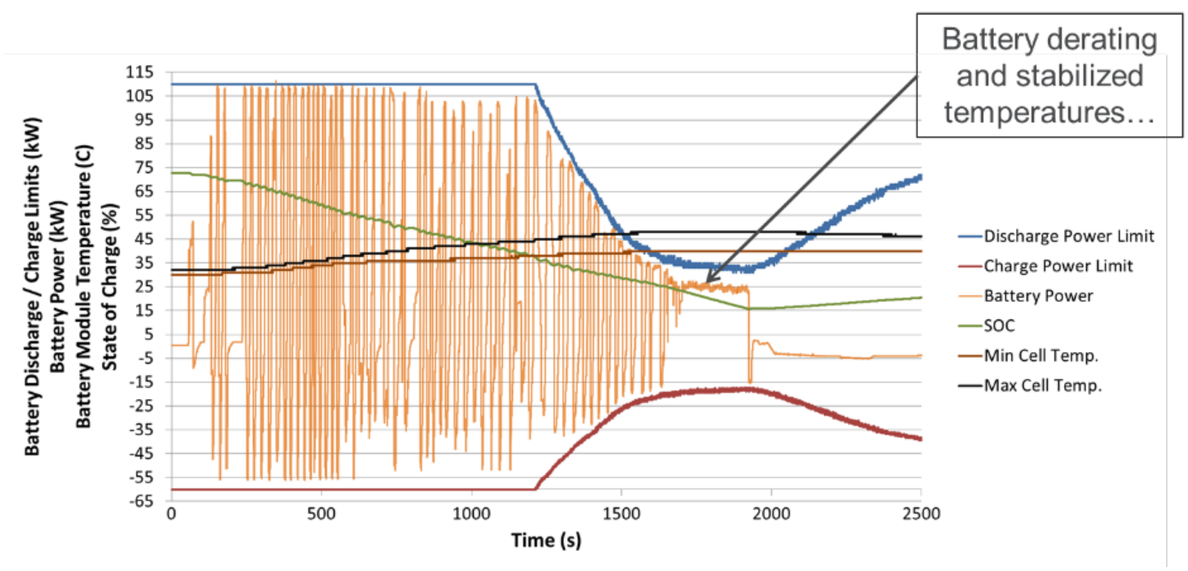

Figure 15: Successful failed RESS cooling test with de-rating and temperature stabilization at roughly 1,500s

2.7.2 Failed Cooling System Procedure

2.7.2.1 If a RESS is thermally coupled to an active cooling system, define a method to induce or simulate a failure which would cause that cooling system to become inoperable or significantly less effective at cooling the RESS. See Section 3.5.1 for further discussion. If the pack does not rely on an active cooling system, no cooling system disabling methodology development is required.

2.7.2.2 For an EV or PHEV, fully charge the RESS at 25 °C, until normal charge termination occurs and the vehicle RESS is at 100 percent ± 5% SOC. For an HEV, complete a conditioning cycle (i.e., single UDDS cycle or similar) at an ambient temperature of 25 °C to ensure SOC is near normal operating limits.

2.7.2.3 Place the vehicle with installed RESS on a dynamometer in a temperature-controlled chamber at the desired ambient air temperature such that thermal de-rating can be observed during over the course of the prescribed charge/discharge cycle. While no specific temperature or soak time is specified, it is expected that the vehicle shall be placed in the chamber for a sufficient time to equalize to ambient temperature: at least 6 hours. Moreover, this combination of preconditioning and ambient operating temperature should be sufficient such that the DUT enables some form of thermal protection or mitigation against continually increasing battery temperatures under load. Chamber temperature shall be logged during testing.

2.7.2.4 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.

2.7.2.5 Place the vehicle into drive and begin a charge/discharge cycle.

To quickly elevate battery temperature and identify battery limits related to temperature, the vehicle shall be driven over back-to-back aggressive acceleration (near 100% pedal apply) and decelerations (near or above regenerative braking limits) until one of the End-of-Test (EOT) criterion is met. For more discussion regarding the justification of charge/discharge cycles for evaluation, refer to Section 3.5.1. For HEVs that will only include a charge-sustaining operation, guidance may need to be provided regarding the acceleration/deceleration usage that leads to maximum or near maximum battery throughput, since most HEVs use the engine as the primary motive force during aggressive accelerations and may scale back on battery throughput. Continue operation until either 1) the vehicle has reached a steady state (the preferred, thermal system fault tolerant case), or 2) battery temperature has risen above a specified threshold, above which it is unsafe to operate the RESS due to risk of thermal incident. For this testing, steady-state can be considered as a case where either the RESS temperature (average pack temperature or maximum individual cell temperature) remains within ±2 °C for 30 minutes and the RESS SOC remains within ±1 percent for 60 minutes, or a rate of discharge of SOC over the previous hour indicates that discharge will require more than 10 hours to complete. Recall that flexibility has been provided in the preconditioning stage such that steady-state operation can be reached prior to the vehicle stopping motion due to a low-SOC condition.

2.7.2.6 Regardless of the point in testing which has been reached terminate the test after 24 hours have elapsed since the start of step 2.7.2.5.

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

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

2.8.1 Procedure Rationale

Uncontrolled operation (especially charging for li-ion chemistries) at low battery temperatures may result in lithium plating or cell damage that could eventually lead to reduced performance or degraded life during subsequent operation. This testing seeks to understand battery protections related to cold operation with a disabled battery heating system. The HEVs used in this testing do not incorporate a battery heating system and only some of the PHEVs used for testing have the capability to heat the battery. Nonetheless, their repose to cold operation can still be assessed with the revised procedure.

Figure 16 below shows the observed de-rating for one of the candidate test vehicles (in this case a BEV). Following an overnight soak at -17 °C (0 °F), significant de-rating is reported by the vehicle's battery management system for both charge and discharge power levels.

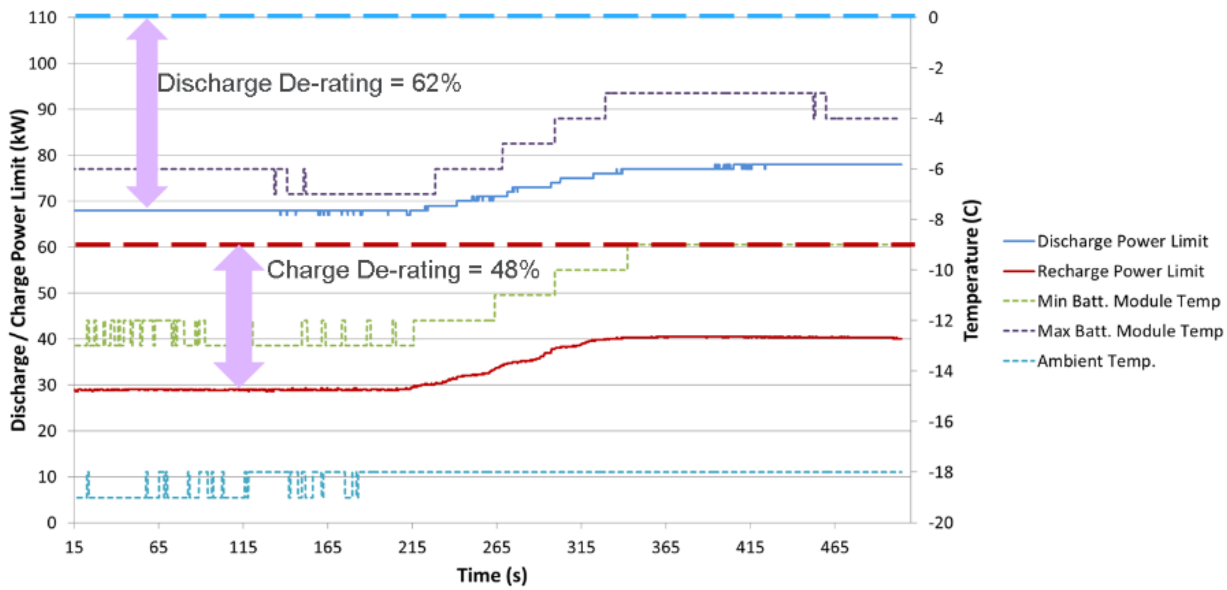

Figure 16: Reported battery de-rating due to cold ambient conditions (-17 °C)

The refined testing also seeks to ensure that the prescribed limits from the BMS are actually adhered to when the vehicle is operating. To these ends, the same back-to-back acceleration and decelerations used in the failed cooling system testing were applied to the vehicle following the extended soak period at cold ambient conditions. The back-to-back testing is helpful since it can better detect both positive and negative battery de-rating, which may differ across a range of temperatures. It is also helpful to overlay the power/behavior from a "normal" ambient condition test versus the cold operating case. An overlay of the power used during testing can quickly indicate both the effective limits as well as the vehicle's ability to adhere to the proposed BMS limits. This behavior is highlighted below in Figure 17.

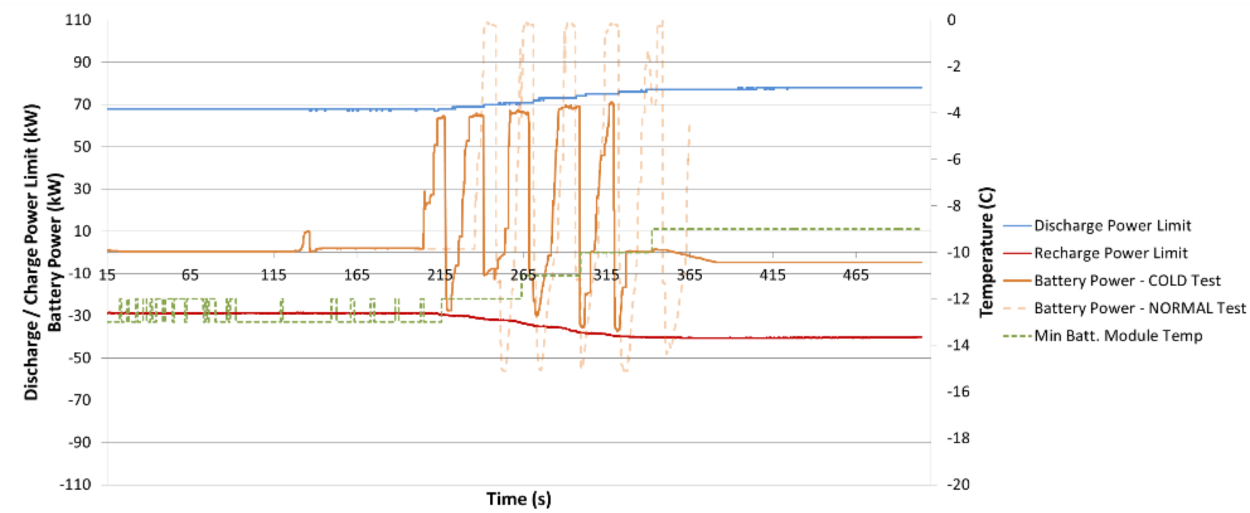

Figure 17: Back-to-back acceleration and deceleration with cold and "normal" battery temperatures to observed de-rating

2.8.2 Failed Heating System Procedure

2.8.2.1 If a RESS is thermally coupled to an active heater, define a method to induce or simulate a failure which would cause that heater to become inoperable. See Section 3.5.1 (same methods for disabling the cooling system in most cases) for further discussion. If the pack does not rely on heaters, or uses only passive heating, no method development is required.

2.8.2.2 For an EV or PHEV, fully charge the RESS at 25 °C, until normal charge termination occurs and the vehicle RESS is at 90-100 percent. For an HEV, complete a conditioning cycle (i.e., single UDDS cycle or similar) at an ambient temperature of 25 °C to ensure SOC is near normal operating limits.

2.8.2.3 Place the vehicle with installed RESS on a dynamometer in a temperature-controlled chamber at −20±2 °C. The vehicle shall be placed in the chamber for a sufficient time to ensure that some form of battery de-rating can be observed (if applicable). A minimum of 6 hours is expected, but many vehicles may require an overnight soak. As with the failed cooling system testing, the soak time is left to the discretion of the OEM or test operator relative to what will lead to an observable de-rating due to the cold operating conditions. Chamber temperature shall be logged during testing. A BEV or PHEV shall remain unplugged during the duration of the cold ambient soak period.

2.8.2.4 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.

2.8.2.5 Place the vehicle into drive and begin an aggressive charge/discharge cycle similar to that in the failed heating test (2.7.2).

2.8.2.6 Operate vehicle for at-least 5 acceleration/deceleration cycles and note any observed de-rating or reduction in discharge or charge performance accordingly. In most cases, de-rating (if applicable) can be observed by comparing charge/discharge power observed to testing under normal operating conditions.

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

2.9 RESS External Short Circuit

2.9.1 Procedure Rationale

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

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

- IEEE 1725 specifies a short-circuit test through a maximum resistance load of 50 mΩ.
- IEC 61233 specifies a short-circuit test through a maximum resistance load of 100 mΩ.
- SAE J2464 and J2929 specify hard short-circuit tests (less than 5 mΩ) of RESS modules and packs. SAE J2464 also specifies a soft short-circuit test (short impedance matched to DC impedance of device under test) of cells connected in parallel.
- UL 1642 and UL 2054 specify short circuit tests through a maximum resistance load of 100 mΩ.
- UL 1973 and UL 2580 specify short circuit tests through a maximum resistance load of 20 mΩ, as well as at a load that draws a maximum current no less than 15 percent below the operation of the short-circuit protection.
- UL 2271 specifies a short circuit test through a maximum resistance load of 20 mΩ, as well as at a load that draws 90 percent 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.

Two short values have been selected for this testing: 1) A shorting resistance of 3-5 mΩ, consistent with SAE J2464 and J2929 test methods (is relatively straightforward to achieve with fuses, high-voltage rated switches, heavy gauge cable, and firmly bolted connections); and 2) A shorting resistance similar to the RESS impedance using the methods discussed in Section 4.

2.9.2 RESS External Short Circuit Procedure

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

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

2.9.2.3 Chock the vehicle to prevent rolling or creep.

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

2.9.2.5 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.

2.9.2.6 Place the vehicle into Drive Mode.

2.9.2.7 Connect the short circuit device to the DC Link (Section 2.4).

2.9.2.8 Create the short circuit across the DC Link, causing a short circuit of the RESS and vehicle high voltage system. See Section 4 for a discussion of the selection of short circuit impedance and methods to verify a value similar to overall pack impedance if so desired.

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

2.9.2.10 Photograph the vehicle with installed RESS.

2.9.2.11 Remove the RESS from the vehicle and photograph the RESS.

3 Test Procedure Validation Testing and Discussion

3.1 Validation Testing Candidate Vehicles

In order to validate and refine the draft procedures for the largest possible range of applicable powertrain technologies, the testing and validation efforts of this work relied on a select set of candidate vehicles taken from Argonne National Laboratory's fleet of test vehicles. The fleet is comprised of a mix of HEVs, PHEVs, and BEVs most of which are heavily instrumented, including extensive CAN and diagnostic message decoding. As mentioned in the introduction, the intent of this project is to validate and refine the procedures, not identify vehicles that pass or fail the draft procedures.

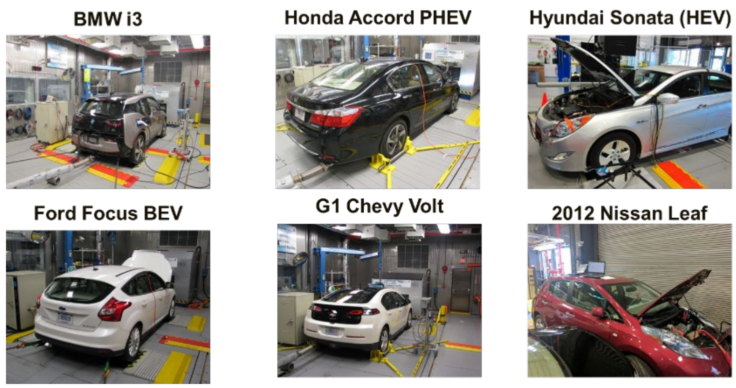

Figure 18: Argonne research vehicles used in RESS procedure validation

Aside from the tests requiring a vehicle dynamometer, the basic evaluation setup is shown below in Figure 19. The vehicle is connected via a DC jumper connection to either a source or sink depending on whether the test is evaluating overcharging or overdischarging. During testing, directly instrumented signals, vehicle CAN, and vehicle diagnostic messages are read and synchronized via the data acquisition system.

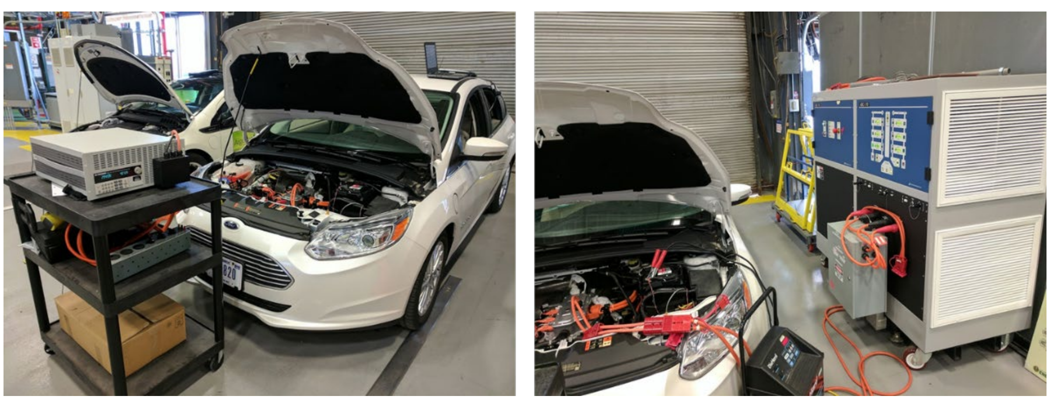

Figure 19: Basic testing setup (low power discharge-left, high-power charge-right)

3.2 Vehicle External DC Link

Validating the external DC Link proposed in the original draft material across a wider range of vehicles is one of the key tasks within this project. While the external DC Link approach was applied successfully to a single BEV vehicle in earlier proof-of-concept materials, this work seeks to validate and update the post-contactor external DC Link procedures for a range of vehicles.

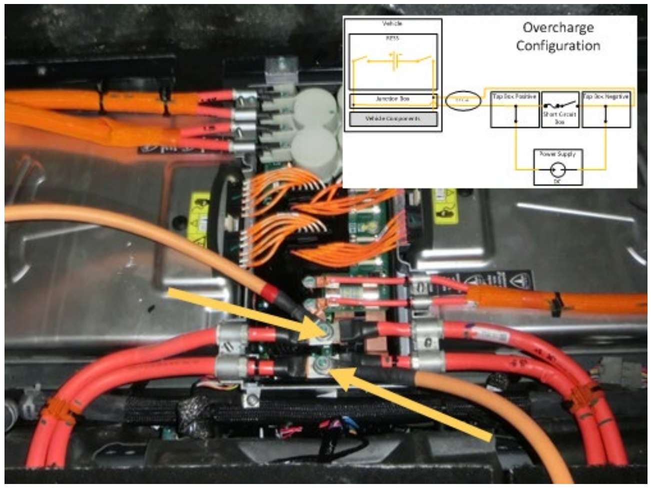

Figure 20: DC Link implementation example

3.2.1 DC Link Validation Results and Discussion

One of the most important conclusions from this validation work is that the external DC Link was implemented and successfully used for charge/discharge testing for all of the candidate vehicles. Prior to testing there were some concerns that the DC Link would create a fault in certain vehicles and this was not the case for any of the vehicles tested. The following subsections seek to provide some additional refinements to the DC Link as well as provide a more detailed discussion regarding why the DC Link can be successfully executed across a wide range of vehicles.

Figure 21 provides an overview of the main components of the DC Link as well as an example implementation. The three main pieces of the link are: 1) a post-contactor connection to the vehicle traction battery, 2) HV fuses to protect the link in the case of unexpectedly large current draws, and 3) a connection to the load bank required for the specific test (i.e., low power discharge or high-power bidirectional capability). When connecting to the battery, ring terminals installed directly onto a traction battery's lugs (if available) is the preferred approach to provide the external link to the battery. The ring terminal and lug approach provides a robust connection that will not shake loose, but care must be taken to ensure that the power used for the tests is within the normal operating region that the selected connection will see in use (i.e., traction side connection versus DC-DC connection max capability). Appropriate fusing should be placed between the vehicle external link and the external load/power-supply. Fusing should be selected so that it does not interfere with the testing, yet can offer protection to the test operators in the case of an unexpected event. The connection to the load bank/power supply for testing is somewhat dependent on the equipment used, but general recommendations include ensuring the connector itself is rated for the expected test loads and that it is sufficiently drop-proof and sufficiently protects the operator from accidental HV exposure.

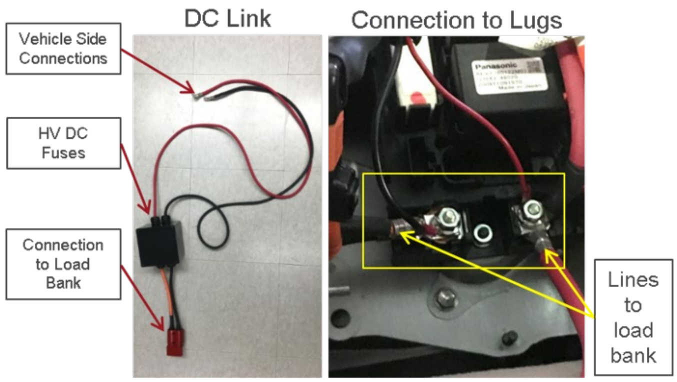

Figure 21: External DC Link overview

For the overdischarge testing, the proof-of-concept testing utilized a resistor bank to perform the necessary external load application. The resistor bank must be sized for the expected pack voltage of a specific vehicle application and may vary significant depending on the DUT. With an eye toward robustness and ease of test application, it is recommended that a programmable HV DC load bank be used in lieu of the resistor bank. This will allow a wider range of vehicles to be discharged at a similar power level without needing to identify the corresponding resistor value.

In addition to the flexibility a variable load bank offers, the display of HV system voltage and current is a useful supplement to any vehicle information being collected. In fact, although not recommended, just the load bank's voltage reading alone could be used to identify that a vehicle has opened its contactors in response to an uncontrolled situation. Battery diagnostic information is strongly preferred as a supplement to this basic information in order to sufficiently identify any safety critical issues prior to them becoming more severe in the case of an insufficiently protected RESS. Further strengthening the case for a programmable load bank is the observation during testing that some of the vehicles required the discharge load to be cycled on and off to robustly identify vehicle mitigation responses associated with overdischarge protection as opposed to other fault conditions. The flexibility of the load bank again proved helpful in that it could be easily activated and adjusted as needed during testing.

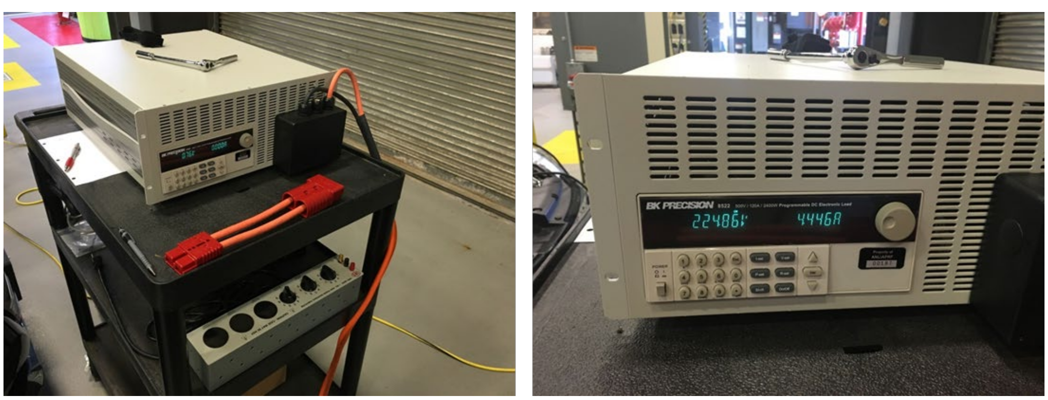

Figure 22: External HV DC load bank

While the DC Link was successfully applied to all of the test vehicles used for this project, the broad range of vehicle applications used to support this work provide some insights into the challenges related to installing the DC Link connection across a wide range of vehicles. More specifically, access to a battery's lugs is still frequently possible, but access appears to be getting a more difficult. Issues related to fewer directly accessible lugs terminals, more tamper-proofing, and ultimately the removal of lug-style connections were identified as challenges to the ease of implementation of the preferred lug/ring-terminal connections. Figure 23 illustrates a technique that needed to be used on several of the candidate vehicles. Lug terminals were still use, but the external wires going to the load bank required access holes drilled in the power-electronics cover to close off the system during testing. While this is very easy to accomplish, care must be exercised to ensure the access port itself does not become a safety issue. Additionally, a new cover would be required if this vehicle were to return to normal service.

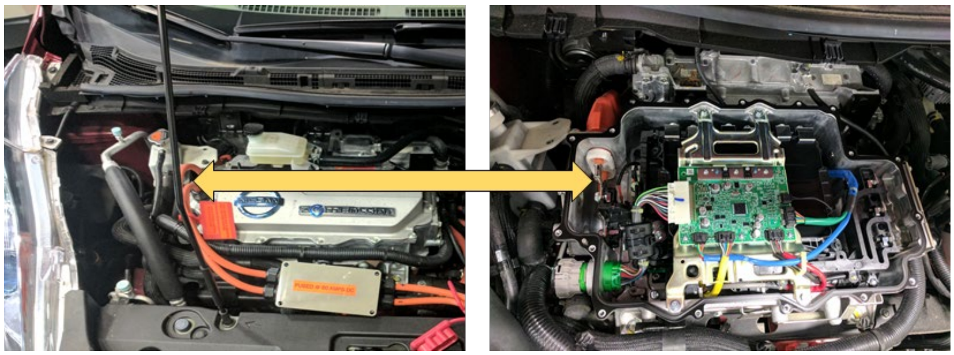

Figure 23: Lug terminal access requiring cover access ports (Nissan Leaf)

Figure 24 illustrates an even more challenging situation relative to connecting the vehicle HV system to the external DC Link. The Chevrolet Volt used in this testing does not have lug terminals and thus the DC link cannot be installed using the ring terminal/lug approach. Rather than a lug terminal, the Volt has a custom spade connection with a relatively tamper-proof assembly. With this issue in mind, it was determined that a spliced cable with a separate connection would be the most robust approach for this situation.

Figure 24: Chevrolet Volt non-lug connections

Shown below in Figure 25, the spliced cable approach allows for a robust and isolated connection to the external DC link/load-bank while retaining vehicle-level isolation protections and integrity. The main issues related to successful implementation of a splice cable are to 1) ensure proper isolation once the splice has been made (in this case via filling the splice box with potting fluid) and 2) reconnecting the shielding around the HV system cables such that the entire shielding system remained isolated and grounded. The spliced cable was created using an additional set of OEM traction battery-to-power electronics cables (both positive and negative sides). Once the spliced cable was completed, the existing cable was removed and the spliced cable was installed on the vehicle. Once in place, the vehicle operated normally without any diagnostic codes or faults in response to the newly spliced cable.

Figure 25: DC-link compatible spliced cable steps [L to R: 1-remove cable insulation and shielding to expose raw cables, 2) splice DC Link connections and +/- vehicle mains and reconnect shielding that was removed for raw cable access, 3) fill box with potting fluid to electrical isolation

When initially implementing the DC Link setup for the test vehicles, there was some concern if a vehicle would detect the DC Link and subsequent connection to the load/source used for the over- and underdischarge testing. Fortunately, none of the vehicles detected the DC-link or its external, uncontrolled usage. One of the key principles in the safe and undetected (no vehicle faults) operation of the DC-link/load bank is properly isolating the offline discharge connection and load bank so that it is not detected by the vehicle's isolation detection system and does not provide a fault path to ground. As can be seen below in Figure 26, the BMS measured/reported isolation values during off-line discharging and standard vehicle charging (DC link not active) fall well above malfunction detection levels and thus the system does not have an issue from an isolation perspective. Moreover, once connected, any isolation issues related to the DC link would similarly be detected by the vehicle's isolation detection system, thus opening contactors in the case of a loss of isolation on either the vehicle or DC-link connections.

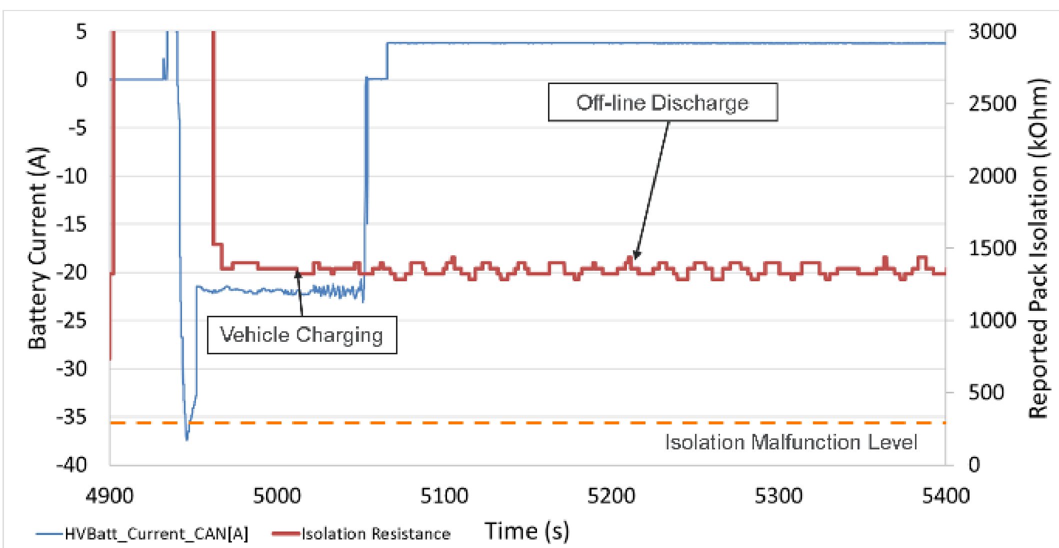

Figure 26: Example reported RESS isolation values with/without offline discharge active

An additional validation experiment was to check if the DC Link usage was only limited to low power usage that could perhaps be considered "noise" in the context of a larger power draw/sink. This capability is useful since the over-charge test is suggested to be at levels higher than the approximately 1kW used for the overdischarge testing. Moreover, a larger power capability allows for more flexible testing for both discharge and charge testing since it allows for flexibility in terms of pushing the battery into the desired state. As can be seen in Figure 27 below, higher power levels can be successfully utilized with the DC Link, again proving a validation case for the successful application of the DC Link to emulate an uncontrolled charge or discharge event. In the example below, power was limited to roughly 15kW due to the fuse selected for the related vehicle testing, but some vehicles were run up to full battery power (~100kW) without any indication of a fault or shutdown of the high-voltage system. Ultimately, the successful application of the DC Link across all the vehicles utilized for this validation testing strengthens the validity of this method as a general way to operate a vehicle battery in an uncontrolled state. One limitation of this method would be if a vehicle checked to see if demanded battery current matched the current flowing from the pack, but as of yet, no vehicle checks of this nature have been observed.

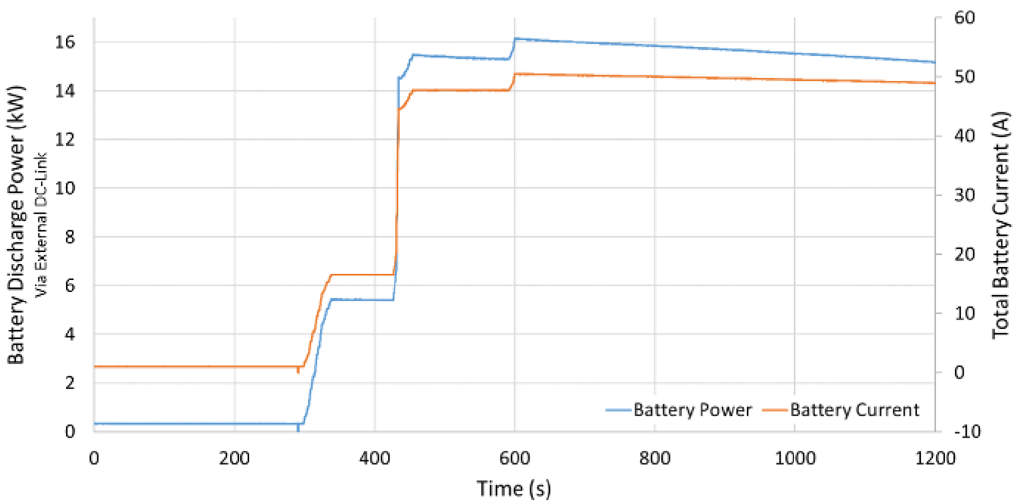

Figure 27: Example power draw at multiple levels (~3kW, 7kW, and 14 kW)

3.3 Vehicle RESS Over-Discharge

3.3.1 Highlighted Validation Results and Discussion

The proposed offline overdischarge procedure (with select modifications) was successfully implemented for all test vehicles within this study, thus validating the modified procedure. Over the course of the validation testing and subsequent analysis and reporting, several procedure modifications, suggestions, and observations were made and the following paragraphs seek to discuss these findings in a bit more detail.

Procedure Modification: *Provide offline 12V power directly to vehicle auxiliary battery to avoid 12V system shut-down and premature end-of-testing (and data recording)*

During testing it became evident that testing could benefit from a supplemental 12V charger applied to the vehicle's 12V battery. During discharge testing, the vehicle will ultimately end up at a state where the HV battery will no longer provide power to the on-board 12V systems due to the complete de-rating of controlled HV battery available power (and the vehicle's control of the DC-DC converter). Since the vehicle diagnostics and CAN buses used for information logging as well as the contactors themselves are powered by the 12V network, certain vehicles ended up stopping testing early due to insufficient 12V system power; a situation illustrated in Figure 28. In a typical operational situation, the ability of the HV system to avoid an overdischarge condition would not be impacted by this supplemental 12V power, yet providing the supplemental power to the 12V system greatly reduces the chance of a test needing to be redone done to an unexpected over depletion of the vehicles 12V system. Furthermore, an uncontrolled overdischarge may occur for a variety of reasons, so having the 12V system die during testing is not a sufficient protection against overdischarge.

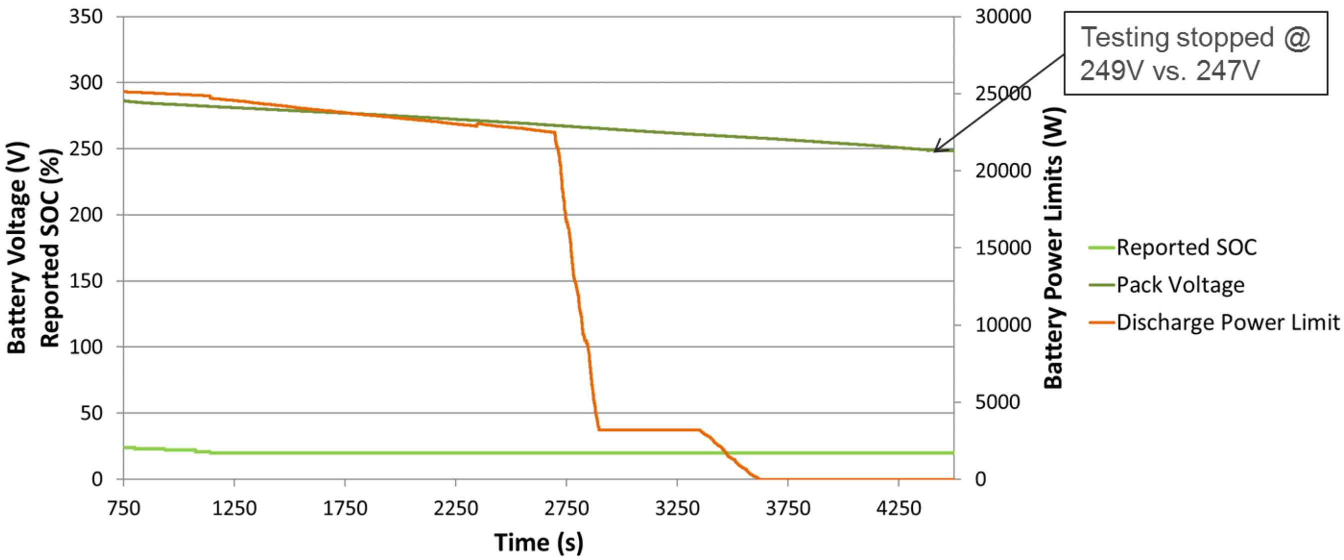

Figure 28: Premature end-of-test due to 12V battery depletion

Procedure Modification: *Fuel tank requirement of 5 percent or lower fill volume will still lead to engine activation, making testing more difficult/time-consuming. Propose an allowance for alternative methods to disable engine-start via: 1) Remove fuel pump fuse or relay, 2) direct fuel-line cutoff via quick connect or similar, 3) remove all fuel from tank, 4) additional (non-software) method with input from manufacturer.*

Previous drafts of the testing procedures discuss having the vehicle fuel tank at a level of 5 percent of capacity or less for an HEV or PHEV. During testing, it was found that the vehicles still activated their engines and provided significant charge power to alleviate the reduced battery SOC. The figure below shows an example of this engine-start event happening at roughly 1,100 seconds, a behavior that was observed for each PHEV and HEV tested without a more robust approach to avoid engine starts.

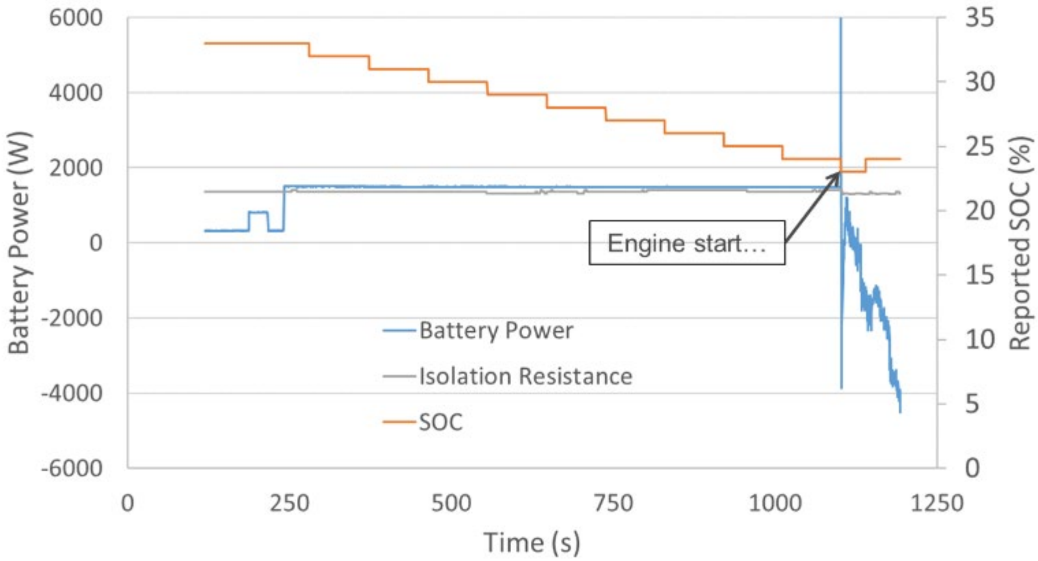

Figure 29: Engine restart prior to EOT due to overdischarge protection

A range of methods to more robustly disable the vehicle's fueling system was evaluated over the course of this work, but the primary approach was to completely restrict fuel from reaching the engine. This was achieved via either removing the fuse/relay associated with a vehicle's fuel pump or by directly blocking fuel flow using a self-sealing fuel line disconnect. Both options and their specific in-vehicle implementations, are highlighted below in Figure 30.

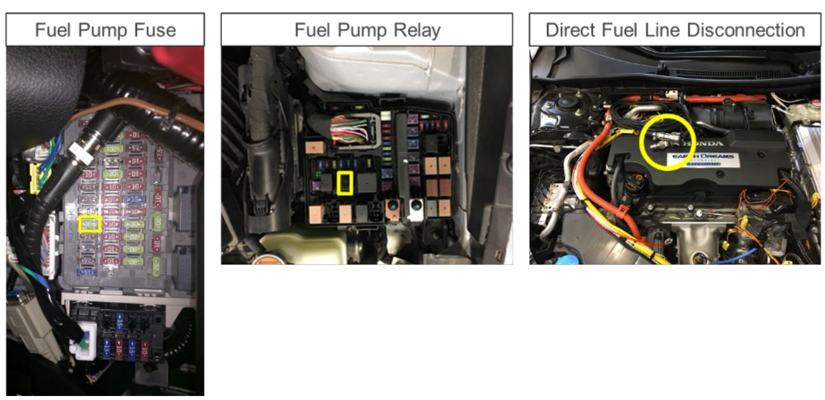

Figure 30: Example methods used to avoid engine starts during overdischarge testing

While the above methods were successful in avoiding an engine start, they also highlighted some additional issues during testing related to truly ensuring that the fault condition observed is related to overdischarge as opposed to an alternative, non-overdischarge related condition. More specifically, several of the vehicles had faults related to repeat failed engine starts. If a vehicle could not start the engine (due to the lack of fuel flow in these cases) a fault condition would be set and the vehicle's contactors would open, seemingly an overdischarge related fault. Upon further experimentation, it was determined that the vehicles could be restarted and battery discharging continue, although subject to faults due to the engine restarting failure happening after several failed engine restarts. Upon further discharging, it could be seen (via tracking the voltage at which the contactors opened as well as the interval between faults), that in the later portion of testing, the contactors were opening due to the overdischarge protection as opposed to the engine restart failure. Summarized below in Figure 31, this behavior was observed across several vehicles and highlights the importance of identifying "why" a fault was set in addition to simply observing it near the condition where it is expected to occur.

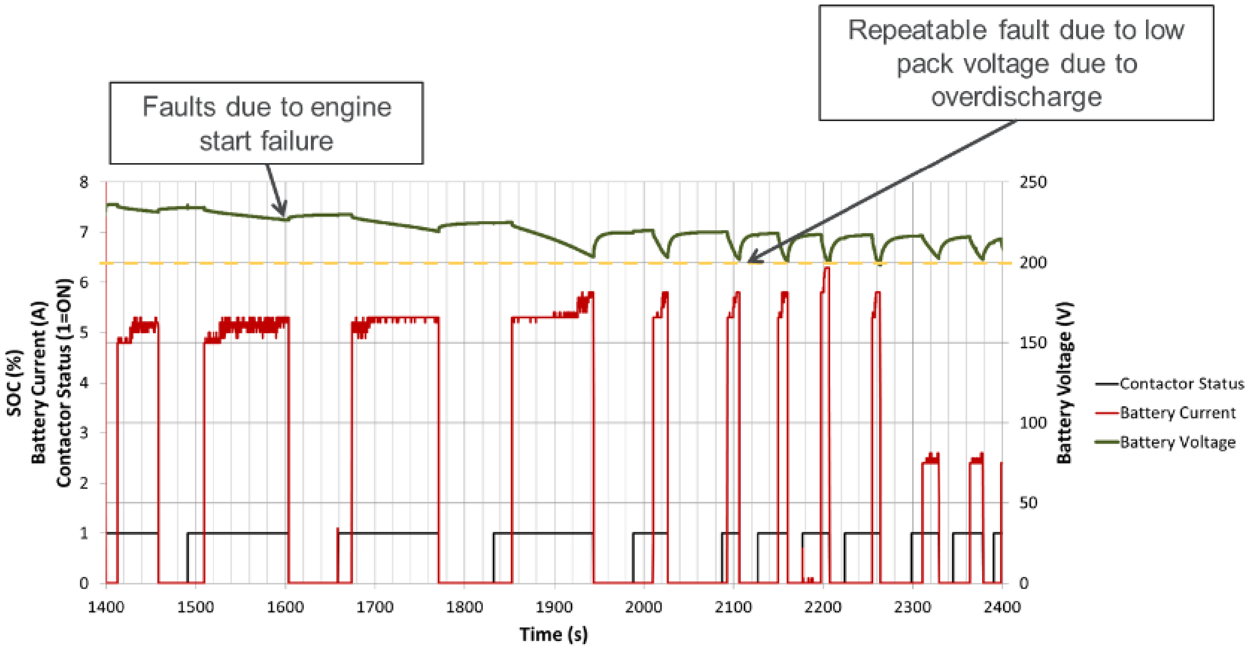

Figure 31: Engine start related faults (1,400s-1,800s) versus overdischarge related faults (2,000s +). Dashed yellow line highlight shows voltage level associated with overdischarge shutdown.

Observation: *Cell-to-cell variation appears to be large in some cases, tracking voltage levels and identifying limits likely useful on both the pack and cell level*

While not observed for all the candidate vehicles used for testing, one observation across select vehicles during the overdischarge testing was that cell-to-cell variation grew rather large during extended battery discharge. Highlighted below in Figure 32, a relatively large variation can be observed between the minimum and maximum cell voltage observed during testing. Moreover, this suggests that monitoring both individual cell voltages as well as overall pack voltage may be preferred if the signals are available. For the example below, the minimum cell voltage under load appears to be at roughly 50 percent of the recommended minimum value per the vehicle's service manual.

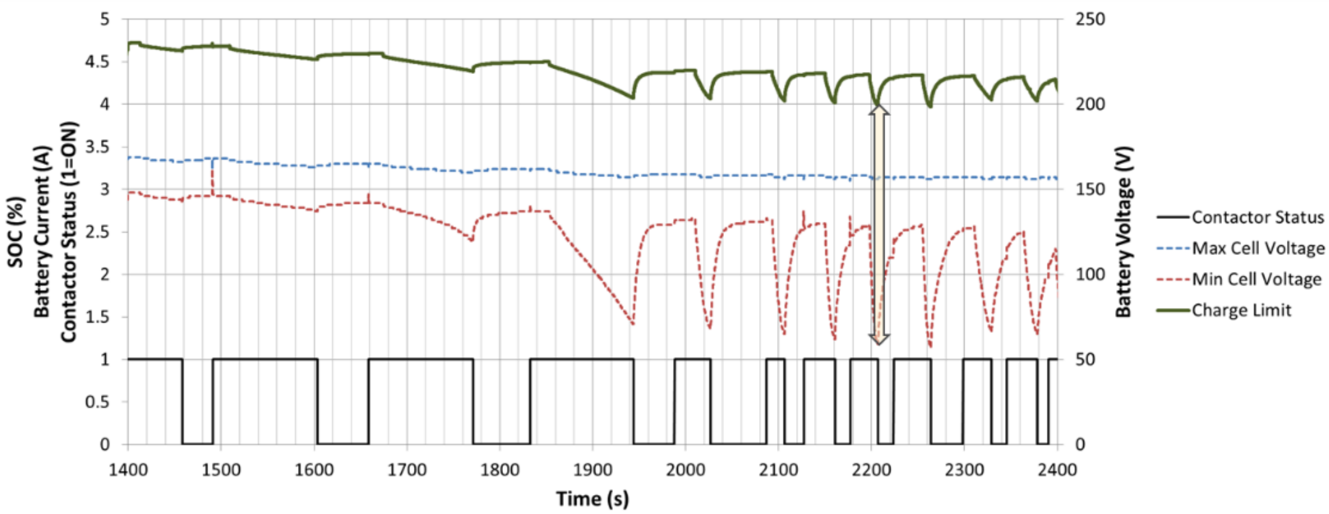

Figure 32: Highlighted cell-to-cell voltage differences during over-discharge

Observation: *An OEM service tool may be needed to supply an engine restart command at the very low SOC level associated with over-discharge protection*

While most vehicles tested were able to restart their engine and recharge the high voltage battery once the fuel system was placed back in a normal operating condition, one of the candidate vehicles required a special command to be sent from a OEM service tool to start the engine at very low SOC levels- While the tools are typically readily purchasable, this highlights the likely need for some manufacturer-specific tools when looking to return a vehicle to its normal operating state.

Suggestion: *While the resistor bank used in the preliminary procedure validation and development work is absolutely acceptable from a test validity and safety stand-point, a programmable DC load is preferred since it is easier to use in terms of activating the system as well as adjusting resistance values for different applications.*

Suggestion: While the test was successfully validated at the previously recommended power level (1kW) more flexibility to control power level during overdischarge testing (>1kW) [per mfg. discretion] would likely allow for more efficient testing without compromising goals due to large batteries requiring a long discharge time at <1kW to reach an overdischarge protection state.

3.4 Vehicle RESS Over-Charge

3.4.1 Highlighted Validation Results and Discussion

As with the overdischarge testing, proposed offline overcharge procedure (with select modifications) was successfully implemented for all test vehicles within this study. Although the test procedures were successfully applied to all vehicles, it should be noted that testing was stopped prior to contactors opening for one of the candidate vehicle due to excessively high individual cell voltage. While not necessarily a safety issue, testing was stopped to avoid unnecessarily damaging a test asset, since the mechanics and principles of the test had been already validated by this and other vehicles. Ultimately, it is expected that the contactors would have opened even for this case, but there was little to be gained from pressing the issue. As with the overdischarge testing, procedure modifications, suggestions, and observations were are included from insights gained during testing. The following paragraphs seek to discuss these overcharge related finding in greater detail:

Modification: *Require a stated max voltage for pack* *<u>and</u>* *individual cells prior to testing AND limit testing to <130% estimated SOC [or mfg guidance] -* *<u>do not test to failure as the baseline case</u>*

As discussed in the introduction, the focus of these test is on functional safety and the ability of a vehicle's RESS protection system to avoid dangerous conditions such as overcharge. Thus, unlike cell-level testing, vehicle-level testing past 130 percent SOC would be a very unique case and should be justified prior to testing. While cells are frequently tested at elevated SOC levels to determine their overcharge reactions, it is suggested that RESS protection testing should stop at a prescribed set of pack voltage, cell voltage, and SOC limits and not be tested to failure as the baseline case. If a manufacturer is confident in its pack to handle severe overcharge safely without a RESS protection system, this is a unique case and should be justified prior to RESS protection testing, otherwise values should be provided for each "end-of-test" condition (and the battery should open contactors at these limits). The choice of 130 percent SOC is an estimate of a relatively stable overcharge condition across a range of observed Li-Ion batteries, but OEM guidance would strongly be preferred if available.

The term "estimated" SOC is used in this context since most vehicles will not report SOC values above 100 percent, thus an estimate needs to be used to help track overcharge conditions that are above the expected values provided by the manufacturer's service information (as was the case for several vehicles). The estimate does not need to be particularly accurate, so it is suggested that SOC reported by the vehicle prior to reaching 100 percent can be used in conjunction with some form of integrated current to provide a basic estimate of SOC during overcharge conditions. Figure 33 highlights the estimated SOC trends and estimated observed end-of-test for a variety of vehicles. Although not necessarily highly accurate, the testing done in support of these revised procedures appears to suggest that an <u>overall</u> pack SOC limit of 130 percent should accommodate a range of vehicle overcharge protection strategies.

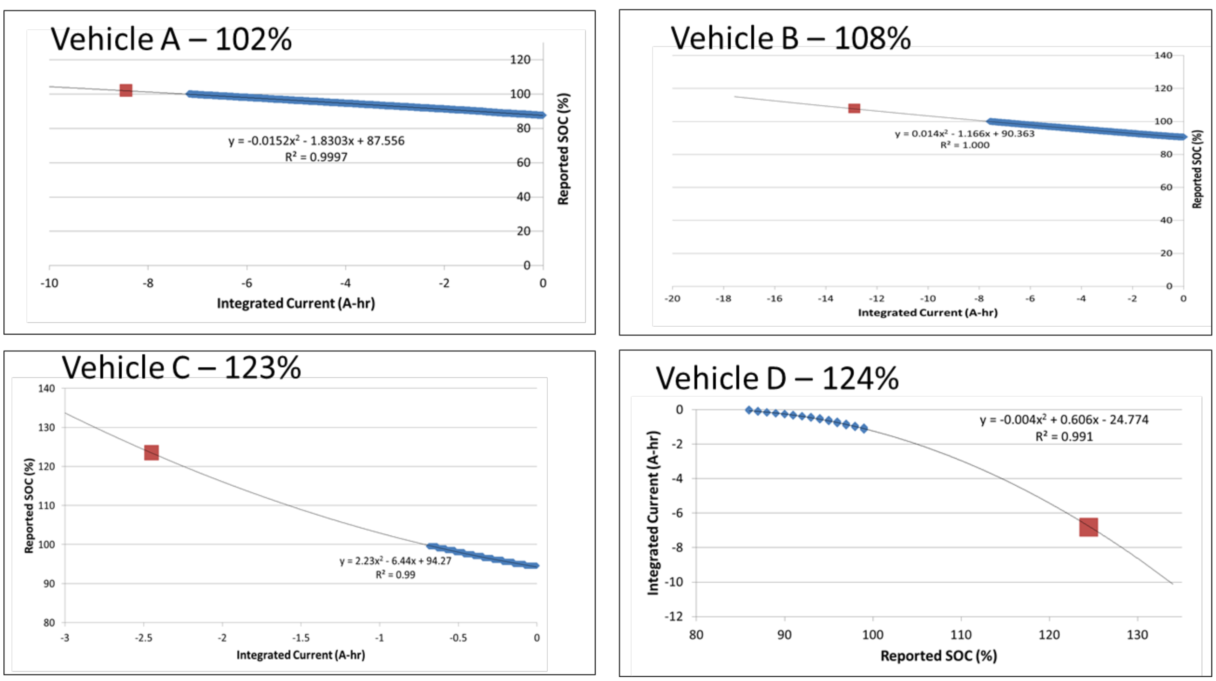

Figure 33: Estimated SOC versus integrated current and overcharge stopping estimate (red point) for select candidate vehicles

Suggestion: *Focus RESS overcharge protection test towards response to uncontrolled overcharge situation and streamline testing scope to parallel overdischarge testing.*

The previously supplied draft procedure provides test cases looking at over-voltage and over-current derived overcharge conditions, which are important but not as closely related to the primary objective of this testing, which entails ensuring single-fault tolerant behavior towards an overcharge condition regardless of how the condition occurs. Thus, a streamlined test and conditions parallel the offline overdischarge testing are used in that an uncontrolled charging condition is created by the test and the RESS response to the condition is monitored. This will allow for more flexibility in how the uncontrolled charging condition is realized on the high-voltage bus and help focus the testing on single-fault tolerance.

Suggestion: *As with the overdischarge testing, more flexibility for starting conditions (SOC) and power level used during testing [per mfg. discretion] would allow for more efficient testing without compromising the intent of the procedure.*

Unlike the overdischarge testing, the overcharge testing suggests using maximum vehicle regenerative braking power, which pushes the testing to very high power levels and dramatically increases the capability of any equipment used to supply power for testing. Moreover, testing at such high power levels accelerates any issues that may not be properly mitigated during testing, while not necessarily providing any additional insights into a vehicle's RESS protection strategy. On the charging side (depending on the vehicles architecture, both multiple RESS contactor responses may need to be tested), the recommended power level of 1.4 kW may be on the low side for a larger pack and result in a longer than needed test time. While the suggested power levels are certainly valid for testing, more flexibility should facilitate less expensive equipment as well as more reasonable testing times for large packs. Although overcharging can be due to either the charging system or the regenerative braking system, regenerative braking power typically (at the time of publication) exceeds offline charging power in most cases [4]. That said, later recommendations in this section will suggest that the overcharge testing need not be done at peak maximum battery charging power. Especially for a battery of unknown safety measures, it is suggested that a low to moderate overcharge power will allow for more time to end testing prior if an unexpected response is observed (or rather a lack of proper response to an overcharge condition).

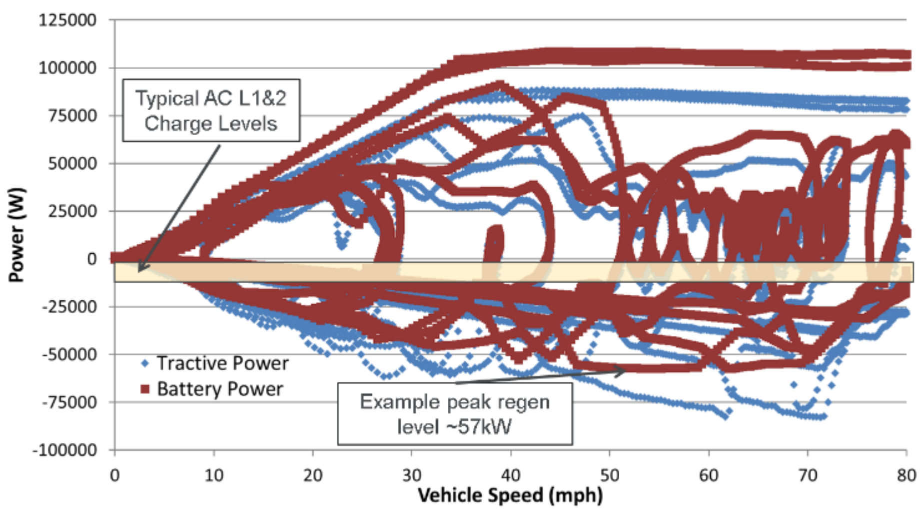

Figure 34: Tractive, regenerative, and charging power comparison for an electrified vehicle

Observation: *Cell-to-cell variation appears to be very large in some cases, tracking voltage levels and identifying limits likely important at both pack and cell levels.*

As mentioned in the procedure modification above, there appears to be a need to highlight expected end-of-test maximum levels for both pack and individual cell voltages during the overcharge testing. Individual cells may see a very high voltage level during overcharge testing depending on the cell balancing strategy (or lack thereof) during the uncontrolled charging. As can be seen below in Figure 35, for one test vehicle, the maximum cell voltage observed during testing is on the order of 4.7V which is much higher than the 4.3V maximum discussed in the vehicle's service documentation. Additionally, the overall pack voltage of 330V also exceeds the state maximum of 310V but is relatively not as far away from the states limits as compared to the maximum single cell voltage. While it is unclear at what voltage level the pack would have an issue, it seems like the voltages observed may be slightly higher than would be expected. Moreover, since the battery was already operating outside of its prescribed operating envelope (per the vehicle's service documentation), there was concern about pushing the testing further despite the overall pack estimated SOC level remaining under the revised limit of 130 percent.

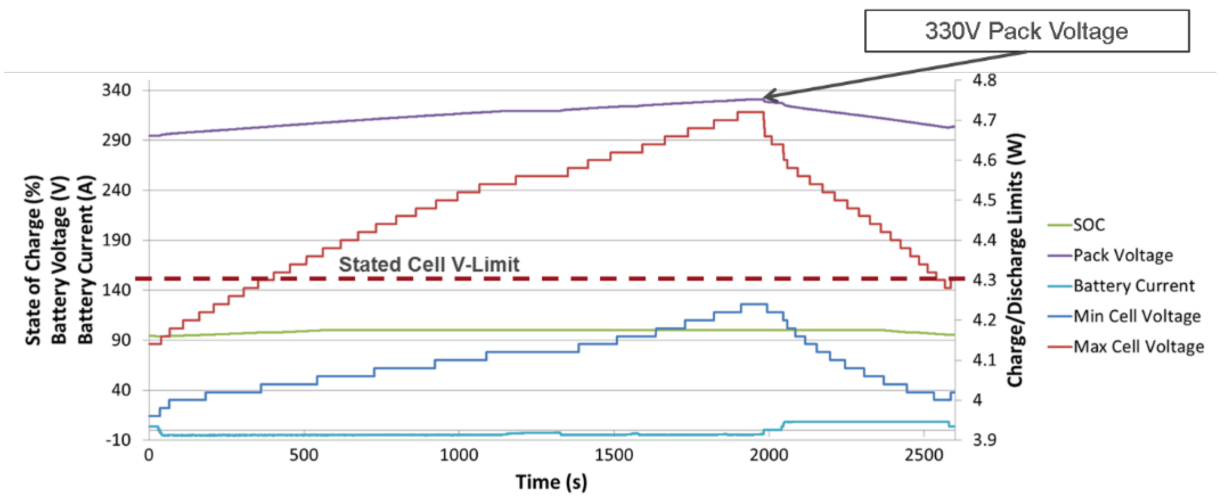

Figure 35: Example of high individual cell voltage during overcharge testing

Observation: *Limited published/correct information on maximum voltage levels makes third-party testing a bit more open-ended regarding when to stop testing.*

One difficulty with the overcharge testing (and to a lesser degree the overdischarge testing) is that there is limited and often incorrect information regarding a battery's voltage/SOC limits at elevated charge/voltage levels. While vehicle service information and error codes provide some insights into the overall pack and individual cell voltages that cause a fault, most of the vehicles tested actuate the contactors at a different voltage level than the published values. The majority of vehicles tested activate the vehicle contactors at a slightly higher pack voltage level that published, although one vehicle reported a dramatically higher fault voltage that the observed voltage at which an actual fault occurred. As discussed above, one vehicle appears to have exceeded both the individual and overall stated voltage limits by more than 5 percent. While the 130 percent estimated SOC limit as a baseline end-of-test condition should go a long way to alleviate some of these concerns, it should be highlighted that in the absence of information regarding pack limits the decision to end testing is somewhat in the hands of the test operator and their tolerance for possible issues. In particular, for individual cell issues which may rise above 130 percent SOC before the overall pack SOC reaches this level.

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

3.5.1 Highlighted Validation Results and Discussion

Several modifications and recommendations for this testing were done prior to validation testing, but following these modifications, all vehicle were successfully evaluated using the developed procedure, again validating the procedure across a range of vehicles. The candidate vehicles used in this testing utilize a range of cooling methods for their respective RESS systems, so one of the first challenges was how to simulate a "failed" cooling system for each type of cooling method. Fortunately, this proved relatively easy for all vehicles and none of the vehicles failed to operate despite a disabled cooling system. As with the previous uncontrolled operating testing, emphasis was placed on identifying non-software methods to disable system cooling allowing for less required OEM/supplier intervention during testing. For packs cooled by cabin air, the simplest solution was to block the cabin air intakes used to provide cooling air flow to the battery. While this appeared robust for the vehicles evaluated, it also appears the cooling fans themselves could be disabled as well to ensure limited airflow within the battery. For liquid cooled packs, a simple clamp was used to fully restrict cooling flow to the battery. One of the vehicles in the evaluation set utilized refrigerant as the working fluid to remove heat from the battery pack, so this system was disabled by removing the refrigerant using common HVAC tools. While some case-by-case investigation may be needed for future vehicles, the candidate set provide a range of cooling types all of which were easily accommodated within the developed procedures.

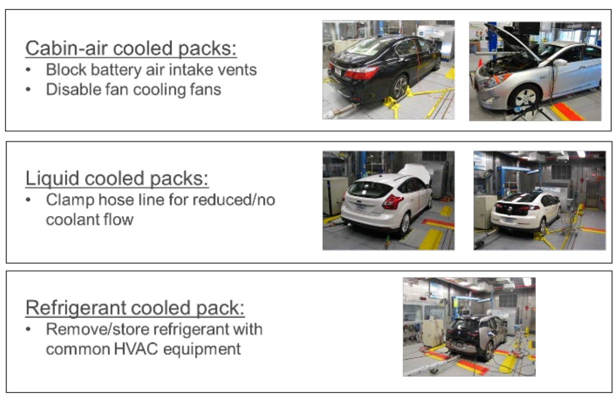

Figure 36: Methods to disable RESS cooling system versus battery cooling type

The following paragraphs again seek to provide some procedure modifications, suggestions, and observations from the validation testing:

Modification: *Modify 6+ hour @ 40C requirement to state: "vehicle shall be preconditioned at a sufficient ambient temperature and for a sufficient amount of time that thermal de-rating and stabilization can be observed."*

The current procedure prescribes a 6-hour vehicle soak at 40 °C to elevate the battery temperature to a level at which thermal de-rating is expected to be observed during operation, but this may be too long or insufficient depending on the size and temperature limits of the battery pack under evaluation. In order to be more flexible, a modification to the procedure is suggested to generalize the soak conditions such that the vehicle can be preconditioned at the discretion of the OEM/supplier/test laboratory as long as thermal de-rating and stabilization can be observed. It should be noted that this flexibility can shorten testing/soak times, but also may extend the required soak times because running out of charge is insufficient to indicate thermal stability during operation with a failed cooling system. At the rare extreme, for cases where no de-rating is expected, consultation with the manufacturer is likely needed to justify RESS stability at very elevated temperatures and aggressive usage.

Modification: *Focus on back-to-back accelerations and decelerations to more aggressively use battery (especially for HEV/PHEV), increase heating, and commonize procedure across vehicle powertrain types.*

As discussed in the previous recommendation, the main goal of this evaluation test is to observe the RESS reach thermal stability despite a failed (or the absence of a) cooling system. To these ends, a more harmonized procedure is suggested as compared to the previous draft procedure that utilized different usage profiles depending on powertrain type and focused on maximum sustained discharge capability or repeated drive-cycles. More specifically, repeated back-to-back aggressive accelerations and decelerations are suggested as a common strategy for exercising most batteries regardless of powertrain type. An example of this revised test scheme is shown below in Figure 37. There are several advantages to this approach. First, it is very easy to identify battery de-rating visually due to restricted vehicle acceleration or battery power in most vehicle cases where electric power is used to assist the acceleration.

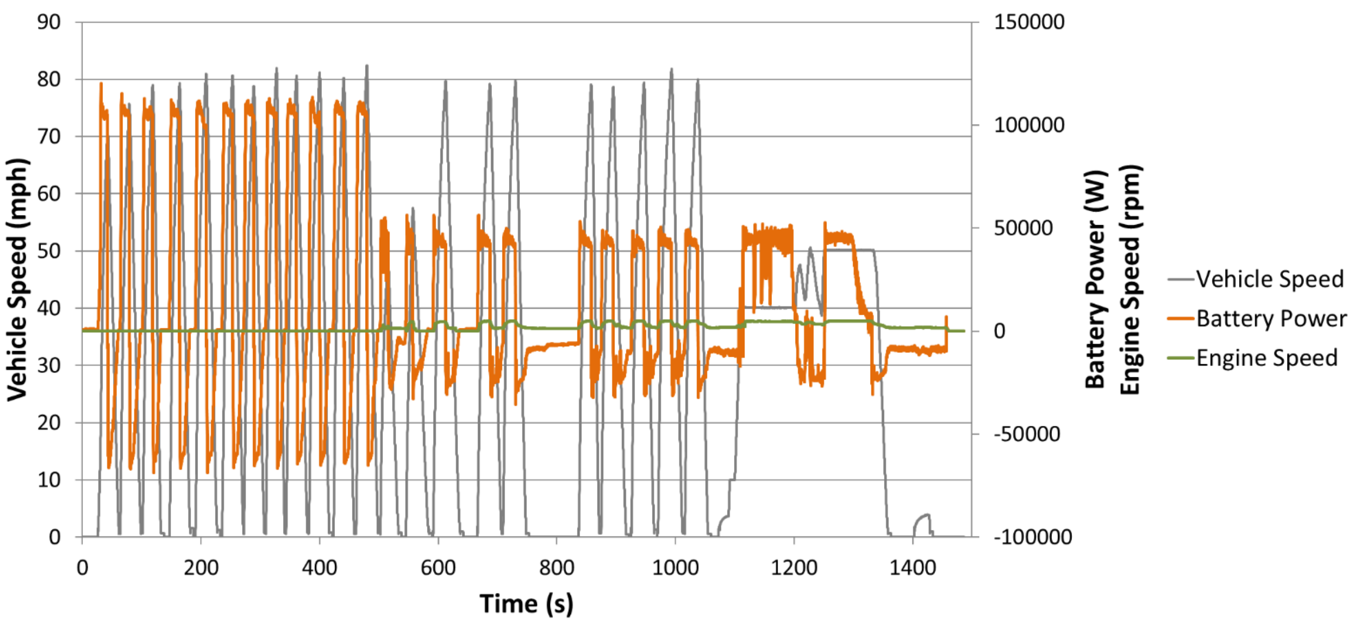

Figure 37: Example back-to-back acceleration testing and related power limits

In addition to visually highlighting areas of de-rating, back-to-back acceleration/deceleration testing allows for more battery throughput over the course of a test period (through regenerative braking) allowing for more battery heating prior to hitting a non-thermal usage restriction (typically low SOC limits). Furthermore, as illustrated in Figure 38 and Figure 39 aggressive battery usage (Figure 38) also allows for elevated temperatures to be reached more quickly that an just overnight soak at relatively elevated ambient conditions (Figure 39), thus working in conjunction with the earlier “sufficient to observe stability” modification, more aggressive usage facilitated by back-to-back accelerations will likely allow for less soaking time and more expedited testing as compared to drive cycle or maximum sustained discharge power operation.

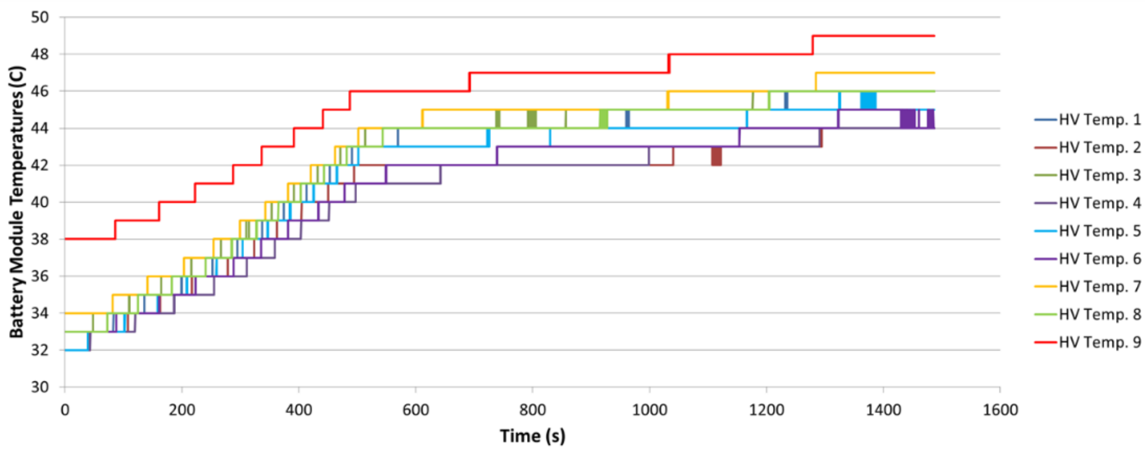

Figure 38: High voltage cell temperatures following aggressive battery usage (following 35C soak period)

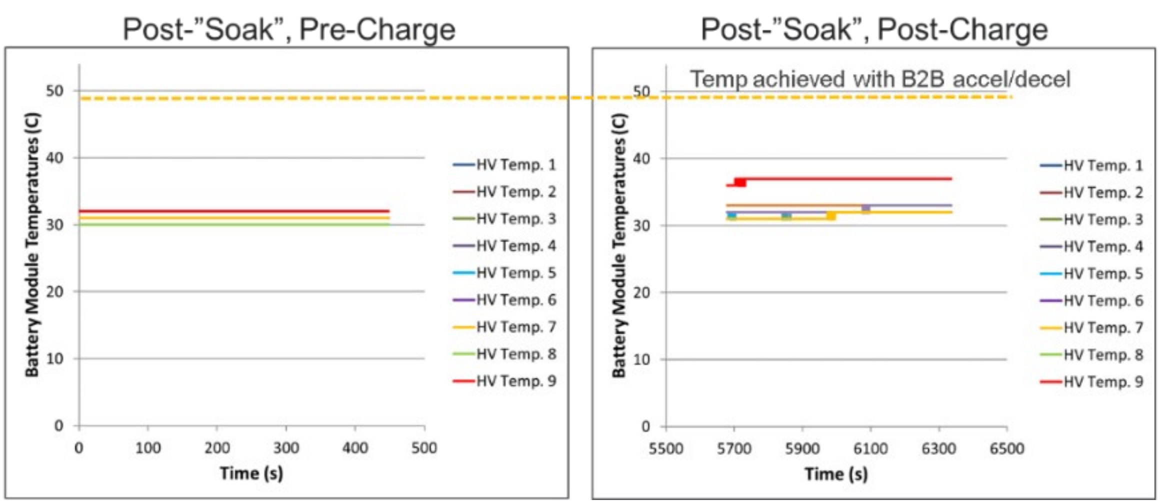

Figure 39: Overnight soak at 35C ambient (compared to temperature achieved during back-to-back accelerations)

While the back-to-back modification should more robustly accommodate a wide range of powertrains and component sizes, HEVs may require guidance from a manufacturer relative to the acceleration and deceleration rate that results in maximum battery power during testing. This is because many hybrid vehicles (and some PHEVs) will only supplement engine power with battery power within a specific torque/speed envelope and maximal accelerations may not necessarily lead to maximal battery usage (although in most cases maximal accelerations will likely be sufficient to observe de-rating after several cycles).

Modification: *Remove current 5% SOC EOT criterion and focus on de-rating and temperature stabilization criteria (±2 °C for 30 minutes).*

The previously draft procedure allowed for an end-of-test criterion that allowed for testing to be considered complete if the RESS reached 5 percent or lower. To better emphasize the intent of the testing (battery thermal stability due to a failed cooling system) and in the context of the more generalized “sufficient to observe thermal stability” criteria, this SOC limit allows for scenarios where the battery has not been sufficiently exercised or soaked at an elevated temperature to observe the true “fault” response and thus should be removed. If a manufacturer believes that its battery system can operate at extremely elevated temperatures for a very long time or will de-rate at temperatures well beyond those encountered in service, justification and data must be provide why the stability criteria do not need to be met to ensure safe operation. Furthermore, in very extreme cases the 24hr testing limit would likely be met in ending testing for a very large, very thermally robust battery system.

Suggestion: *Once temperature has somewhat stabilized and significant de-rating has been observed, 30 minutes may be a bit long for SS confirmation.*

While the POC test procedure’s 30-minute stabilized operation check is certainly acceptable for validation purposes, most of the vehicles tested exhibited very stable cell temperatures beyond a particular de-rating threshold. Particularly for PHEV/HEVs, as illustrated in Figure 40, once sufficient de-rating has occurred temperatures remain very stable and thus a shortened time for EOT maybe be allowable, although the level of de-rating at which stabilization occurs will likely vary from vehicle to vehicle (i.e. de-rating is typically ramped in over time, so initial de-rating may still lead to increasing temperatures depending on system components). From a validation perspective, the 30 min criterion is certainly acceptable, but some flexibility may aid in providing a bit more efficiency in terms of overall testing time required.

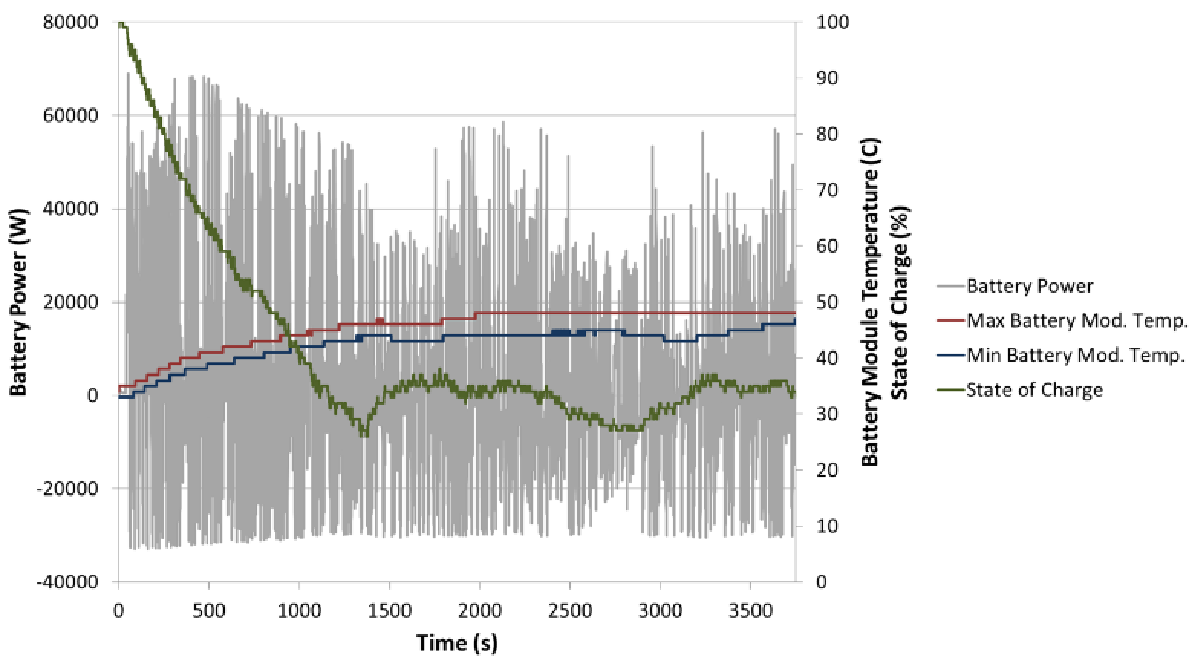

Figure 40: PHEV testing achieves stabilization quickly once de-rating occurs

Observation: All vehicles were drivable with “failed” cooling system, most provided an indicator that low cooling performance was being observed.

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

3.6.1 Introduction

This testing seeks to understand battery protections related to cold operation with a disabled battery heating system. The HEVs used in this testing do not incorporate a battery heating system and only some of the PHEVs used for testing have the capability to heat the battery. Nonetheless, their repose to cold operation can still be assessed with the revised procedure. Furthermore, for the candidate vehicles with a heating system, the same methods (working fluid removal or clamping) were used to effectively "disable" the battery heating system.

To provide some context related to battery heating in cold ambient conditions, Figure 41 shows the battery current draw and AC "wall" power during recharging and soaking following depletion in cold ambient conditions (-17 °C). In this figure, the spikes at roughly 40,000s and 60,000s represent wall power being used to heat the battery as opposed to recharge the battery (as indicated by no battery current at during the "wall" power draw. Furthermore, it can be observed that no heating is provided during the first charge/soak period, yet heating is provided during the second and third charge/soak period due to the battery temperatures continuing to decrease on average (excluding operation). This highlights the fact that getting a battery to a very low temperature takes a relatively long soak time and suggests that the initial soak time may need to be extended for large BEV and PHEV packs.

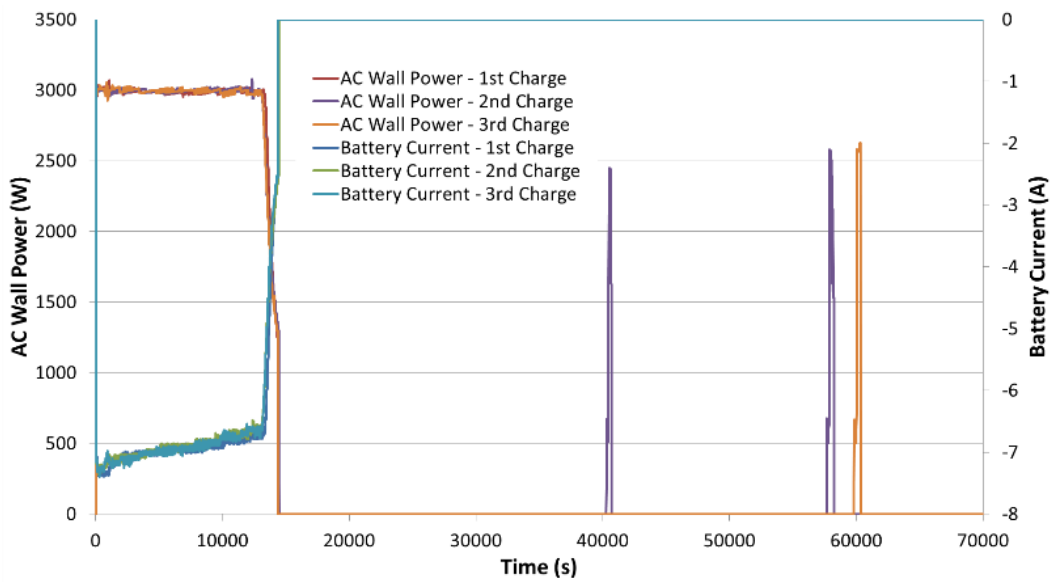

Figure 41: Battery and AC "wall" power during recharging and soaking at cold ambient conditions over three days of testing and overnight soaking (power spikes around 40,000s and 60,000s represent battery heating)

While many vehicles will show de-rating to some degree at colder temperatures, it should be noted, that the specific temperatures at which de-rating occur as well as the degree of de-rating is very chemistry and implementation specific, so while this test parallels the failed cooling system, assessing a RESS's de-rating strategy may take some additional input from the supplier or manufacturer since the strategies to avoid damaging the battery due to cold-battery operation can vary significantly.

3.6.2 Highlighted Validation Results and Discussion

Modification 1: *Refocus procedure on observing vehicle de-rating guidance for BMS and confirming vehicle adheres to temperature limitations during operation.*

Previous "failed" heating system test concepts mainly checked if the vehicle would operate following an extended soak period at cold ambient conditions and with a disabled heating system. Additionally, for a BEV, this test sequence was done at maximum discharge capability and thus does not investigate both charge and discharge limitations. Moreover, at the -20 °C recommended ambient soak conditions, many vehicles would likely still be operational although with some active charge/discharge limitations. Furthermore, a full set of drive cycles may not be needed since this testing is to observe if a vehicle reports a temperature-based limitation and whether it follows the de-rating guidance provided by the BMS. To better focus this testing on detecting thermal limits and a vehicle's response to these limits, the test procedures has been revised to utilize the back-to-back acceleration/deceleration testing as discussed previously in the failed cooling system test. Testing can be completed quickly, once the vehicle's de-rating due to temperature has been noted (both + and – usage) and it has been confirmed that the vehicle operates within these boundaries testing can be complete. To summarize the revised procedure, following a long soak period (likely overnight+): 1) log vehicle reported discharge and charge limits and 2) operate vehicle over back-to-back accel./decel. segments or another operating condition to confirm if de-rating is observed relative to standard operation and vehicle reported limits (sufficient for EOT) at normal operating temperatures. It should be noted that many RESS will provide some level of power at very low temperatures, even around -40 °C, so de-rating is likely to be observed, but it is possible that the vehicle will function somewhat normally (although at lower peak power levels).

Observation 1: *Vehicle de-rating at cold temperatures often impacts charging power more than discharging (especially for HEV/PHEVs), although not always.*

As discussed in the previous modification section, the failed heating test has been revised to investigate both positive and negative battery usage. This is an important modification since many vehicles de-rate battery charging power (i.e., regenerative braking) prior to or to a larger degree versus discharging power (traction power). Several of the candidate vehicles evaluated using the revised test plan showed a moderate de-rating of cold temperature related charging power, but showed no signs of discharge power deration. It should also be noted that even mild battery usage was typically enough to heat small batteries beyond the de-rating temperature threshold, so test practitioners must carefully evaluate the first few regenerative braking events of a specific test cycle. Although taken from an earlier, non-back-to-back set of testing done in the early stages of these efforts, Figure 42 below shows mildly reduced battery charge power limits, but these values quickly become very close to the "normal" limits, eventually matching within ~600s of Urban-Cycle operation.

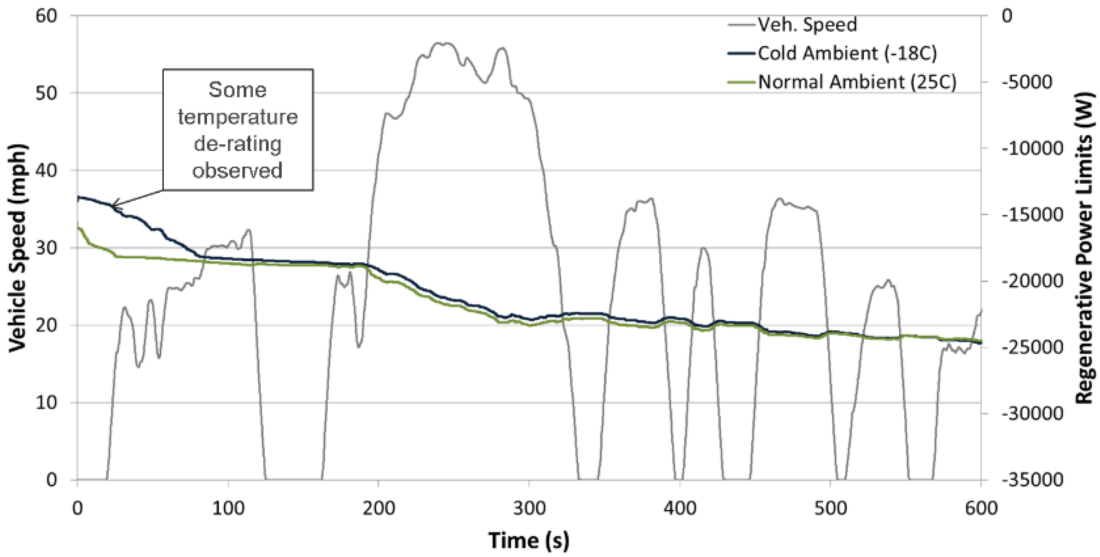

Figure 42: De-rating observed during initial cold ambient operation

Observation 2: *While future vehicle may differ, disabling heating system was not actually necessary for the vehicles tested. The candidate vehicles that did have battery heating capabilities only did-so when connected to offline power via a charger.*

While future vehicles may differ from the initial observations done for this validation work, none of the vehicles evaluated utilized the battery heating system when disconnected from their charger (i.e., heating was only done if the vehicle remained connected during to a charger and was not directly powered via the RESS itself). With issue in mind, it appears that vehicle usage following a cold-ambient soak may be sufficient to observe de-rating and thus the thermal system may not need to be disabled since the initial usage will highlight any de-rating.

4 RESS External Short Circuit – Investigating a "Soft' Short Condition Resistance Determination Method

In addition to the RESS safety testing procedure revisions and validation testing done for this report, an additional risk condition, to be reported at a future date, was identified. This subject area is associated with methods to identify the resistance that would be reasonable for a vehicle-level "soft" short test (i.e., slightly higher resistance versus the ~5-10 mOhm used in current short circuit testing). As a supplement to "hard" short testing a "soft" short test seeks to test the battery's response at a short-resistance closer to that of an actual battery. In some cases, this elevated resistance is believed to better represent "cell" response as opposed to the behavior of connectors and other component in the system [5].

While "hard" short testing uses a very low resistance for all test cases, this "soft" short concept seeks to identify a short resistance that is similar in scale to the overall pack resistance. While it is not imperative to have an exact value for this resistance value, a procedure to generate an estimated pack resistance in a consistent and robust manner is desirable. Specifically, since pack resistance varies so dramatically from vehicle to vehicle and by powertrain type (HEV, PHEV, BEV) a quick data driven process to estimate pack resistance is the goal of this subsection. It should be noted that this work simply provides a validated procedure that can be used and does not get into the details regarding how, when, and why a "soft" short test condition should be used in contrast to a "hard" short.

4.1 Procedure Overview

The goals of the resistance determination procedure are to have something that can roughly approximate a pack's resistance given minimal external modifications and instrumentation. Building off of the most basic definition of a battery's terminal voltage ($V=iR_{pack}$) this procedure uses a battery current and terminal voltage measurement from a vehicle's CAN bus to estimate the overall pack resistance. While actual pack voltage dynamics are often more complex, this simplification should allow an easy to calculate pack resistance estimate. Moreover, using CAN voltage and current estimates requires no instrumentation on the vehicle aside from tapping signals that are already available on the vehicle bus, thus avoiding issues with high-voltage instrumentation. Furthermore, CAN based voltage and current measurements have been found to be very accurate for the majority of vehicles tested at Argonne and elsewhere and can be easily verified with basic high-voltage instrumentation if there are any questions regarding their accuracy. The basic outline to collect data and provide a resistance estimate are provided below. The procedure to generate the data/resistance is purposely left relatively broad so that it can be used to assess resistance at a range of conditions (hot/cold battery, high/low SOC) or shortened to arrive at a specific value more efficiently (i.e., single SOC).

Process to generate battery system resistance:

1) The same drive cycle is repeated from a fully charged battery until the battery is depleted (or within the specific widow of desired SOC operation).

2) The current and voltage are measured at 10Hz using CAN provided current and voltage information (either decoded or provided by the manufacturer/supplier).

3) Basic polarization curves are created from the 10Hz data showing current versus terminal voltage.

4) The battery system resistance is derived from a least-squares linear regression of the form $V(i) = R_{pack\_est} x(i) + V_{opencircuit(SOC)}$, where the open circuit voltage and resistance is estimated for a subset of the overall operation of interest (i.e., high/low SOC).

The process is summarized below in Figure 43 and Figure 44.

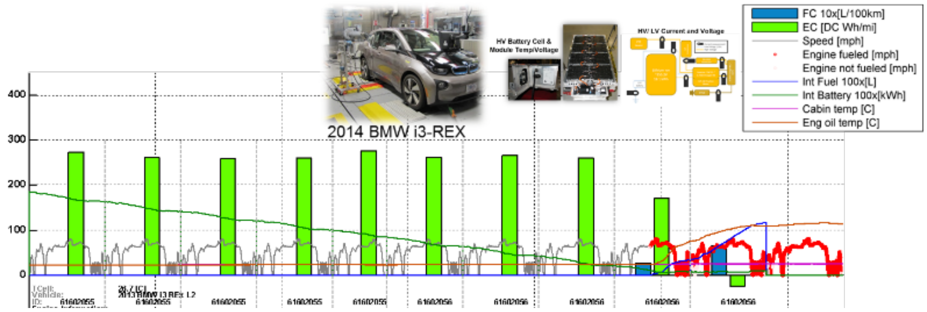

Figure 43: Visual overview of resistance determination procedure

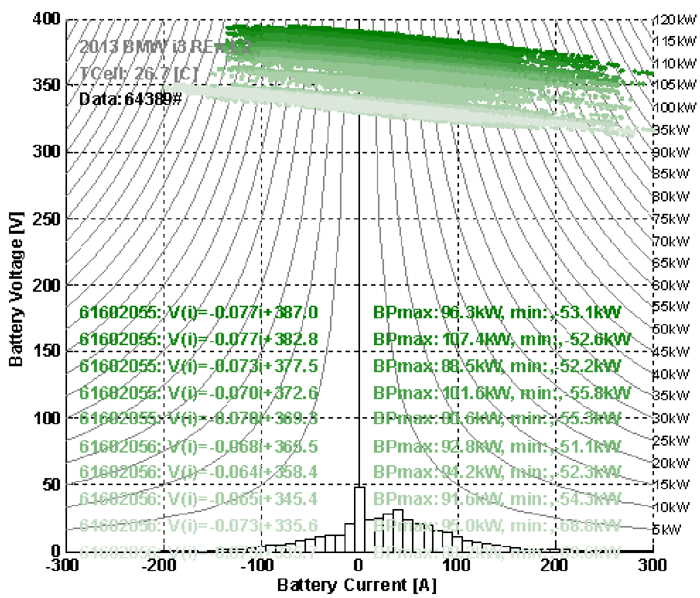

Figure 44: Example polarization curves for a full battery depletion organized per-cycle

4.2 Procedure Observations

The proposed resistance evaluation method was done for several of the candidate vehicles across a range of SOC and at two ambient temperatures (72F and 20F).

One of the primary validation questions related to the proposed method is how close CAN measurements are relative to the actual instrumented voltage and current measurements. Since it is strongly preferred for the proposed approach to use CAN an investigation was done validating the developed procedures for but CAN and directly data measurements. Table 1 highlights the estimated pack resistance for three candidate vehicles at high and low SOC levels as well as an additional fully charged point operating in 20F ambient conditions. As can be seen in the table below, the results are not exactly, the same, the maximum error is on the order of 5 percent which is well within the accuracy needed for the "soft" short testing. Also worth noticing are the general trends of significant elevated resistance at low temperatures which helps strengthen the flexibility of this simplified methodology to focus on certain conditions if desired.

Table 1: POC pack resistance estimate results using CAN versus using direct voltage/current sensing

Vehicle	Battery SOC	Test Temp. [F]	Resistance from measurement [ohm]	Resistance from reported data [ohm]
BMW i3 REX	Full	72F	0.077	0.073
BMW i3 REX	Low	72F	0.065	0.062
BMW i3 REX	Full	20F	0.261	0.254
Chevy Volt	Full	72F	0.071	0.073
Chevy Volt	Low	72F	0.063	0.066
Chevy Volt	Full	20F	0.134	0.139
Ford Focus BEV	Full	72F	0.057	0.052
Ford Focus BEV	Low	72F	0.049	0.044
Ford Focus BEV	Full	20F	0.129	0.127

Similar to the larger RESS test procedure validation efforts the procedures developed here, with an eye towards ease of implementation and flexibility, again have been validated with a range of vehicles, suggesting the developed procedures are likely achievable for a wide range of vehicle candidates.

5 Conclusions

As discussed in the introduction, this report documents a project to independently evaluate, refine, develop, and validate vehicle-level BMS and RESS safety test procedures that can be robustly applied to a wide range of vehicle technologies and battery configurations. Building off a set of commonly accepted failure modes, hazards, and cell/module pack evaluation procedures, evaluation procedures have been developed to evaluate the in-vehicle response of a RESS and its integrated Battery Management System to protect from:

- Overcharge Protection System Single Point Failure
- Overdischarge Protection System Single Point Failure
- Thermal Control System Single Point Failure (both RESS heating and cooling system failure)

All of the refined RESS safety tests have been successfully validated for a range of vehicle powertrain types (HEV, PHEV, BEV) as well as for a range of manufacturers. As needed, the procedures were modified with an eye towards clarity of testing goals and flexibility. Moreover, efforts were made to commonize the procedures to better accommodate different powertrains within the same overall test procedure. The procedures have also been modified to more strongly focus on confirmation of a defined mitigation strategy, whereas some common cell and module procedures seek to only confirm the absence of incident (smoking, thermal runaway, etc.). Overall, the refined procedures should help battery and vehicle developers identify and evaluate BMS safety strategies and actuation concepts to provide basic RESS protection.

6 References

1. Ressler, G. Application of System Safety Engineering Processes to Advanced Battery Safety. *SAE International Journal of Engines 4*, no. 2011-01-1369 (2011): 1921-1927.
2. SAE J2929_201302, Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-based Rechargeable Cells, Revised 2013-02-11 (Current Version).
3. Guo, Rui, Languang Lu, Minggao Ouyang, & Xuning Feng. (2016). Mechanism of the entire overdischarge process and overdischarge-induced internal short circuit in lithium-ion batteries. *Scientific Reports 6*: 30248.
4. Rask, E., Santini, D., & Lohse-Busch, H. (2013). Analysis of Input Power, Energy Availability, and Efficiency during Deceleration for X-EV Vehicles. *SAE International Journal of Alternative Powertrains 2*(2): 350-361. Available at https://doi.org/10.4271/2013-01-1473.
5. SAE J2464_200911, Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing, Revised 2009-11-06 (Current Version).

Appendix A - Applicable Publications

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

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

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

IEEE 1725 Standard for Rechargeable Batteries for Cellular Telephones.

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

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.

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

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

UL 1642 Standard for Lithium Batteries.

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

UL 2054 Household and Commercial Batteries.

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

UL 2580 Batteries for Use in Electric Vehicles.

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

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

United States Department of Transportation – Code of Federal Regulations.

49 CFR Part 173.185 "Lithium cells and batteries."

Appendix B - Overdischarge Procedure Validation Testing Results

This appendix provides supplemental test results for each of the candidate vehicles used for testing.

Honda Accord PHEV

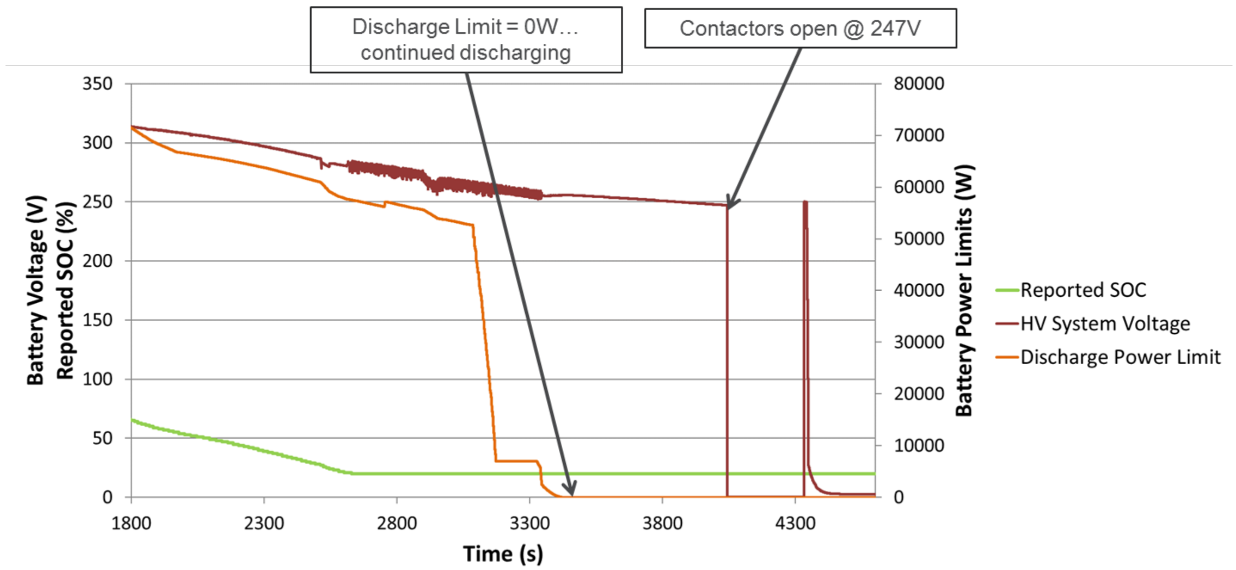

Figure 45: Honda Accord PHEV - Overdischarge test validation

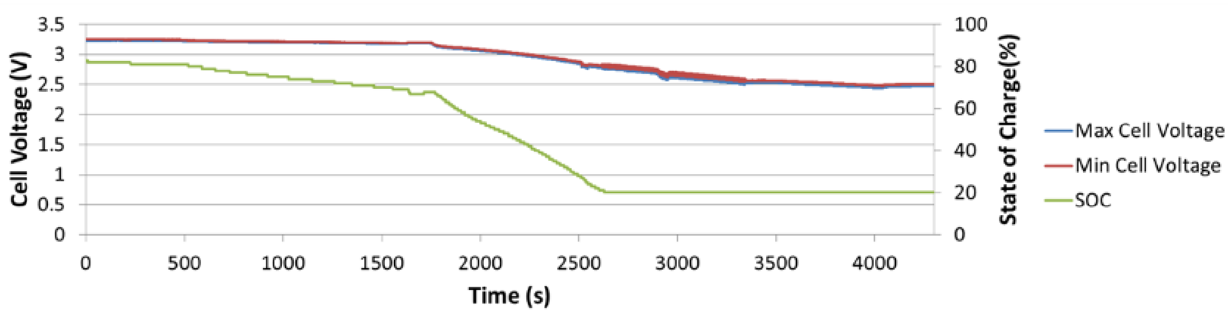

Figure 46: Honda Accord PHEV cell-to-cell variation during overdischarge testing

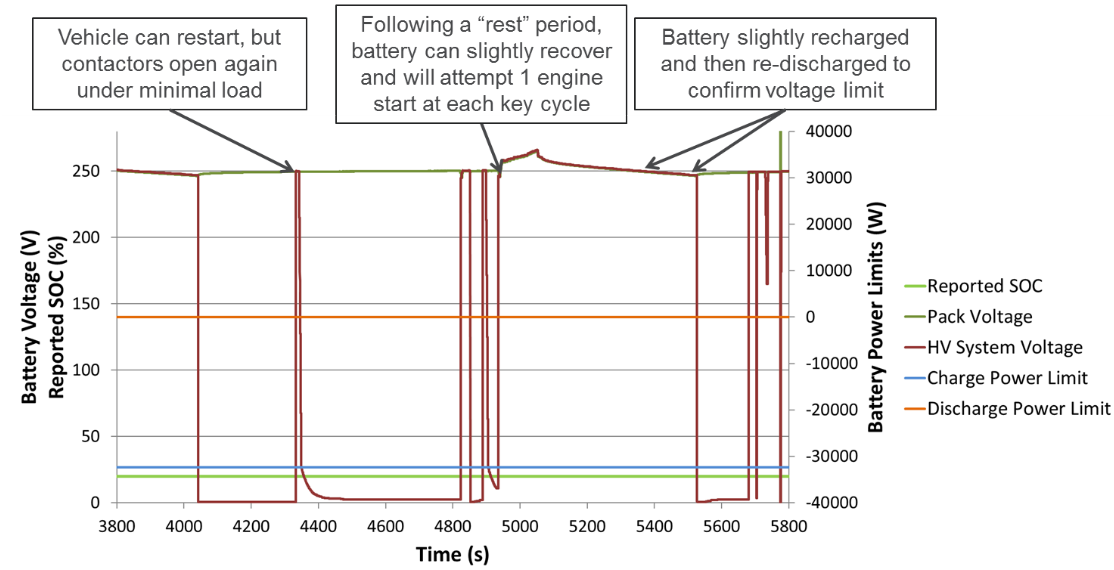

Figure 47: Honda Accord PHEV repeated overdischarge evaluation

Figure 48: Honda Accord PHEV engine restart and normal operation after fueling enabled

Hyundai Sonata HEV

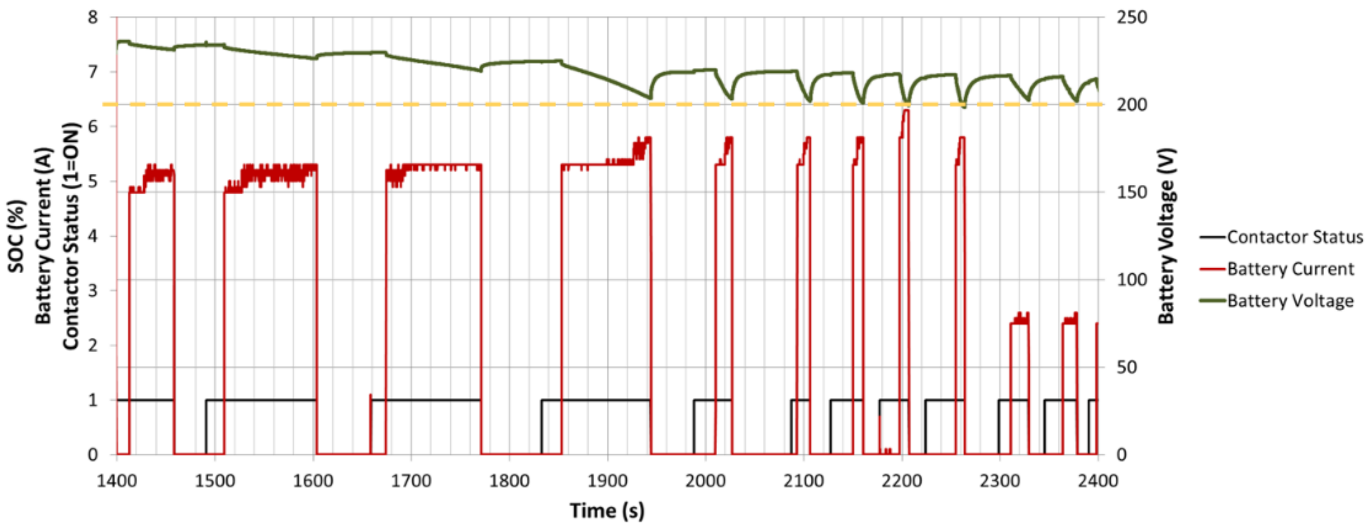

Figure 49: Hyundai Sonata HEV - Overdischarge test validation

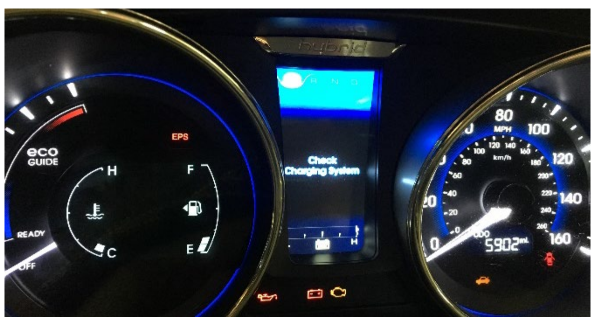

Figure 50: Hyundai Sonata - In-vehicle fault indication

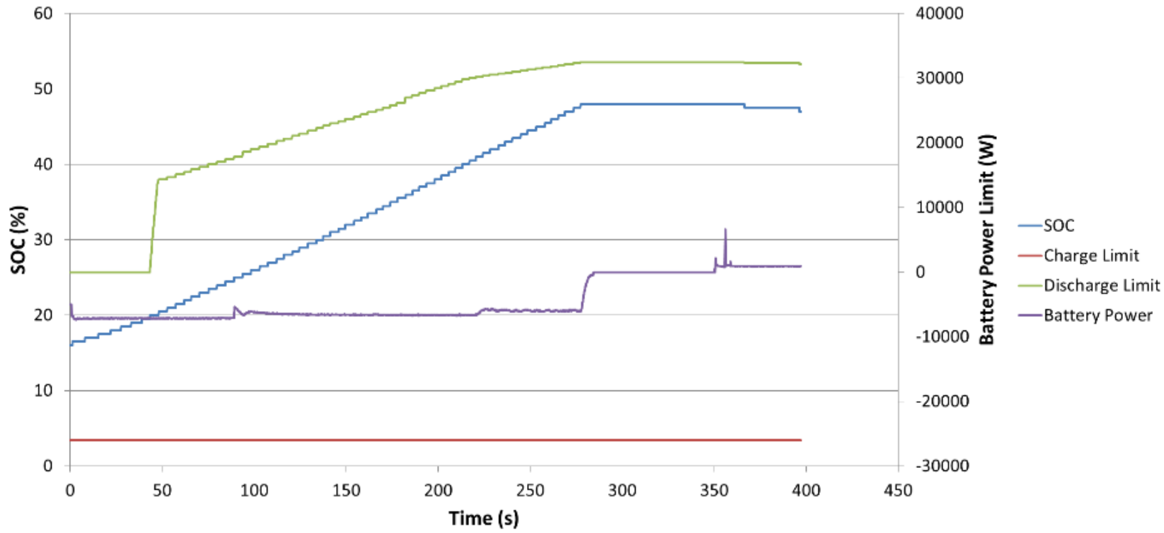

Figure 51: Hyundai Sonata resumption of normal operation (after sccantool supported engine start)

Ford Focus BEV

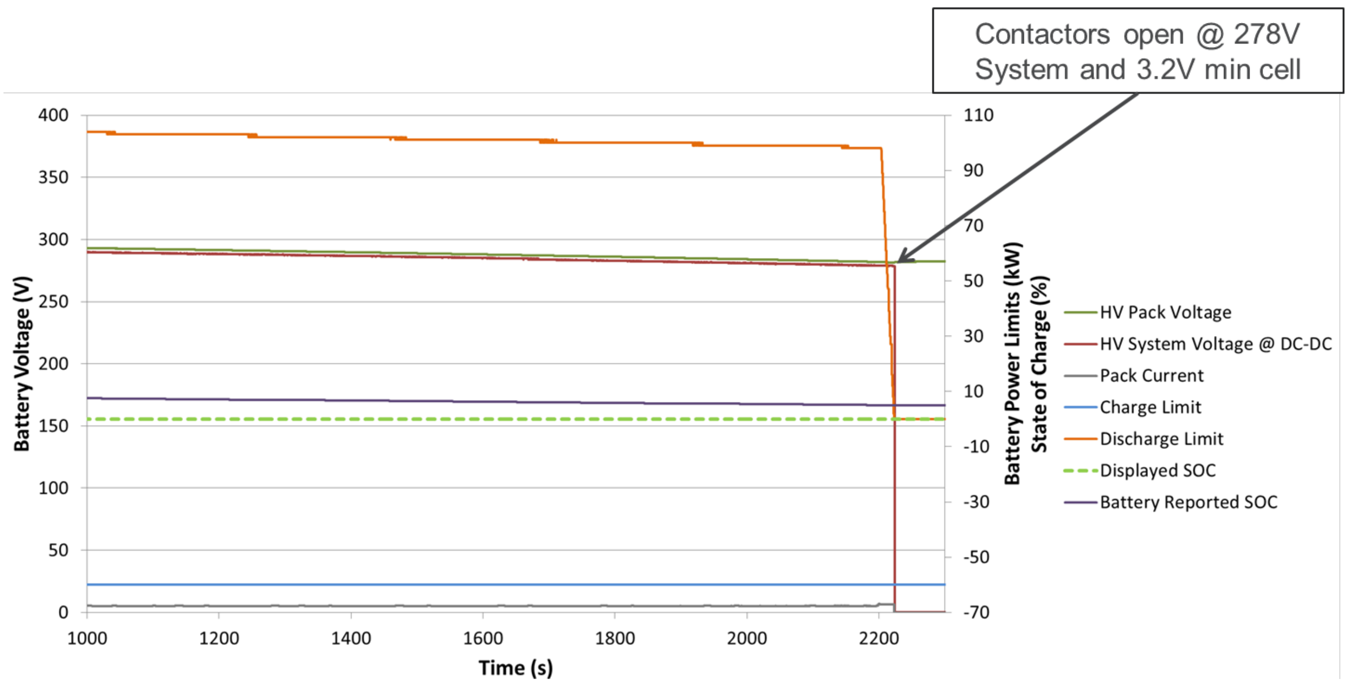

Figure 52: Ford Focus BEV overdischarge test

Chevrolet Volt

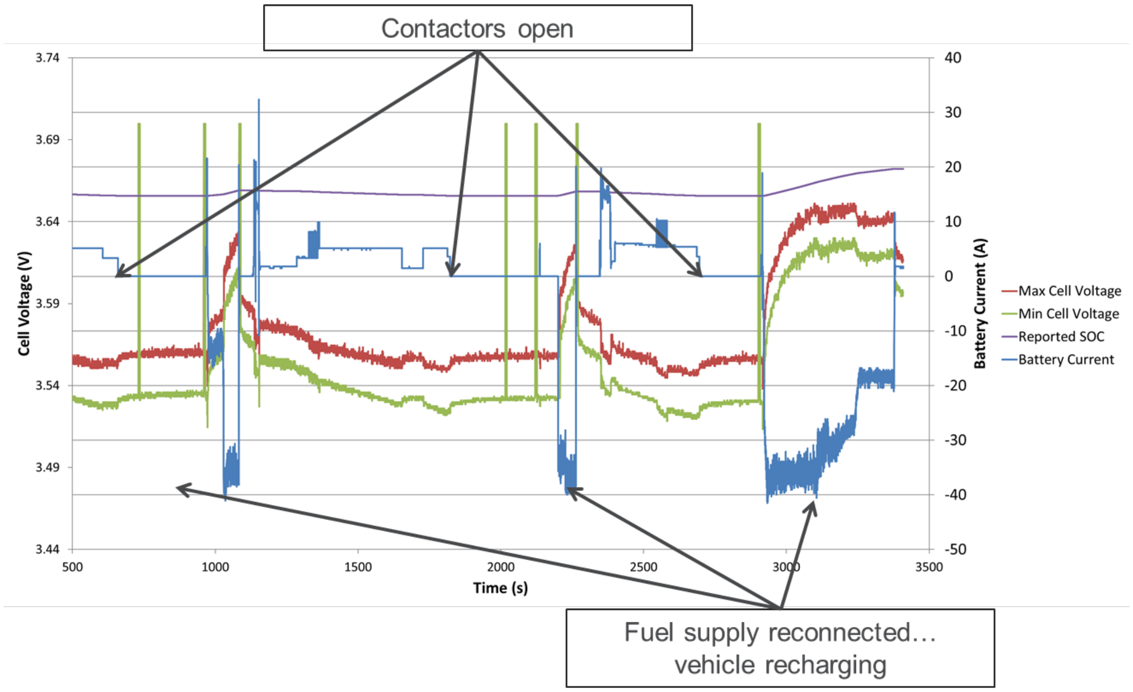

Figure 53: Chevrolet Volt - Overdischarge test

Nissan Leaf

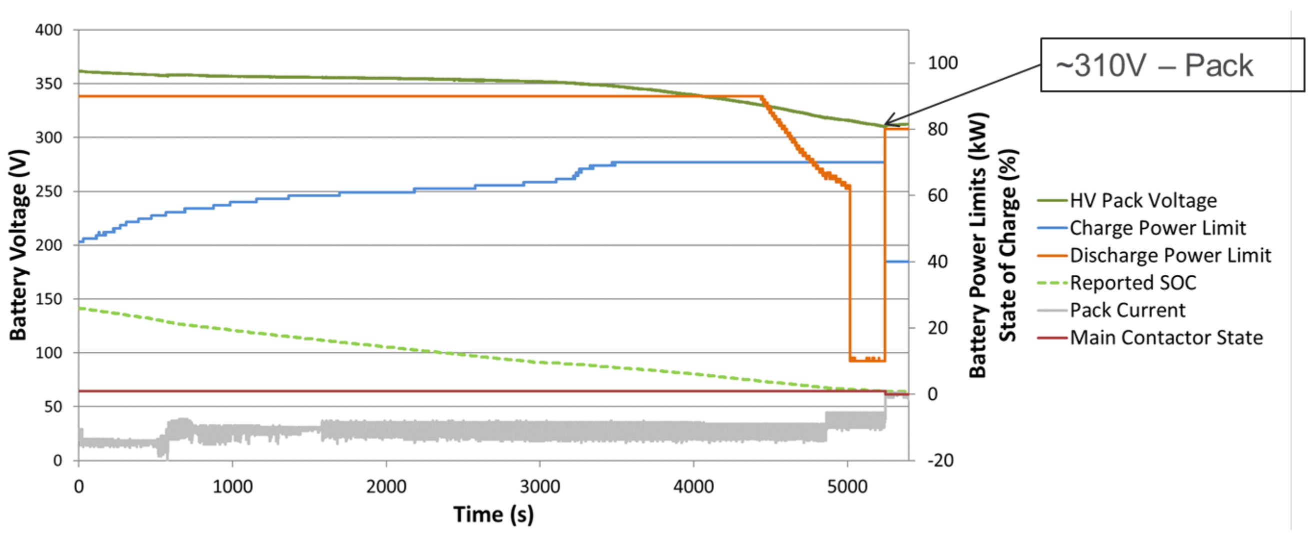

Figure 54: Nissan Leaf - Overdischarge test

Appendix C - Overcharge Procedure Validation Testing Results

This appendix provides supplemental test results for each of the candidate vehicles used for testing.

Honda Accord PHEV

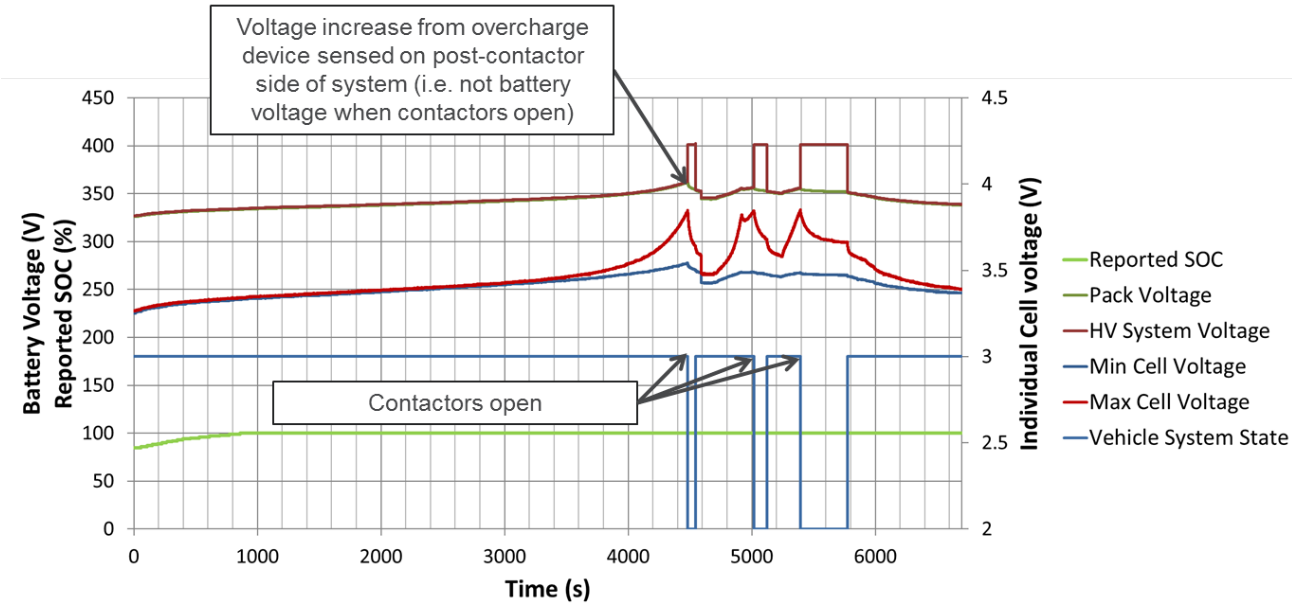

Figure 55: Honda Accord PHEV - Overcharge test validation results

Hyundai Sonata HEV

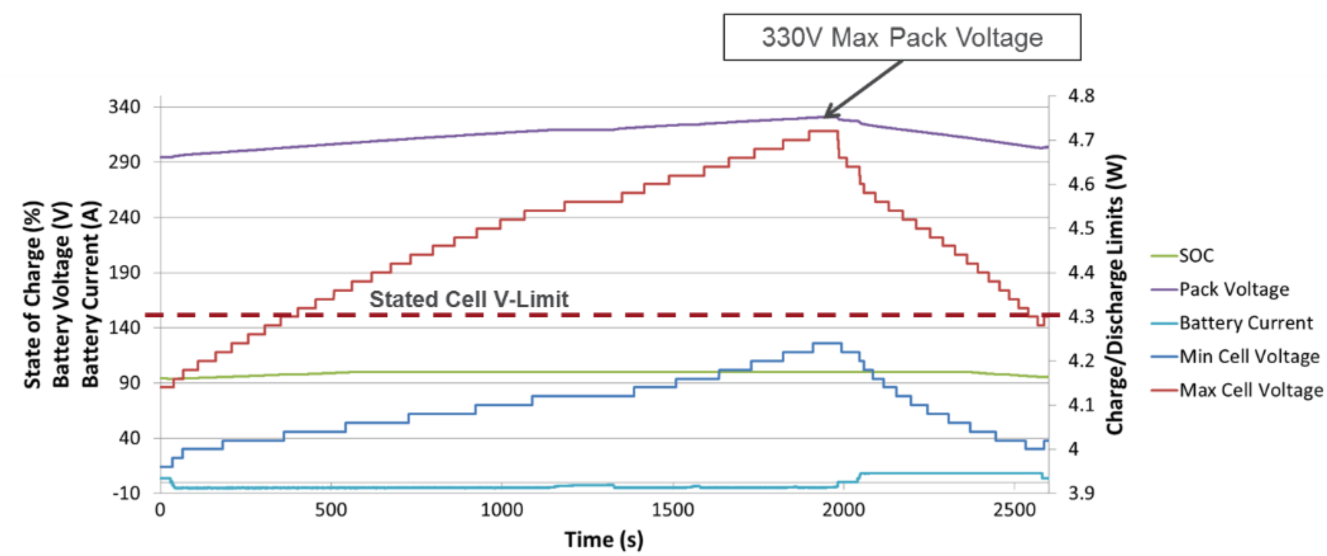

Figure 56: Hyundai Sonata HEV - Overcharge test validation results (testing ended manually)

Ford Focus BEV

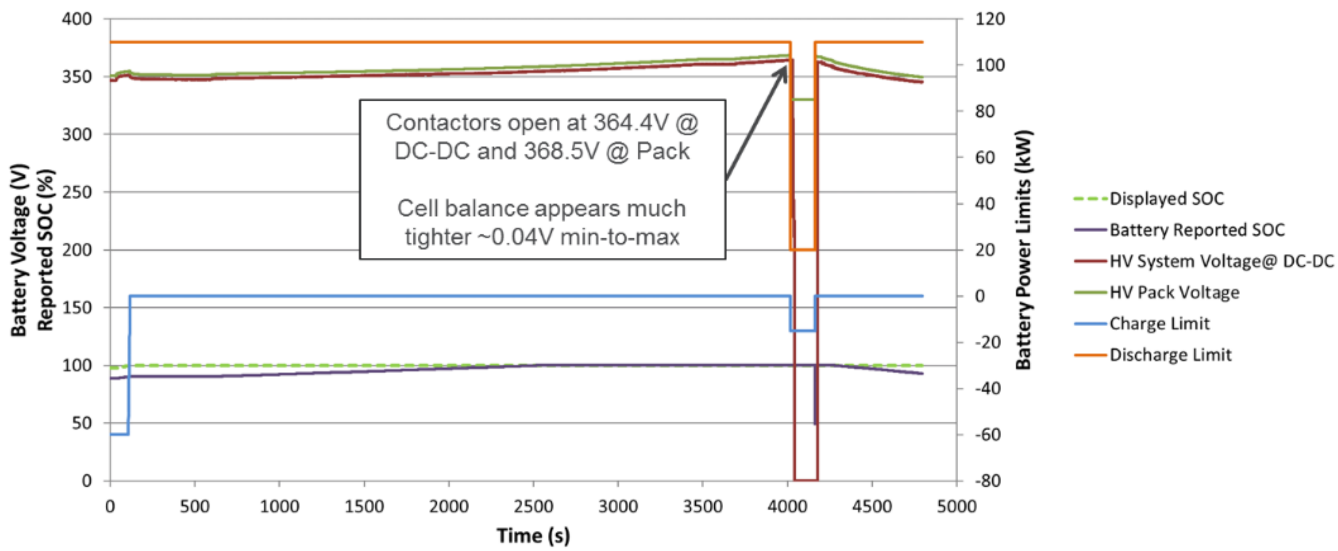

Figure 57: Ford Focus BEV - Overdischarge validation testing result

Chevrolet Volt

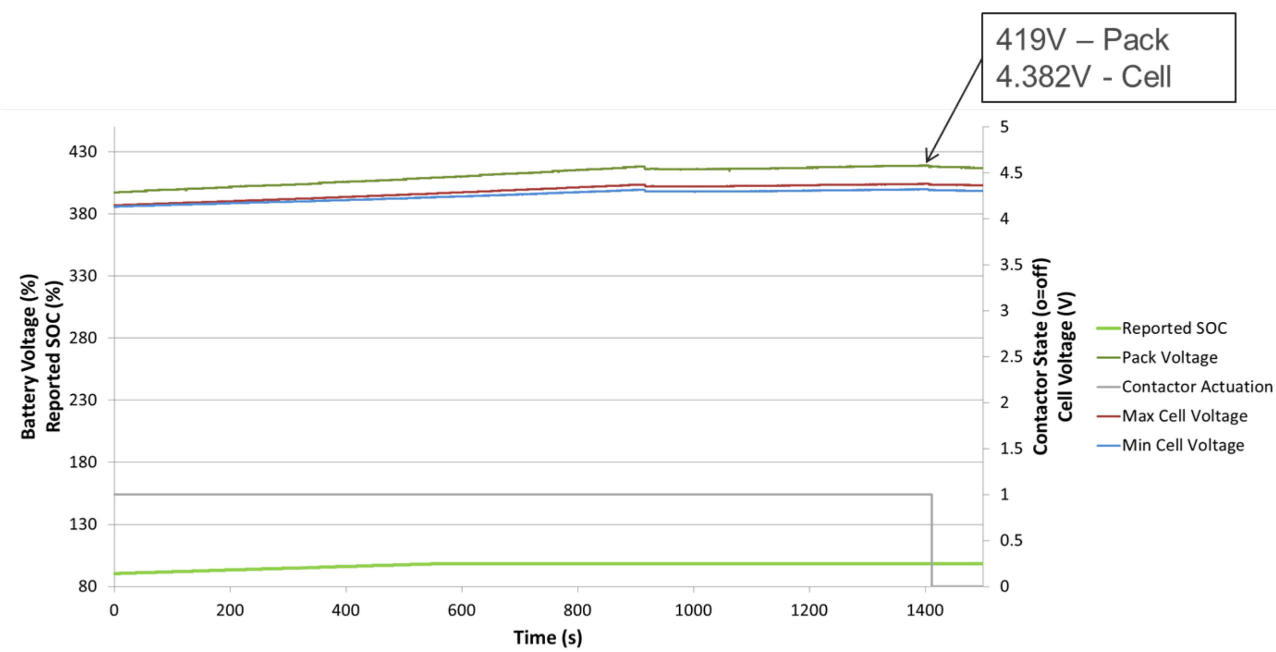

Figure 58: Chevrolet Volt - Overcharge validation testing

Nissan Leaf

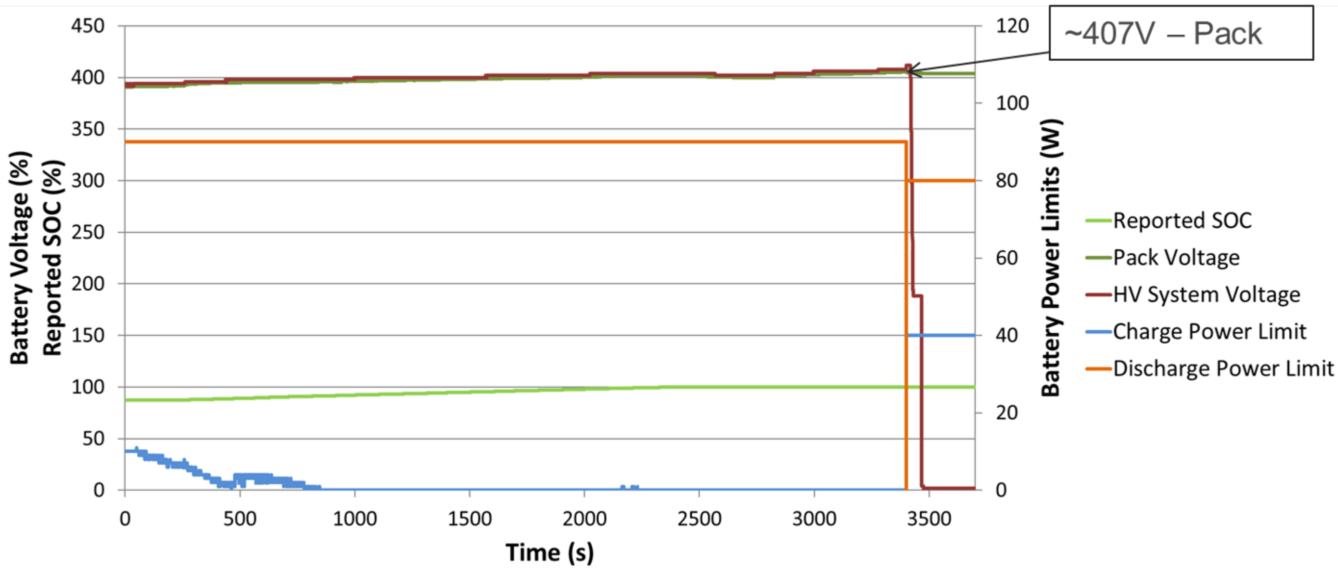

Figure 59: Nissan Leaf – Overcharge validation testing

Appendix D - Failed Cooling System Procedure Validation Testing Results

Honda Accord PHEV

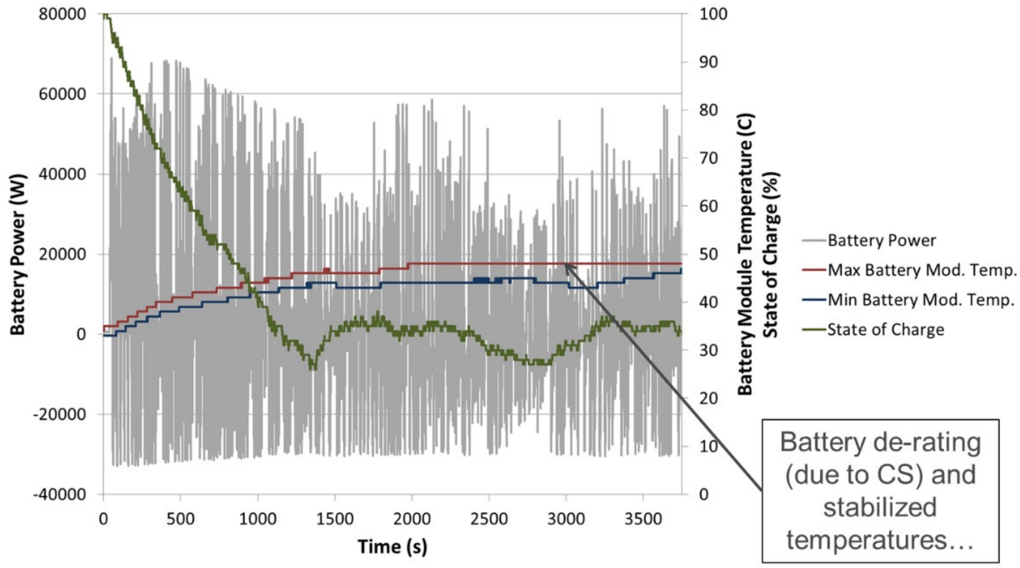

Figure 60: Honda Accord PHEV - Failed cooling system validation testing

Hyundai Sonata HEV

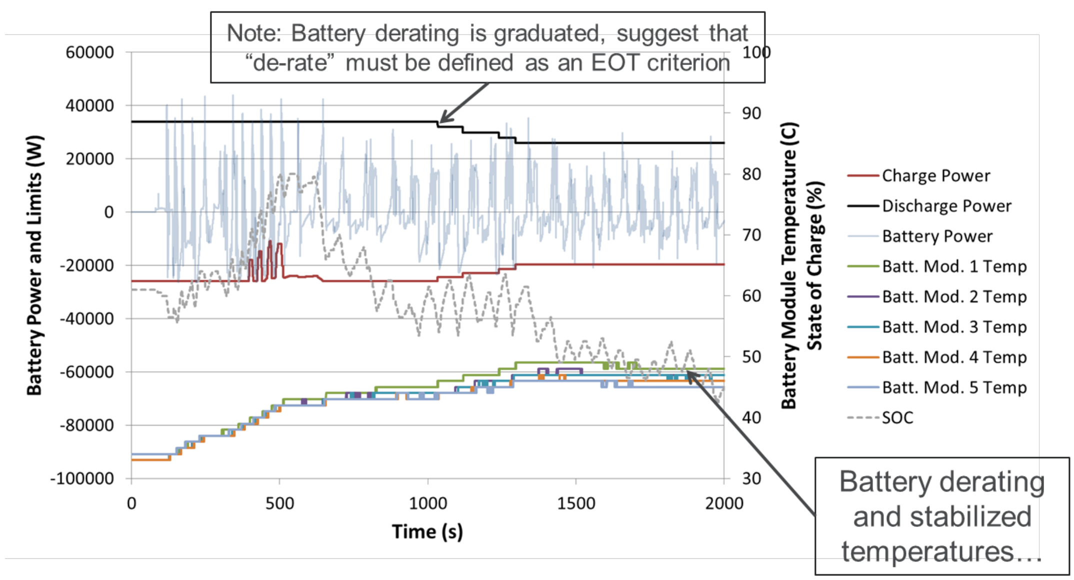

Figure 61: Hyundai Sonata HEV failed cooling system validation

Ford Focus BEV

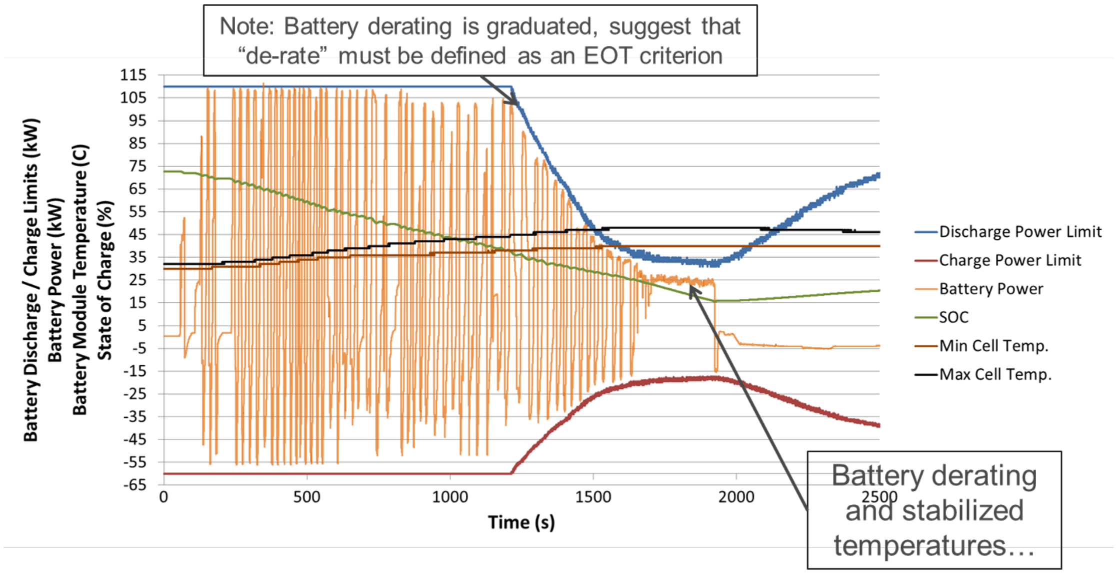

Figure 62: Ford Focus BEV failed cooling system evaluation

Chevrolet Volt

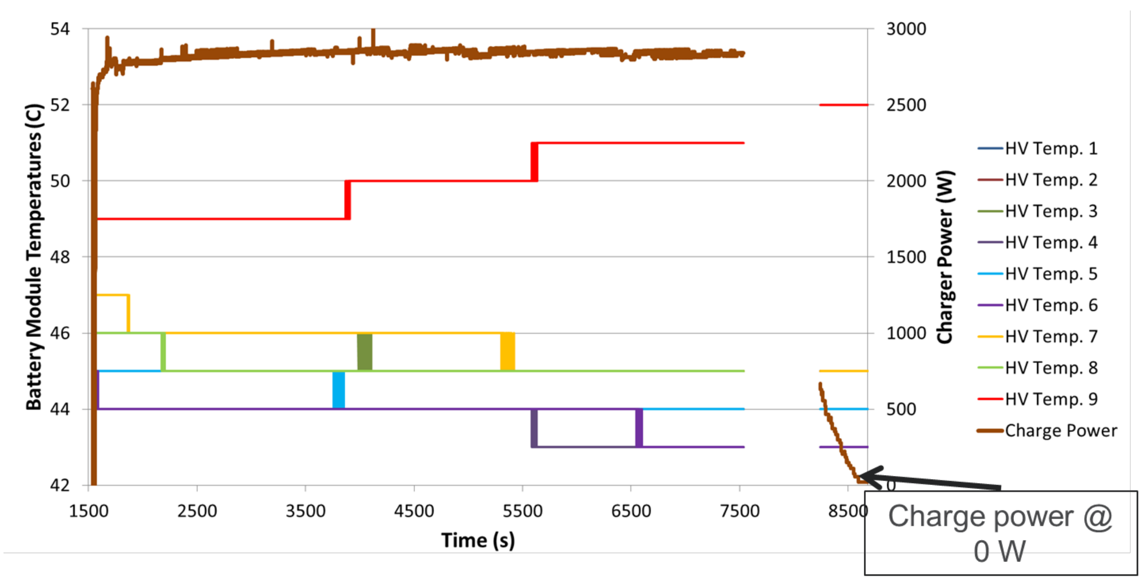

Figure 63: Chevrolet Volt failed cooling system testing and validation

Appendix E - Failed Heating System Procedure Validation Testing Results

Honda Accord PHEV

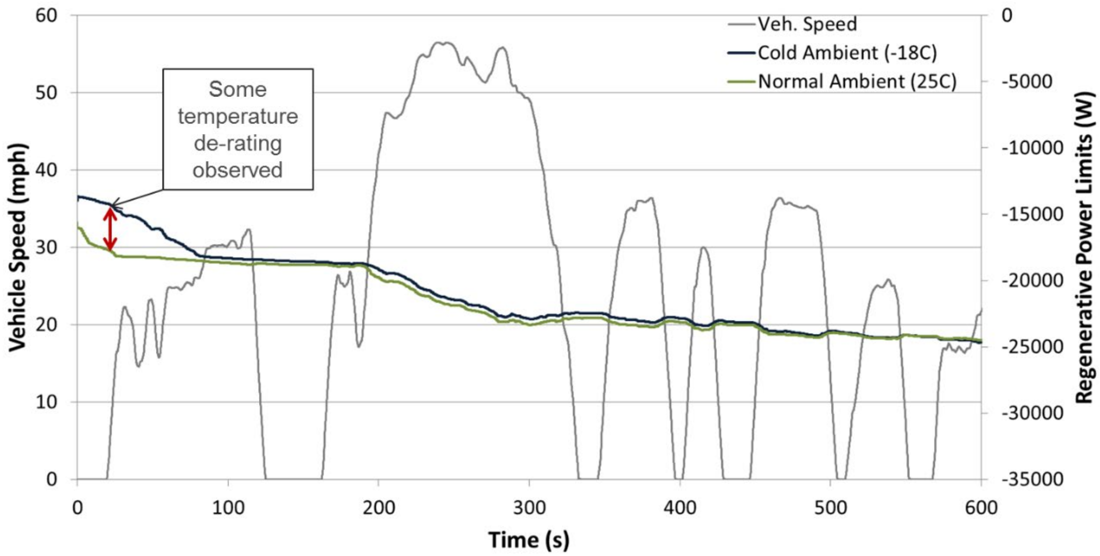

Figure 64: Honda Accord PHEV failed heating system validation

Ford Focus BEV

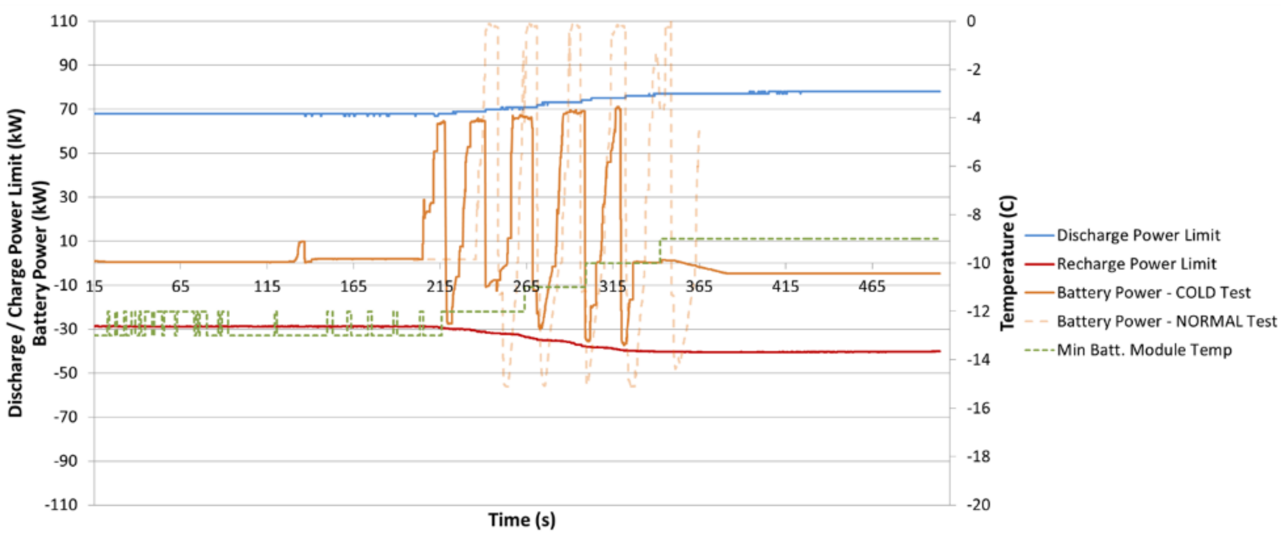

Figure 65: Ford Focus BEV failed heating system validation

Nissan Leaf

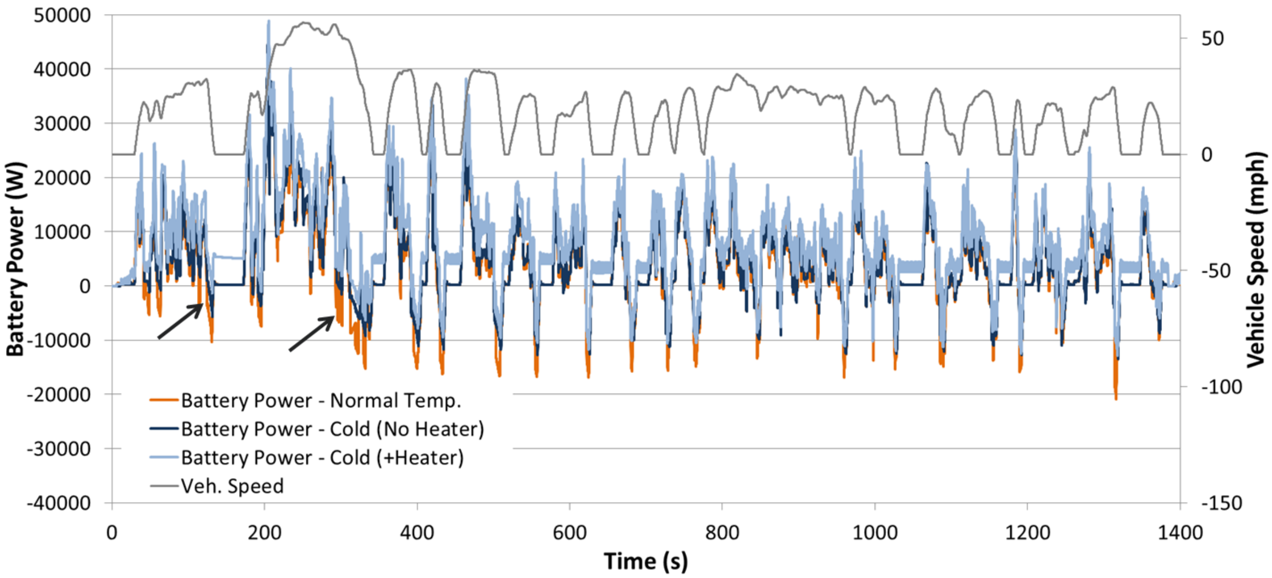

Figure 66: Nissan Leaf failed heating system validation

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