US Proposal for BMS Functionality
Sequential Fault Testing Requirements

1) Extreme-Temperature Protection

Low Temperature
High Temperature

2) Over-Discharging

Driving mode
Charging mode

3) Overcharging

Over-voltage
Over-current

4) Short Circuit

Text for requirements in Section 5

5.3.5 Sequential Fault Testing

This sequential test shall be conducted, under in-use operating conditions, either with:

1. a complete vehicle or
2. a complete REESS with related REESS subsystem(s), including the cells and their electrical connections. If the manufacturer chooses to test with related subsystem(s), the manufacturer shall demonstrate that the test result can reasonably represent the performance of the complete REESS with respect to its safety performance under the same conditions.

The test may be performed with a modified Tested-Device provided these modifications shall not influence the test results.

Contracting Parties may choose to adopt one of the above test configurations or both.

5.3.5.1 **Low-Temperature Protection**

The test shall be conducted in accordance with paragraph 6.3.5.1

During the test there shall be no evidence of; electrolyte leakage, rupture (applicable to high voltage REESS(s) only), smoke, fire or explosion.

[The evidence of electrolyte leakage shall be verified by visual inspection without disassembling any part of the Tested-Device].

For a high voltage REESS, the isolation resistance measured after the test in accordance with paragraph 6.1.1shall not be less than 100 Ω/Volt.

5.3.5.2 **High-Temperature Protection**

The test shall be conducted in accordance with paragraph 6.3.5.2

During the test there shall be no evidence of; electrolyte leakage, rupture (applicable to high voltage REESS(s) only), smoke, fire or explosion.

The evidence of electrolyte leakage shall be verified by visual inspection without disassembling any part of the Tested-Device.

For a high voltage REESS, the isolation resistance measured after the test in accordance with paragraph 6.1.1 shall not be less than 100 Ω/Volt.

5.3.5.3 **Over-discharge protection**

The test shall be conducted in accordance with paragraph 6.3.5.3

During the test there shall be no evidence of; electrolyte leakage, rupture (applicable to high voltage REESS(s) only), smoke, fire or explosion.

The evidence of electrolyte leakage shall be verified by visual inspection without disassembling any part of the Tested-Device.

For a high voltage REESS, the isolation resistance measured after the test in accordance with paragraph 6.1.1 shall not be less than 100 Ω/Volt.

5.3.5.4 **Over-current Overcharge protection**

The test shall be conducted in accordance with paragraph 6.3.5.4

During the test there shall be no evidence of electrolyte leakage, rupture (applicable to high voltage REESS(s) only), smoke, fire or explosion.

The evidence of electrolyte leakage shall be verified by visual inspection without disassembling any part of the Tested-Device.

For a high voltage REESS, the isolation resistance measured after the test in accordance with paragraph 6.1.1 shall not be less than 100 Ω/Volt.

5.3.5.5 **Over-voltage Overcharge protection**

The test shall be conducted in accordance with paragraph 6.3.5.5

During the test there shall be no evidence of electrolyte leakage, rupture (applicable to high voltage REESS(s) only), smoke, fire or explosion.

The evidence of electrolyte leakage shall be verified by visual inspection without disassembling any part of the Tested-Device.

For a high voltage REESS, the isolation resistance measured after the test in accordance with paragraph 6.1.1 shall not be less than 100 Ω/Volt.

5.3.5.6 **External short circuit protection**

The test shall be conducted in accordance with paragraph 6.3.5.6

During the test there shall be no evidence of; electrolyte leakage, rupture (applicable to high voltage REESS(s) only), smoke, fire or explosion.

The evidence of electrolyte leakage shall be verified by visual inspection without disassembling any part of the Tested-Device.

For a high voltage REESS, the isolation resistance measured after the test in accordance with paragraph 6.1.1 shall not be less than 100 Ω/Volt.

6.3.5 Sequential Fault testing

Definition:

UDDS: An urban operation simulating discharge cycle described in Appendix 1 to part 86 of the CFR, whose required operational precision is specified in 86.115-78 (*http://www.ecfr.gov/cgi-bin/text-idx?SID=4092415fbb4caf92f0b7c5db616c39bf&mc=true&node=se40.19.86_1115_678&rgn=div8*). For the purpose of this document only the speed and time requirements of this cycle will be applied**.**

DC Link: A DC link is a break-out box that consists of a switchboard, a discharge resistor unit, and a power supply that can be connected to the positive and negative terminal of the REESS.

The DC Link is used for the REESS over-discharge, over current overcharge, over voltage overcharge, and external short circuit tests. The switchboard contains a short circuit box to allow for shorting of the REESS, as well as two Tap boxes. The Tap boxes allow for a switched connection to the positive and negative terminal of the DC Link. All switches are rated for voltages up to 600 V and the entire switchboard is touch safe. See Appendix ( )

6.3.5.1 Low-temperature protection

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

6.3.5.1.1 If a REESS is thermally coupled to an active heater, and if the REESS will remain functional without heating function being operational, the heating system will be deactivated for the test

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

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

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

6.3.5.1.5 Place the vehicle with installed REESS 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 equalize to ambient temperature: at least 6 hours. Chamber temperature shall be logged during testing.

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

6.3.5.1.7 If an EV or PHEV is being tested, connect the vehicle to a charging system capable of supplying the maximum allowable charge rate for that vehicle, and attempt to charge the vehicle. Allow normal charge termination, or terminate charging one hour after the vehicle reaches a “steady state”: either a battery temperature remaining within ±2°C for 30 minutes and an SOC remaining within ±1% for 60 minutes, or a rate of change of SOC over the previous hour indicating that charging will require more than 10 hours to complete. If an HEV is being tested move to Step 6.3.5.1.8.

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

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

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

6.3.5.1.9 For an HEV, this test will terminate when discharge is complete, continue to step 6.3.5.1.12.

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

6.3.5.1.11 Regardless of the point of testing which has been reached, terminate the test after 24 hours have elapsed since the start of the step 6.3.5.1.8.

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

6.3.5.2 Vehicle Charge and Discharge during High Temperature Conditions: Failed Cooling System Simulation

6.3.5.2.1 If a REESS is thermally coupled to an active cooling system, and if the REESS will remain functional without cooling function being operational, the cooling system will be deactivated for the test.

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

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

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

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

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

For a vehicle with only a charge depleting operational mode (EV), adjust the vehicle speed and the dynamometer rolling resistance to induce the maximum sustained discharge power load for the vehicle REESS as determined in Section 6.3.5.1.2. Continue the discharge until the vehicle, reaches 5% SOC, the vehicle will no longer provide motive power, or for one hour after the vehicle has reached a steady state: either the REESS temperature remains within ±2°C for 30 minutes and the REESS SOC remains within ±1% for 60 minutes, or a rate of discharge of SOC over the previous hour indicates that discharge will require more than 10 hours to complete.

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

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

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

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

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

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

6.3.5.2.10 Regardless of the point in testing which has been reached terminate the test after 24 hours have elapsed since the start of step 6.3.5.2.6.

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

6.3.5.3 REESS Over-Discharge Test Procedure

6.3.5.3.1 Make the connection to the DC Link. Installation may require that the REESS be removed from the vehicle, and subsequently re-installed.

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

6.3.5.3.3 Chock the vehicle to prevent rolling or creep.

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

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

6.3.5.3.6 **Drive Mode Over-Discharge Attempt**

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

Install the ‘over-discharge resistor’ into the terminals of the DC Link connection box, and close the positive and negative terminal switches to create a circuit across the DC Link with a resistive load.

Allow the REESS to discharge at a power load of less than 1kW.

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

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

6.3.5.3.7 Should the vehicle not have separated driving and charging modes (e.g. an HEV), continue to step 6.3.5.3.9.

6.3.5.3.8 **Charge Mode Over-Discharge Attempt**

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

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

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

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

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

6.3.5.4 REESS Over-Current Overcharge Test Procedure

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

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

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

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

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

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

6.3.5.4.7 Connect the Over-Current Supply to the DC Link. Set the current limit and voltage limit on the Overcurrent Supply based on steps 6.3.5.4.5 and 6.3.5.4.6.

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

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

6.3.5.4.10 Place the vehicle into charging mode. For an EV or PHEV, connect a Level 1 charger to the vehicle and initiate charging. If the vehicle is a HEV with no separate charging and discharging mode, place the vehicle into an operational mode. Allow charging currents to stabilize.

6.3.5.4.11 Turn on the Overcurrent Supply connected to the DC Link and linearly increase the attempted charging current over 1000 seconds from zero current until it reaches the maximum charging current determined in step 6.3.5.4.6 or until the REESS isolates itself from the power supply.

6.3.5.4.12 Continue to attempt to charge at the final charging current reached in step 6.3.5.4.11 until the automatic disconnect in the REESS opens and remains open for at least 2 hours, 24 hours elapse.

6.3.5.5 REESS Over-Voltage Overcharge

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

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

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

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

6.3.5.5.5 Determine the appropriate current limit: divide 1.4 kW (Level 1 charging power) by the maximum voltage determined in step 6.3.5.5.4.

6.3.5.5.6 Connect an Overvoltage Supply to the DC Link. Set its voltage limit to the maximum voltage determined in step 6.3.5.5.4. Set the current limit to the maximum current determined in step 6.3.5.5.5. If the Overvoltage Supply is of the type which features both a current/voltage limit and a trip current/voltage setting, the trip values should be set 10% higher than the current/voltage limit.

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

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

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

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

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

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

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

6.3.5.6 REESS External Short Circuit

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

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

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

6.3.5.6.4 Chock the vehicle to prevent rolling or creep.

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

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

6.3.5.6.7 Place the vehicle into Drive Mode.

6.3.5.6.8 Connect the short circuit device to the DC Link.

6.3.5.6.9 Create the short circuit across the DC Link, causing a short circuit of the REESS and vehicle high voltage system. The total impedance of the short circuit shall be between 2 and 5 mΩ. It shall not be greater than 5 mΩ.

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

APPENDIX ( )
DC Link Function and Installation

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

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

- The Vehicle OEM should provide the testing agency with documentation detailing how a DC Link can be installed with minimum disruption to the vehicle systems. Generally, vehicle high voltage cables should be accessible adjacent to the RESS-to-vehicle high voltage connection.
- The DC Link should be electrically connected as close as possible to the outside of the RESS enclosure. There should be no active or passive protection components between the DC Link connection and the RESS unless they are contained within the RESS. This includes devices such as fuses, thermally activated switches, or relays. Examples of DC Link installation points in a variety of vehicles are shown in Section 8.1.
- The Vehicle OEM should provide information regarding expected short circuit current, maximum operational pack voltage, and a pack charge capacity vs. voltage curve to allow construction of an appropriate DC Link including cable gauge.
- The DC Link shall be sufficiently isolated from all other parts of the vehicle. This isolation shall be capable of withstanding a voltage difference equal to U + 1695V.
- Joints or terminals shall be of a design capable of secure and low resistance connection such as a bolt secured lug.
- Cables used in the DC Link shall be rated to safely conduct the currents levels expected in all test procedures such that they do not become a failure point.
- Exposed high voltage should be minimized as part of the DC Link.
- Many functionally equivalent circuits are possible, but care should be taken to select components which are rated for the appropriate currents and voltages.
- Vehicle shall be able to charge and discharge normally with the DC Link connection installed.

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

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

- Appropriate information regarding sizing of the fuses in the vehicle and RESS should be provided by the Vehicle OEM.
- The switch shall be capable of withstanding the short circuit discharge current of the RESS.
- The short circuit box shall be fused to protect the DC link cables, connections and shorting switch. The short circuit device should be sized such that it does not interrupt the test. After the short circuit test, the fuses should be checked and if still intact then the test is valid. Otherwise, the short circuit device needs to be scaled up such that the vehicle or RESS interrupts the short circuit test.

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

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

- The over-discharge resistor may represent a significant hazard during operation, and should be physically isolated from other circuit components and flammable material.
- This unit should be sufficiently cooled, for example, with air blowing fans, to allow it to maintain a safe operating temperature.

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

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

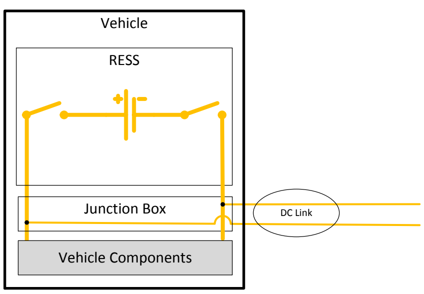

Figure 1: Diagram of DC link for as tested for Manufacturer A.

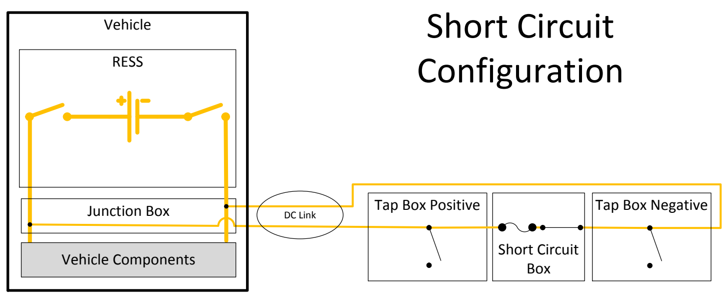

Figure 2: Diagram of DC Link with switchboard configured for the Short Circuit Test.

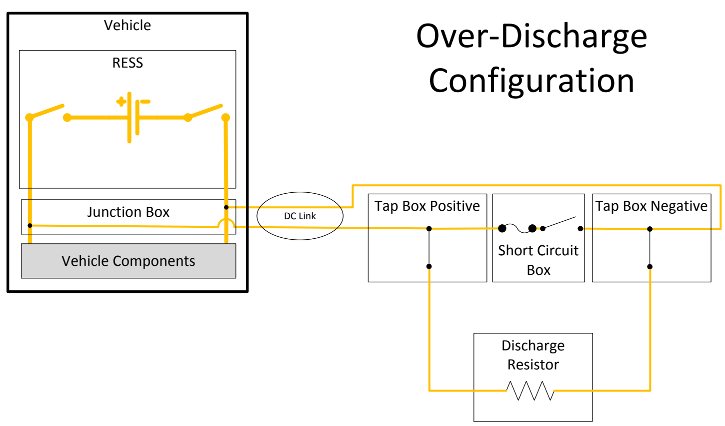

Figure 3: Diagram of DC Link with switchboard and discharge resistor configured for the Over-Discharge Test.

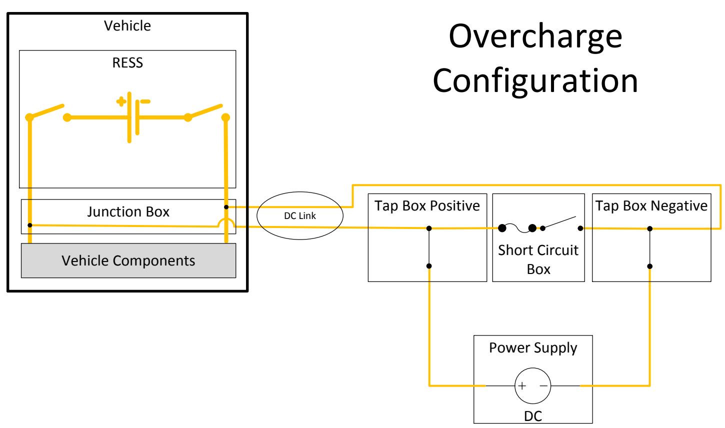

Figure 4: Diagram of DC Link with switchboard and power supply configured for the Overcharge Tests.

Figure 5: The switchboard (left) and discharge resistor (right). The discharge resistor is protected beneath a mesh cage to prevent inadvertent contact by an operator. During use a fan provided cooling air across the resistors to maintain their temperature.

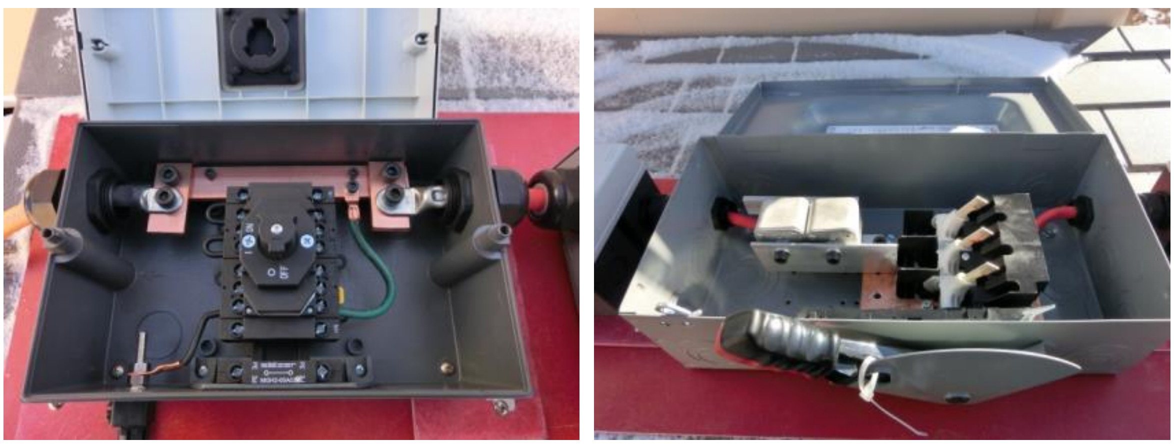

Figure 6: The interior of a Tap box (left) and the fused short circuit box (right). The fused shorting switch connects directly to the copper bus-bar seen inside the Tap box and to the same component on the other Tap box.

Rationale for sequential fault testing for GTR part A

1.1. Low Temperature, Failed Heating System Simulation

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

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

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

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

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

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

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

1.2. High Temperature, Failed Cooling System Simulation

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

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

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

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

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

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

1.3. Over-Discharge

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

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

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

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

1.4. Over-Current Overcharge

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

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

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

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

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

1.5. Over-Voltage Overcharge

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

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

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

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

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

1.6. External Short Circuit

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

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

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

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