National Highway Traffic Safety Administration

Status Update on NHTSA's Lithium-ion based Rechargeable Energy Storage System Safety Research Programs

May 2014

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NHTSA Vehicle Safety Research

Background

Fundamental Analysis

Test Procedure Development

- Pack Level Crush
- Overcharge
- Broad Range Impedance Short Circuit
- BMS Performance – DC Level 3 Fast Charge
- Vehicle Immersion
- Single Cell Thermal Runaway Initiation
- Thermal Containment
- Fire Exposure
- Vibration with Shock and Thermal Cycle
- Comprehensive Vehicle System Test
- Internal Isolation

Safety Assessment Methods and Tools

- Diagnostic Tool Set
- Stranded Energy

Automotive RESS Safety Management

Fundamental Analysis

FMEA has been received and is under final review

Hazard Analysis – (see: Automotive RESS Safety Management)

Test Procedure Development

All - Projects will be completed Sept 2014

Safety Assessment Methods and Tools

Diagnostic Tool Set – ongoing

Stranded Energy – Project will be complete Nov 2014

Automotive RESS Safety Management

Projects will be complete Dec 2014

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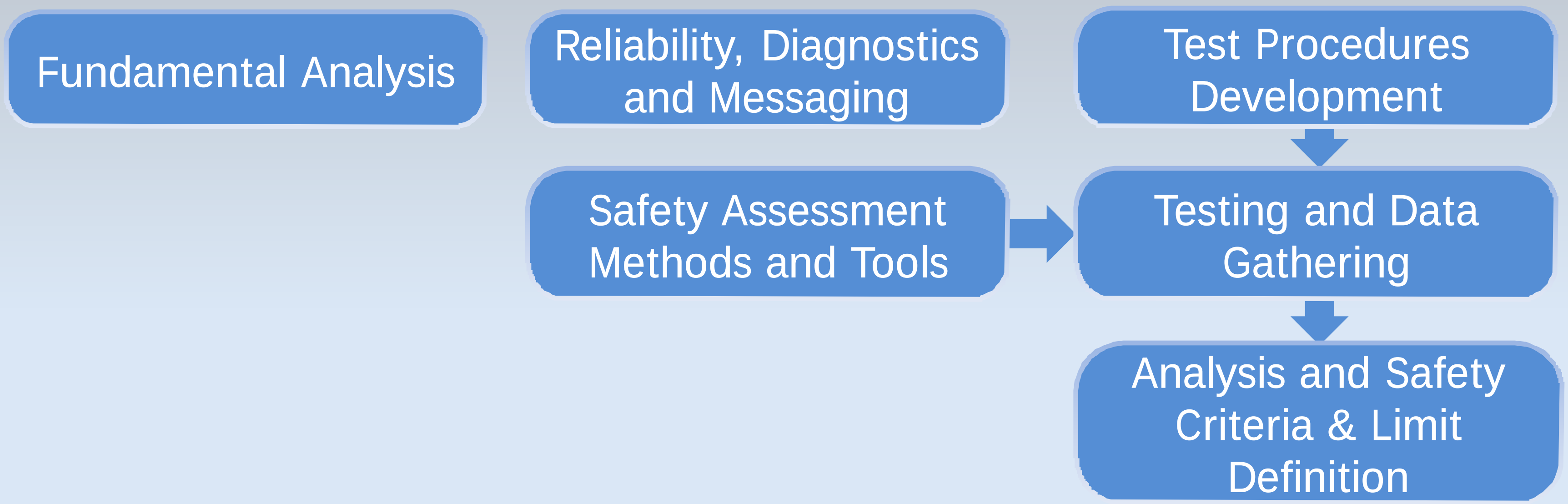
Background:

In 2010 NHTSA initiated research focused on the vehicle level safety performance attributes of a Li-ion RESS used in electric vehicle applications. The results of this research could potentially be used by NHTSA to support and establish minimum safety performance standards and compliance test procedures for RESS equipped passenger vehicles and light truck applications.

Background:

In 2010 NHTSA initiated research focused on the vehicle level safety performance attributes of a Li-ion RESS used in electric vehicle applications. The results of this research could potentially be used by NHTSA to support and establish minimum safety performance standards and compliance test procedures for RESS equipped passenger vehicles and light truck applications.



Research Partners include:

Sandia National Laboratories
SAE International
Ford
Ricardo
TÜV SÜD
U.S. Department of Energy
GM
Piston Group
Tesla
Intertek
Transport Canada / Transports Canada
TARDEC
Toyota
Argonne National Laboratory
NAVSEA Naval Sea Systems Command
AVL
INL Idaho National Laboratory
Southwest Research Institute
UL
Battelle The Business of Innovation
mga research corporation
Daimler
Volpe
ASG Renaissance
Nissan
Oak Ridge National Laboratory
Honda
NFPA
MFRI Maryland Fire and Rescue Institute

Others ...

Fundamental Analysis:

Both NHTSA and it's research partners performed and relied on a variety of fundamental engineering analysis techniques including: FMEA, FTA, STPA, and Hazard Analysis in project descriptions and completion.

1) Originally titled as a Failure Modes and Effects analysis (FMEA), this project describes and catalogs li-ion technology and the numerous hazards detailed to its components and various operational and abuse conditions.

2) Hazard Analysis and System Theoretic Process Analysis (STPA) has been used in the projects evaluating System functional safety, diagnostics and messaging, and prognostic indication.

Test Procedures Development:

Contracts were awarded to develop comprehensive and repeatable safety test procedures, comparison metrics, and performance criteria to analyze automotive style Li-ion based RESS against their potential safety related failure modes.

The scope of these projects are to focus on complete systems, in-vehicle when possible and component level where necessary.

The range of battery operation being considered includes all modes and environments throughout complete vehicle/battery life.

Test Procedures Development:

The test procedures address both single point and dual point failure modes as may be experienced in a vehicle having lost function of its active portion of the control system during charging or operation.

These projects intended to:

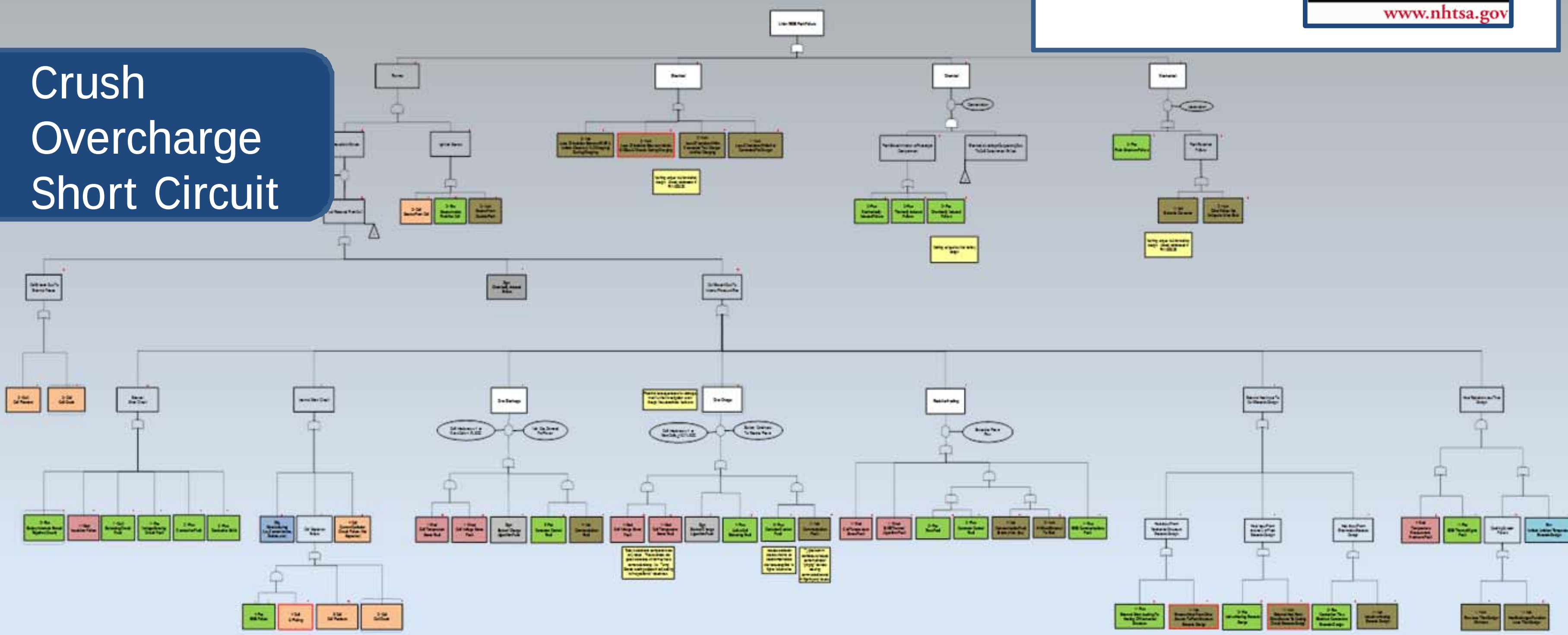
1) Leverage subject matter experts from a diverse set of stakeholders within this technology
2) Build upon existing standards from automotive and similar applications
3) Introduce new test methods which will better assess system level safety performance.

All the following examples and summaries of test procedures are excerpts or references from draft procedures that have been developed for NHTSA research.

Test Procedures Development:

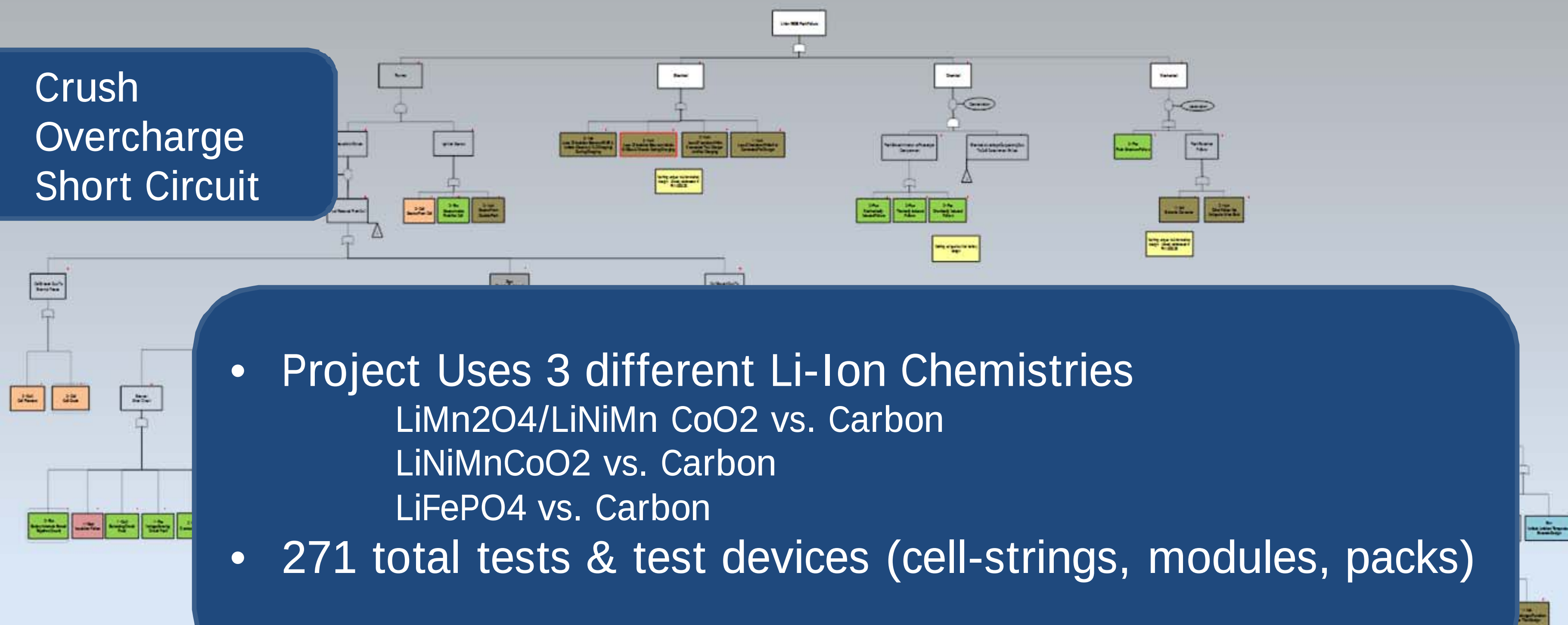
Cooperative Research Program

- Crush
- Overcharge
- Short Circuit



Test Procedures Development:

- Crush
- Overcharge
- Short Circuit



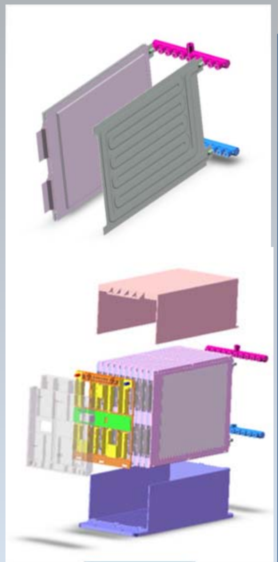
- Project Uses 3 different Li-Ion Chemistries
  - LiMn2O4/LiNiMn CoO2 vs. Carbon
  - LiNiMnCoO2 vs. Carbon
  - LiFePO4 vs. Carbon
- 271 total tests & test devices (cell-strings, modules, packs)

Test Procedures Development: Example #1

Pack Level - Crush

Goal:
Develop a pack-level crush test reflecting 3-axis inputs supported by progressive data derived from cell-string, module, and pack data.

Safety Metric:
Quantifying both venting (EUCAR 3-4) and fire (EUCAR 5) in each axis of the device under test (DUT).



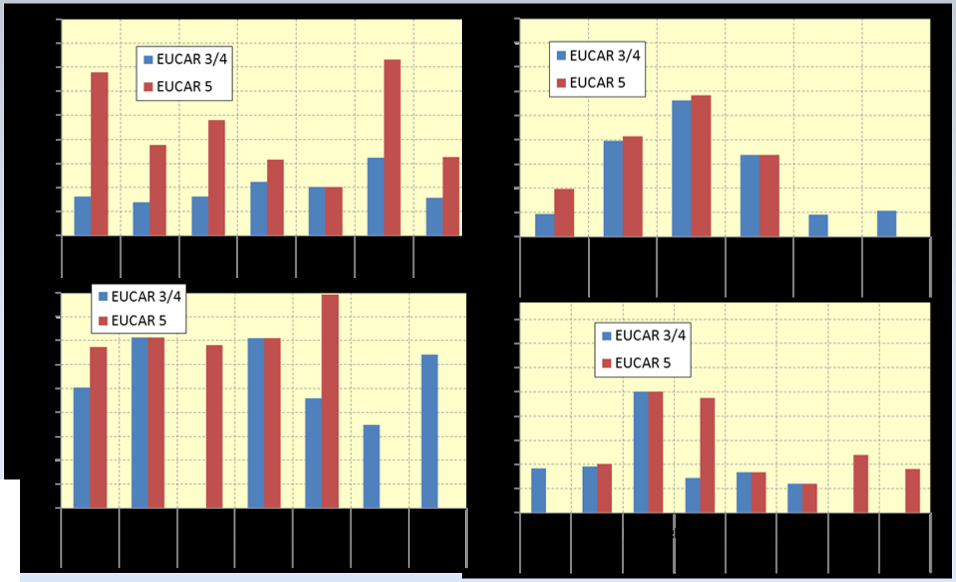
Test Procedures Development:

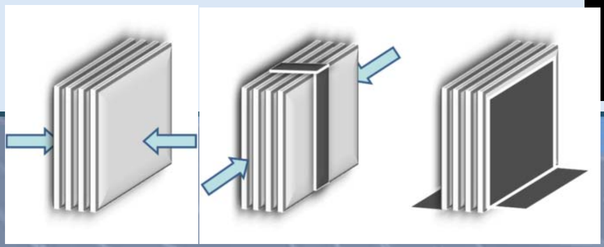
Pack Level - Crush

Approach:

The procedure analyzes two separate techniques:

1. Quasi-static crush (Stepped) up to 85%, with a single cycle at each stop point.
2. Continuous crush up to 85% crush





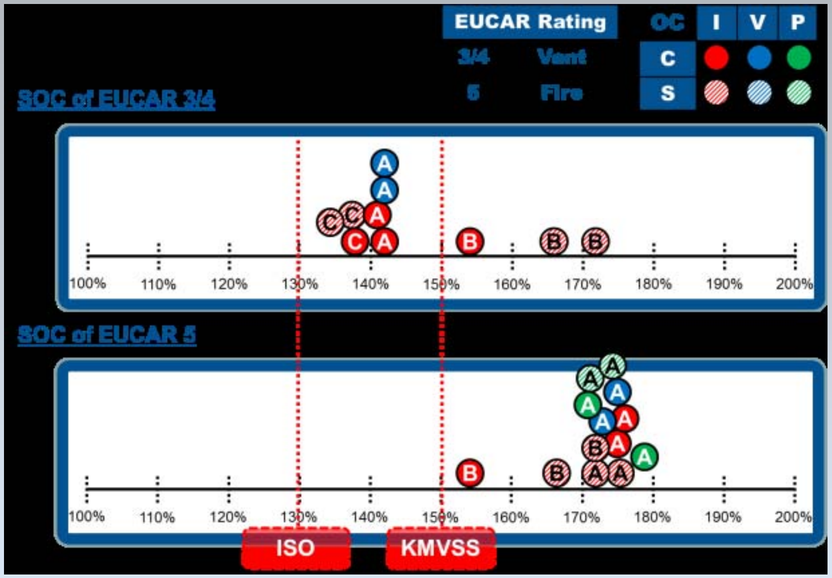
Test Procedures Development: Example #2

Overcharge Test

Goal:
Develop a test to analyze the safety limit of overcharge (cell-string, module, pack)

Safety Metric:
Quantify both (EUCAR 3-4) venting and (EUCAR 5) fire

Approach:
Utilizing both constant and scaled (Current, Voltage, and Power)



Test Procedures Development: Example #3

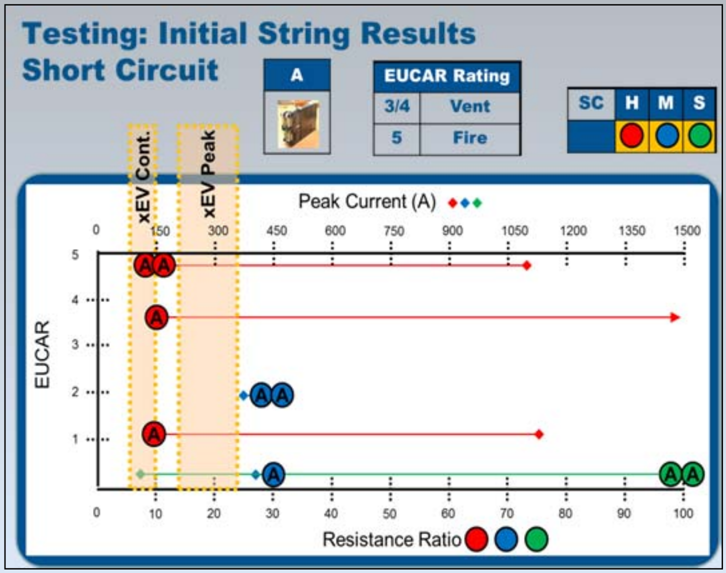
Broad Range Impedance Short Circuit

Goal:

Develop a test to quantify the safety effect of short circuit exposure in a variety of impedance conditions (soft, medium, hard) in cell-string, module, and pack configurations

Safety Metrics:

Measuring peak current and (EUCAR 3-4-5) evaluations



Test Procedures Development:

Cooperative Research Program

- BMS Performance (DC Level 3 fast charge)
- Vehicle Immersion
- Single Cell Thermal Runaway Initiation
- Thermal Containment & Mitigation
- Fire Exposure
- Vibration with Shock & Thermal Cycle
- Comprehensive Vehicle System Test
  - Over-discharge
  - Under temperature charge
  - Over temperature test
  - Over-voltage overcharge
  - Over-current, under temperature overcharge
  - External short circuit
- Internal Isolation

Test Procedures Development: Example #4

DC Level 3 Fast Charge – BMS performance

Goal: Test methods to evaluate RESS BMS response to failure modes and boundary condition limits during a DC Level 3 Fast Charge

Safety Metric: Evaluate the BMS safety response to charging system conditions

Approach:

1. Failure Mode Identification and Evaluation
   - Developed a Block Diagram of BMS interaction with vehicle functions and prepared a comprehensive list of Failure Modes
   - Use DFMEA experience gained from prior analysis of commercial battery pack
   - Developed concept for “Breakout Box” interface between charger and vehicle.
2. Validate and Demonstrate (Full Vehicle Test 5/12/14 – 6/27/14)

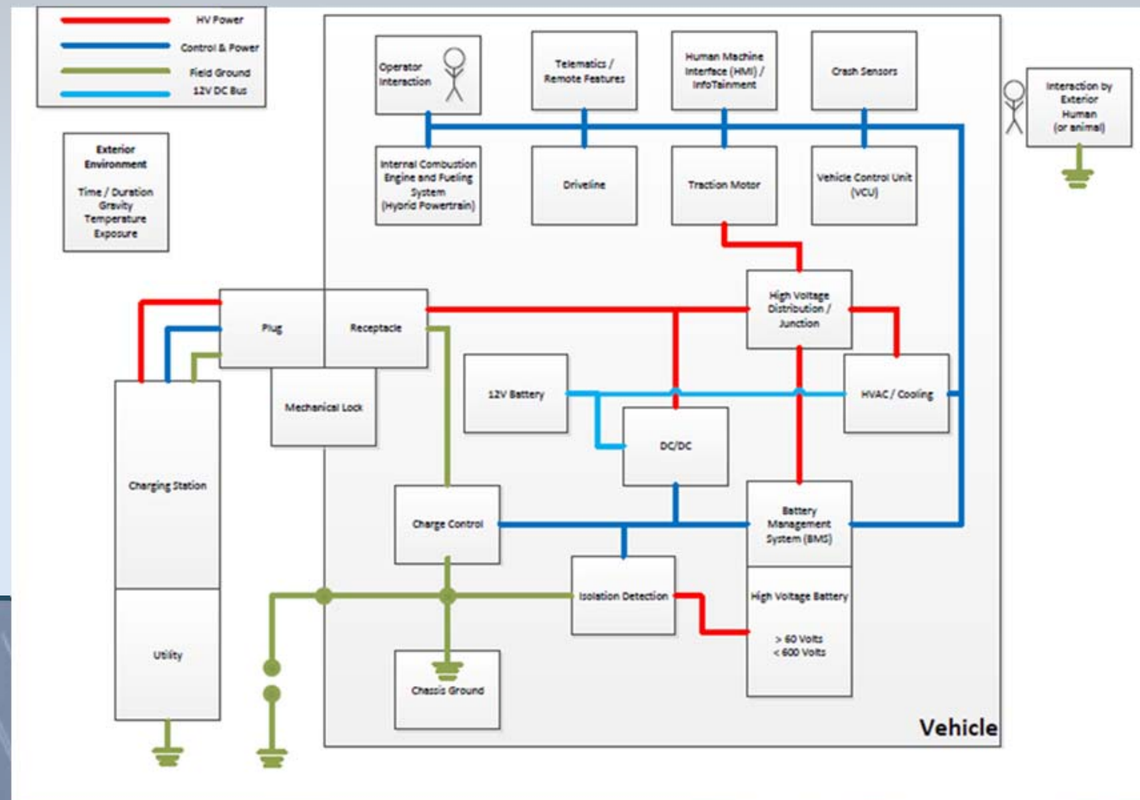
Test Procedures Development:

DC Level 3 Fast Charge – BMS performance

Block Diagram:

A Block Diagram developed was used as the framework to identify failure modes. The list of failure modes will be presented in a matrix which will contain the following information:

- Identify Failure Mode.
- Cause(s).
- Desired BMS reaction.
- Identify how to induce the failure.
- Measure response of BMS.
- Develop Pass/Fail criteria.



Test Procedures Development:

DC Level 3 Fast Charge – BMS performance

System Sub-tests:

- Ground Fault Test
- Chassis Ground Offset Test
- DC Bus Short Test
- DC Bus Held High Test
- System Overvoltage Test (12V Board)
- 12V System Under voltage Test
- 12V System Disturbance Test
- 12V System EMI/EMC Test
- Vehicle Movement Test
- Vehicle Crash or Bump Test
- Charge Operation Disturbance Test
- Charge Connector Control Signal Disturbance Test
- Charge Connector Field Ground Connection Disturbance
- Charge Connector HV Connection Disturbance
- Visual Inspection of Charge Port
- Cooling Heating System
- BMS Internal Fault Detection
- Overcharge Test

Test Procedures Development:

DC Level 3 Fast Charge – BMS performance

Approach:

Each of the 18 test procedures has the following components:

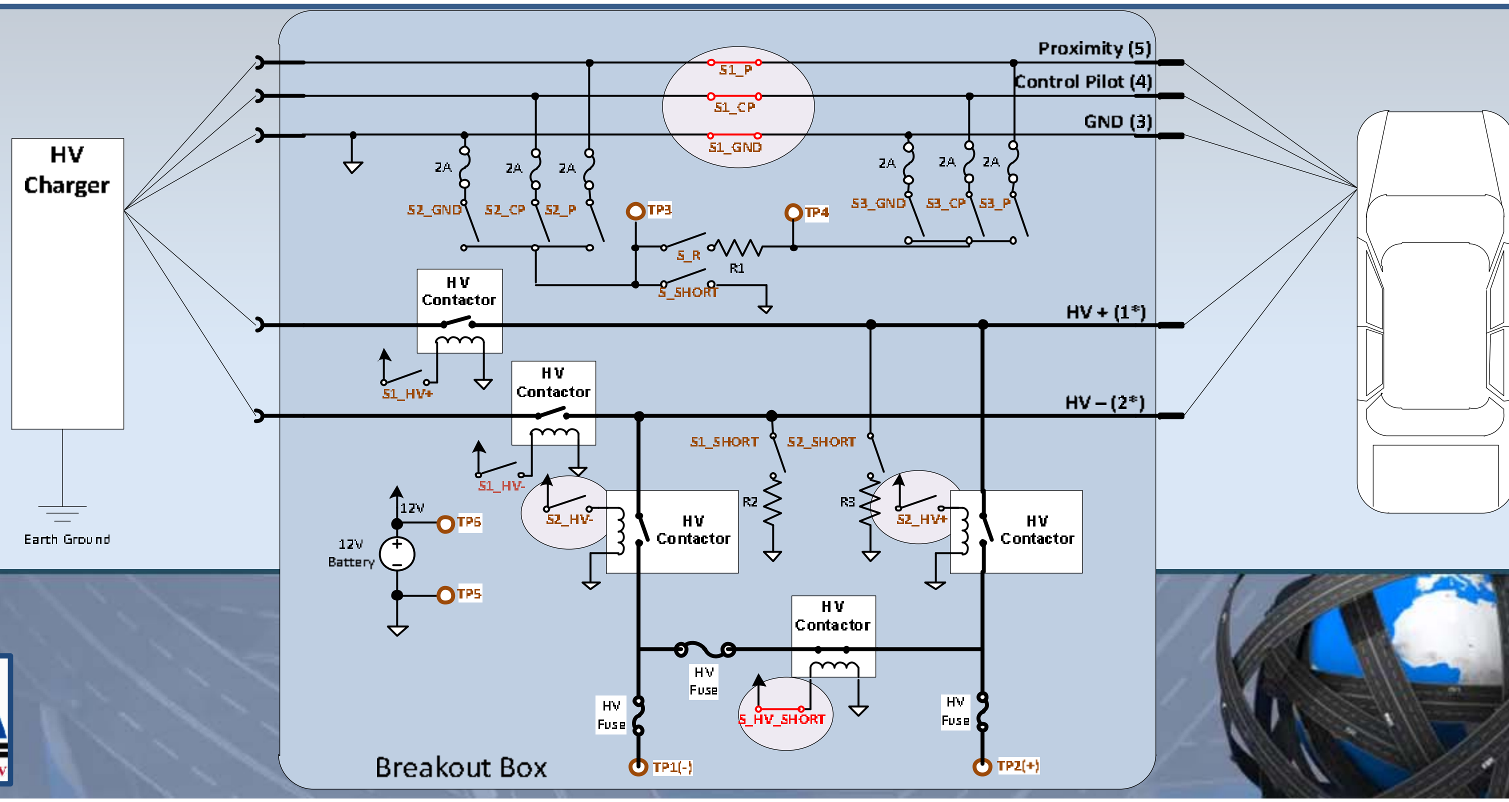
1. Purpose
2. Rationale and Description
3. Sample Preparation
4. Equipment Setup
5. Test Method and Procedure
6. End of Test Procedure
7. Documentation and Evaluation
   a. Documentation
   b. Pass Fail Criteria

Test Procedures Development:

DC Level 3 Fast Charge – BMS performance

Breakout Box demonstrating: DC Bus Short Test

CLOSED FOR INITIAL CONFIGURATION AT EQUIPMENT SETUP																	
MANIPULATED DURING TEST																	
S1_P	S1_CP	S1_GND	S2_P	S2_CP	S2_GND	S3_P	S3_CP	S3_GND	S_R	S_SHORT	S1_SHORT	S2_SHORT	S1_HV+	S1_HV-	S2_HV+	S2_HV-	S_HV_SHORT
CLOSED	CLOSED	CLOSED															CLOSED



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Test Procedures Development: Example #5

Vehicle Immersion Test

Goal: Test methods at the vehicle level (full system operational) for evaluating the effect of immersion in 3.4% salt water

Safety Metric: Determine safety effect in terms of:

- Loss of HV isolation
- Toxic gas exposure and flammability
- Thermal activity

Approach:

Immersion in a steel container (2.1m (h) x 2.4m (w) x 6m (l))

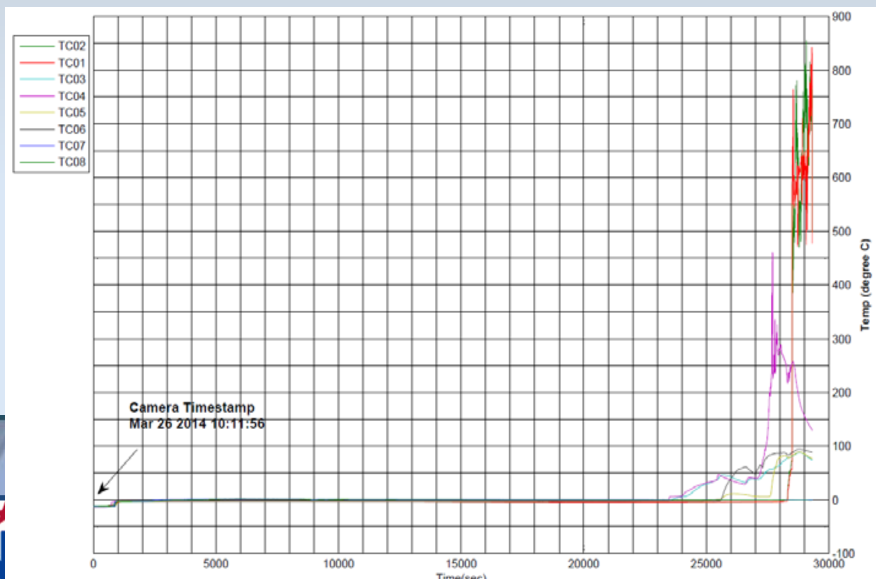
- 10 minute fill to 1 meter above bottom of the battery tray
- 2hr. Hold
- 10 minute drain
- 6 Week Observation

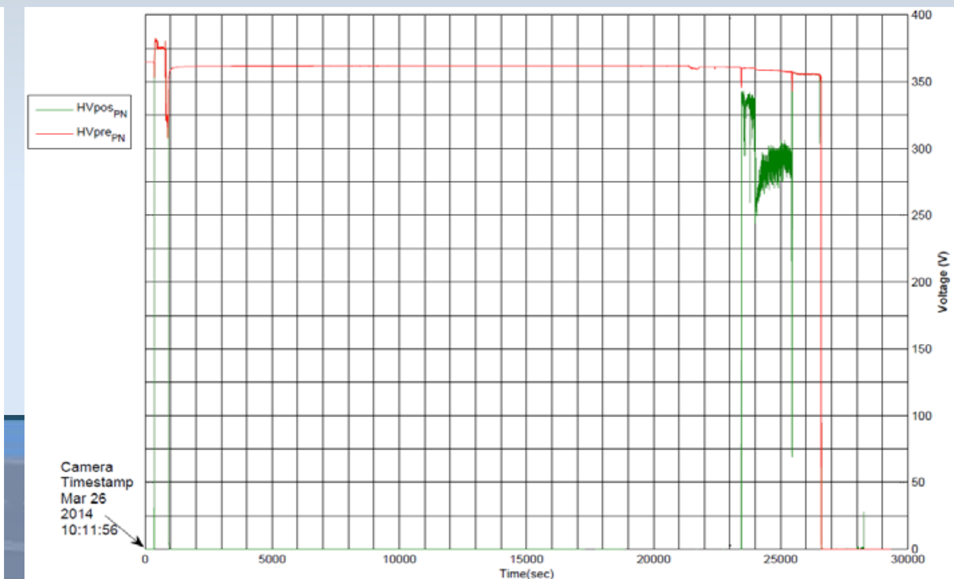
Test Procedures Development:

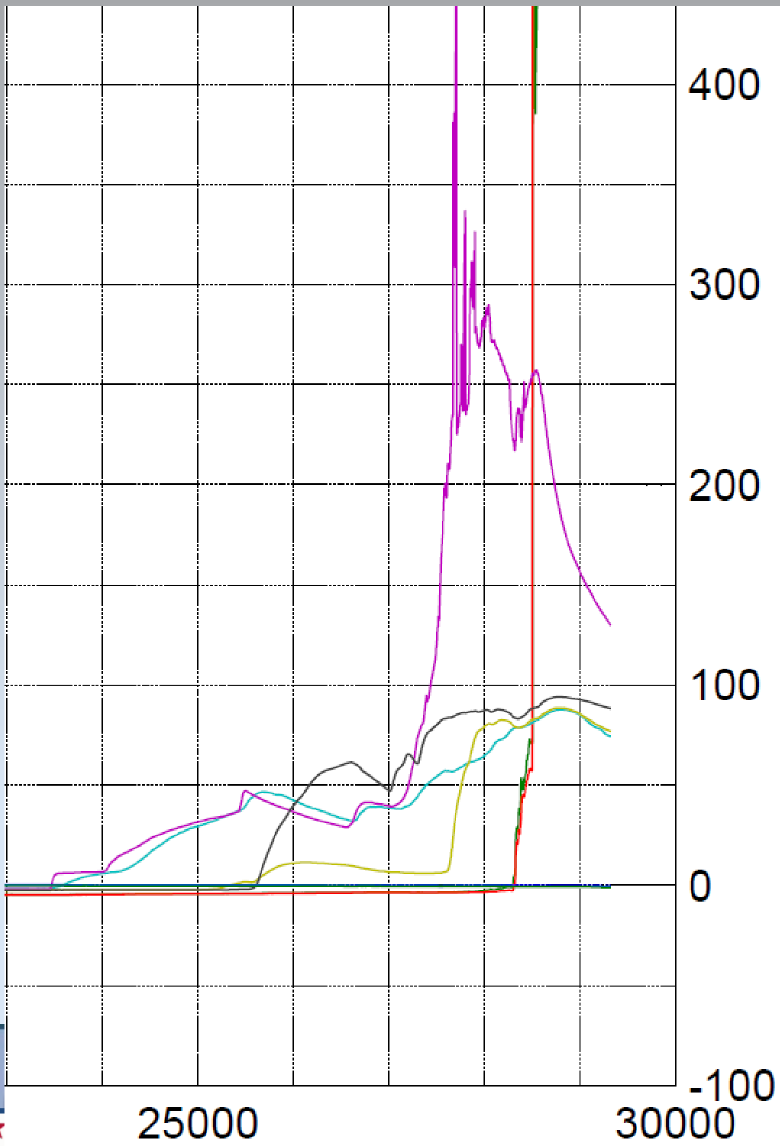
Vehicle Immersion Test

Measurement:

1. Voltage sensing and loss of isolation measurement (internal to pack)
2. Temperature sensing: thermocouple type K
3. Gas detection: sensors for Chlorine gas (Cl_2), Hydrogen (H_2) & Methane (CH_4)
4. Video: Standard video & Photographic: digital recording



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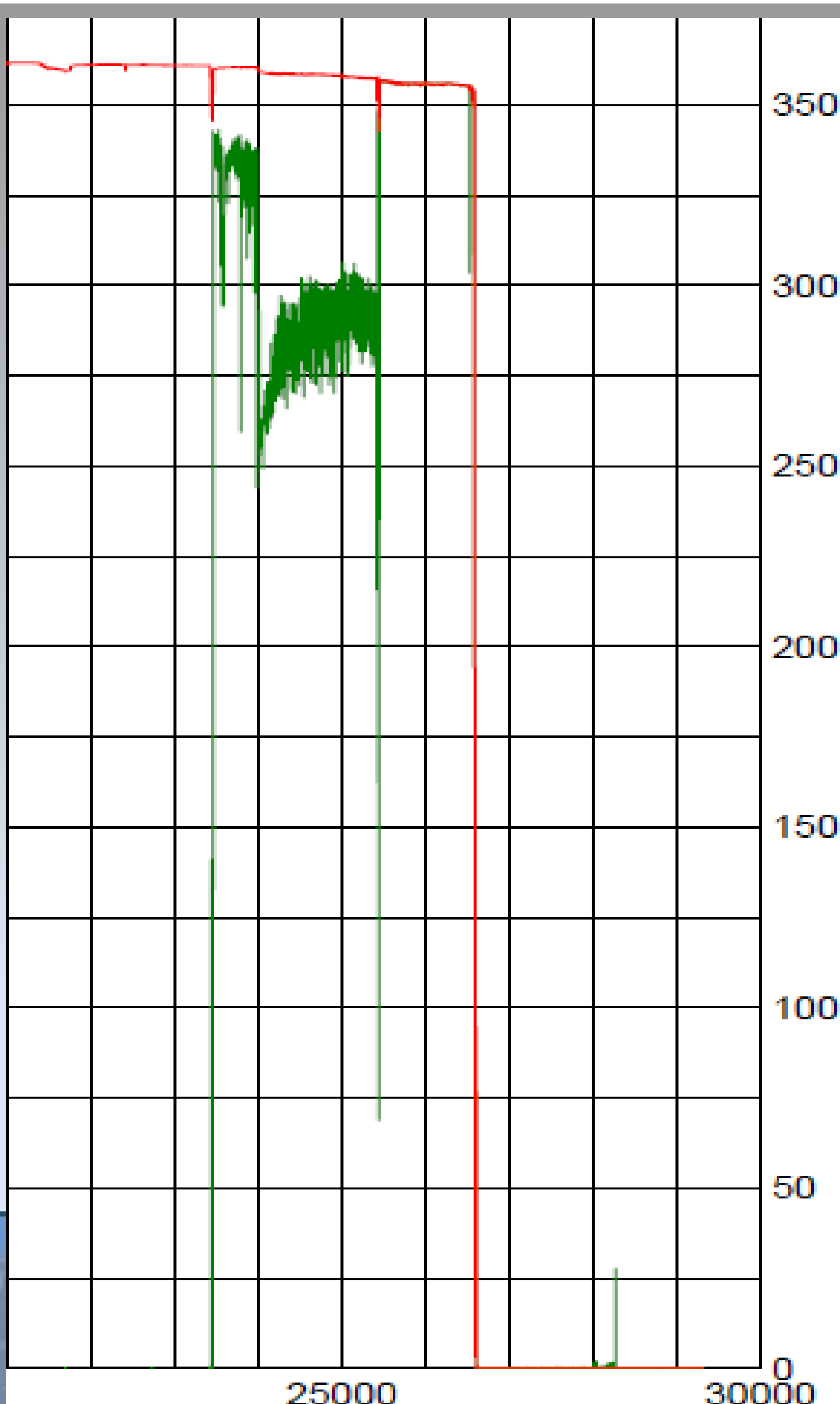
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Test Procedures Development: Example #6

Single Cell Thermal Runaway Initiation

Goal: Test method to evaluate the effect of a single cell runaway in a RESS.

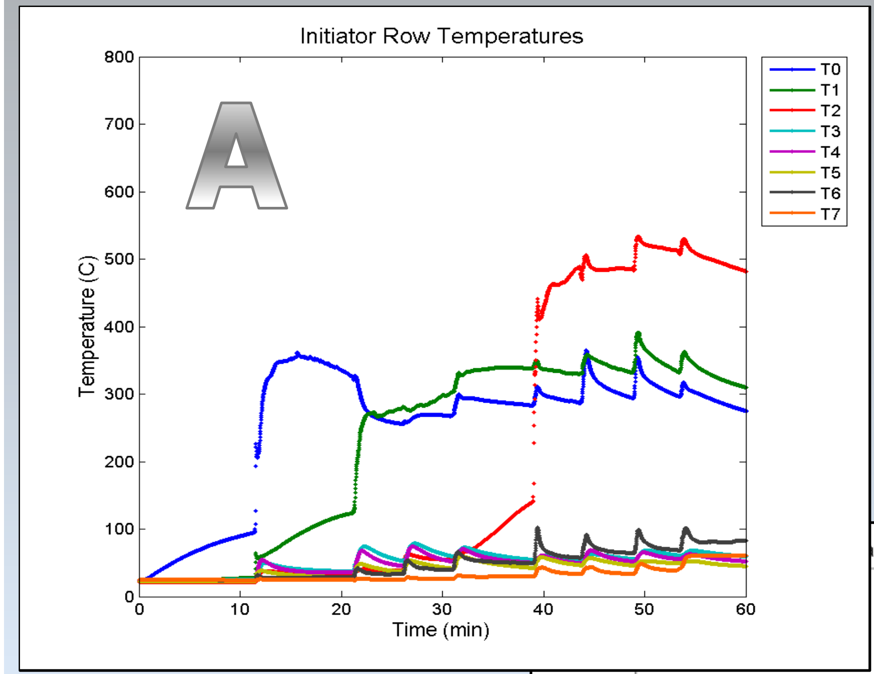
Safety Metric: Measure and compare thermal data and toxic gases in the DUT and cabin with respect to time.

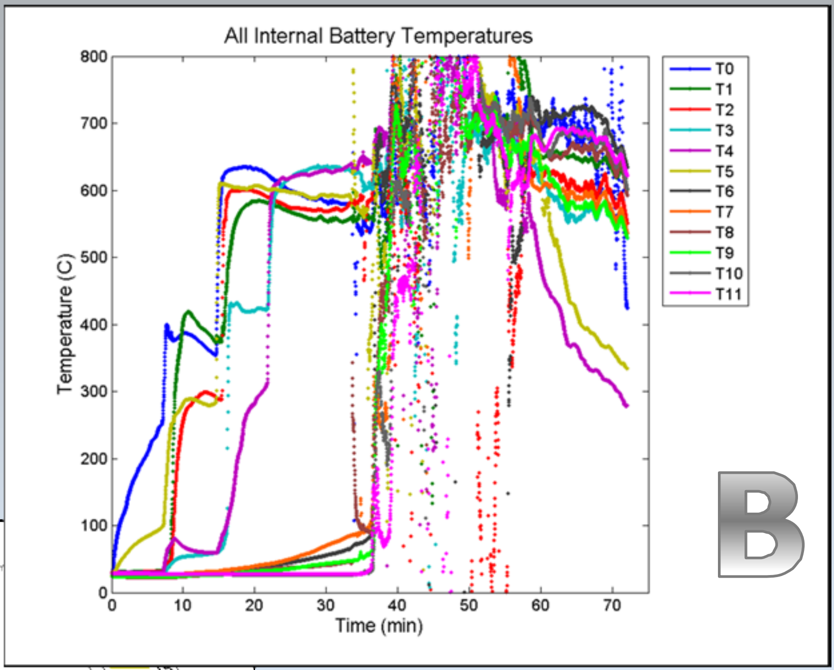
Approach:
The test procedure described is composed of three parts:

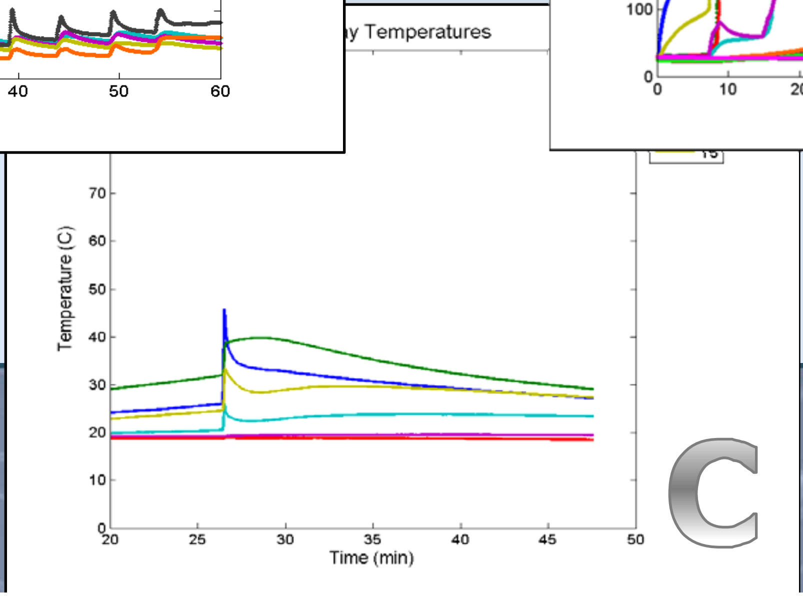
1. Selecting an appropriate single cell thermal runaway initiating methodology
2. A single cell thermal runaway initiation method may need to be verified through coupon or module level testing
3. Full scale; in-vehicle testing to assess whether a single cell thermal runaway within a RESS will pose a significant hazard to the vehicle's occupant or the surrounding environment.

Test Procedures Development:

Single Cell Thermal Runaway Initiation







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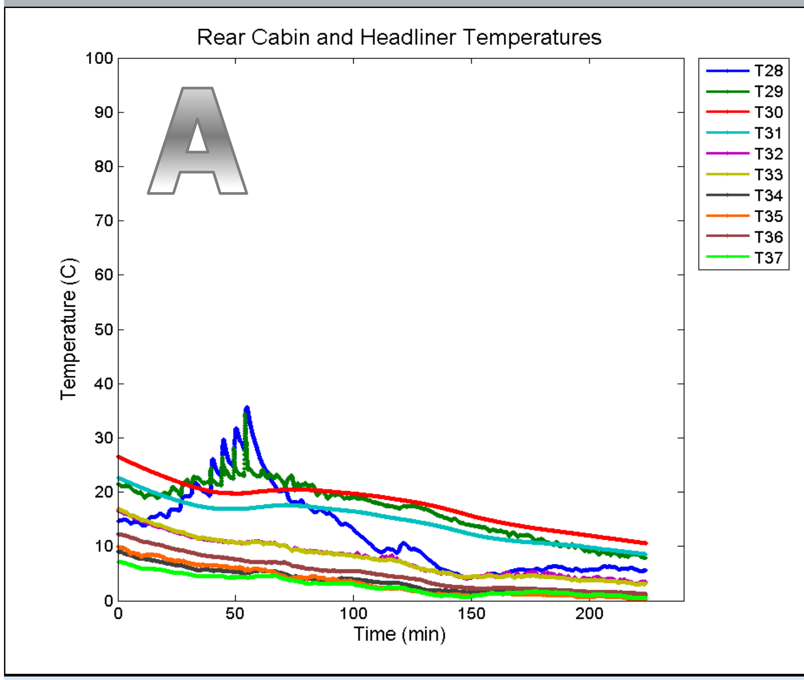
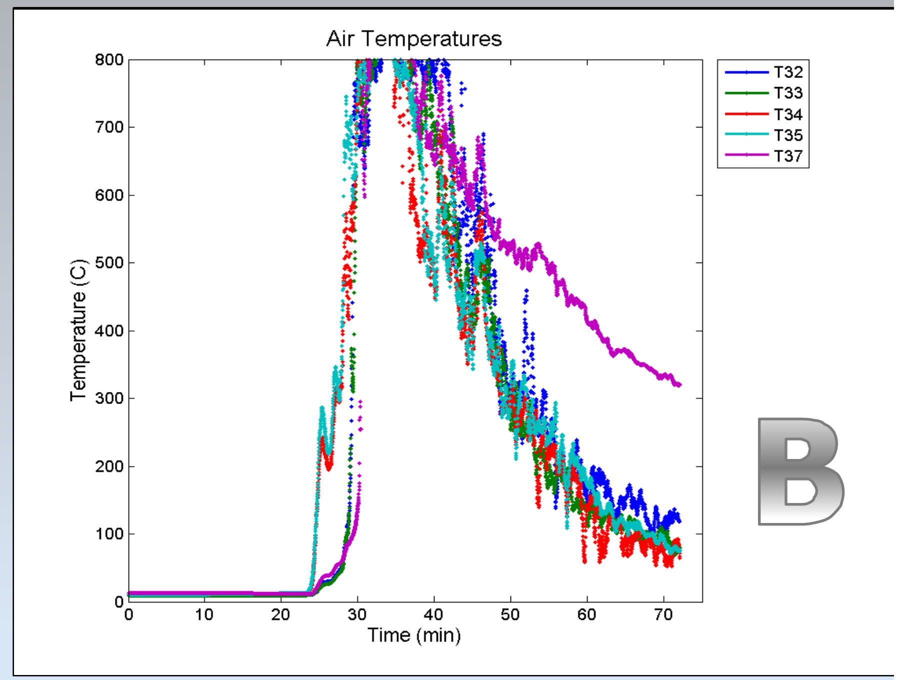
Test Procedures Development:

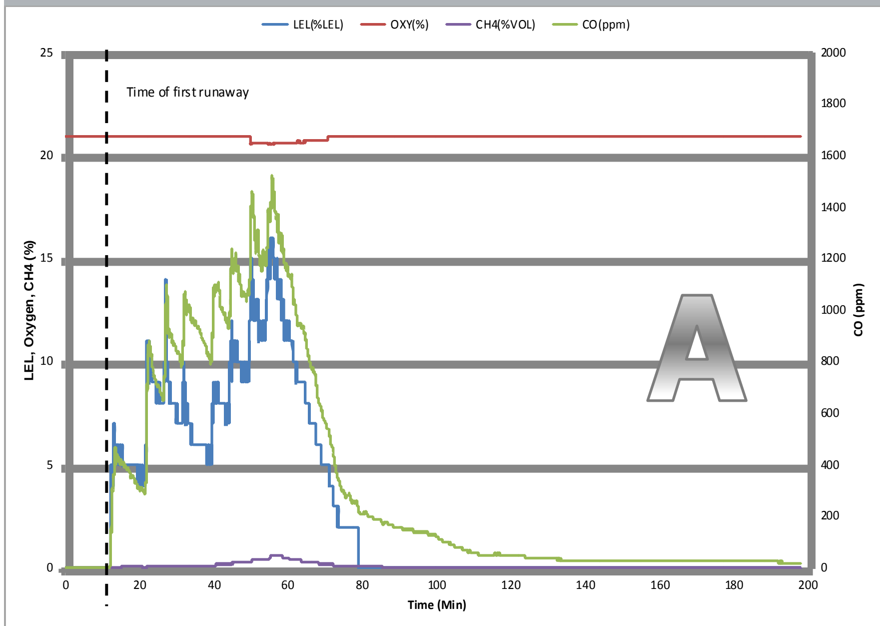
Single Cell Thermal Runaway Initiation

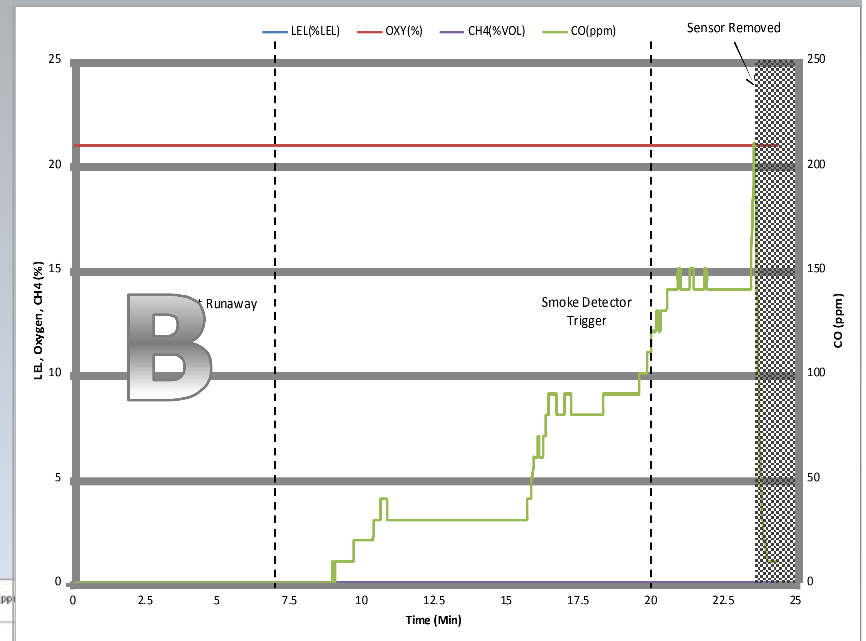


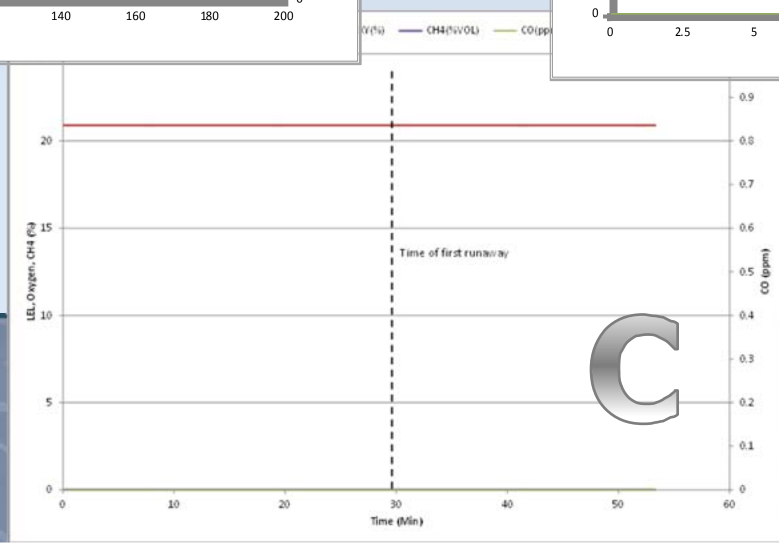


Test Procedures Development:

Single Cell Thermal Runaway Initiation







Test Procedures Development: Example #7

Thermal Containment

Goal: Test method to evaluate the effect of an internal battery fire involving forced thermal runaway of many cells as might be observed from a substantial abuse condition.

Safety Metric: Measure and compare thermal and toxic gas data in the DUT and vehicle cabin with respect to time. Specific emphasis on occupant exposure and RESS safety mitigation.

Approach: Trigger pack thermal runaway by multiple heater assemblies (5) installed into the battery pack (Higher wattage than the single cell thermal runaway initiation)

Trigger cell should reach 400°C within 5 minutes

Very high heat rate (temperature rise ~70 °C/min)

A thermal calculation procedure to help determine the electrical power requirement for provoking cell thermal runaway and fire has been developed

Test Procedures Development:

Thermal Containment

For the case where only one cell is being provoked:

- At least that cell or one of its neighbors is undergoing thermal runaway OR
- Self sustaining pack fire is evident OR
- One module is completely engaged in internal fire, OR
- Heaters' temperature has exceeded 500^{o}C for 20 minutes with no evidence of venting or fire OR
- All heaters' have ceased to function

For the case where 3 cells are being provoked:

- 3 or more cells are detected undergoing thermal runaway OR
- Self sustaining pack fire is evident OR
- One module is completely engaged in internal fire, OR
- Heaters temperature has exceeded 500^{o}C for 20 minutes with no evidence of venting or fire OR
- All heaters' have ceased to function

Test Procedures Development:

Thermal Containment

Determination of Heaters:

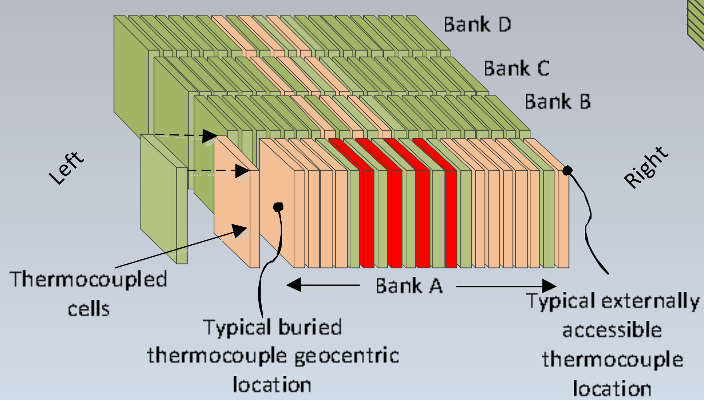
The Subject Matter Expert has developed a simple thermal calculation procedure to help determine the electrical power requirement for provoking cell thermal runaway and fire. The procedure makes use of the Partial Differential Equation (PDE) Toolbox incorporated in Matlab software to numerically solve the heat transfer PDE in two dimensions *i.e.*

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right)$$

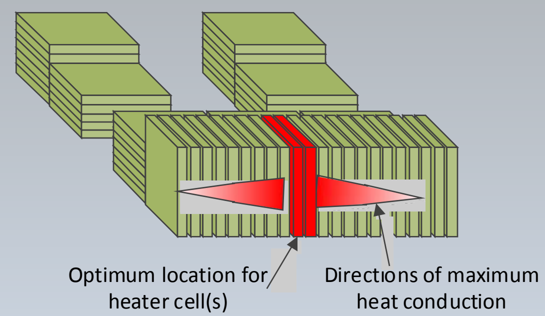
Test Procedures Development:

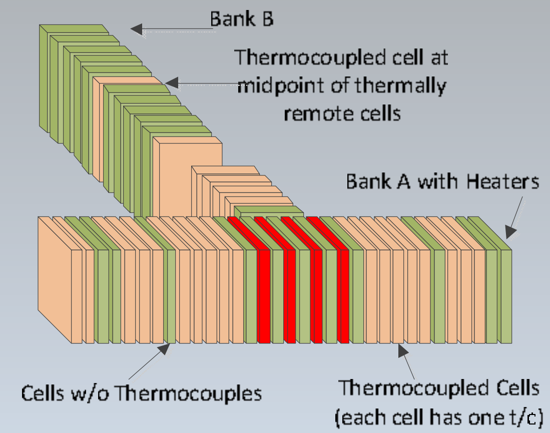
Thermal Containment

Determination of Heaters:

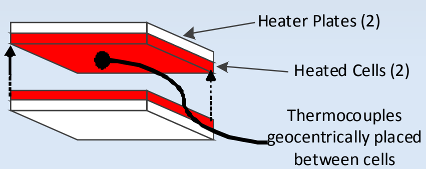


Thermocouple Locations

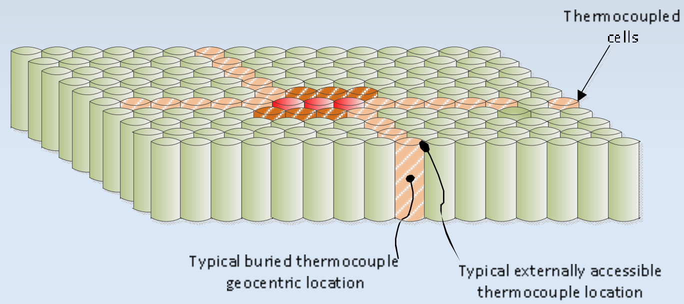




TEE Pack Thermocouple Locations



Heater Plates and Thermocouples Located in Small Modules

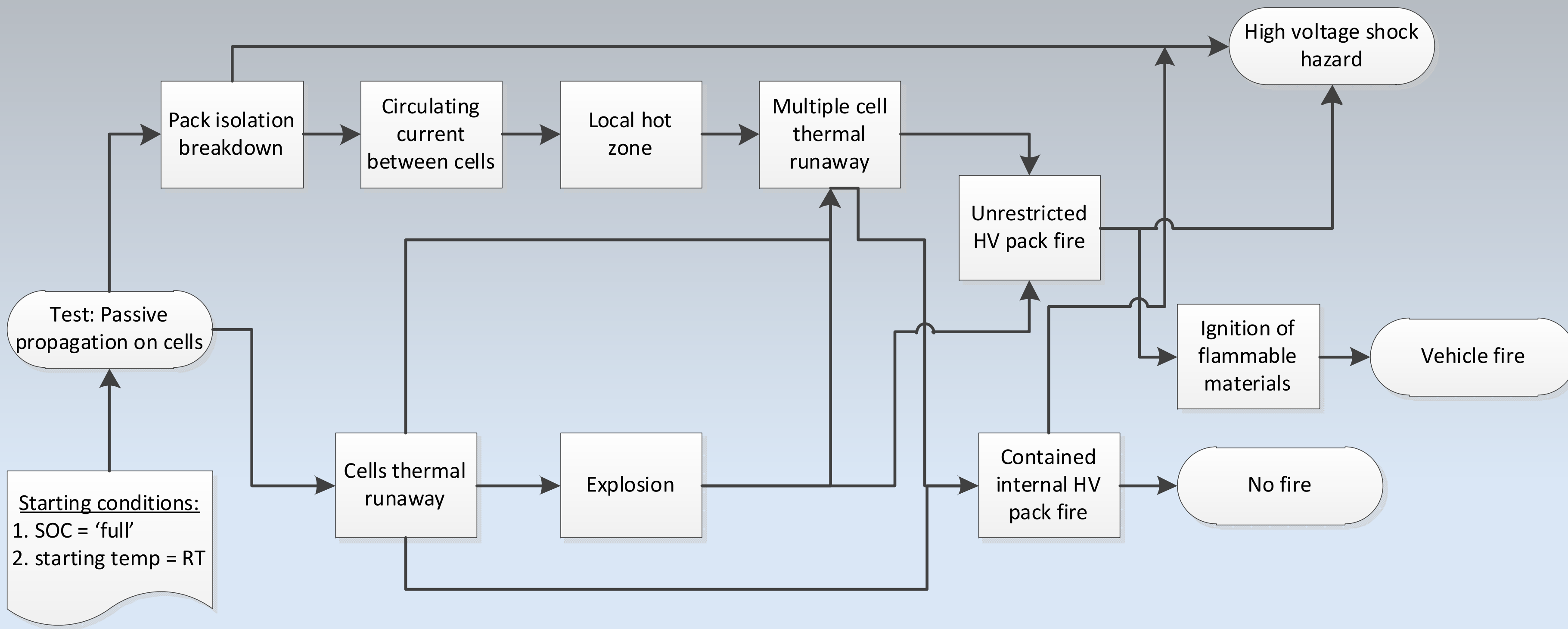


Pack of Cylindrical Cells Equipped with Thermocouples

Test Procedures Development:

Thermal Containment

Propagation Period Flow Diagram:



Test Procedures Development: Example #8

Fire Exposure

Goal:

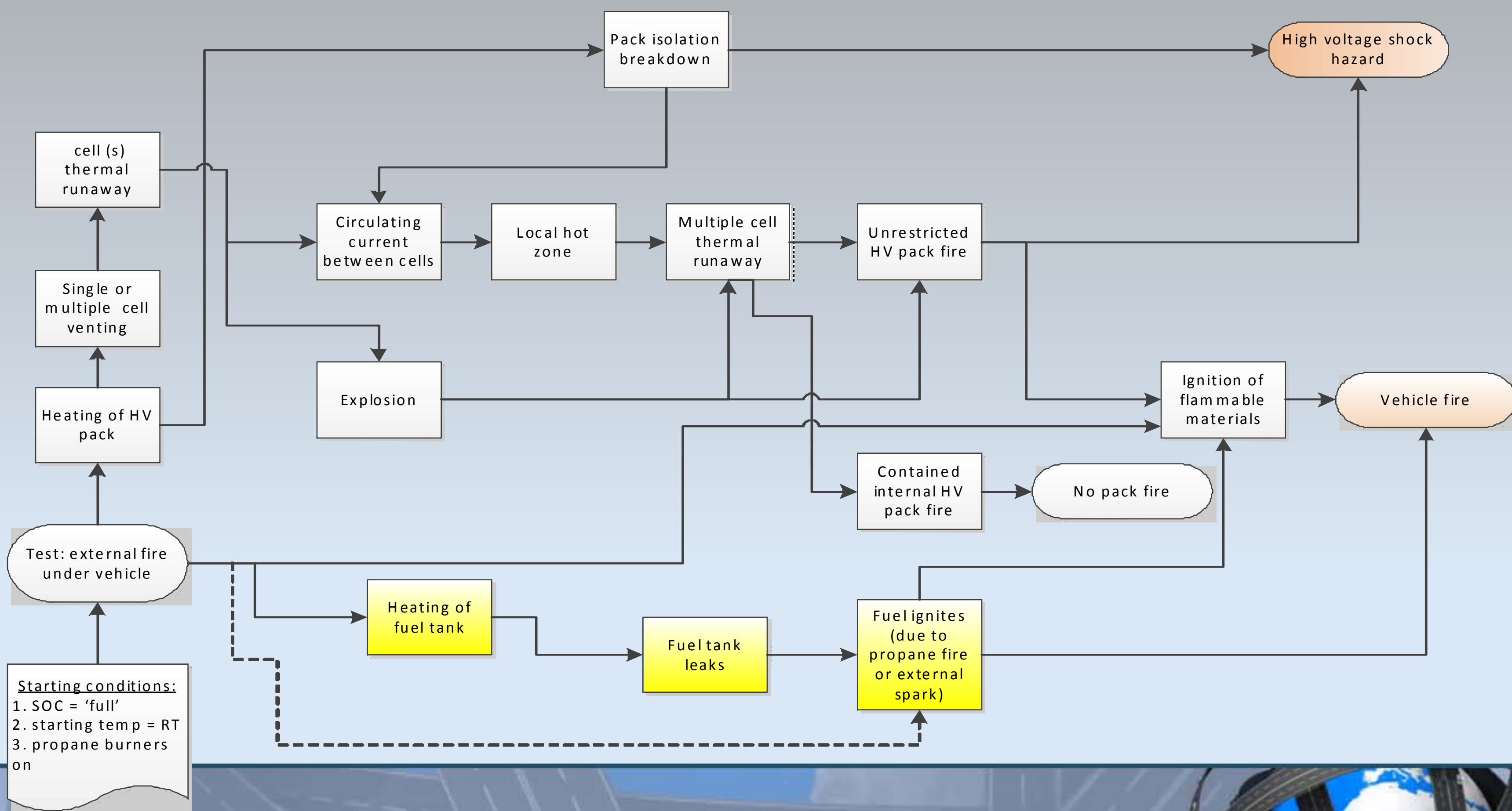
This set of tests is to evaluate the effect of an external fire on a traction battery pack installed in a vehicle and the consequent effects on the vehicle and environment. The secondary purpose is to evaluate how effective this test is in measuring the effects of the external fire.

Approach:

This test method will mimic the characteristics of a typical fuel fire within the geometry of the xEV vehicle environment on a road surface and within the typically observed ground clearance. The vehicle will be subjected to a propane burner array which is correlated to a gasoline pool fire.

Test Procedures Development:

Fire Exposure



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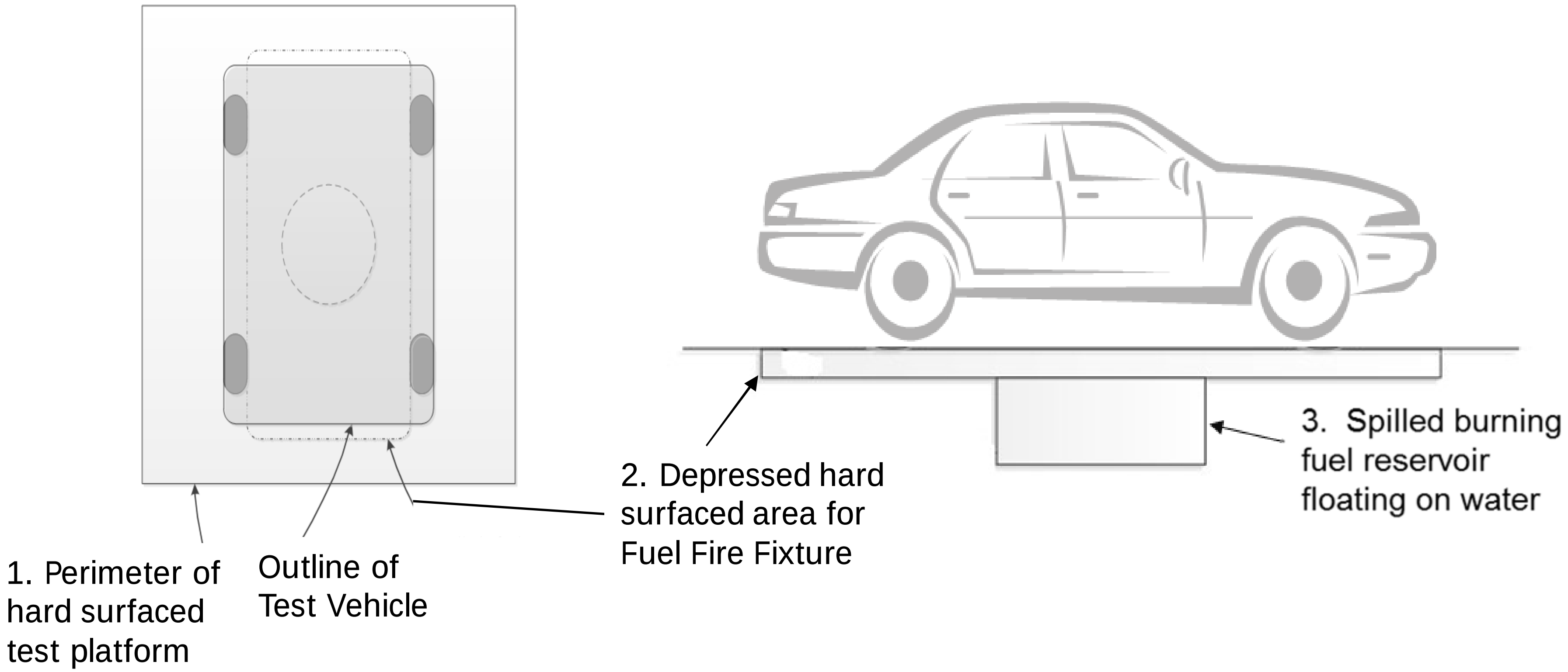
Test Procedures Development:

Fire Exposure



Test Procedures Development: Example #9

Vibration with Shock and Thermal Cycle

Goal:
Define a combined Vibration, Shock, and Thermal Cycling safety performance test for a Li-ion RESS.

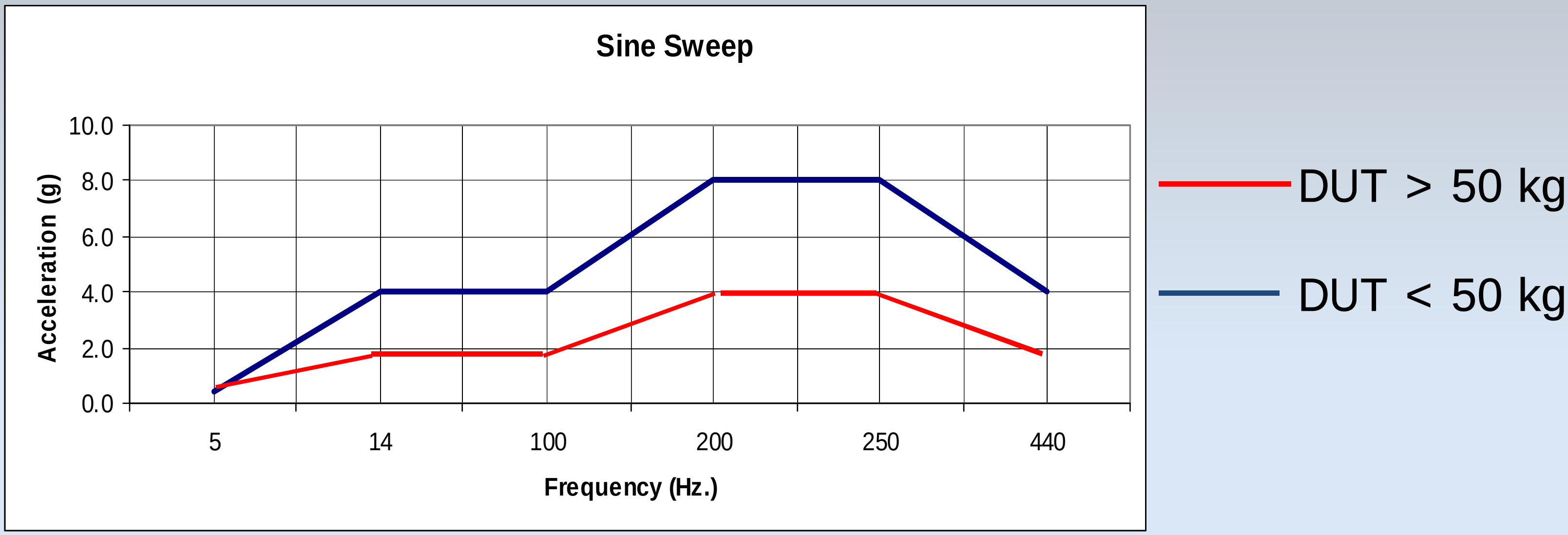
Safety Metric:
To Be Determined - Use vibration and thermal cycling (accelerated aging) testing to detect failures which can be correlated to safety performance

Test Procedures Development:

Vibration with Shock and Thermal Cycle

Approach:

1. Conduct a pre-test characterization of the resonance modes via a 3 axis Sine Sweep

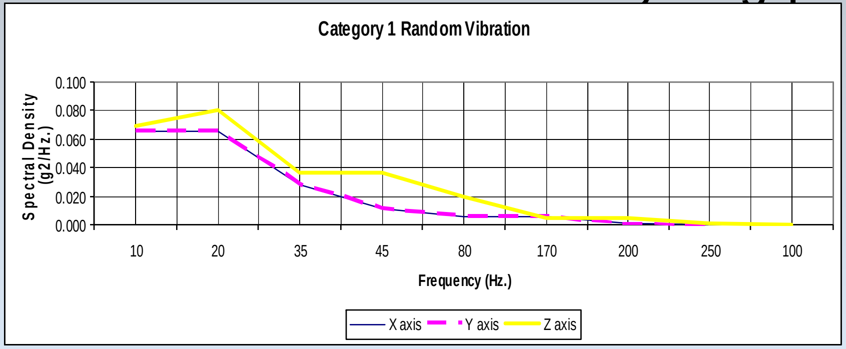


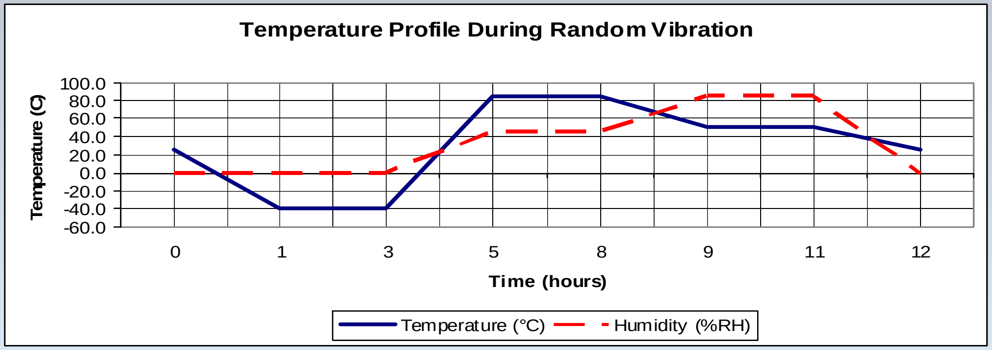
Test Procedures Development:

Vibration with Shock and Thermal Cycle

Approach:

2. The test cycles combine 3-axis random on random (ROR) vibration profile combined with a thermal cycling profile.





Time (hours)	Temperature (°C)	Humidity (%RH)
0	25	NA
1	-40	NA
3	-40	NA
5	85	45
8	85	45
9	50	85
11	50	85
12	25	NA

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Test Procedures Development:

Vibration with Shock and Thermal Cycle

Approach:

3. The test cycles combine mechanical shock inputs, 3-axis random on random (ROR) vibration profile and a thermal cycling profile.
12 hour temp. cycle from +25°C → -40°C → +75°C → +50°C → +25°C (2 hr holds)

Acceleration	Duration	Pulse Type	Number of Pulses
G	mS		
25	15	Half Sine	3/axis both positive and negative directions for a total of 18

4. The test concludes with a post-test characterization of the resonance modes via a 3 axis Sine Sweep (to be compared to the Pre-test data) and a functional cycling of the DUT.

This test procedure is being reviewed by an academic institution to compare the test to published research.

Test Procedures Development: Example #10

Comprehensive Vehicle System Test

Goal:

A Comprehensive Vehicle Level Test which includes an optional initial battery pre-conditioning protocol followed by a sequential series of tests conducted on a battery pack installed in a vehicle

1. High and Low Acceleration Factors (City and Highway Drive Cycle)
2. Mechanical, Thermal, Environmental, Electrical Aging
3. Maximum Road-load Input (In Vehicle)
4. Maximum Load-test Cycle (In Vehicle)

Safety Metric:

Vehicle-level tests post “pre-conditioning” protocol

1. Over-discharge
2. Under temperature charge
3. Over temperature test
4. Over-voltage overcharge
5. Over-current, under temperature overcharge
6. External short circuit

Test Procedures Development: Example #11

Internal Isolation Test

Goal:
Test Procedure to measure internal isolation of a RESS

Safety Metric:
Isolation between each high voltage bus and vehicle chassis/enclosure

Approach:
Information on this test procedure has not been received by NHTSA at this time.

Safety Assessment Methods and Tools:

To address the need for a definitive safety assessment of a Li-ion RESS in a post-test or post-abuse event, NHTSA is partnering with the National Labs to develop or identify technology.

- Safety Assessment – Diagnostic Tool Set
- Stranded Energy Diagnostics and Liberation

Safety Assessment Methods and Tools

Safety Assessment – Diagnostic Tool Set

Goal:

Develop a diagnostic tool set to identify battery state-of-health and stability characteristics that commonly assess the safety a RESS DUT after a test, abuse condition, or during normal use.

Approach:

The body of this work is cell to module to pack progressive and will be in part a derivative of cell level Complex Impedance Spectroscopic Properties leveraging the scientific experience and expertise of Sandia National Labs. This project will also adopt Idaho National Labs developed "rapid impedance spectra measurement techniques" that can be adapted to a BMS monitoring board.

Partners:

Sandia N.L., Idaho N.L., National Research Canada, Argonne N.L. (Stranded Energy)

Safety Assessment Methods and Tools

Stranded Energy Diagnostics and Liberation

Goal:

This project seeks to define and demonstrate a <u>common</u> strategy for diagnostics of an inoperable and potentially damaged RESS that is physically or electronically isolated within its enclosure, and describe the architectural requirements to assist in liberation of the energy when necessary.

The scope of the project defines:

This project is intended to inform and bridge gaps in technology and standards that may exist in areas of safe handling of the RESS devices and exposure to people within the entire community from a “cradle to grave” perspective.

Partner:

Argonne National Laboratories

Automotive RESS Safety Management

Background

- **<u>Project Concern</u>:** The automotive application and use of a RESS, such as Lithium-ion battery based system, imposes certain safety risks to the operators and occupants of these vehicles, which are different than that of vehicles using only an internal combustion engine.

- **<u>Potential Safety Risk</u>:** Thermal runaway of the battery pack(s), which in some cases may result in fire or pressure events.

- **<u>Project Scope</u>:** This research focuses on the safe management of an automotive RESS, i.e. its BMS and any electronic failures associated with it.

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Goal and Objectives

Identify diagnostic and prognostic elements based on a comprehensive hazard analysis of an automotive RESS and determine information and messaging needs for operators and responders.

- ❑ Delineate the hazards and their severity levels pertaining to the functional safety of automotive RESS controls, and identify safety requirements and constraints
- ❑ Define system diagnostics, prognostics, and data logging
- ❑ Identify safety-critical information needs and effective methods to communicate this information to operators, first and second responders, and service technicians
- ❑ Address safety-related instructions and training needs

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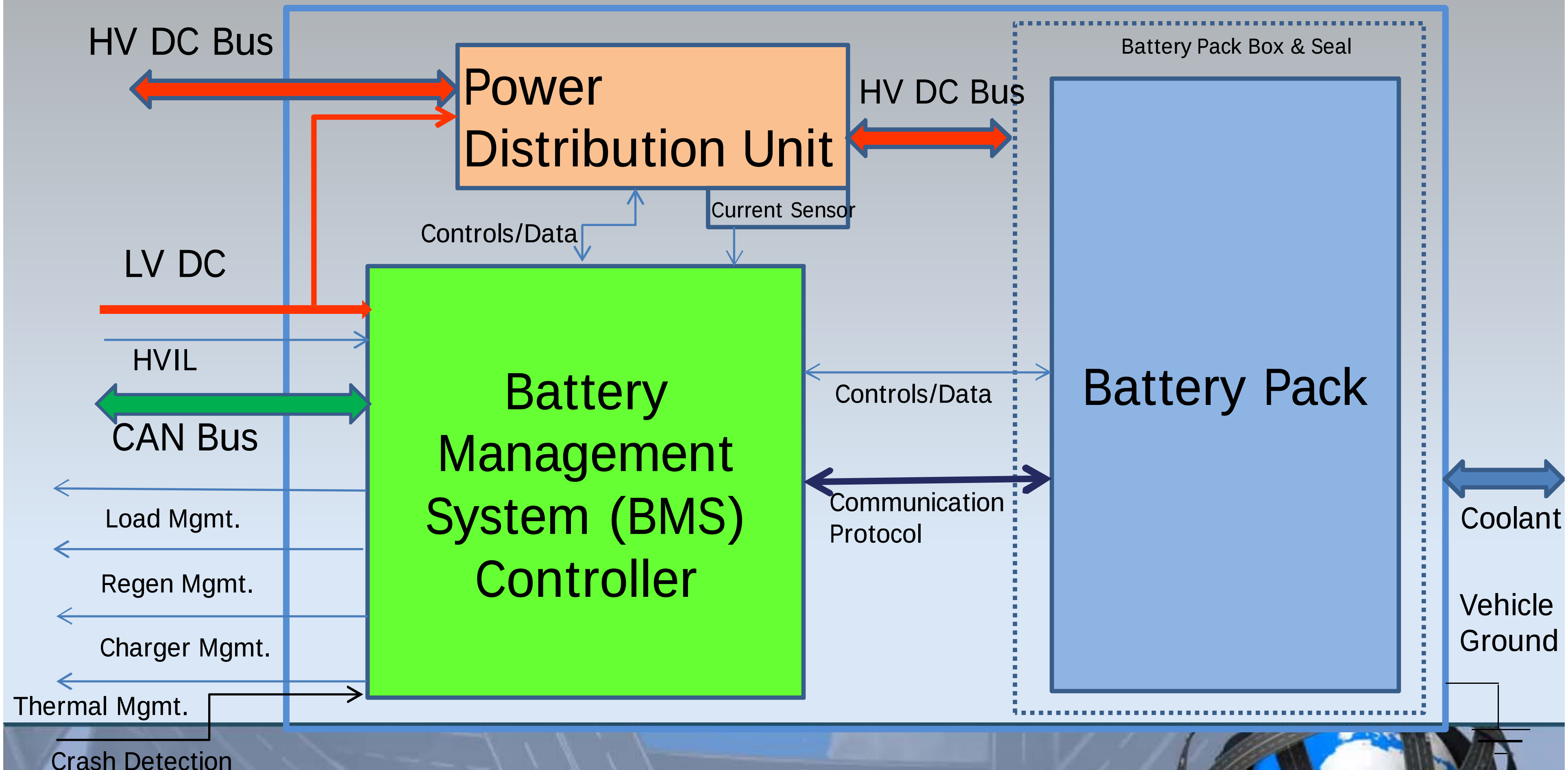
System Scope



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System Description

- The system includes three major parts; the battery pack, the battery system management controller, and the power distribution unit
- System Function:
  - It stores electrical energy received from the charger or the vehicle, and it delivers energy to the vehicle systems.
  - It maintains safe vehicle operation, and communicates with other vehicle module for proper vehicle functions.

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System Description: Battery Pack

- Description: Housed in a sealed vented box, it includes the battery modules, voltage sensors, cell voltage balancers, temperature sensors, condensation sensors, and ground fault detection circuitry.

- Function: It stores electrical energy, delivers electrical energy to the vehicle, and reports information on the status of the cells and the electrical grounding of the HV bus.

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System Description: BMS Controller

- Description: It includes the algorithms and controls of the RESS including SOC, SOH, Diagnostics, Prognostics, Communication, Data Storage, and Safety.
- Function: It manages the energy in and out of the battery pack based on the SOC, it acts on safety related requests from other vehicle systems, and maintains the safety of the RESS.

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System Description: Power Distribution Unit

- Description: It houses the main and pre-charge contactors, relays, and fuses.

- Function: It connects and disconnects the battery pack to the HV bus, and it ensures that the system power limits are respected.

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Safety Scope

- ❑ This research the functional safety of an automotive RESS, i.e. its BMS and any electronic failures associated with it.

- ❑ In addition to, it shall also consider the external vehicle interfaces in terms of their impact on the safe operation of an automotive RESS.

  - ➢ The RESS must be able to tolerate external failures and maintain safe state.

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Project Status

- ❑ Technical Approach – Hazard Analyses
  - ▪ ISO 26262 Functional Safety Approach
    - o Hazard Analyses and Risk Assessment (HARA)
    - o Safety Goals
    - o Functional Safety Concepts
    - o Safety Mechanisms
  - ▪ System Theoretic Process Analysis
- ❑ Diagnostic Trouble Code (DTC) Review
- ❑ Communications and Messaging

Technical Approach

- Engage multiple professionals with experience in ISO 26262, RESS design, and/or advanced hazard analysis
- Apply multiple approaches to ensure a comprehensive analysis
- Collaborate on system safety aspects, but initially conduct separate hazard analyses
- Cross-reference results with existing DTC's
- Consolidate results and safety approaches into a comprehensive report

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DTC Review

- ❑ Chevy Volt
- ❑ Toyota Prius
- ❑ Nissan Leaf
  - DTC Analysis is complete
  - Cross referencing of DTC's with J2012 is complete
  - Cross referencing of DTC's with the results from the hazard analyses is ongoing

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Communications and Messaging

- ❑ Identify safety-critical information needs of owners and operators
- ❑ Describe effective means to communicate this information
- ❑ Describe barriers to effective communication and opportunities to remove them

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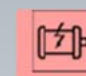
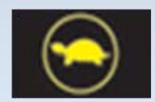
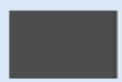
Communications and Messaging

	High Temp.	Voltage Fault	Malfunction	Low Power	Hazard/Other
BMW Mini E			 	 	  
Chevrolet Volt		SERVICE HIGH VOLTAGE CHARGING SYSTEM	SERVICE BATTERY CHARGING SYSTEM 		
Fisker Karma	ENGINE OVERHEATED – TURN VEHICLE OFF				
Nissan Leaf					
Tesla Roadster (Model S not available complete)				Remaining range unknown. Charge now or cycle key to access final reserve.	
Toyota Prius PHEV	HYBRID SYSTEM OVERHEAT		CHECK HYBRID SYSTEM, STOP THE VEHICLE IN A SAFE PLACE		HAVE TRACTION BATTERY INSPECTED

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Questions and Discussions