NHTSA

NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

Alternative Fuels Research

NHTSA Safety Research Portfolio Public Meeting: Fall 2021

October 20, 2021

Introduction

- This session provides an overview of NHTSA's research on Alternate Fuels.
- Vehicle Safety Research at NHTSA has been conducting safety research for alternative fuel vehicles since the mid 2000's.
  - Battery testing at the cell, module, battery pack and full electric vehicle systems.
  - Evaluating test methods for hydrogen and CNG vehicles.
  - Working with EMS and first responder groups to develop best practices and training materials.
- Working closely with Department of Energy to keep up with new technology.

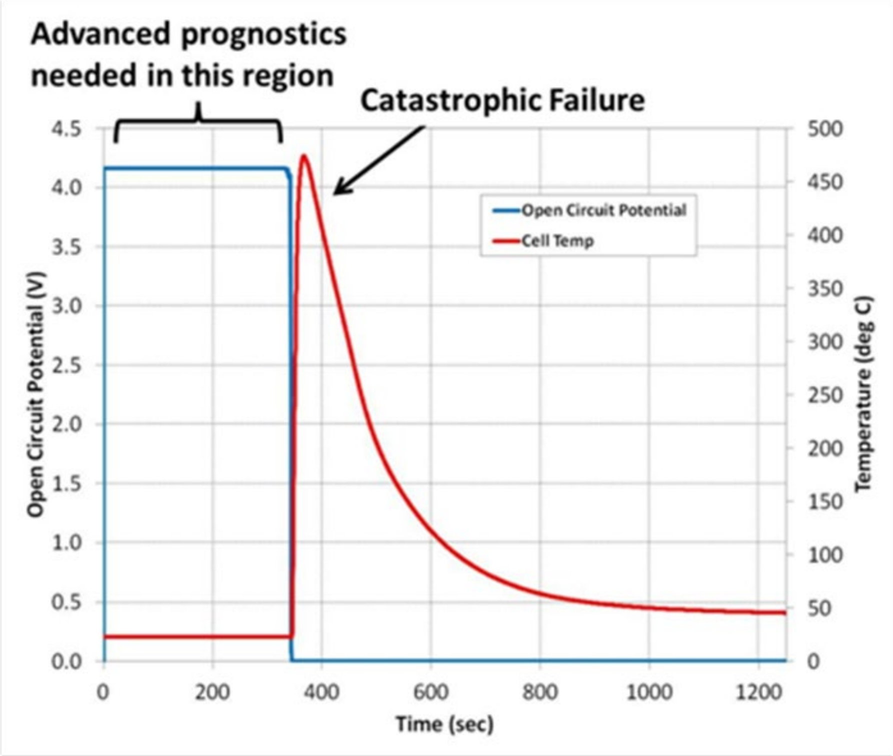
Panel Presentations

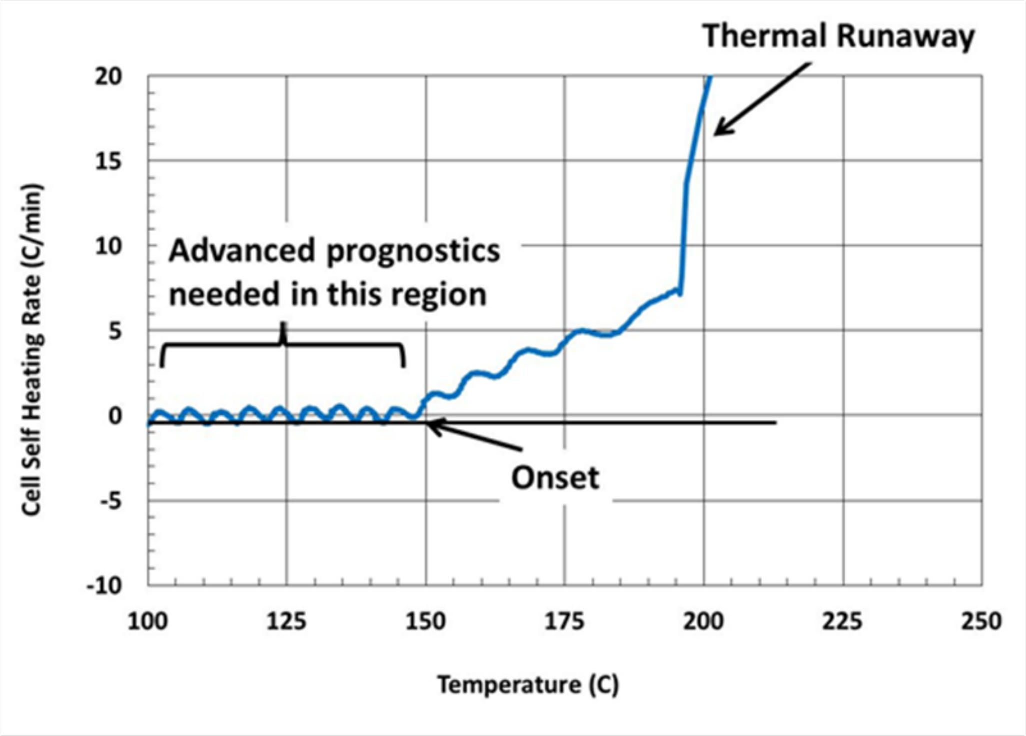
1. Integration and Demonstration of Battery Failure Diagnostics – Stephen Summers
2. Failure Modes and Effects Analysis for Wireless and Extreme Fast Charging – Stephen Summers
3. Li-Ion Battery Pack Immersion Exploratory Investigation – Stephen Summers
4. Electric Vehicle Safety: An Outlook on Thermal Runaway Initiation & Propagation Testing – Stefanie Goodwin
5. Outreach to First Responders – Dave Bryson
6. Best Practices and Concerns for Fire and EMS responders – Whitney Tatem
7. Hydrogen Cylinder Fire Testing – Ian Hall

Integration and Demonstration of Battery Failure Diagnostics

Stephen Summers

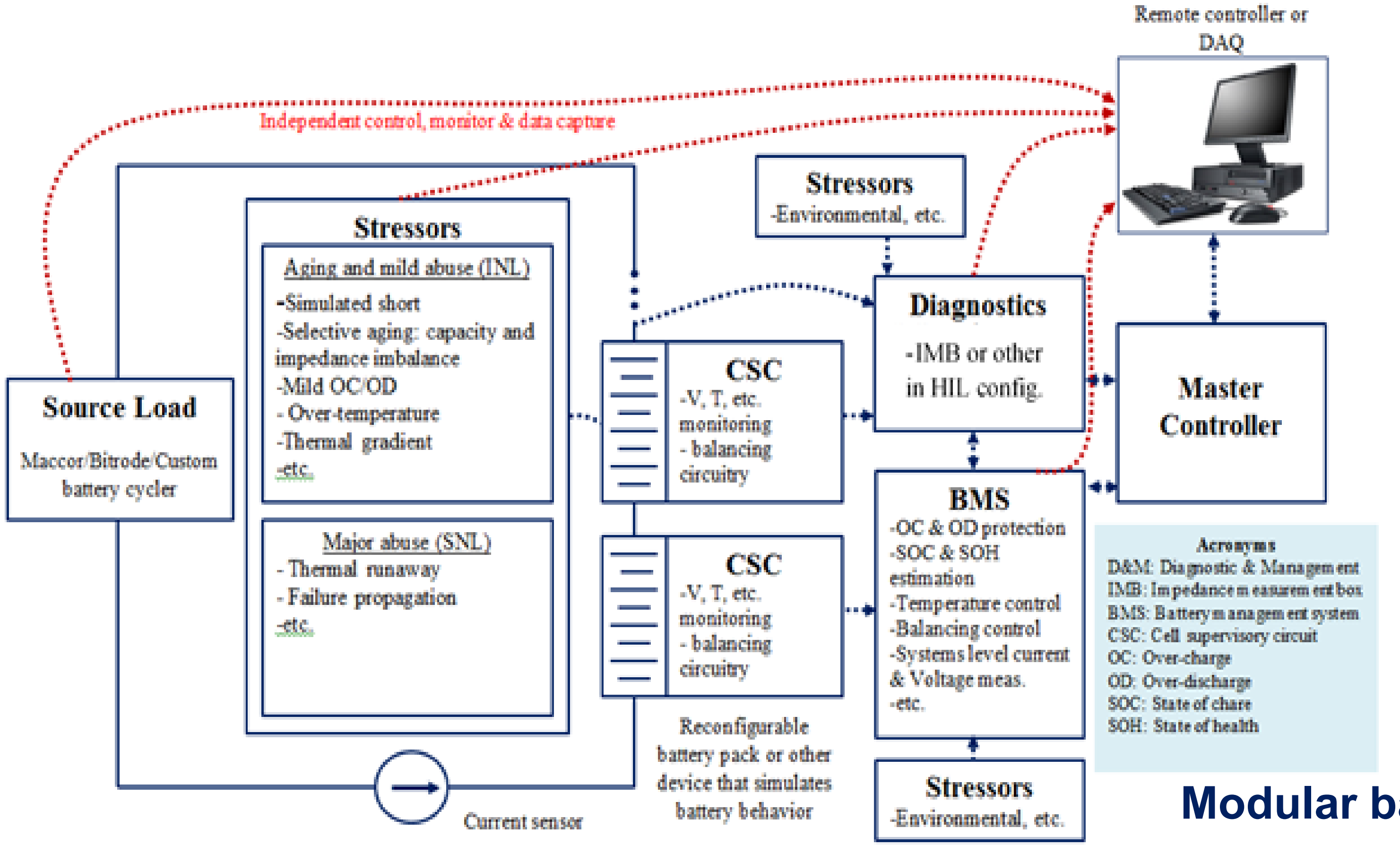
Advanced Diagnostics for Early Detection of Battery Failure

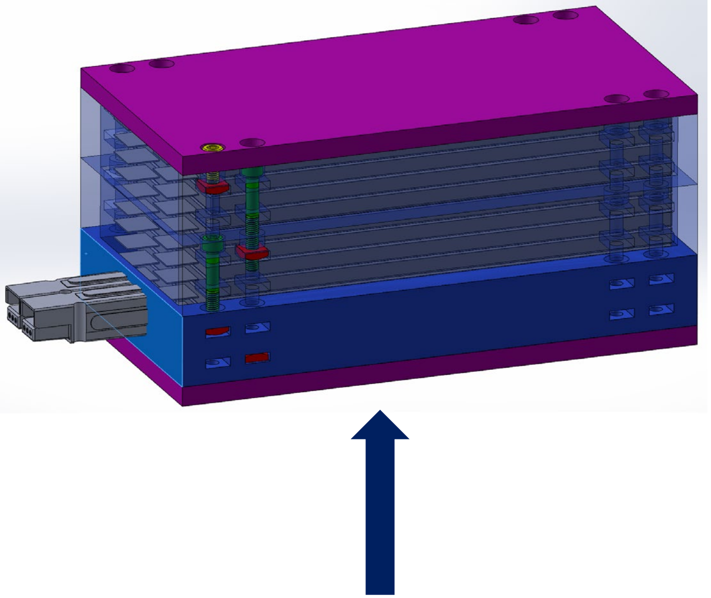




- Conventional battery monitoring is limited to voltage, temperature, and current
- Voltage and temperature are lagging indicators of failure when driven by an internal change (like an internal short circuit) and often will not indicate a problem until catastrophic failure is occurring
- Advanced diagnostics must be integrated into existing battery management systems

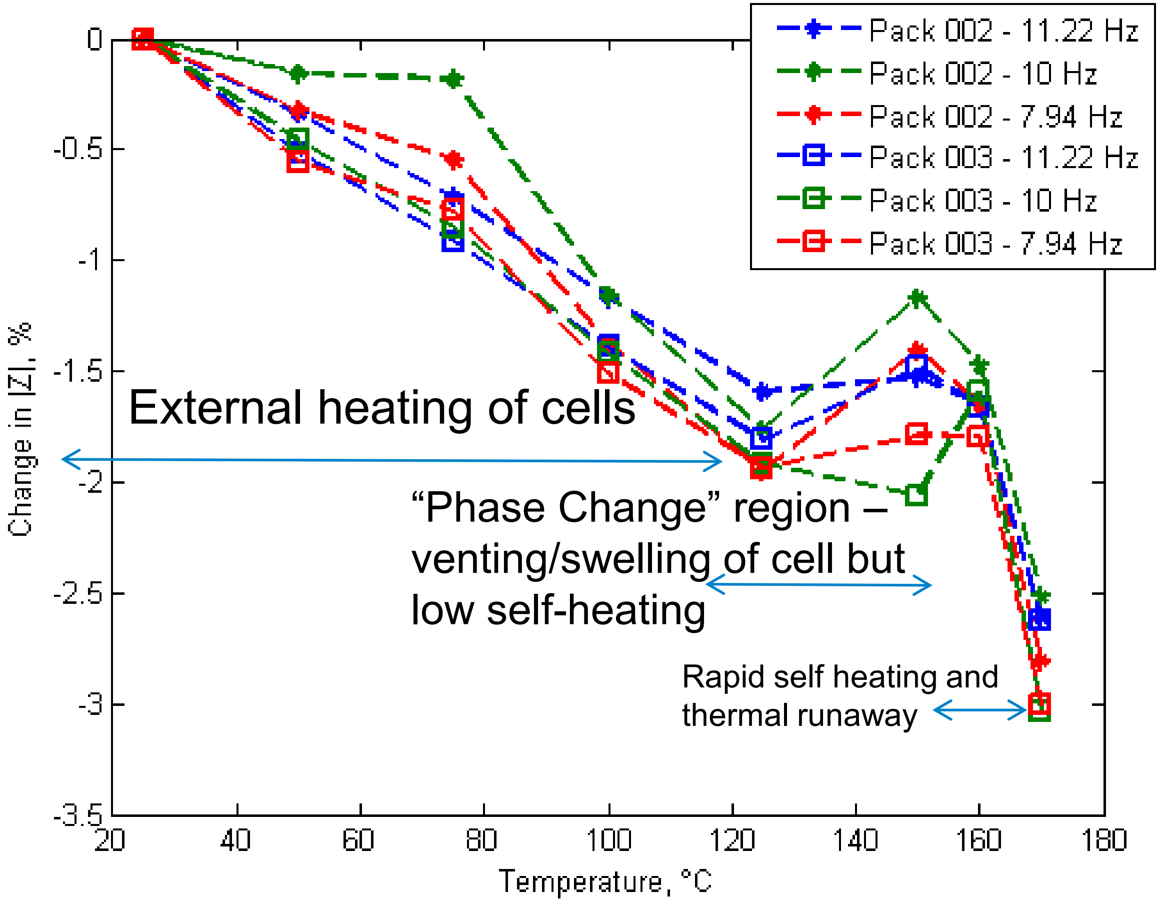
Current Project – Integration of Battery Failure Diagnostics

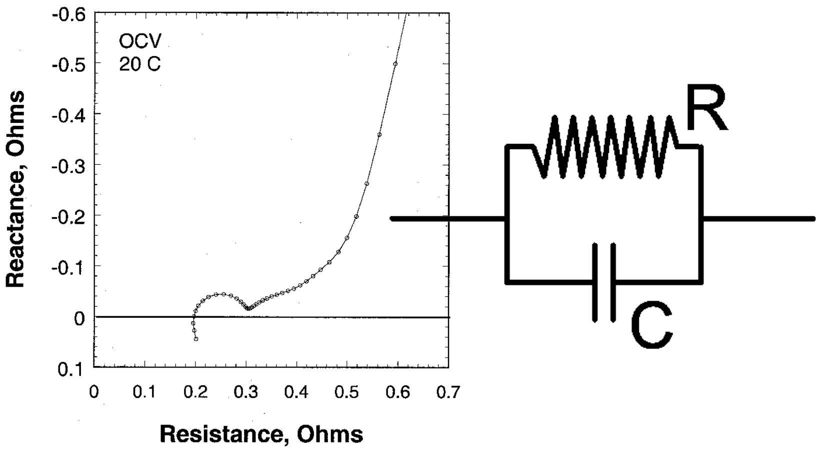




Modular battery pack designs for test articles up to 3S4P (12 cells in a module series-parallel configuration)

Electrochemical Impedance Diagnostics





- Example of strategy to develop new diagnostics that integrate at the pack level

Battery State of Health and Stability Diagnostic Tool Set Development

https://rosap.ntl.bts.gov/view/dot/43642

Background – In-operando measurements of abused cells

- IRiS Fast EIS system
  - Note: earlier testing was performed on an earlier prototype version with similar specs to commercial unit
- In-operando testing of batteries up to 50 V

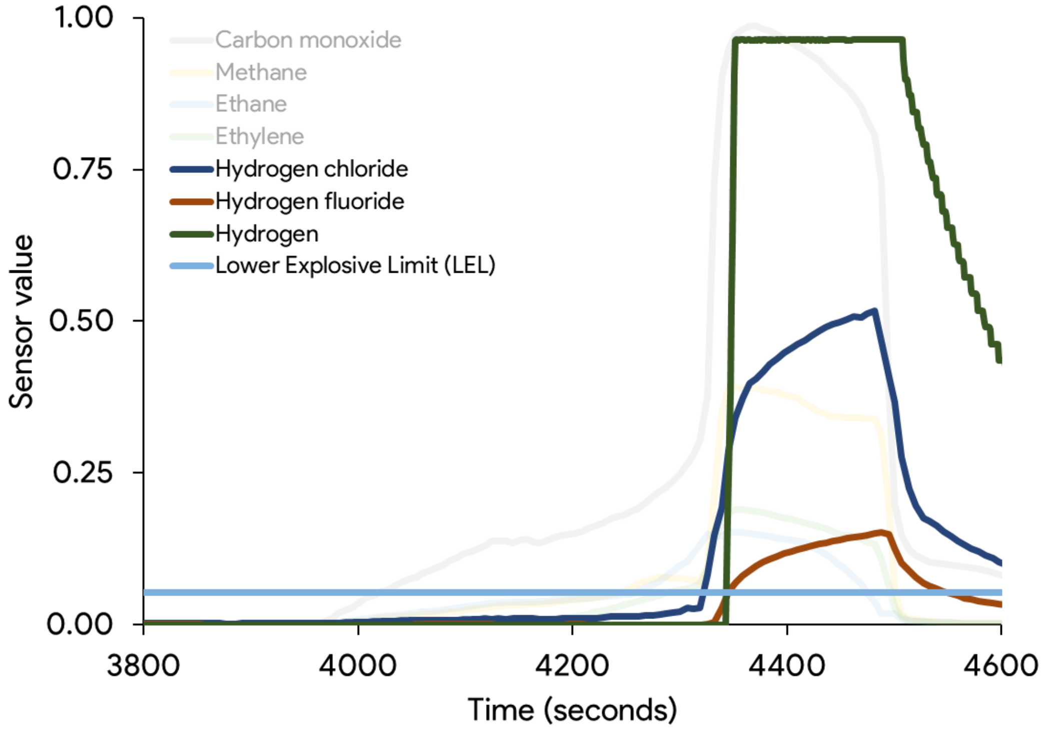
- Abuse coupled impedance testing
  - Measurement during thermal ramp/overtemperature tests
  - Measurements at various levels of overcharge
  - In-operando measurements during overcharge
- Advanced coulometry
  - Performed with precision battery cycling equipment (not-shown)
  - Allows for differential coulometry (dQ/dV) at high rates of charge/discharge

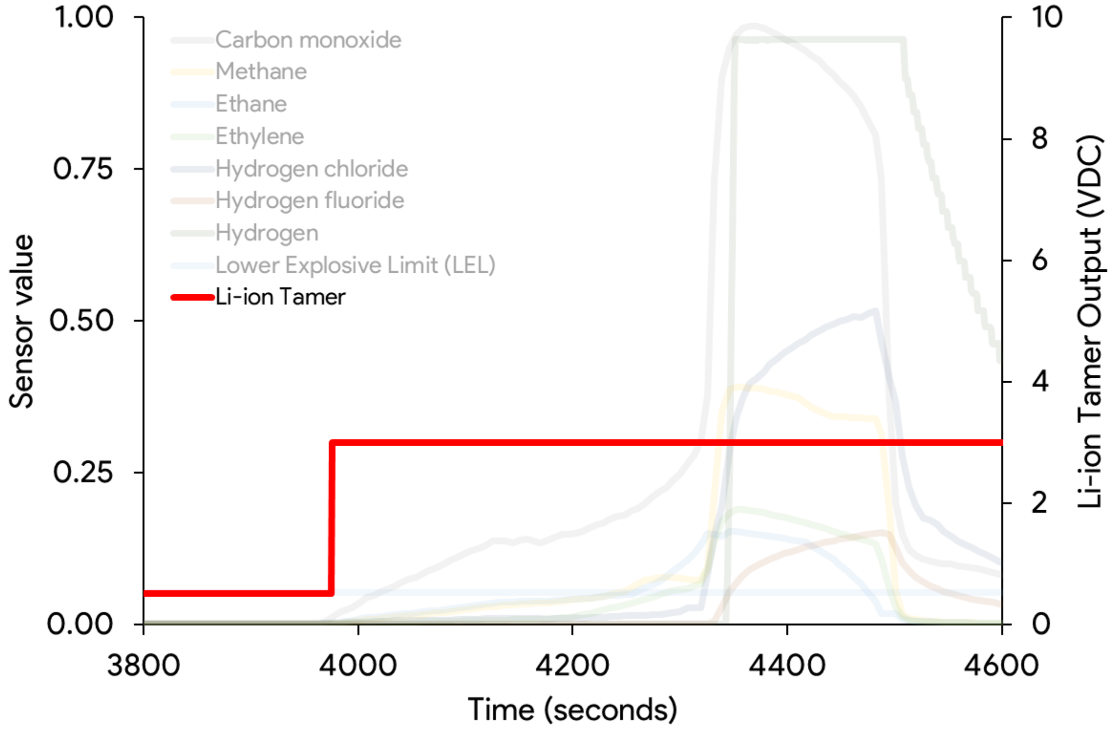
Testing of alternative detection techniques – Li-ion tamer

Product Benefits

- **Early warning** of lithium-ion battery failures
  - Average of 10-minute early warning based on experimental results (100+ battery failures)
- **Prevent thermal runaway** with proper mitigating action
  - If abuse factor is stopped early, failure can be altogether prevented
- **Single cell failure detection** without electrical or mechanical contact of cells
  - Easy installation and localized monitoring enables detection at the earliest sign
- **Calibration-free** product
  - Innovative machine learning algorithms create maintenance-free product
- **Auto diagnostic** capabilities
  - System will automatically diagnose any sensors that are malfunctioning
- **Extended lifetime**
  - Sensors have extended lifetime that exceeds lithium-ion battery systems (15+ years)
- **Reduction/removal of false positives**
  - Network of reference sensors removes possibility of false positive alarms

Li-ion Tamer Presentation at the 2020 ESS Safety and Reliability Forum





Schedule

- Test platform is being assembled and verified
- Preliminary testing in fall / winter
- Inclusion of additional diagnostic devices
- Results next summer

Failure Modes and Effects Analysis for Wireless and Extreme Fast Charging

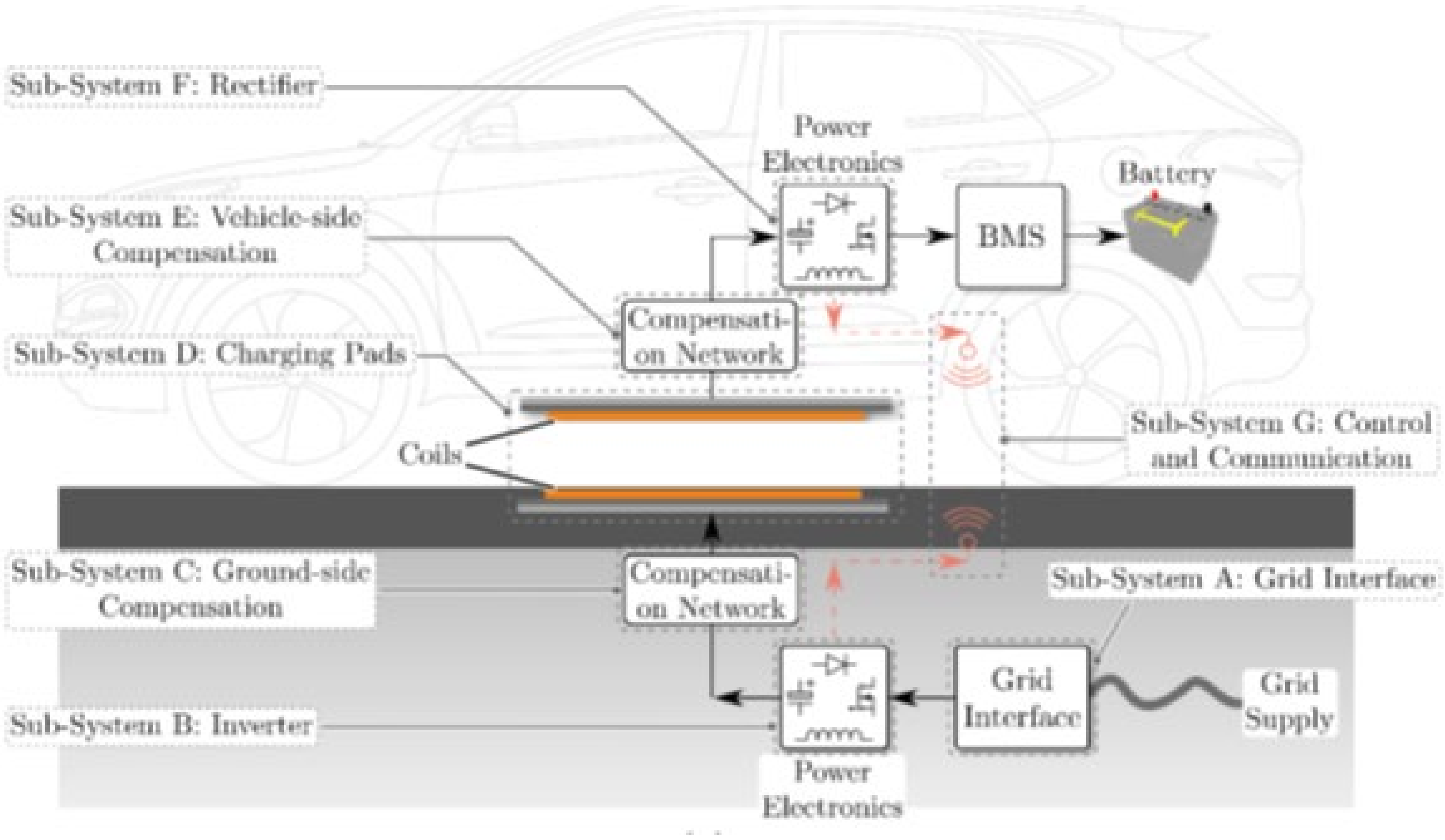
Stephen Summers

Failure Modes and Effects Analysis (FMEA) for Wireless and Extreme Fast Charging

- NHTSA published several reports evaluating electric vehicle charging safety
    - DC and AC Charging Safety Evaluation Procedure Development, Validation, and Assessment, DOT HS 812 778
    - DC Charging Safety Evaluation Procedure Development, Validation, and Assessment; and Preliminary Draft AC Charging Evaluation Procedure, DOT HS 812 754
    - System-Level Rechargeable Energy Storage System (RESS) Safety and Protection Test Procedure Development, Validation, and Assessment–Final Report, DOT HS 812 782
    - Failure Modes and Effects Analysis for Wireless and Extreme Fast Charging, DOT HS 813 137

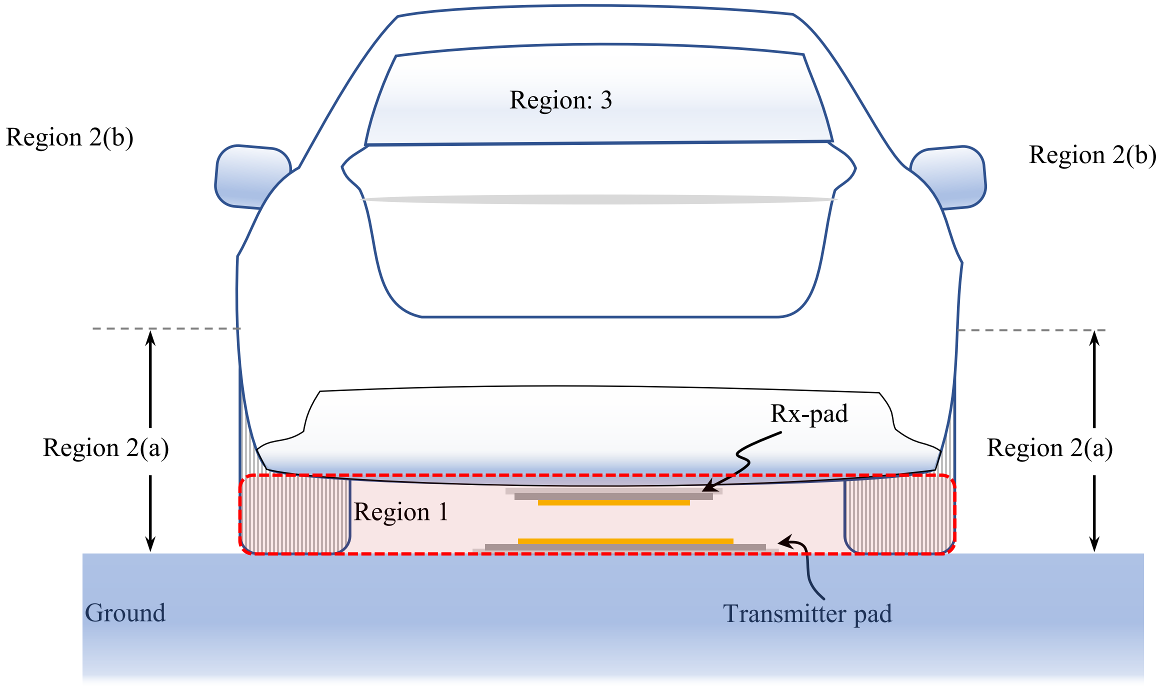
Wireless Charging Systems

- Operational principles
- Overviews of codes and standards for design, testing, and safety
- FMEA for 3 design concepts
  - Potential failures
  - Implications
  - Risk



Conducted and Radiated Electromagnetic Interference (EMI)

- Electro-magnetic field emissions standards
- Coil shapes and topologies
- Alignment, airgap, and efficiency effects
- Standards for wireless pad designs and interoperability



Wireless Extreme Fast Charging

- 10-to-15-minute charging time from 20% to 80% levels
  - Power levels and site requirements
- Compares charging structures based on resonant and non-resonant power converter topologies
- Design of megawatt extreme fast charging (XFC) systems require a comprehensive analysis to consider failures and their effects on individual components and subsystems

Failure Mode and Effects Analyses

- Bulk of the report is contained in the Appendix tables.
  - List major components, potential failures, implications, and risk rating
- Compensation networks, coil design, and topology strongly affect failure modes and potential hazards, especially at XFC power levels.
- Sensing, monitoring, and control needed to detect and mitigate XFC failure mechanisms

Li-Ion Battery Pack Immersion Exploratory Investigation

Stephen Summers

Li-Ion Battery Pack Immersion Exploratory Investigation

Immersion of an electrified vehicle's battery pack is a relatively infrequent occurrence in the real world

Seven batteries were tested for immersion as well as post-immersion smoking or fire.

Report published August 2021

Previous testing published in 2019

Existing Immersion Standards

- SAE J2464 NOV2009 – 4.3.5 Immersion Test (Module or Pack Level)
  - “With the DUT in its normal operating orientation and at full state of charge, immerse the DUT in ambient temperature salt water (5% by weight NaCl in H2O) for a minimum of 2 hours or until any visible reactions have stopped ….” (SAE International, n.d.)
- USABC Battery Abuse Testing – 4.4 Water Immersion
  - “Salt water should be an approximation of seawater (3.5% (600 mM, 35 ppt) sodium chloride)…. The DUT should remain immersed for (1) a minimum of 2 hours or (2) until failure of the DUT (HSL ≥5)…. DUT should be monitored for at least 30 minutes after the completion of the test.” (Orendorff et al., 2017)
- ISO 6469-1:2019 – 6.4.2 Immersion into Water
  - “Immerse the DUT in ambient temperature salt water (3.5-5% by weight) for 2 hours” + 2 hours post-immersion observation time. Requirements: No fire, no explosion.” (International Organization for Standardization, 2019)

Test Program

Test Asset #	Battery Type	Capacity	Key Test Parameters
1	PHEV	8.8 kW-hr	Frequent immersion and observation intervals every 15 minutes
2	BEV	16 kW-hr	30-minute immersion time and 1 hour observation time
3	BEV	30.5 kW-hr	Immersion and observation intervals every 15 minutes for 45 minutes.
4	BEV	32.9 kW-hr	2-hour immersion and 2-hour observation
5	BEV	60 kW-hr	1-hour immersion time + 2-hour observation
6	BEV	60 kW-hr	1-hour immersion time + 2-hour observation. 0.1 percent Salinity
7	PHEV	8.9 kW-hr	Short duration initial immersion of 20 minutes prior to first observation period. 0.1 percent Salinity

Batteries were immersed near 100% capacity or the expected maximum charge level achieved during normal vehicle charging.

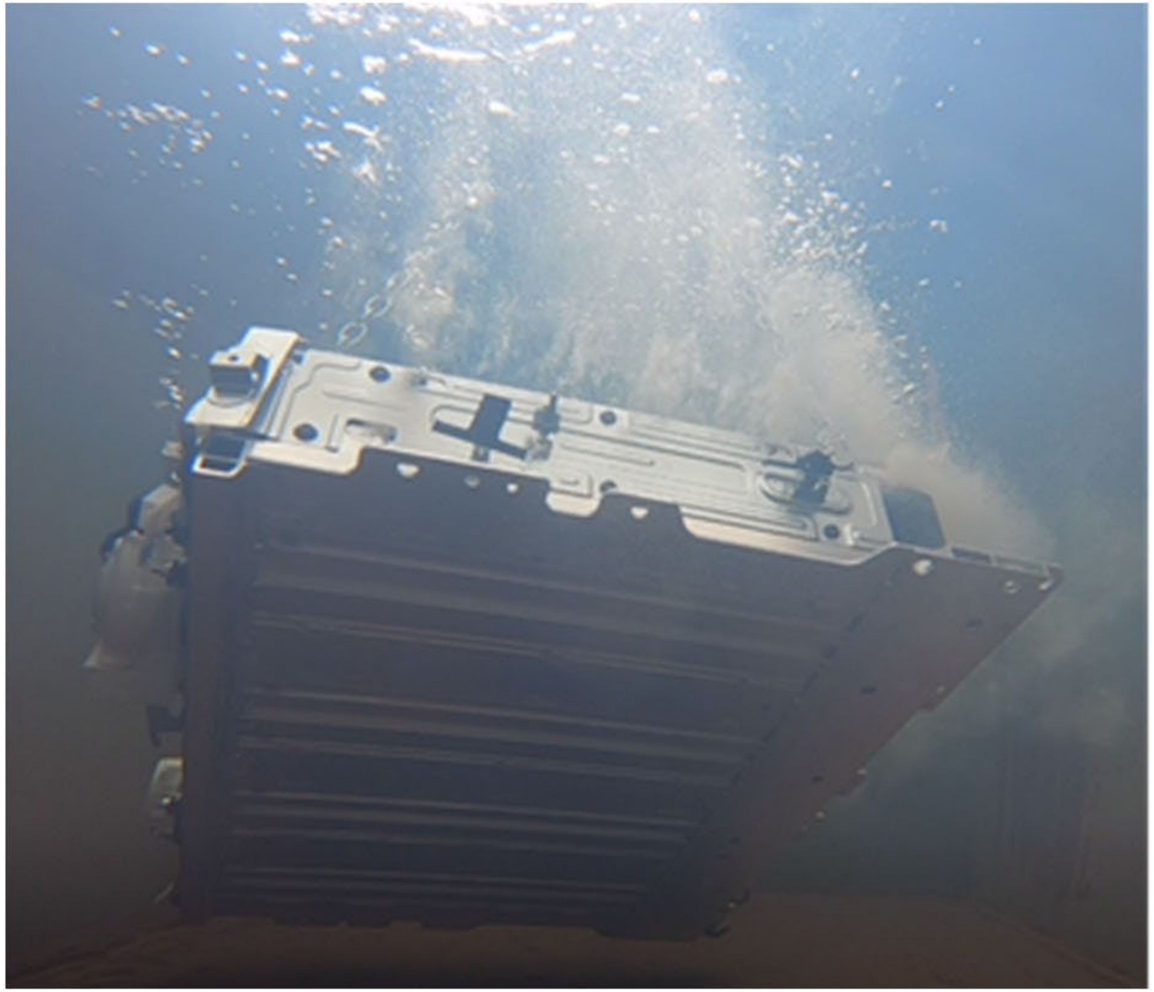
Samples were selected from a range of manufacturers

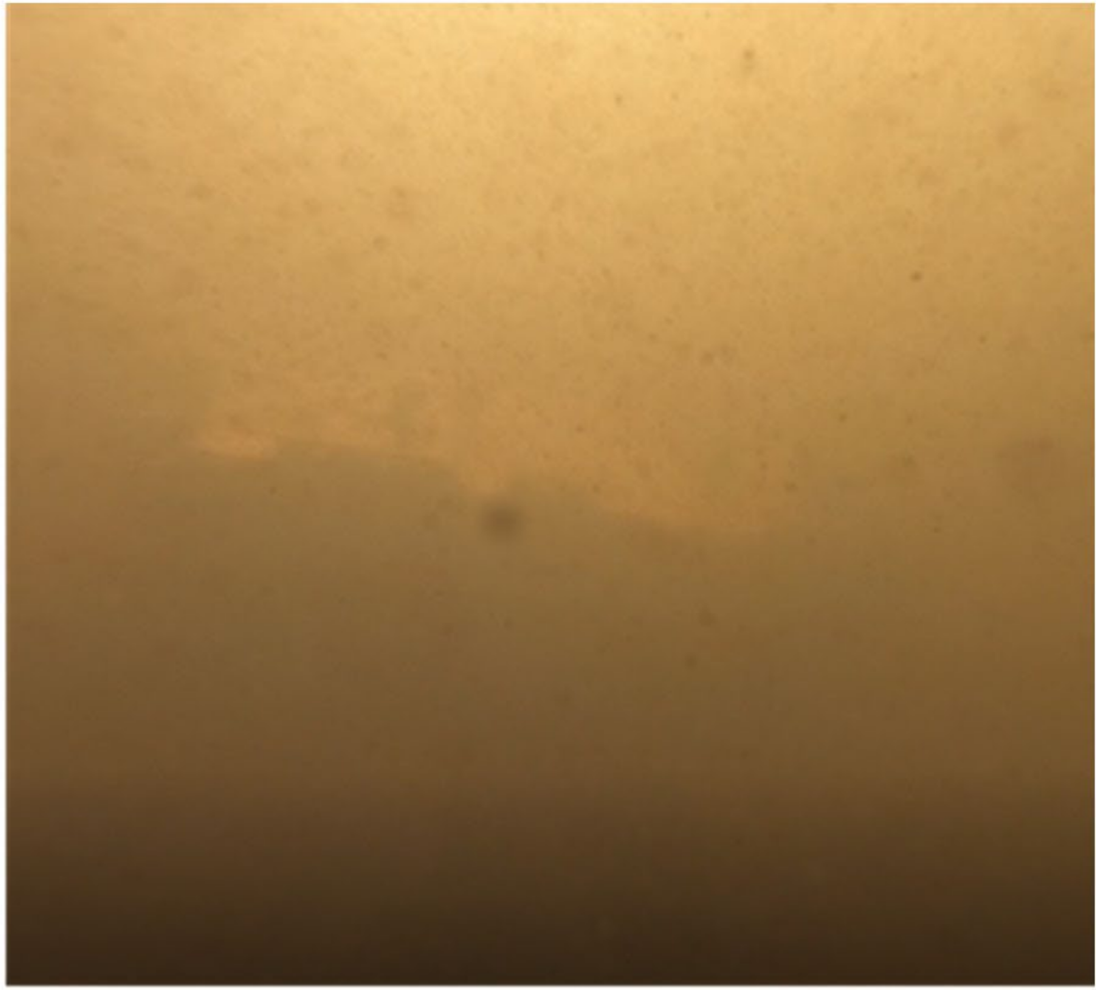
5 batteries immersed with 3.5% salinity; 2 tests used reduced salinity to resemble coolant fluid

Test Setup

Battery Immersion

Immediately After Immersion & 10 minutes later





Observations

- There were no battery issues during immersion
  - 2 batteries had smoke/venting during first 20 min of immersion
- Primary reactions during immersion appeared to last between roughly 30-60 minutes. Larger capacity batteries took longer.
- All the batteries showed significant signs of degradation
- Post immersion batteries were under 50V
- Battery deterioration occurred quicker in 3.5% salinity water.

Electric Vehicle Safety: An Outlook on Thermal Runaway Initiation & Propagation Testing

Stefanie Goodwin

GTR No. 20 Background

Phase 1

- **Documentation Requirements for Manufacturers**

Phase 2

- **Thermal Runaway (TR) Propagation Test** is under consideration
- The methods of thermal runaway initiation under consideration are:
  - (1) *Rapid Heating Method*
  - (2) *Nail Penetration Method*

Thermal Runaway Propagation Test Methods

A

Localized Rapid External Heating Method

- ***New***: ISO 6469-1:2019/CD AMD1 (Section 6.7.7)
- Thermal Runaway Initiation Method (TRIM)
  - Developed by National Research Counsel (NRC) Canada[2]
- A high-powered heat pulse is applied to a small area on the cell's external surface until TR is achieved

B

Nail Penetration Test

- ***New***: GTR 20 Phase 1 Test Procedure
- Drill Hole position and direction are selected
- Hole is drilled in the enclosure of the battery system
- Nail is inserted
- Nail perforates the cell causing TR

[2] Source: "Localized Rapid Heating Methodology and Testing Fully Operational Vehicles" Presented by Transport Canada to NHTSA, February 23, 2021.

Thermal Runaway Test Methods - Possible Challenges

General

- ***Possibly Intrusive & potentially compromises*** the battery pack
- May not be representative of the ***heat output***, ***gas emissions***, and ***ignition characteristics***
- ***Cell Selection*** for TR Initiation - ***Difficult***
- **TR Initiation Methods may not be representative of actual fault conditions and lack objectivity**

A ***Rapid Heating Method***

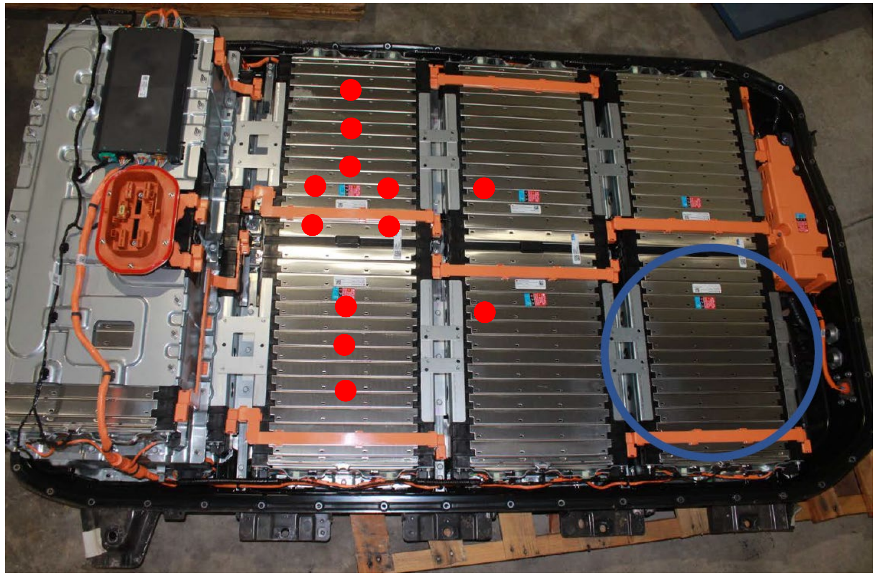
- ***Rechargeable Electrical Energy Storage System (REESS)*** Modification for Surface Mounting:
  - Risk potentially altering REESS functionality
- May result in heating more than one cell
- If heater is inserted between 2 cells, risk TR initiation in 2 cells simultaneously
- Heater Selection (power & size) dependent on cell size & type

B ***Nail Penetration Test***

- Perforation Depth of Nail & Direction may vary
- Nail penetration may damage more layers
  - ***Result***: higher heat output than in an actual fault condition

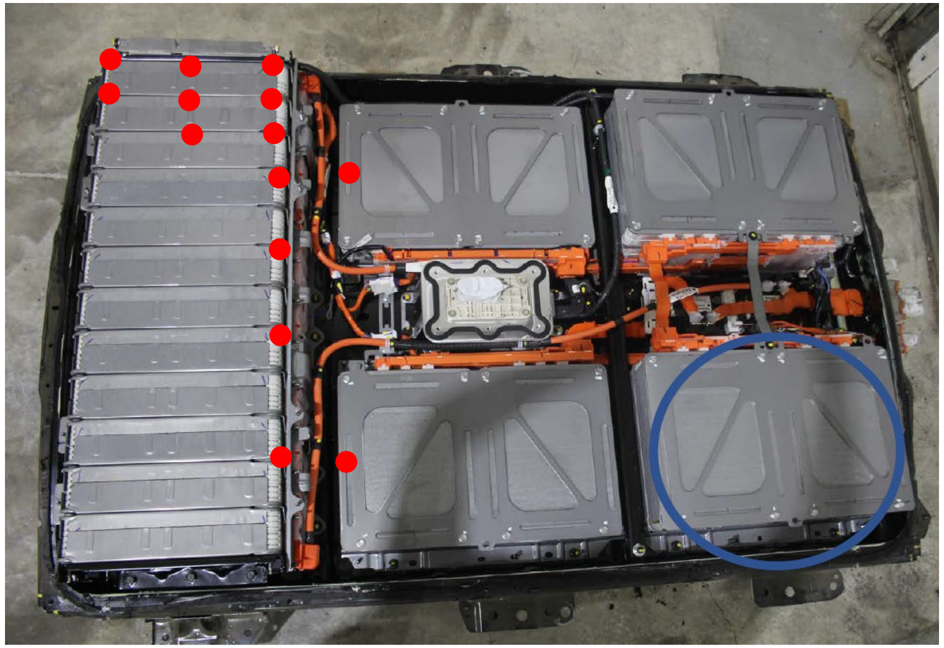
Unclear if these Test Methods Achieve: Feasibility, Objectivity (Repeatability & Reproducibility), Practicability across all EV Makes & Models

Research Objectives



Evaluate

Feasibility, Objectivity, and Practicability of test methods on different REESSs



Compare

Test results from the ***heating method*** with results from the ***nail penetration*** method

Test Matrix

- I. 4 Vehicle Models with different battery cell technology (e.g. cylindrical, prismatic, etc.)
- II. Repeated on 1 Vehicle Model twice to evaluate repeatability
- III. Conducted on 3 (new) EVs
- IV. Comparison of heating method & nail penetration test results for the same (but new) vehicle models

Vehicle Model	Rapid Heater Test	Nail Penetration (III.) Test
A	(II.) 2	0
B	1	1
C	1	(IV.) 1
D	1	1

(I.) Rows A–D

Outreach to First Responders

Dave Bryson

First Responder Outreach

- Since 2011, NHTSA has partnered with Federal partners, national FR organizations, the FR community, and others to disseminate information, research, and guidance on safely responding to high voltage battery incidents.

First Responder Outreach

- The FR community includes law enforcement, fire service, emergency medical services agencies, towing/wrecking, and any other entity that responds to, or helps mitigate, a high voltage battery incident.

First Responder Outreach

- NHTSA partnered with DOE, USFA, the National Fire Protection Association (NFPA) and others to draft a series of interim guidance documents for law enforcement, fire service, EMS clinicians, towing & wrecking, and vehicle owners.

- Last updated in 2014, information about the hazards of flooded high voltage battery systems was added from lessons learned during Hurricane Sandy.

First Responder Outreach

- NHTSA and DOE supported the NFPA to produce high voltage battery fire and crash training for first responders. Courses and additional information can be found on the NFPA's website:

  https://www.NFPA.org/EV

First Responder Outreach

- NHTSA's Office of EMS (OEMS) is responsible for the development and revision of the National EMS Education Standards (NES)
    - The NES are the basis for educating all EMS practitioners in clinical and operational aspects of patient care and clinician health & well-being
    - **Responding to EV incidents (operations) and caring for patients involved in EV incidents (clinical) are included in the current NES**

First Responder Outreach

- NHTSA OEMS also has real-time capability to get critical info on EVs and other transportation-related issues out to the FR community

  - ***NHTSA Update*** e-mail blasts.
  - www.EMS.gov

- Our Federal partners, national FR organizations, the FR community and others also help NHTSA distribute EMS.gov postings and EMS Update info through their established networks.

Best Practices and Concerns for Fire and EMS responders

Whitney Tatem

Best Practices and Concerns for Fire and EMS Responders

NHTSA is engaged in an Inter-Agency Agreement (IAA) with the United States Fire Administration (USFA) in support of this research.

Purpose:

The objective for this IAA is to perform a comprehensive review of existing electric vehicle (EV) and EV battery fire reports, research, regulations, and codes, manufacturer guidance documents, and training programs related to first responders.

Goal:

Develop an ‘Electric Vehicle Fire/Rescue Response Operations, Health, and Safety’ guide.

Special Safety Concerns for EV Batteries

There are several common risks for first responders associated with electric vehicle fires:

- **Stranded energy** (electrical shock)
- **Thermal runaway**
- **Reignition up to 24h after initial extinguishment**
- Lithium burns
- Toxic fumes and runoff

For more information, see USFA's blog, 'Know the threats before you attack an electric vehicle fire.'

Reducing the Risk

There are a variety of ways to mitigate the risk of electric vehicle fires to first responders, but many can be improved:

- Easy ways to identify an EV upon arrival at the scene
- Thermal imaging cameras to identify heat sources
- Adequate water supplies (or alternative extinguishing techniques)
- Accessible battery power down/discharge
- Monitoring/eliminating reignition

For more information, see USFA's blog, 'Know the threats before you attack an electric vehicle fire.'

Specific Research Tasks

1. Comprehensive review of existing EV hazardous incident and EV battery fire reports, research, regulations, standards, codes, manufacturer guidance documents, and training programs.

2. Develop study findings into a report – ‘Electric Vehicle Fire/Rescue Response Operations, Health and Safety Guide.’

3. Share research findings and the guide with standard-setting organizations.

Establishing Best Practices

Our guide, ‘Electric Vehicle Fire/Rescue Response Operations, Health, and Safety,’ will aid in teaching first responders how to safely deal with electric vehicle fires.

- Document current tactics for efficiently and safely controlling EVs themselves and their energy storage systems (which includes both the batteries and charging systems) when an incident occurs.

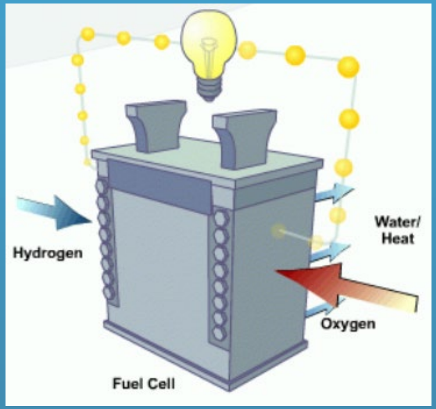
- Clearly identify:
  - Key chemical and electric hazards when responding to an EV event.
  - Best and most common suppression strategies.
  - Safety issues that persist for first responder’s given today’s technologies and procedures.

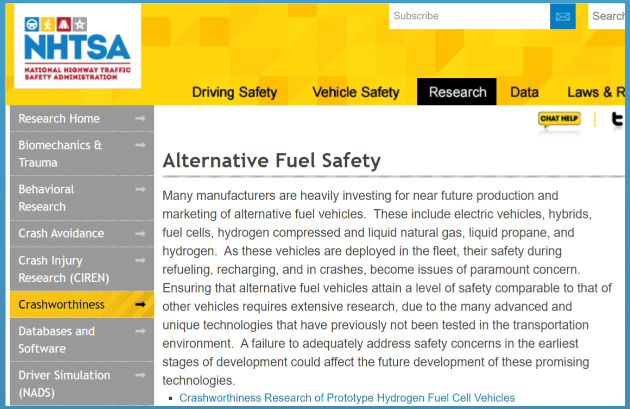
Hydrogen Cylinder Fire Testing

Ian Hall

Introduction to Fuel Cells

- Fuel Cells
  - Individual Hydrogen molecules are split and combined with Oxygen, resulting in water and heat.
  - Process creates a current, which can be used to drive a vehicle via an electric motor.
  - Hydrogen gas is stored in compressed pressure storage systems (CHSS).
- Prior Research
  - Listed on NHTSA website. (Alt. Fuel Safety)
  - Full-vehicle crash tests on hydrogen prototype vehicle.
  - Post-impact fuel system integrity research for hydrogen.
  - Hydrogen leakage limits.
  - Analyzed the Global Technical Regulation (GTR) procedures the life cycle durability of hydrogen storage tanks





Current Research

- Hydrogen Tank Fire Testing
  - Supporting the development of GTR-13 "Hydrogen and fuel cell vehicles."
  - Conducted four fire tests on a single tank to evaluate the test procedure.
    - Pre-test burner evaluation
    - Localized fire test
    - Engulfing fire test
  - Recorded Lessons' Learned.

Current Research

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Future Research

- Continue evaluating GTR-13 test methods.
- Temperature Pressure Relief Device (TPRD) Component-level testing
  - Accelerated life test,
  - Stress corrosion cracking test,
  - Leak test, etc.
- Check Valve and Shut-off Valve Component-level testing
  - Extreme temperature pressure cycling,
  - Vibration test,
  - Leak test, etc.

Thank you for your time and attention

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