Tanvir Tanim, R&D Scientist and Group Lead
Energy Storage Technology Group, Department of Energy Storage and Electric Transportation

Early Detection of Electric Vehicle Battery Failures

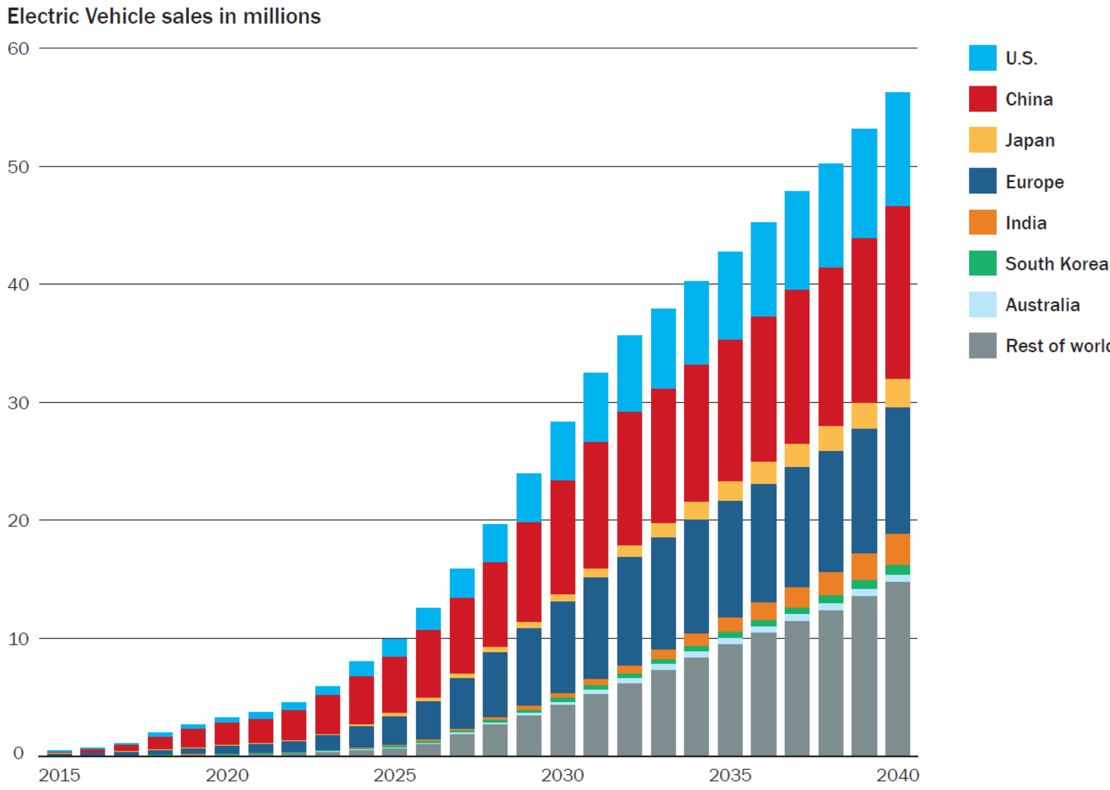
EV Battery Safety Session

SAE Government/Industry Meeting
January 17-19, 2023, Washington DC.

Idaho National Laboratory

Electric Vehicles and Battery Safety

- Many countries are pushing for rapid expansion of electric vehicles (EVs).
- Most have full or near complete transition targets by 2030-2040.
- Significant R&D efforts are going on to increase the current state-of-the-art LiB's specific energy from ~250 $Whkg^{-1}$ to as high as 500 $Wh.kg^{-1}$
  - Battery performance and safety evolve with aging
- An unsafe battery in EV at any point in its service life could have many implications
  - Safety of end users: EV owners, including used cars and other 2nd used scenarios.
  - OEMs and insurance companies: warranty and liability-related financial loss. Negative public perception.
  - Unsafe stranded energy: 1st and 2nd responders, EV owners, and 2nd used scenarios.



Bloomberg New Energy Finance Long-Term Electric Vehicle Outlook 2019. Page 2 of Executive Summary.
https://bnef.turtl.co/story/evo-2020/ page/3?teaser=yes.
National Blueprint for Lithium Batteries

Electric Vehicles and Battery Safety (Cont.)

- A potentially damaged/defective battery with an unknown state of safety might go into a thermal runaway without proper monitoring, diagnosis, controls, and handling—thereby leading to potential loss of life and property.

2020 Chevy Volt Fire due to battery defect

2011 Chevy Volt Latent Battery Fire at DOT/NHTSA Test Facility

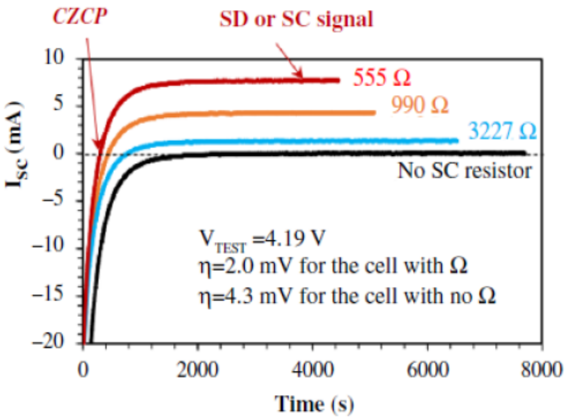
2022 EV Battery Fires at Florida after Hurricane Ian

- Advanced diagnosis and proper handling can play a crucial role for early detection and mitigation.
  - Safety diagnosis methods and tools have been lagging but starting to catch up.

https://insideevs.com/news/621377/two-years-after-chevy-bolt-recall/
https://abc7news.com/hurricane-ian-ev-car-fires-electric-cars-damaged-florida-flood-damage/12356326/
Safety Risks to Emergency Responders from Lithium-Ion Battery Fires in Electric Vehicles, NTSB/SR-20/01 PB2020-101011

Battery Safety Diagnostics in the Market

Short detection technique



S. V. Sazhin, E. J. Dufek, K. L. Gering, *J. Electrochem. Soc.* **164**, A6281–A6287 (2016)

https://www.novussentry.com/

https://www.keysight.com/us/en/products/application-specific-test-systems/lithium-ion-battery-self-discharge-measurement-solutions.html

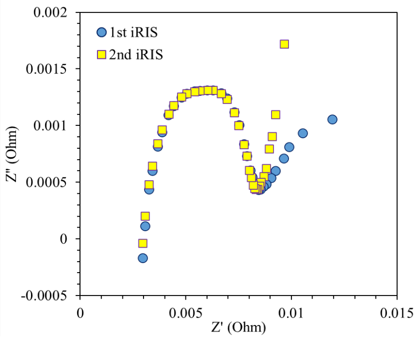
Detection time ~ in the range of 1-2 h

Battery Safety Diagnostics in the Market

Rapid impedance diagnostics

Dynexus iRIS (10 to 20 sec)

https://www.dynexustech.com/products



Cadex Spectro rapid impedance diagnostics

Cadex Spectro rapid impedance diagnostics (<2 min)

https://www.cadex.com/products/spectro

Off gas-based diagnostics

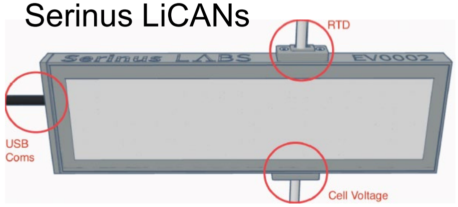
Nexceris Li-ion Tamer Gen2+

https://xtralis.com/product/203/li-ion-tamer-monitoring-system

Metis battery safety sensor

https://www.metisengineering.com/

Serinus LiCANs



https://www.serinuslabs.com/about

FDA241 – li-ion off-gas detector by Siemens

https://www.amphenol-sensors.com/en/

Battery Safety Diagnostics in Late R&D Stage

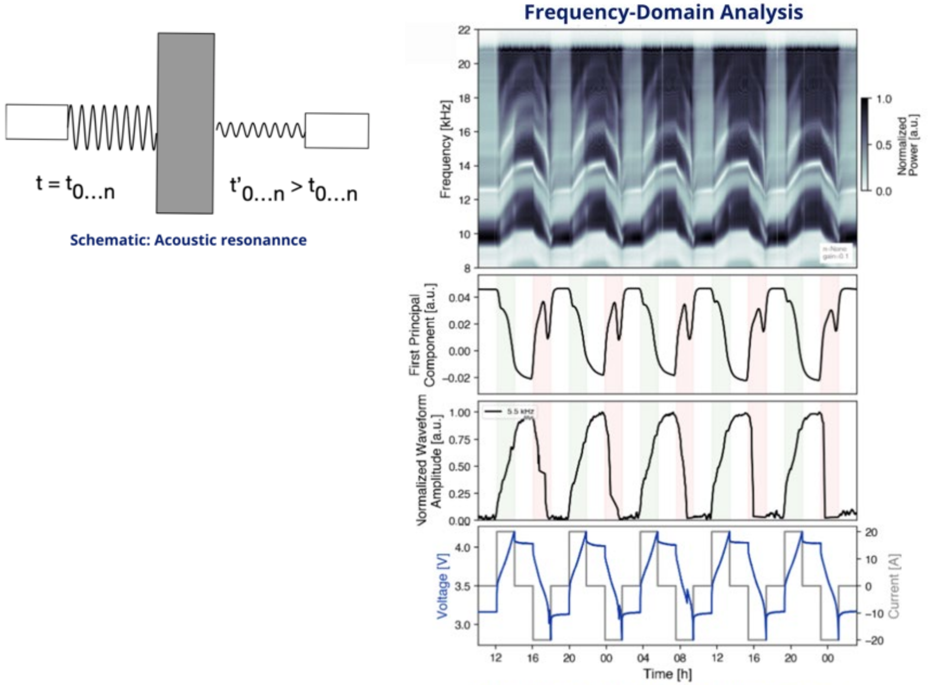
Electrochemical Magnetic Induction Spectroscopy (EMIS)

Parthian Energy

- Observe and quantify 2D current distribution maps and correlate them with state of safety (SoS) and (SoH).
- Based on AC electromagnetic field (EMF) monitoring, EMIS enables non-invasive detecting and measuring various manufacturing and operation-induced defects, without interrupting the normal operations (DC cycling) of the battery, using a 2 mm thick planar sensor.
- EMIS is chemistry, shape and size agnostic and can be used as a long-awaited manufacturing screening solution, preventing future recalls or enabling reliable used battery applications, or as a breakthrough sensor, enabling next generation BMS solutions.

Ultrasonic-based diagnostics

Tracks amplitude and frequency shifts



46.4 Ah Module cycled at C/2 without liquid couplant. Frequency sweep 5-21 kHz with a frequency interval of 100 Hz. Sweep interval 200 s

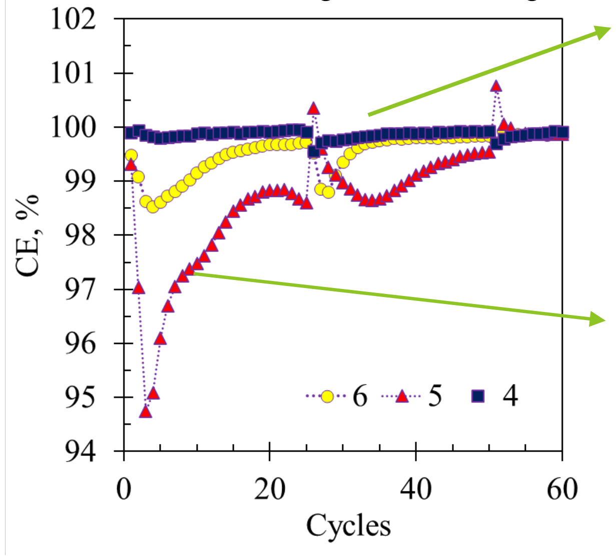
G. Thorsteinsson, Poster from Gordon conference, 2022

https://www.parthianenergy.com/

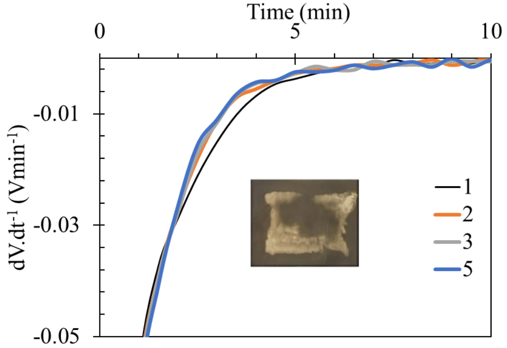
Battery Safety Diagnostics in the Early R&D Stage: Detecting Li Plating

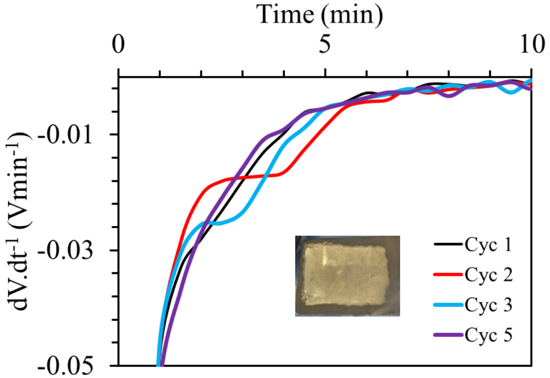
Coulombic efficiency (CE)

6C CC-CV charge/C/2 discharge

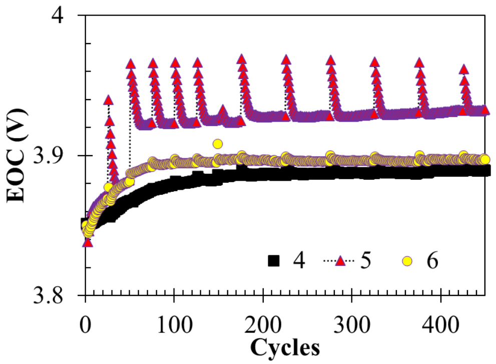


Post- charge dV/dt signature

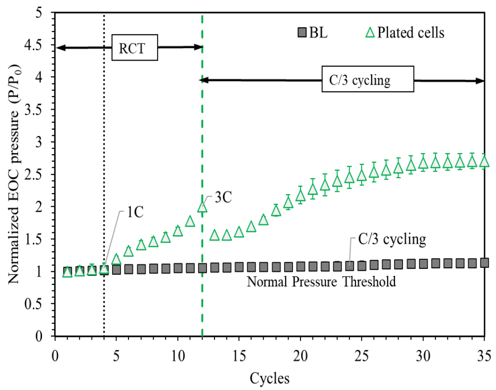


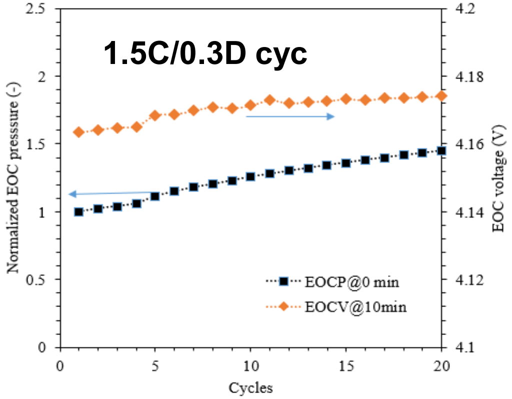


Other signatures

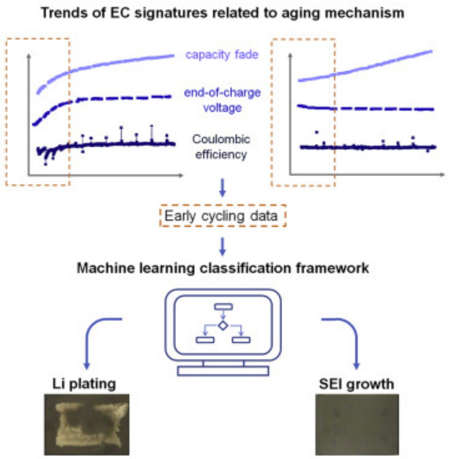


11 Ah Gr/NMC MLPC, 3-4.2V, 30°C





Machine Learning



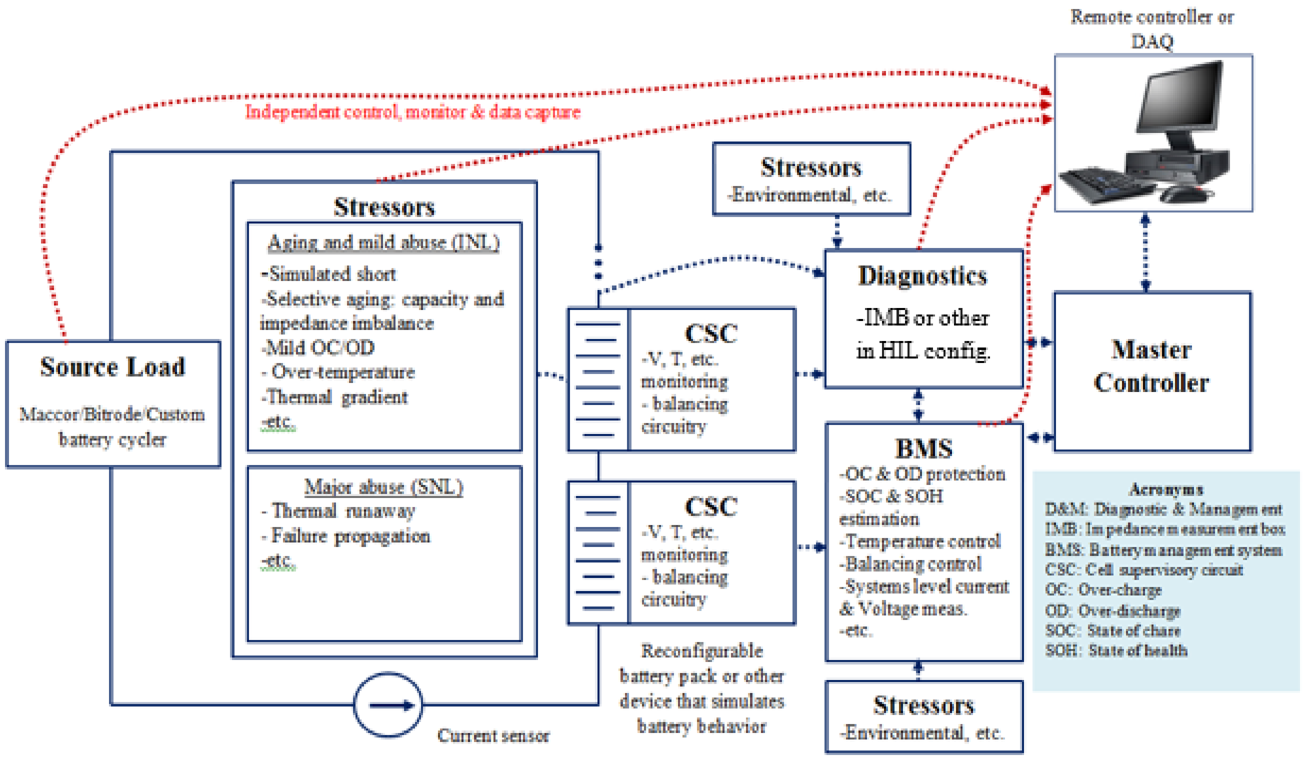
Chen et al., Cell Reports Physical Science, 2 (3) 2021, 100352

- Electrochemistry and pressure-based diagnostics can be helpful, but reliability could be an issue.
- Implementing advanced analytics using multiple signatures could provide more robust detection.

Tanim et al., Cell Reports Physical Science, 1 (7) 2020, 100114

Diagnostic Platform to Evaluate Battery Diagnostic and Management Systems

- A reconfigurable diagnostic evaluation platform capable of **communicating with and evaluating different diagnostic tools** in real-time in HIL fashion.
- The demonstration platform will be able to directly compare D&M technologies in a standard manner and their ability to detect off-normal behavior indicative of potential safety risks.

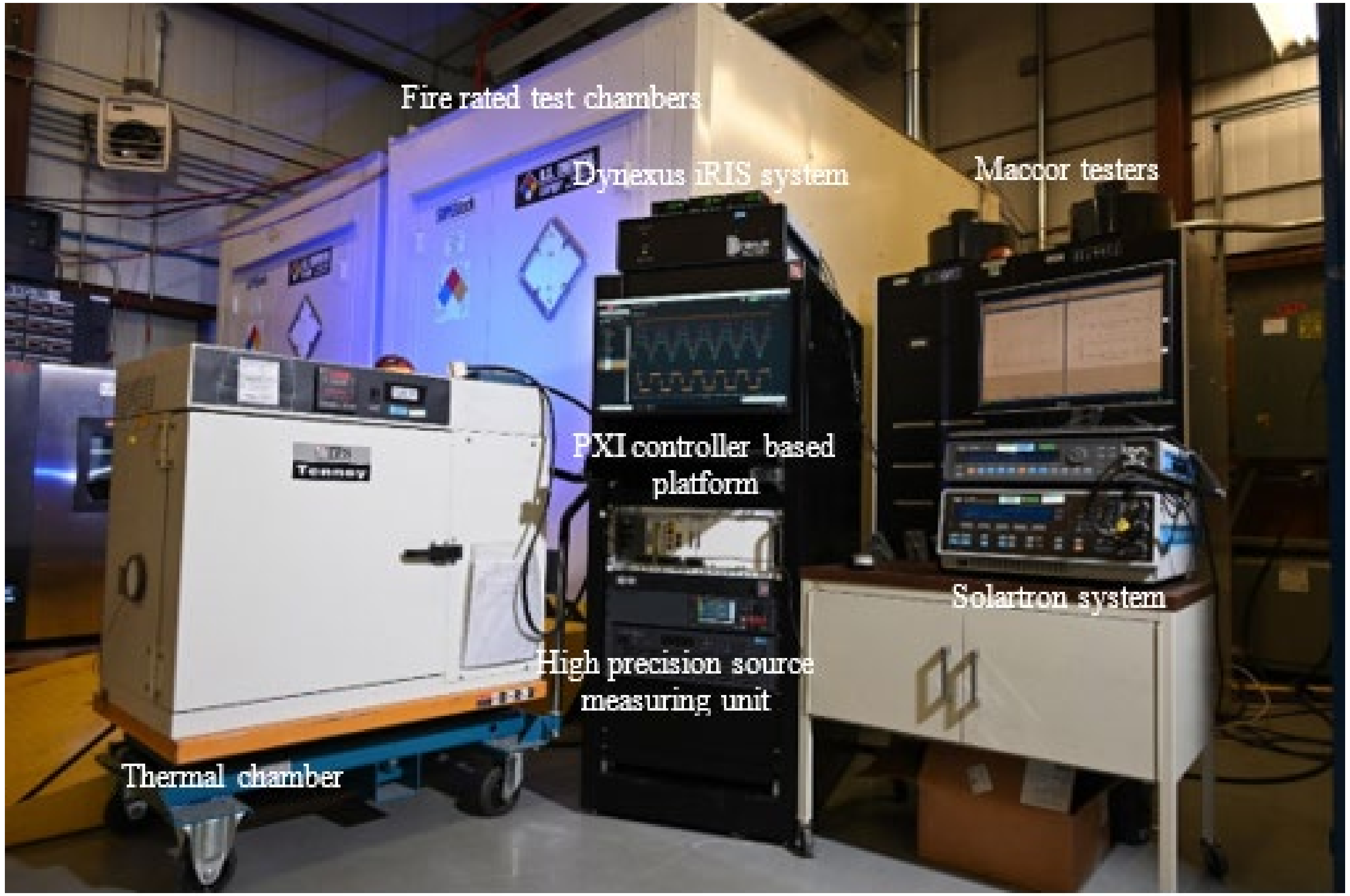


Conceptual layout of **B**attery **A**dvanced **D**iagnostic **E**valuation (BADgE) Platform

Key capabilities-

- Directly compare different battery diagnostic and mgt. technologies in real time
- Simulate different battery architectures, drive cycles and fault conditions
- Simulate different off normal battery scenarios
  - Open/short circuit
  - Overcharge/discharge
  - Temperature heterogeneity
  - Aging heterogeneity
  - Balancing issues
  - Other major abuses
  - Etc.
- Diagnostic method development, verification and validation based on real or emulated signal

BADGE Platform



Current capabilities:

- PXI controller- based platform.
  - Seamless communication with battery tester
    - Handles different types of data seamlessly, Display live data, Query, view and analyze historical data, event detection and triggering high speed data collection, calculated channels
  - Triggering capacity to external devices, e.g., iRIS, LionTamer.
  - Implemented support for additional hardware, e.g., diagnostics and BMS
  - Module-level battery emulator (work in progress)

BADgE Platform supports safety diagnostic development, comparison, and validation activity.

BADgE Capability

- Multiple diagnostics integrated with BADgE
- Coordinated testing is being performed at INL and Sandia

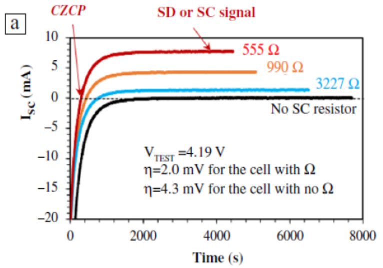
Impedance-based (implemented)

Off gas-based (implemented)

Metis

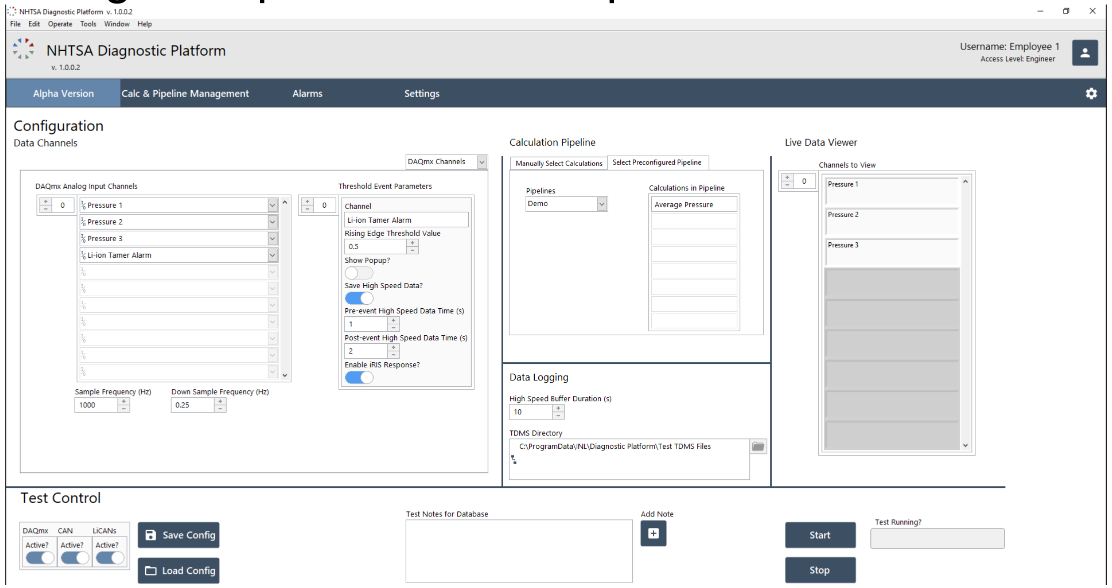
Others (to be implemented)

NOVUS SENTRY
RETHINKING BATTERY SAFETY & RELIABILITY

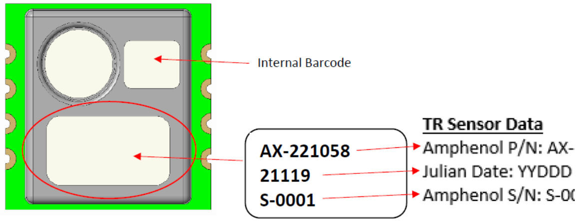


S. V. Sazhin, E. J. Dufek, K. L. Gering, *J. Electrochem. Soc.* **164**, A6281–A6287 (2016)

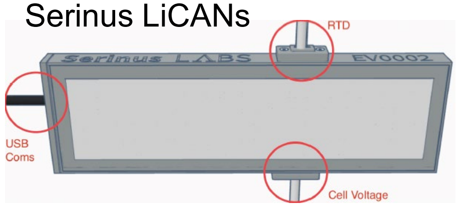
BADgE Graphical User Interphase



Amphenol



Serinus LiCANs

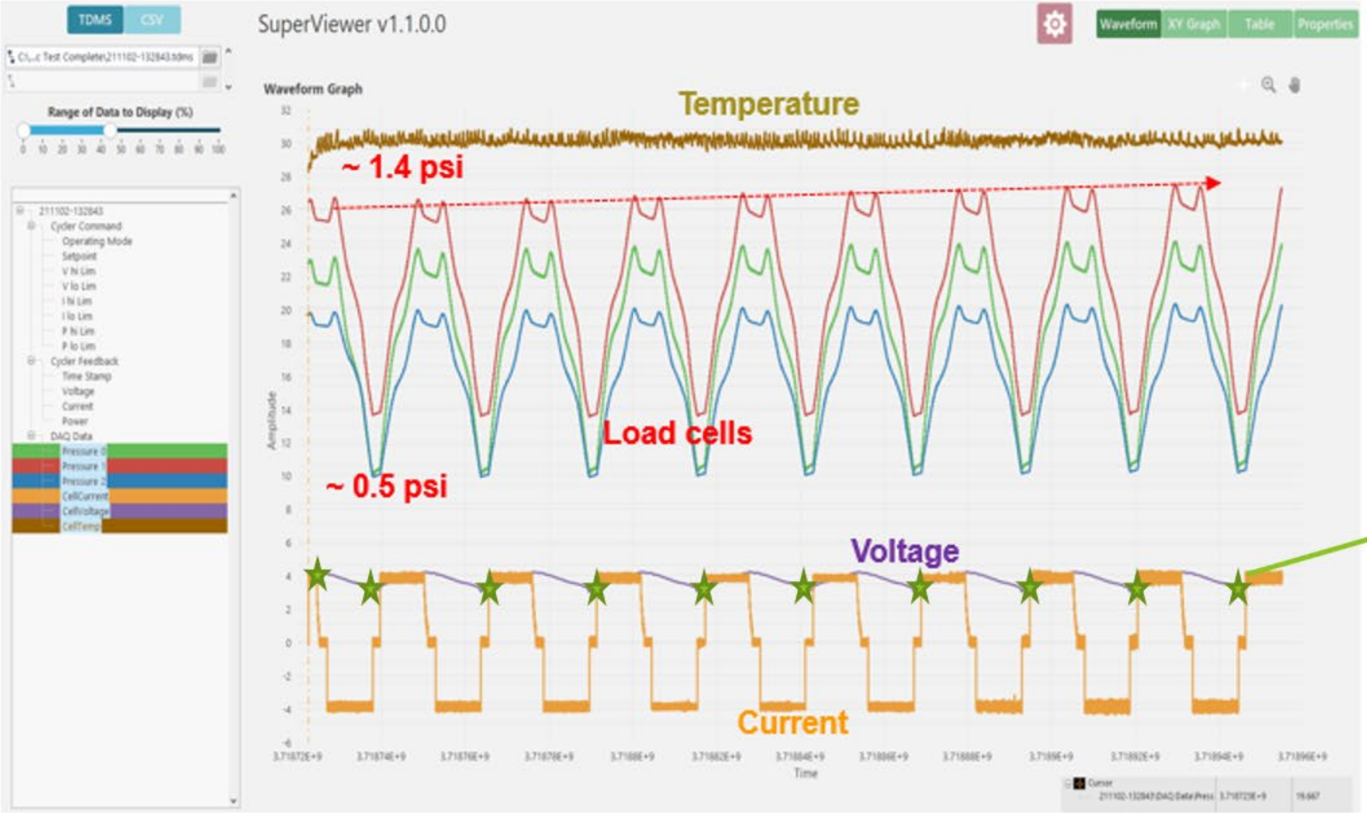


Cadex Spectro rapid impedance diagnostics (<2 min)

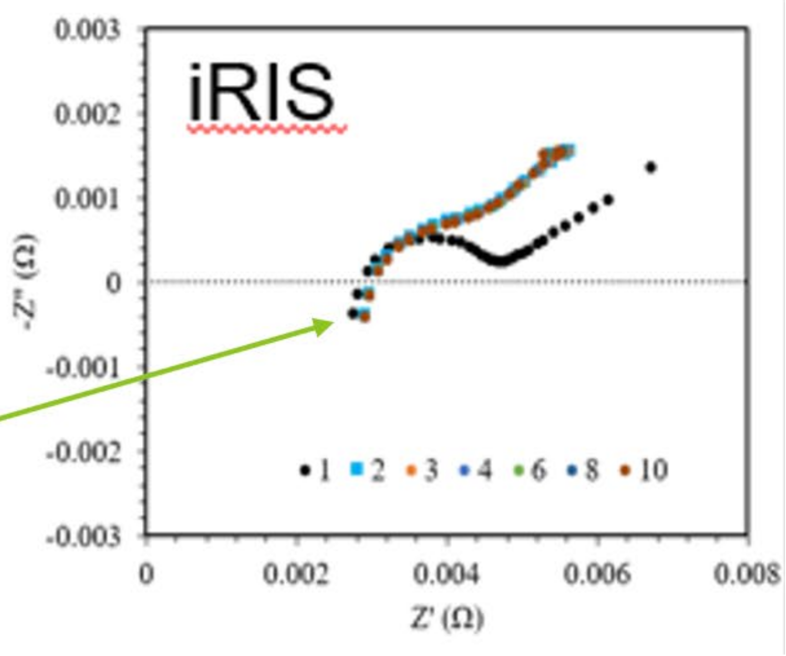
https://www.cadex.com/products/spectro

BADgE Capability: Case Study 1

- Collects and display different types of data simultaneously, which could be used to develop and verify advanced analytics-based diagnostics.



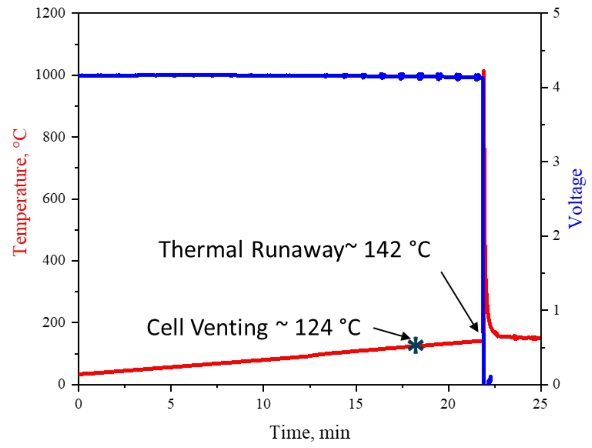
Time domain data

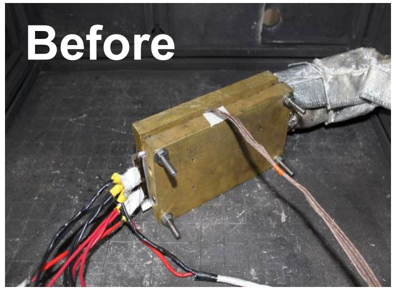


Frequency domain data

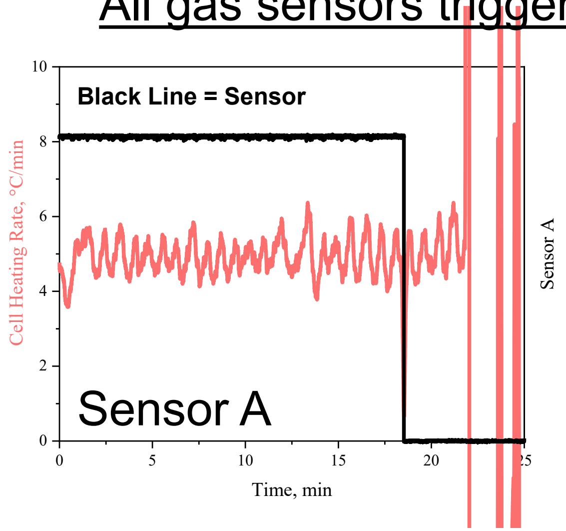
BADgE Capability: Case study 2

- Coordinated test with BADgE platform using multiple sensors.
- 11.6 Ah NMC Single Cell – **Overtemperature to Failure**
  - Continuous gas sensing and electrochemical impedance measurements were collected for the duration of the test using BADgE.

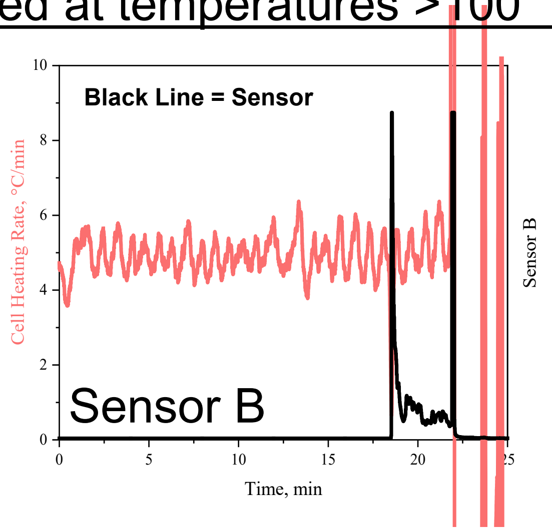




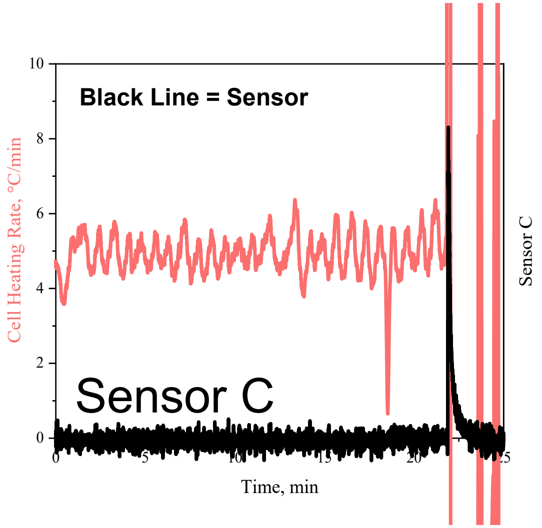
All gas sensors triggered at temperatures >100 °C



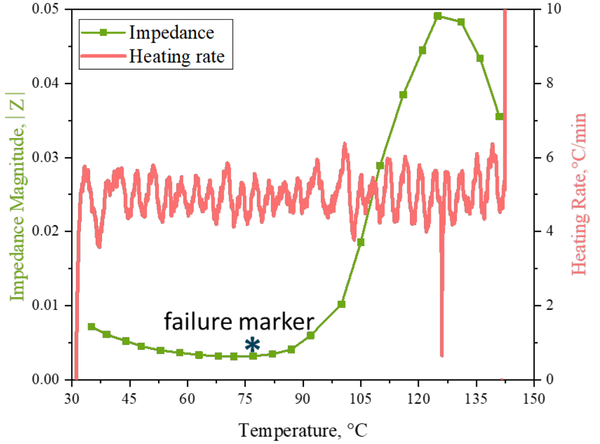
Sensor triggered during cell venting (~3 min before thermal runaway)



Sensor triggered during cell venting (~3 min before thermal runaway)



Sensor triggered during thermal runaway

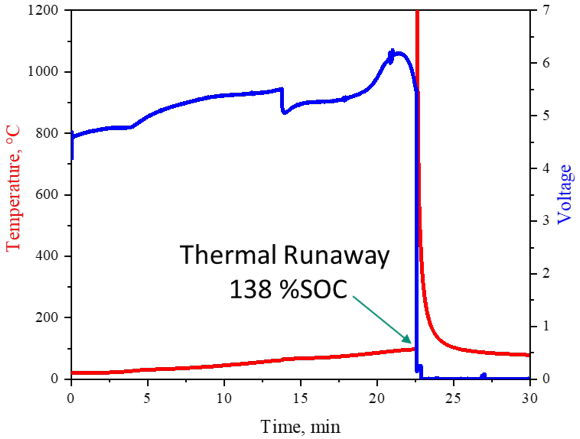


Failure marker identified 13 minutes prior to thermal runaway

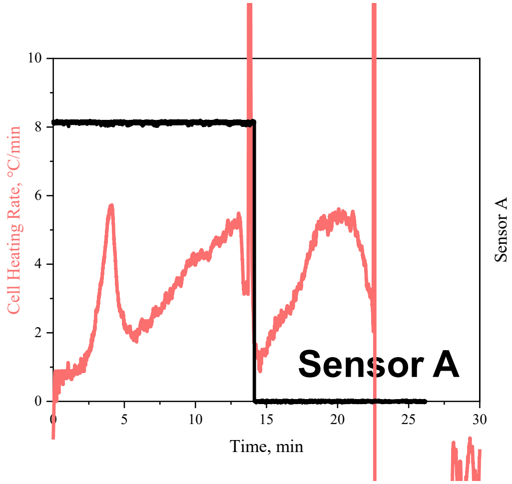
Tests performed at Sandia.

BADgE Capability: Case study 3

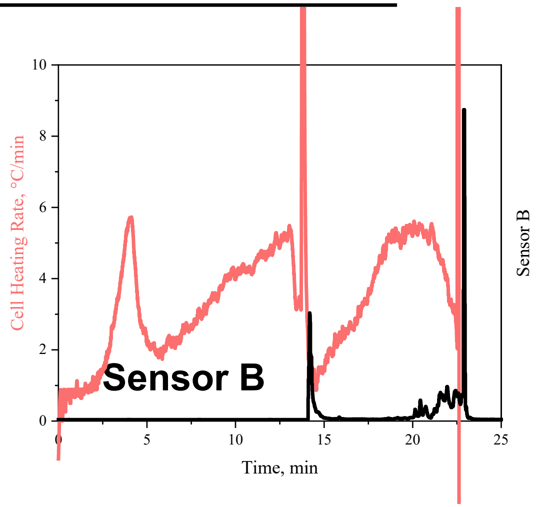
- Coordinated test with BADgE platform using multiple sensors.
- 11.6 Ah NMC Single Cell – **Overcharge/ Electrical Abuse**
  - Continuous gas sensing and electrochemical impedance measurements were collected for the duration of the test using BADGE.



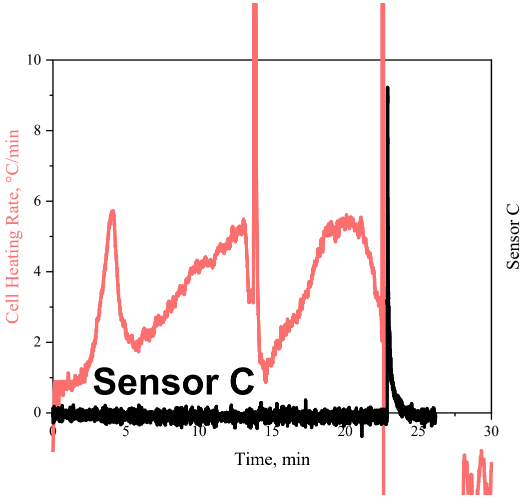
<u>All gas sensors triggered at SOC >120%</u>



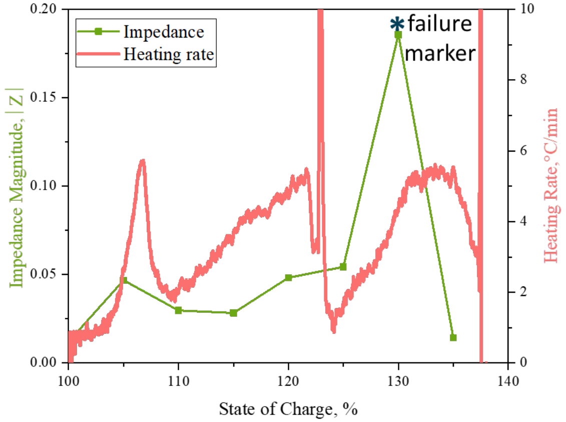
Sensor triggered 8 minutes before thermal runaway



Sensor triggered 8 minutes before thermal runaway



Sensor triggered during thermal runaway

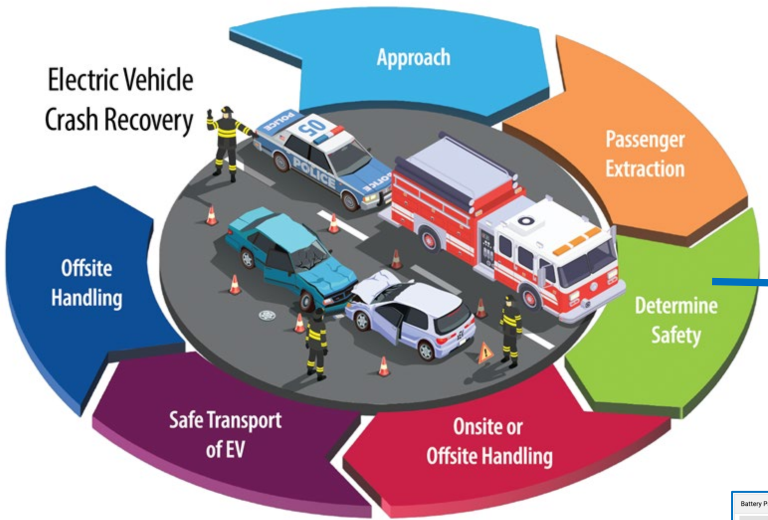


Failure marker identified 4 minutes prior to thermal runaway

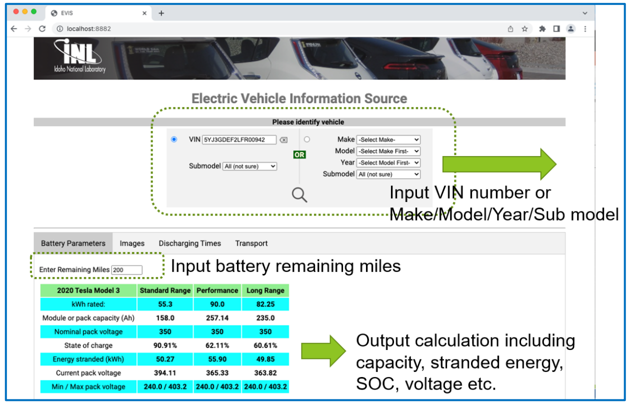
Tests performed at Sandia.

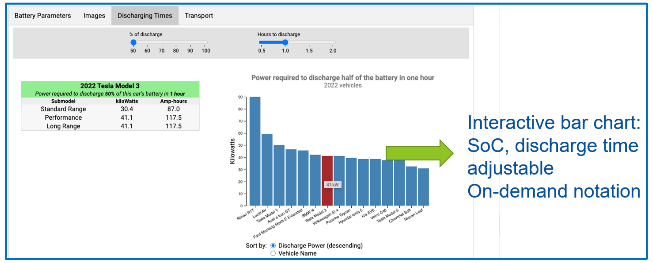
Handling Stranded Energy

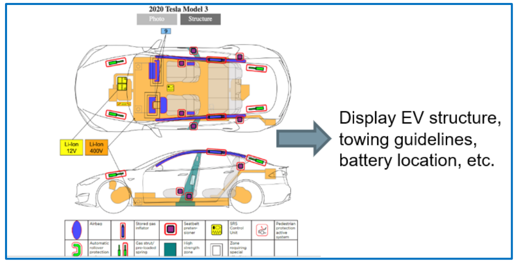
- **Stranded energy is the energy remaining inside any undamaged or damaged battery following any undesirable incident/accident.**



Tools to provide EV information and emergency response guidelines quickly to emergency responders.





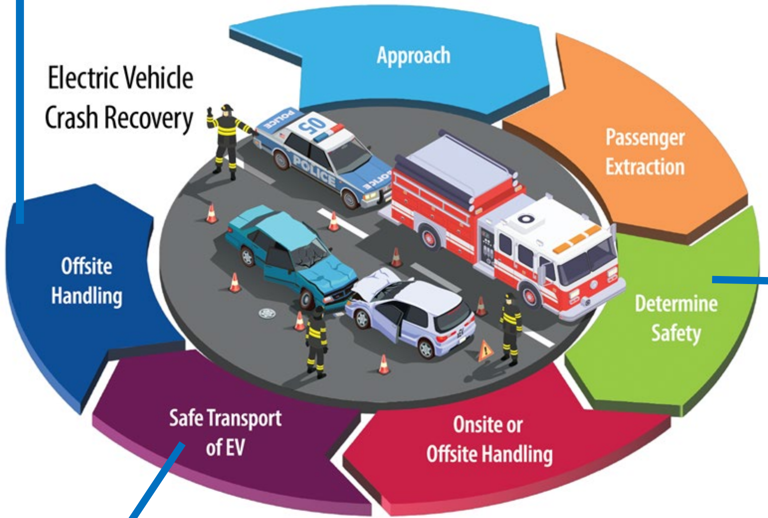


Training materials/contents for safe handling of EVs.

Zhang et al., Electric Vehicle Post-Crash Recovery—Stranded Energy Issues and Mitigation Strategy, J Power Sources, 552 232239 (2022)

Handling Stranded Energy (Cont.)

- **Battery fault detection is limited by advanced fault detection diagnostics and methods**.



Capture voltage, temperature, and other safety-related diagnostic data through OBD II. Develop advanced pack fault detection diagnostics using onboard data.

Standardization of CAN library would be beneficial.

Ford Mustang Mach-E

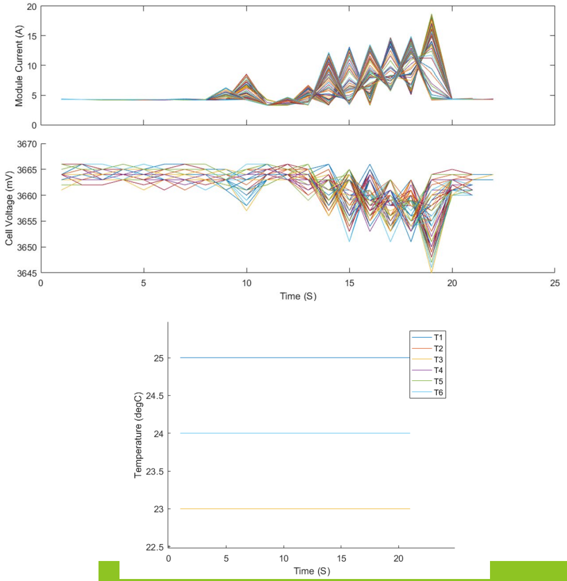


Figure 1. A stranded vehicle scenario requiring safe transport.

Figure 2. A specialized transport vehicle with a specialized shipping container.

Zhang et al., Electric Vehicle Post-Crash Recovery—Stranded Energy Issues and Mitigation Strategy, J Power Sources, 552 232239 (2022)

Conclusions

- Ensuring safety of EVs throughout their service life is a unique challenge and opportunity.
- Developing advanced battery safety diagnostics is a key need.
  - Understanding what works and what does not work is crucial.
  - Using multiple diagnostic signals could be useful.
  - Rapid validation of different diagnostics in both R&D and early development phases is important to bring best candidates to the market
- The stranded energy issue
  - Examine suspected packs for safety, developing safe handling procedure, training, pack fault diagnostics, etc.
- Requires coordinated effort among researchers, OEMs, and policy makers

Acknowledgements

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  - NHTSA, DOT
  - Stephen Summers, Sanjay Patel, Tony Thampan, Peter Martin.
- **Other INL Contributors**
  - Lee Walker, Matthew Shirk, Bo Zhang, Randy Bewley, Jordan Todd
- **External Collaborators**
  - Sandia National Laboratories: Loraine Torres-Castro, Alex Bates
  - Columbia University: Prof. Dan Steingart
  - Penn State University: Prof. Christopher Rahn

Thank you!

Idaho National Laboratory