Sandia National Laboratories

7540 POWER SOURCES TECHNOLOGY GROUP

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COMPONENT SCIENCE, ENGINEERING, & PRODUCTION





Defining Diagnostic Parameters for Early Detection of Thermal Runaway

PRESENTED BY

Alex Martin Bates

2023 Energy Storage Systems Safety & Reliability Forum

06/06/2023

Capabilities and Infrastructure

Cell and Module Testing
Battery Abuse Testing Laboratory (BATLab)

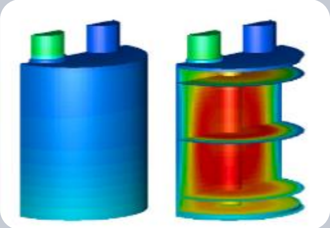
Battery Pack/System Testing
Thermal Test Complex (TTC) and Burnsite

Battery Calorimetry

Safety Science

Materials R&D
- Non-flammable electrolytes
- Electrolyte salts
- Coated active materials
- Thermally stable materials

Testing
- Electrical, thermal, mechanical abuse testing
- Battery calorimetry
- Large scale thermal and fire testing (TTC)
- Failure propagation testing on batteries/systems
- Degradation and diagnostics during and post battery failure



Simulations and Modeling
- Multi-scale models for understanding thermal runaway
- Validating failure propagation models
- Fire Simulations to predict the size, scope, and consequences of battery fires

Procedure Development and Stakeholder Interface
- USABC Abuse Testing Manual (SAND 2005 3123)
- OE Energy Storage Safety Roadmap
- R&D programs with NHTSA/DOT to inform best practices, policies, and requirements

- Sandia is uniquely positioned to study the entire life cycle of a technology.
- New technologies present new risks. A high rigor environment at Sandia allows those risks to be adequately managed.

Detecting an Unsafe or Unstable Battery

2013 Boeing Dreamliner Battery Fires, FAA Grounds Fleet

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

Voltage and temperature are lagging indicators of a battery failure. By the time a measurable trend is detected, it may be too late to arrest a catastrophic thermal runaway.

Advanced diagnostics can play a key role for early detection and mitigation

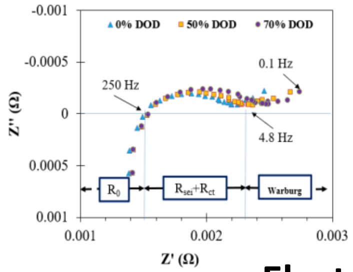
The Need for Standard Testing Methods and Evaluation Platforms

R&D efforts in developing and maturing diagnostics toolsets are expected to continue

Reconfigurable test and validation platforms could provide mechanisms and support for testing, refinement, and benchmarking of emerging battery diagnostic technologies

Such activities would also ensure appropriate tools are in place for consumer and emergency-responder safety

Rapid impedance-based diagnostics

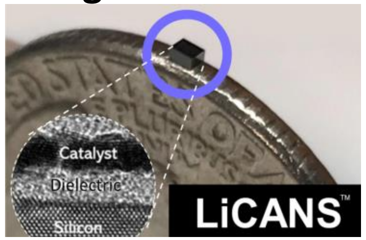


https://www.dynexustech.com/products

Electromagnetic Field

Gas based diagnostics

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

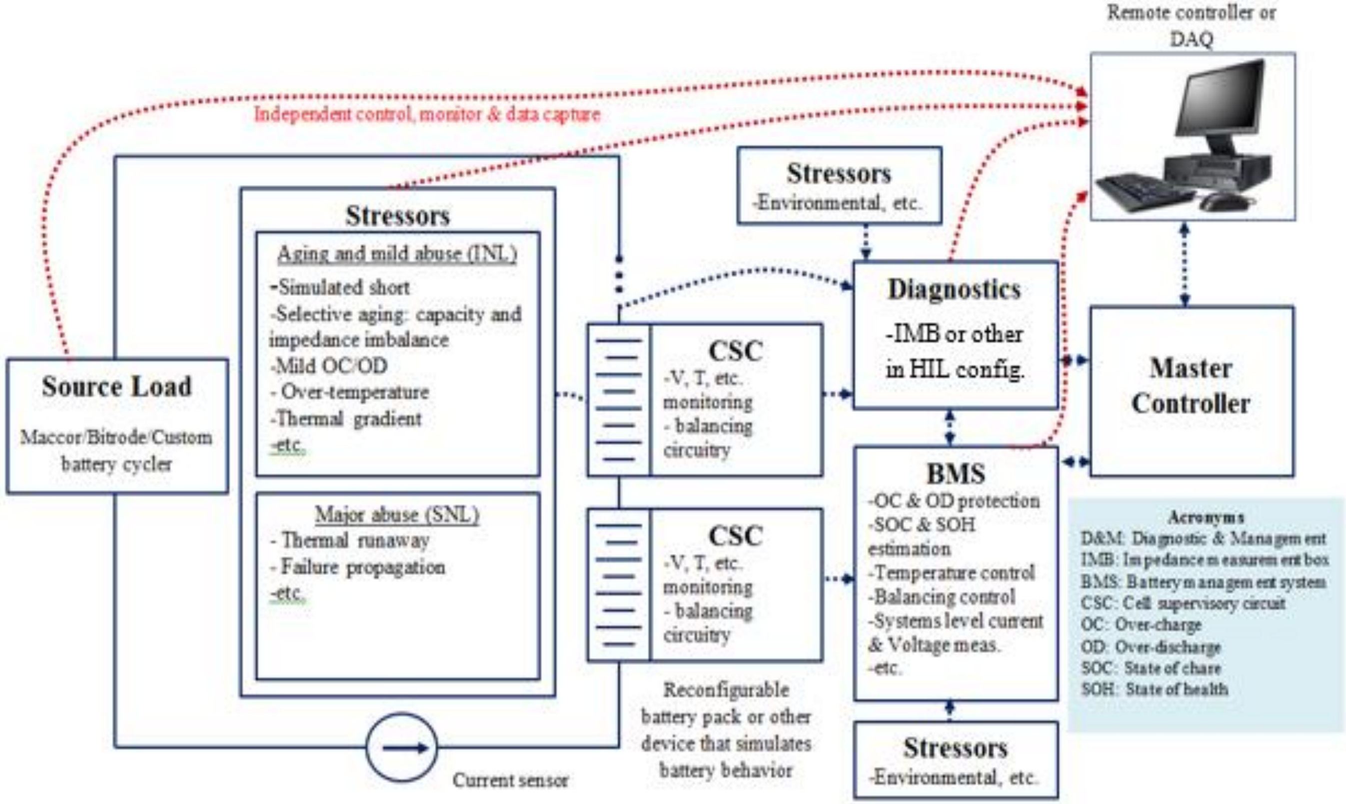


https://www.serinuslabs.com/home

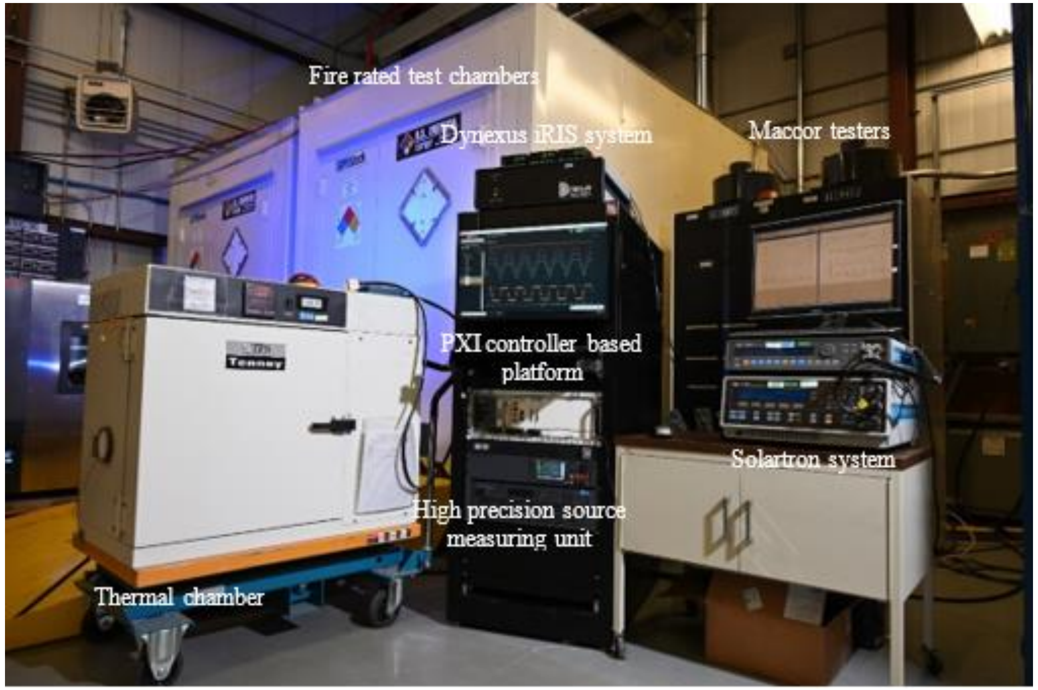
https://www.metisengineering.com/

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

Diagnostic Platform to Evaluate Battery Diagnostics (platform developed by INL)



The BADGE Platform



Key capabilities

- Directly compare different battery diagnostic and mgt. technologies in real time to detect off-normal behavior indicative of potential safety risks
- Diagnostic method development, verification and validation based on real or emulated signal

Early detection for Intervention

Motivation

Understand the advantages and limitations of diagnostic tools designed to detect off normal conditions that precede thermal runaway.

- What is the impact of cell chemistry, configuration, and single cell vs. pack?

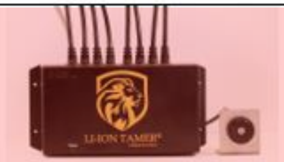
Key metric

Time between off normal condition detection and self heating or thermal runaway

Early Detection Diagnostics Tools

Detection Type	Company	Tool
Gas sensor	Li-ion Tamer	
Gas sensor	Metis Engineering	
Gas sensor	Amphenol	
Gas sensor	Serinus Labs	
Electromagnetic field	QuSpin	
Rapid electrochemical impedance	Dynexus Technology	

Early Detection Diagnostics Tools Evaluated

Detection Type	Company	Tool
Gas sensor	Li-ion Tamer	
Gas sensor	Metis Engineering	
Gas sensor	Amphenol	
Gas sensor	Serinus Labs	
Electromagnetic field	QuSpin	
Rapid electrochemical impedance	Dynexus Technology	

Testing Details

NMC/Graphite Cell Specifications

Capacity, Nominal		11.6 Ah
Internal Impedance		≤ 2.8 mΩ
Energy Density	Gravimetric	246 Wh/kg
	Volumetric	571 Wh/L
Voltage	Upper Limit	4.2
	Nominal	3.67
	Lower Limit	2.7
Charge	Max Charge	11.6 (1C)
	Max Discharge	23.2 (2C)

Overtemperature

1) **Single cell**
2) **1S4P (failure of one cell)**

SOC: 100%

Heating rate: 5°C/min

End conditions: 250°C or failure

Diagnostics, Sensors, Analytical Techniques: Rapid EIS, Li-ion Tamer, Metis, Amphenol, Voltage, Temperature, FTIR, Mass Spec

Overcharge

1) **Single cell**
2) **1S4P (failure of one cell)**

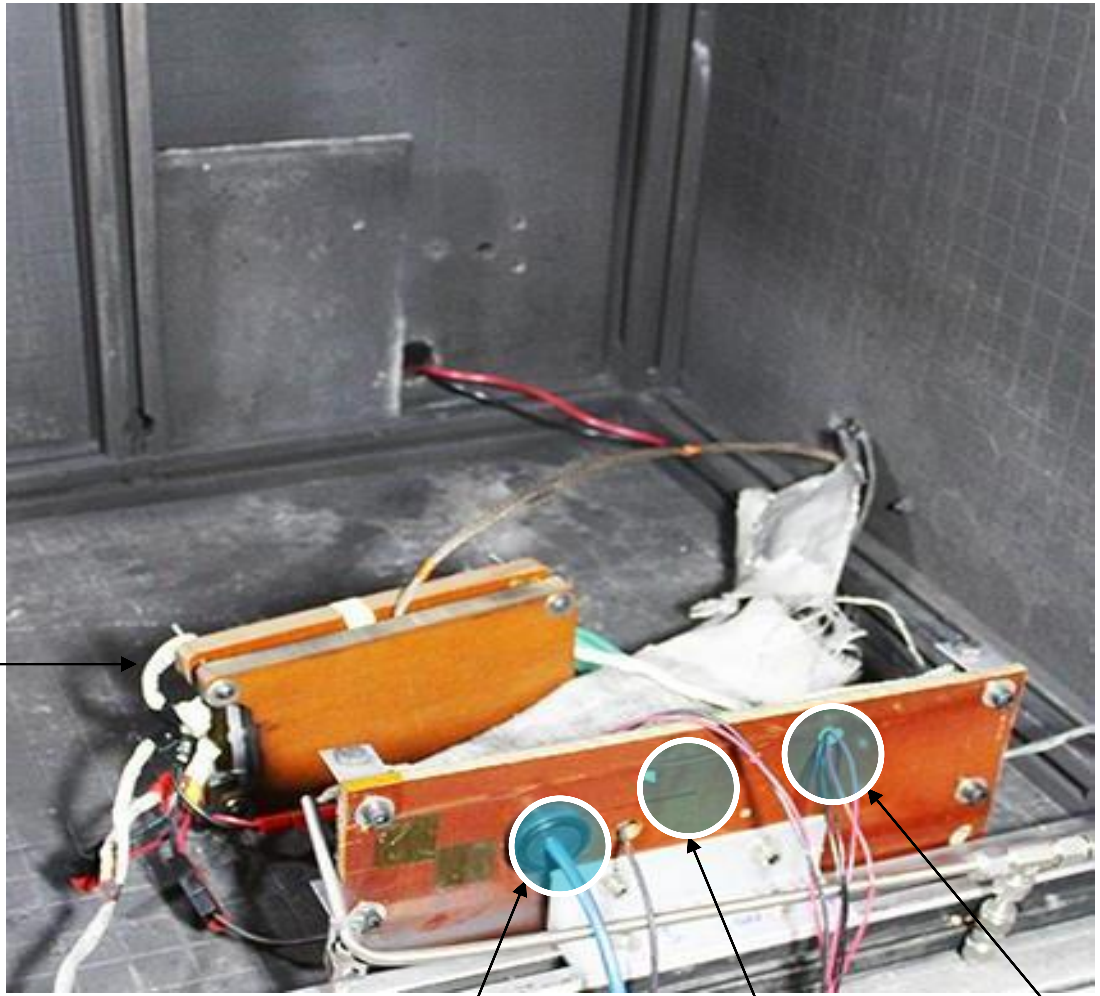
SOC: 100%

Heating rate: 1C rate (11.6 A)

End conditions: 250 %SOC, 20V or failure

Diagnostics, Sensors, Analytical Techniques: Rapid EIS, Li-ion Tamer, Metis, Amphenol, Voltage, Temperature, FTIR, Mass Spec

Gas Sensors Layout



Test Article

Gas Sensor A

Gas Sensor B

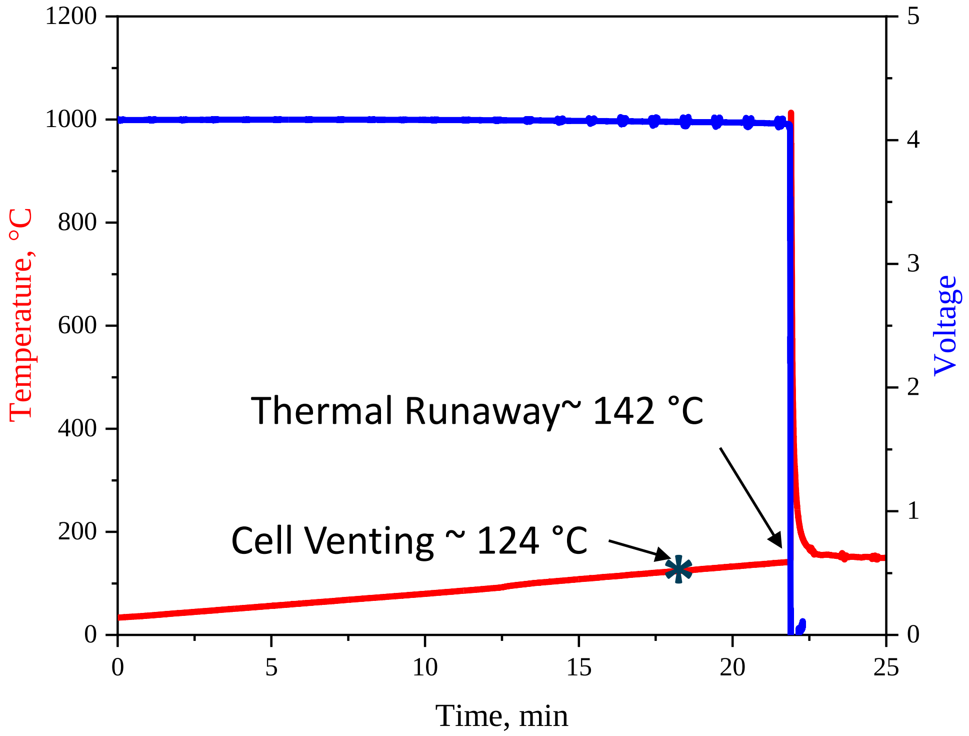
Gas Sensor C

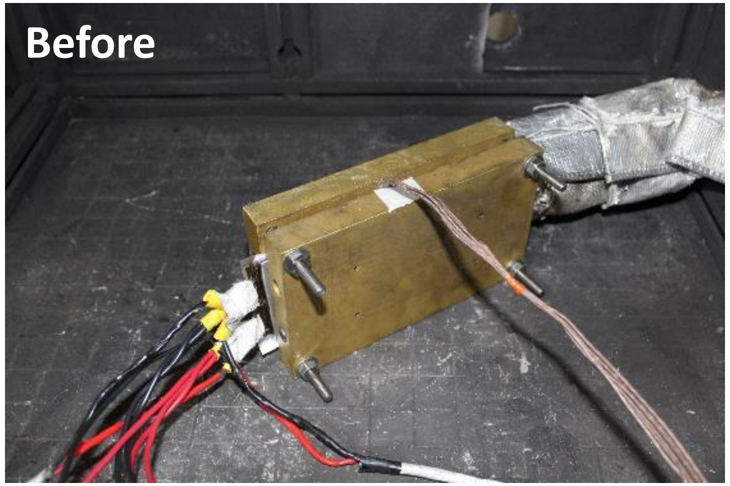
Distance between the gas sensor and test article is ~ 9 in

Detecting Failure Markers Prior to Thermal Runaway Threshold

<u>11.6 Ah NMC Single Cell – Overtemperature to Failure</u>

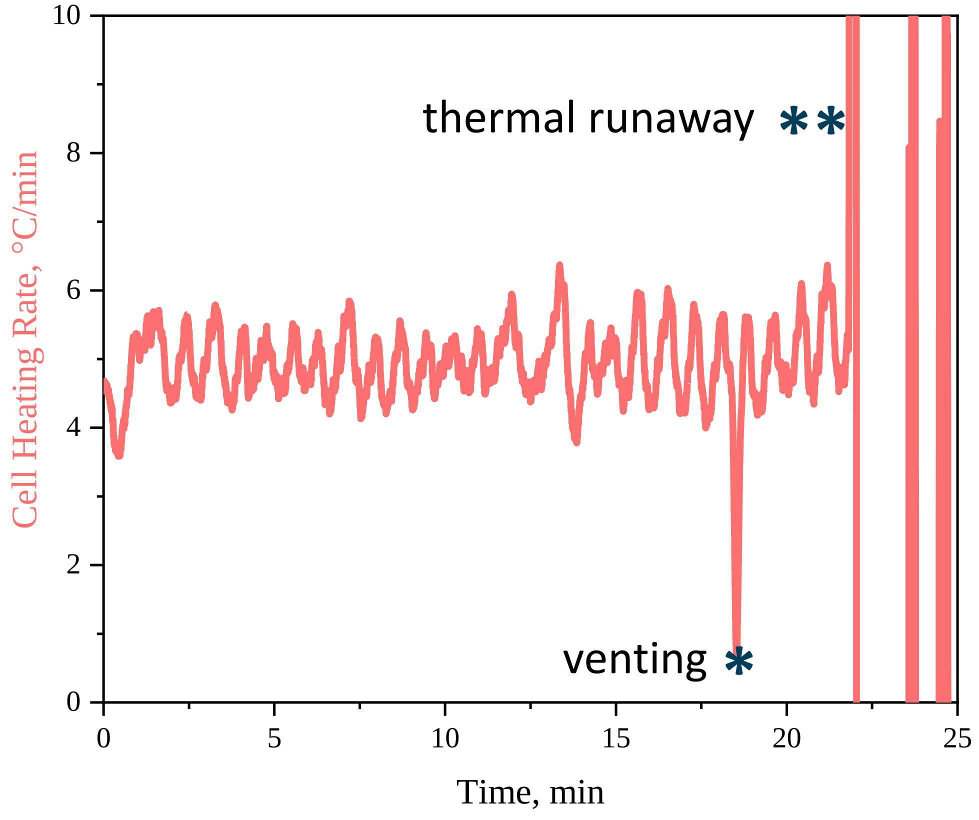
Continuous gas sensing and electrochemical impedance measurements were collected for the duration of the test using BADGE.





Detection of failure markers prior to venting and thermal runaway thresholds is critical for intervention and mitigation.

Heating Rate to Identify Cell Venting and Onset to Thermal Runaway



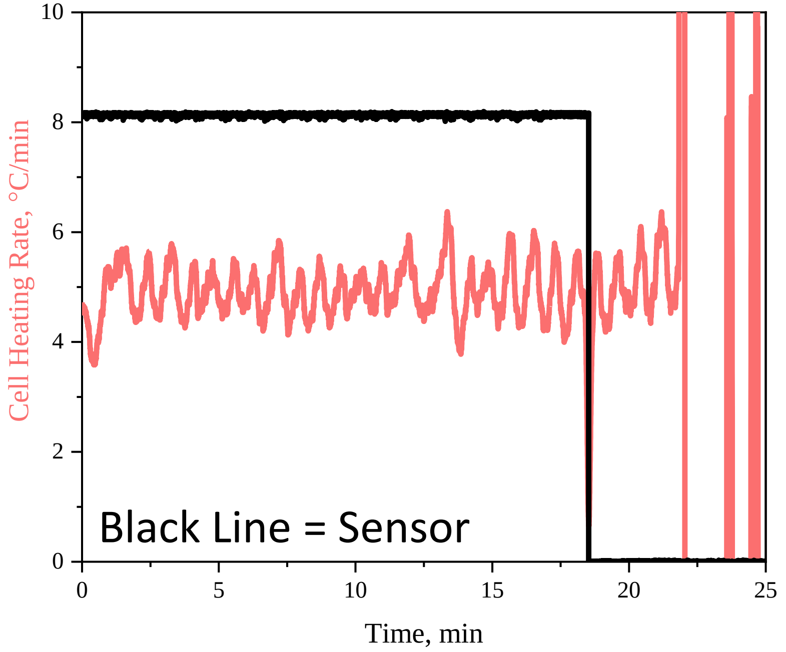
* Sudden decrease in heating rate is often indicative of cell venting.

** Sharp increase in heating rate is classified as a thermal runaway event.

Variation in Gas Sensor Response for Thermal Abuse

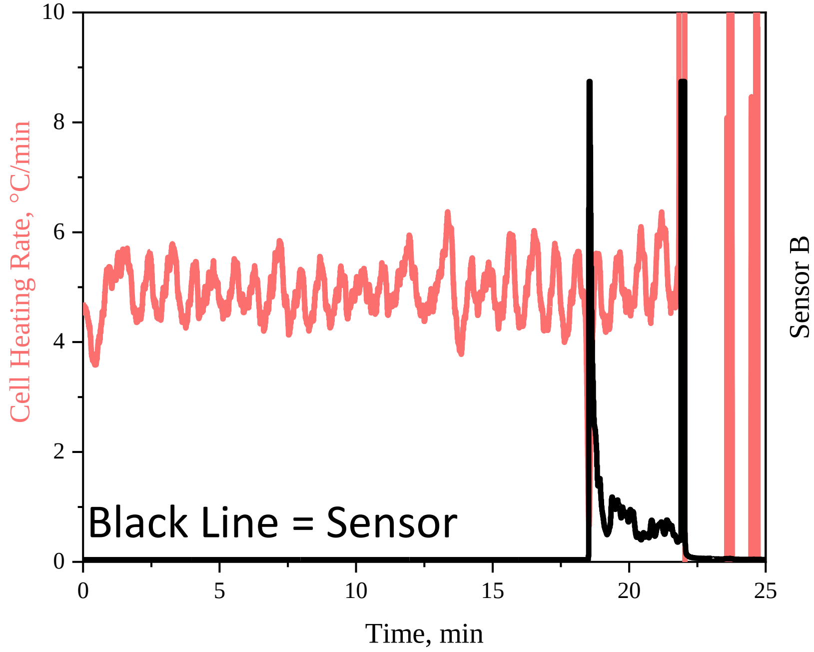
<u>All sensors triggered at temperatures >100 °C</u>

Sensor A



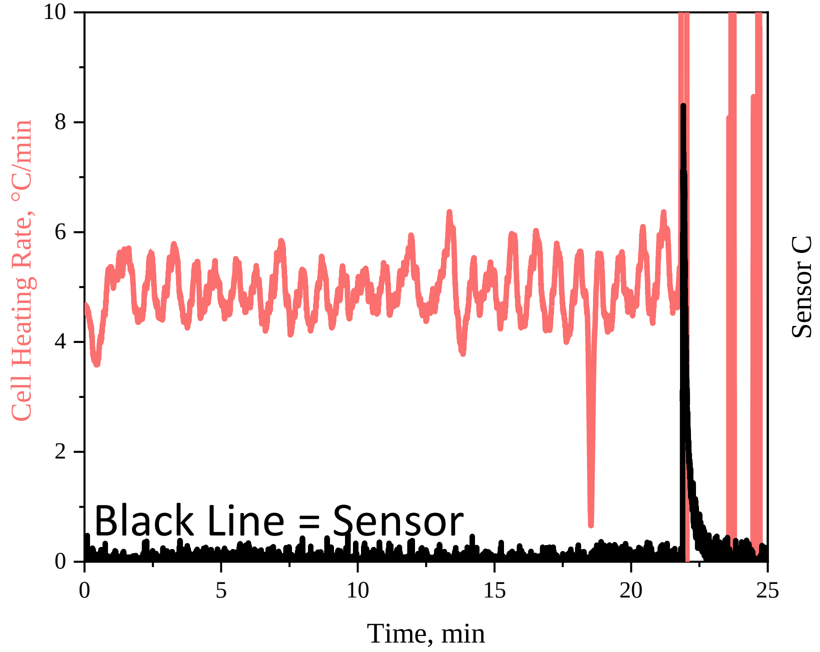
Sensor triggered during cell venting (~3 min before thermal runaway)

Sensor B



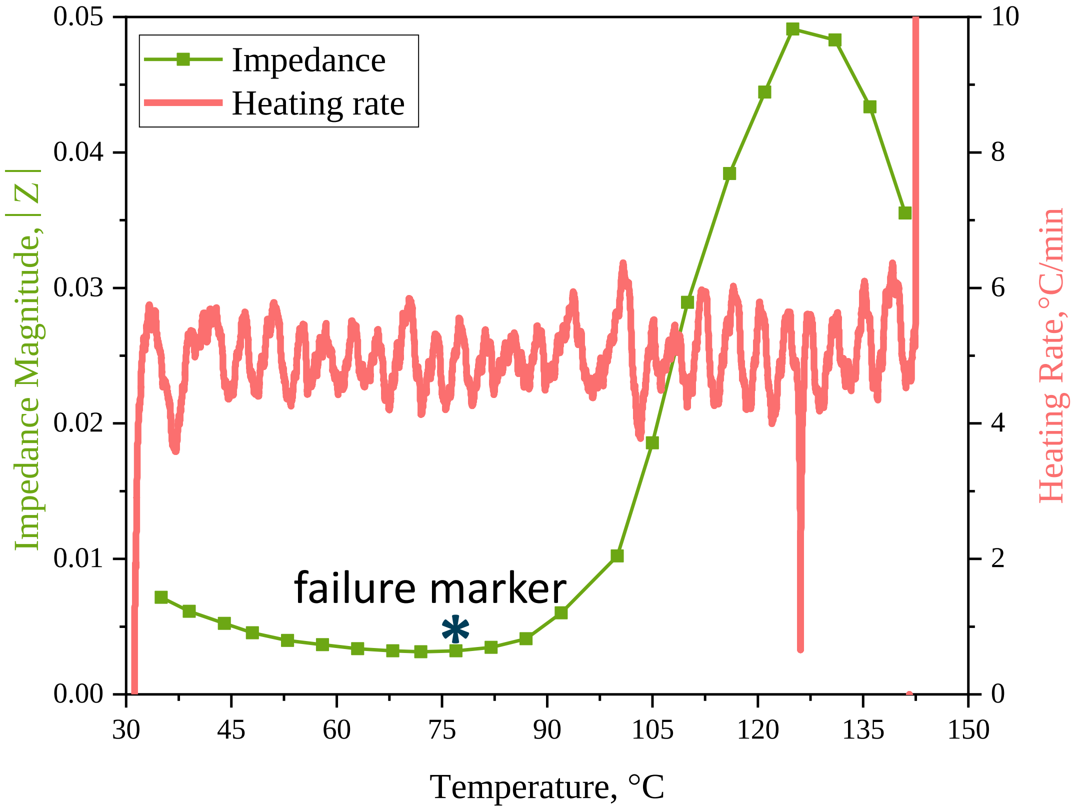
Sensor triggered during cell venting (~3 min before thermal runaway)

Sensor C



Sensor triggered during thermal runaway

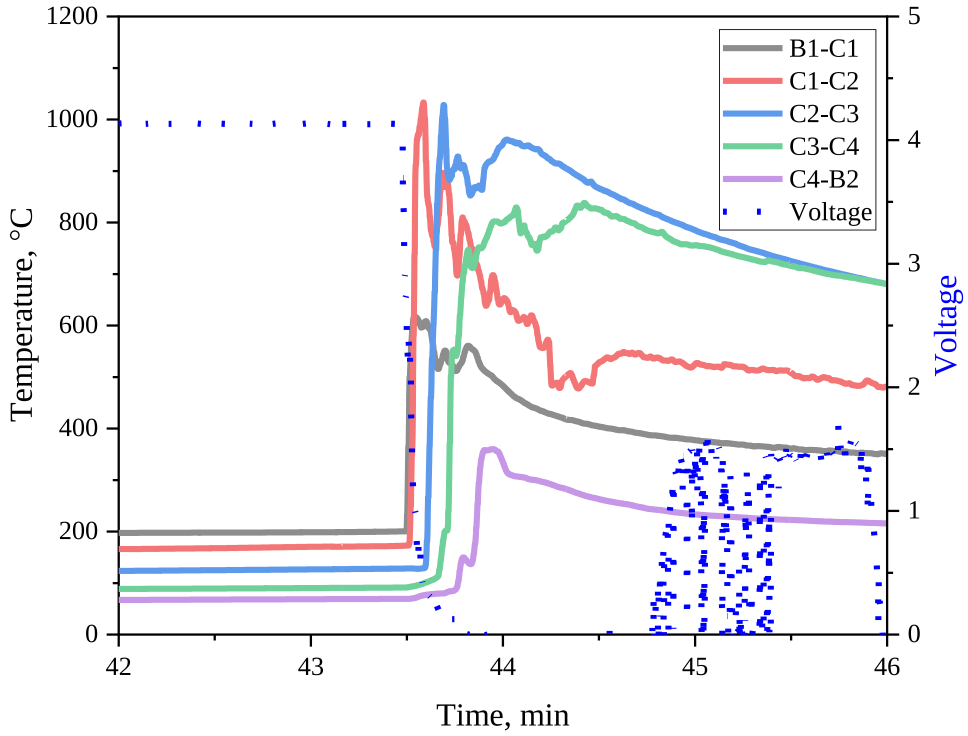
Earlier Detection with Rapid Electrochemical Impedance Spectroscopy

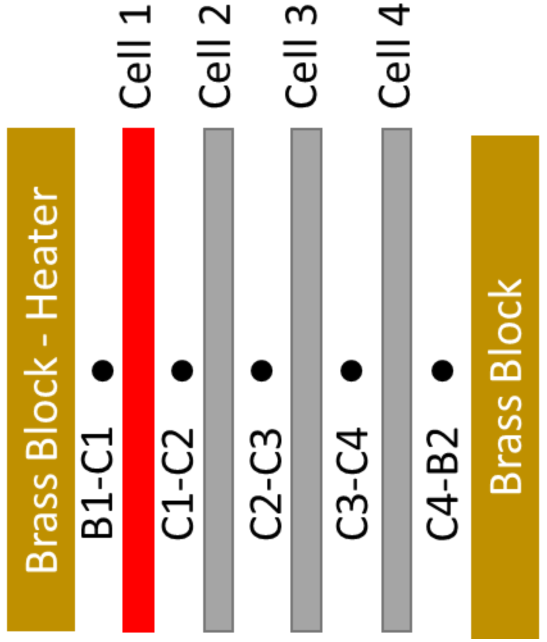


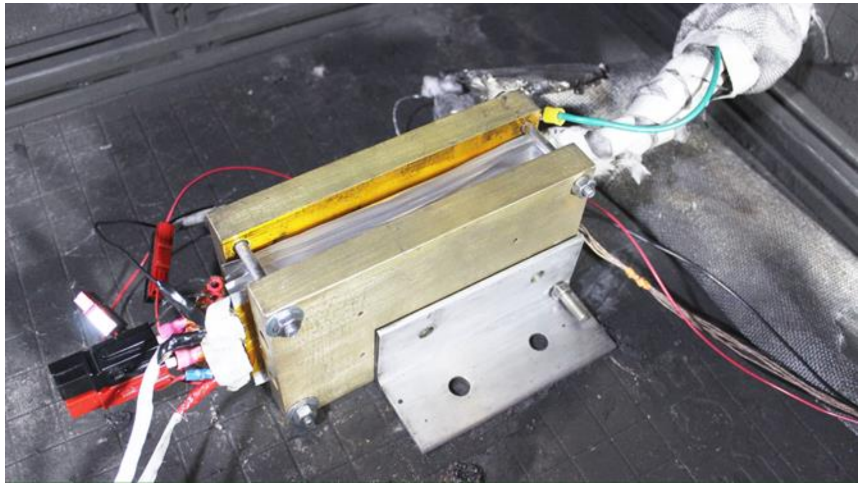
- Failure marker identified 13 minutes prior to thermal runaway
- Rapid EIS offers earlier detection compared to gas sensors

Diagnostics of a Battery Pack to Mitigate Thermal Propagation

1S4P NMC Pack (46 Ah) – Failure Initiated on Edge Cell



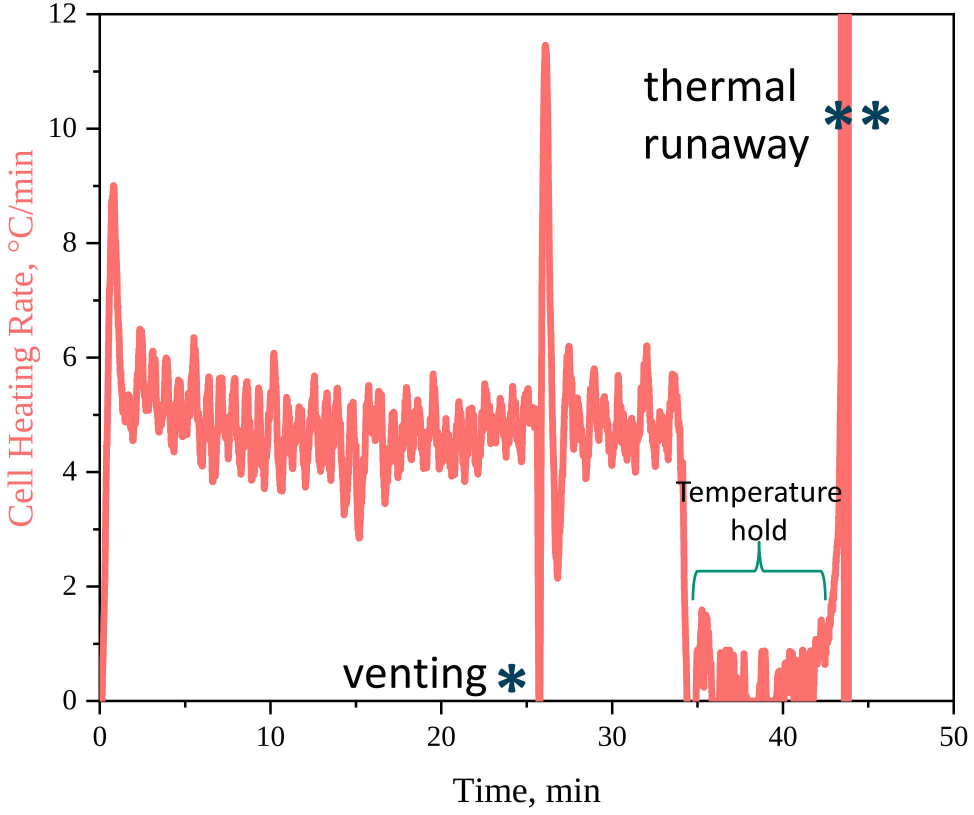




Failure was initiated in a single cell within the pack and continuous gas sensing and electrochemical impedance measurements were collected at the pack level using BADGE

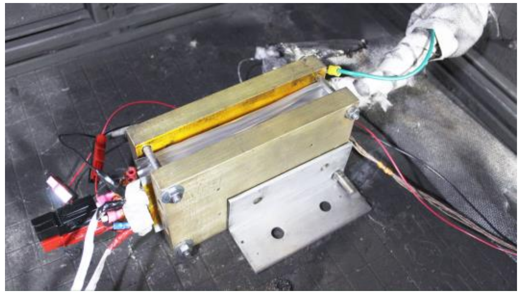
Can diagnostics at the pack level detect a potential failure of a single cell within the pack? Does it provide enough lead time to reduce the risk of thermal propagation?

Heating Rate to Identify Cell Venting and Onset to Thermal Runaway



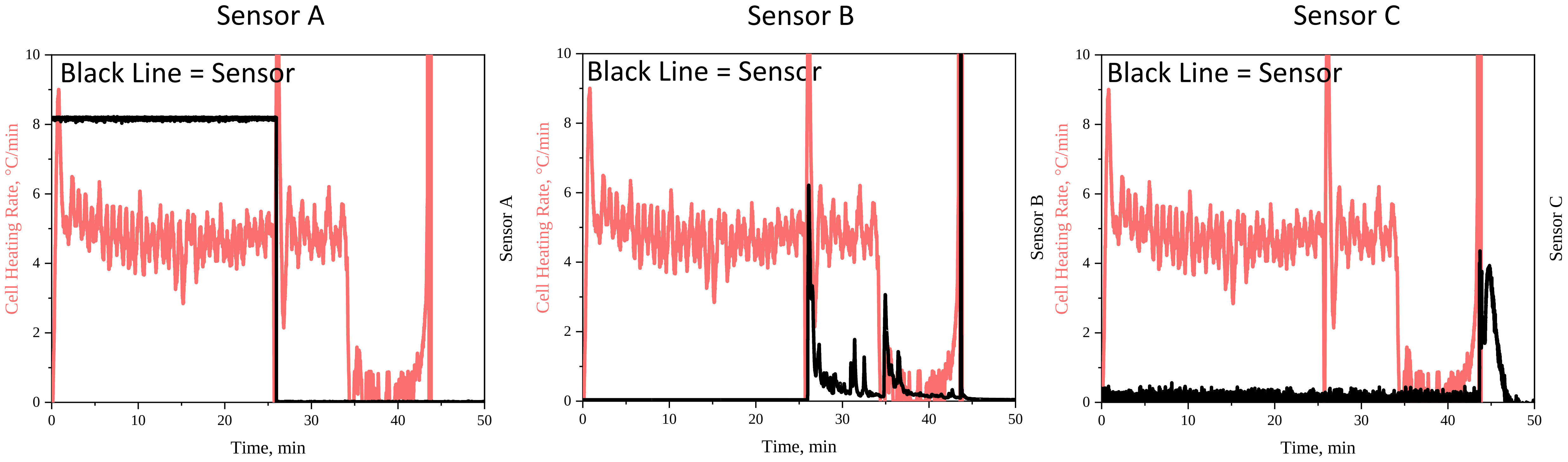
* Sudden decrease in heating rate is often indicative of cell venting.

** Sharp increase in heating rate is classified as a thermal runaway event .



Consistent Gas Sensor Onset for Single Cells and 1S4P Pack

1S4P NMC Pack (46 Ah) – Failure Initiated on Edge Cell



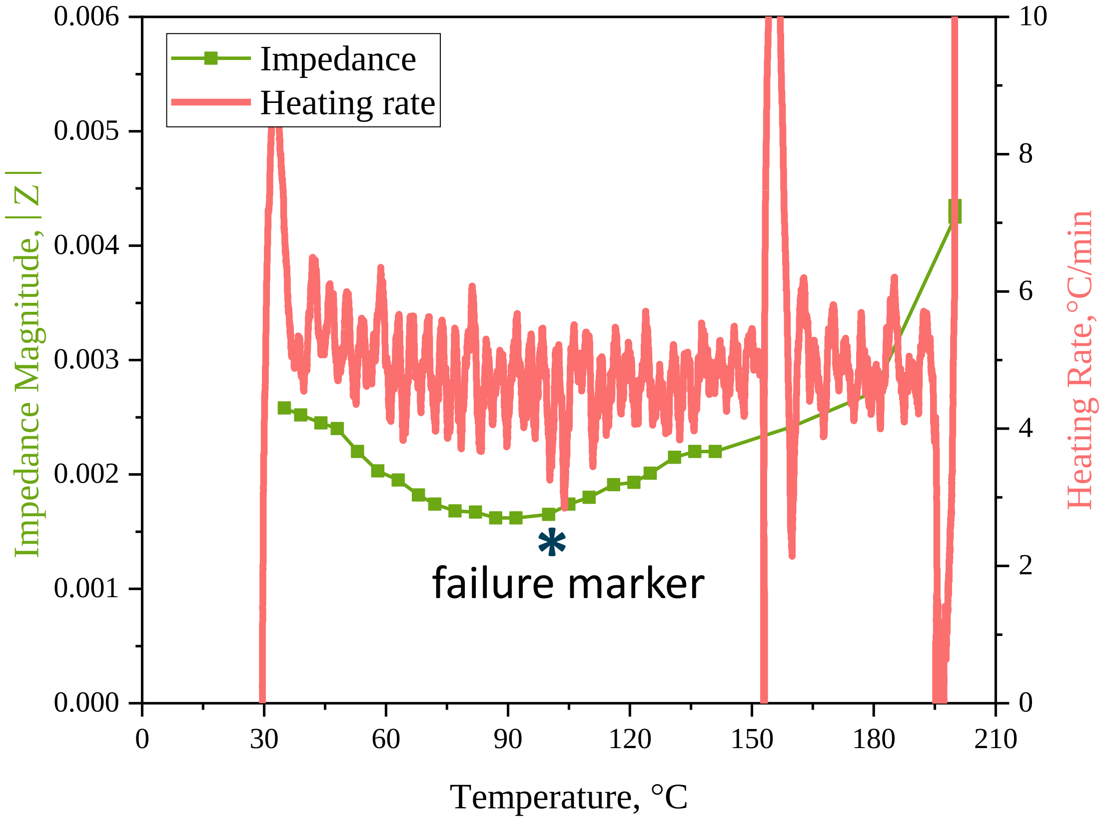
Sensor triggered during cell venting (~16 min before thermal runaway)

Sensor triggered during cell venting (~16 min before thermal runaway)

Sensor triggered during thermal runaway

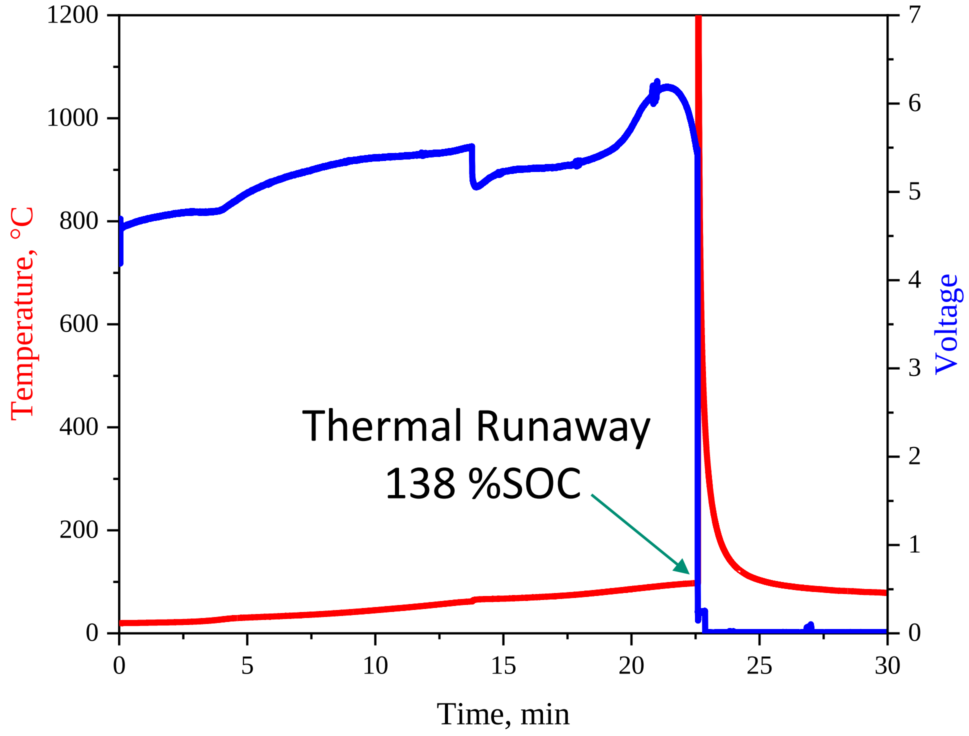
Similar trend for pack level and single cell failure detection. The increased time delay for pack level is attributed to heating the cell on one side for the 1S4P pack while for the single cell experiments, the cell was heated on both sides.

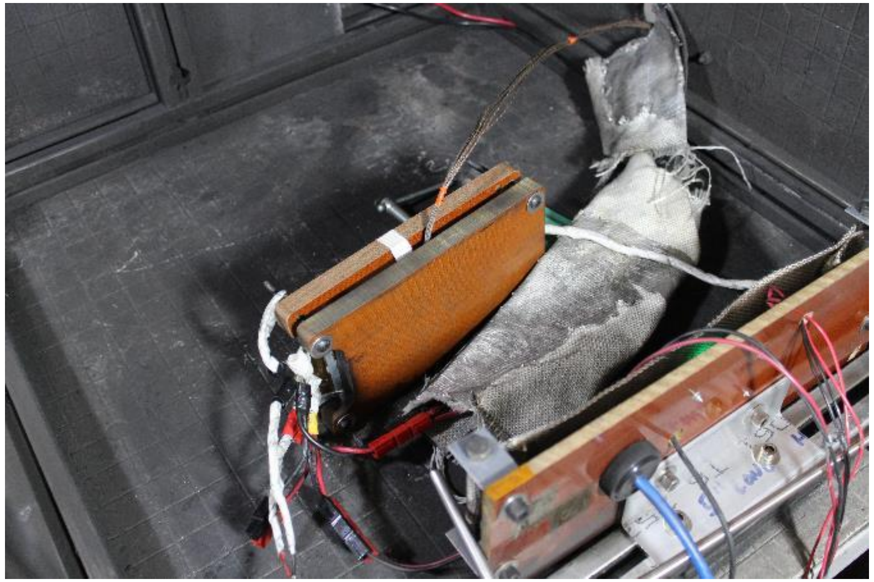
Earlier Detection with Rapid Electrochemical Impedance Spectroscopy



- Failure marker identified 28 minutes prior to thermal runaway
- Rapid EIS offers earlier detection compared to gas sensors
- Rapid EIS detection at the pack level occurred at ~100 °C while for single cell was ~75 °C.
- The increased time delay for pack level is attributed to heating the cell on one side for the 1S4P pack while for the single cell experiments, the cell was heated on both sides.

Failure Detection During Single Cell Overcharge



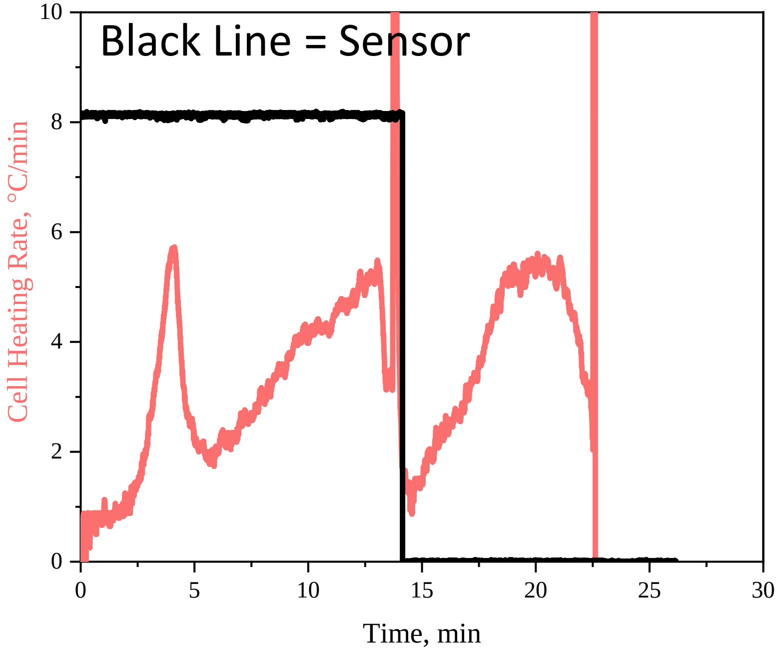


Continuous gas sensing and electrochemical impedance measurements were collected for the duration of the test using BADGE.

Variation in Gas Sensor Response for Electrical Abuse

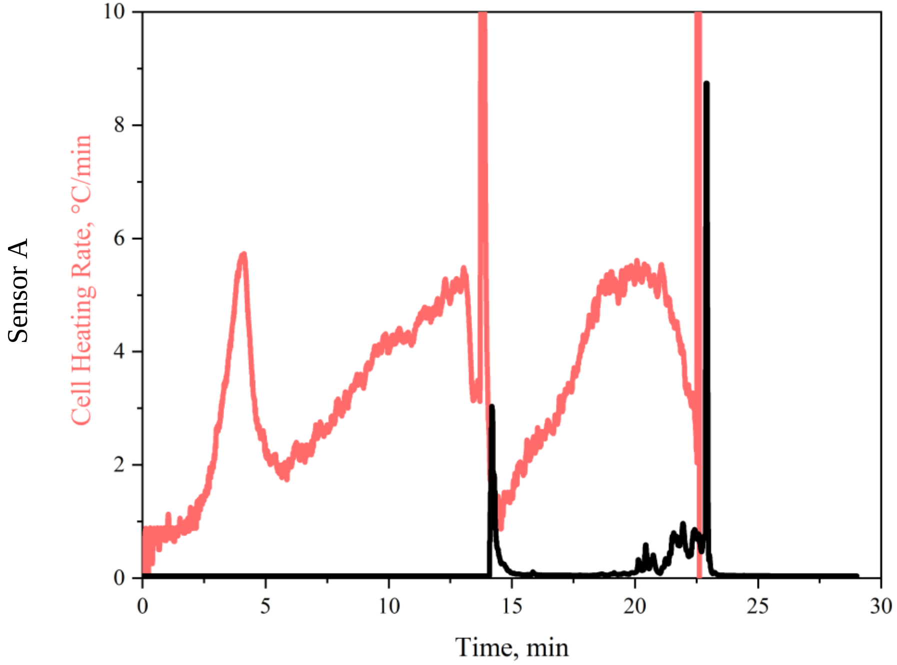
<u>All sensors triggered at SOC > 120 %</u>

Sensor A



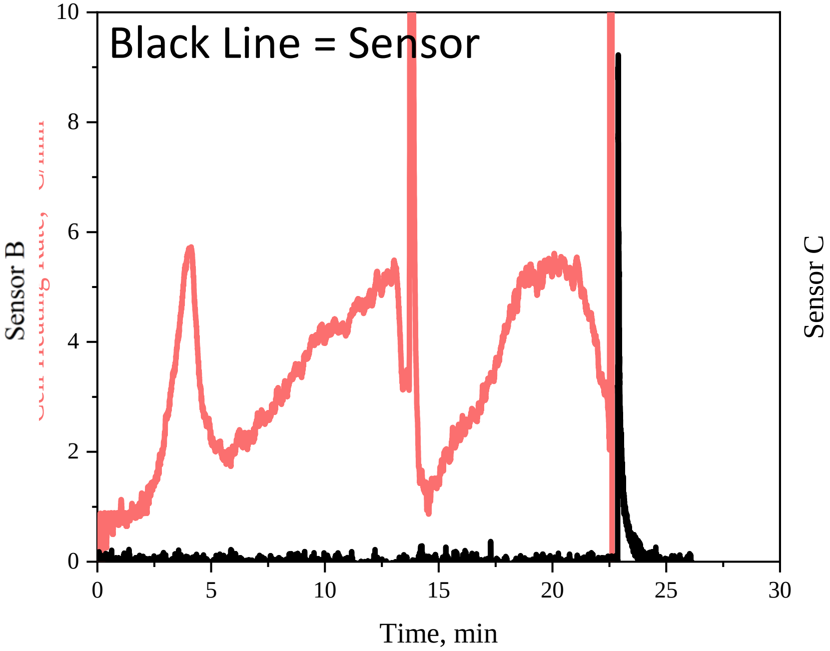
Sensor triggered 8 minutes before thermal runaway

Sensor B



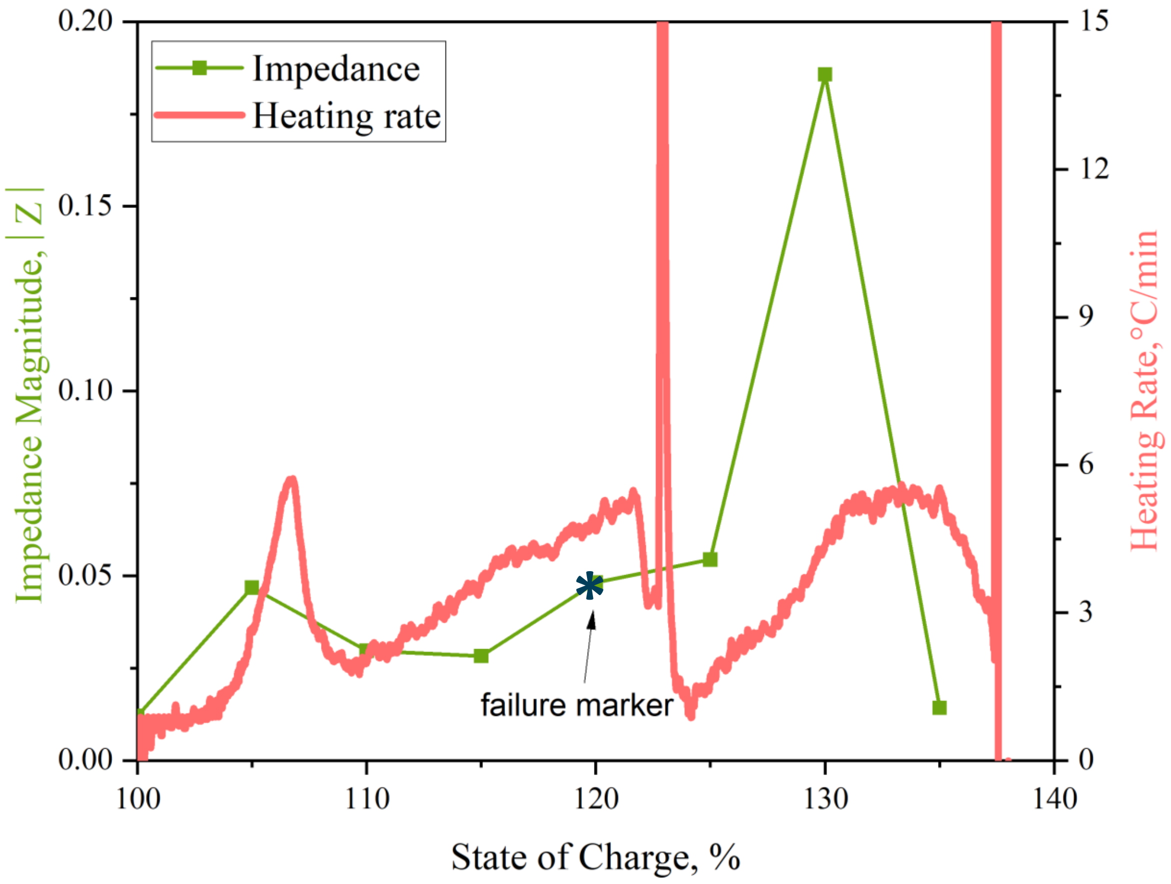
Sensor triggered 8 minutes before thermal runaway

Sensor C



Sensor triggered during thermal runaway

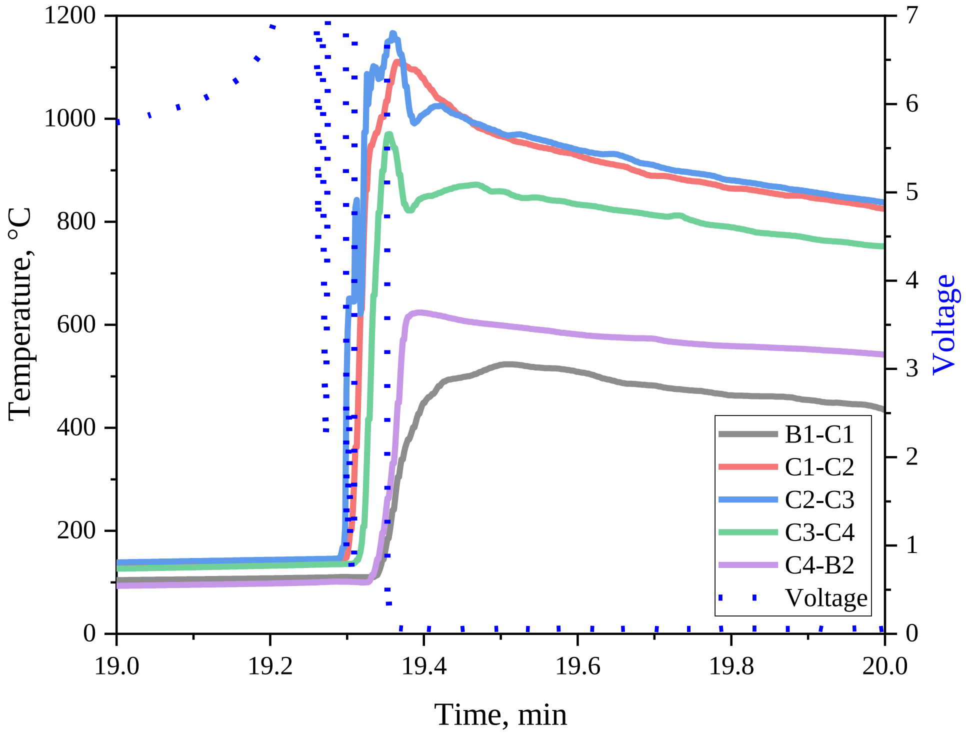
Gas Sensors Provide Greater Advance Warning Compared to Rapid EIS During Electrical Abuse

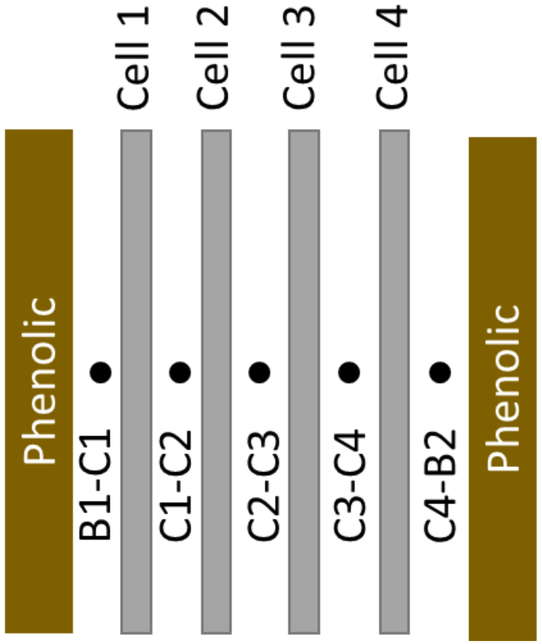


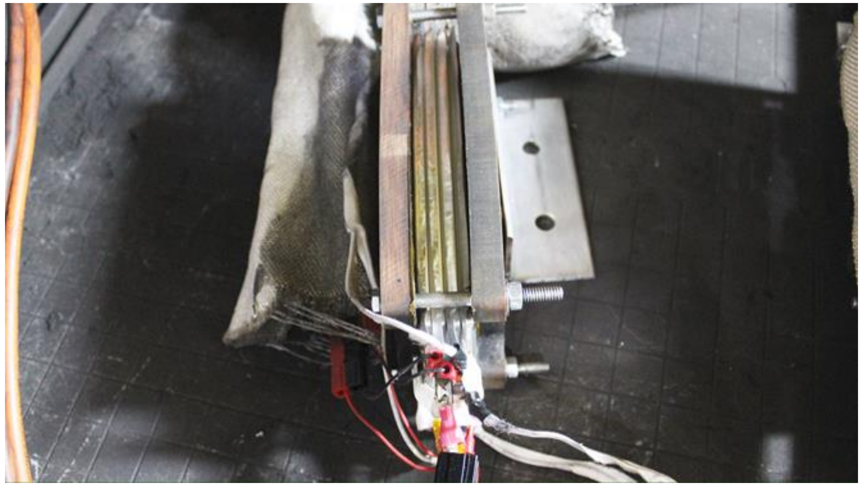
- Failure marker identified 11 minutes prior to thermal runaway (at 120% SOC)
- Rapid EIS offers earlier detection compared to gas sensors for single cell overcharge

Effect of Electrical Connections on Failure Detection

1S4P NMC Pack (46 Ah) – Pack Overcharge



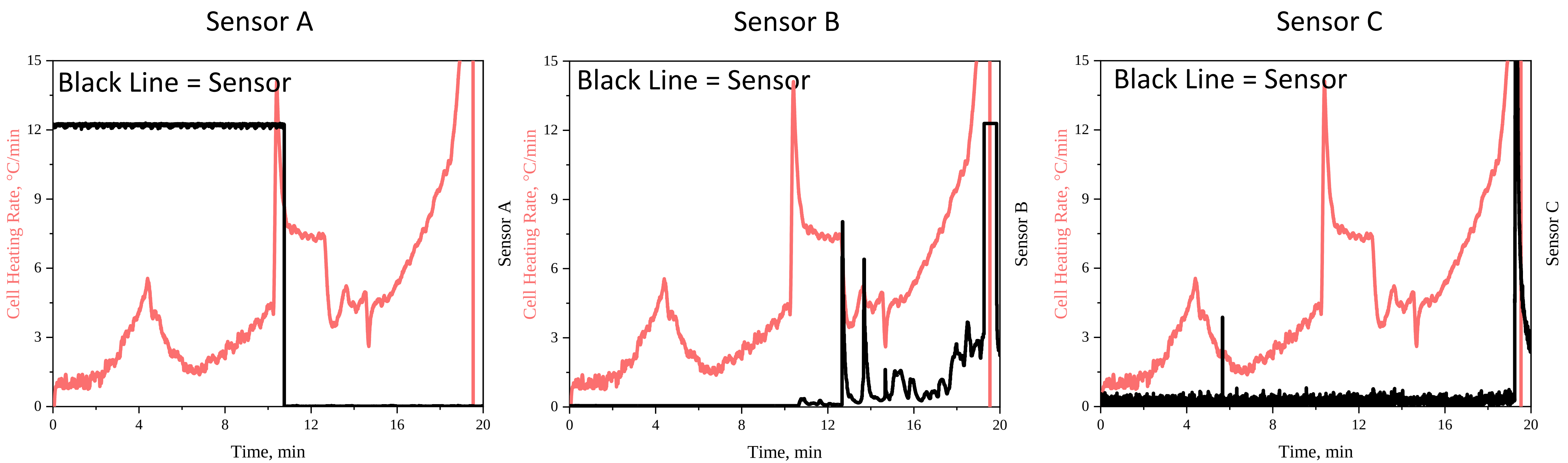




Onset state of charge to thermal runaway was ~133% SOC

Consistent Gas Sensor Onset for Single Cells and 1S4P Pack

1S4P NMC Pack (46 Ah) – Pack Overcharge



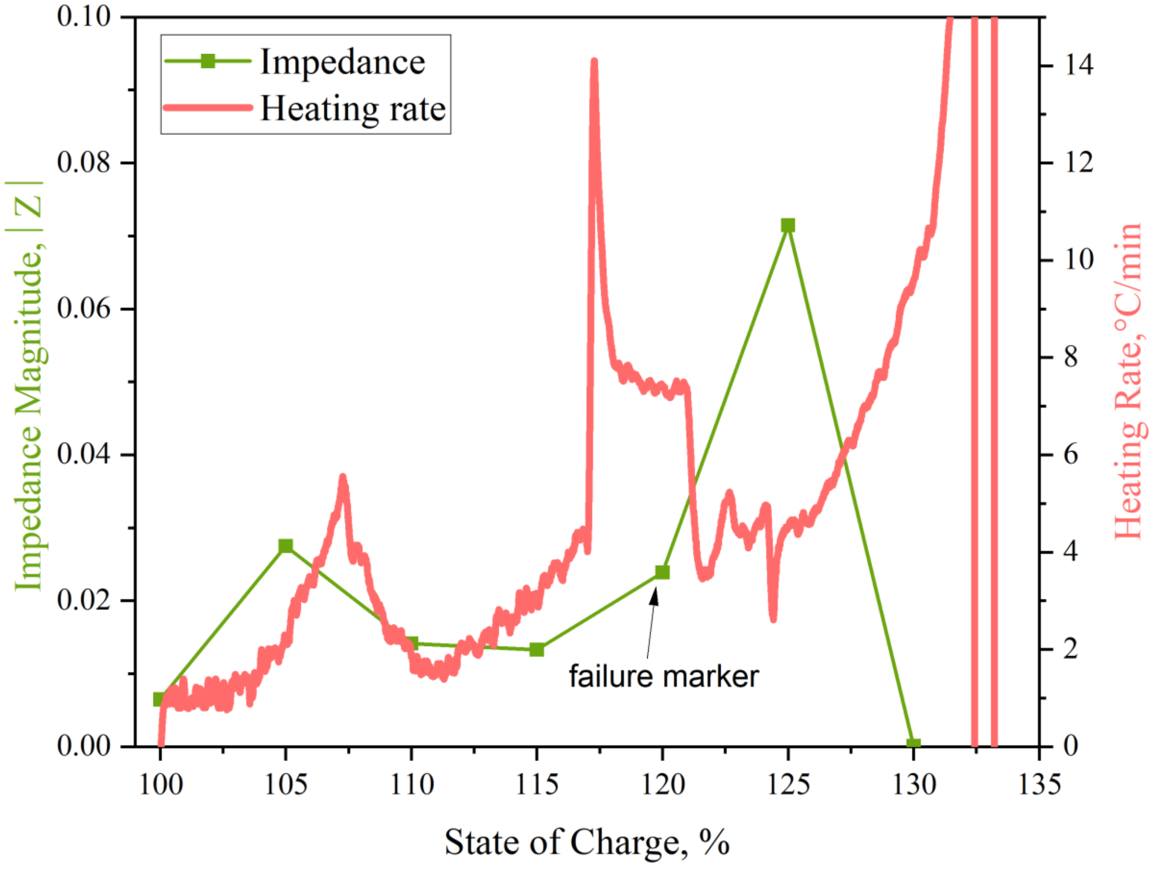
Sensor triggered 8 minutes before thermal runaway

Sensor triggered 8 minutes before thermal runaway

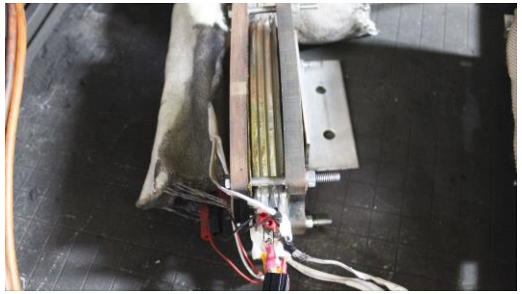
Sensor triggered during thermal runaway

Thermal runaway for the 1S4P pack occurred ~3 minutes earlier compared to the single cell test; however, the advance warning in both cases was consistent.

Rapid Electrochemical Impedance Spectroscopy Identified a Potential Failure After the Gas Sensors

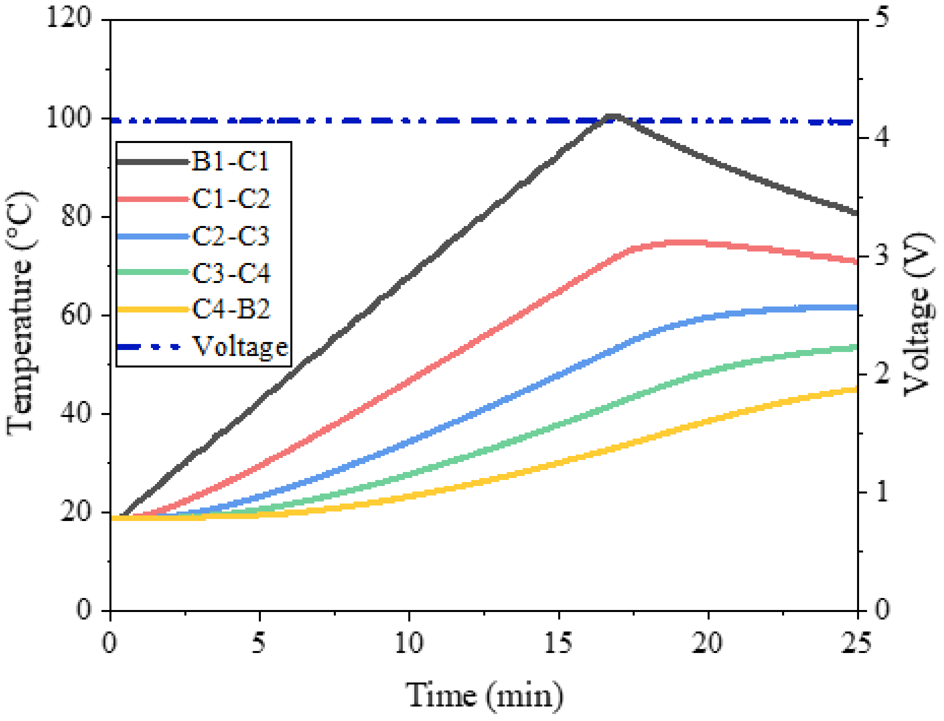


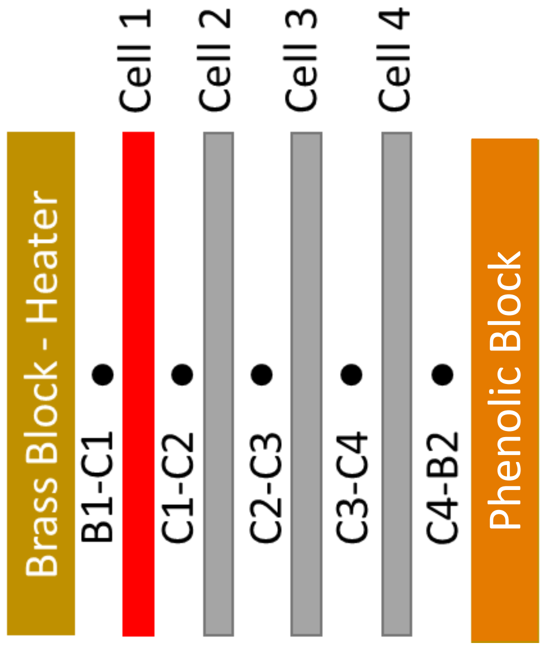
- Failure marker identified 8 min 18 sec prior to thermal runaway (at ~120% SOC)
- Rapid EIS offers slightly earlier detection than gas sensors
- Rapid EIS detection at the single cell and pack level occurred at ~120% SOC

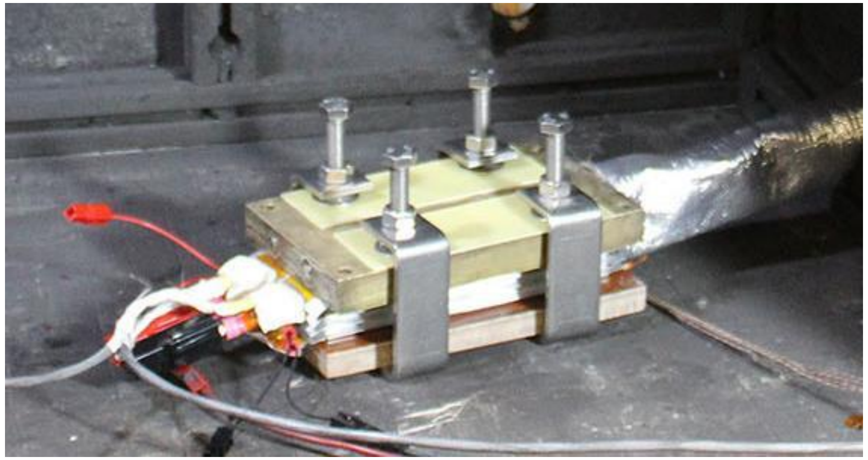


Demonstration Test – Using Failure Markers to Intervene

1S4P NMC Pack (46 Ah) – Failure Initiated on Edge Cell



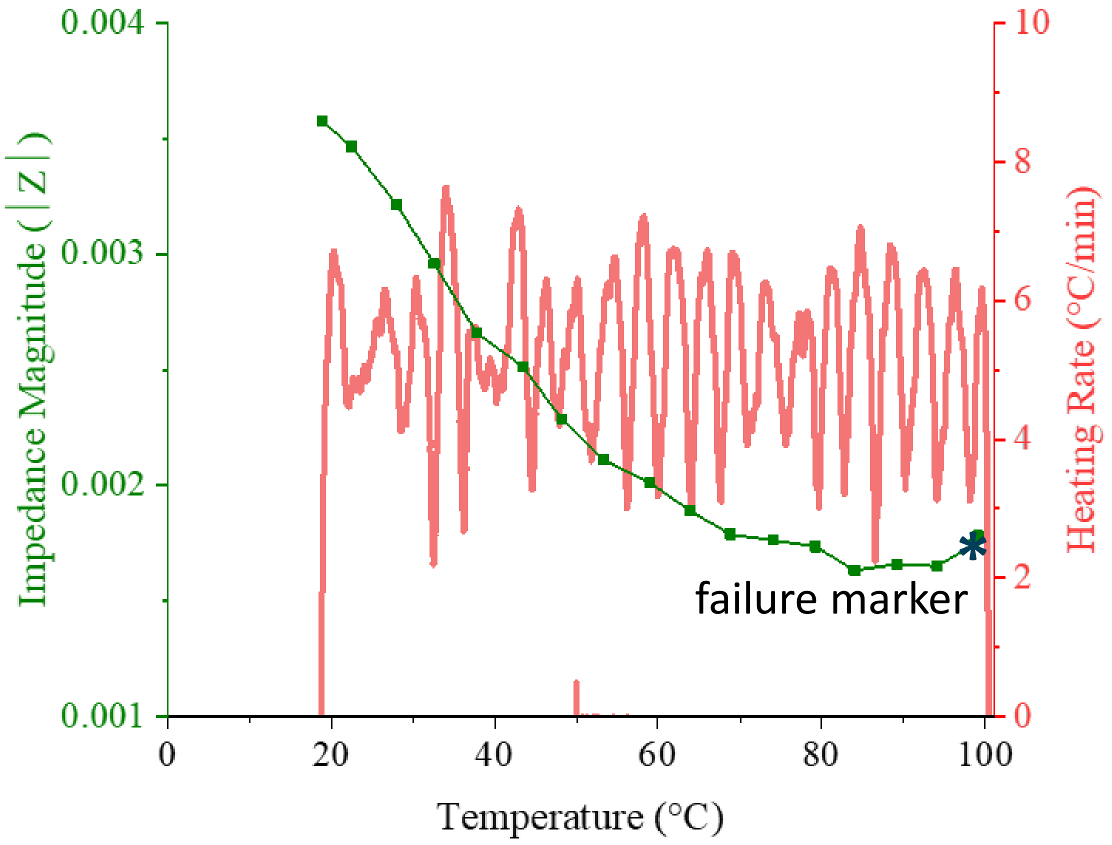




Failure was initiated in a single cell within the pack and continuous gas sensing and electrochemical impedance measurements were collected at the pack level using BADGE

Can diagnostics at the pack level detect a potential failure of a single cell within the pack? Does it provide enough lead time to reduce the risk of thermal propagation?

Earlier Detection with Rapid Electrochemical Impedance Spectroscopy

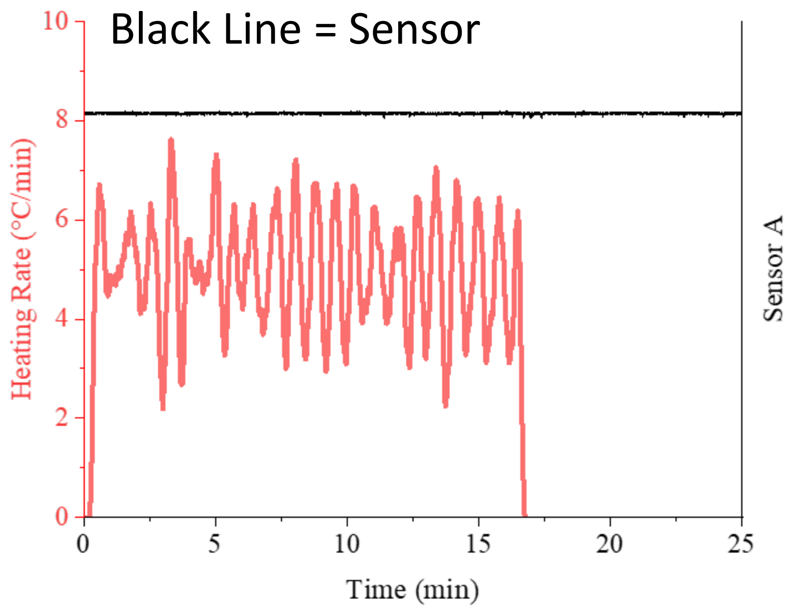


- Failure marker identified, heaters shutoff
- Rapid EIS detection at the pack level occurred at ~100 °C while for single cell was ~75 °C.

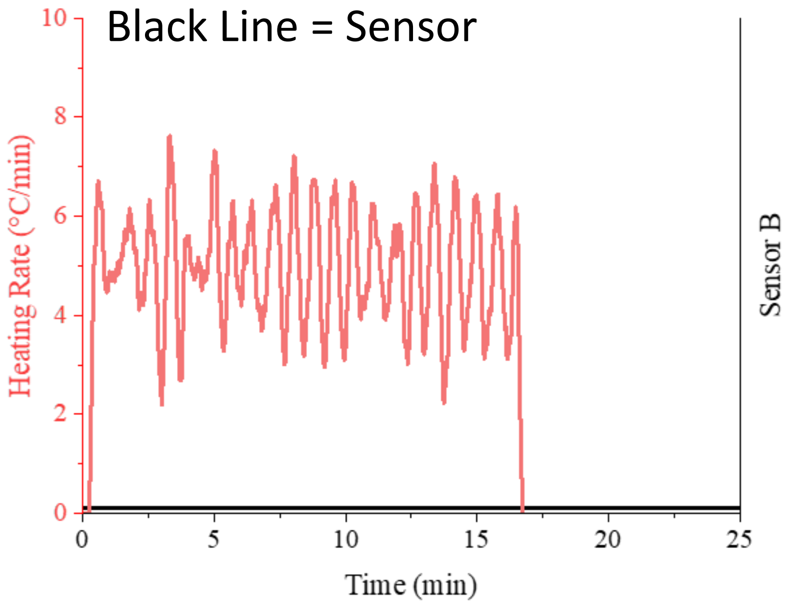
Consistent Gas Sensor Onset for Single Cells and 1S4P Pack

1S4P NMC Pack (46 Ah) – Failure Initiated on Edge Cell

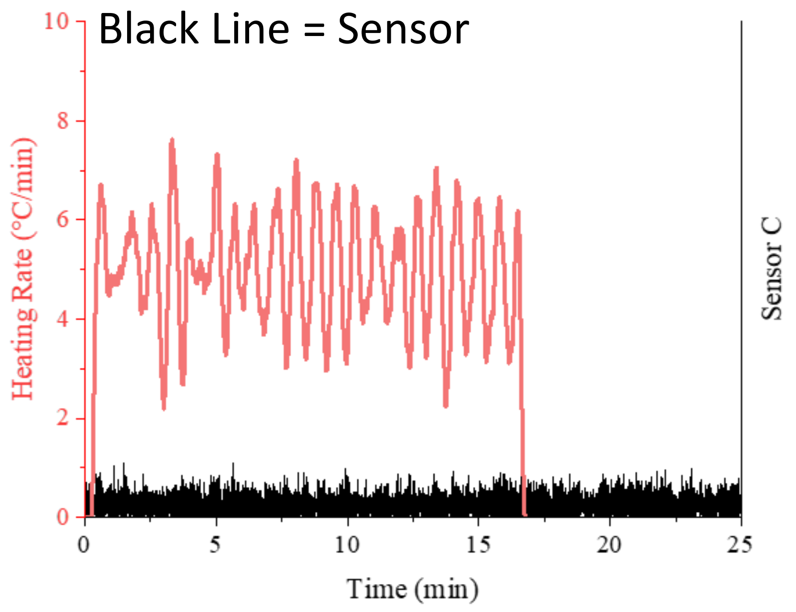
Sensor A



Sensor B



Sensor C



No gas sensor triggers and no thermal runaway

Summary

Advanced diagnostics are key for early detection and mitigation

- Collaborative project with Sandia and Idaho National Laboratories
- Various diagnostics methods were evaluated with batteries subjected to external stressors to simulate battery failure, including thermal abuse and electrical abuse
- Failure indicators have the potential to provide enough warning time for intervention

Key Takeaway

Battery technology is a moving target and we NEED to evaluate the advantages and limitations of different diagnostics through testing, refinement, and benchmarking.

Acknowledgements

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- NHTSA, DOT

SNL Contributors

- Loraine Torres-Castro
- Genaro Quintana
- Lucas Gray
- Jill Langendorf

External Collaborators

- Idaho National Laboratory

Thank you!

Name of presenter: Alex Martin Bates
Corresponding email: ambates@sandia.gov