Defining Diagnostic Parameters for Early Detection of Thermal Runaway

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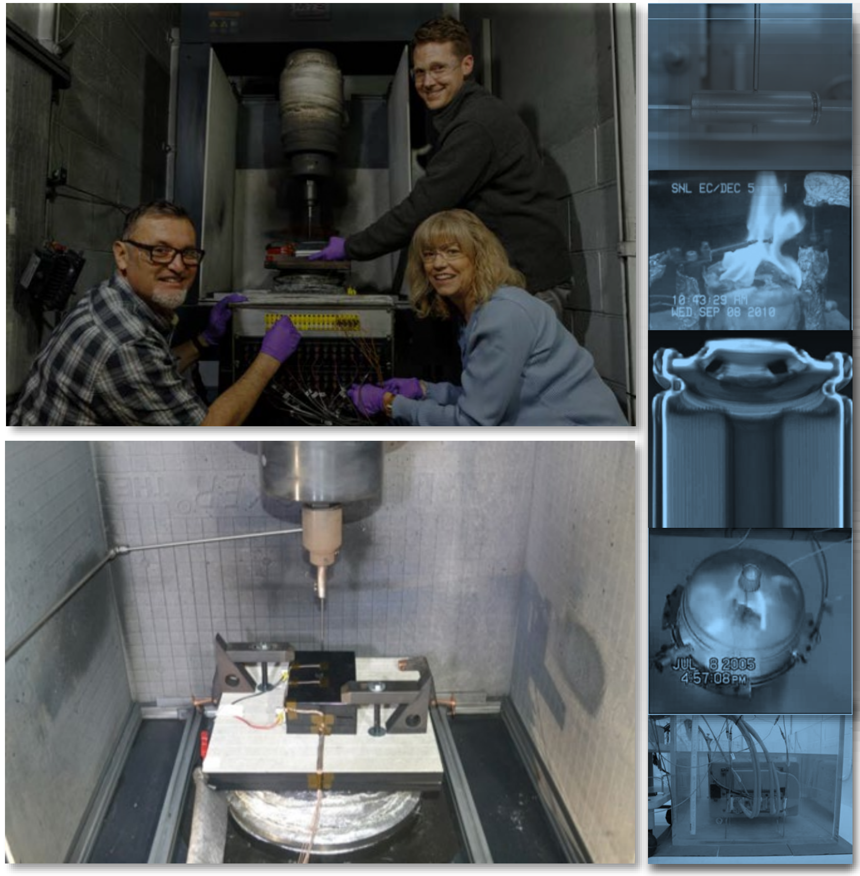
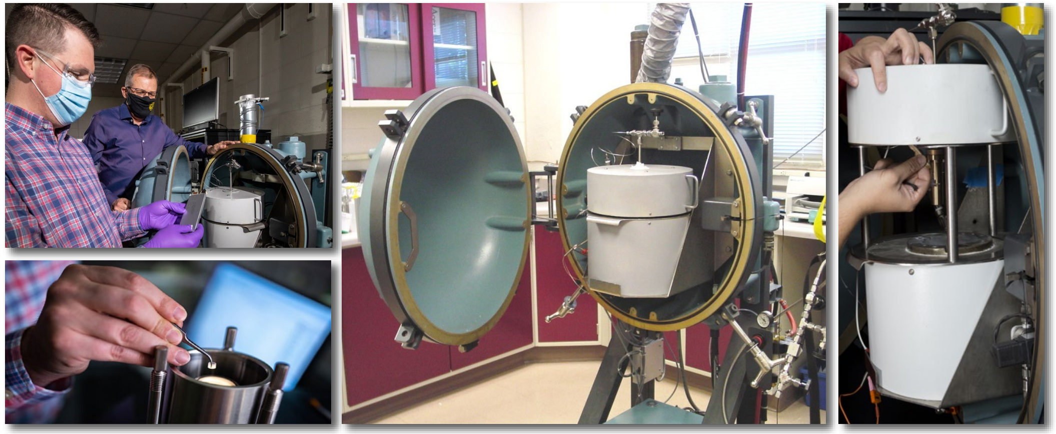
Capabilities and Infrastructure

Cell and Module Testing
Battery Abuse Testing Laboratory (BATLab)



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

Battery Calorimetry (multi-scale)



Sandia Addresses All Aspects of Battery Safety Science

Materials R&D

Thermal stability
Gas evolution
Degradation

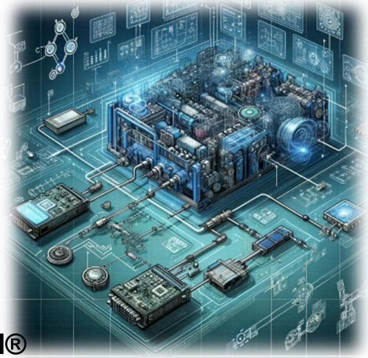
Cell and Module Testing

Aging
Diagnostics
Abuse testing
Thermal propagation

Simulations and Modeling

Multi-scale models
Fire dynamic simulations
Predictive simulations

System Level Design and Analysis



Hazard analysis methods
Predictive maintenance
Power electronics

Outreach, Codes, and Standards

ES safety working group
IEE BMS standard
EPRI ESS data guidelines

Detecting an Unsafe or Unstable Battery

Voltage and temperature parameters are delayed indicators of battery failure

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

2022 Electric Bus Fire in Europe

2022 EV Battery Fires in Florida after Hurricane Ian

A battery with an undetermined state of stability has many implications

1. *Warranty, liability, and financial loss*
2. *Safety of end users*
3. *Safety of 1^{st} and 2^{nd} responders (unsafe stranded energy)*
4. *Negative public perception*

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

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

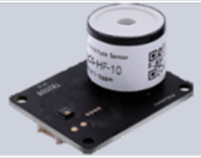
$$\Delta t_{warning\ time} = TR_{time} - S_{activation\ time}$$

$\Delta t_{warning\ time}$ = warning time provided by a diagnostic

TR_{time} = time of sensor activation

$S_{activation\ time}$ = onset time of thermal runaway

Commercial-Off-The-Shelf Diagnostics Tools

Detection Type	Manufacturer/Vendor	Tool
Rapid Electrochemical Impedance	Dynexus Technology	
Electromagnetic field	QuSpin	
VOC gas sensor	Li-ion Tamer	
Combined VOC, CO_2, H_2 gas sensor	Metis Engineering	
H_2 gas sensor	Serinus Lab	
H_2 gas sensor	Amphenol	
HF gas sensor	Amphenol	

Commercial-Off-The-Shelf Diagnostics Tools Evaluated

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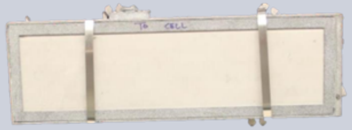
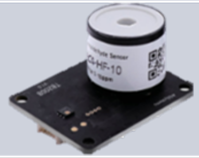
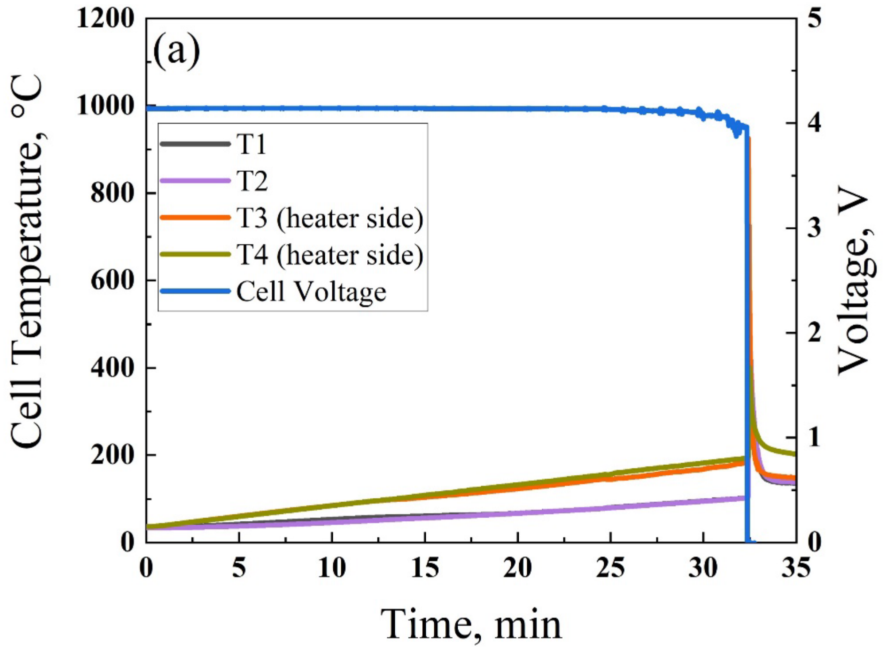
H_2 gas sensor	Serinus Lab	
H_2 gas sensor	Amphenol	
HF gas sensor	Amphenol	

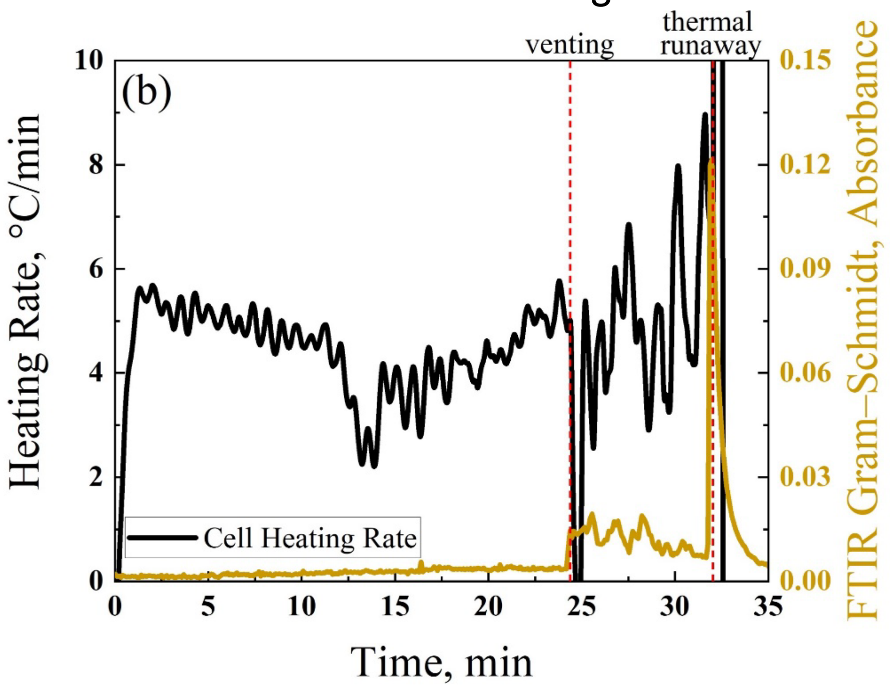
Failure Markers Prior to Thermal Runaway Threshold

11.6 Ah NMC Single Cell – Overtemperature to Failure

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



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



Time-resolved fourier-transform infrared spectroscopy measurements were conducted during the test to provide crucial insights into gas emissions that occur during venting and thermal runaway - $\Delta t_{warning\ time} = 7.8\ min$

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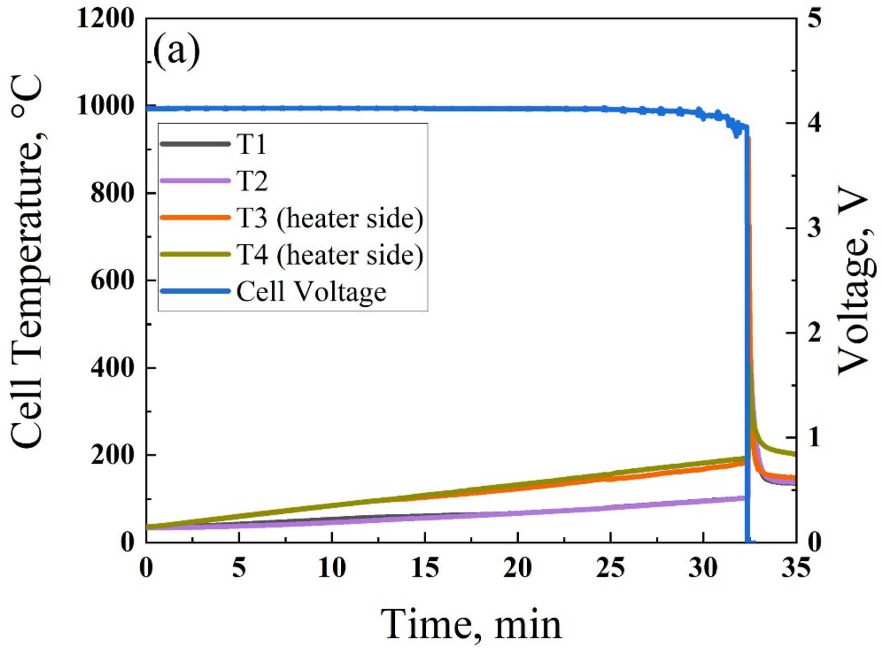

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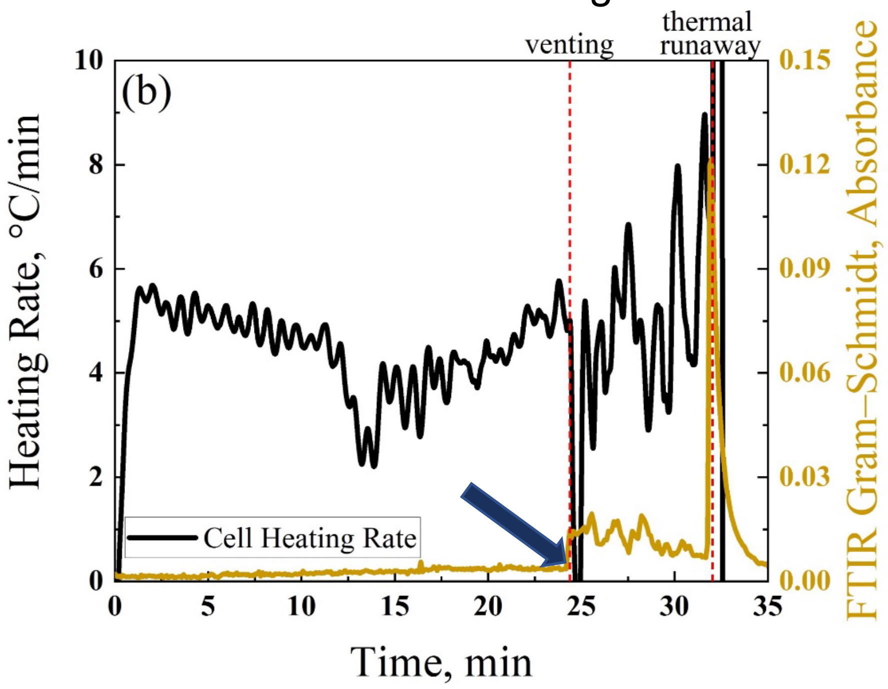

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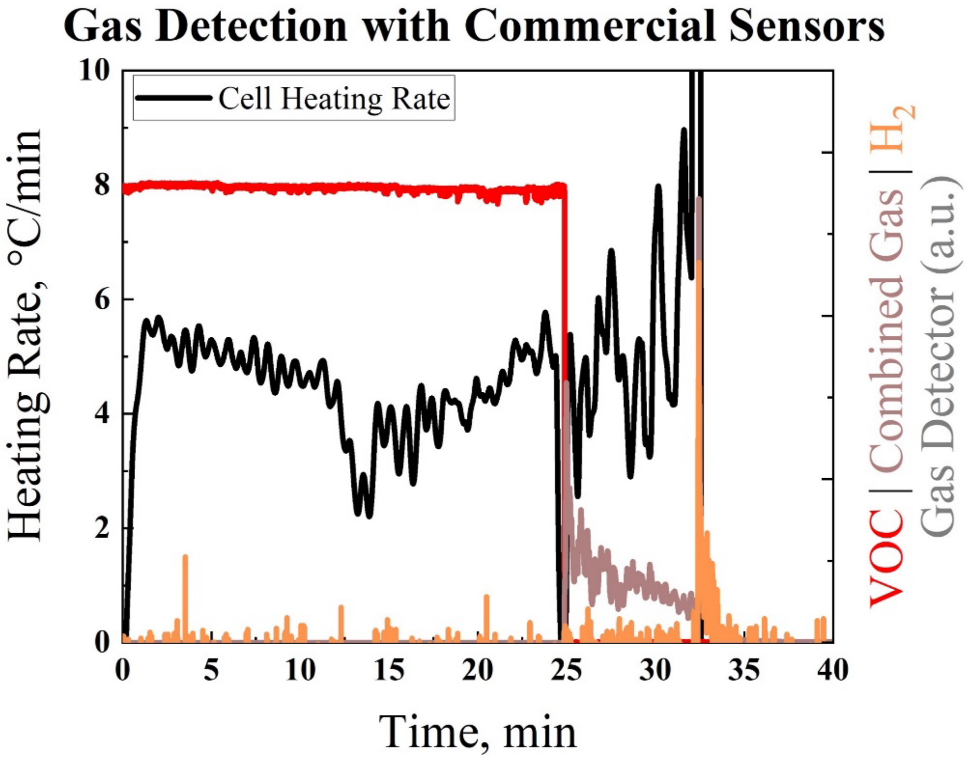
Variation in Gas Sensor Response for Thermal Abuse



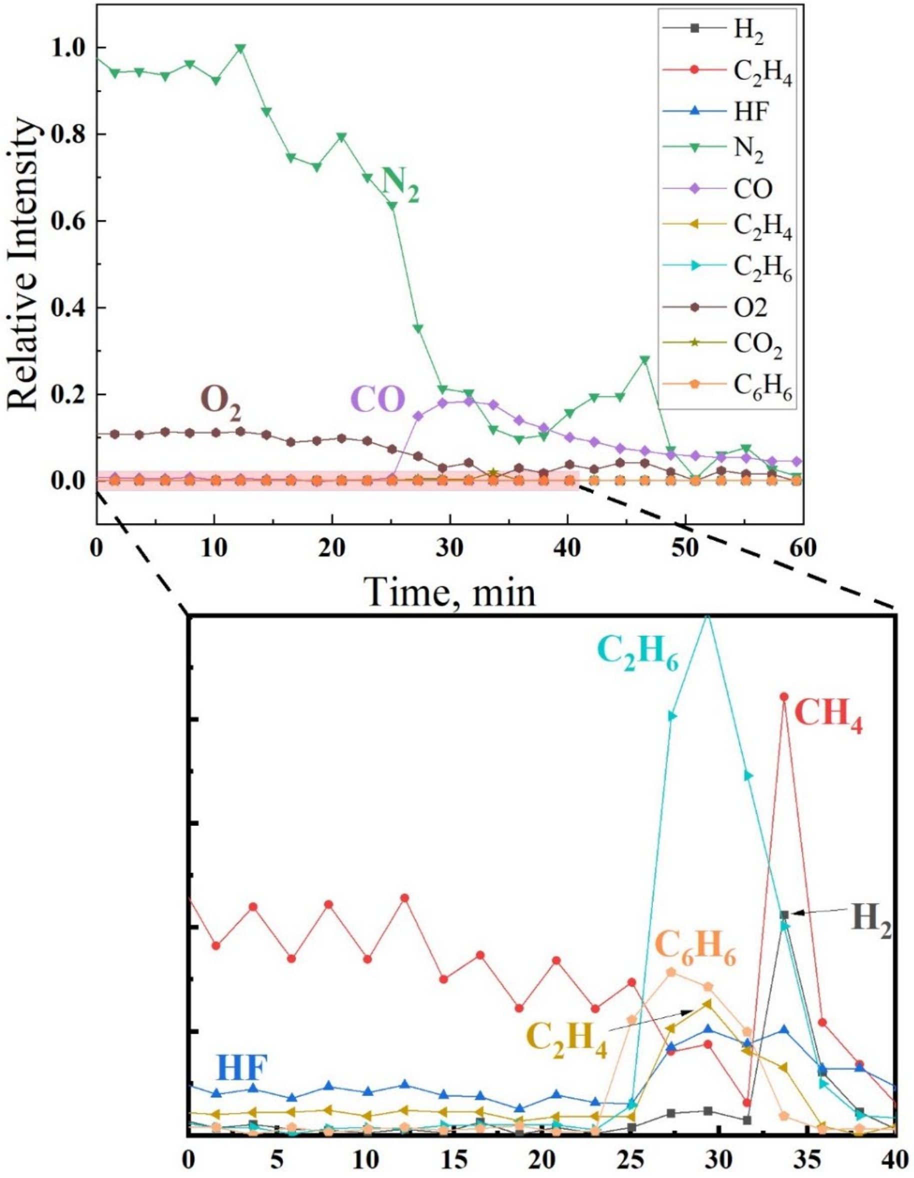
All sensors triggered at temperatures >100 °C

Sensor	$\Delta t_{\text{warning time}}$ (min)
VOC	7.1
Combined Gas	7.1
H_2	-0.4
Fourier-transform infrared spectroscopy	7.8

Insight from Mass Spectrometry

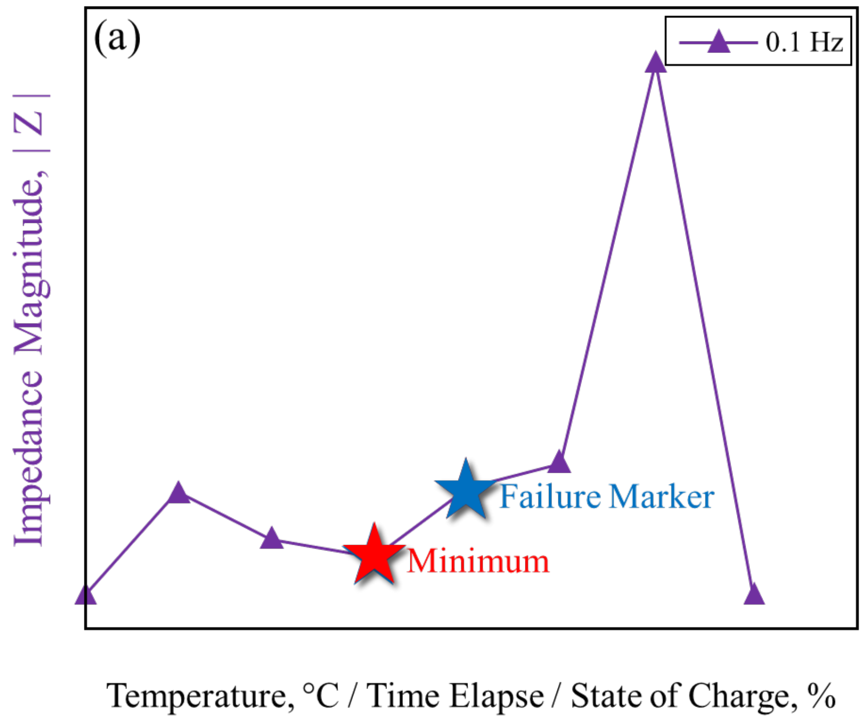
Hydrocarbons detected during cell venting enables activation of VOC and Combined Gas sensors

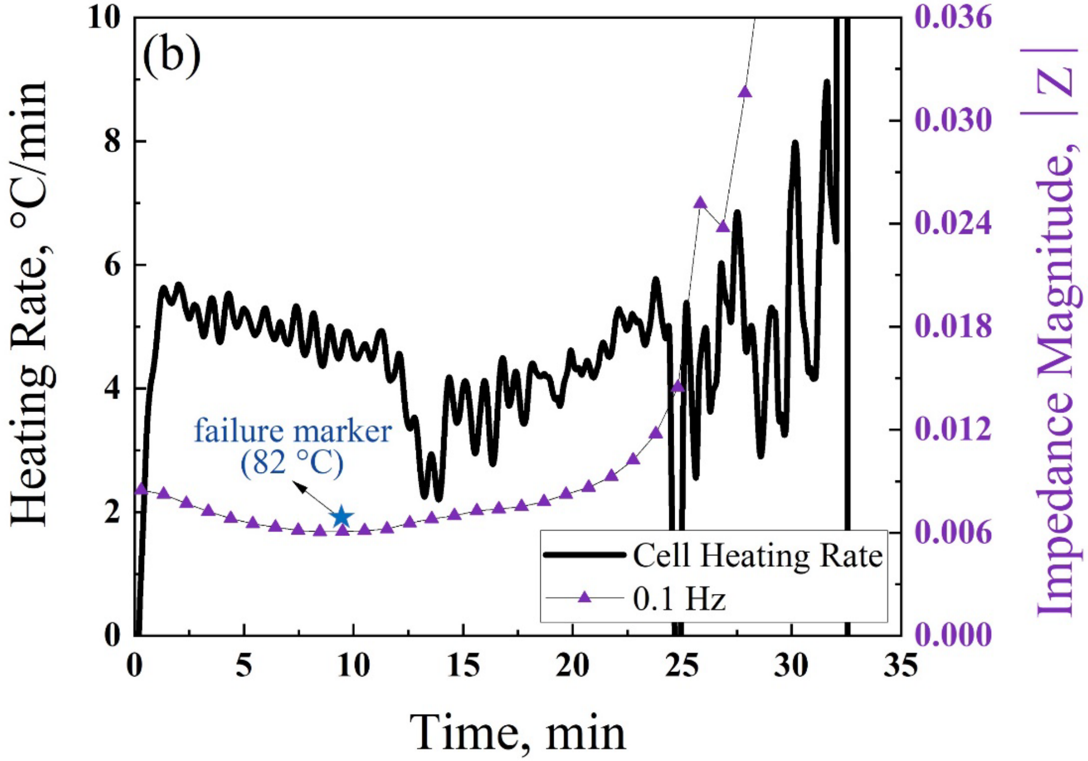
Hydrogen detected during thermal runaway enables activation of H_2 sensor



Early Detection with Rapid Electrochemical Impedance Spectroscopy (EIS)

How to find the failure marker?



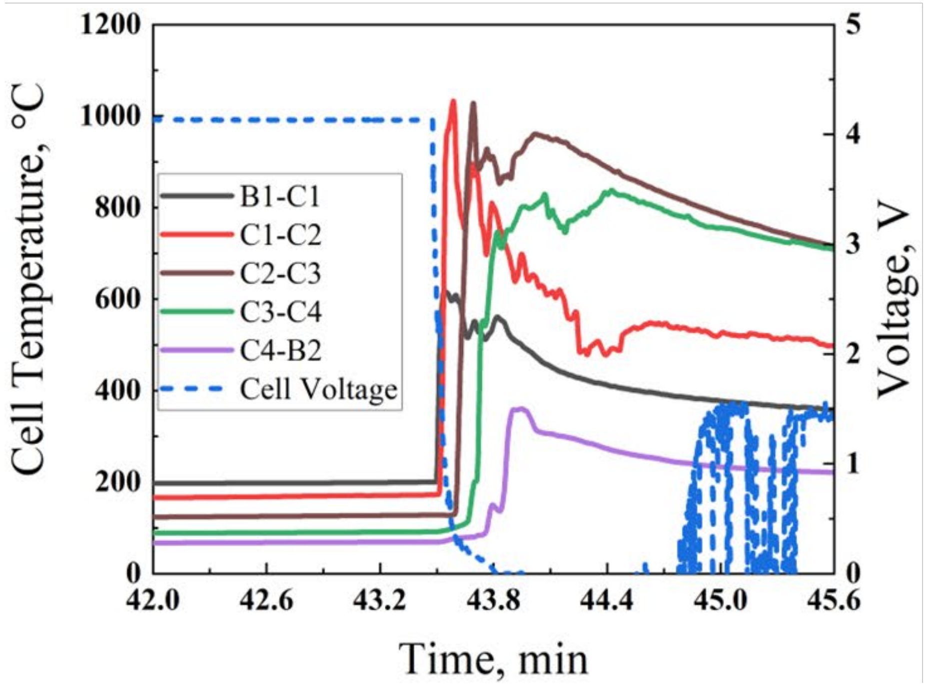


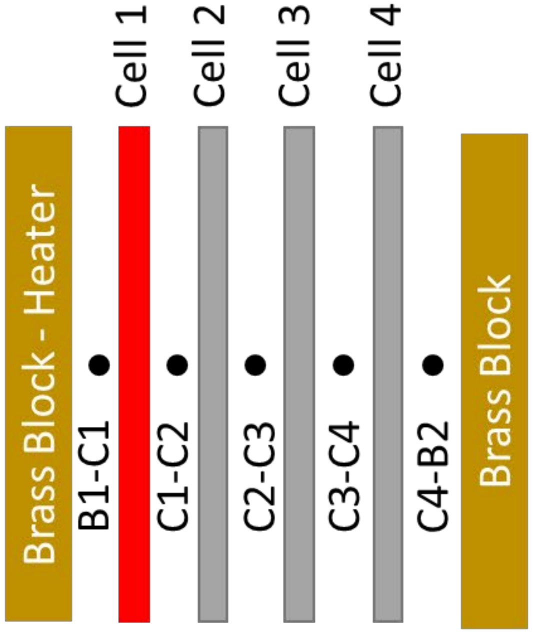
$\Delta t_{\text{warning time}}$ **= 22.5 min**

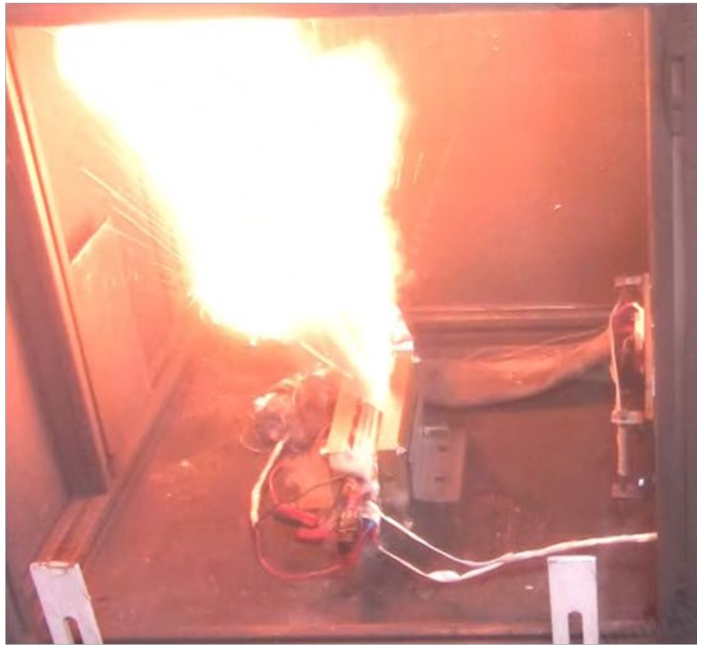
Rapid EIS offers earlier detection compared to gas sensors for this scenario

Diagnostics of a Battery Pack to Mitigate Thermal Propagation

<u>1S4P NMC Pack (46 Ah) – Failure Initiated on Edge Cell</u>



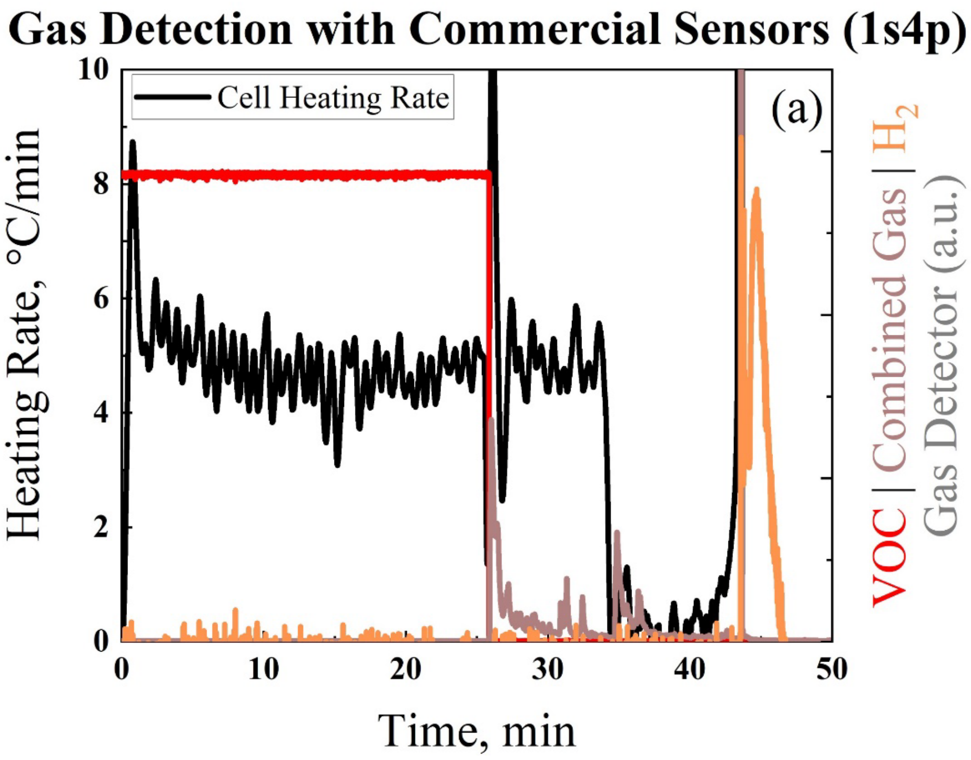




Failure was initiated in a single cell within the pack and continuous gas sensing and electrochemical impedance measurements were collected at the pack level

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?

Consistent Gas Sensor Triggering Time Between Single Cells and a 1s4p Pack

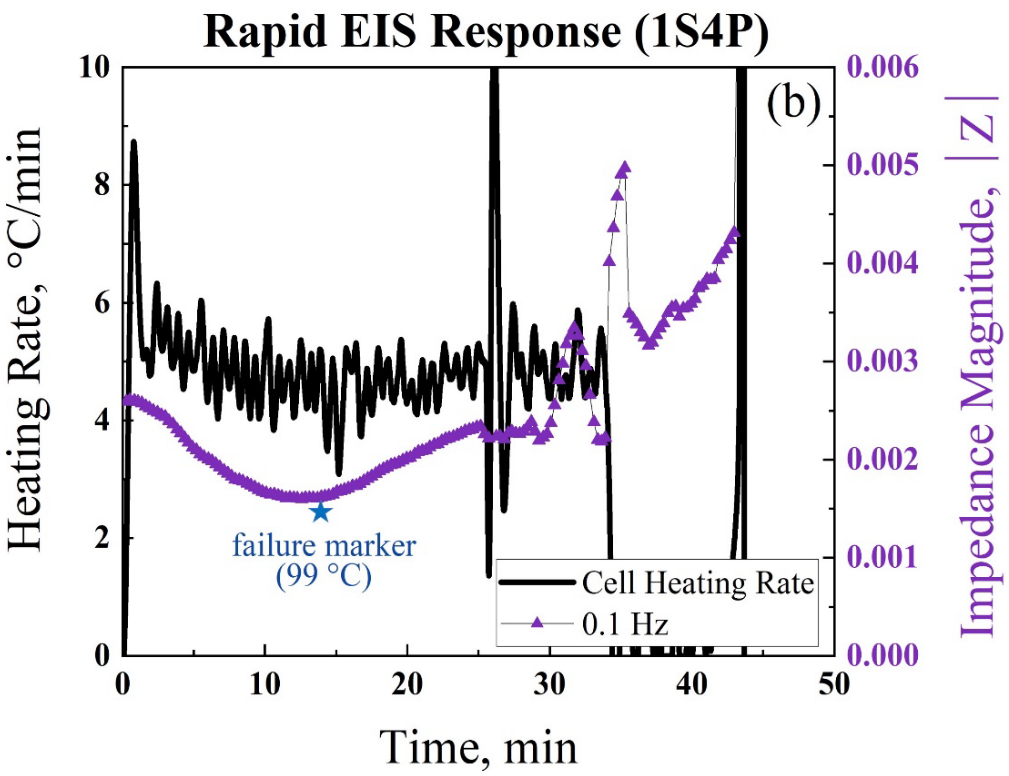


Sensor	$\Delta t_{\text{warning time}}$ (min)*
VOC	17.3
Combined Gas	17.3
H_2	-0.4

* warning time calculated based on ***TR_{time}*** of cell 1

Increased warning time for the 1S4P pack is attributed to heat dissipation through adjacent cells and interconnections after cell venting. Both units—single cell and battery pack—experienced venting roughly at the same temperatures (144–152 °C) but the pack experienced thermal runaway at a higher temperature.

Earlier Detection with Rapid Electrochemical Impedance Spectroscopy (EIS)



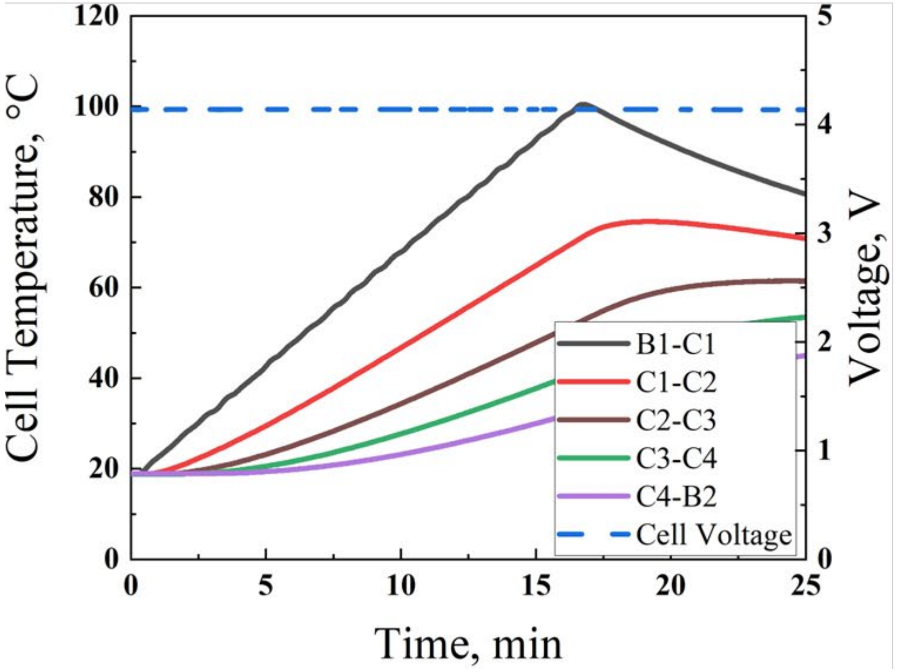
$\Delta t_{warning\ time}$ = 29.2 min

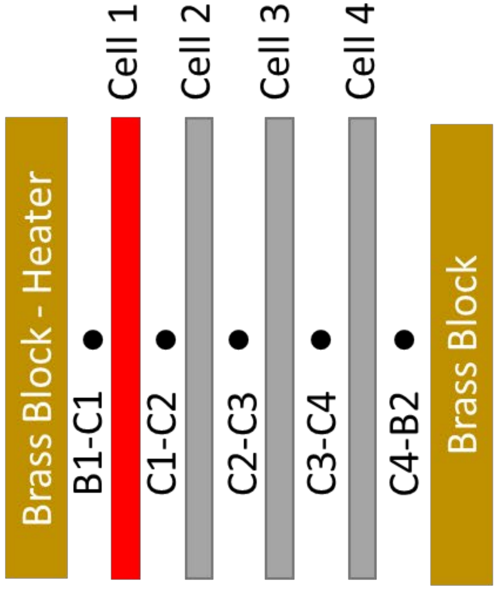
Rapid EIS

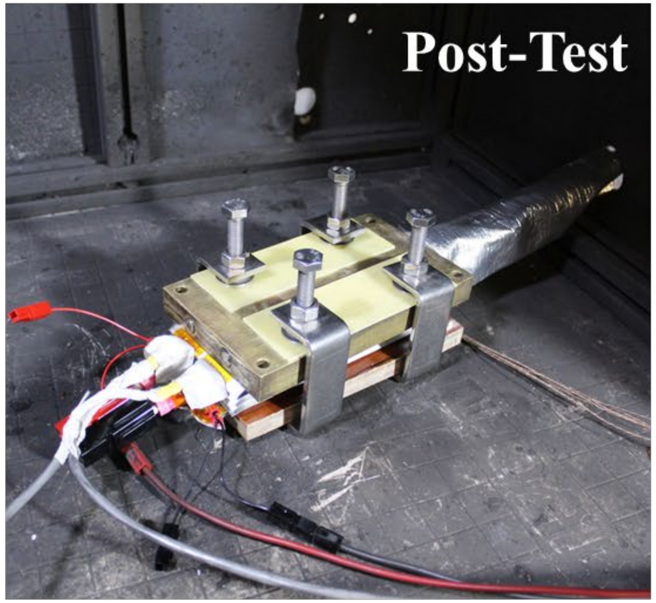
- Provided earlier detection compared to gas sensors in this scenario
- Detection occurs at a much lower temperature (99 °C) compared to the gas sensors (153 °C)
- Detection at the pack level occurred at 99 °C while for single cell was 82 °C

Intervention Based On The Failure Marker Identified During Overtemperature

Are failure markers sufficient to not only mitigate failure but also potentially prevent energetic thermal runaway?



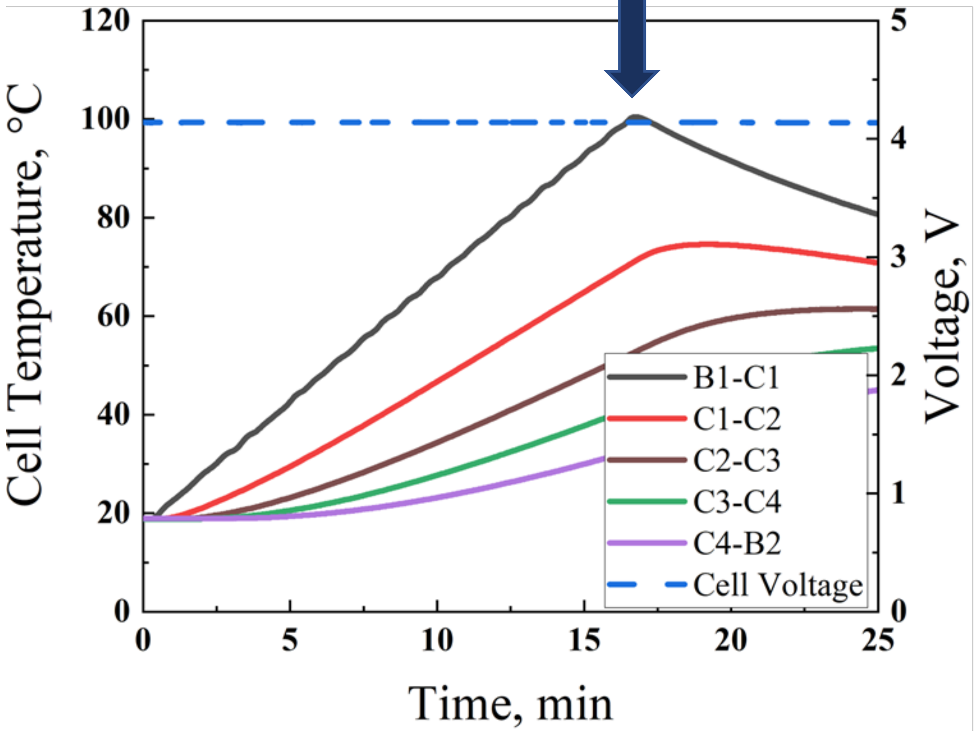


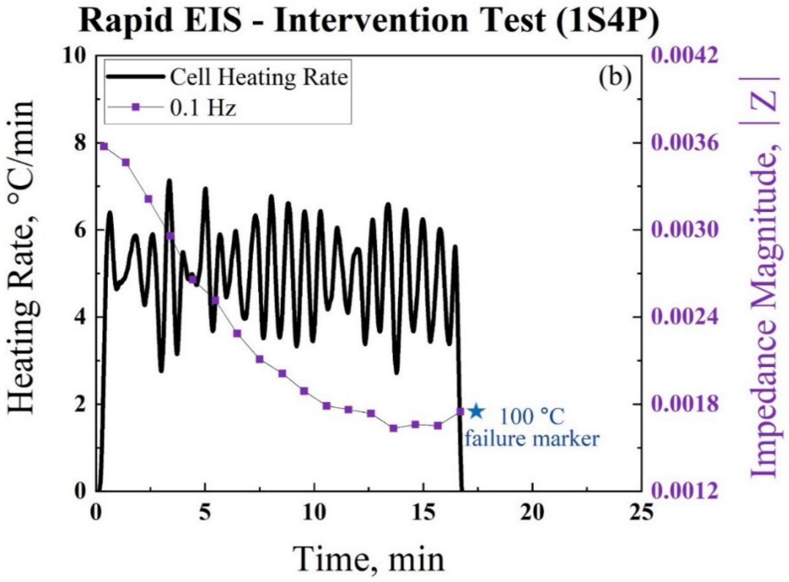


During this experiment, the heating element was deactivated upon either the triggering of the gas sensor or the identification of a failure marker through impedance magnitude.

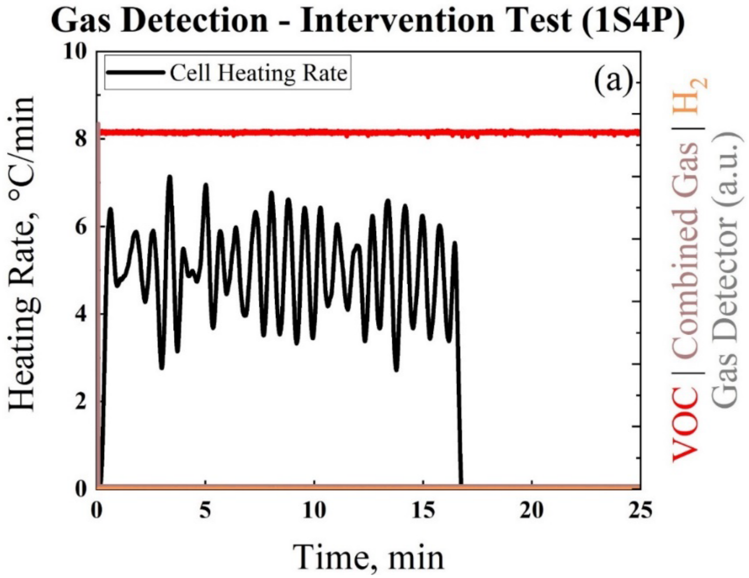
Rapid Electrochemical Impedance Spectroscopy Provided Advanced Warning To Halt Thermal Runaway

heating element deactivated





Failure marker detected



No activation of gas sensors

Summary of Results

Cell Configuration	Sensor	$\Delta t_{warning\ time}$ (min)
Single cell	VOC	7.1
	Combined Gas	7.1
	H_2	-0.4
	Rapid EIS	22.5
1s4p (OT of cell 1)	VOC	17.3
	Combined Gas	17.3
	H_2	-0.4
	Rapid EIS	29.2
1s4p (OT of cell 1, intervention test)	VOC	No Runaway
	Combined Gas	No Runaway
	H_2	No Runaway
	Rapid EIS	No Runaway

Conclusion

- Evaluation of the warning times obtained by gas sensor and rapid electrochemical impedance spectroscopy (EIS) diagnostics found that rapid EIS consistently showed an earlier trigger point.
- The reliability of picking up impedance changes in single cells within a pack decreases as the packs become more complex.
- Warning time is not a fixed parameter but can vary depending on multiple factors (e.g., thermal properties, how closely packed the cells are, the efficiency of the thermal management system)
- An ideal BMS would incorporate multiple diagnostics in combination with traditionally collected data points (i.e., voltage and temperature), to achieve detection of failure markers prior to venting.
- By delving into the interplay between design, warning mechanisms, and response times, the pathway towards a more efficient and effective management of potential failures in the dynamic realm of battery technology is elucidated.

Project Team

Loraine Torres-Castro (PI)

Alex Bates (CO-PI)

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Other team members

Genaro Quintana

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NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

External Collaborators

Idaho National Laboratory

Thank you!

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Additional Slides

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)**
3) **2S4P (failure of 1s4p string)**

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