The Versatile VSP2: Battery Testing

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Agenda

Introduction to Battery Testing:

- Thermal Runaway
- Battery Fires
- UL9540a
- Data Applications

Extensions of the VSP2 for Battery Testing:

- Preconditioning Equipment
- Abuse Methods
- Gas Capture, Analysis, & Flammability Testing
- Video Recording

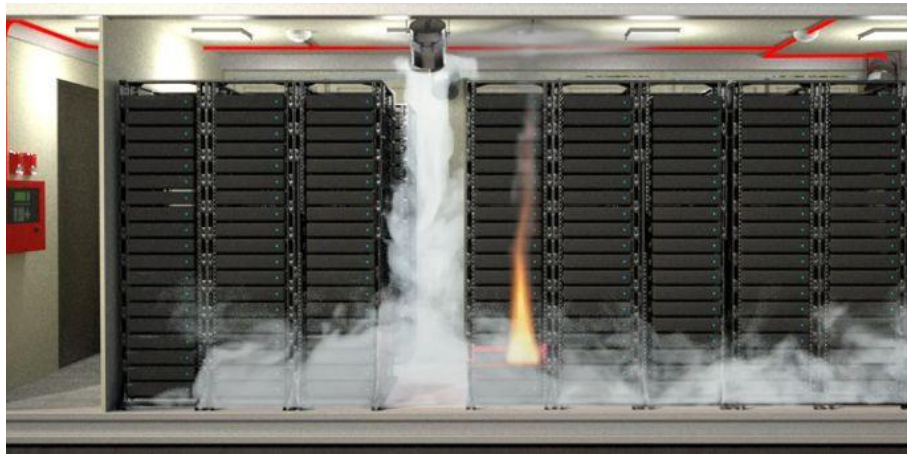
Case Studies:

- Thermal Abuse of an 18650 Cell in a 4L Vessel
- Thermal Abuse of Coin Cells

Introduction to Battery Testing

Thermal Runaway – Battery Fires

- Thermal runaway: The progressive production of heat from a chemical process that occurs when the rate of heat production exceeds the rate of heat removal
- Batteries, specifically lithium-ion, are increasingly important in industry and everyday life
- Battery thermal runaway ejects flammable gases, causing fires and potentially explosions



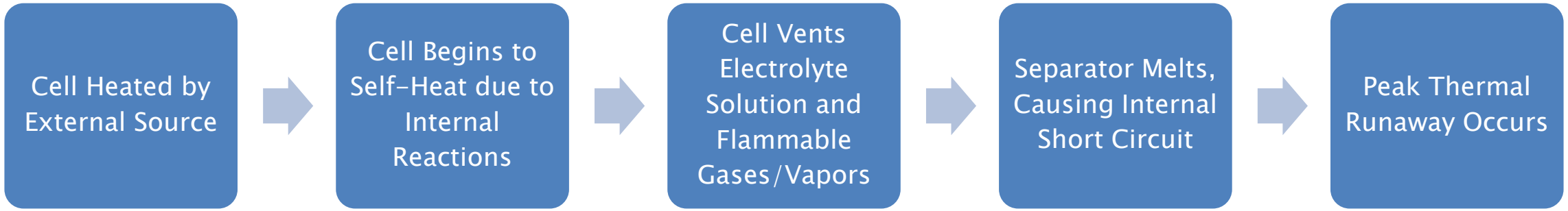
https://movitherm.com/solutions/early-fire-detection/fire-protection-for-lithium-battery-storage/?msclkid=71702313177110efcb1b4a0443cbb519&utm_source=bing&utm_medium=cpc&utm_campaign=IoT%20-%20Early%20Fire%20Detection%20-%20RSA%2FDSA%20%232&utm_term=battery%20energy%20storage%20system%20fire%20protection&utm_content=Lithium%20Battery%20Fire%20Protection

https://energybite.org/2016/05/23/episode-154-why-do-batteries-catch-fire/

https://image5.sixthtone.com/image/5/17/441.gif

Battery Fires – Common Terminology

- During normal discharging, electrons flow from a battery's anode (negative terminal) to cathode (positive terminal). Lithium ions flow in the opposite direction through an electrolyte solution
- Preconditioning: The process of subjecting a cell to several charge and discharge cycles to simulate chemical changes in real-life use, including the formation of a stabilizing solid electrolyte interphase
- Separator: A porous solid material that physically separates the anode and cathode to prevent short circuiting while permitting transport of ionic charge carriers
- Cell Vent Onset: The point at which the internal pressure of the cell exceeds the relief vent pressure, followed by the release of flammable vapors and gases
- Typical Progression of Thermal Runaway (via thermal abuse):

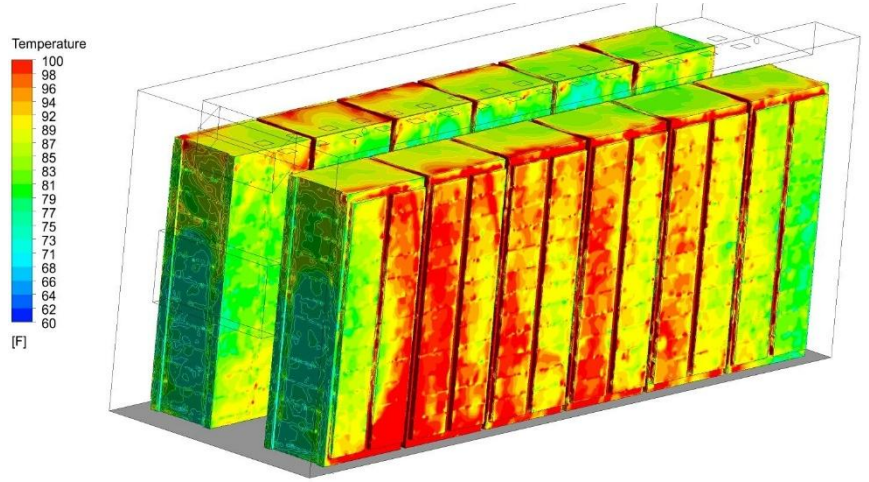


Battery Fires – Testing Methodology (UL9540a)

- UL9540a prescribes four levels of thermal runaway testing: cell, module, unit, and installation
- For cell-level testing, UL9540a prescribes three acceptable methods:
  - Thermal Abuse
  - Mechanical Abuse (Nail penetration, crushing, etc.)
  - Electrical Abuse (Overcharging, overdischarging, external short circuit, etc.)
- With all methods, cells must be preconditioned:
  - Cell must be charged to 100% State of Charge (rated capacity) and discharged to manufacturer End of Discharge Voltage for a minimum of 2 cycles
  - Cells must then be allowed to stabilize between 1 and 8 hours before testing

Battery Fires – Applications of Testing Data

- Cell vent and thermal runaway temperatures, pressures:
  - Early warning and mitigation systems
- Quantification of heat released at various temperatures:
  - Cell internal design, cell spacing, thermal barriers, cooling system design
- Modeling of runaway reaction kinetics at different phases:
  - Fire propagation modeling
- Collection of cell vent and thermal runaway gas:
  - Flammability testing, modeling, and relevant relief sizing
  - Installation of gas detectors and alarms



https://blog.priceindustries.com/battery-energy-storage-and-thermal-runaway

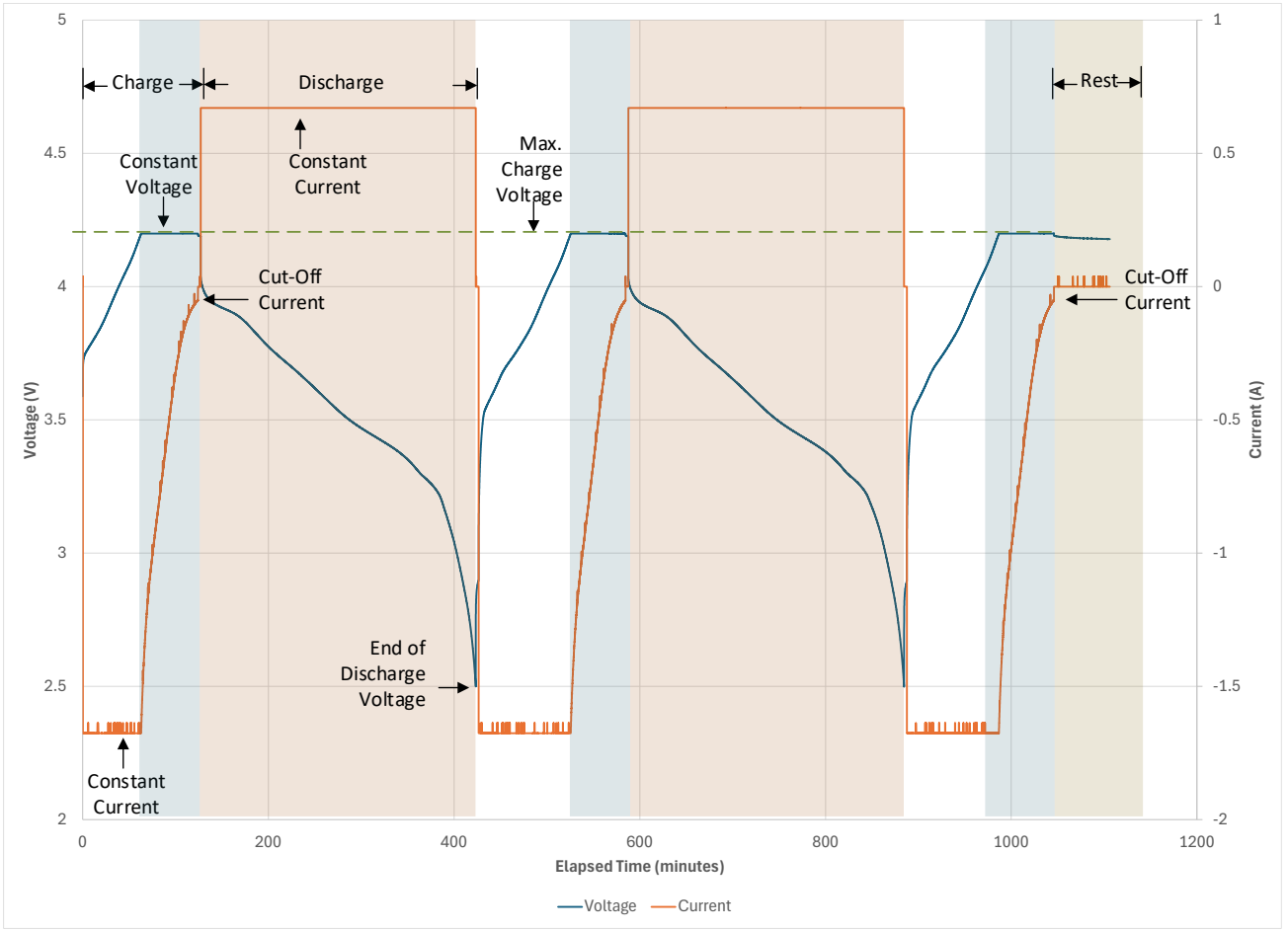
Extensions of the VSP2 for Battery Testing

Vent Sizing Package 2 (VSP2) Background and Extensions

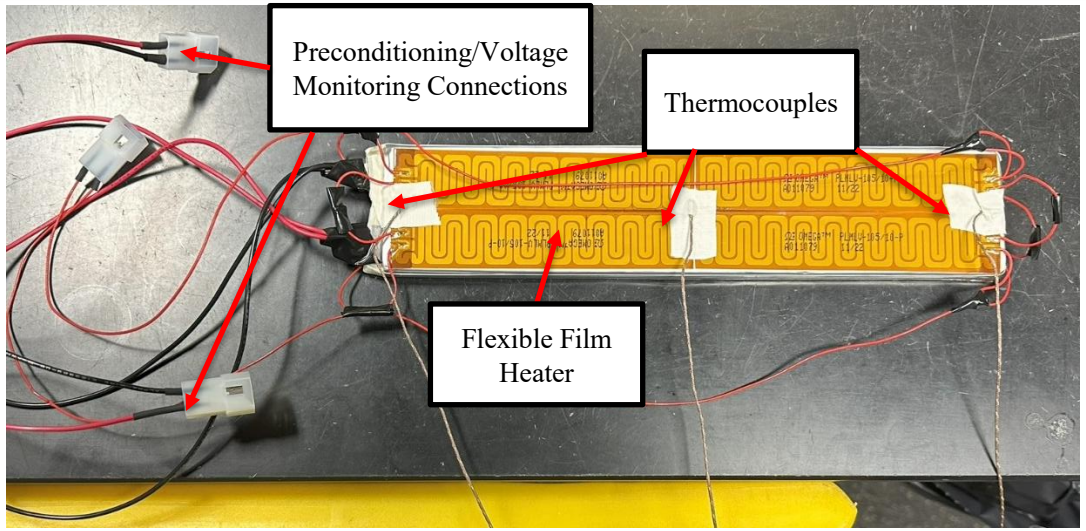
- Adiabatic calorimeter, traditionally used to study runaway chemical reactions
- Controls and monitors the time, temperature, pressure response of a system under adiabatic conditions
- Extensions to VSP2 system enable various capabilities, including:
  - *In situ* voltage monitoring and preconditioning
  - Thermal initiation and adiabatic tracking of cell venting and thermal runaway
  - Quantification of evolved gases from both cell vent and runaway
  - Activation of alternative abuse methods
    - External short circuit device
    - Mechanical (nail) penetration device

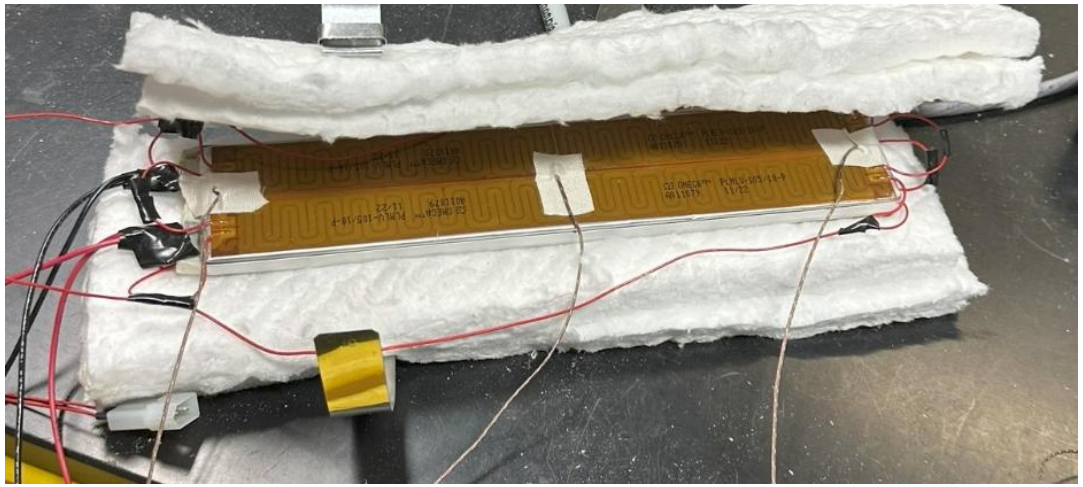
VSP2 System Extension – Equipment for Cell Preconditioning and Voltage Monitoring

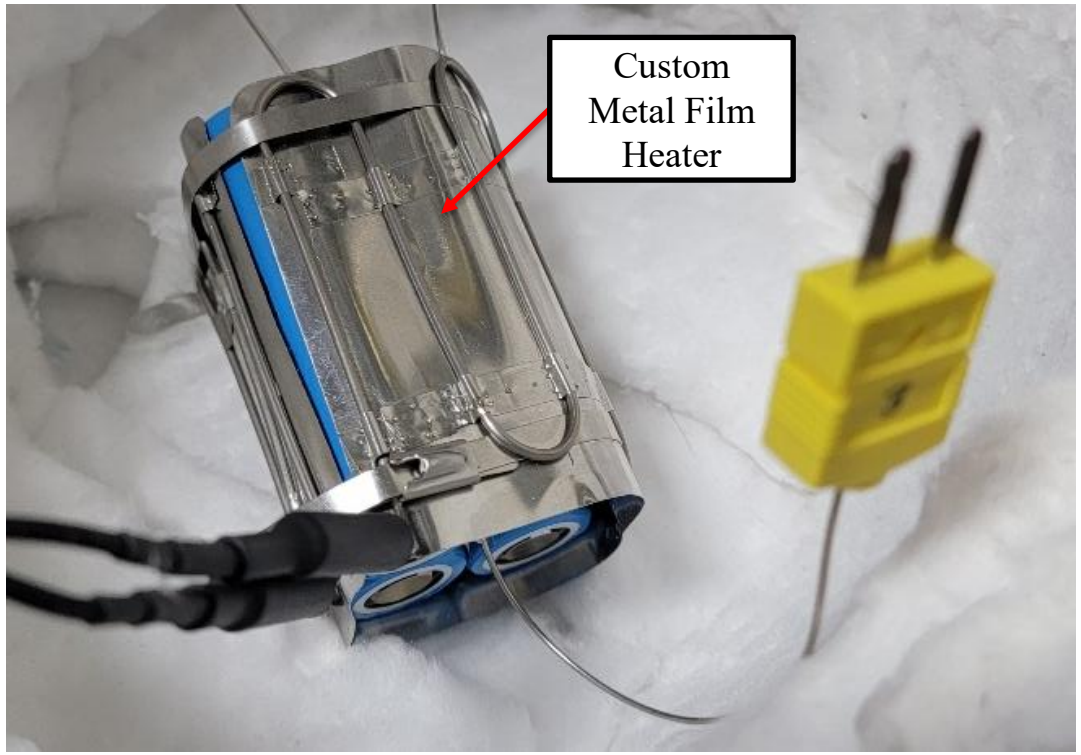
- Commercially available DC supplies and loads were used to charge cycle the lithium-ion cells prior to testing
- All tests were conducted at an initial state of charge (SOC) of 100% using the charging and discharging procedures specified in the respective cell data sheets
- Supply and load equipment were used to monitor voltage and current during several tests



VSP2 System Extension – Thermal Abuse (Film Heaters)

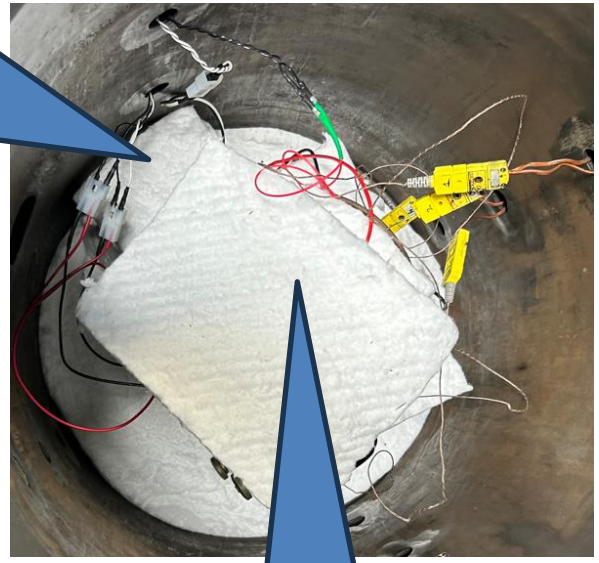


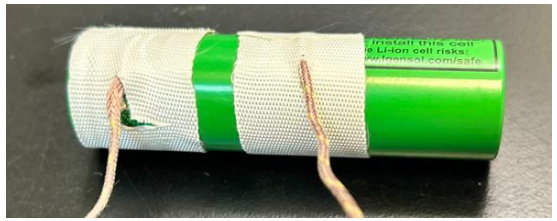


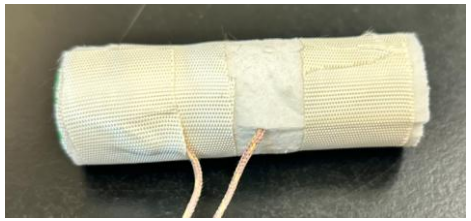


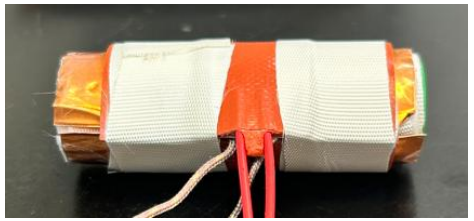
VSP2 System Extension – Electrical Abuse (External Short Circuit)

- DC supply/load
  - *In situ* preconditioning
  - Cell voltage monitoring
- Flexible film heater controlled by VSP2
  - Provides adiabatic boundary via guard heater
  - Alternate method of heating cell if short circuit device fails
- High-current relay triggered by VSP2
  - Used to apply external short circuit to cell

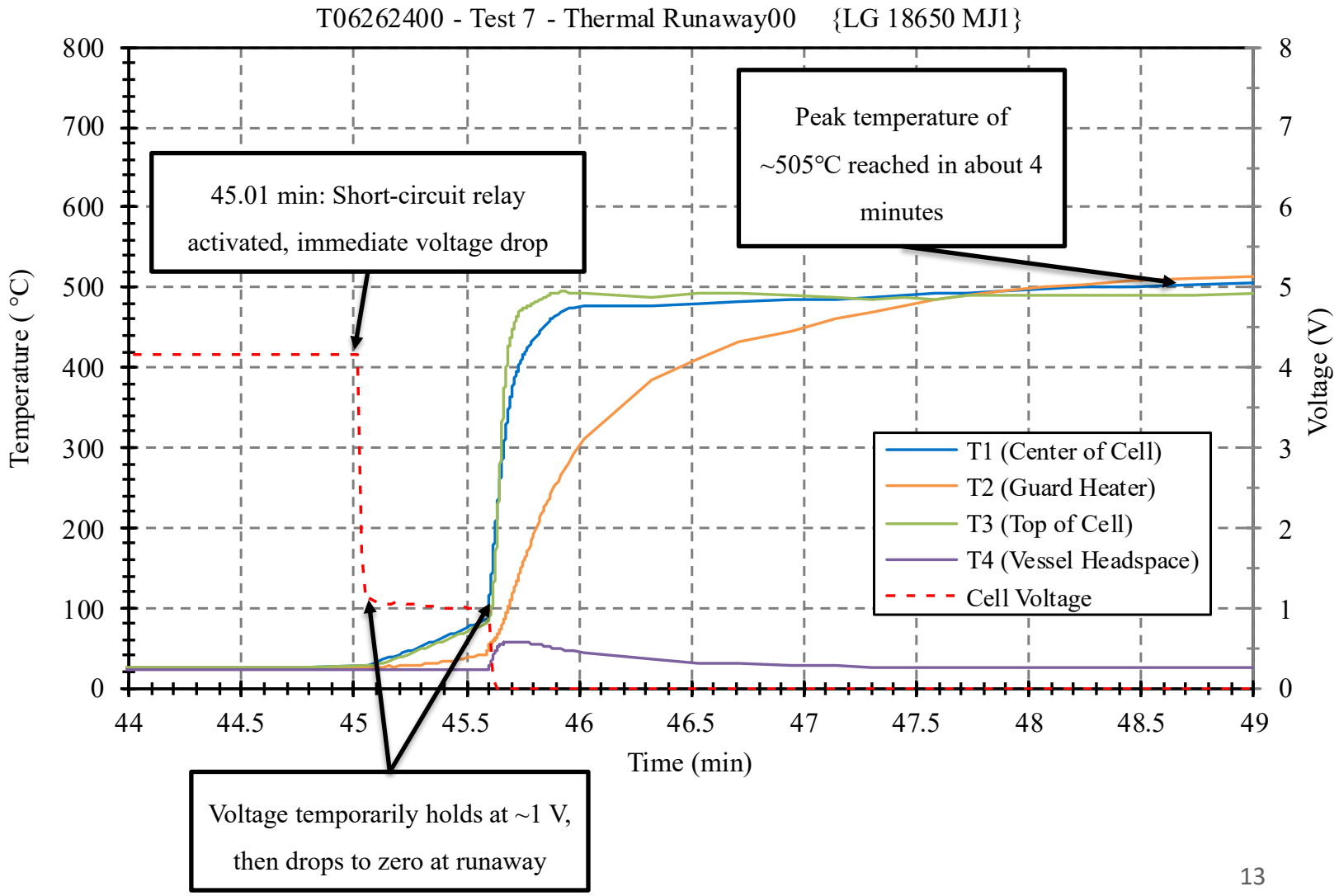






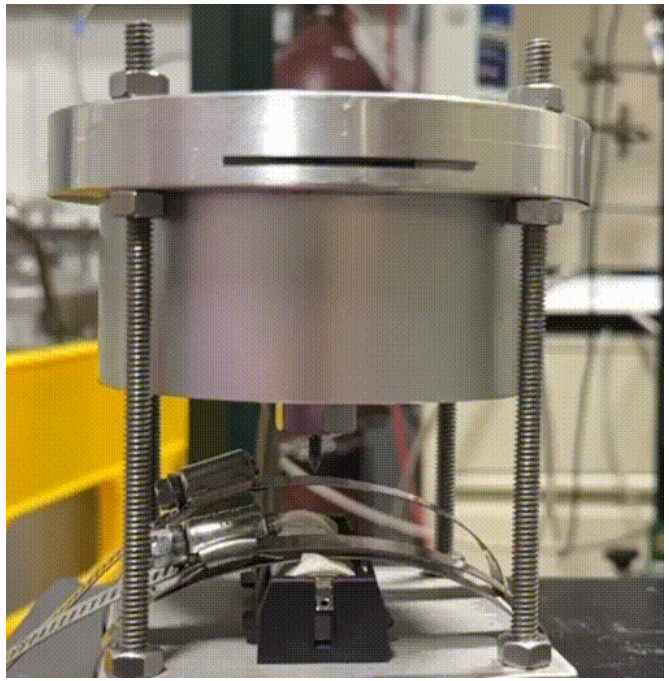


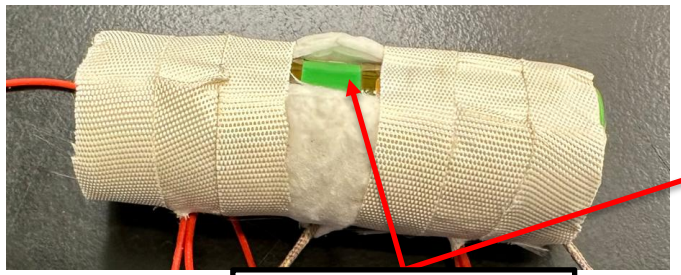
VSP2 System Extension – Electrical Abuse (External Short Circuit)

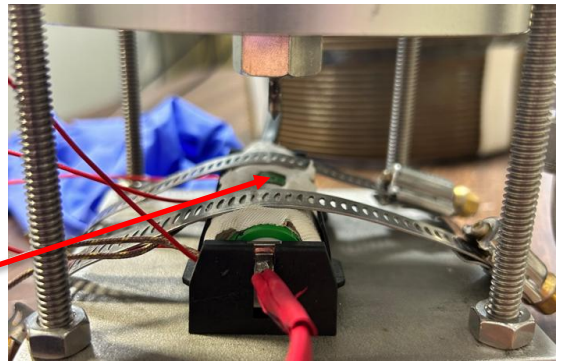


VSP2 System Extension – Mechanical Abuse (Nail Penetration)

- DC supply/load
  - *In situ* preconditioning
  - Cell voltage monitoring
- Flexible film heater controlled by VSP2
  - Controlled as auxiliary heater
  - Alternate method of heating cell if nail penetration device fails
- Pneumatic piston triggered by VSP2
  - Used to extend a nail into the battery surface

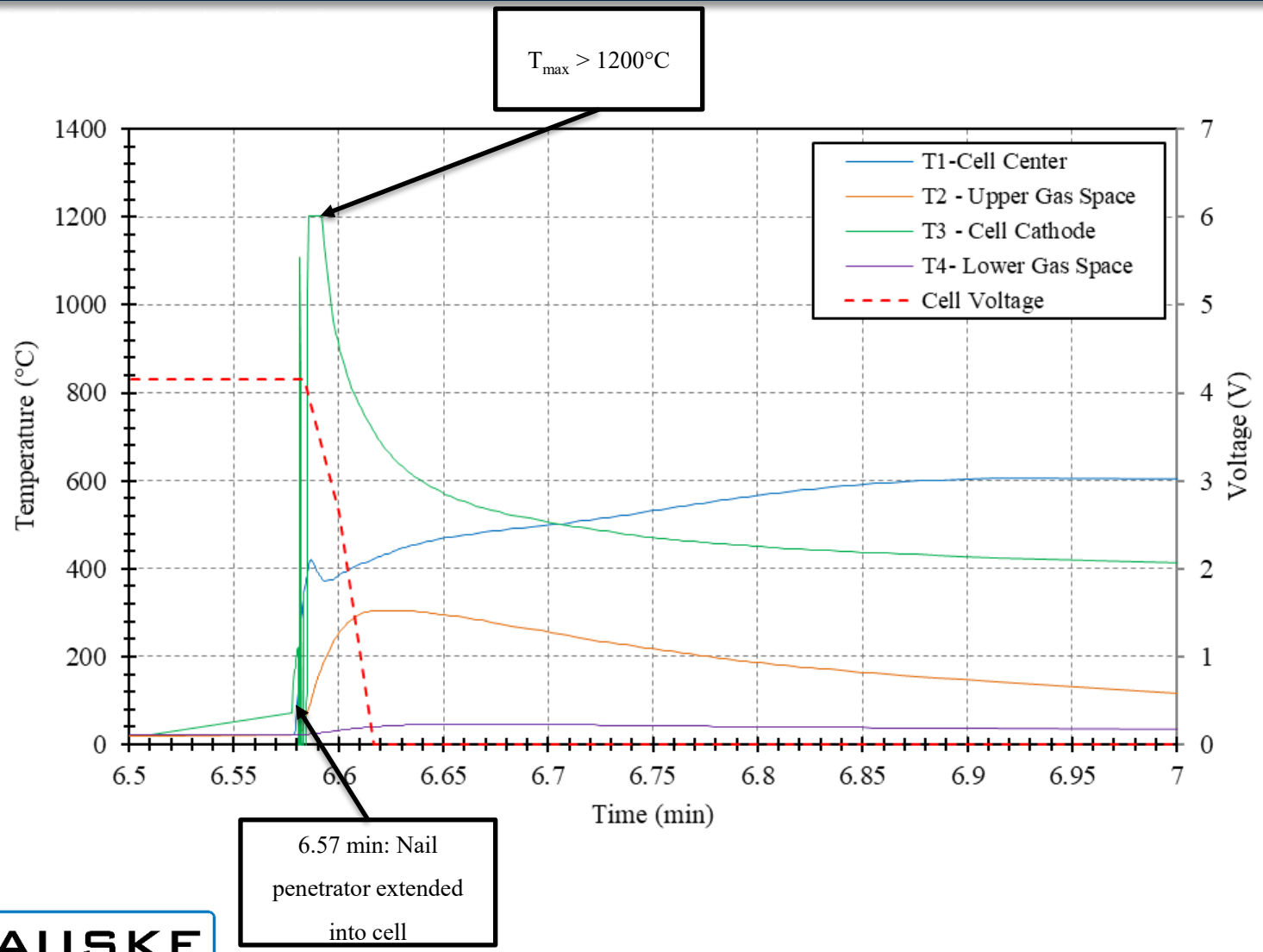


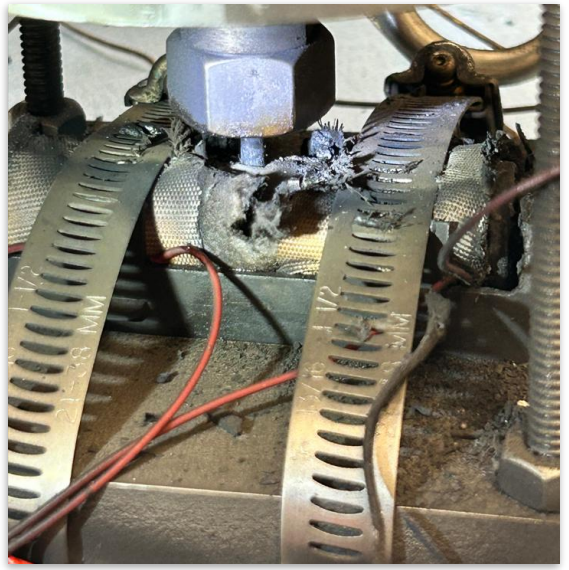


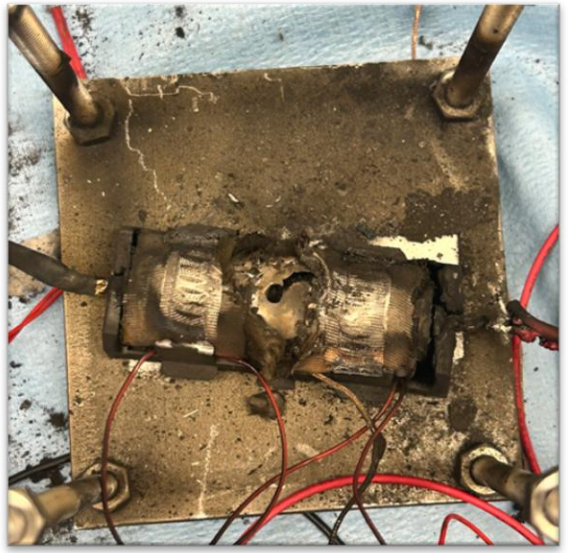


Target Penetration Area

VSP2 System Extension – Mechanical Abuse (Nail Penetration)



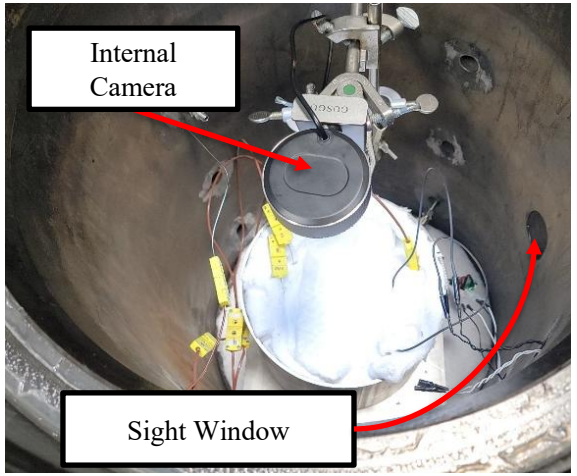


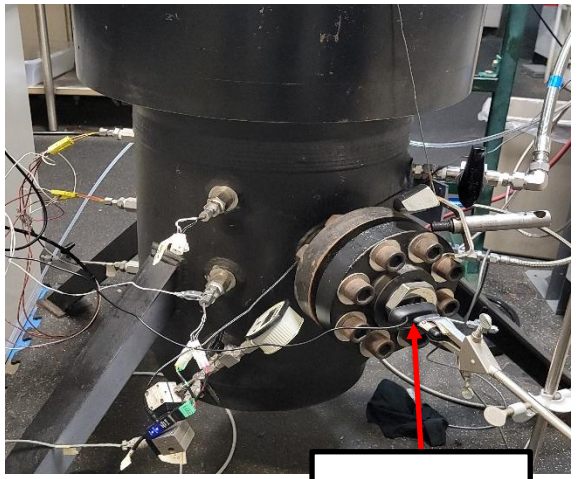


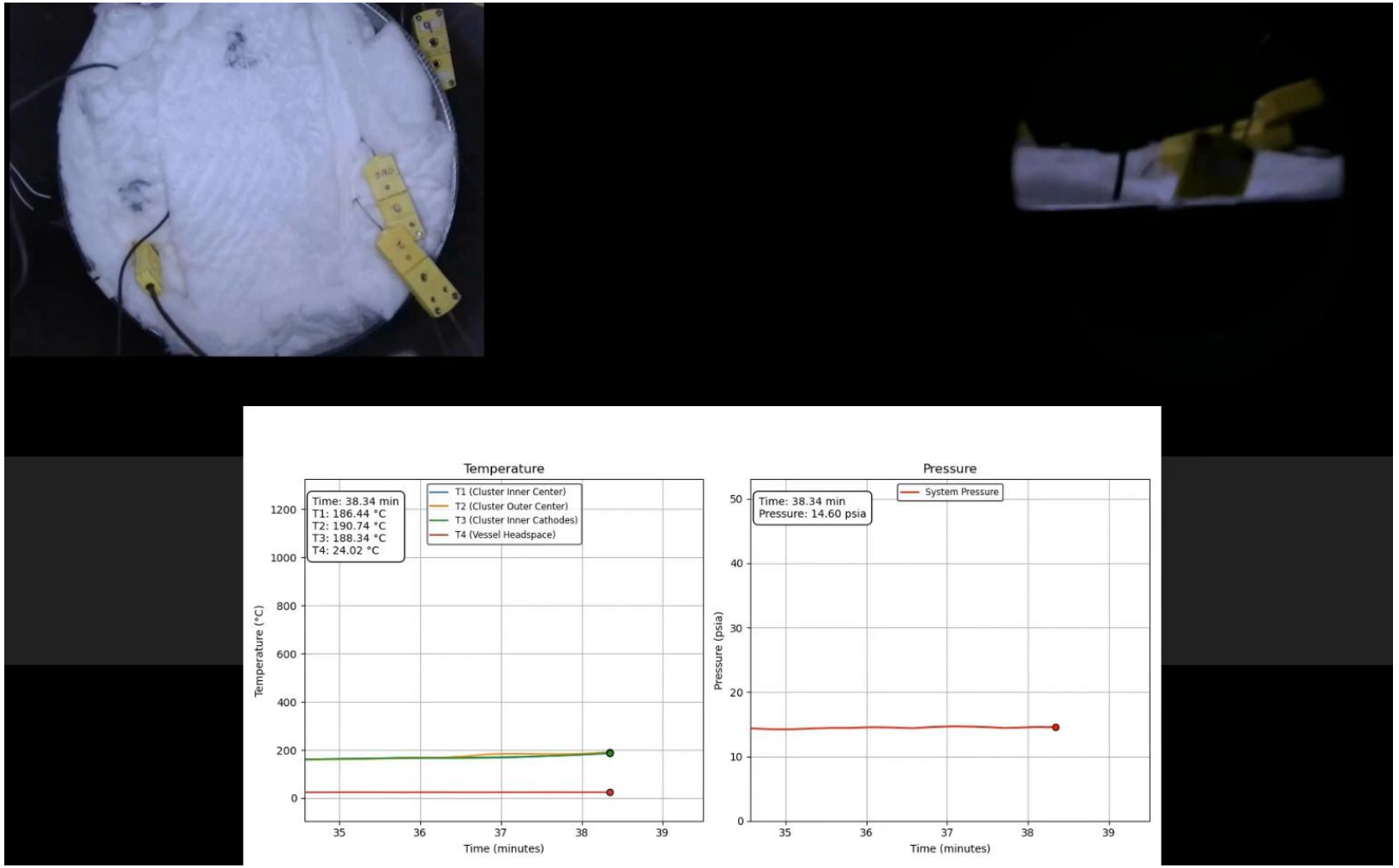
VSP2 System Extension – Capture, Analysis, & Flammability Testing of Battery Off-Gas

- Captured gas/vapors from cell vent and thermal runaway can be analyzed with GC/MS and other methods to determine composition
- Determination of composition enables production of bulk quantity mixtures for testing
- Flammability Parameters Determined from Cell Vent Gas Testing at FAI:
  - LFL/UFL
  - Burning Velocity
  - P_{max}
  - K_G

VSP2 System Extension – Video Recording







Case Study: Thermal Abuse of an 18650 Cell in a 4L Vessel

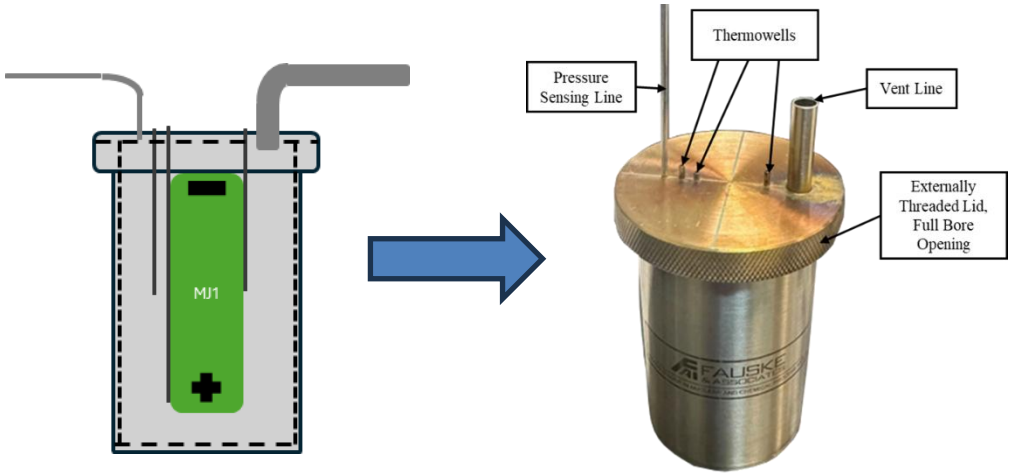
Thermal Abuse of 18650 in 4L Vessel – Maintaining Adiabaticity & Collection of Uncontaminated Gas Samples

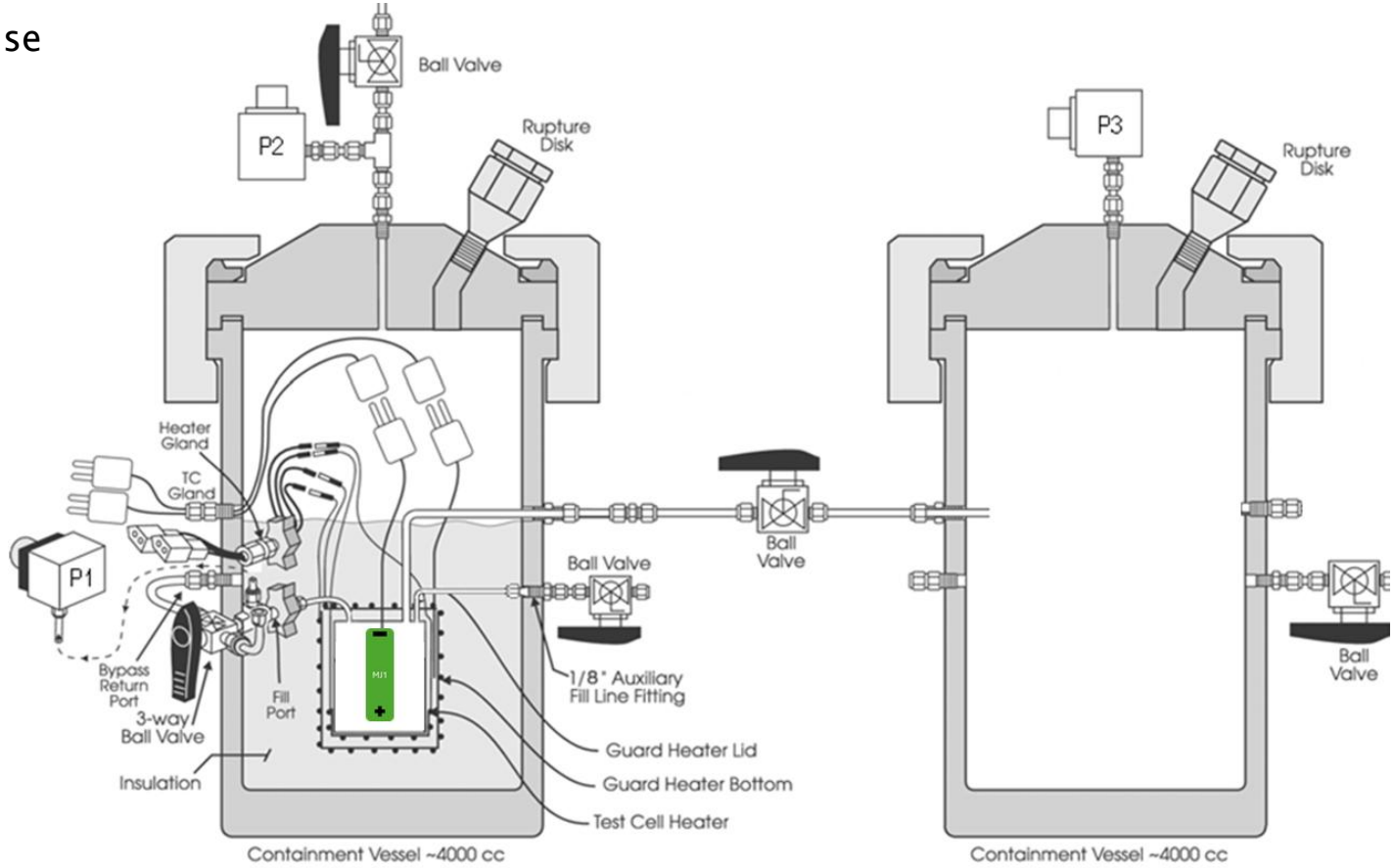
Test Can with Standard VSP2 Heater Assembly:

- Smaller volume → larger pressure increase → more precise detection
- No direct gas interaction with external assembly

Tests Performed:

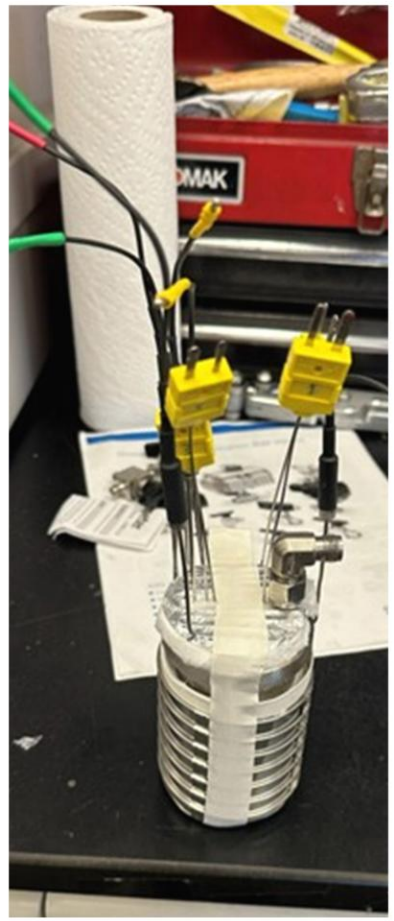
- 4°C/min thermal ramp under N_2 (Test A)
- 1°C/min thermal ramp under N_2 (Test B)
- **0.3°C/min ramp under He (Test C)**

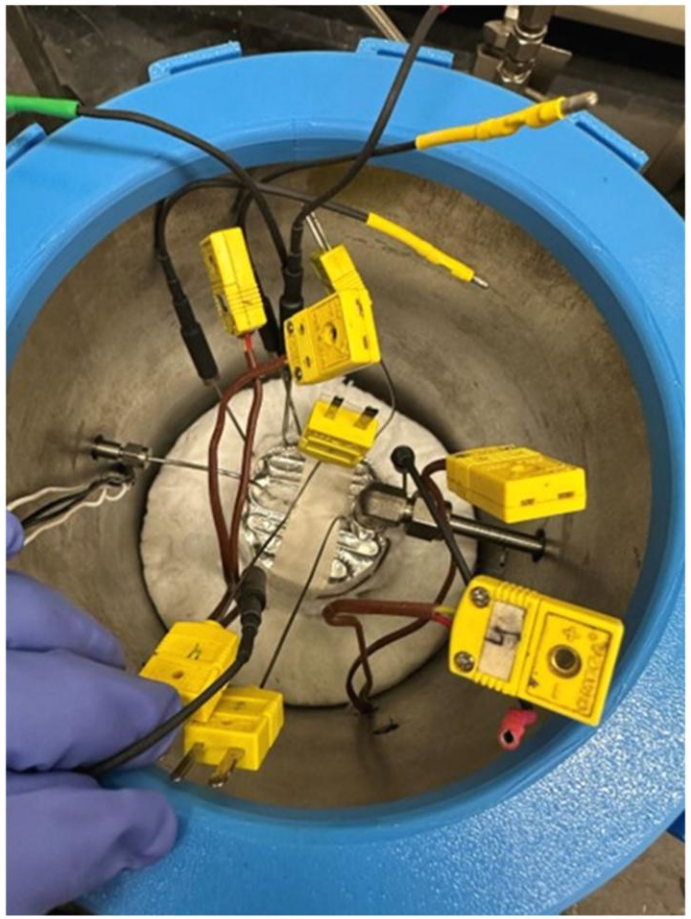




MAWP: 1900 psig

Thermal Abuse of 18650 in 4L Vessel – Test Can Assembly





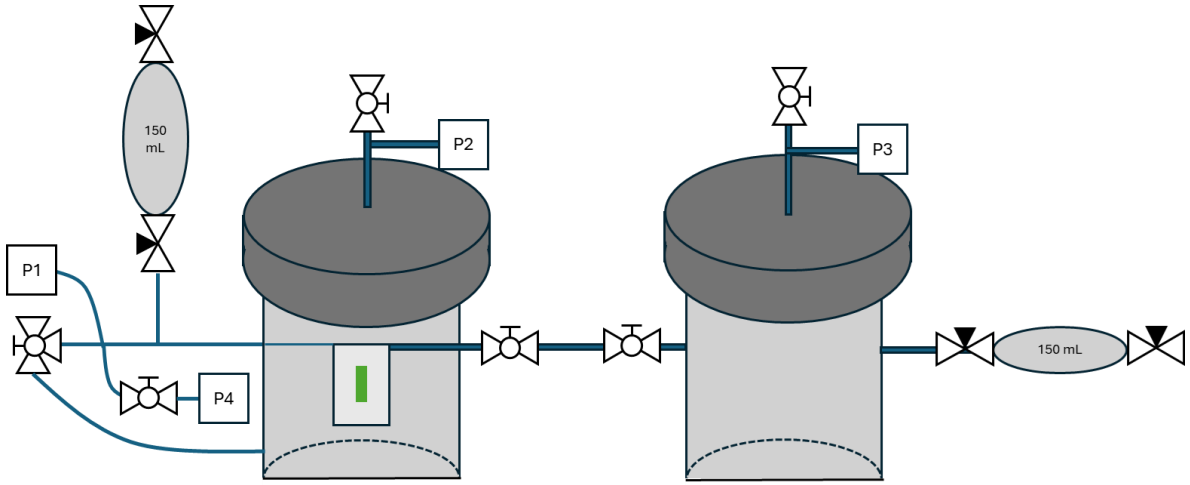
Thermal Abuse of 18650 in 4L Vessel – Test C

Setup Features:

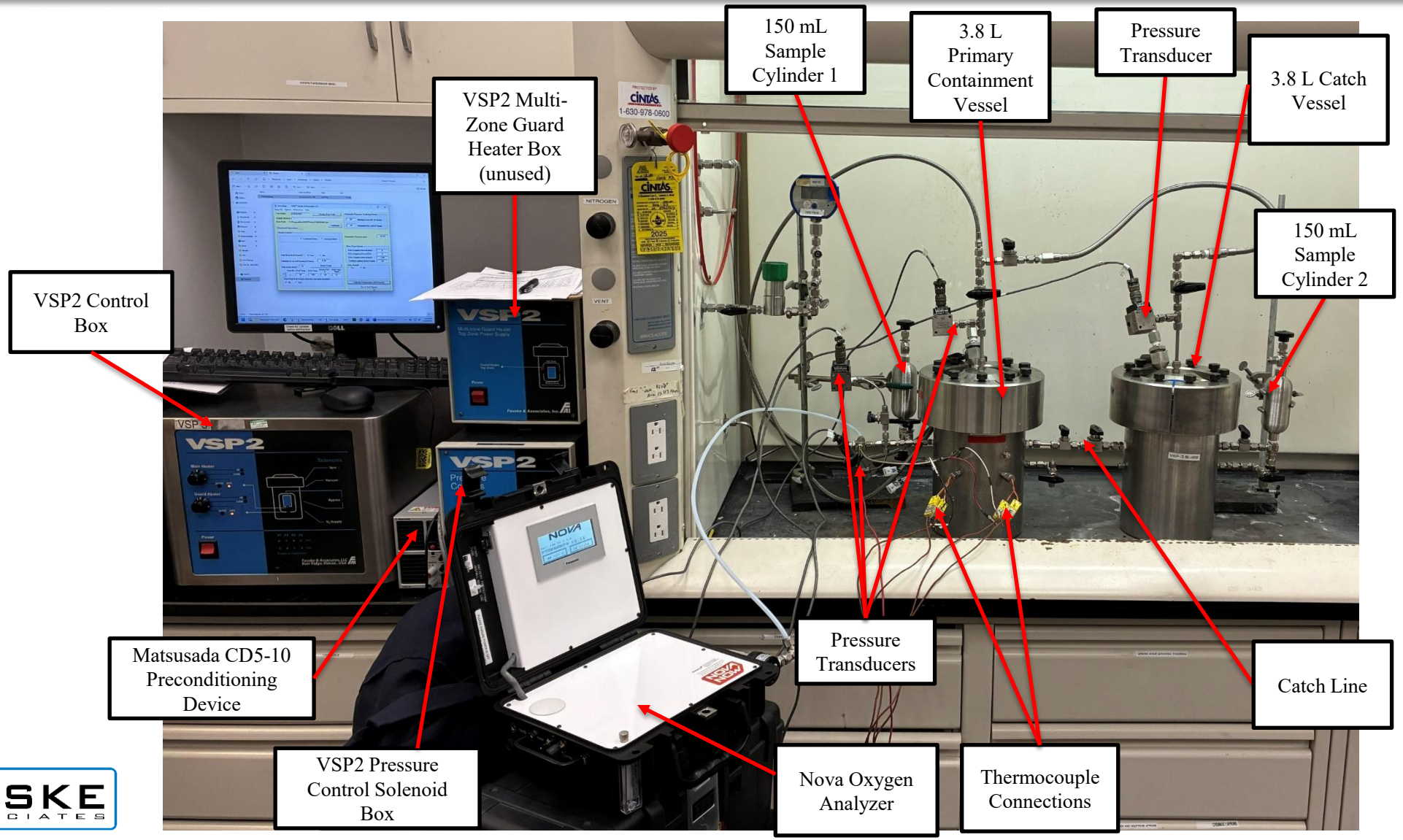
- 4 L Primary Containment Vessel connected to 4 L Catch Vessel to relieve overpressure from runaway
- Split range pressure transducers to improve precision during cell vent (2000 psig vs. 125 psig)

General Procedure:

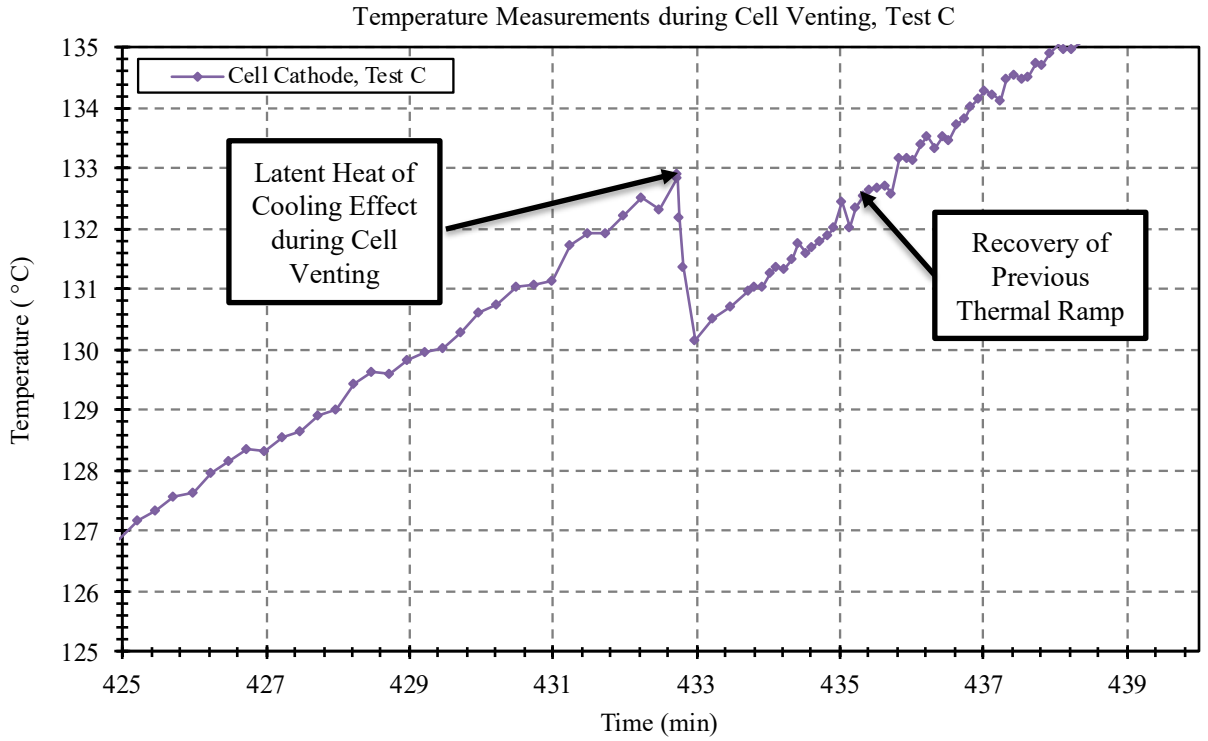
- LG INR18650 MJ1 cell heated in test can at ~0.3°C/min
  - Test can isolated prior to cell venting
  - Reduced volume of evolved gas increased precision of pressure measurements
- Following cell venting, test can was opened to catch vessel, then the cell was heated to runaway
- One gas sample taken at cell vent, one taken after runaway

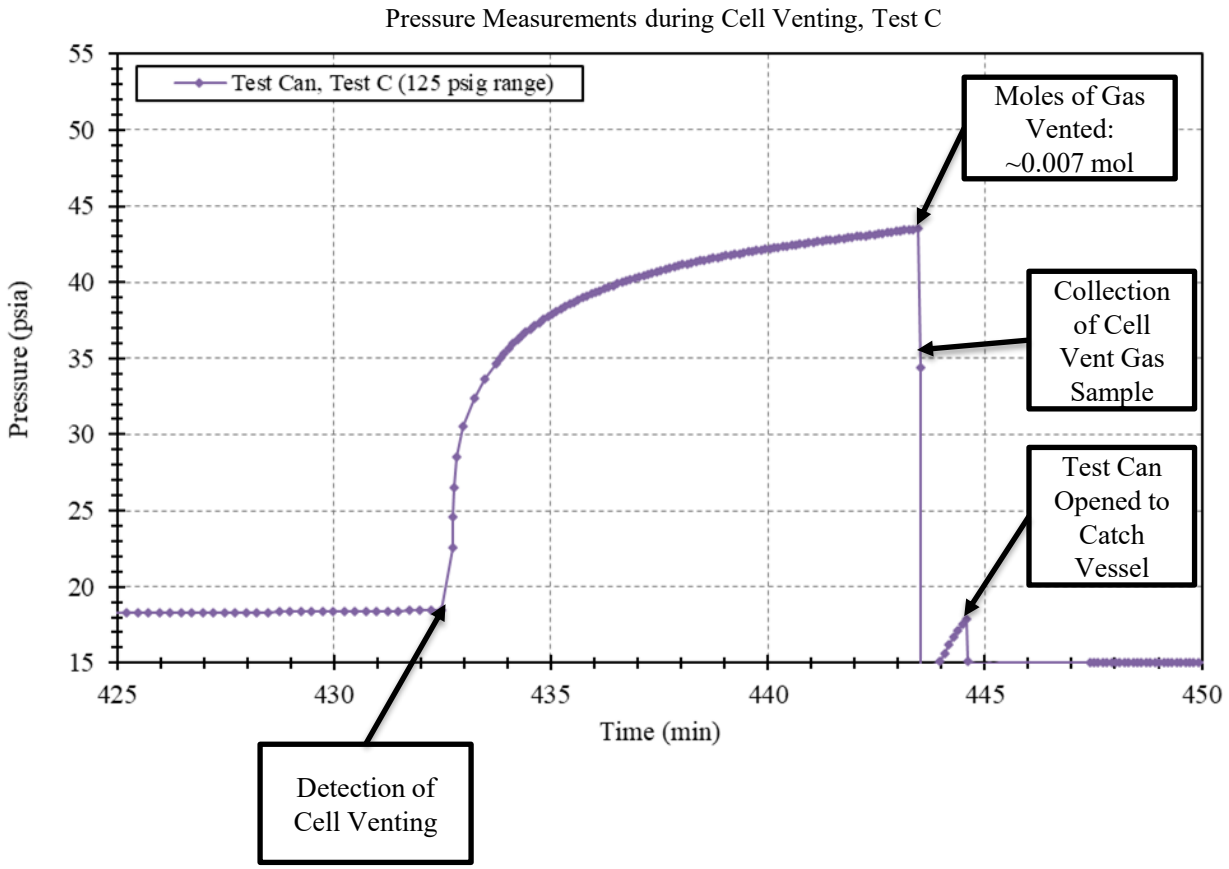


Thermal Abuse of 18650 in 4L Vessel – Test C Setup

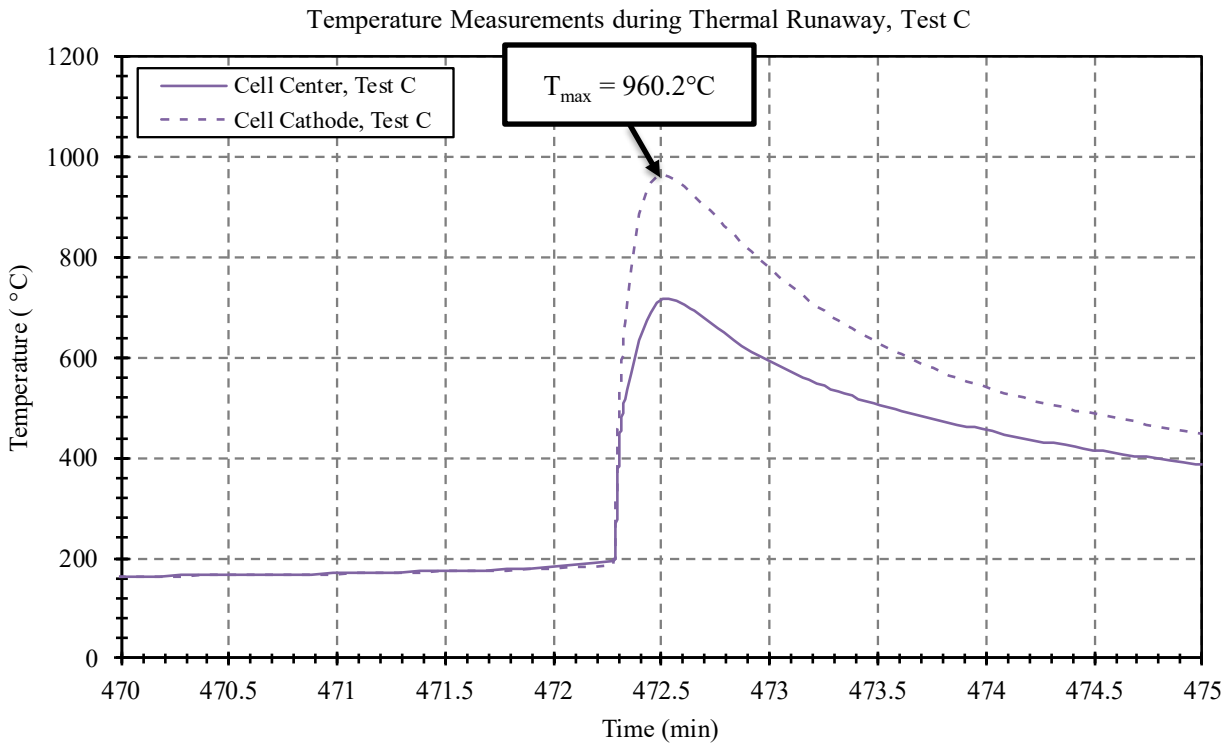


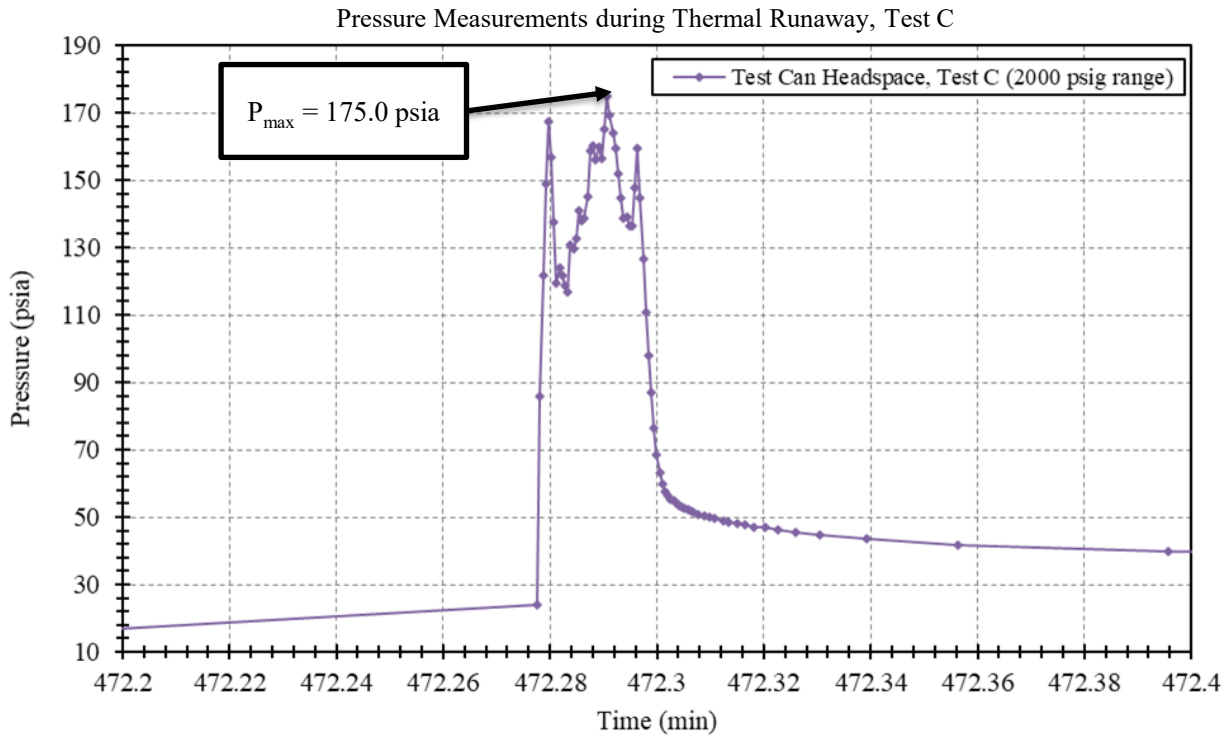
Thermal Abuse of 18650 in 4L Vessel – Cell Vent Behavior



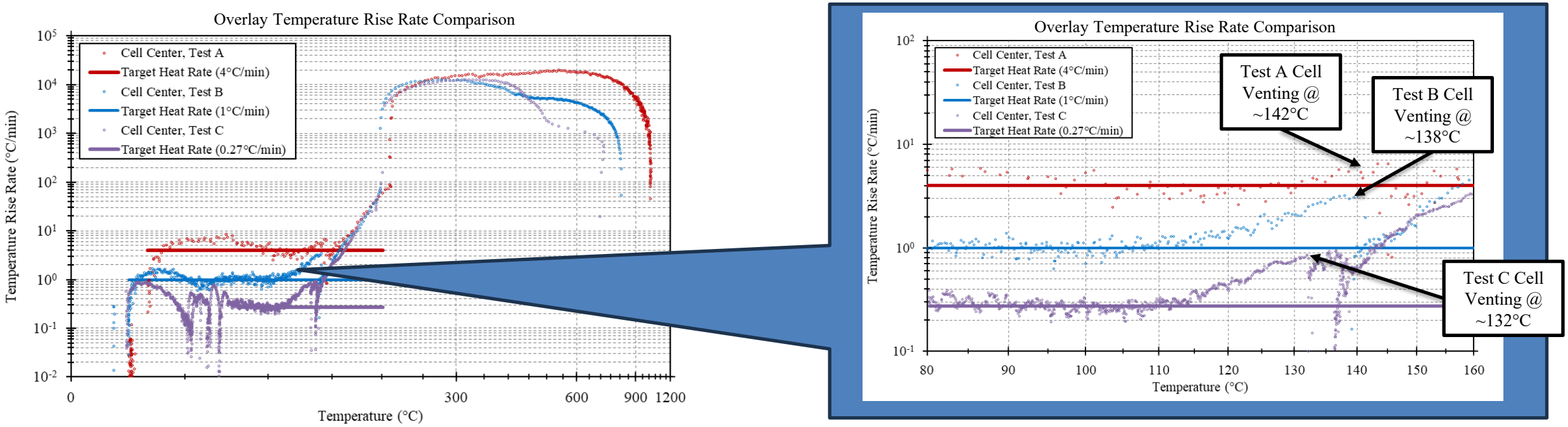


Thermal Abuse of 18650 in 4L Vessel – Thermal Runaway





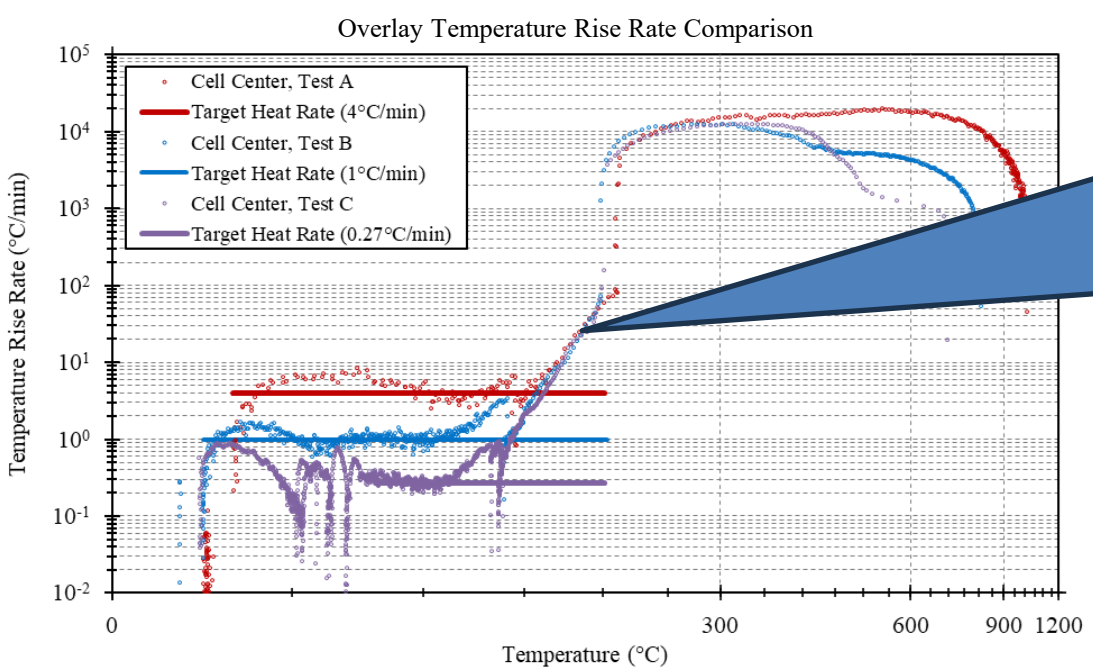
Thermal Abuse of 18650 in 4L Vessel – Temperature Rise Rates

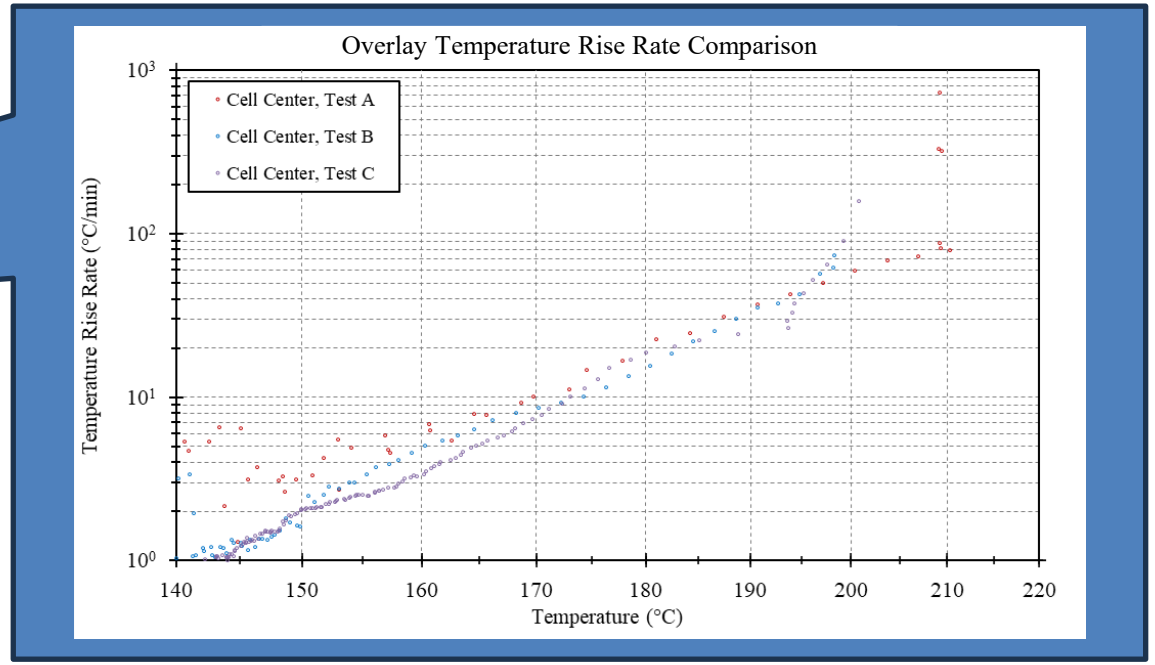


Trends:

- Lower ramp rate allows for lower detection of self-heating by VSP2
- Cell vent temperature decreases with lower thermal ramp rate
- Arrhenius-like kinetics prior to cell-vent

Thermal Abuse of 18650 in 4L Vessel – Temperature Rise Rates

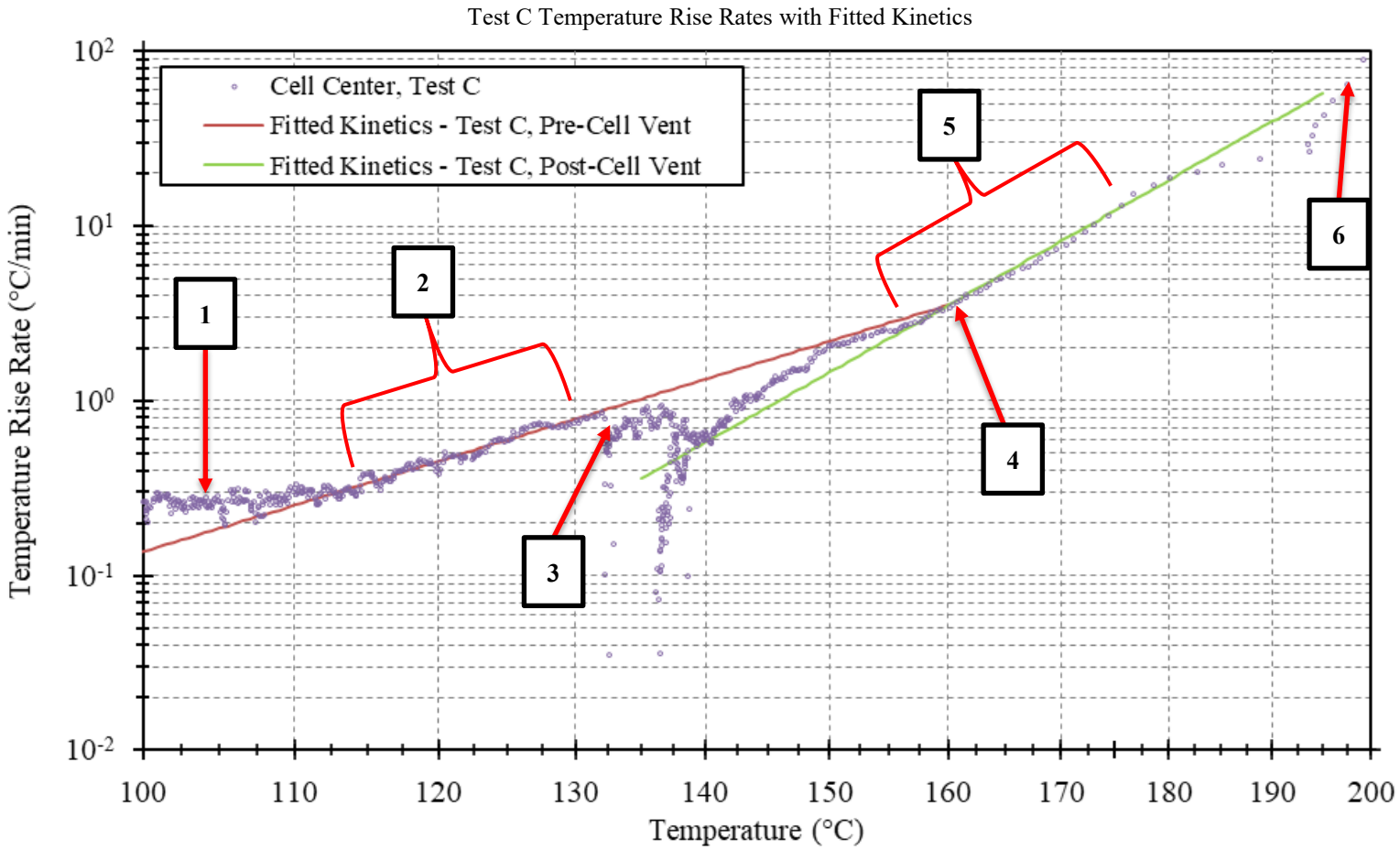




Trends:

- Similar Arrhenius-like kinetics following cell vent until ~170-180°C
  - PVDF separator material fully melts at ~170°C
- Regression of kinetics allows for estimation of time to maximum rate (TMR)
- Possible differences in kinetics based on headspace (N2, He, etc.)

Thermal Abuse of 18650 in 4L Vessel – Analysis



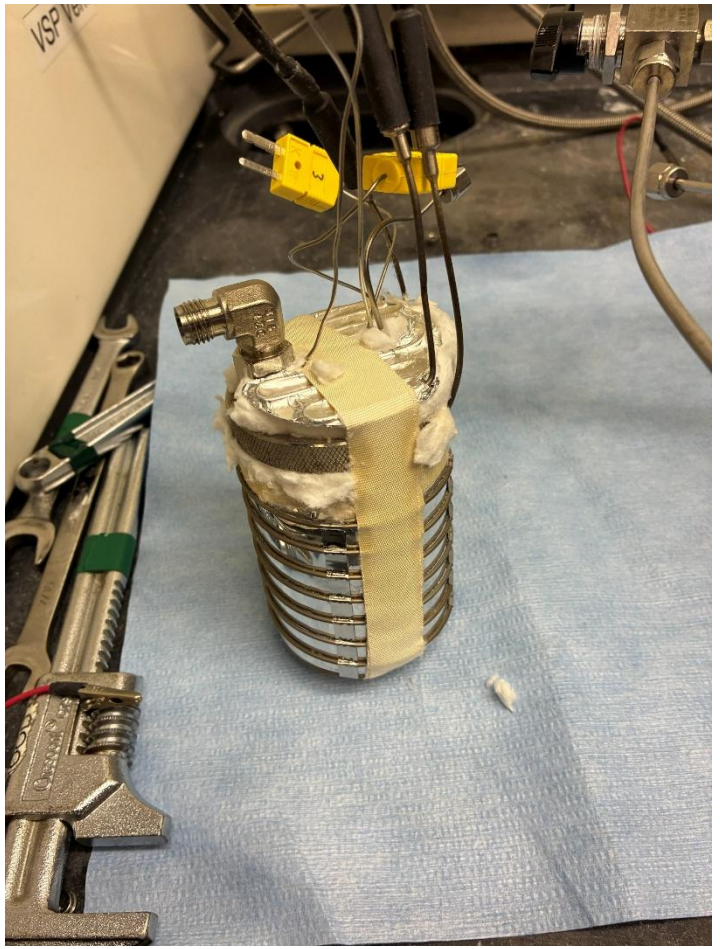
$$\frac{dT}{dt} = Ae^{-\frac{B}{T}}$$

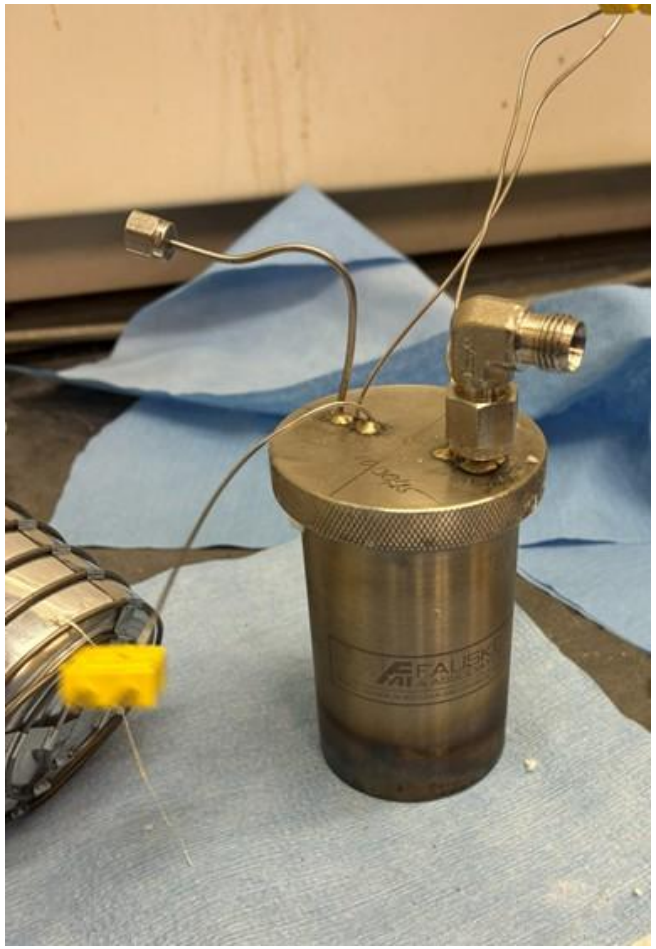
A = Pre-exponential factor $(\frac{\mathrm{K}}{\mathrm{min}})$

B = Activation Temperature (K)

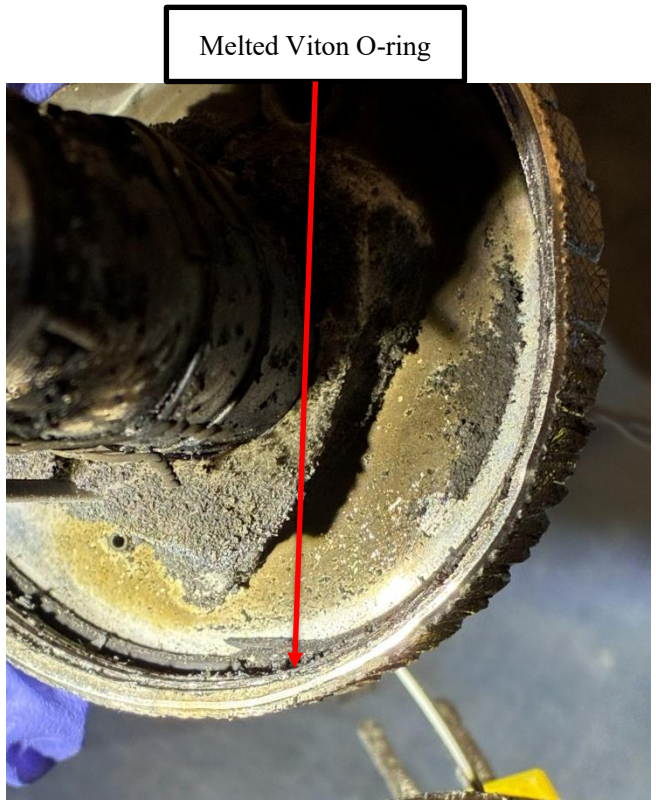
1. Baseline Heating Rate (~0.27°C/min)
2. Pre-vent zero-order kinetics fitted to data from 115°C to 130°C
3. Temperature rise rates fall to zero at cell vent (~132°C)
4. Lower heating rate reveals that pre-vent kinetics dominate until onset of separator melt (~150°C)
5. Post-vent zero-order kinetics fitted to data from 155°C to 175°C
6. Peak runaway reaction following separator melt

Thermal Abuse of 18650 in 4L Vessel – Post-Test Photographs

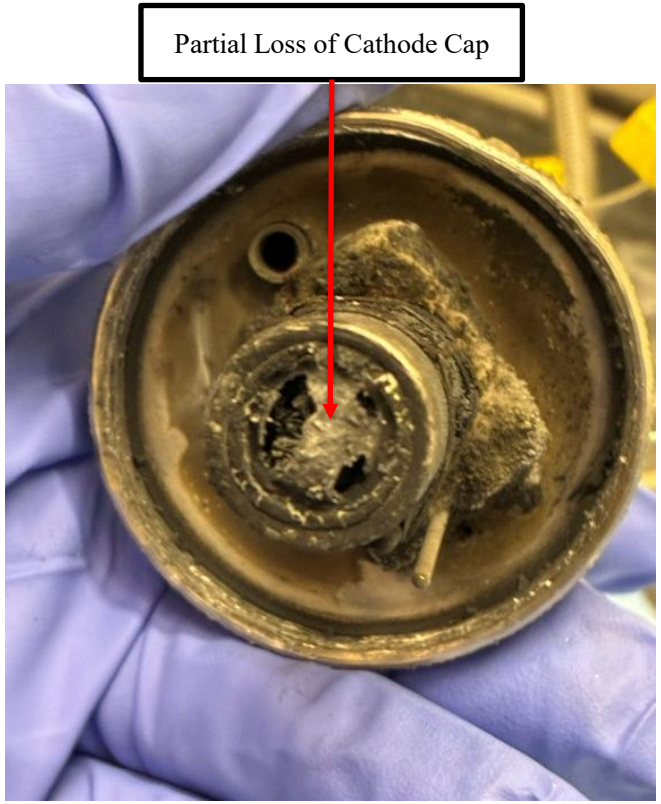




Thermal Abuse of 18650 in 4L Vessel – Post-Test Photographs



Test Can Lid
(Bottom View)

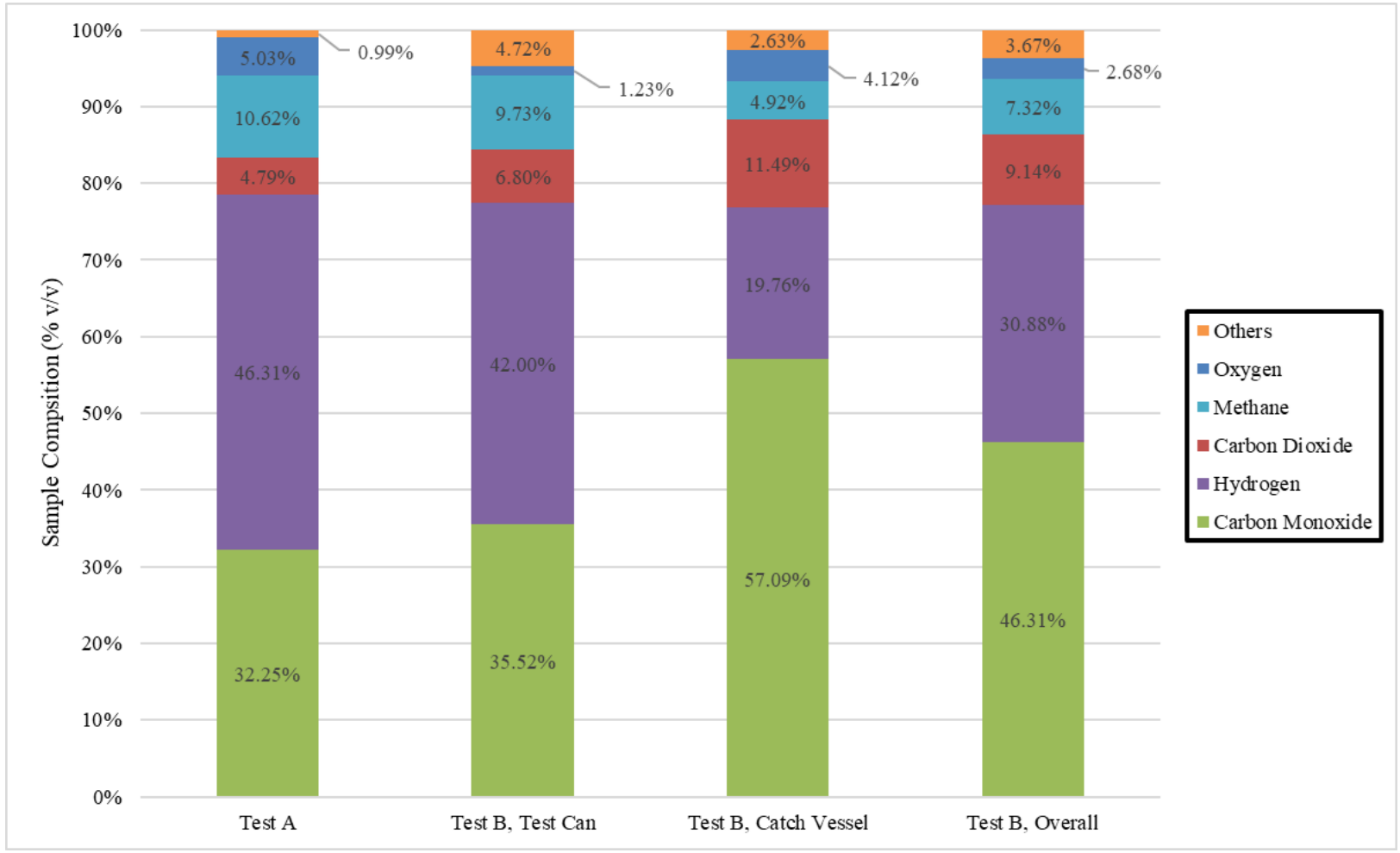


Test Can Lid
(Bottom View)

Test Can Body
(from Above)

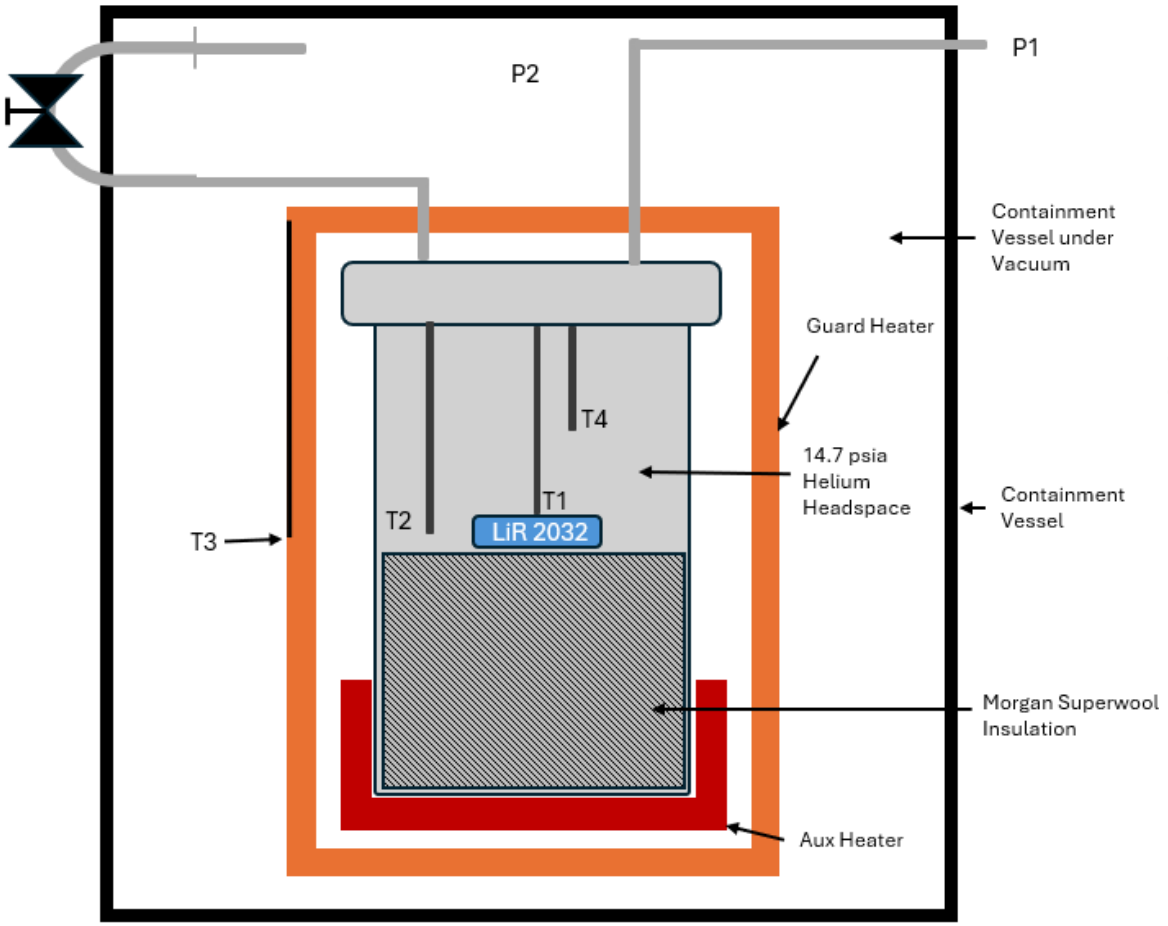
Catch Vessel
(from Above)

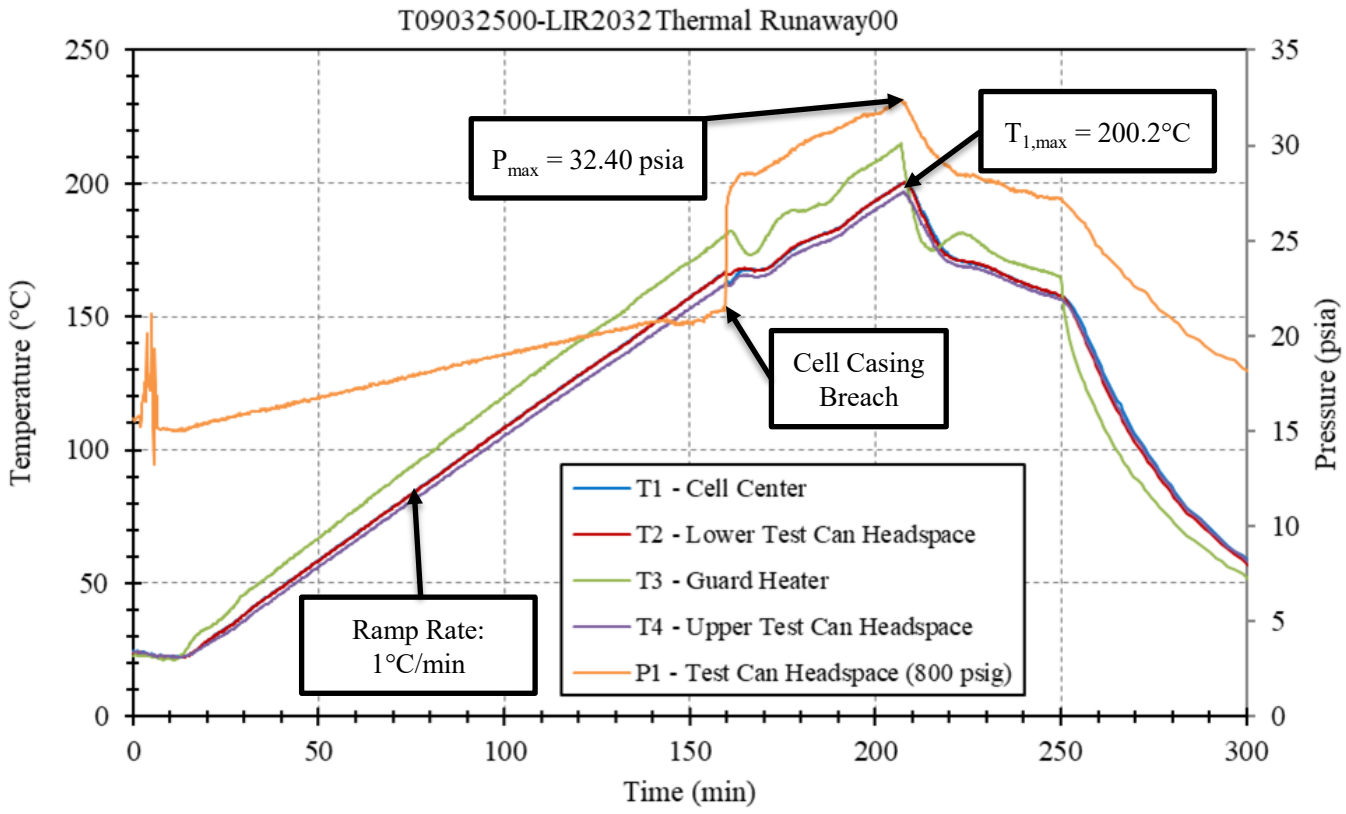
Thermal Abuse of 18650 in 4L Vessel – Gas Sample Analysis



Case Study: Thermal Abuse of Coin Cells

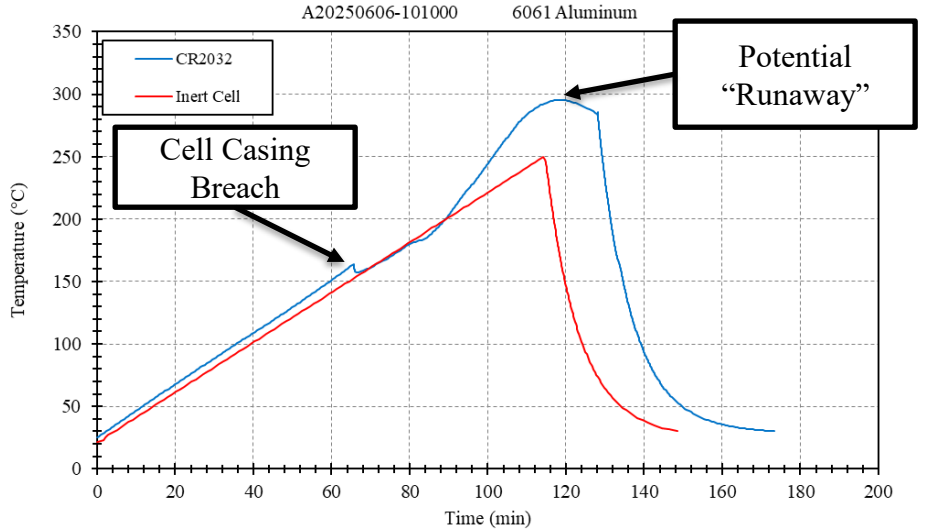
Thermal Abuse of Coin Cells in the VSP2

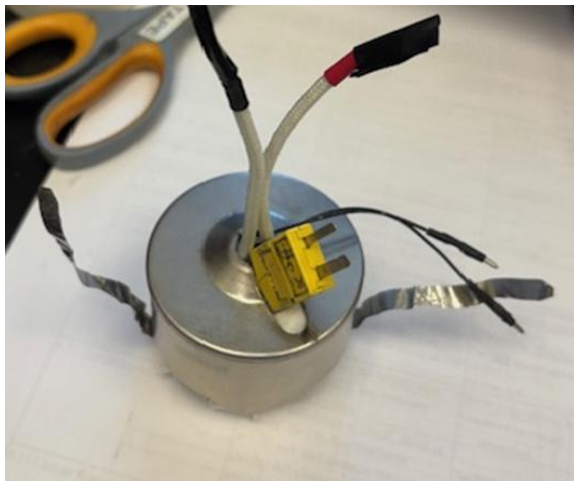




Thermal Abuse of Coin Cells in the ARSST

- Developed heating polynomials using aluminum “dummy” cells
- Cell Assembly:
  - Single thermocouple
  - Standard ARSST heater
  - Secured with cloth electrical tape
  - Packed with insulation in stainless steel sheath
- *In situ* preconditioning with Matsusada CD5-10
- Testing:
  - Thermal ramp using polynomial or PID mode
  - Monitor temperature, pressure, voltage during thermal abuse
  - Much less violent reaction than with larger-scale cells





Summary

- The Vent Sizing Package 2 (VSP2) is an extremely versatile tool for battery testing
- Current extensions to the VSP2 system include:
  - *In situ* cell conditioning and voltage monitoring
  - Various methods of abuse (Thermal, Mechanical, Electrical)
  - Collection, analysis, and flammability testing of cell vent and thermal runaway gas
  - Video recording of cell-level abuse testing
  - Testing in standard 4L vessel with custom test can, standard heating equipment
- These testing capabilities continue to expand with both the VSP2 and ARSST
- FAI currently offers custom battery testing services and is developing an upgraded solution to enable VSP2 users to perform these tests in the future

Questions? Contact Us!

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