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Effect of Cell State-of-Charge on Outcome of Internal Cell Faults: Preliminary Report

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Purpose of Testing

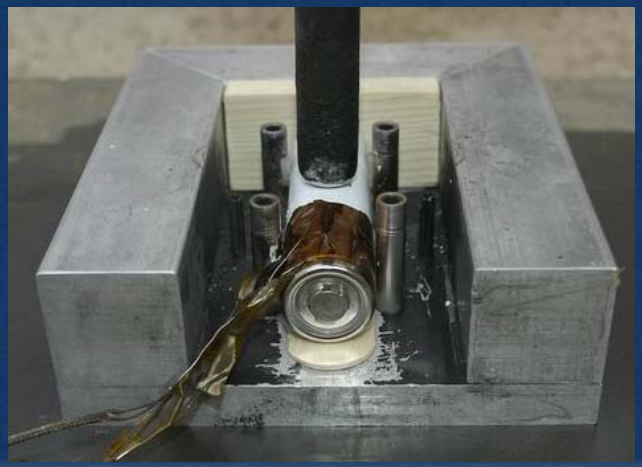
- Examine the effect of cell state-of-charge (SOC) on the outcome of a low impedance internal cell fault
- SOC is the charge level of a battery cell divided by its charge capacity
  - The higher the SOC, the more energy available for release by an internal cell fault for comparable capacity cells. Higher energy release increases the probability of severe outcomes:
    - Fire
    - Energetic disassembly
  - For a given cell, the nature of the internal cell fault will determine the initial rate of energy release and potentially the severity of outcome

Purpose of Testing (cont)

- An internal cell fault could result from several causes, including:
  - Mechanical damage
  - External overheating
  - Overcharging or other charging anomalies
  - Charge cycling a cell with a manufacturing defect

General Test Methodology

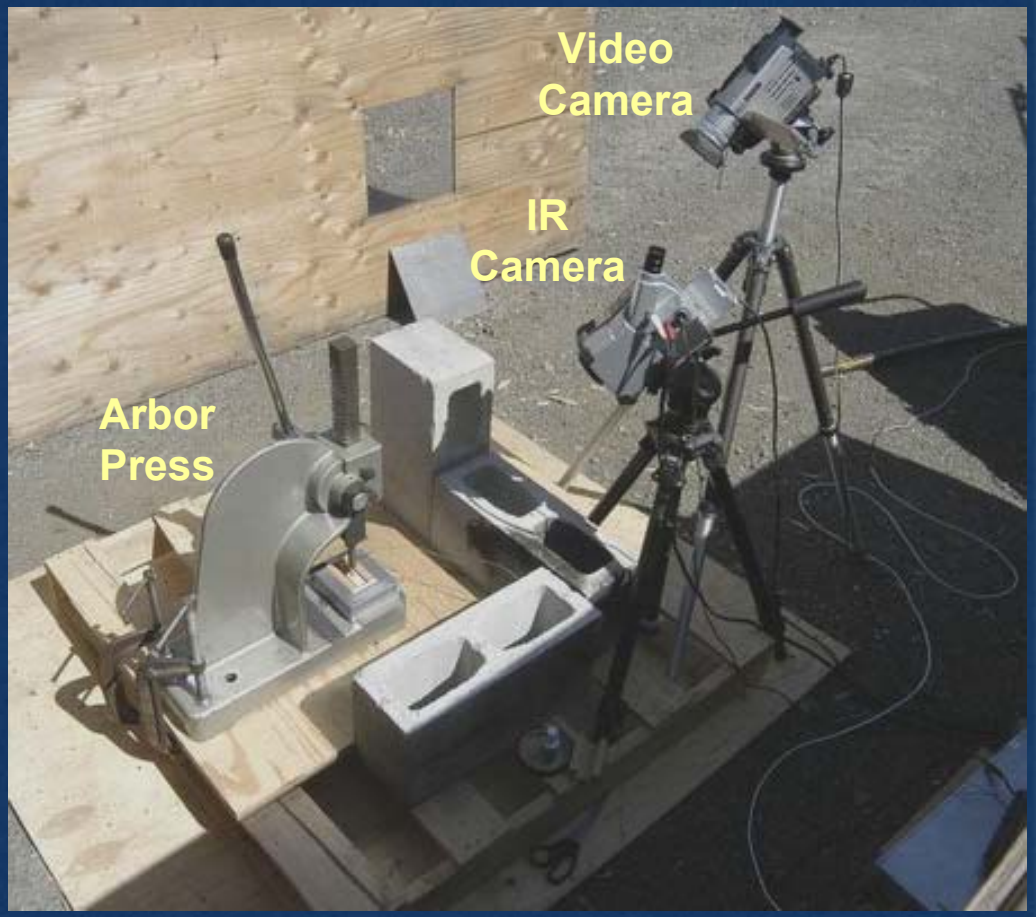
- Induce low impedance internal cell fault in controlled and repeatable manner
  - Crush cell with arbor press*
    - Cell crush represents severe abuse conditions resulting in
      - Multiple low impedance shorts
      - Potential for rapid energy release
    - Provides a method to explore cell behavior during high discharge rate internal cell faults



* General approach described in IEEE 17th Annual Battery Conference on Applications and Advances paper "On the Testing Method of Simulating a Cell Internal Short Circuit for Lithium Ion Batteries" by J.Loud, S.Nilsson, and Y.Du, Long Beach 2002.

Test Setup and Instrumentation

- Cell temperature measurements
  - Thermocouples on cell surface near crush zone
  - Infrared (IR) camera measures cell temperatures (surface painted white to allow accurate readings)
- IR data correlates to localized thermocouple measurements



Crush Profile

- To initiate a severe internal cell fault
  - Crush must be aggressive enough to create low impedance shorting within cell
    - Goal is to induce an “internal short” condition leading to thermal runaway
      - Cell heating (temperature rises to >100 °C)
      - Rise in internal pressure
  - Crush must not be so aggressive that it cracks the cell case
    - A case crack would act as a secondary cell vent
    - A case crack would reduce severity of outcome
    - Tests where the case cracks during crushing should not be directly compared to tests where case integrity has been maintained

Crush Profile

- Cell designs vary between manufacturers and brands
  - Thickness of case wall
  - Ductility of case material
  - Rigidity of cell windings (“jelly roll”)
- Preliminary testing showed
  - Any single crush profile (force or depth) has limitations
    - Might induce low impedance shorts in cells by some manufacturers, while not inducing them in others.
    - Might induce low impedance shorts in all cells, but also cause case cracks with a particular cell design

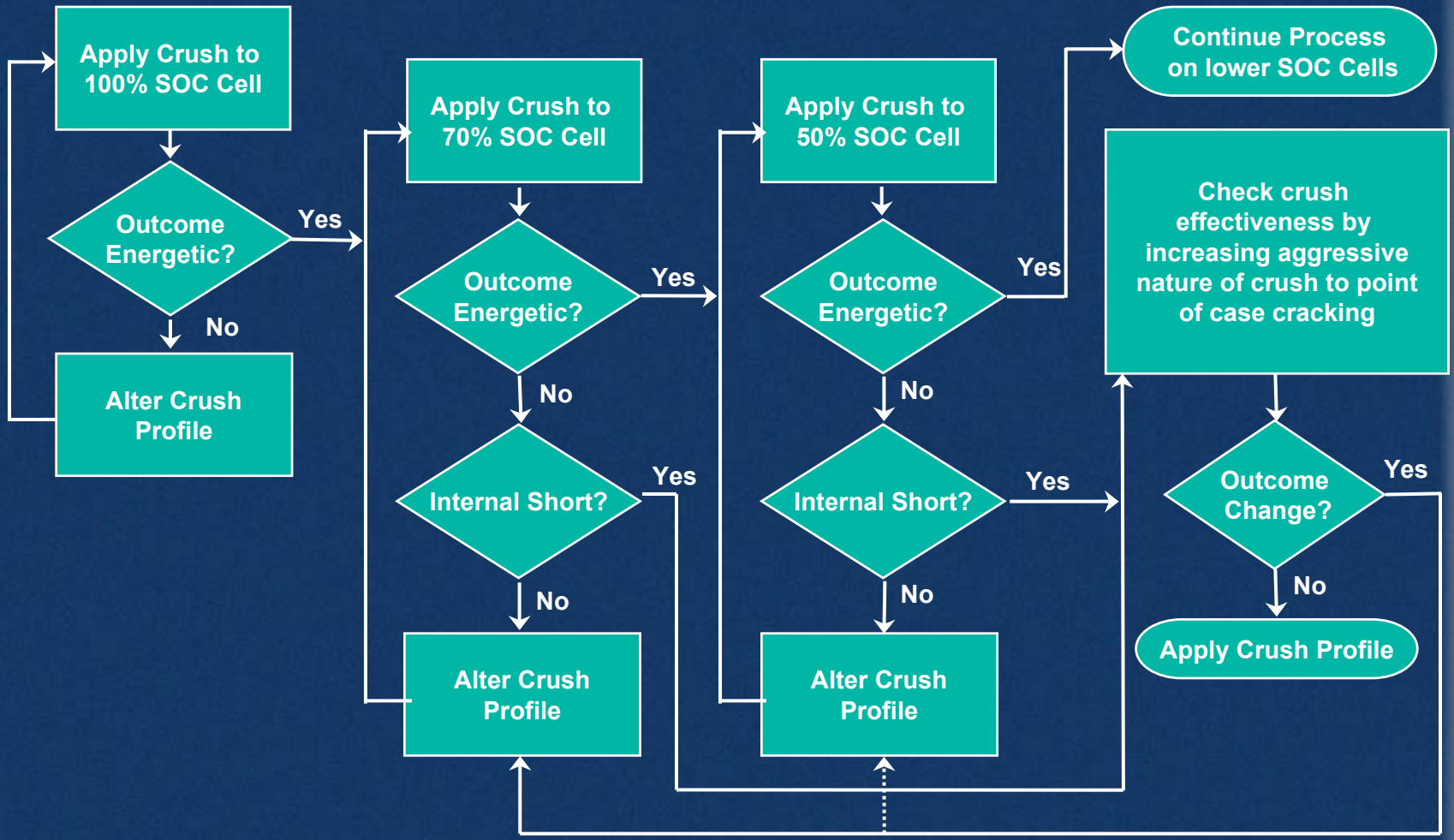
Crush Profile

- Preliminary testing showed
  - Crush profile can be tailored on a per brand or manufacturer basis to induce internal short by causing low impedance shorting with cracking the case
    - Increase crush aggressiveness until internal short achieved
    - Stop just short of causing case cracking
    - If internal short not achievable without also causing case cracking, try a multi-pulse crush

Crush Profile

- Crush tests that consistently achieve a low impedance cell fault have the following advantages
  - Allow direct comparison of different test cell brands or manufacturers
  - Allow for varying states-of-charge and difference capacities
  - Allow for estimating the performance of other lithium-ion cells with similar energy densities and technologies

Crush Profile Determination



Note: An energetic outcome includes fire or energetic disassembly.

Cells Used in Testing

- State of the art (at the time of testing) 18650 style cells were obtained from three manufacturers
- 5 Cells per manufacturer were measured to verify cell capacity

Manufacturer Identification Color Code	Nominal Rated Capacity	Measured Capacity
A (Orange)	2.10 Ah	2.16 Ah ± 1.5%
B (Green)	2.20 Ah	2.16 Ah ± 2.0%
C (Blue)	2.15 Ah	2.15 Ah ± 1.5%

Manufacturer Cell Capacity Evaluation

- Capacity variation determined before discharging to selected SOC
  - 5 cells per manufacturer were charged to 4.2 V and discharged through a calibrated resistor to 3.0 V while recording voltage, current, temperature, and time
    - Nominal capacities were within 3% of manufacturer specifications
    - Cell-to-cell capacity within brand varied 3-4%
- The SOC was set by discharging at 0.75 C
  - The 0.75 C rate was calculated using the specified cell capacities
  - 1 C is the constant discharge current that drains the nominal cell capacity in 60 min.
  - 0.75 C drains a fully charged cell in 80 min.

Setting SOC

- Nominal capacities for the three manufacturers are 2.10, 2.15, and 2.20 Ah
- Charging to 4.2 V (100% SOC)
- Discharging from 100% SOC with a constant 0.75 C across a dynamic load for a pre-determined period of time to reach lower SOCs

SOC [%]	Discharge time [min]
100 → 100	0
100 → 70	24.0
100 → 50	40.0
100 → 40	48.0
100 → 30	56.0

Observed Crush Outcomes

- Observed crush outcomes have been classified into four categories, listed in decreasing order of severity
  - Fire: a “Severe” outcome
  - Energetic Disassembly: a “Severe” outcome
  - Case Rupture: a “Moderate” outcome
  - Internal short: a “Minimum” outcome
- Characterization is based on the most severe result observed:
  - Though an internal short condition was induced in all cells, a particular test was labeled “internal short” only when it did not exhibit any of the other outcomes.
  - Though the incidence of fire is sometimes accompanied by an energetic disassembly, all tests that resulted in fire were included only in the “Fire” category

Fire Outcome

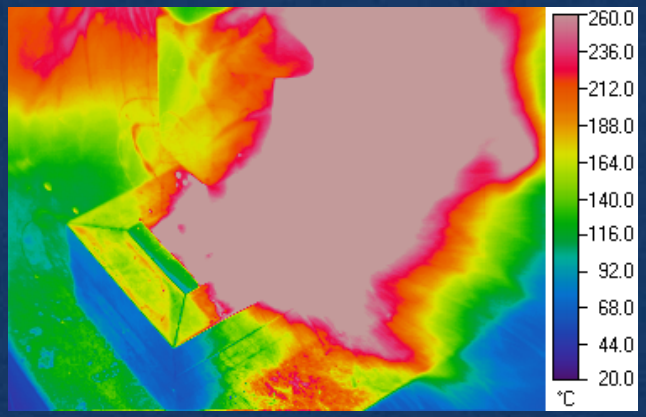
- Coincident with crush action
  - Appearance of flames
  - “Pop” or “hissing” sound
  - Cell may or may not disassemble or rupture
  - Rapid temperature rise immediately upon crush, on the order of 100 °C per second

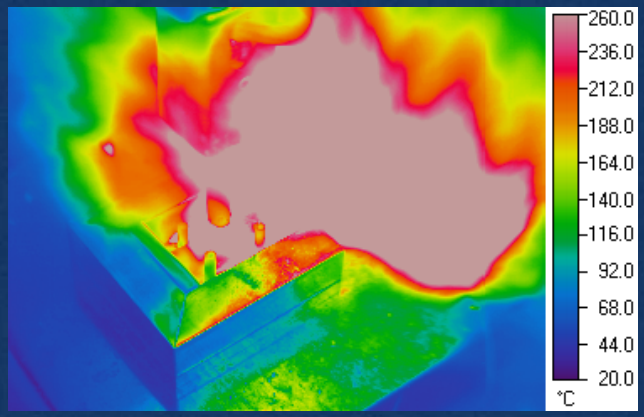
Fire with Case Rupture

Fire with Cell Venting

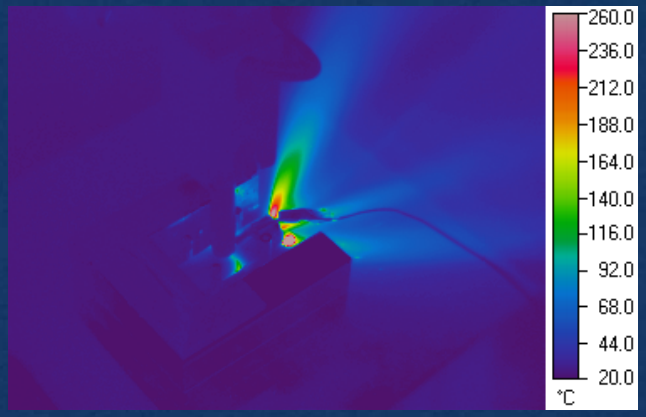
Fire with Energetic Disassembly

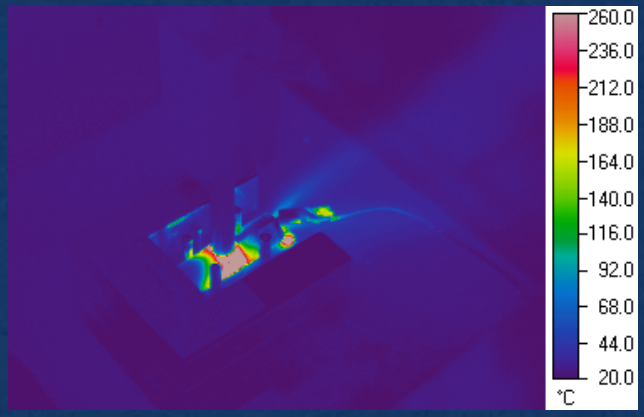
Fire Outcome





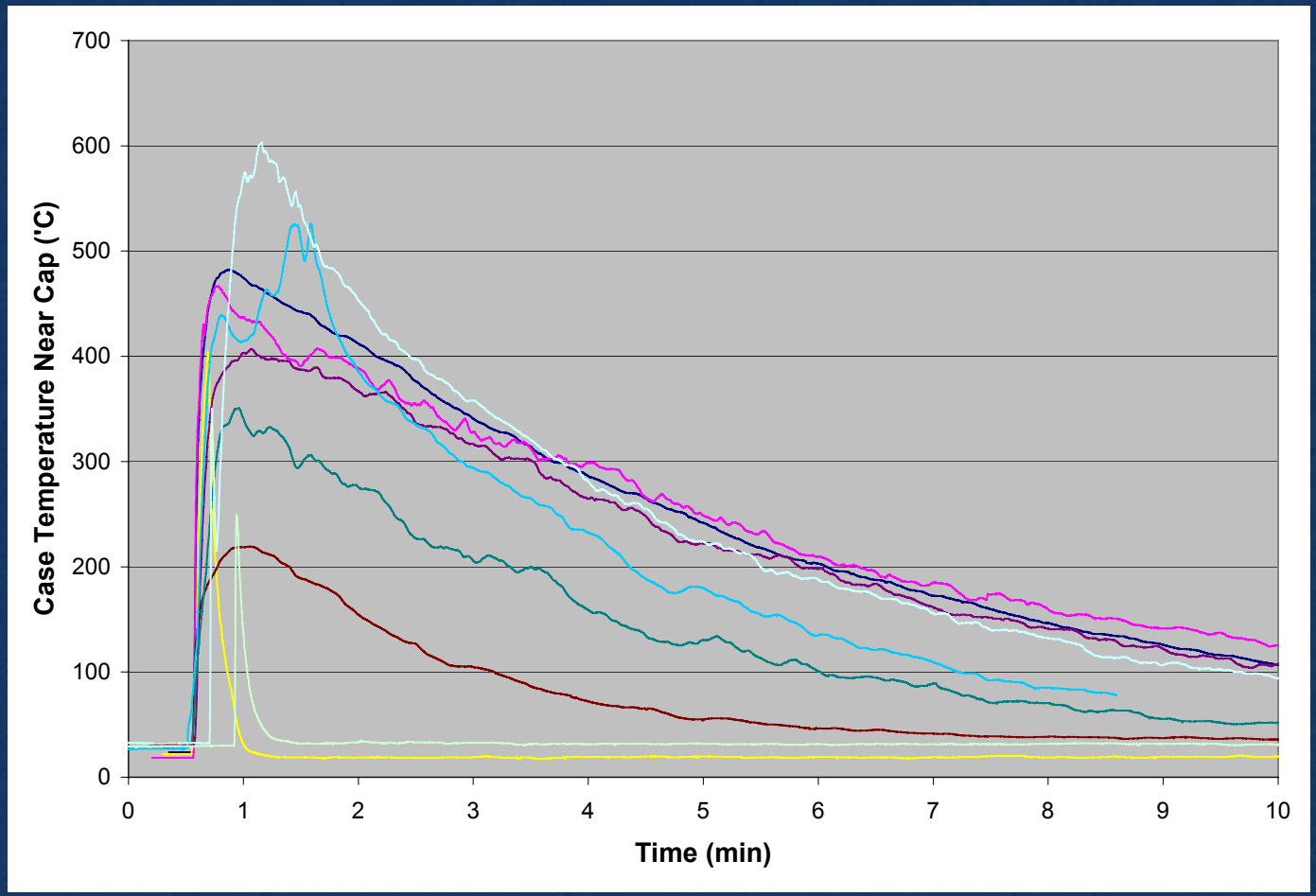
Example 1: 70% SOC, early stage (left), later stage (right)





Example 2: 70% SOC, early stage (left), later stage (right)

Fire Outcome

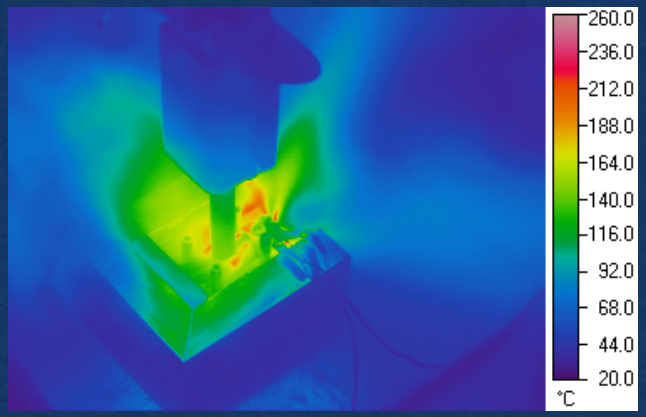


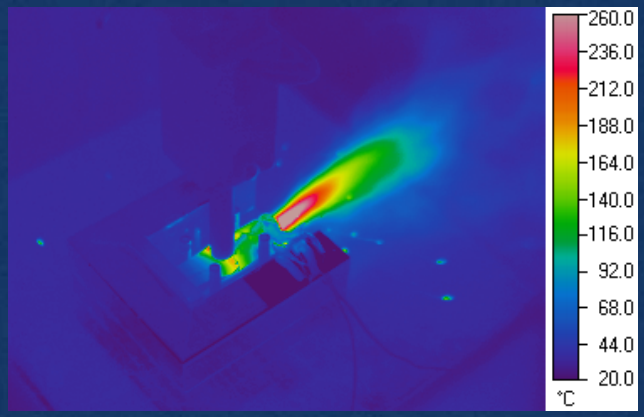
Thermocouple Data for nine 70% SOC cells

Energetic Disassembly Outcome

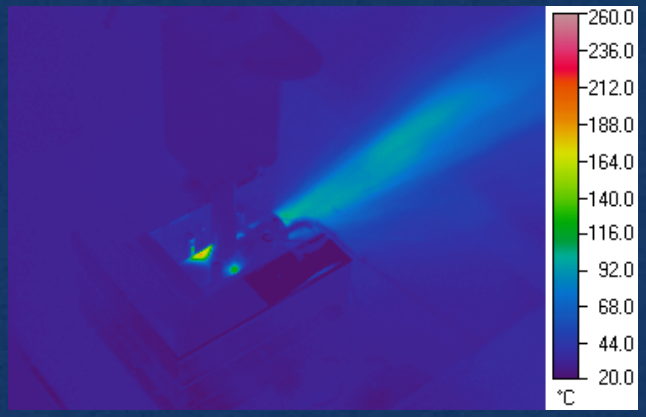
- **Coincident with crush:**
  - Loud “Pop” sound
  - Cell cap may be projected
  - Significant portion (~ 1/3 to 1/2) of jellyroll may be ejected
  - Local temperature rise similar to fire outcome for a short period
  - Temperature rise of remaining jellyroll similar to internal short

Energetic Disassembly Outcome



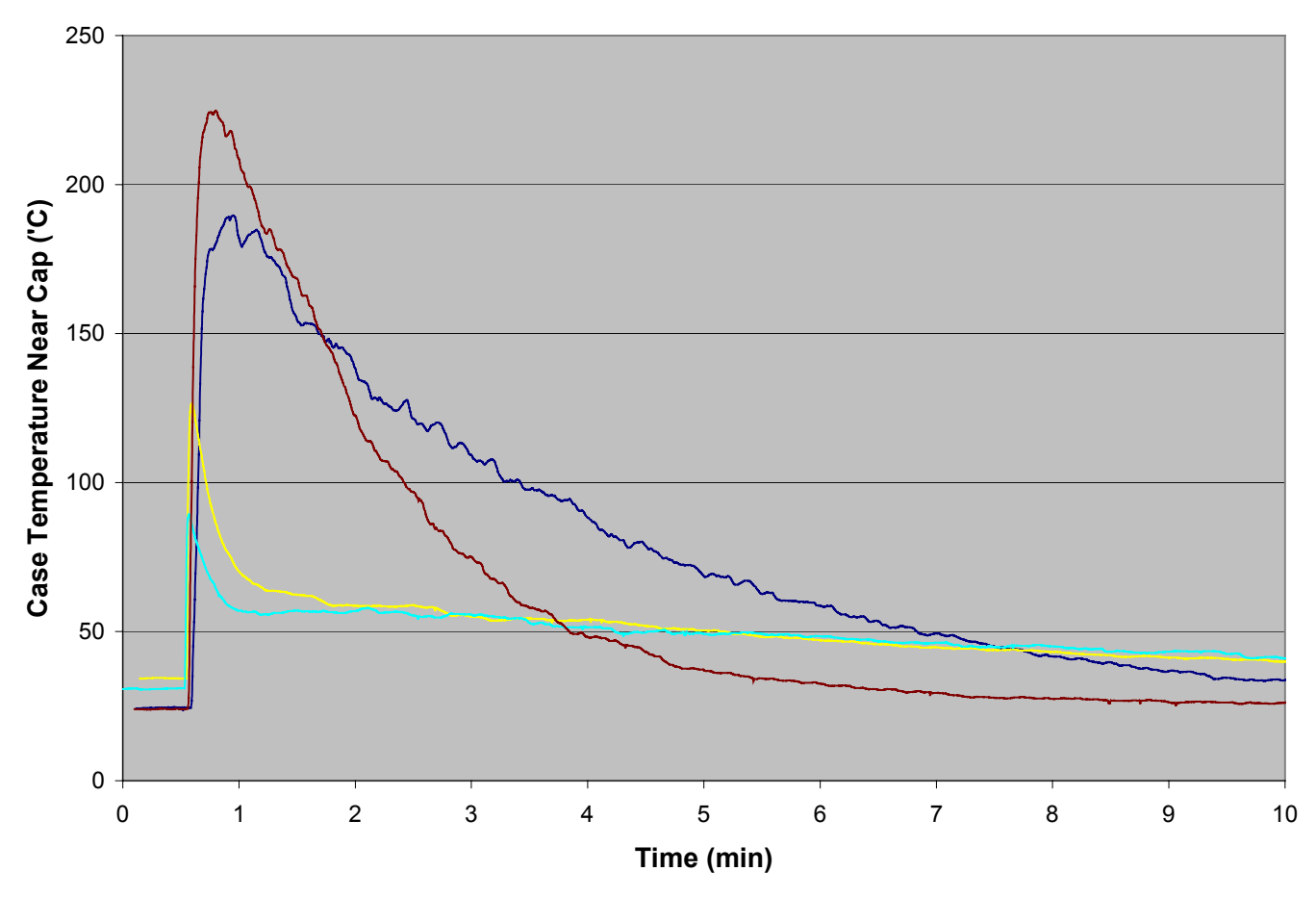


Example 1: 70% SOC, initial stage (left), ejection (right)



Example 2: 70% SOC, ejection (left), later stage (right)

Energetic Disassembly Outcome

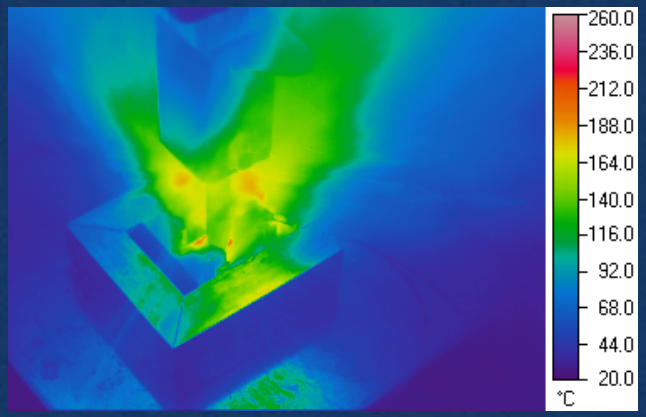


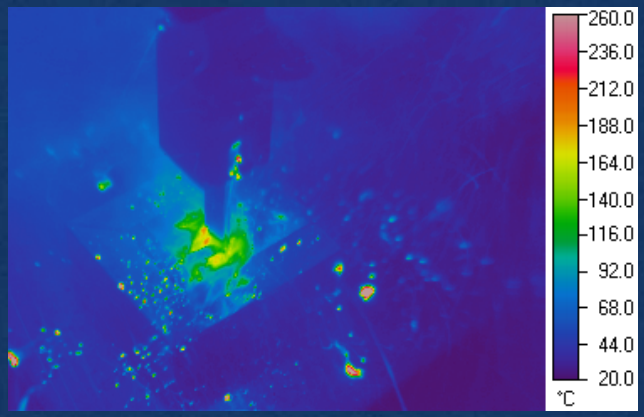
Thermocouple Data for three 70% SOC & one 100% SOC cells

Case Rupture Outcome

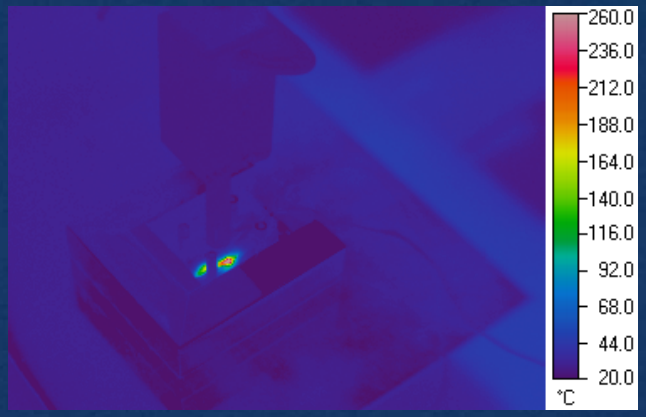
- Coincident with crush:
  - Loud “Pop” sound
  - Brief release of hot gases
  - Case ruptures along the side (fish-mouth opening created)
    - Bulk of jellyroll remains in place
    - Portions of exposed jellyroll windings expelled
    - Cap remains in place, vent activates
  - Case temperature maximum and rise rate similar to internal short outcome
- Case ruptures caused by overpressure during the internal short

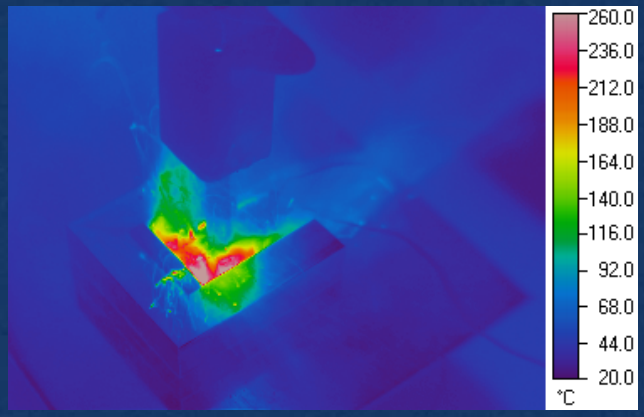
Case Rupture Outcome





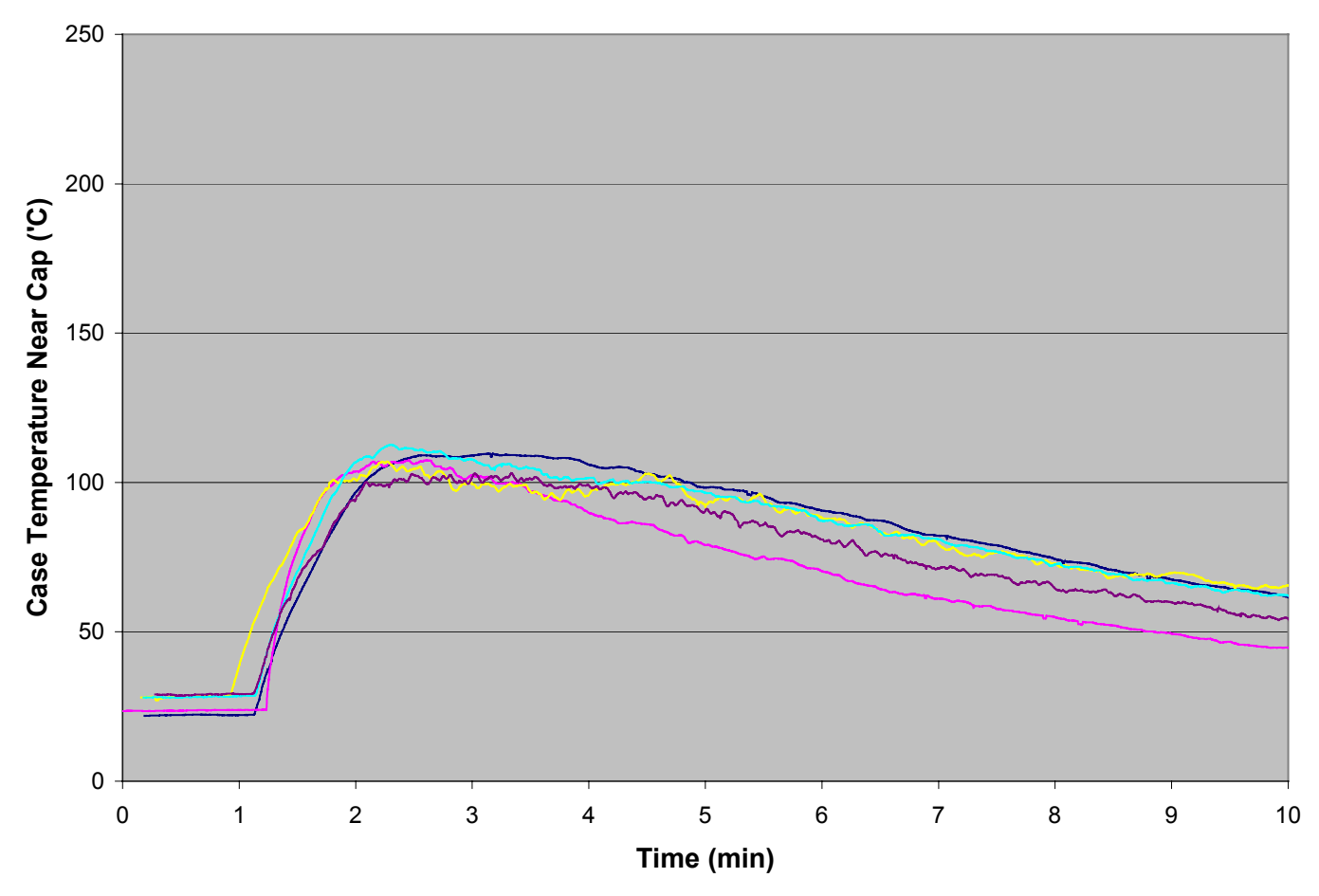
Example 1: 70% SOC, early stage (left), later stage (right)





Example 2: 50% SOC, early stage (left), later stage (right)

Case Rupture Outcome

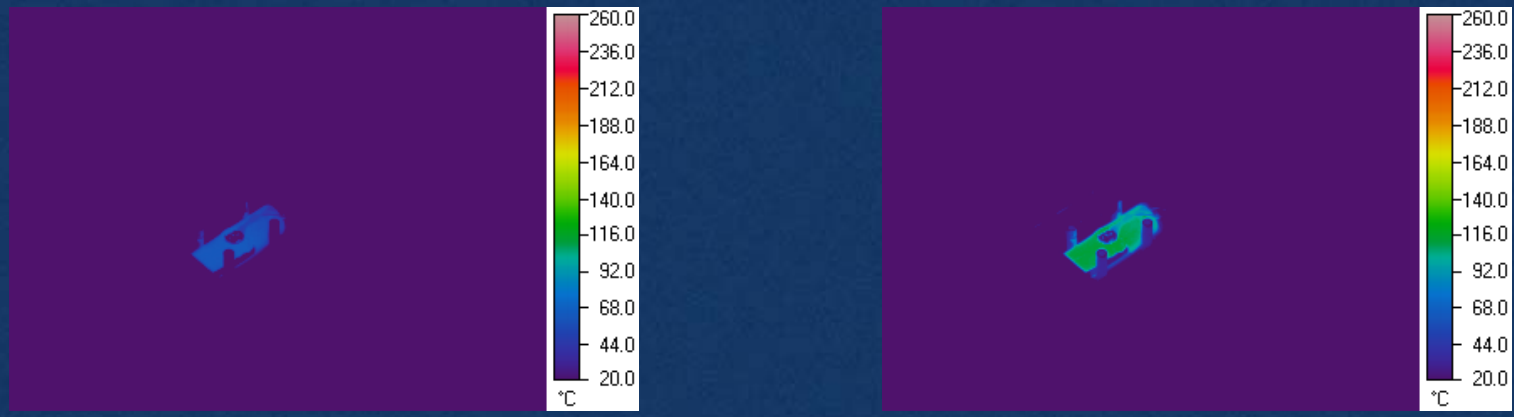


Thermocouple Data for one 50% SOC & four 70% SOC cells

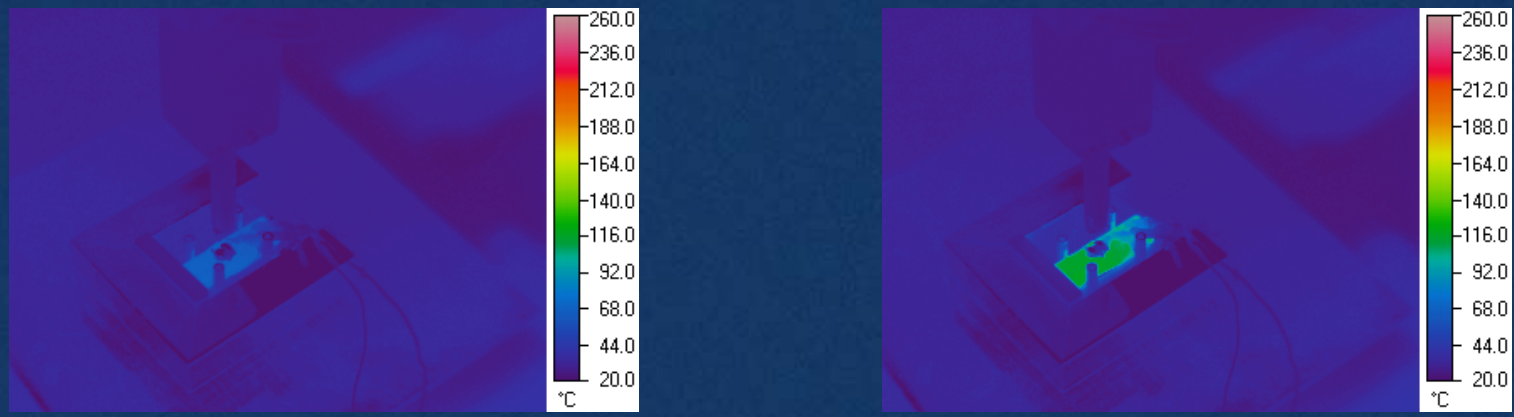
Internal Short Outcome

- Coincident with crush:
  - Soft or inaudible “pop” sound (vents activating)
  - Some designs contain up to three stages of vents
- After crush
  - Cell heating
    - To >100 °C, at a rate of approximately 70 °C/min
  - Electrolyte can be released through vent

Internal Short Outcome

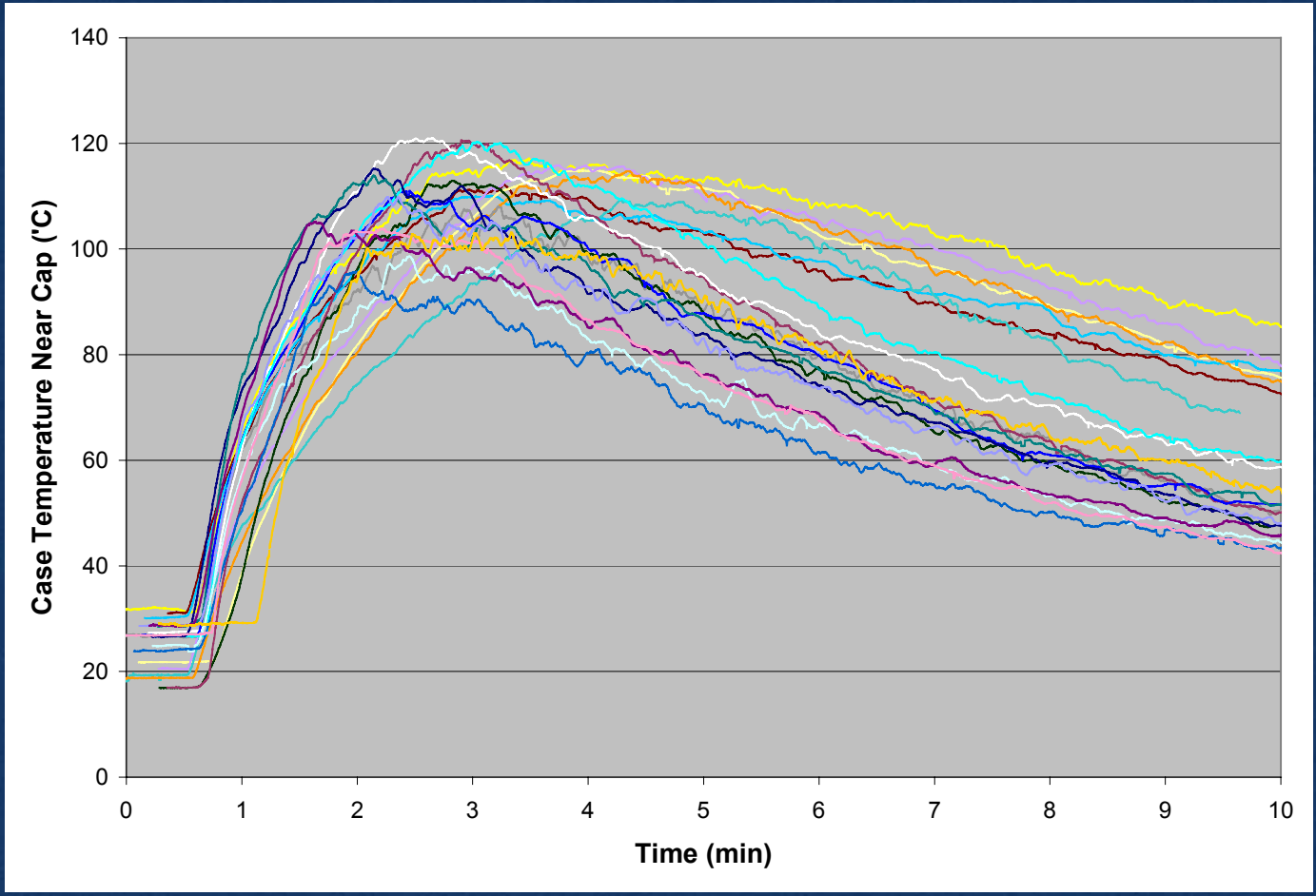


Example 1: 70% SOC, early stage (left), peak heating (right)



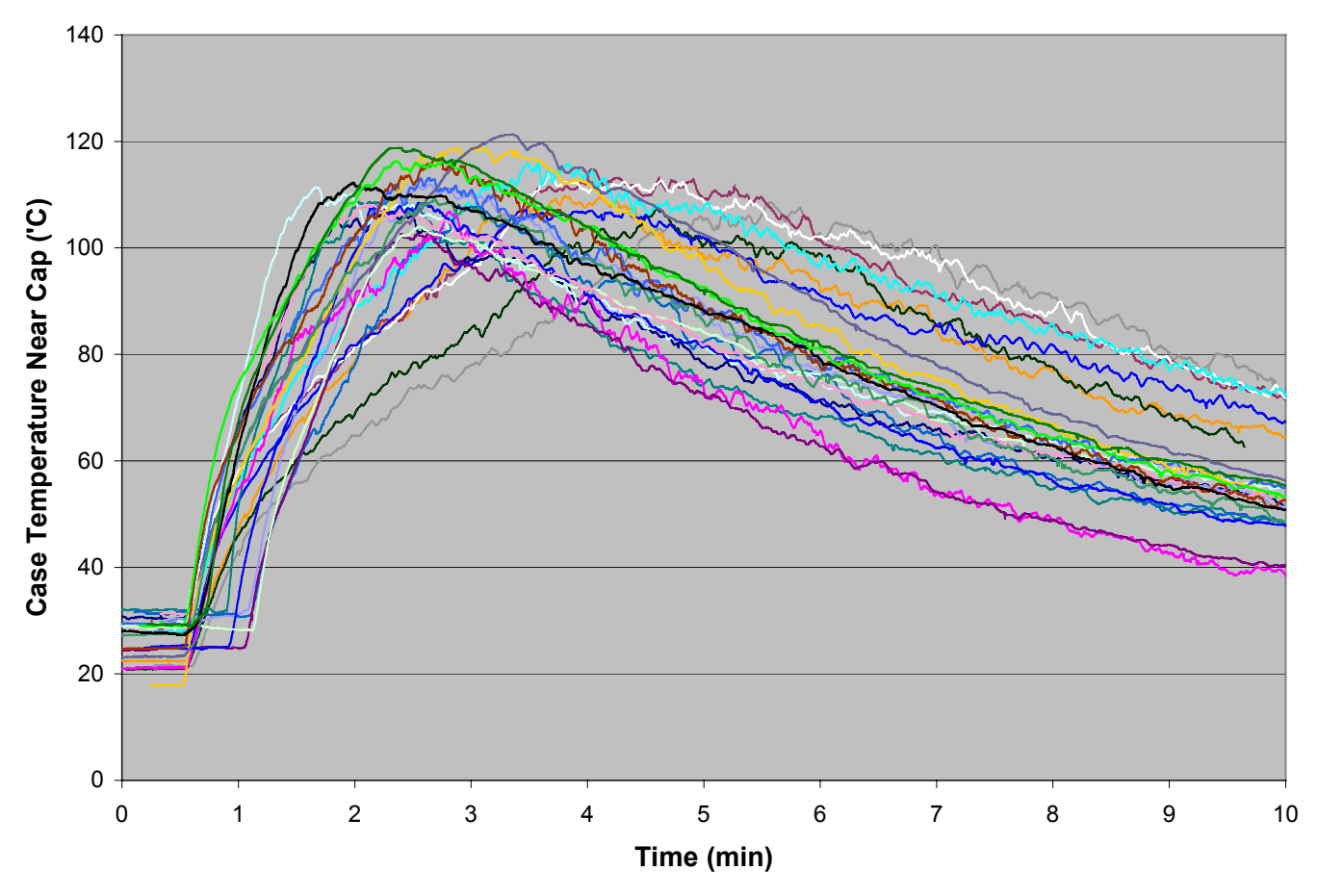
Example 2: 40% SOC, early stage (left), peak heating (right)

Internal Short Outcome



50% SOC Thermocouple Data

Internal Short Outcome



40% SOC Thermocouple Data

Raw Data in Order of Testing

Fire				**XXX (3)** **XXXXX (5)** **XXXX (4)**		*xxxxxx (6)* *xxxx (4)*
Energetic Disassembly				**XXXX (4)** *xx (2)* **X (1)**		*x (1)*
Case Rupture		**X (1)**		**XXX(3)**		
Internal Short	**XXXXXXXXX (9)** **XXXXXCC (7)** *xxxx (4)* **XXCXXCXXCX (10)**	**XXXXXCXXX (9)** **XXCXXXCX (8)** *xxx (3)* **CXXXXXXX (8)**		**X (1)** **CCCC (4)** *x (1)* **C (1)**		*xxc (3)*
High impedance internal short Temperature Rise < 70 C	*xc (2)*	*cxxxxx (6)*		*cxxcxx (6)*		*cxxc (4)*
SOC	**40%**	**50%**		**70%**		**100%**

'X' denotes individual crush test w/o case crack

'C' denotes individual crush test with case crack

Bold face denotes refined crush method

Italic/lower case denote preliminary crush method

Refined Data

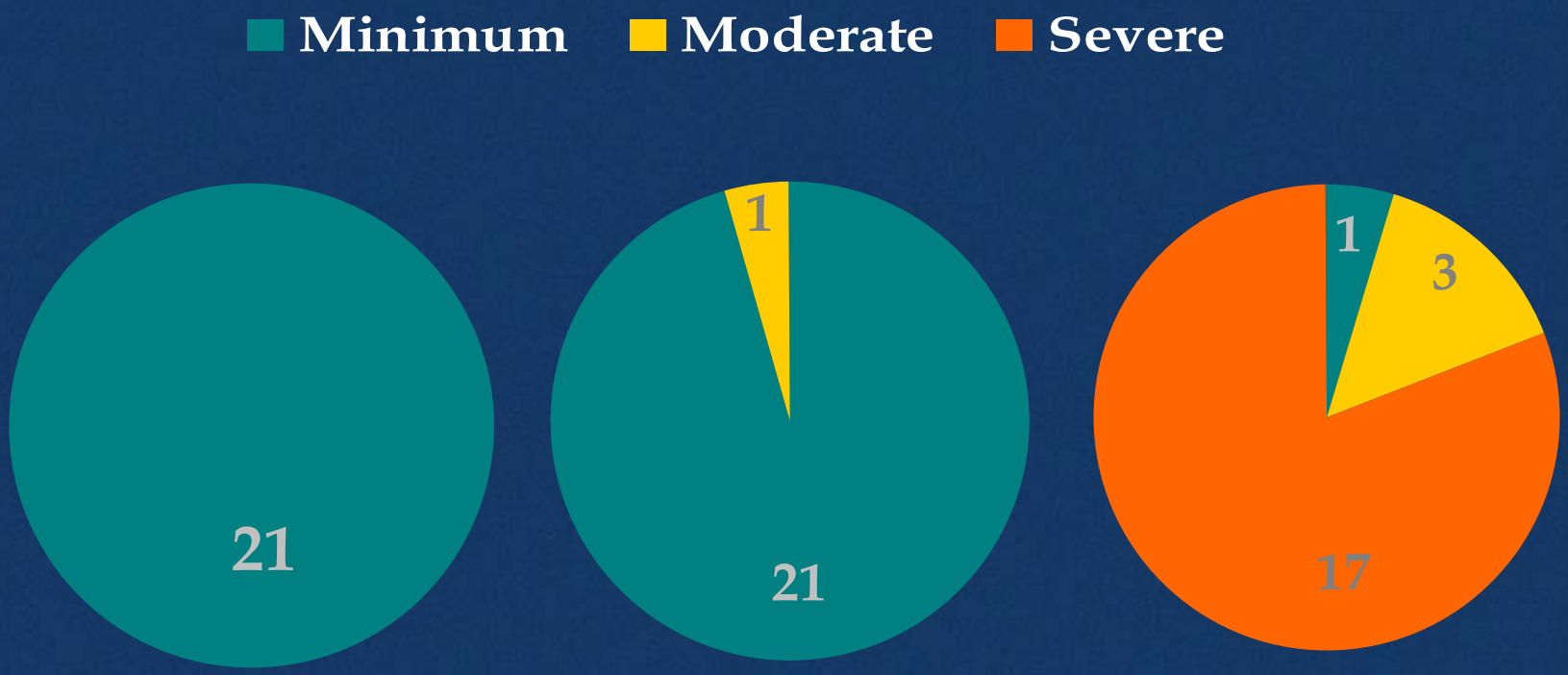
- Set aside results of tests that do not meet criteria for a low impedance internal short or where the case cracked by the mechanical crushing and not from internal pressure

Fire			XXX (3) XXXXX (5) XXXX (4)
Energetic Disassembly			XXXX (4) X (1)
Case Rupture		X (1)	XXX(3)
Internal Short	XXXXXXXXX (9) XXXXX (5) XXXXXXX (7)	XXXXXXXX (8) XXXXXX (6) XXXXXXX (7)	X (1)
SOC	40%	50%	70%

Discussion of Crush Results

- At 100% SOC, a refined crush would typically produce a severe outcome using a refined test method.
- At 70% SOC, a refined crush resulted in severe outcomes for a majority of tests for each brand.
- At 50% SOC, all tests but one resulted in a minimum outcome. The one test resulted in a moderate outcome (case rupture).
- At 40% SOC, all of the tests resulted in a minimum outcome.

Crush Outcome Trends



40% SOC
21 Refined Tests

50% SOC
22 Refined Tests

70% SOC
21 Refined Tests

Preliminary Conclusions

- The refined crush profile method was found to accommodate differences in “cell design” between manufacturers.
- The severity of crush outcome is strongly affected by state of charge. No severe or moderate outcomes were observed during any test of a cell with 40% SOC.
- The severity of crush outcome was not significantly affected by which company manufactured the cell.