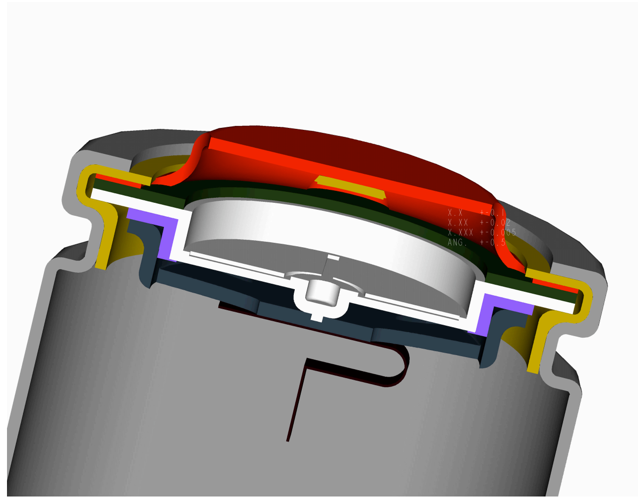

Cell PTC Device Characterization

by
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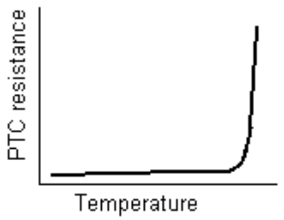
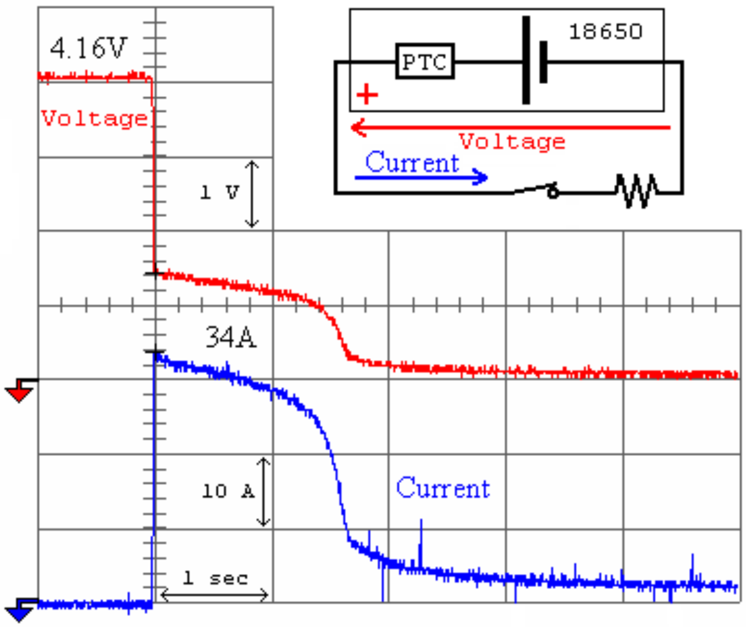
For
2008 NASA Aerospace Battery Workshop
Huntsville, AL

PTC Device: Background

- Commercial Lithium Ion 18650 cells typically have a current limiting PTC (Positive Temperature Coefficient) device installed in the cell cap to limit external currents in the event of an external short to the cell.
- The PTC device consists of a matrix of a crystalline polyethylene containing dispersed conductive particles, usually carbon black.* The resistance of the PTC device increases with temperature (Positive Temperature Coefficient, PTC).
- The PTC has a resistance that increases sharply with temperature. When a short is applied to a cell, the elevated currents cause the PTC to self-heat and move to a high resistance state in which most of the cell voltage is across the PTC but the current is significantly reduced.
- As long as the short is maintained, the PTC device produces enough heat to keep itself in this tripped state (lower current being offset by greater voltage drop across PTC).

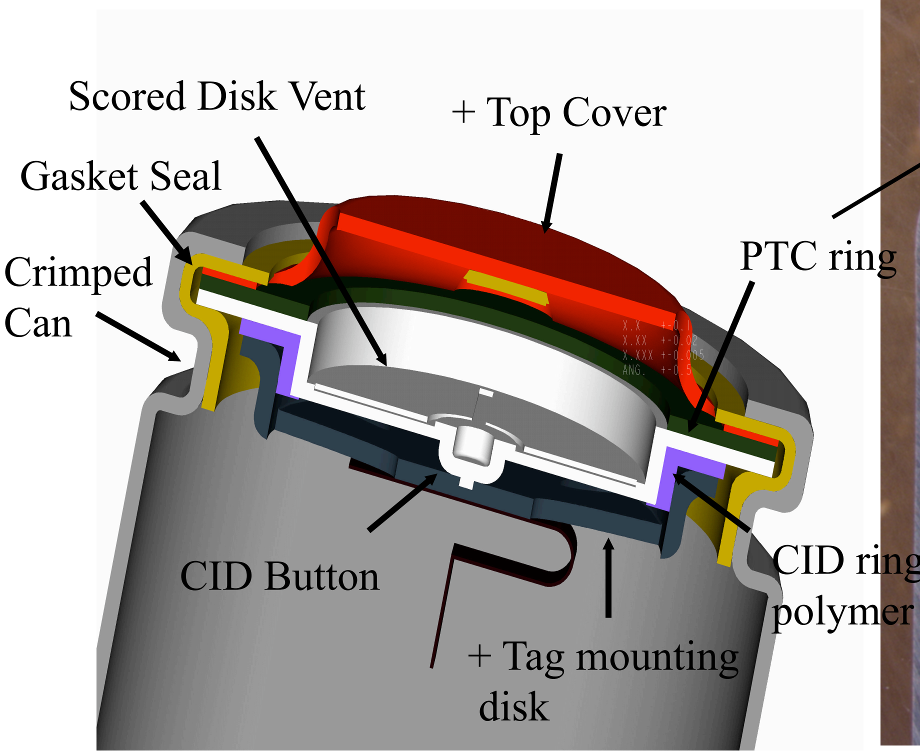


Single Cell Short:

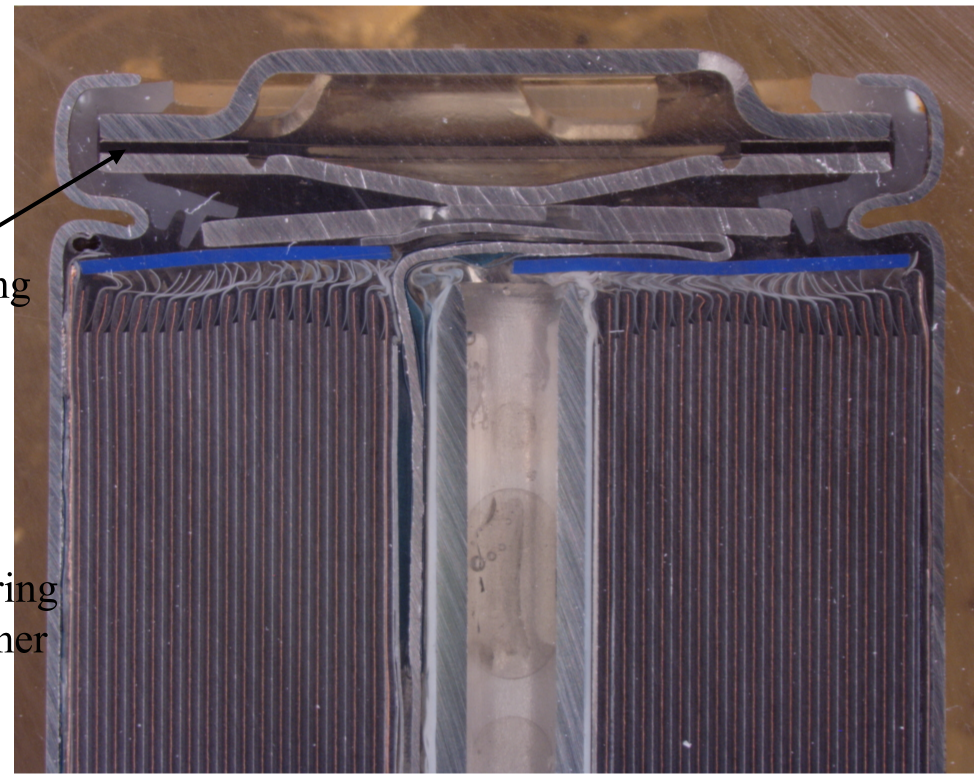


*Doljack, F., IEEE Transactions on Components, Hybrids, and Manufacturing Technology, **4**, 732, 1981

Cell Design Features for Abuse Tolerance



Sony HC Cell



Moli ICR-18650J

Previous Conclusions (2007 Workshop)

- Verifying the withstanding voltage limits of the PTC device in your selected commercial Li-ion cell is necessary to assure safe battery designs.
  - Thresholds for leakage and electrical damage can be significantly different
  - Must perform the test with visual in-situ inspection to detect odor & slight leaks
- The cell PTC device is a thermal regulator, which under tripped conditions dissipates 3.2 to 3.5W steady state **when at single cell ambient temperature benchtop conditions**, regardless of inrush current.
  - This heat must be properly dissipated in large, densely packed battery designs to ensure safe over-current protection
  - PTC device failure due to overstress is suspected root cause of thermal runaway of 66P-2S module at Fedex cargo plane terminal in Memphis (2004)

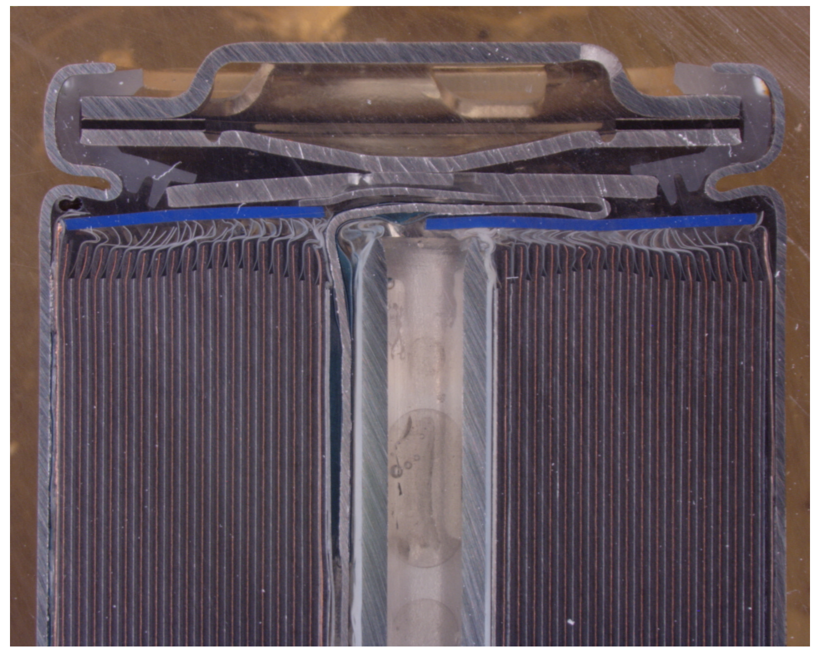
66P-2S Module after external short

Objectives of Current Work

- Determine the temperature dependence of the current limiting performance of the PTC device while in-situ
  - Moli 18650J
  - 18650LV
- Determine size and volume changes during tripping while in-situ
- Determine the performance of the Moli PTC device under short circuit conditions
  - 4P and 16P banks
  - 4S string

Determine R=R(T) of the PTC while in-situ

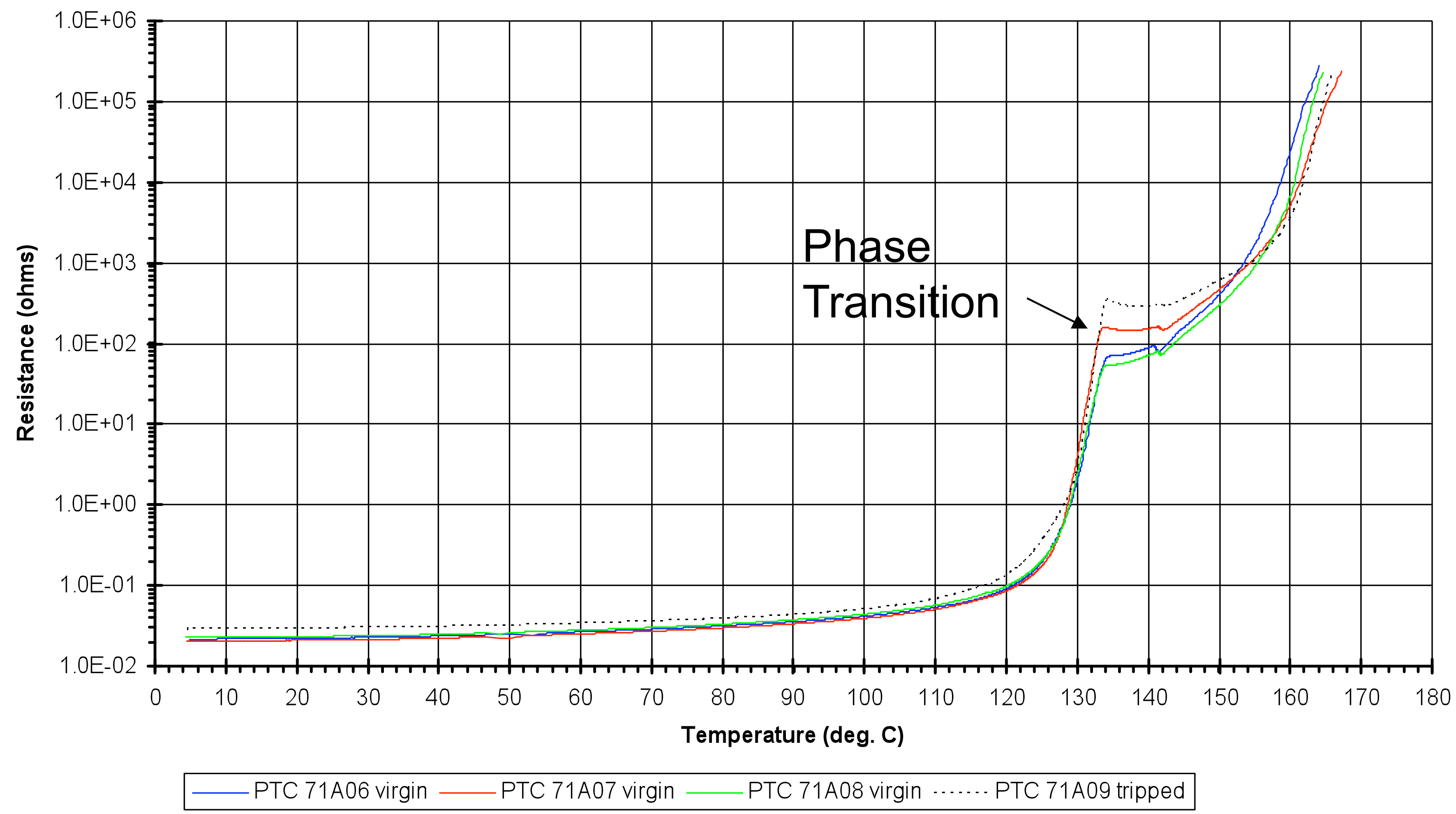
- Method used at SRI
  - Detach cell headers from cells without disturbing its assembly
  - Attach voltage sense leads on cell terminals and on CID disc to measure voltage drop across PTC
  - Route thermocouple through cell cap holes and attach as close as possible to PTC device
  - Attach current leads to the cell terminals
  - Measure resistance of virgin cell PTC device in cell to ± 5% while not inducing more than 1 mW of power dissipation by controlling the applied voltage
  - Perform test in thermal chamber and sweep from 5 to 170 °C on 3 different cell headers
  - Repeat test with once tripped cell header
  - Repeat test on complete cell with virgin PTC for confirmation



PTC Resistance versus Temperature; Moli ICR-18650J

Cell header removed from cell without disturbing closure configuration

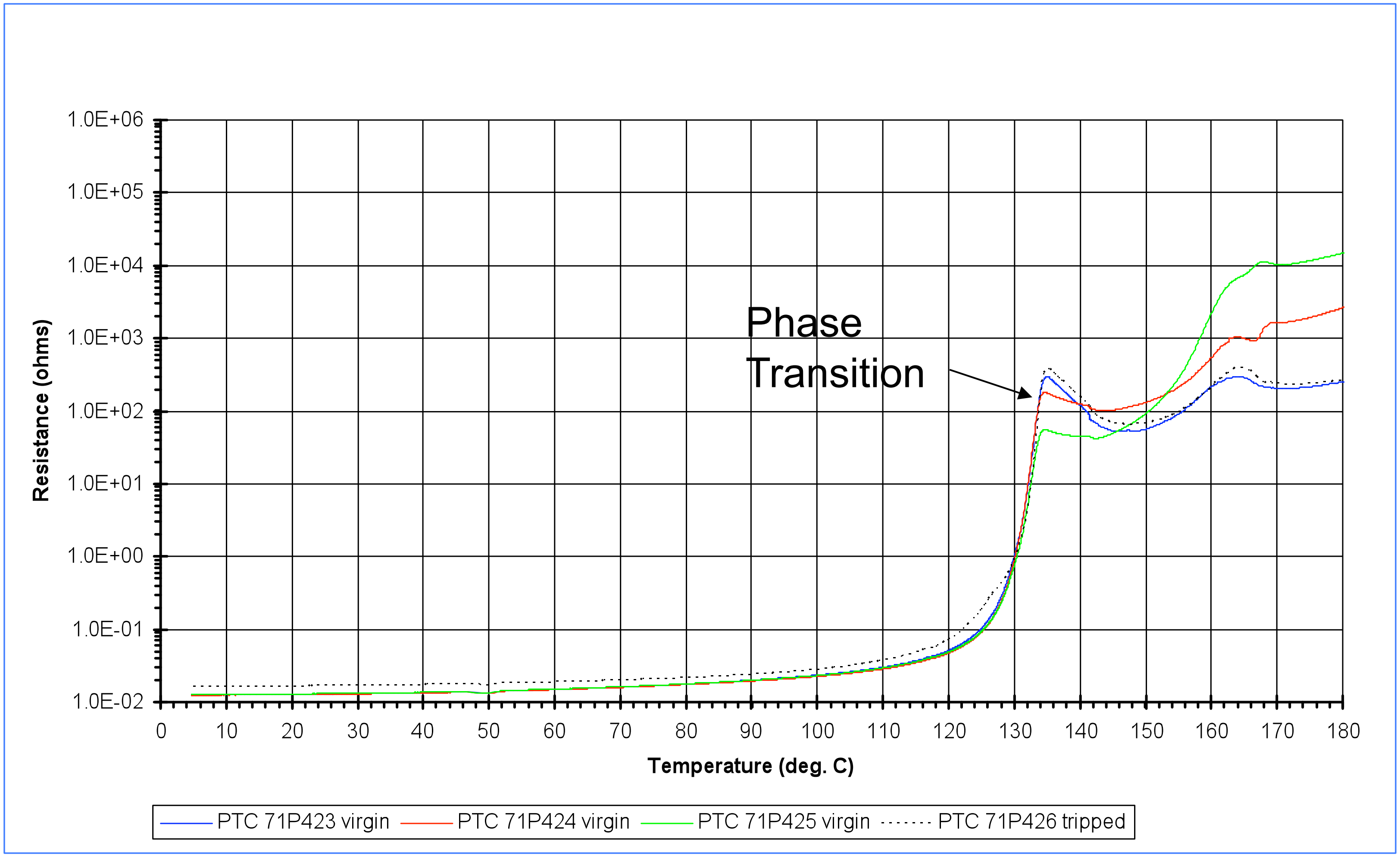
Resistance measurements taken from rupture disk surface to positive button



PTC Resistance versus Temperature; 18650LV

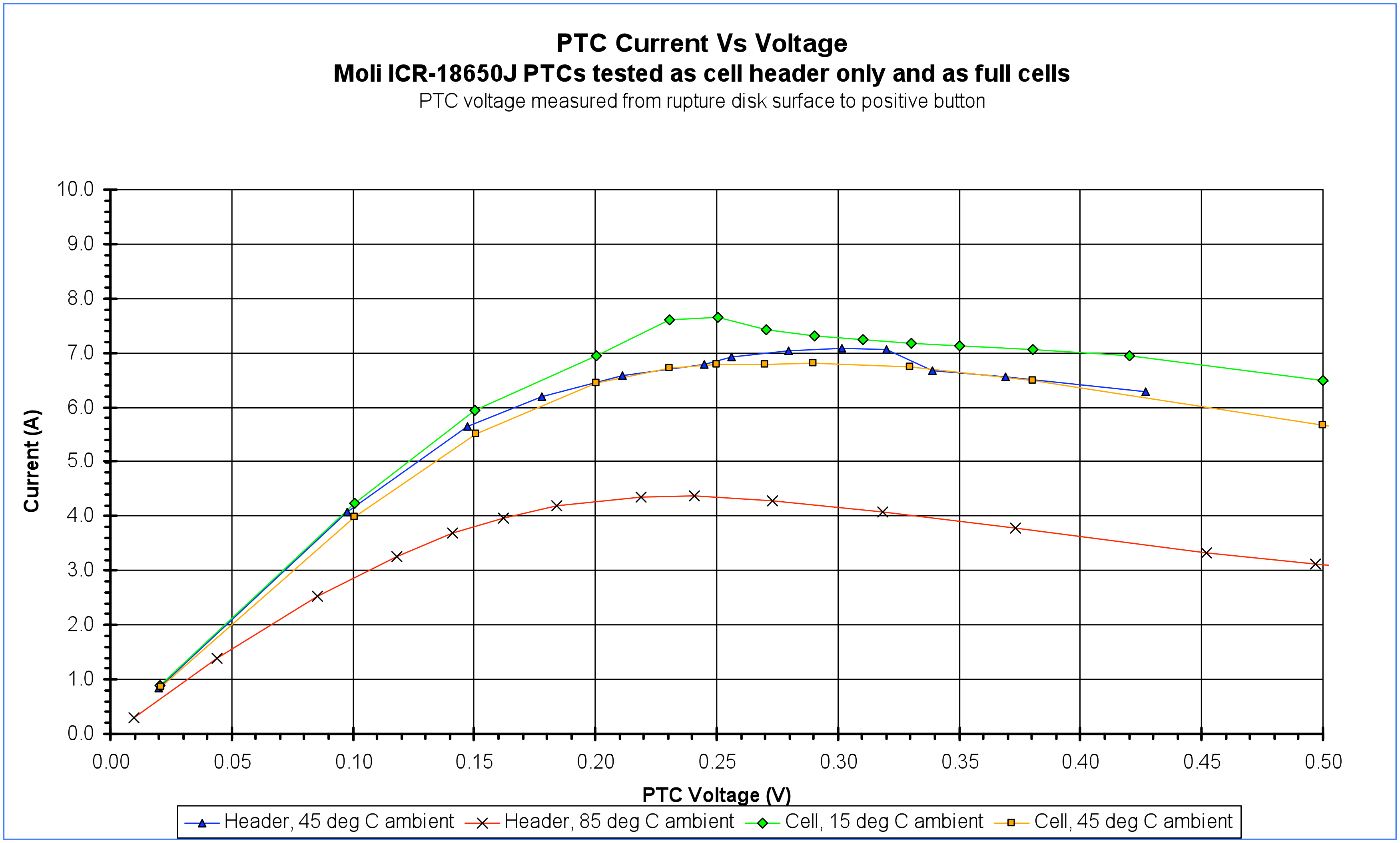
Cell header removed from cell without disturbing closure configuration

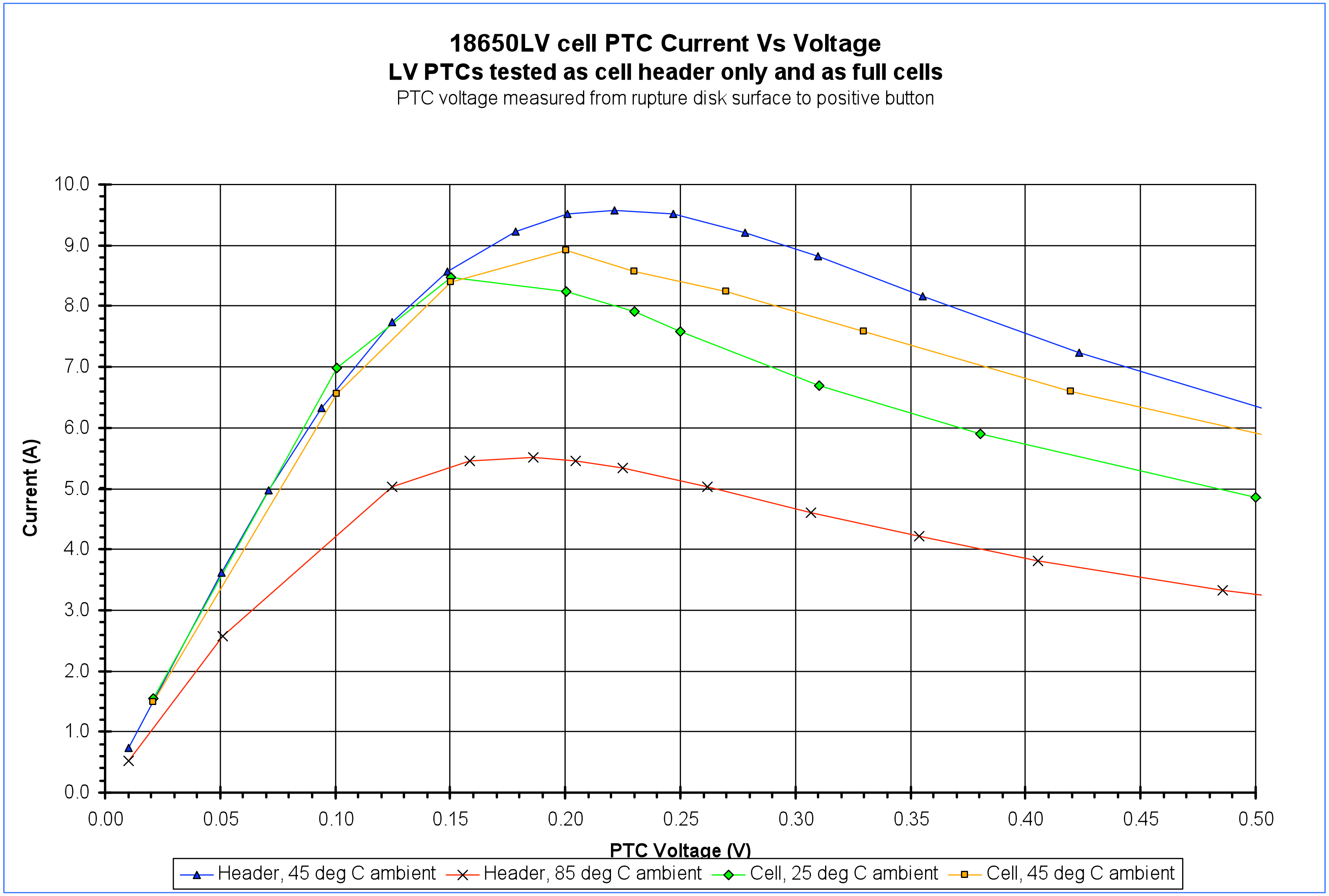
Resistance measurements taken from rupture disk surface to positive button

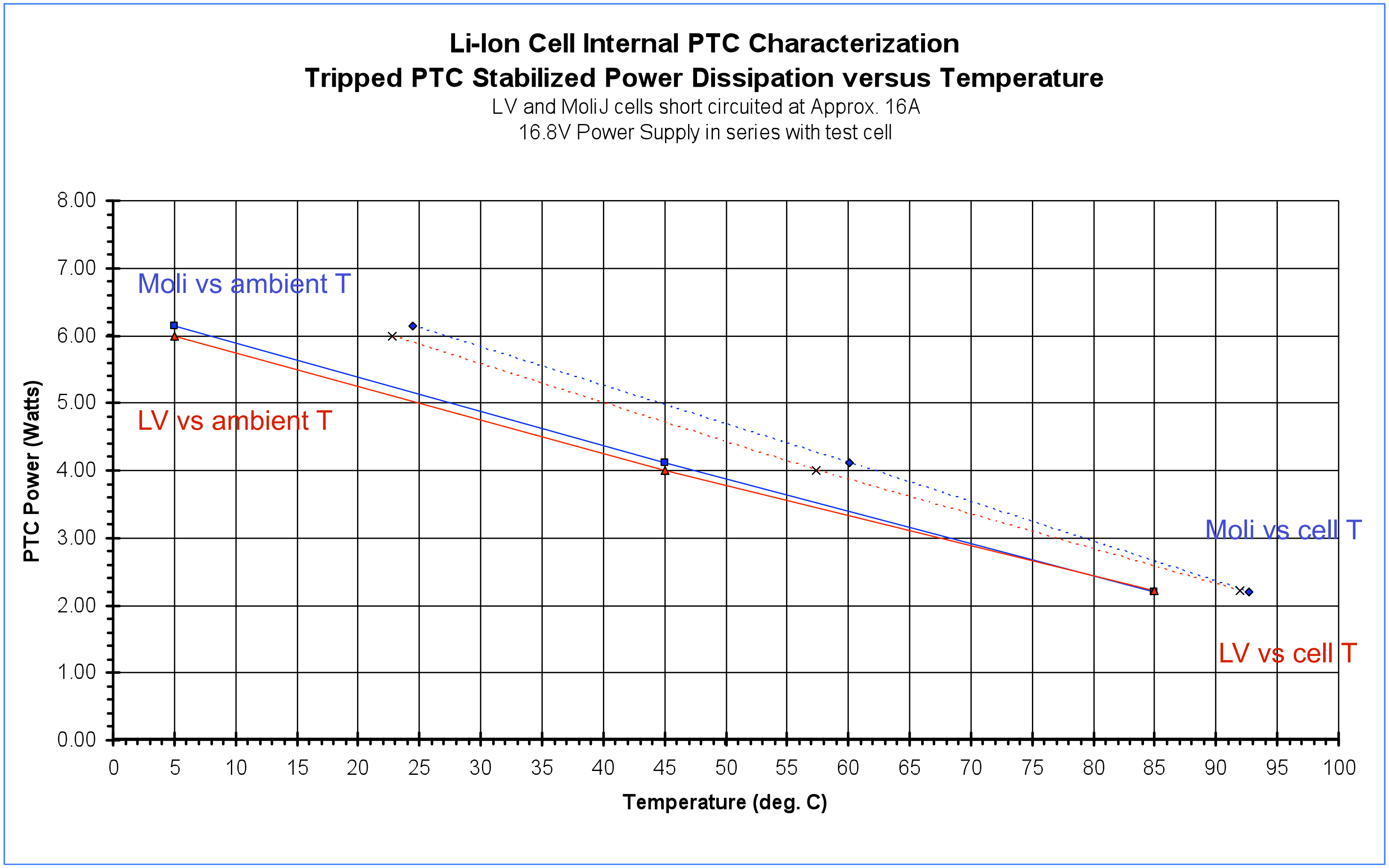


Behavior Principles of PTC Devices

- Two states of PTC devices all within 40 °C range
  - Low resistance current conducting state (< 50 mΩ)
  - Current limiting state with high resistance (>1 kΩ)
- Minimum and maximum base resistance (given ambient T)
  - Minimum is for virgin (never been tripped) devices
  - Maximum is for once (or more) tripped devices
- Ultimate trip current, I_u, is the highest equilibrium current possible in the low resistance state of the device for a given temperature
  - It's the maximum current achieved in an I vs V curve for a given ambient temperature, for example, at 45°C
    - MoliJ's I_u = 7A
    - LV's I_u = 9A
- Power generated in device = power dissipated in device
  - The trip time depends on size of the overcurrent, ambient T, thermal mass of the device, its specific heat, its heat dissipation coefficient, and its base resistance
  - Steady state trip current is inversely proportional to voltage applied and ambient temperature

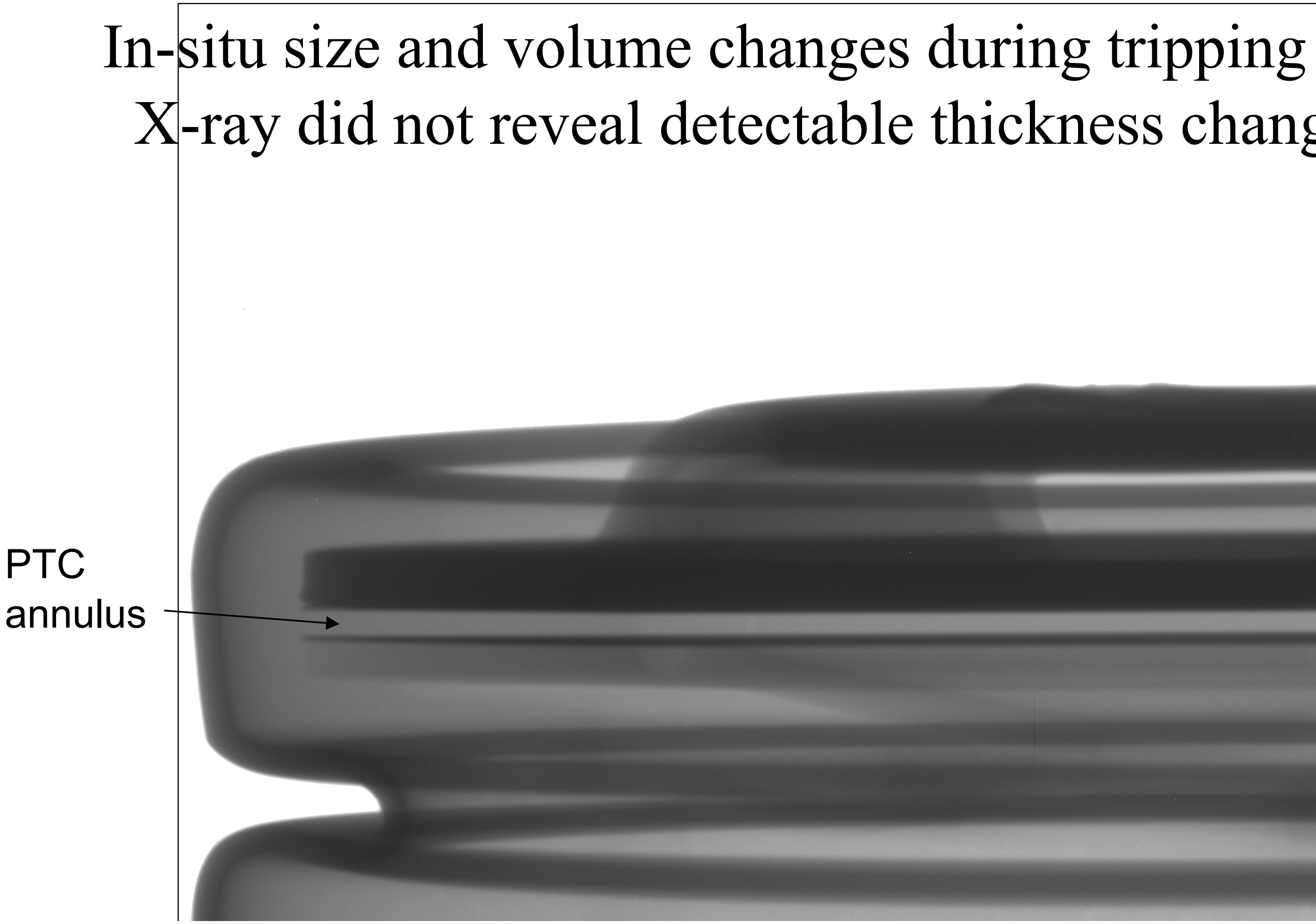

PTC Current Vs Voltage
Moli ICR-18650J PTCs tested as cell header only and as full cells
PTC voltage measured from rupture disk surface to positive button
Current (A)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
PTC Voltage (V)
Header, 45 deg C ambient
Header, 85 deg C ambient
Cell, 15 deg C ambient
Cell, 45 deg C ambient


18650LV cell PTC Current Vs Voltage
LV PTCs tested as cell header only and as full cells
PTC voltage measured from rupture disk surface to positive button
Current (A)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
PTC Voltage (V)
Header, 45 deg C ambient
Header, 85 deg C ambient
Cell, 25 deg C ambient
Cell, 45 deg C ambient



Heat generated at tripped PTC device inversely proportional to ambient T

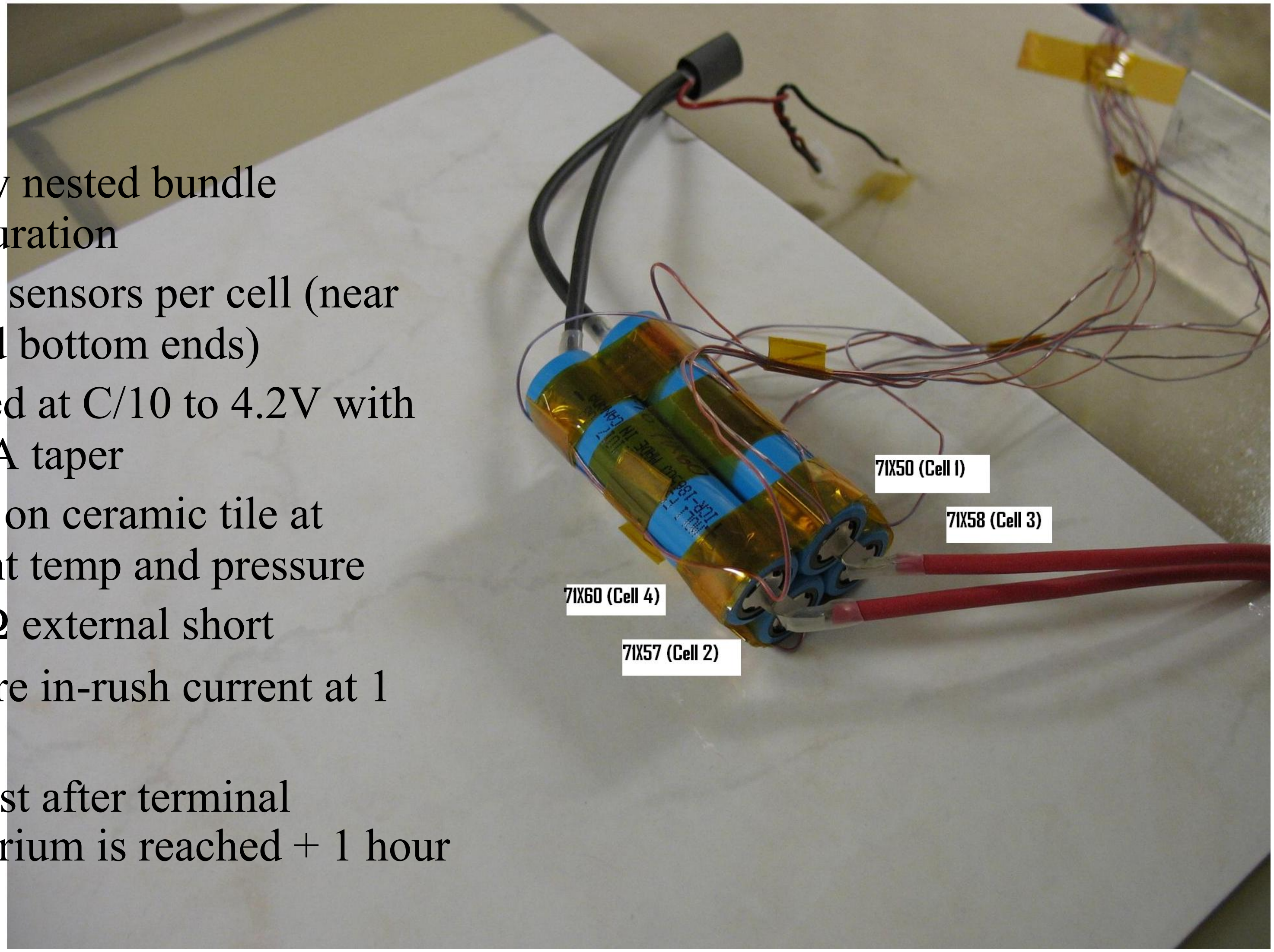
In-situ size and volume changes during tripping via X-ray did not reveal detectable thickness changes



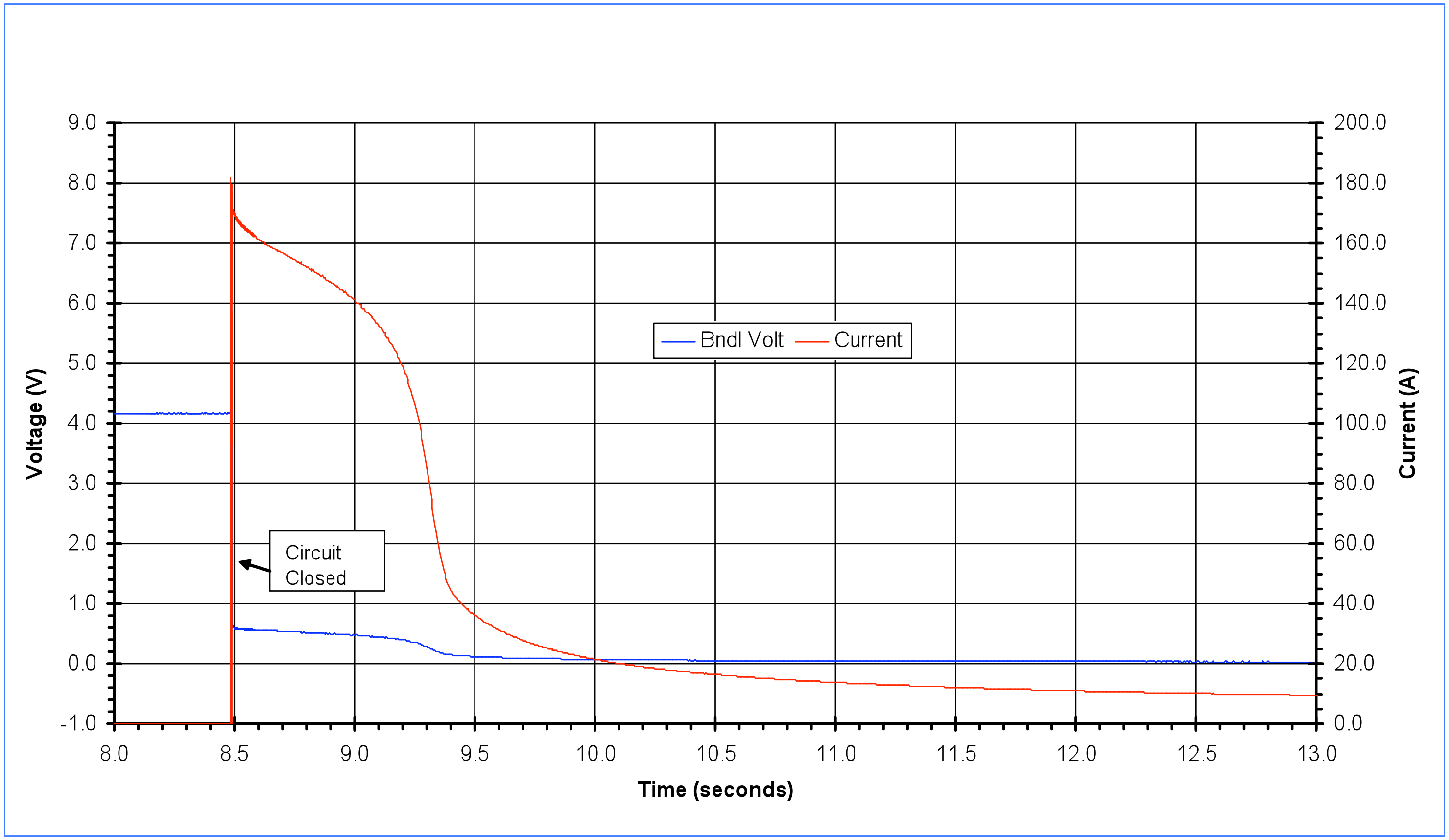
Polymer displacement towards inner diameter is possible and not detectable by X-ray

4P Moli Bundle Short Circuit

- Closely nested bundle configuration
- 2 temp sensors per cell (near top and bottom ends)
- Charged at C/10 to 4.2V with 400 mA taper
- Placed on ceramic tile at ambient temp and pressure
- 4.8 mΩ external short
- Measure in-rush current at 1 MHz
- Stop test after terminal equilibrium is reached + 1 hour

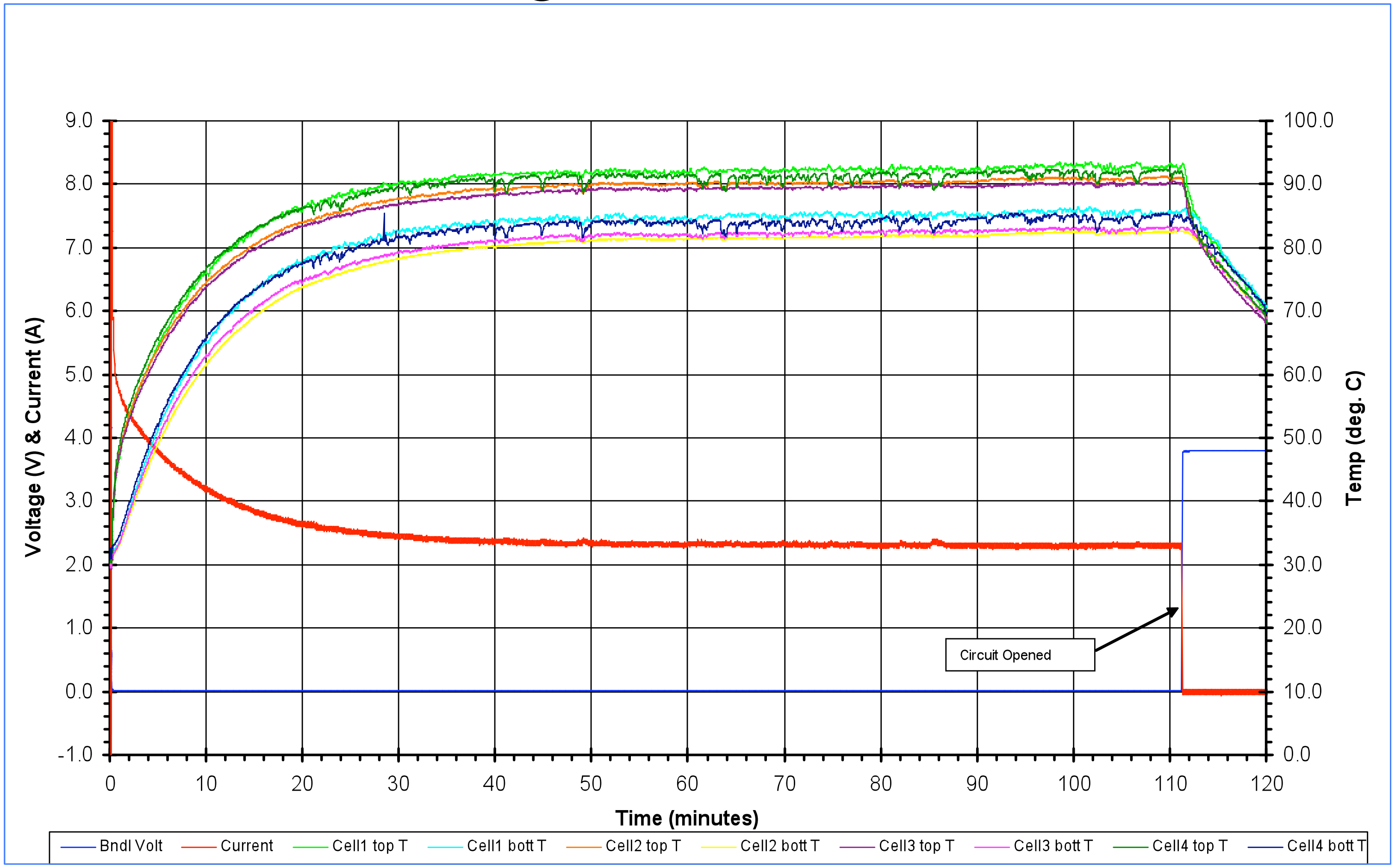


1S4P Bank Short Circuit; Inrush Detail
Short Circuit through 4.8 milliohm external circuit



182A max in-rush current! Requires ~1s to trip.

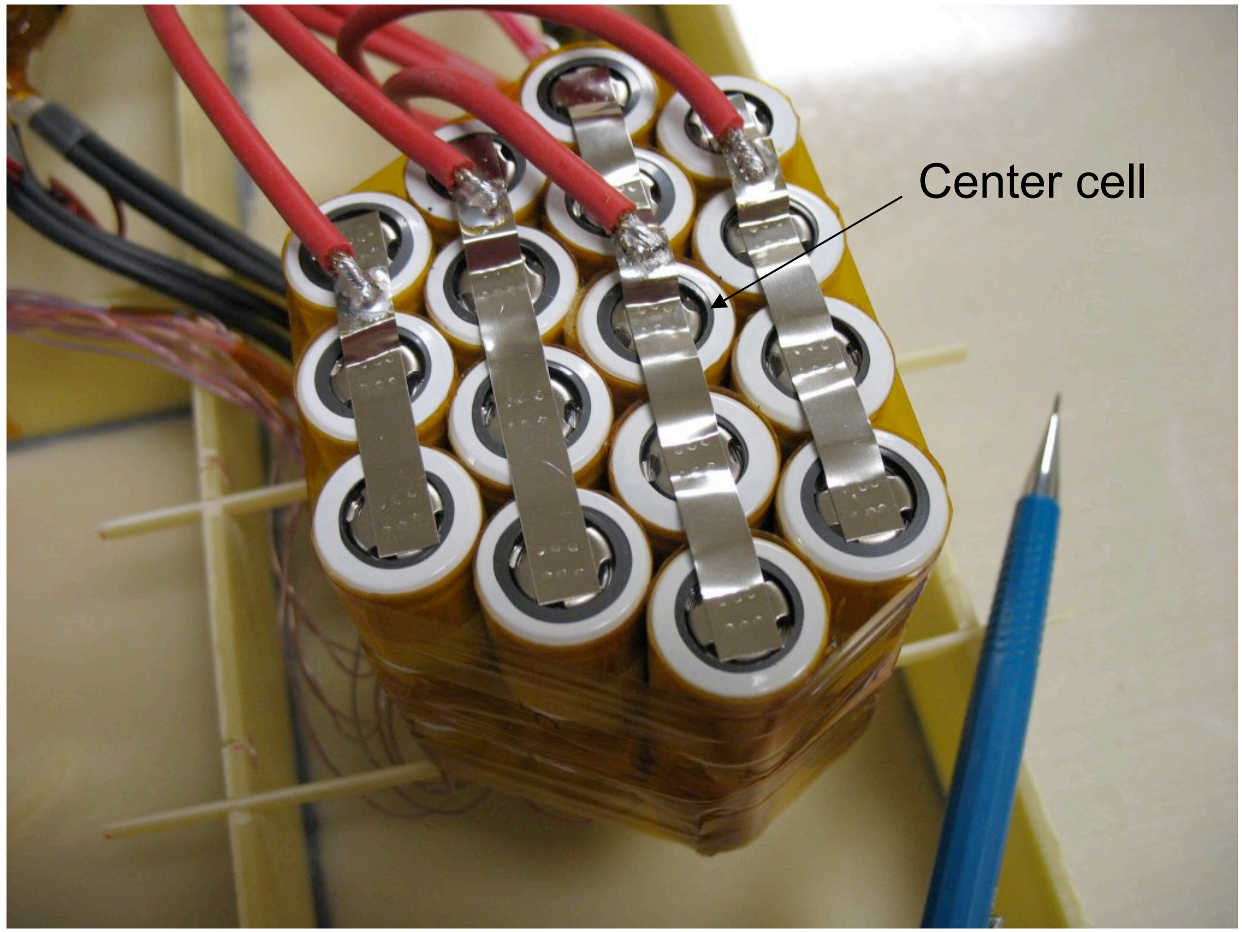
1S4P Bank Short Circuit
Short Circuit through 4.8 mohm external circuit



Top and bottom cell temps are > 10°C higher vs single cell test

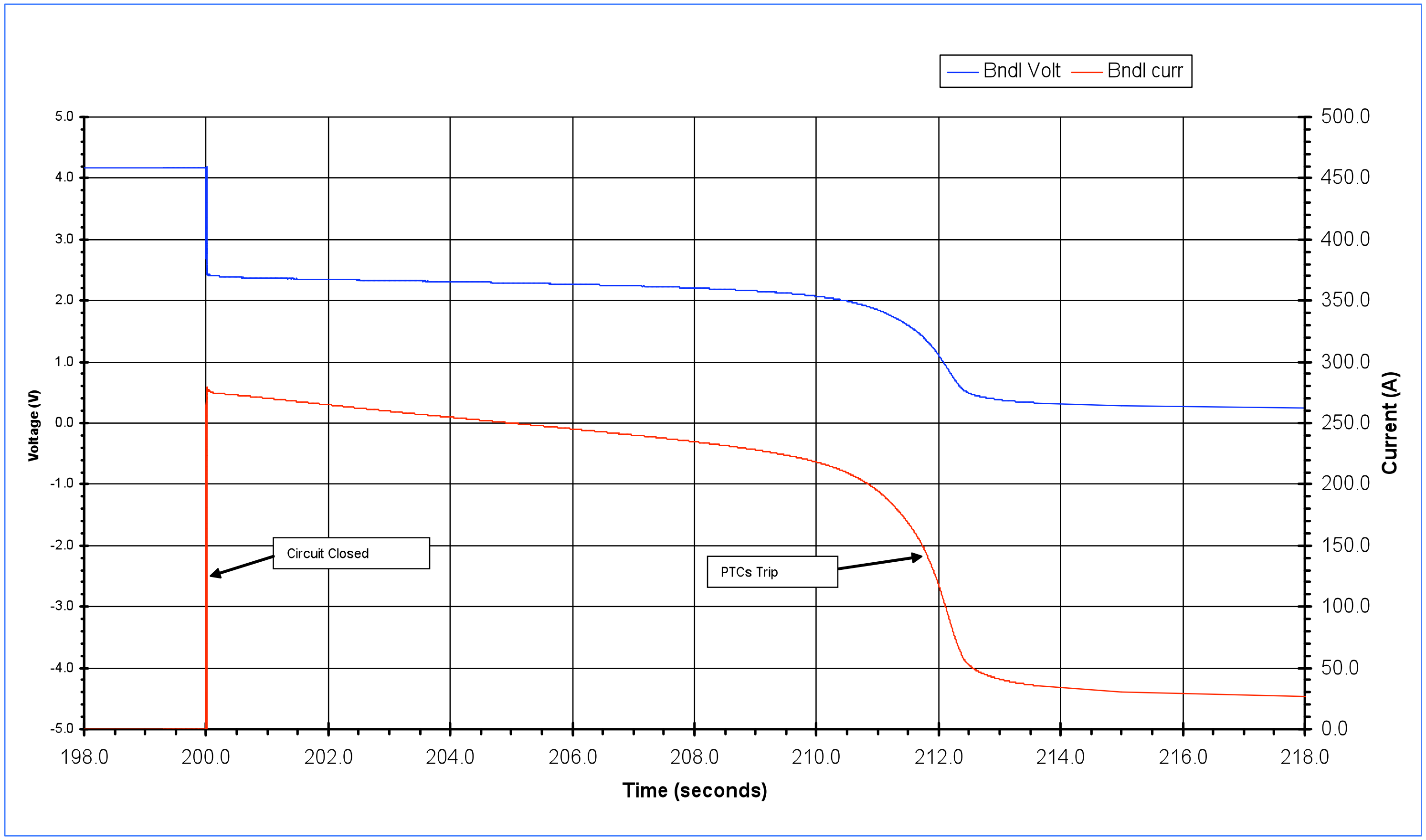
16P Moli Bundle Short Circuit

- Closely nested bundle configuration
- 1 temp sensors per cell except 2 for center cell (near top and bottom ends)
- Charged at C/10 to 4.2V with 1.6A taper
- Propped up on non conductive sticks at ambient temp and pressure
- 9.35 mΩ external short
- Measure in-rush current at 1 MHz
- Stop test after terminal equilibrium is reached + 1 hour



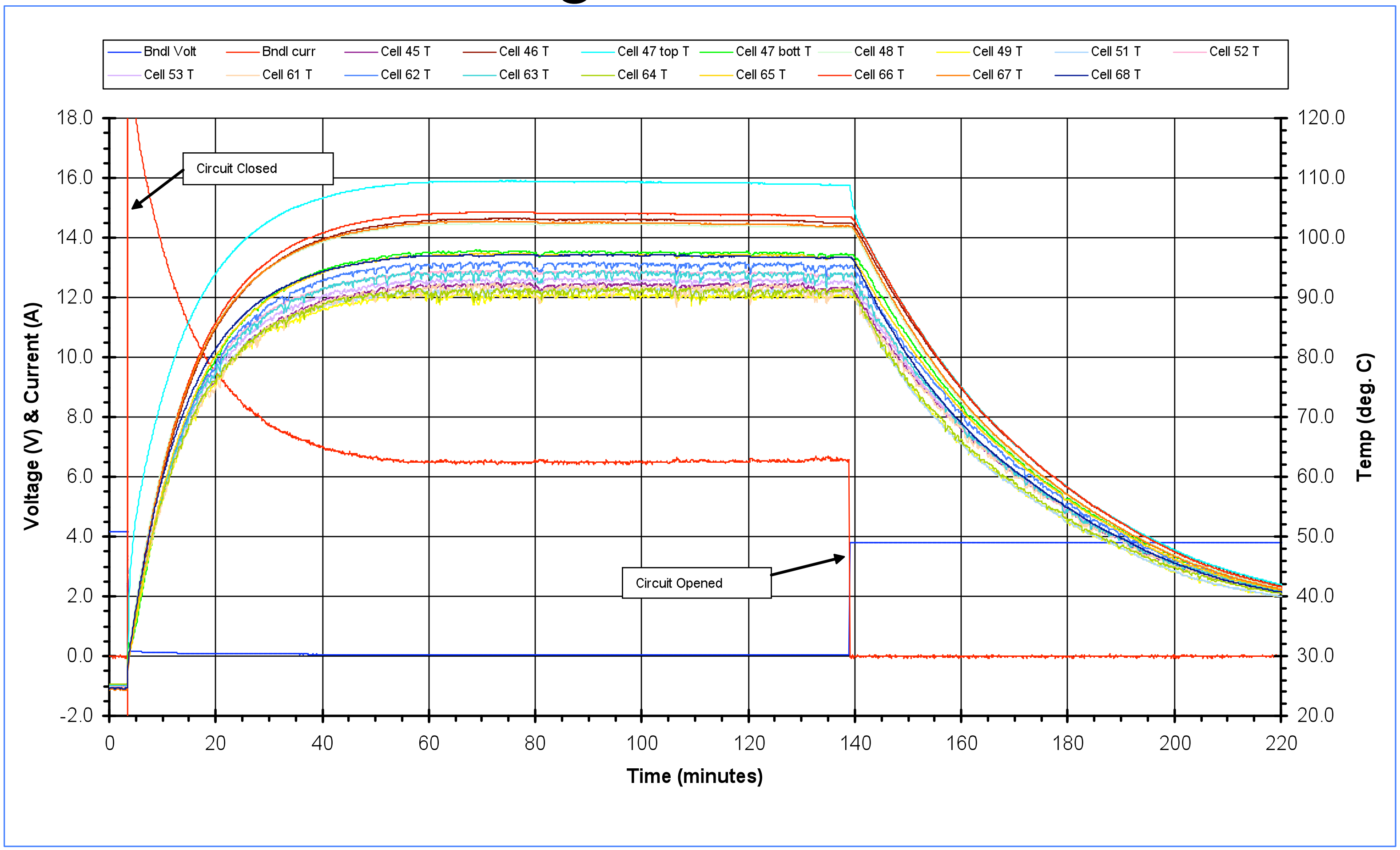
After picture: cells averaged 10 mg mass loss

1S16P Bank Short Circuit; In-rush Detail
Short Circuit through 9.35 mohm external circuit



279A max in-rush current! Requires 12s to trip.

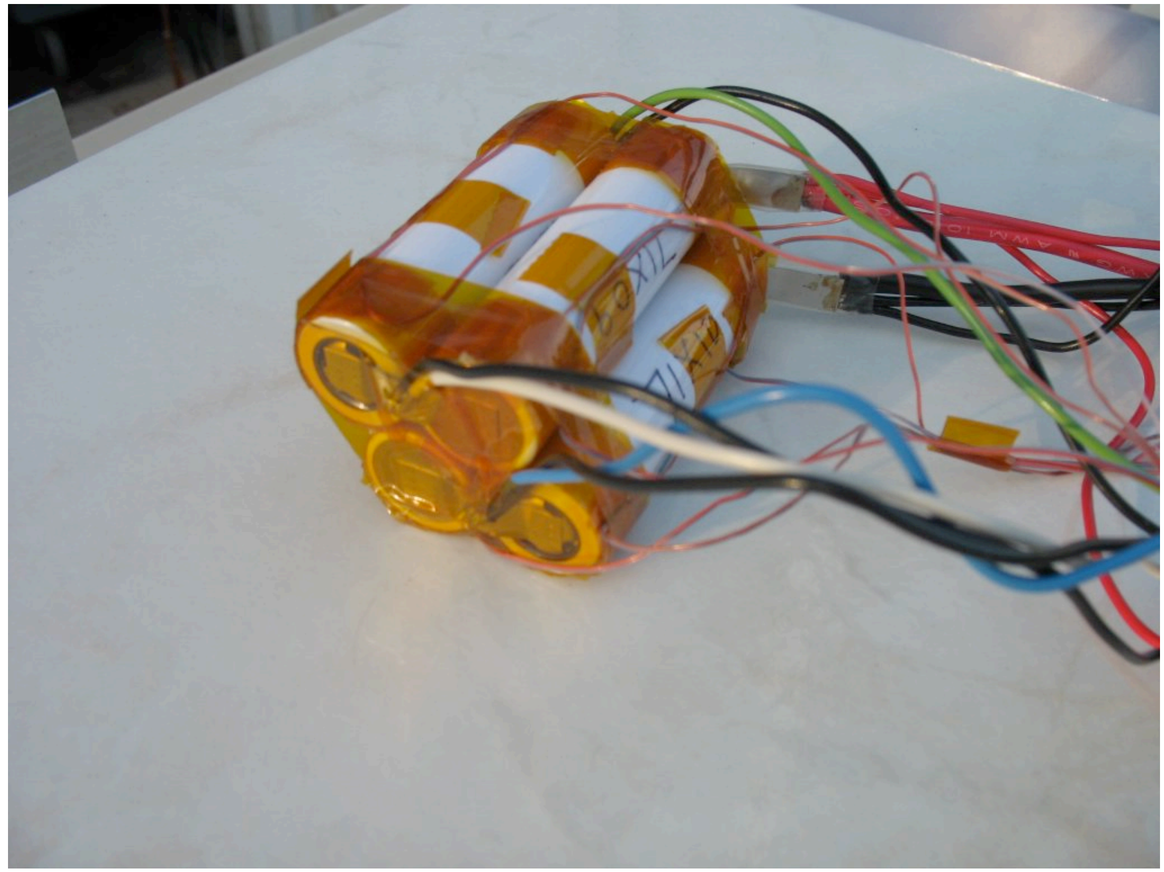
1S16P Bank Short Circuit
Short Circuit through 9.35 mohm external circuit



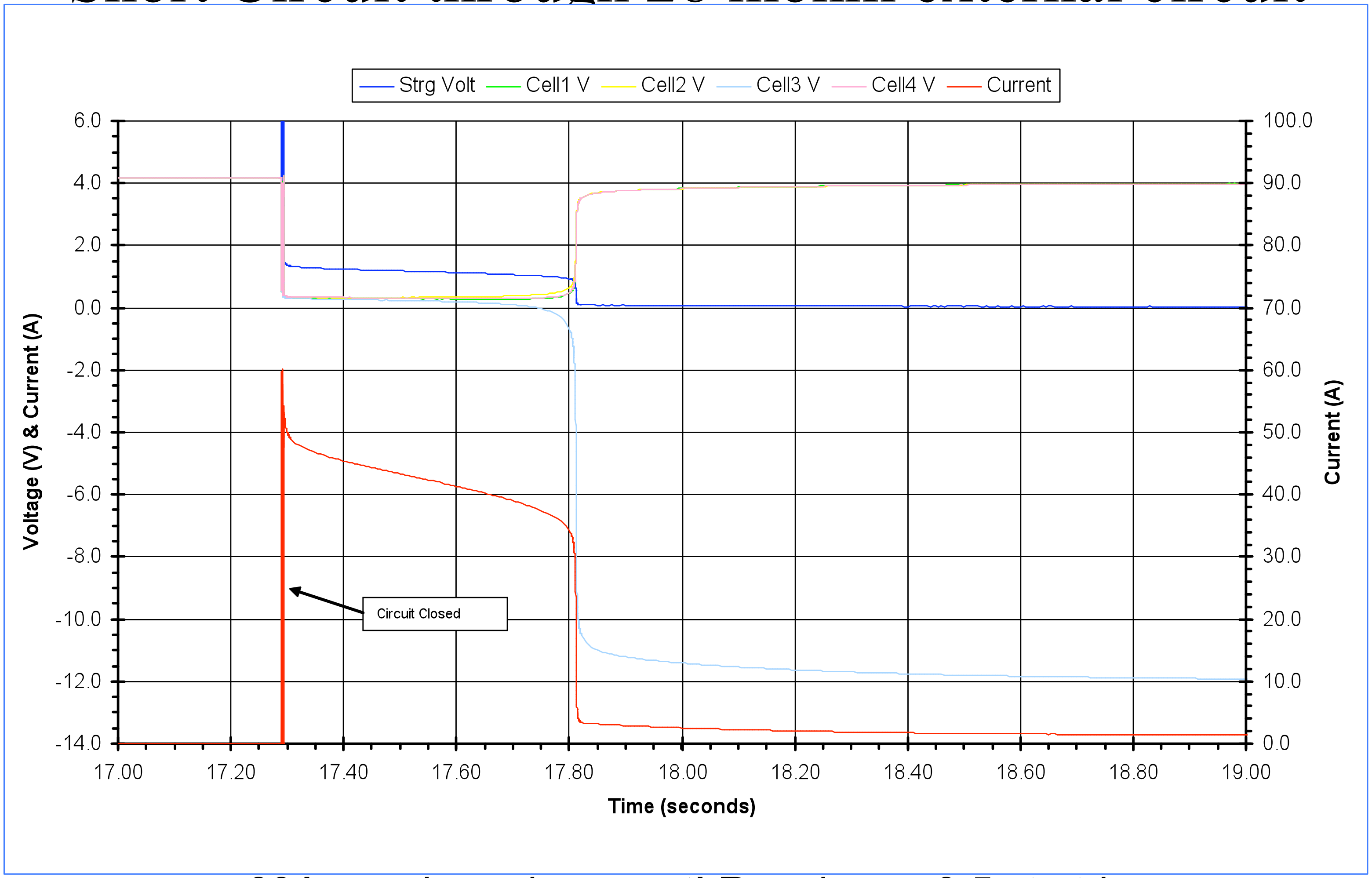
Top and bottom cell temps are > 25°C higher vs single cell test

4S1P Moli String Short Circuit

- Closely nested bundle configuration
- 2 temp sensors per cell (near top and bottom ends)
- Charged at C/10 to 16.8V with 50 mA taper
- Placed on ceramic tile at ambient temp and pressure
- 28 mΩ external short
- Measure in-rush current at 1 MHz
- Stop test after terminal equilibrium is reached + 1 hour

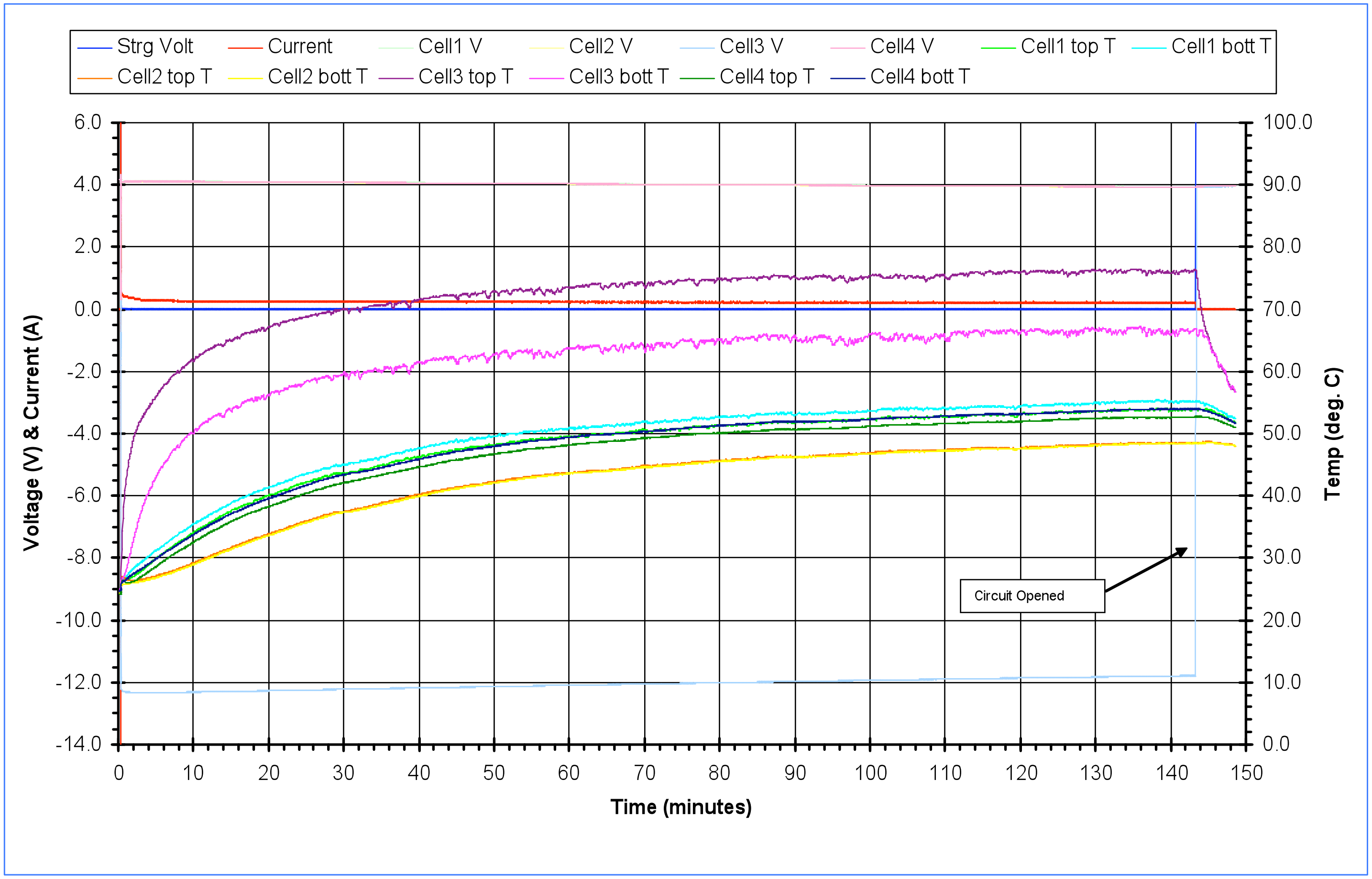


4S1P String Short Circuit; In-rush Detail
Short Circuit through 28 mohm external circuit



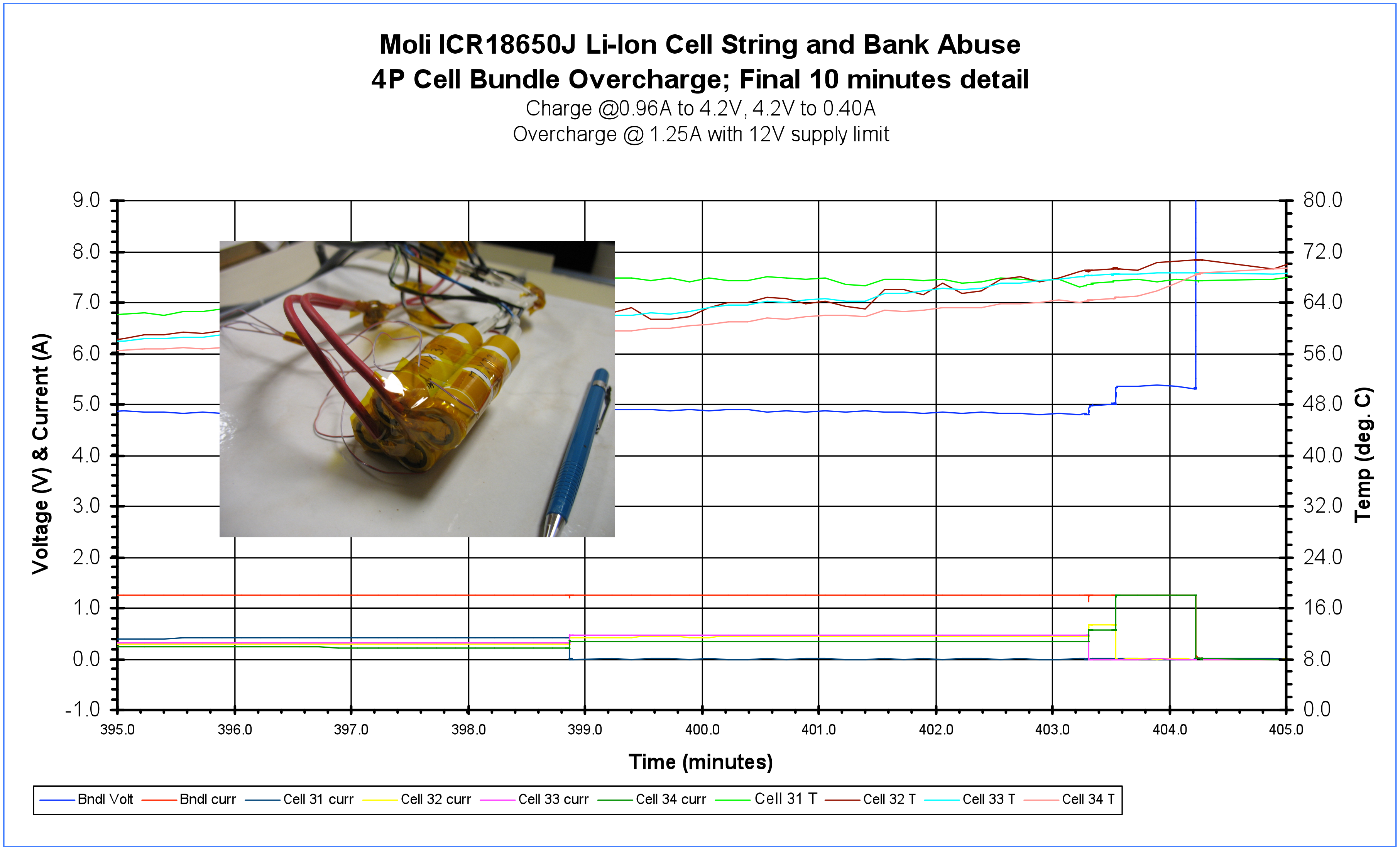
60A max in-rush current! Requires ~ 0.5s to trip.

4S1P String Short Circuit
Short Circuit through 28 mohm external circuit



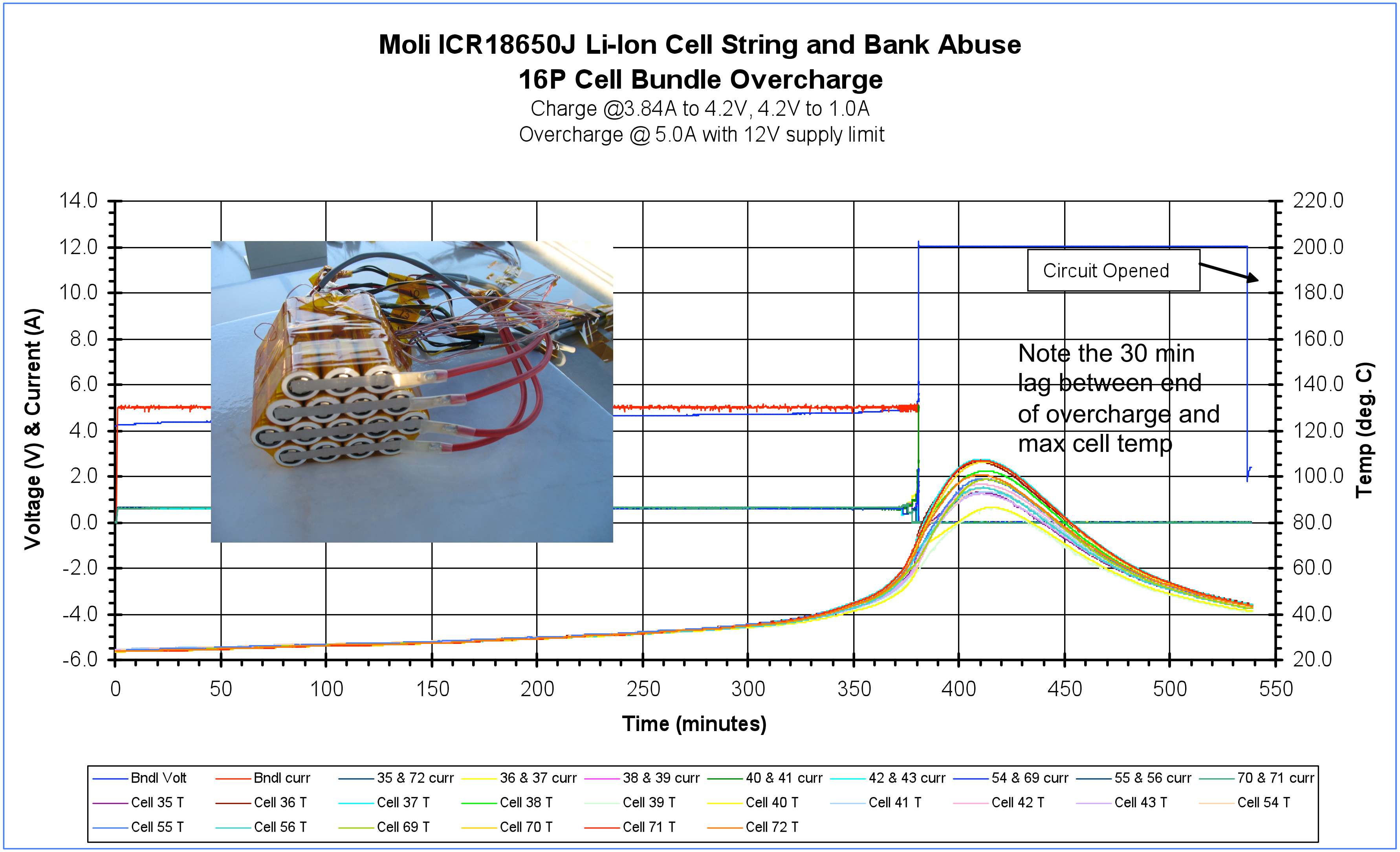
Top and bottom cell temps are > 4°C higher vs single cell test

4P bundle



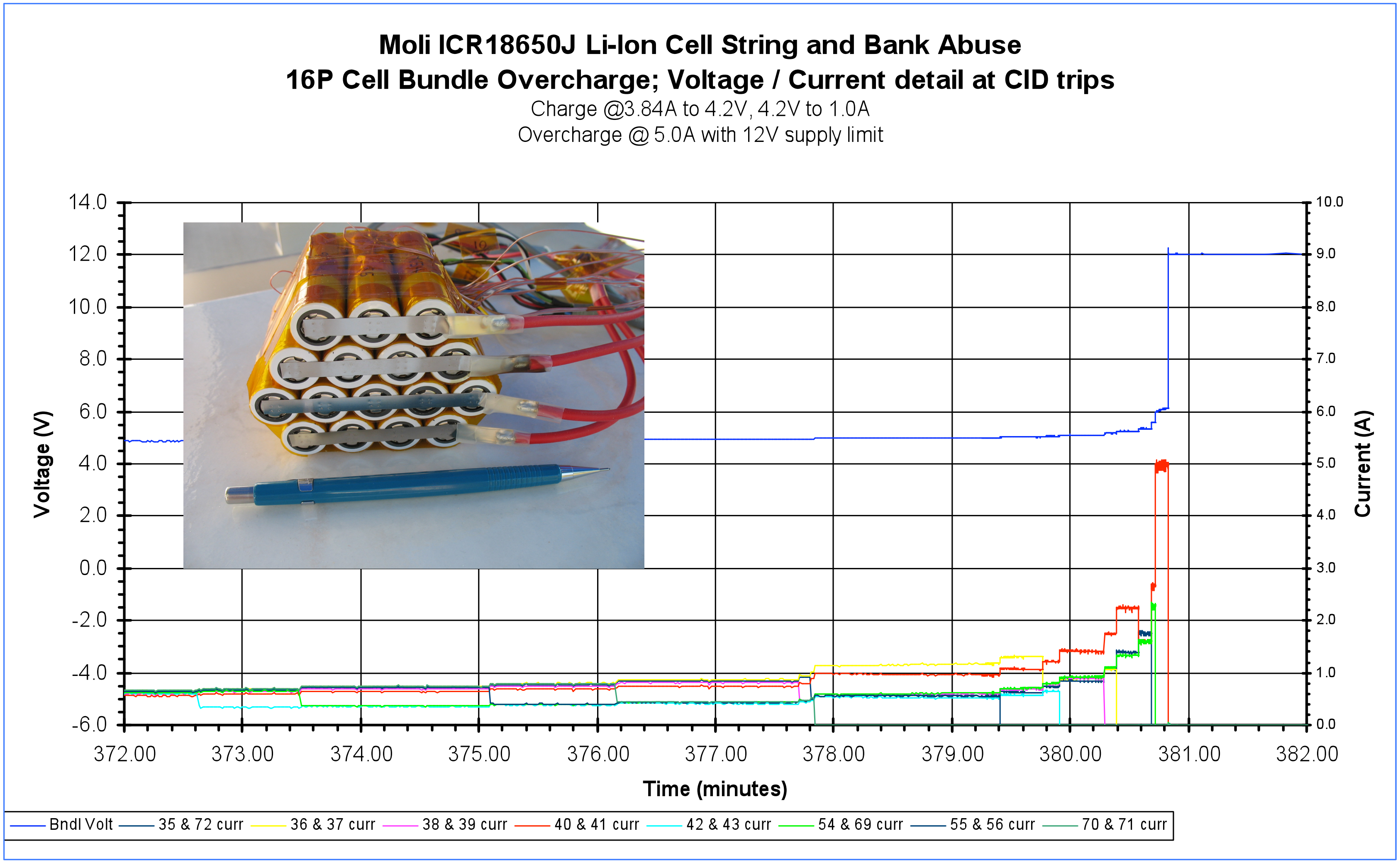
Cell CID's activate in turn over 5 minutes to safely terminate overcharge current

16P bundle



Cell CID's activate in turn to safely terminate overcharge current

16P bundle



Cell CID's safely activate in turn over 10 minutes without PTC transitions

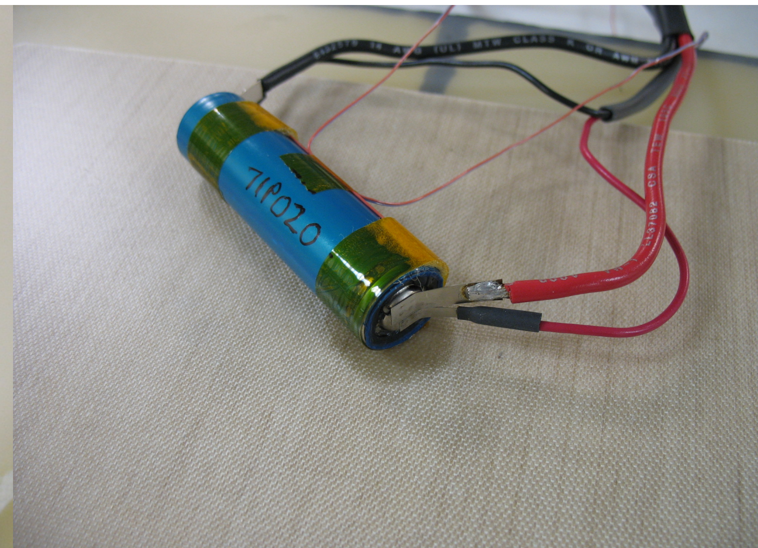
Conclusions

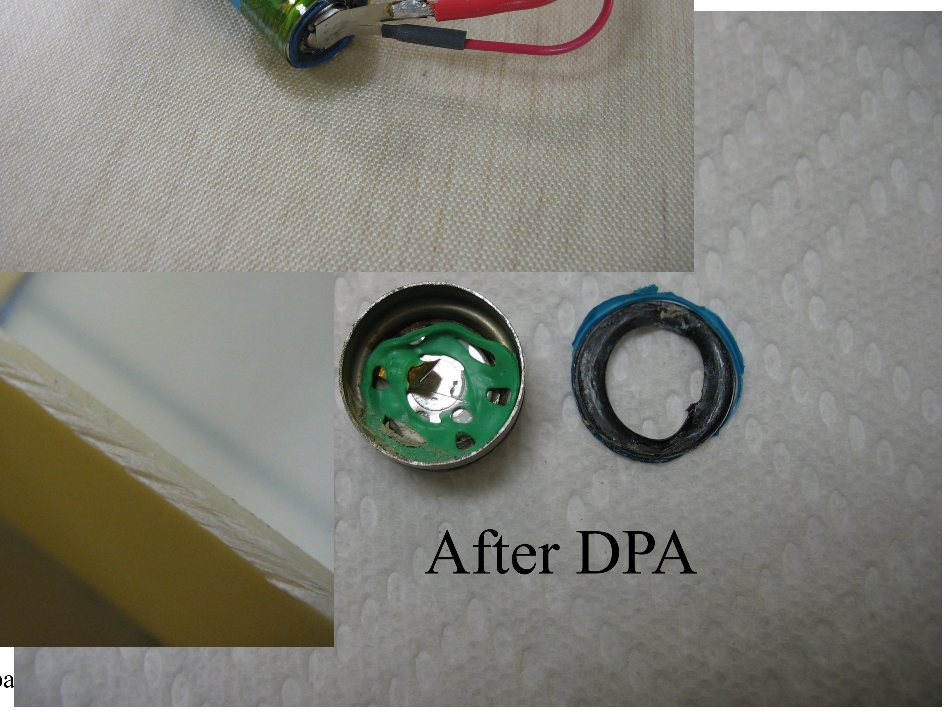
- Cell PTC device resistance as function of ambient temperature established for 2 cell designs
  - Cell PTC device increases 3 orders of magnitude over 5 to 133 °C temperature range
  - Polymer phase change occurs > 133 °C
  - Current vs voltage relationship defines the ultimate trip current of the device for a given ambient temperature
- PTC device volume and thickness changes were not detectable by in-situ X-ray
- Moli cell PTC devices are effective protection against short circuit in nested bundles under the following conditions;
  - 4P at 4.8 mΩ with 182A in-rush current (92 °C max temp)
  - 16P at 9.35 mΩ with 279A in-rush current (109 °C max temp)
  - 4S at 28 mΩ with 60A in-rush current (76 °C max temp)
- Moli cell PTC devices not interfere with safe CID charge termination
  - Demonstrated at 4P and 16P under C/8 overcharge conditions

Acknowledgements

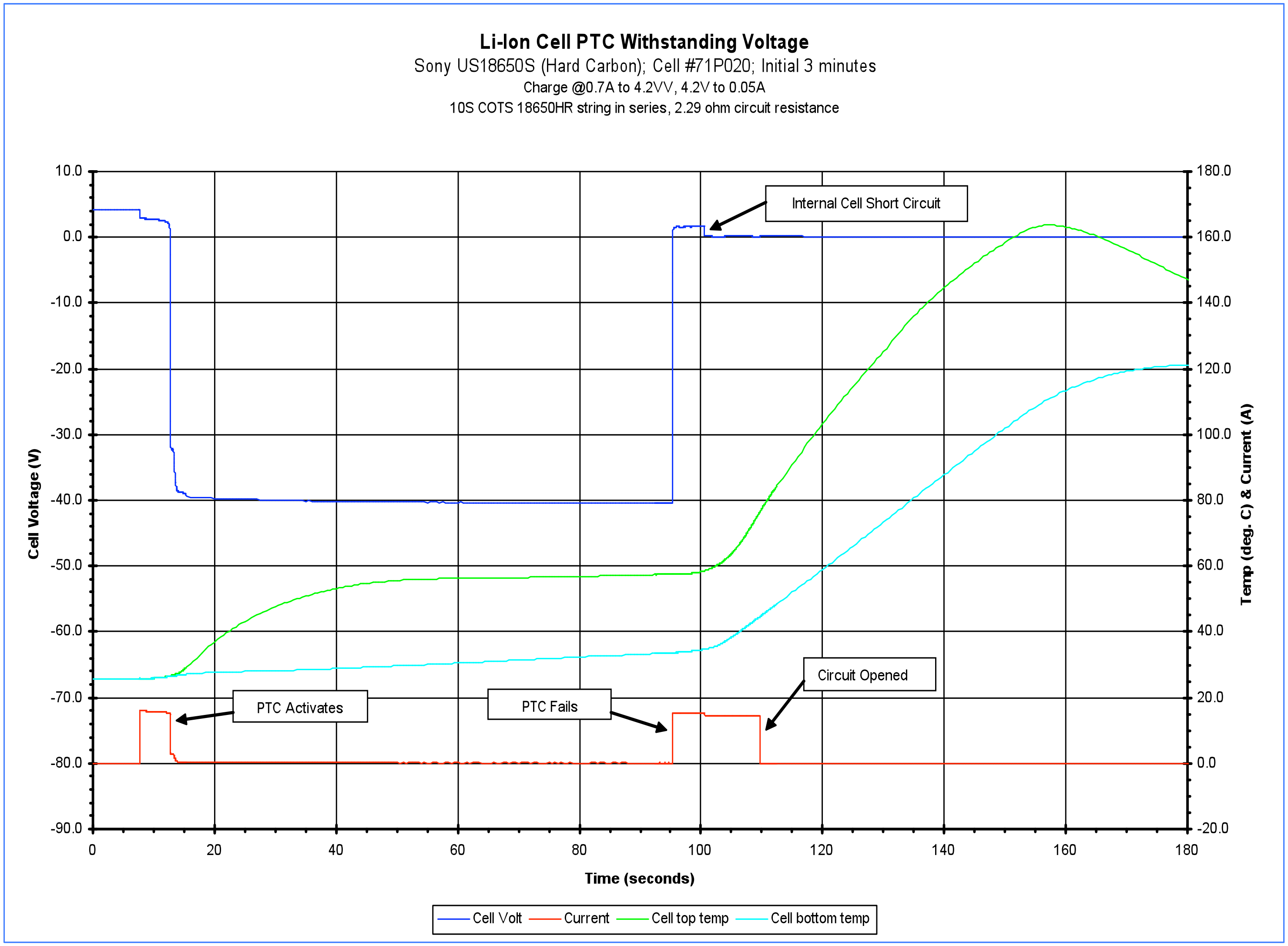
- Thanks to NREL team for numerous consultations to help define the goals and products of this effort
- Thanks for the EMU spacesuit battery project for funding the effort

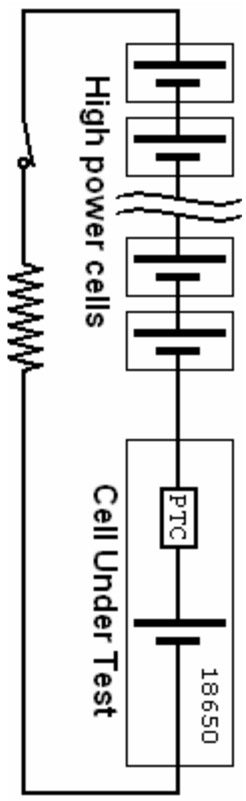
Sony HC cell – At 11S, PTC tripping power is estimated at 20W, followed by 3W to stay tripped. This caused seal damage leading to an internal short.





HC Can't Safely Handle 11S Short!





An overwhelmed PTC device can fail and internally short its cell