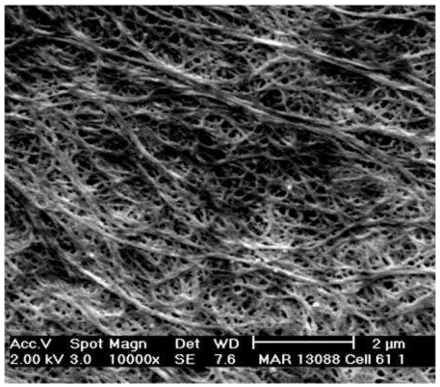
Separators used in Li-ion Cells

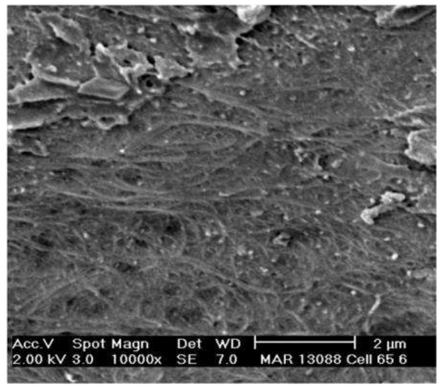
	1	2	3	4
Material	PE	PP/PE/PP	Alumina/PE/Alumina	Nonwoven
Process	Dry	Dry	Wet	Wet-laid [11]
Thickness (μm)	25	25	16 (2/12/2)	31
Porosity	36%–46%	39%	37%	46%
Pore size (μm)	0.01–0.1	0.05 × 0.21	0.1 (average)	0.2 (average on mat surface)

Zhang et al., J. Power Sources, 327, 2016, 693.

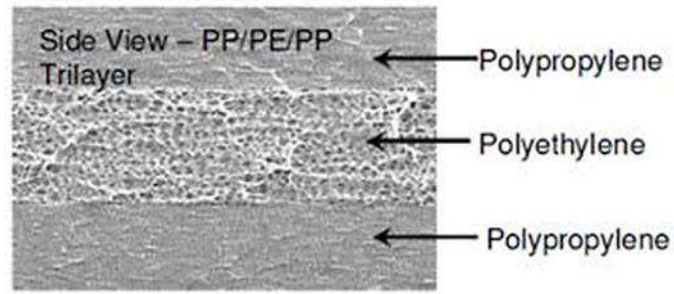
Shut-down Separator – PP/PE/PP



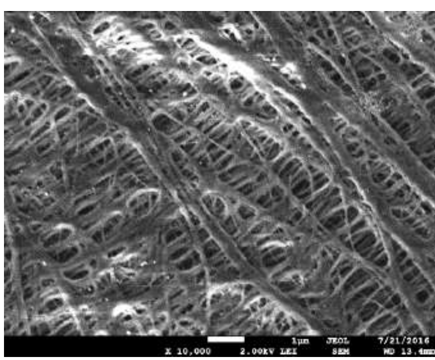
Unactivated Separator



Activated Separator

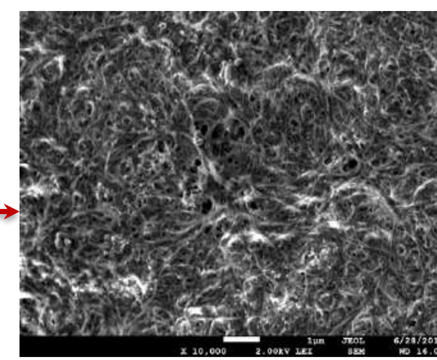


Shut-down temperature is very close to temperature at which initiation of thermal runaway occurs. So, not all shut-down separators are effective in mitigating catastrophic cell failures



Unactivated Polymer Separator (no Coating)

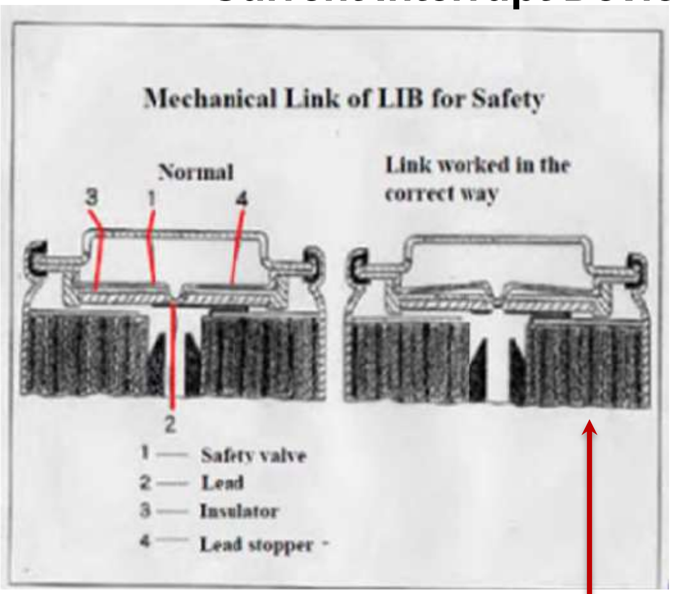
Unactivated Polymer Separator with Alumina Coating



Judith Jeevarajan, Ph.D. / UL

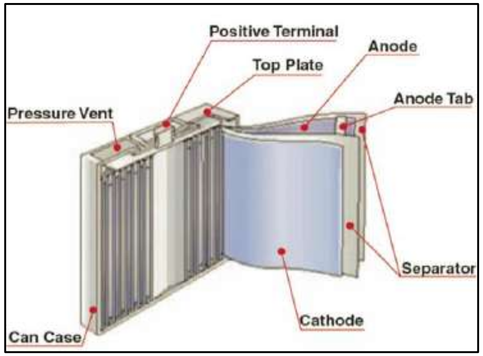
Li-ion Cell Construction and Internal Protective Features

Current Interrupt Device (CID)

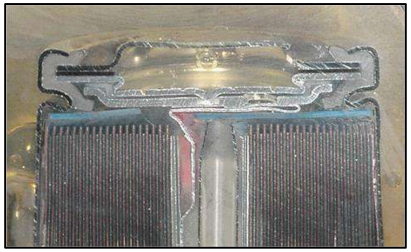


$LiPF_6 + Li_2CO_3 \rightarrow POF_3 + CO_2 + 3LiF$

Prismatic Metal Can Cell

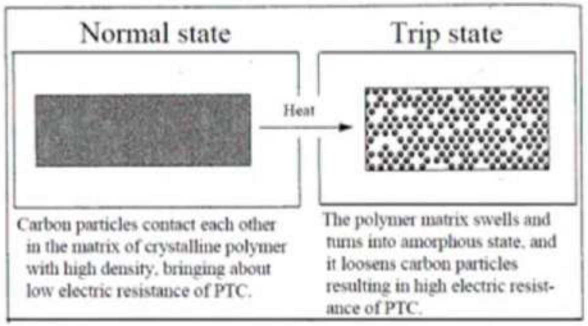


Cylindrical Cell



Gas production inside the cell causes irreversible flip of CID disc

Behavior of PTC Device



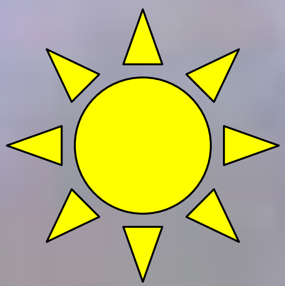
Prismatic Pouch Cell

No Overvoltage Protection in the Cell

PTC: Positive Temperature Coefficient

Judith Jeevarajan, Ph.D. / UL

Li-ion Cell Hazards



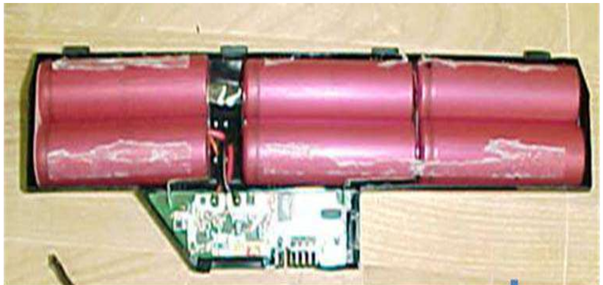
Thermal

Mechanical

Electrical

Li-ion Battery Designs and Challenges

Low Voltage/ Low Capacity



High Voltage/High Capacity

Incidents of Li-ion Fires

Lithium polymer fire burns down shop

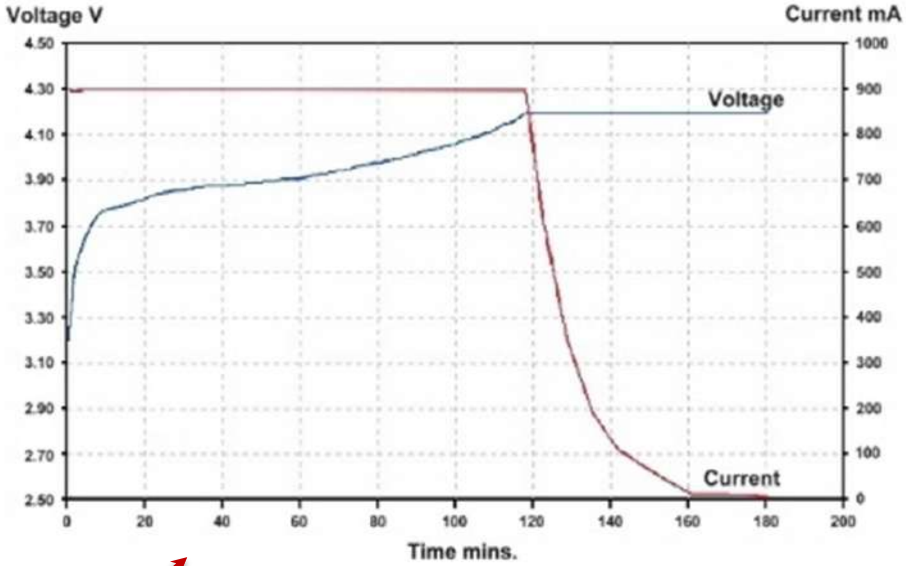
Fire Incidents in Portable Applications

Fire Incidents in Cell Manufacturing Facilities

Fire in Battery Recycling Facility

Judith Jeevarajan, Ph.D. / UL

Charge / Discharge Characteristics of Li-ion



Discharge Protocol:
Varies from Constant Current
or Power to pulse

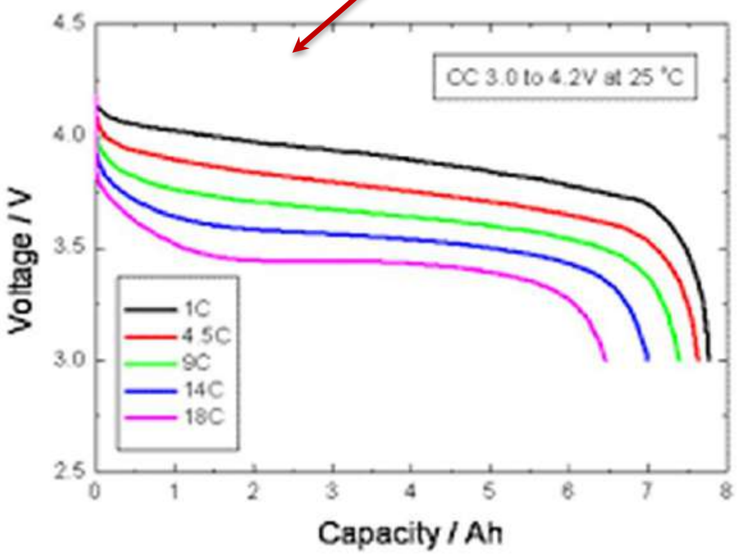
Anode in fully discharged state

Discharge

Charge

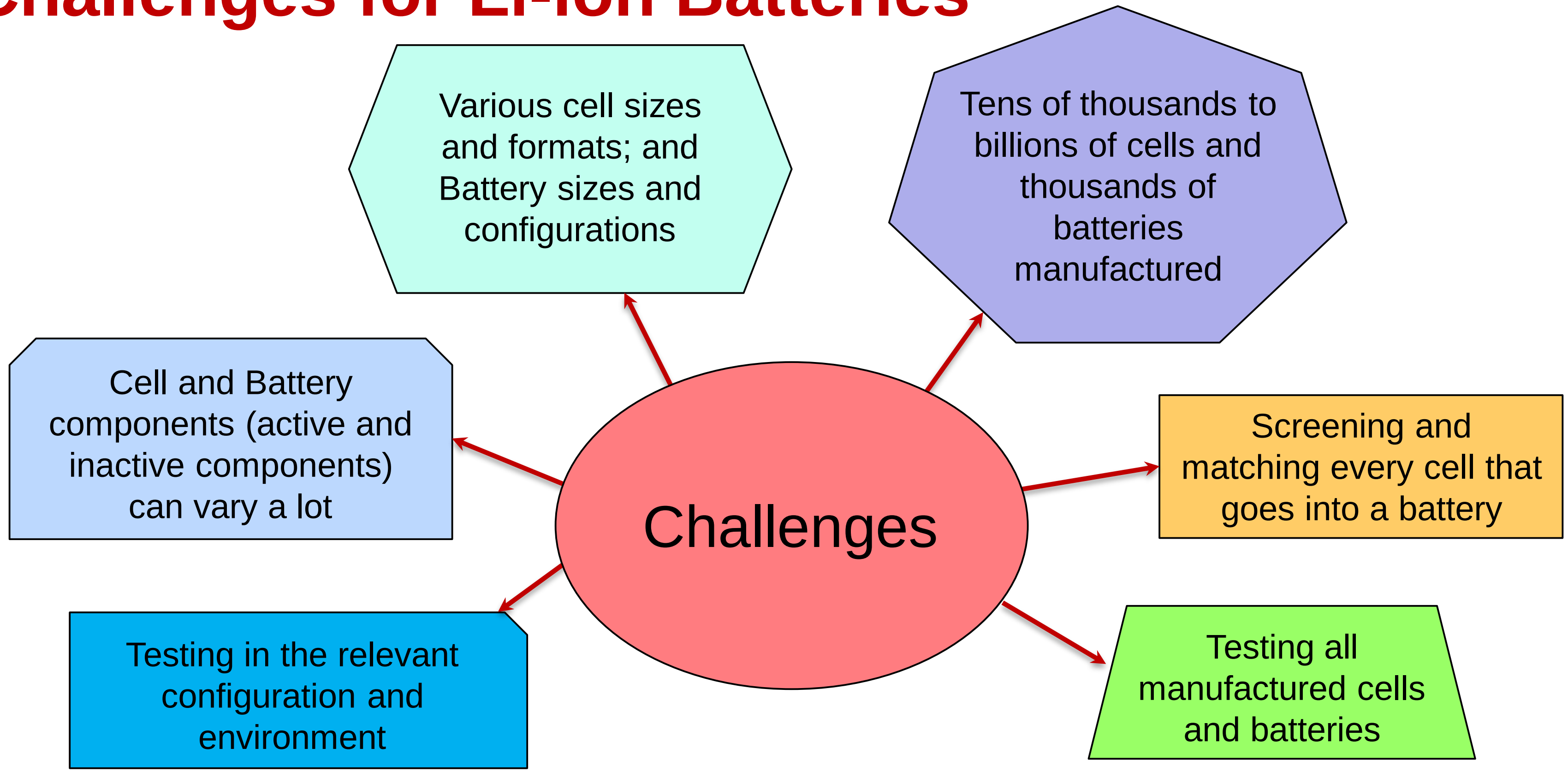
Charge Protocol:
Constant Current/Constant Voltage
Typical Voltage Range
2.7 V to 4.2 V

Anode in fully charged state



Judith Jeevarajan, Ph.D. / UL

Challenges for Li-ion Batteries



Learnings from extensive safety and performance testing on li-ion batteries testing in the past 23 years

- Cell level controls do not necessarily translate to module or battery level controls
- Learned that all safety controls need to be verified by testing at the appropriate level and in the relevant environment
- Hazards such as overcharge and external short have opposite outcomes in pressurized versus non-pressurized environments due to the difference in heat dissipation

Hazard Causes - Electrical

Overcharge

Over-voltage / High-rate Charge

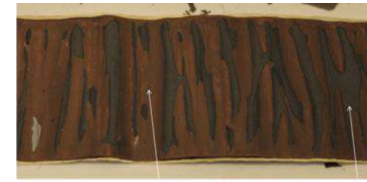
- Electrolyte Decomposition (formation of gases such as H_2, CO and CO_2
- Cathode destabilization and release of Oxygen

Lithium metal dendrites (can pierce the separator causing short circuit)

High Temperatures
Venting
Fire
Thermal Runaway

Overdischarge

Undervoltage / High Rate Discharge → Dissolution of Copper Current Collector → Benign Internal Shorts



Cathode showed heavy copper plating

Delaminated area, where active material was adhered to separator

J. Nemanick *et al.*, International Batt Seminar, March 2016

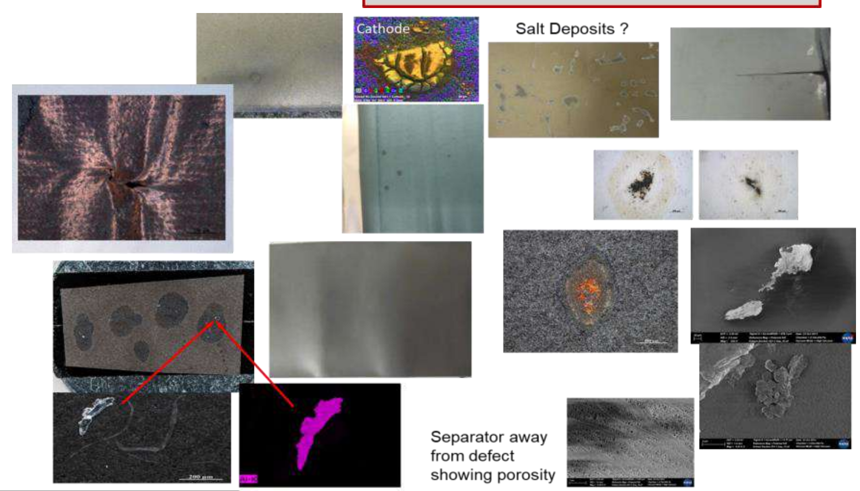
Internal Short

Internal Short

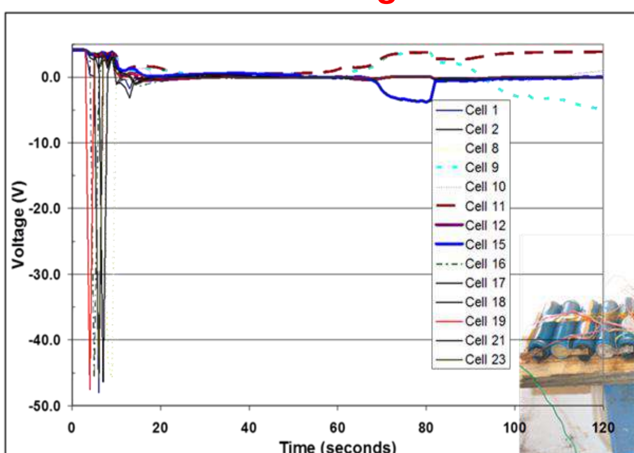
- **Manufacturing Defect**
- **Field Failures**

Manufacturing Defect
Major defects can be screened by manufacturers
Subtle defects need to be identified and screened out during acceptance testing. Defects include poor manufacturing (creases, tears, delamination, etc.), introduction of foreign or native object debris,

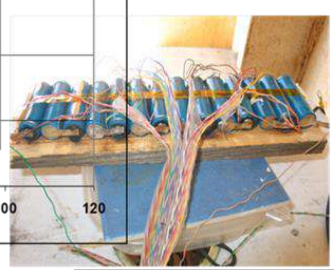
Field Failures
Avoided by **use within manufacturer's specification** (I, V, T); **stringent cell and battery selection and screening criteria**; **stringent monitoring and control (I, V, T)**; **cell balancing**, **health checks** (with issue-recognizable tests); **good thermal design.**



External Short – High and Low Impedance



Only venting observed, no fire
Cell Voltages in bold – No visible signs of Venting or damage, but no voltage;
All others vented with Obvious leakage or discoloration

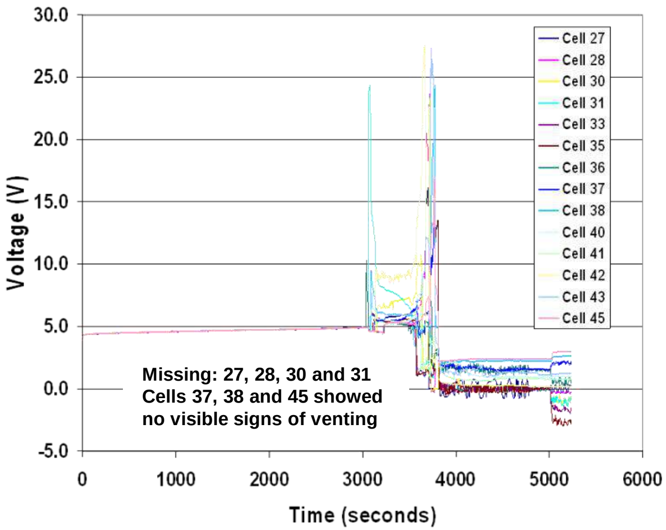


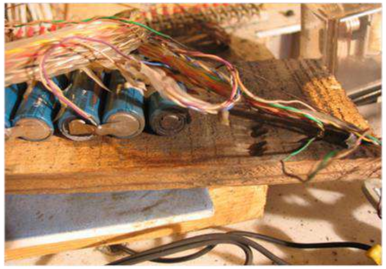
Rapid cell venting within the first 10 seconds

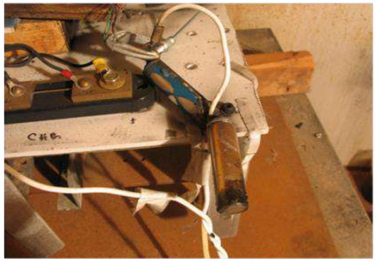
Judith Jeevarajan, Ph.D. / UL

Overcharge Test on a 14S-Cell String of 18650 hard-carbon Li-ion Cells

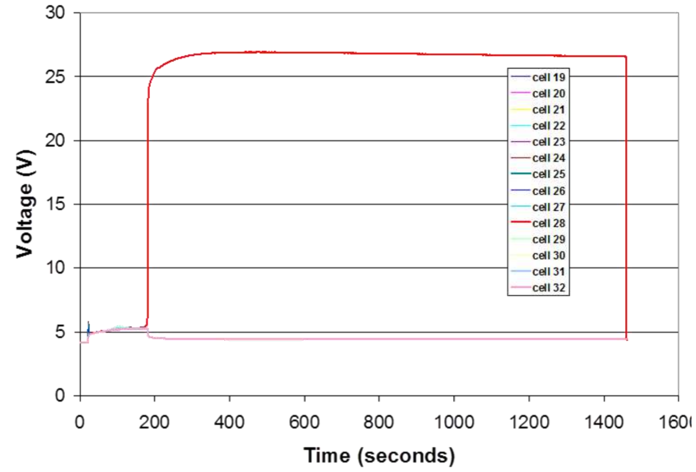
Ambient Pressure



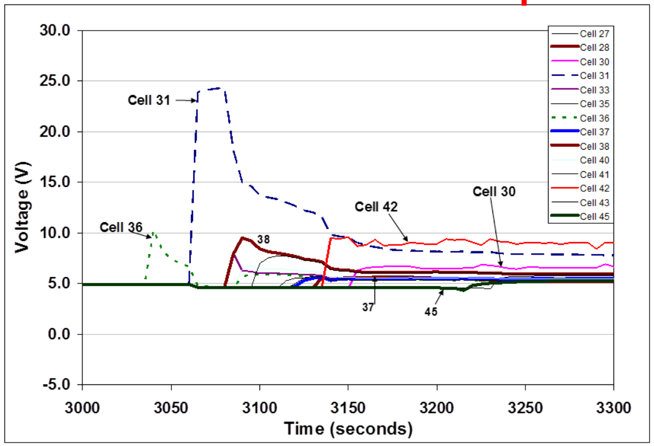


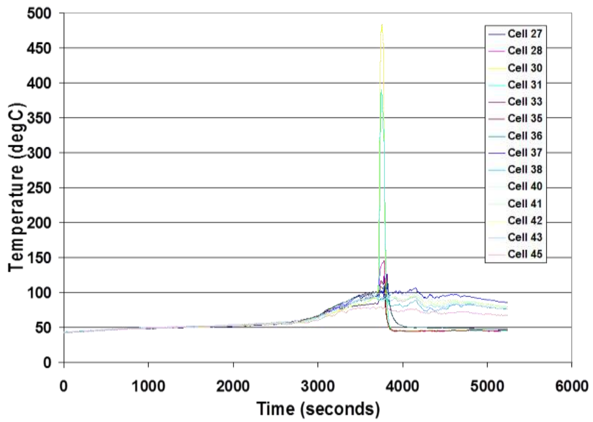


Vacuum

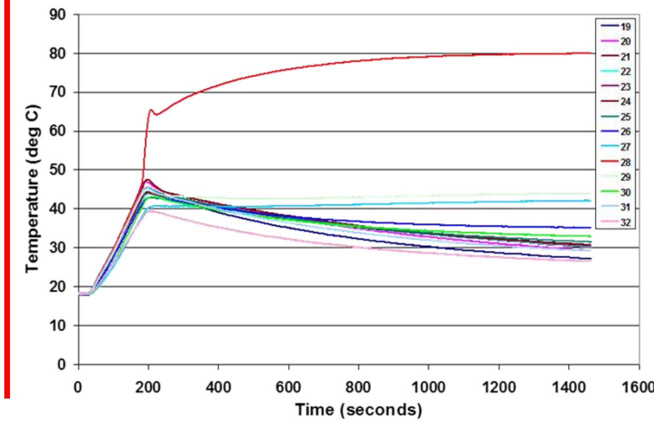


Catastrophic Thermal Runaway



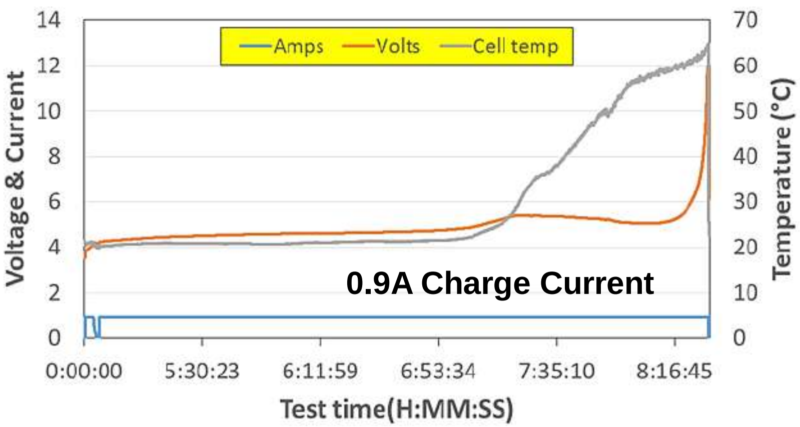


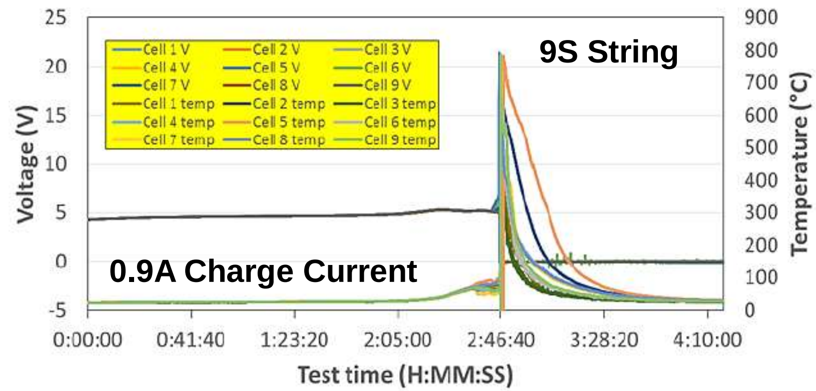
No thermal runaway
Benign CID activation



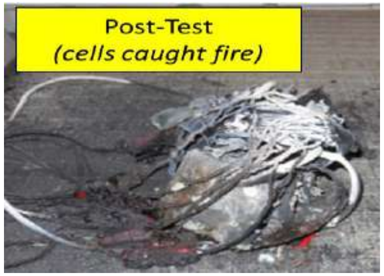
Judith Jeevarajan, Ph.D. / UL

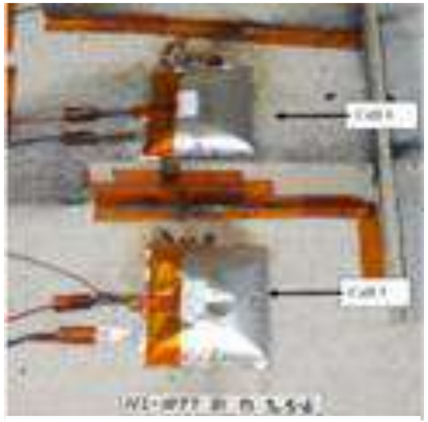
Pouch Cell Studies-Overcharge- Cell vs String (9S) or Bank (8P)





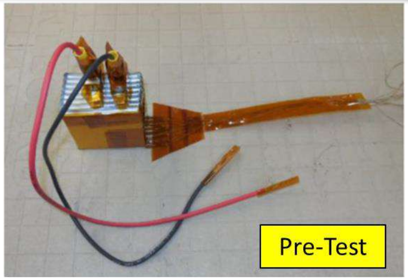
Full Thermal Runaway



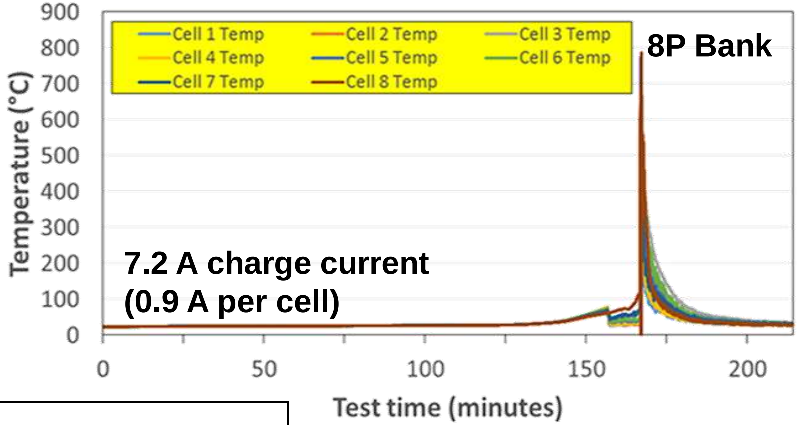


Single Cell

Cell swelling only observed with C/3 overcharge current



Full Thermal Runaway

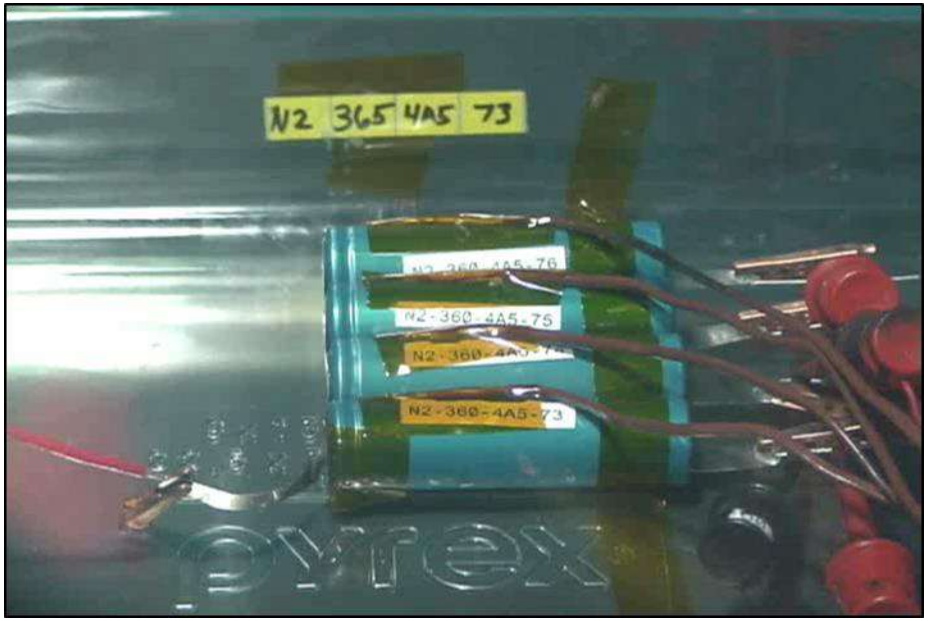


Judith Jeevarajan, Ph.D. / UL

Videos for Overcharge test

Pouch Cells

Cylindrical Cells)



Judith Jeevarajan, Ph.D. / UL

Take-away

1.

- Battery Design - Two-failure tolerance to overcharge/ overvoltage hazard

2.

- Cell level safety controls do not translate to module or battery level controls

3.

- Testing in the relevant battery configuration and environment

4.

- Cell Level Monitoring and Control should be incorporated in BMS

5.

Cell Internal Protective Features:

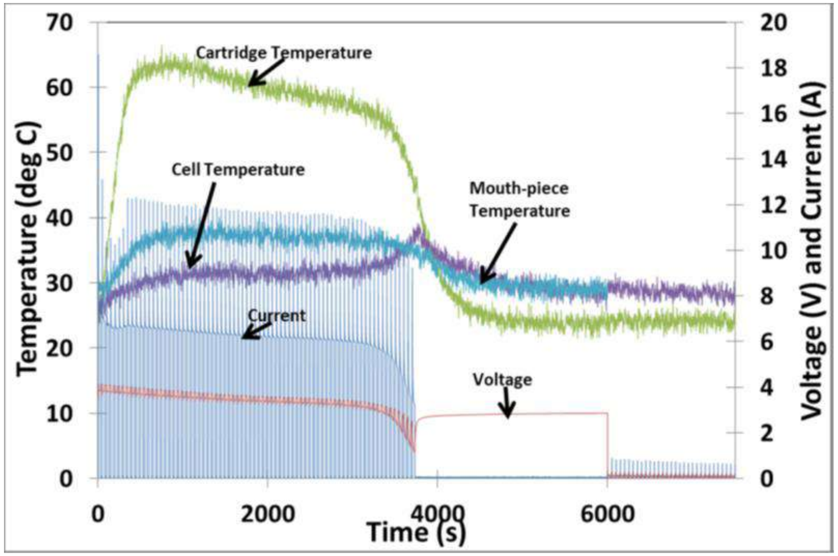
1. Have limitations with respect to voltage, current and temperature
2. Cannot be relied upon for the first two levels of control
3. Should be verified to protect at the appropriate module and battery configuration.

Publications:

1. **J. A. Jeevarajan** *et al.*, Characterization of Commercial Li-ion (Polymer) Cells in Pouch Format", Proceedings of the 2014 Space Power Workshop", April 2014.
2. **J. A. Jeevarajan** *et al.*, "Safety of Lithium-ion Cells at Different States of Charge", Proceedings of the 2014 NASA Battery Workshop, November, 2014.

Overdischarge

- **Discharging a cell below the manufacturer specified voltage** is called **overdischarge**.
- **Dissolution of copper current collector** occurs during overdischarge.
- **Copper deposits on the cathode, anode and separator** forming short circuits.
- When cells undergo **severe overdischarge** into negative voltages, the **cell/cells is/are not usable** any more.
  - When this happens in a string of cells where the BMS is not controlling the cell-level voltages, subsequent charging may result in lithium dendrite formation.
  - Decomposition of electrolyte producing gases occurs during overdischarge conditions also.
- When cells undergo **subtle overdischarges** (below manufacturer's specified end of discharge cutoff but not severe overdischarge), it is possible to have **lithium dendrite deposition on the copper which has deposited on the electrodes and separator.**



Separator burned through

Swelling of damaged cell due to electrolyte decomposition due to overdischarge

Anode with burn marks due to internal shorting

Circled areas show internal short circuit burns. In some cases, the short circuit burned completely through the separator

Judith Jeevarajan, Ph.D. / UL

Take-away

Overdischarge / undervoltage protection at cell and battery level should be provided for all applications

Stringent cell screening, matching required

Cell balancing required

Publication:

J. A. Jeevarajan *et al*., “Hazards due to Overdischarge in Lithium-ion Cylindrical 18650 Cells in Multi-cell Configurations”, Proc. of the 44th Power Sources Conf., June 2010.

External Short Circuit Hazard

Electrical Shock to the cell or battery

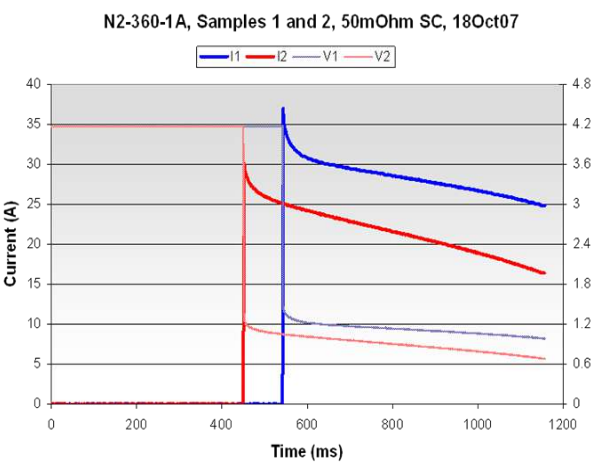
Hard Short – Low impedance: Internal Resistance equal to or less than the cell / battery

Soft Short - High Impedance: load higher than that specified by manufacturer but not lower than the internal resistance of the cell / battery; can be just below the value of protective fuse

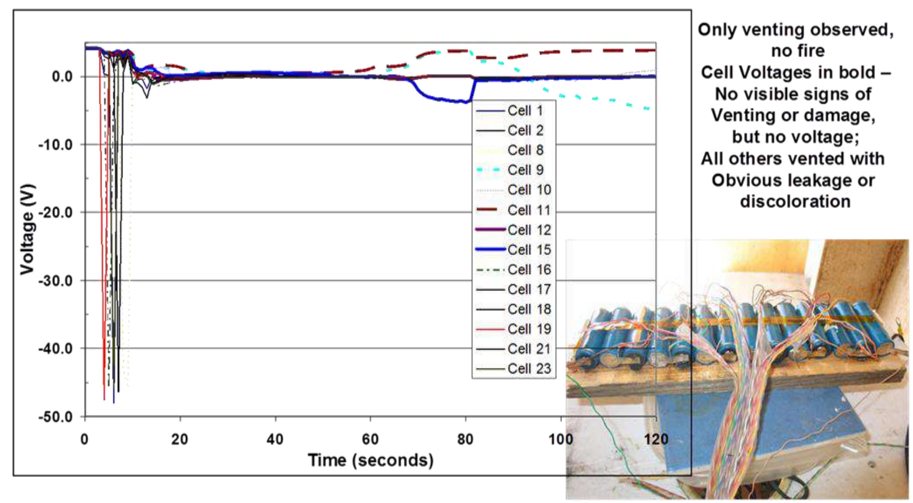
High Temperatures, Venting, Fire

18650 Hard carbon cell with PTC (Single Cell Test)

PTC Activation - occurs reliably



18650 Hard carbon cells with PTC (14S Configuration)



Only venting observed, no fire
Cell Voltages in bold – No visible signs of Venting or damage, but no voltage;
All others vented with Obvious leakage or discoloration

Rapid cell venting within the first 10 seconds

Publications:

J. A. Jeevarajan *et al*., “Limitations of Internal Safety Devices in Lithium-ion Cylindrical Cells in Multi-Cell Configurations”, Proceedings of the 43rd Power Sources Conference, July 2008.

Judith Jeevarajan, Ph.D. / UL

Take-Away

Internal protection at single cell level does not translate to module or battery level

Heat dissipation between cells in battery pack important

Limitations of Protective devices (internal and external) should be determined

Design for minimum risk – anodization, appropriate wires, cables and connectors, no sharp corners, no chafing of wires and cables, etc

Testing in the relevant configuration and environment is critical

Publications:

1. **J. A. Jeevarajan** *et al.*, "Limitations of Internal Safety Devices in Lithium-ion Cylindrical Cells in Multi-Cell Configurations", Proceedings of the 43rd Power Sources Conference, July 2008.
2. **J.A. Jeevarajan** *et al., "*Safety of COTS Lithium-ion Cylindrical Cells in Multi-Cell Configurations in a Vacuum Environment", Proceedings of the 2008 NASA Battery Workshop, November 2008.