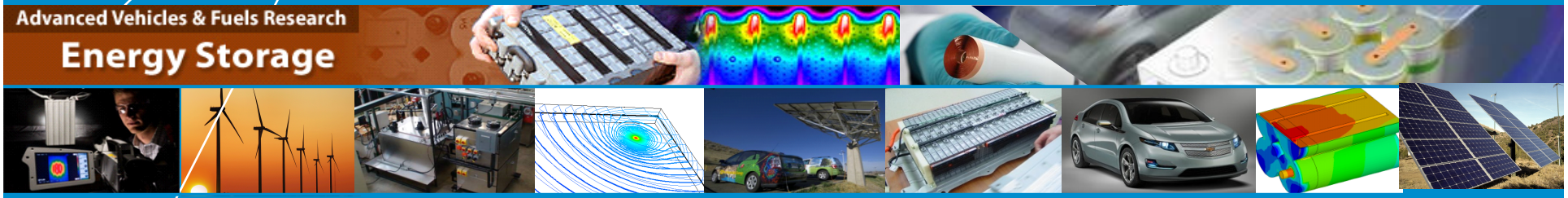
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

33rd ANNUAL
International Battery SEMINAR & EXHIBIT
ADVANCED BATTERY TECHNOLOGIES FOR CONSUMER, AUTOMOTIVE & MILITARY APPLICATIONS
March 21-24, 2016
Fort Lauderdale Convention Center
Fort Lauderdale, FL
LONGEST RUNNING 33rd ANNUAL ANNUAL BATTERY EVENT

NREL Multiphysics Modeling Tools for Designing Safer Li-Ion Batteries



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Golden, Colorado

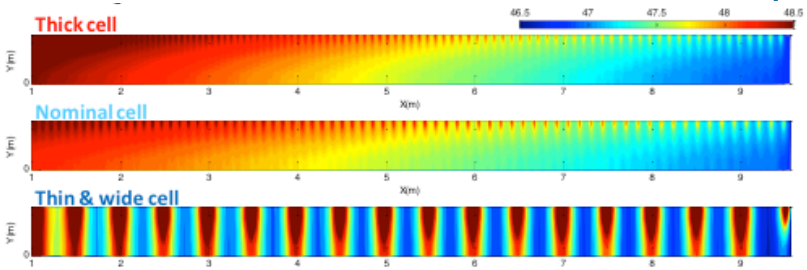
March 24, 2016

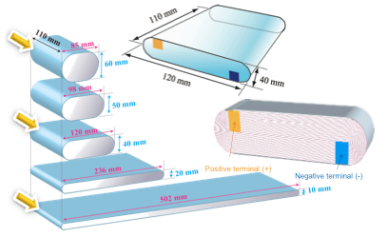
BATTERY SAFETY
Innovations to Improve Lithium Battery Safety from Cell to Systems

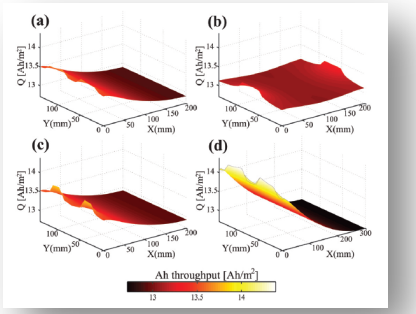
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

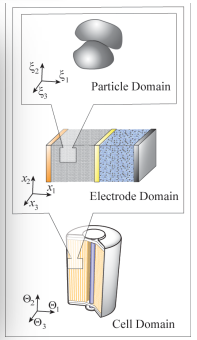
NREL Lithium Ion Battery Safety Portfolio - 1

- Electrochemical-thermal (ETC) models

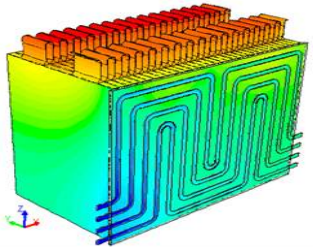


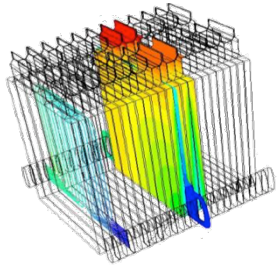


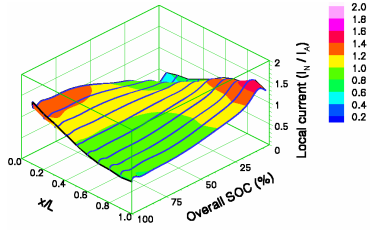


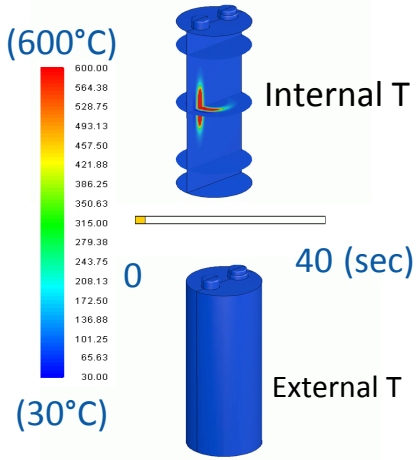


- Computer Aided Engineering for Batteries (CAEBAT)





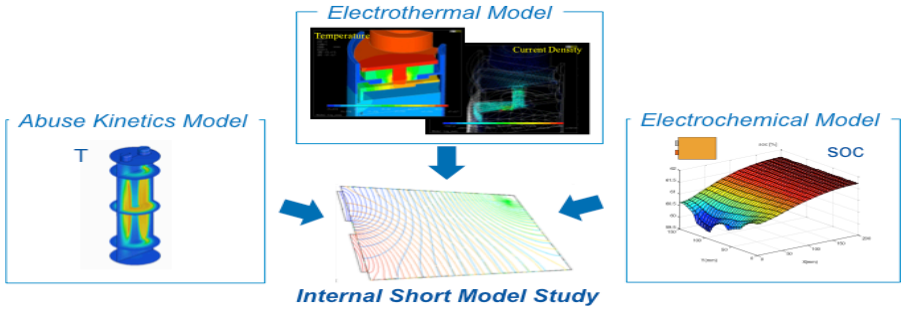




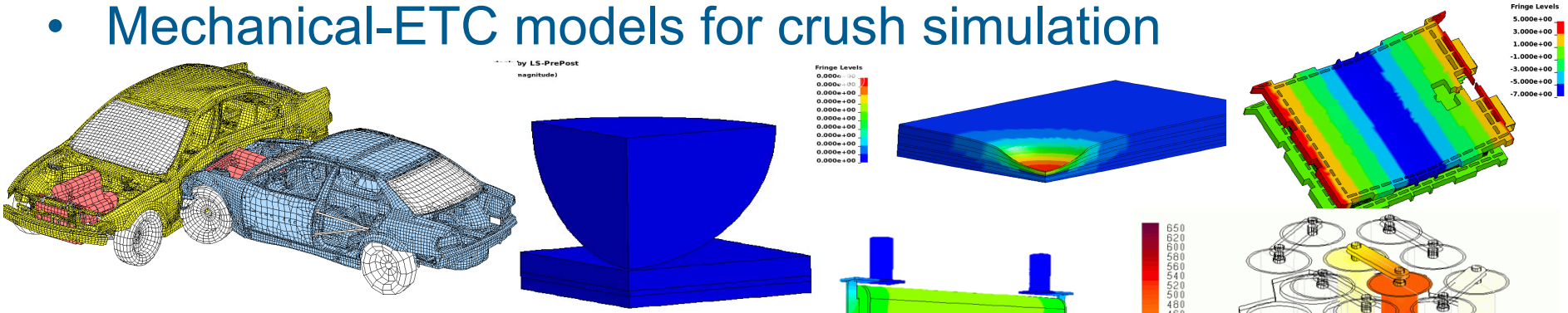
- Chemical kinetics reaction modeling
- Overheating (thermo-chemical) simulations

NREL Lithium Ion Battery Safety Portfolio - 2

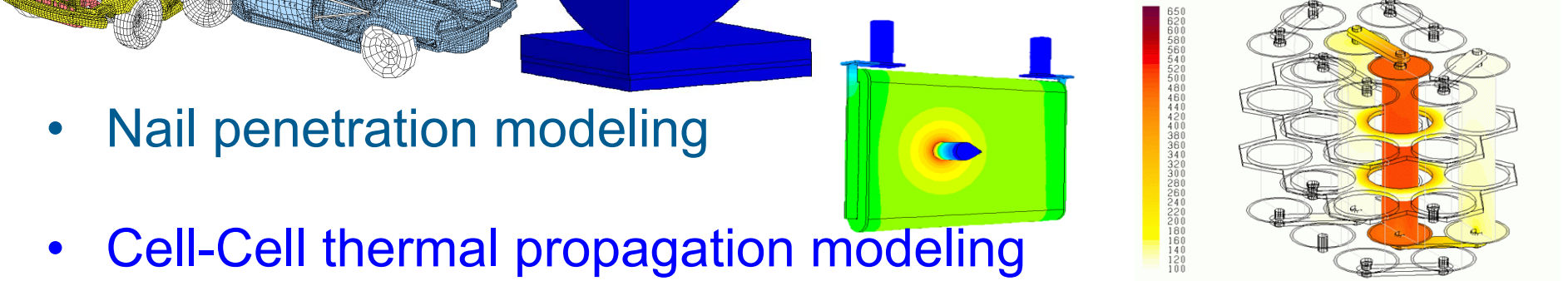
- Internal short circuit modeling



- Mechanical-ETC models for crush simulation



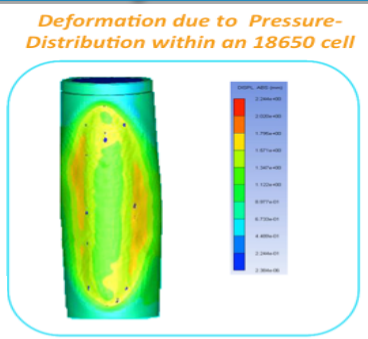
- Nail penetration modeling



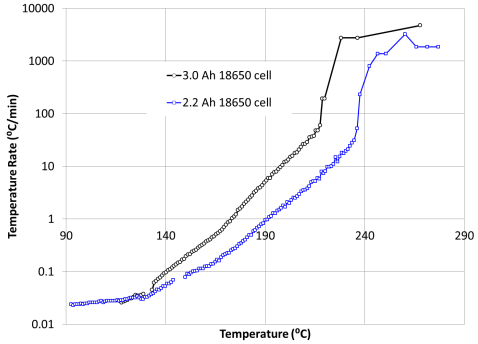
- Cell-Cell thermal propagation modeling

NREL Lithium Ion Battery Safety Portfolio - 3

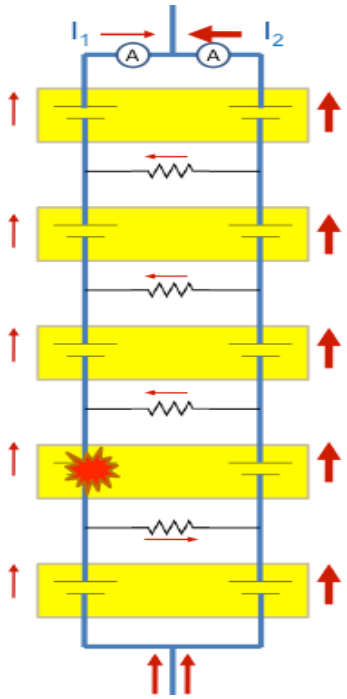
- Overcharge modeling and testing



- Accelerating rate calorimeter testing



- Fail safe design architecture development



- Battery Internal Short Circuit Device (Patented)

Objective/Outline

- Show how NREL safety tools can support our industry partner, Cadenza Innovation
  - Provide further details on
    - NREL Battery ISC Device
  - Discuss validation study with Cadenza
    - Introduce the novel module architecture by Cadenza
    - Cell-to-cell thermal propagation modeling of Cadenza module
    - Comparison with abuse experimental data
    - Demonstrate safe behavior of the Cadenza module

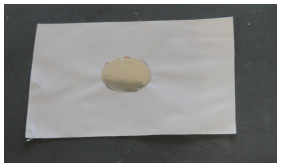
Motivation for Battery ISC Device

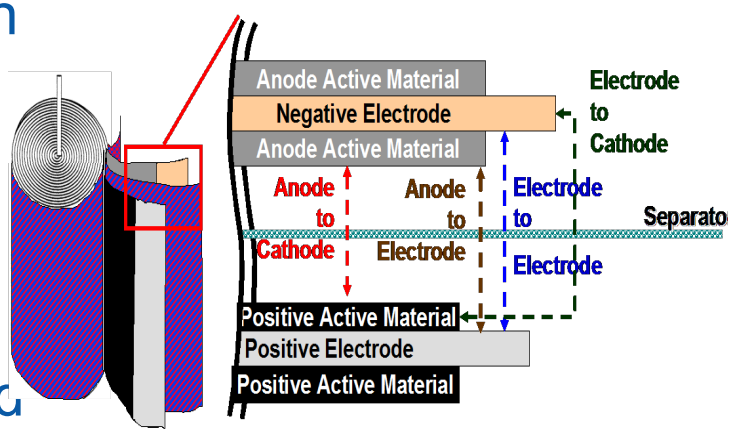
- One changeling safety issue is internal short circuit (ISC)
- New designs/materials R&D underway to improve ISC safety
- The challenge is how to evaluate these improvements
- Existing methods to trigger ISC (penetration or crush) perceived by many to be deficient and not representative
- NREL/NASA developed a very thin, implantable "thermal switch" to emulate ISC
- Use the ISC emulator to evaluate cell and module safety improvements

NREL Cell Internal Short Circuit Development

- Small, low-profile and implantable into Li-ion cells during assembly
- Key component is an electrolyte-compatible phase change material (PCM)
- The ISC device can be placed anywhere in a cell to create any of 4 types of ISC
- The ISC device is triggered by heating the cell above PCM's melting temperature (of about 40°C – 60°C)
- When PCM melts, a current path is created between positive and negative sides

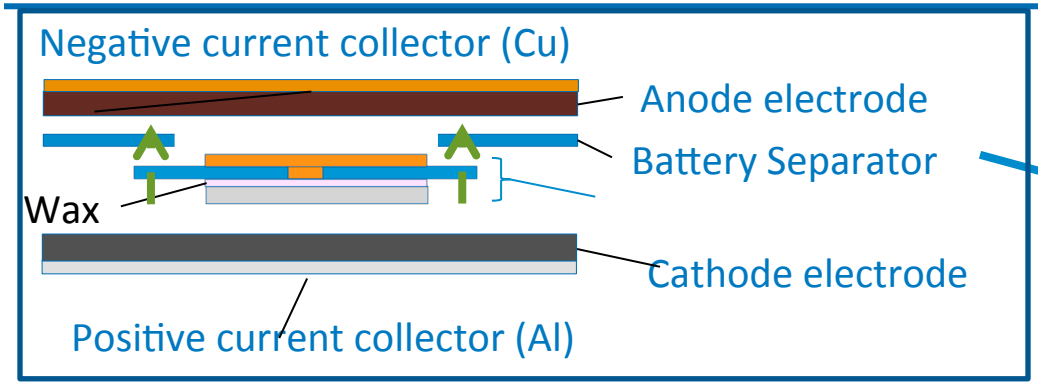
Patented ISC Device

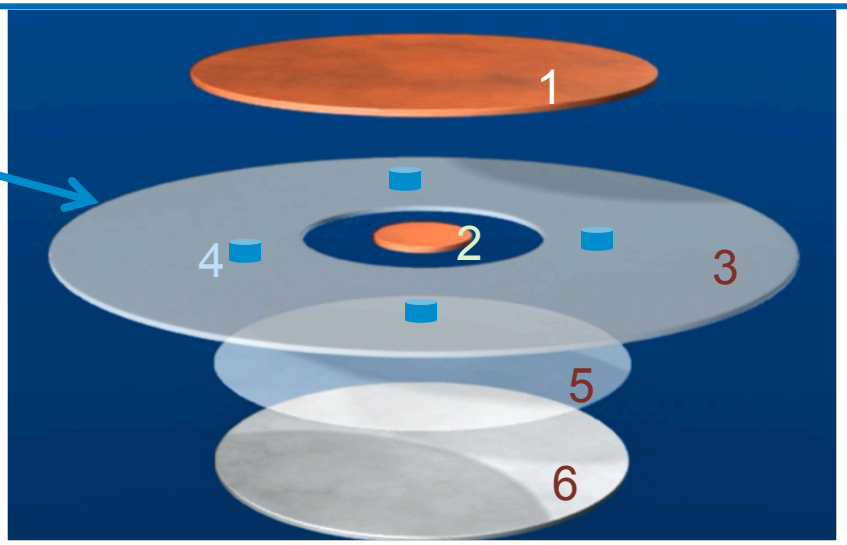




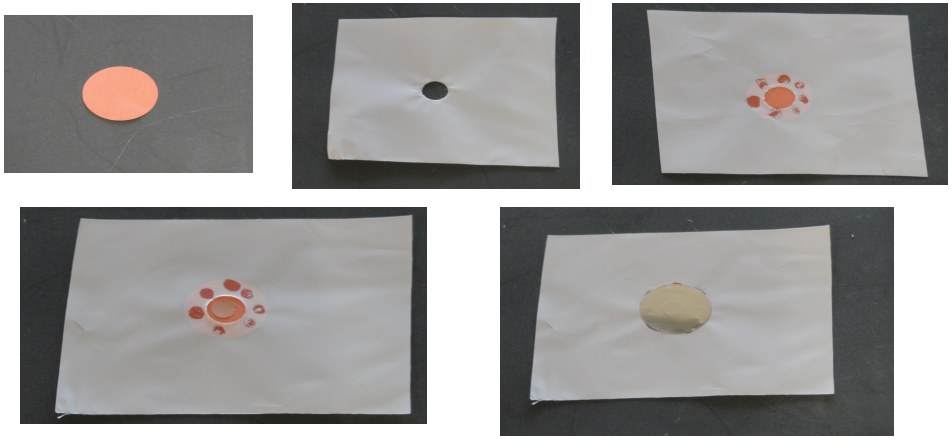
Spiral wound battery shown – can also be applied to prismatic batteries.

NREL/NASA ISC Device Design





Graphics are not to scale
and for illustration only



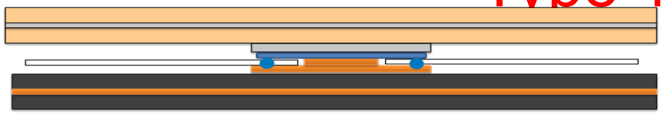
Top to Bottom:

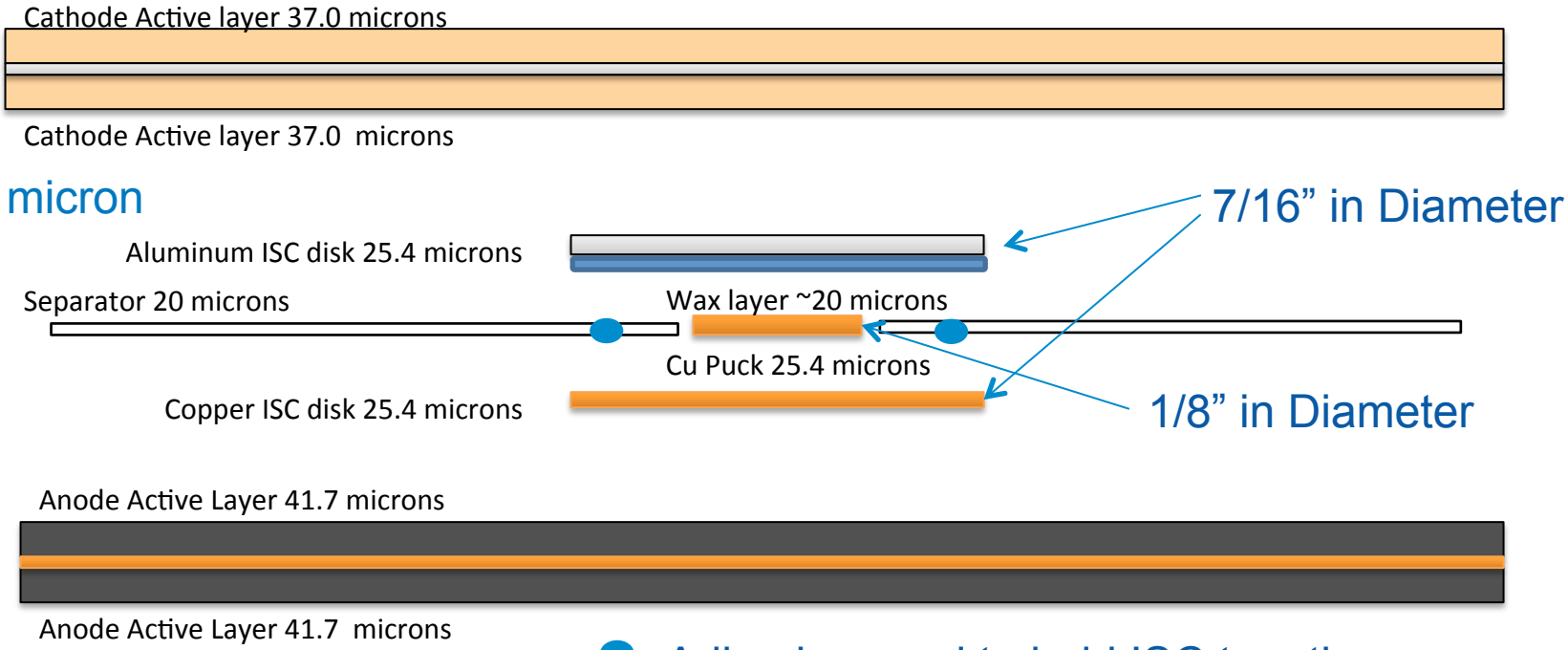
1. Copper Disc
2. Copper Puck
3. Battery Separator
4. Adhesive/glue
5. Phase Change Material (wax)
6. Aluminum Disc

ISC Device Example for a Type 1 Short

Anode active material to Cathode active material

Type 1

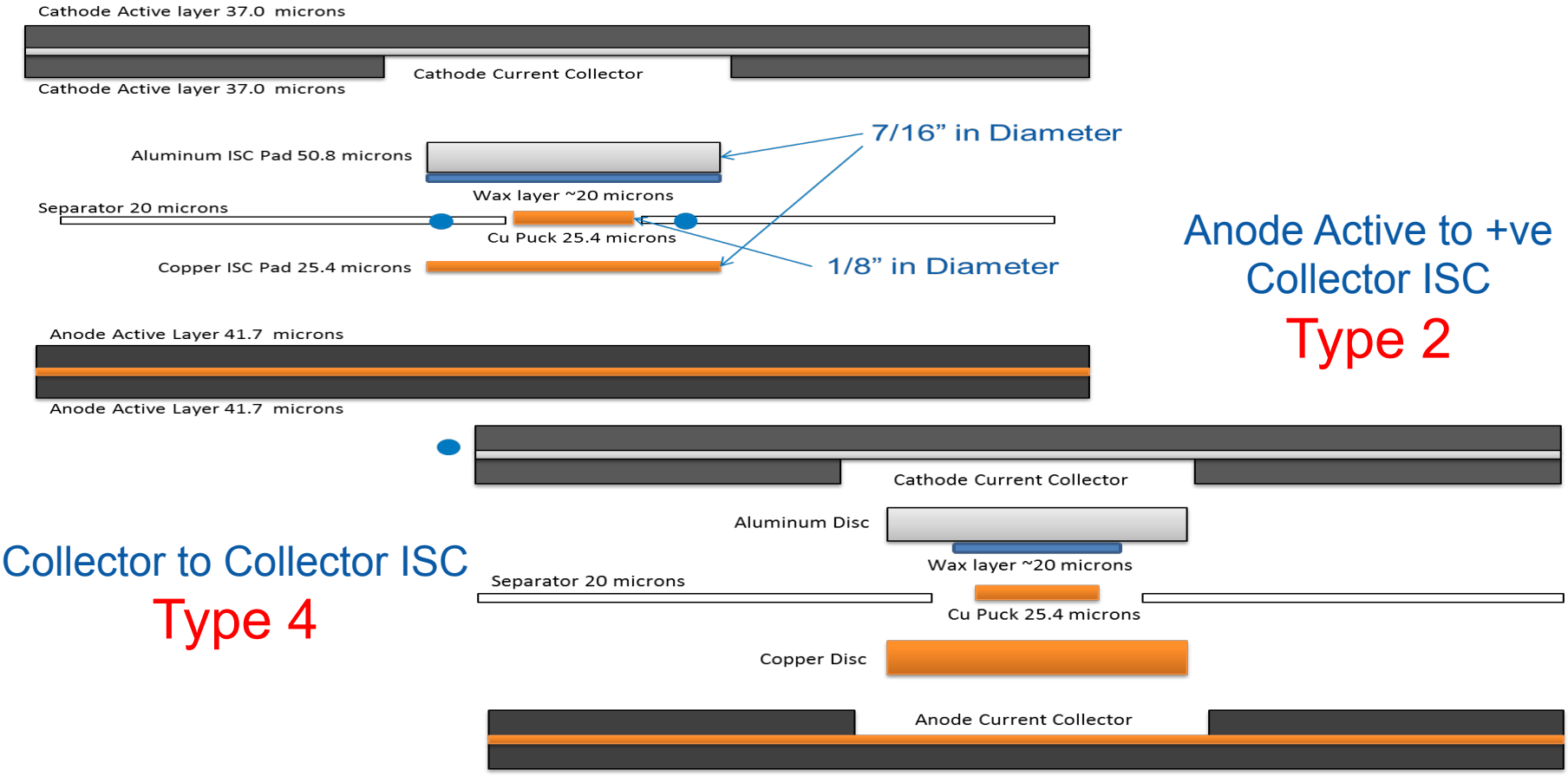




Patented

Adhesive used to hold ISC together.

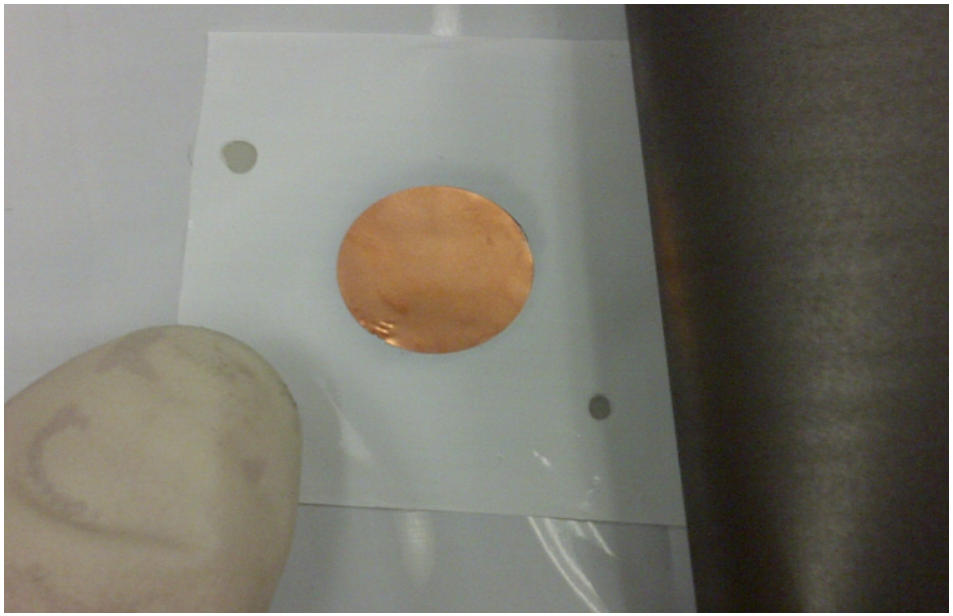
Other types of ISC



Example Test Results of Cells with ISC Device

- NREL built ISC devices (in Golden, CO)
- Sent ISC device to E-one Moli (in Canada)
- E-one Moli implanted the ISC Device in 2.4Ah18650 Cylindrical Cell (NCA/graphite) during electrode winding
- E-one Moli assembled the cell and did formation
- Cell capacity did not change with ISC Device in them
- E-one Moli sent the modified cells to NASA (Houston, TX)
- NASA activated the ISC device by heating the cells to observe safety behavior

ISC Implantation – in E-one Moli Cells
18650 NCA/graphite – 2.4 Ah



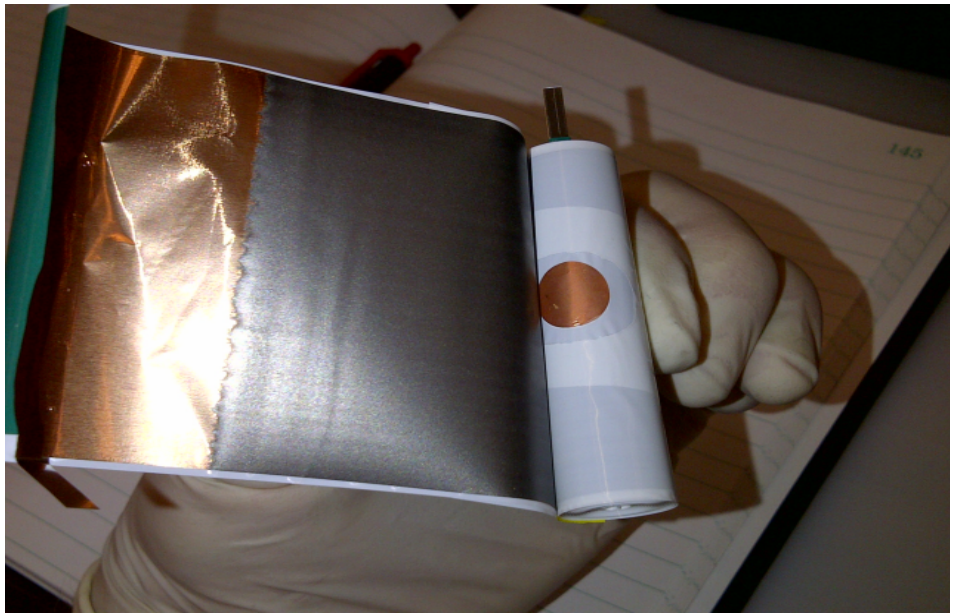
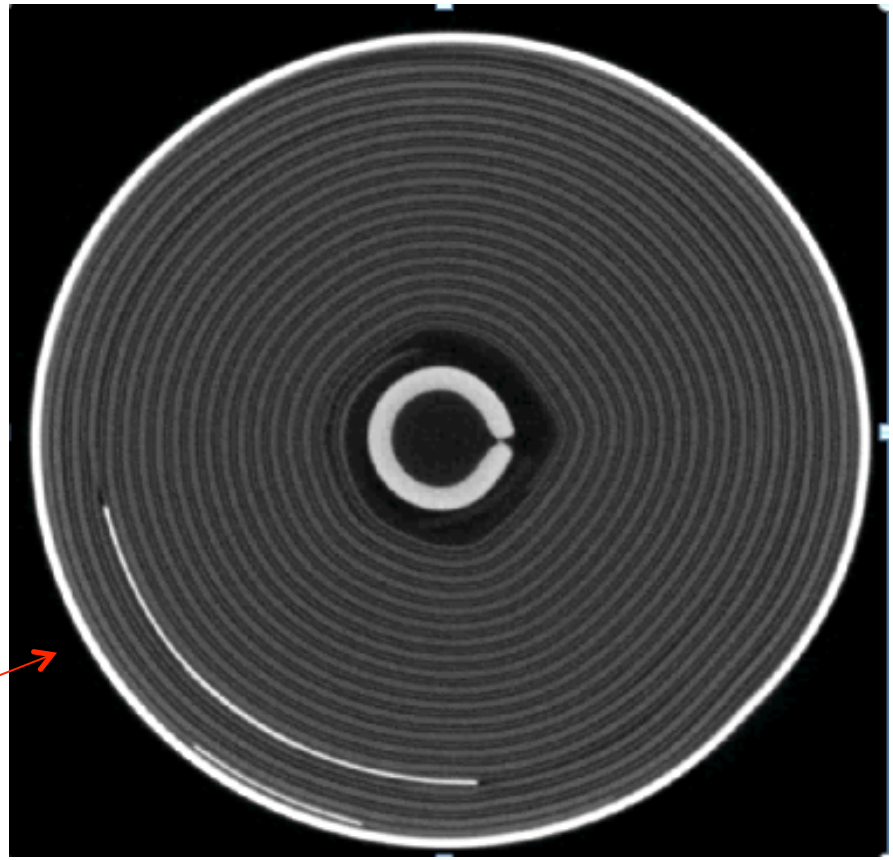


Photo Credits: Mark Shoesmith, E-One Moli

CT Scan of ISC in E-One Moli Cell

Click on Image to see video approximately 10 seconds into video the ISC will appear in the lower left hand corner of the cell.



ISC Device inserted

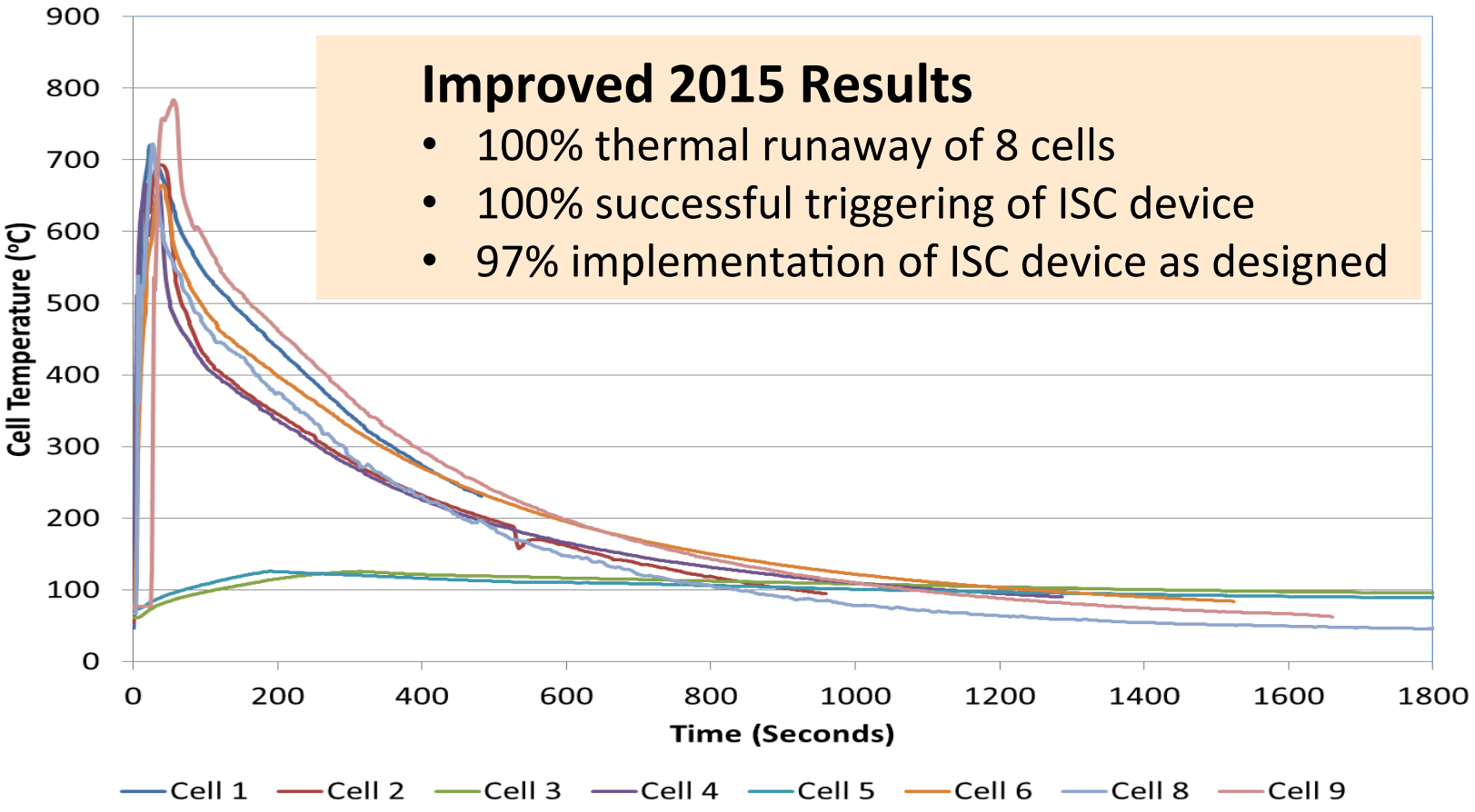
Photo Credits: Mark Shoesmith, E-One Moli

Type 2 (Al-Anode) Repeatability Study - 2014

Cell	Successful Formation	Successful Activation?	Thermal Runaway?
1	Yes	Yes	Yes
2	Yes	Yes	Yes
3	Yes	Yes	No
4	Yes	Yes	Yes
5	Yes	Yes	No
6	Yes	Yes	Yes
7	Yes	No	-
8	Yes	Yes	Yes
9	Yes	Yes	Yes
10	Yes	No	-

2 out of 10 ISCs did not activated (quality issues during fabrication)
6 out of 8 went to thermal runaway

Type 2 ISC – 75% Repeatable Results -2014



Al to Anode (2) ISC Activation
18650 Cell Activation – 100% SOC

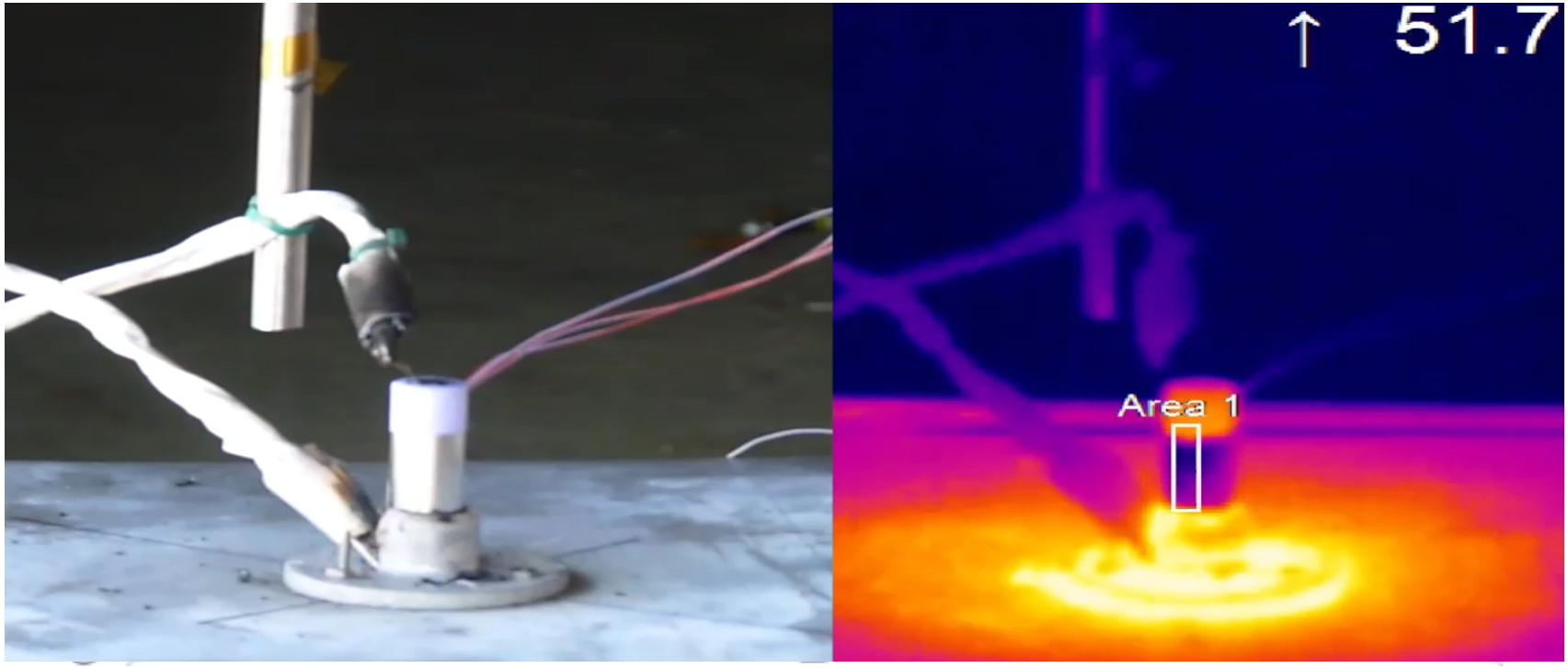
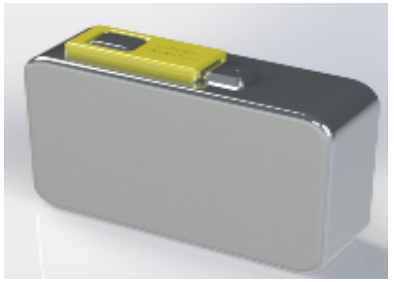


Photo Credit: Mark Shoesmith, E-One Moli

A Novel Li-ion Packaging Technology: High Energy, Low Cost, Safe

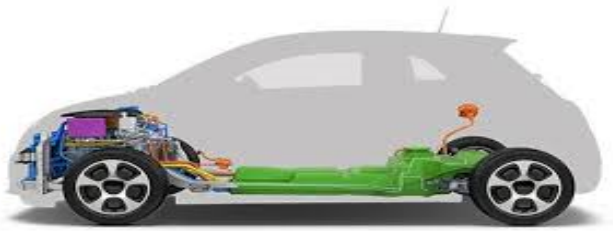
- **Credenza's large prismatic cell technology for grid storage and PEV**
  - Uses of commoditized 26mm jelly rolls – "ease of supply"
  - Proprietary housing material with thermal quenching ability developed by Morgan Advanced Materials
  - Large cells ranging from 30Ah to 200Ah in development
  - Low cost $125/kWh
  - Ability to survive internal short without cascading allows high module energy density
  - No expansion and contraction during cycling



110 Ah demo cell

- **US Department of Energy/ARPA-E Range Project Team:**
  - Cadenza Innovation LLC (Principal), Fiat Chrysler Automobiles, NREL, Samsung SDI NA, Morgan Advanced Materials, Magna Styer Battery Systems NA, Alcoa, Karotech LLC, and Impact Design LLC

Using NREL's ISC Device has shown non-cascading feature of cells



- **Indented application of ARPA-E project**
  - Fiat 500e (24kWh original battery)
  - DEMO battery project: 38kWh (in the same volume)

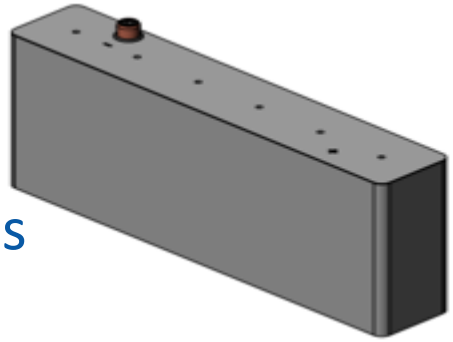
110 Ah demo cell

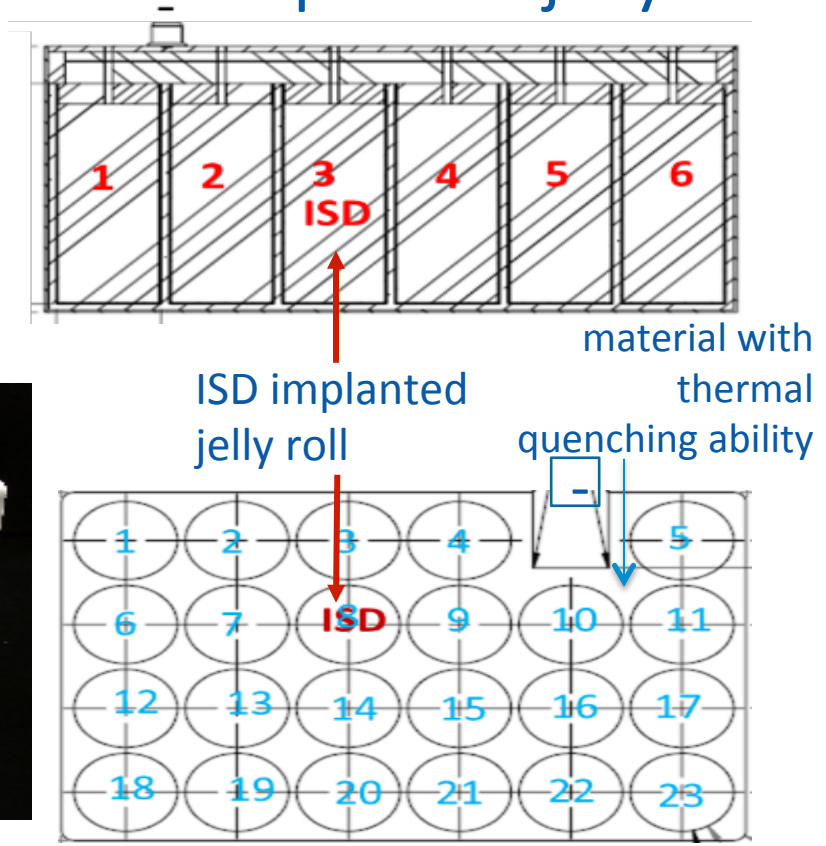
- **A Proof-of-concept cells to date:**
  - Single row cell (Gen-0 cell): 30Ah (NMC) & 36Ah (NCA); and
  - 23 x jellyroll array: 80Ah (NMC) & 90Ah (NCA)
  - 24 x jellyroll array: 110 Ah prototype cell currently in validation

ISC Device in A 30Ah Gen-0 NCM cell and a 90 Ah Gen-1 NCA

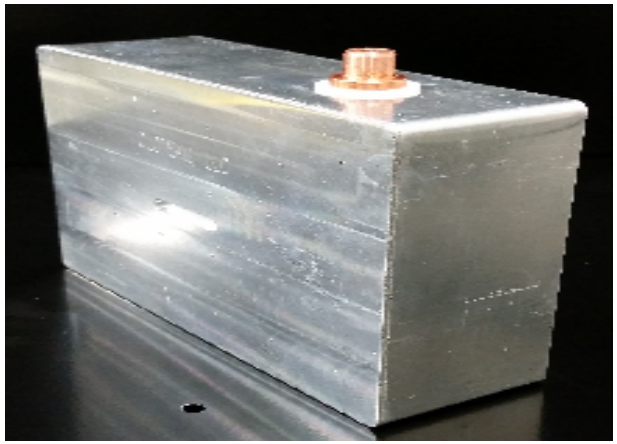
One Cell with internal short circuit device implanted jelly rolls

30Ah Gen-0 cell consisting of 6 x 5Ah NCM jelly rolls



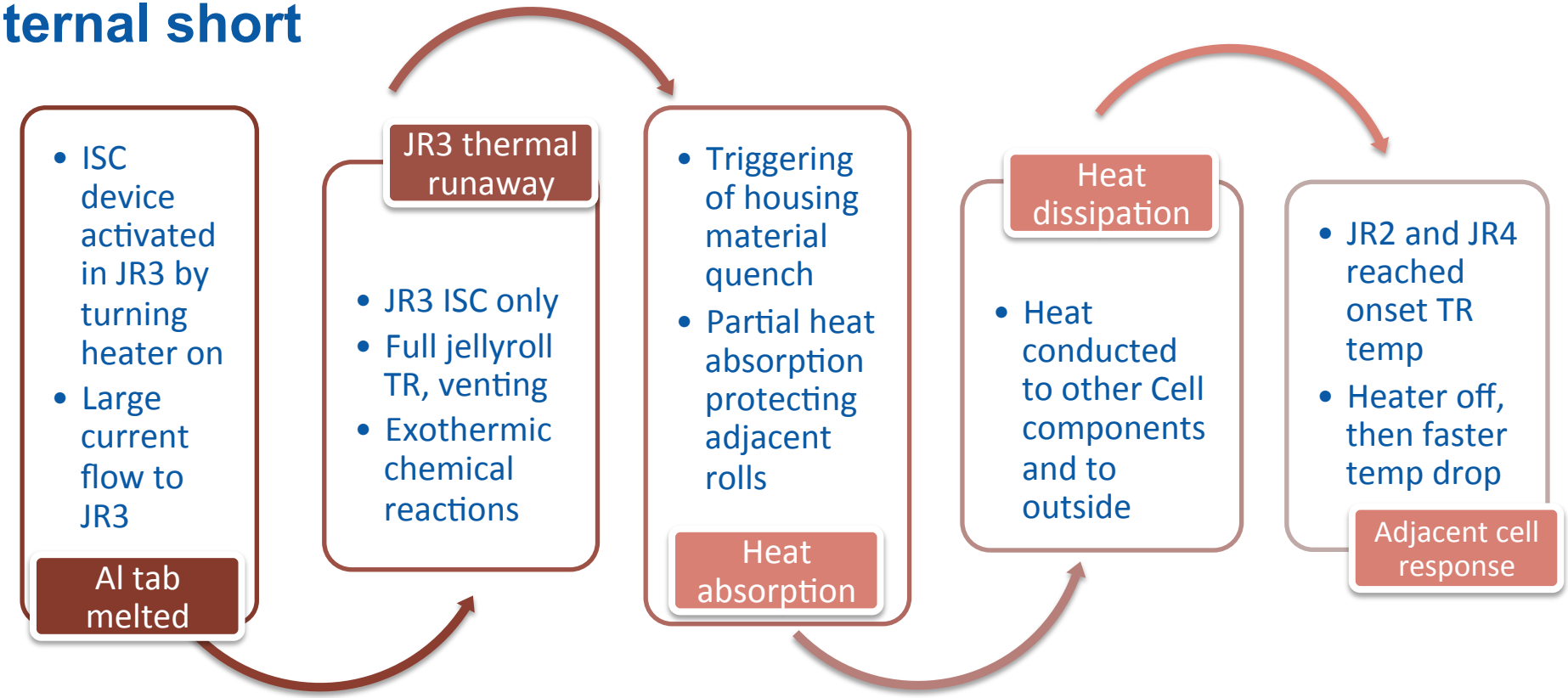


90 Ah Gen-1 cell consisting of 23 x 3.9Ah NCA jelly rolls



Modeled Thermal Behavior of Cell (ISC Triggered)

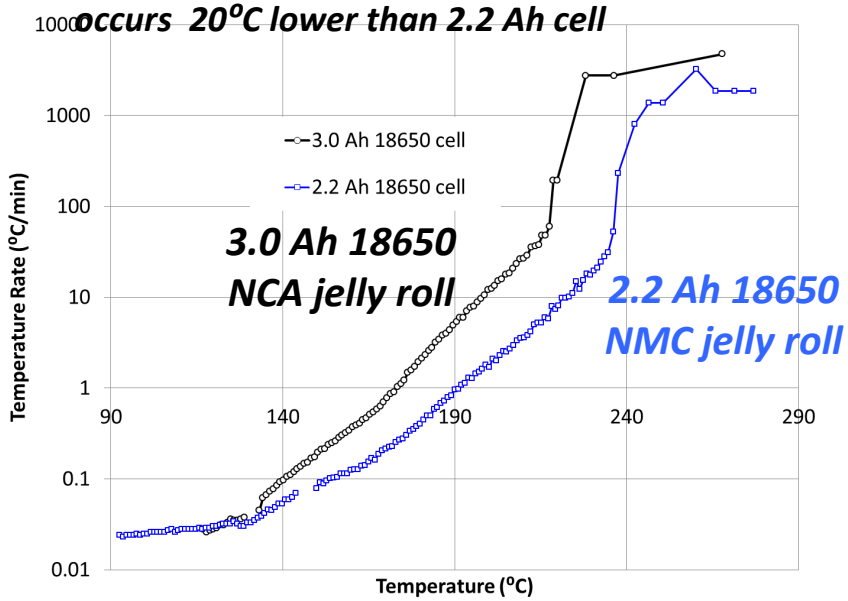
to see if housing material quenches a jelly roll under internal short



ARC Testing – TR Heat Measurement for Model

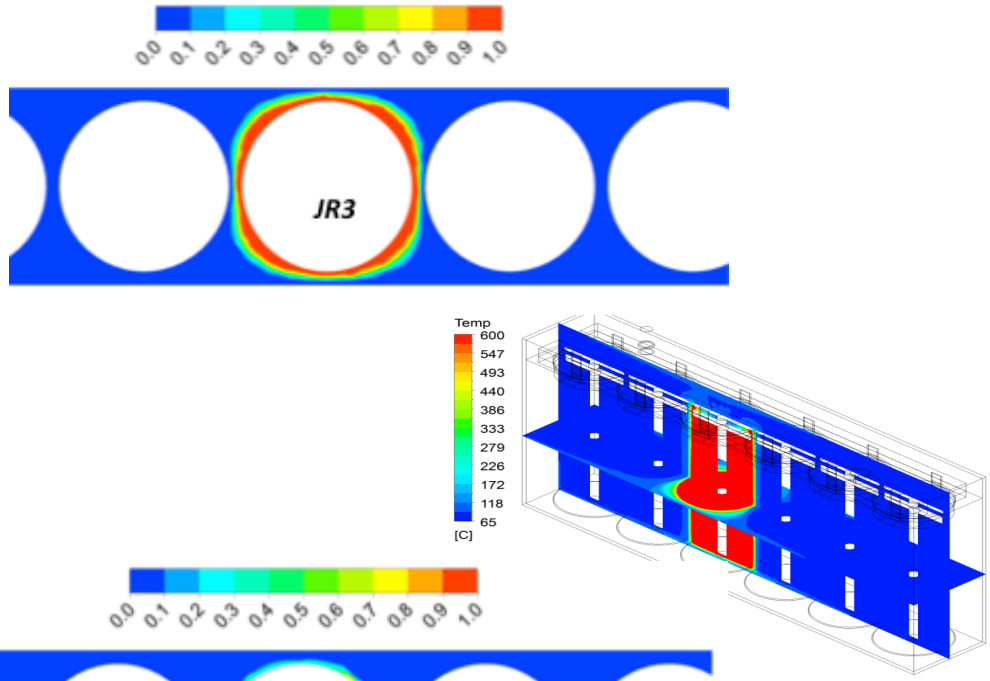
NREL's THT EV Accelerating Rate Calorimeter

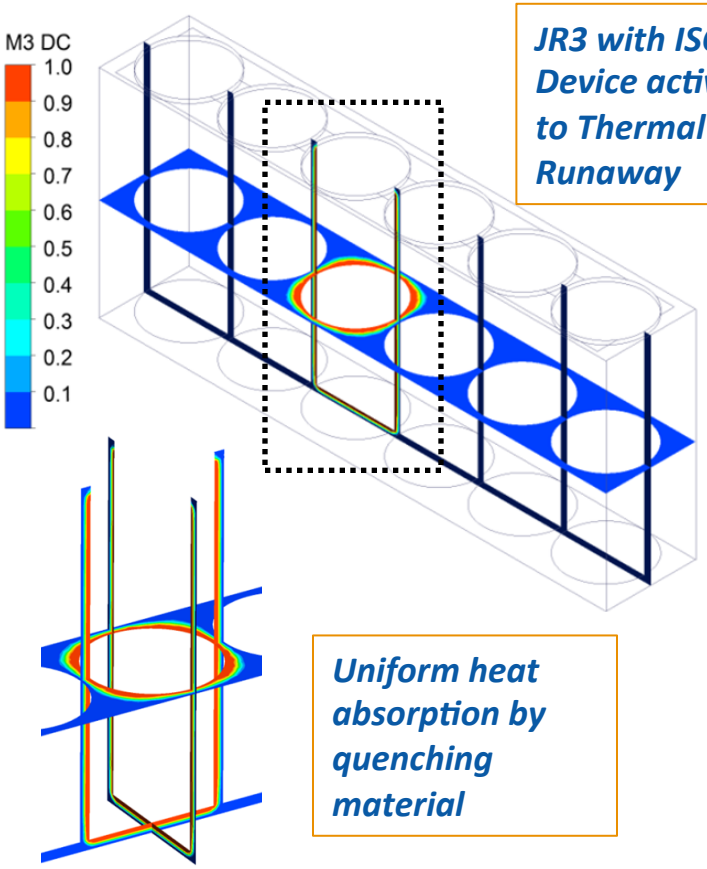
3 Ah jelly roll rapid thermal runaway (>10°C /min) occurs 20°C lower than 2.2 Ah cell



Jelly Roll	Weight (g)	Onset Temp (°C)	Peak Temp(°C)	Venting Temp(°C)	Total Heat Generation (J)	Runaway Enthalpy(kJ/Ah)	Mass Change (g)
18650 3.0 Ah	45.23	111.6	932.4	128.0	31,002.91	10.33	13.27 (29.3%)
18650 2.2 Ah	43.34	91.5	782.7	143.7	25,016.76	11.37	8.97 (20.1%)

Thermal Modeling Showed TR Was Not Cascaded



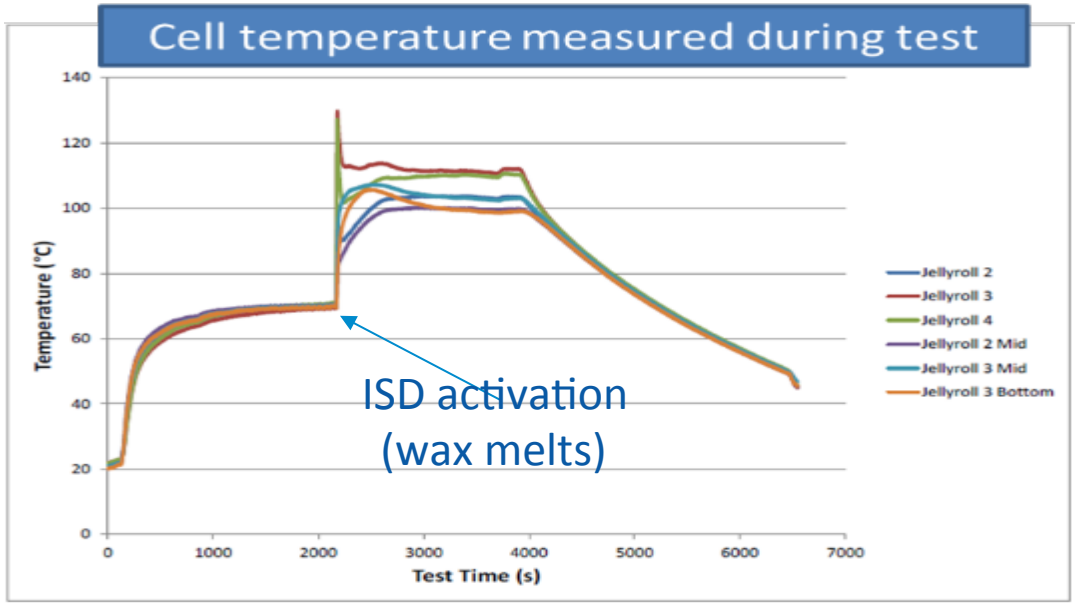


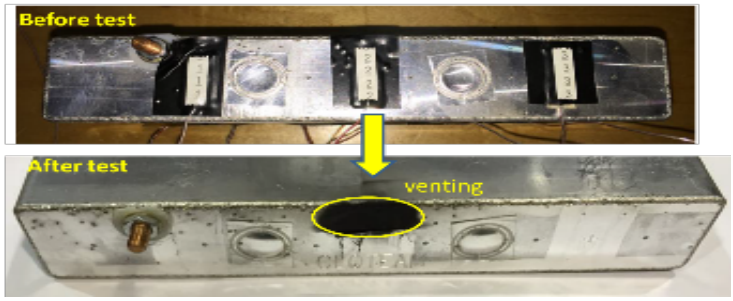
JR3 with ISC Device activated to Thermal Runaway

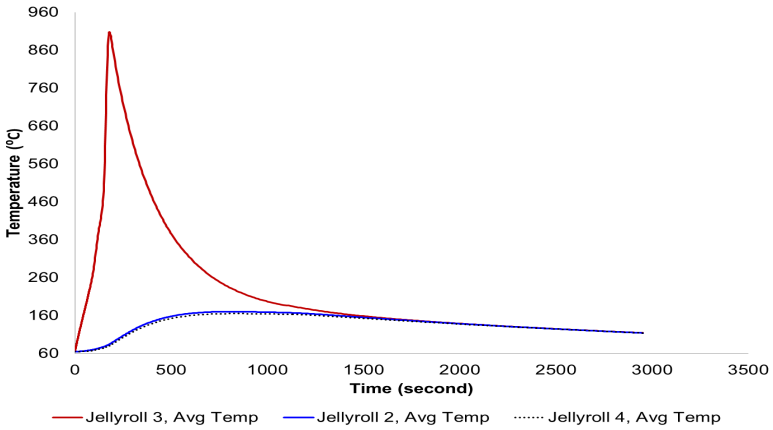
Uniform heat absorption by quenching material

Experiments Showed No Cascading TR

for 30Ah Gen-0 NCM cell after initiating the internal short circuit

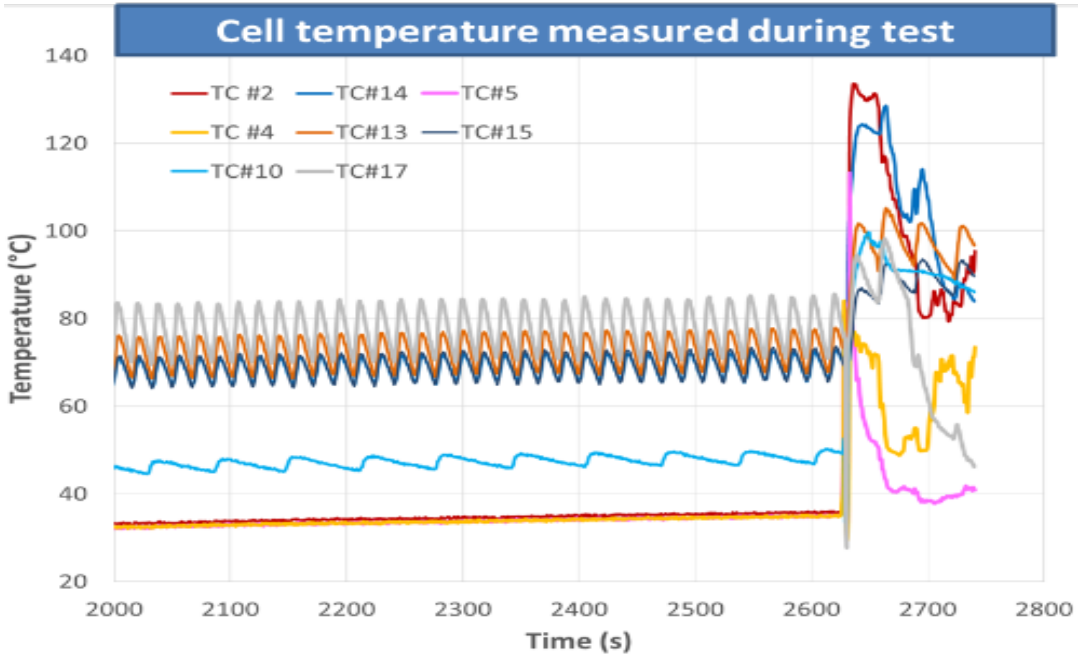




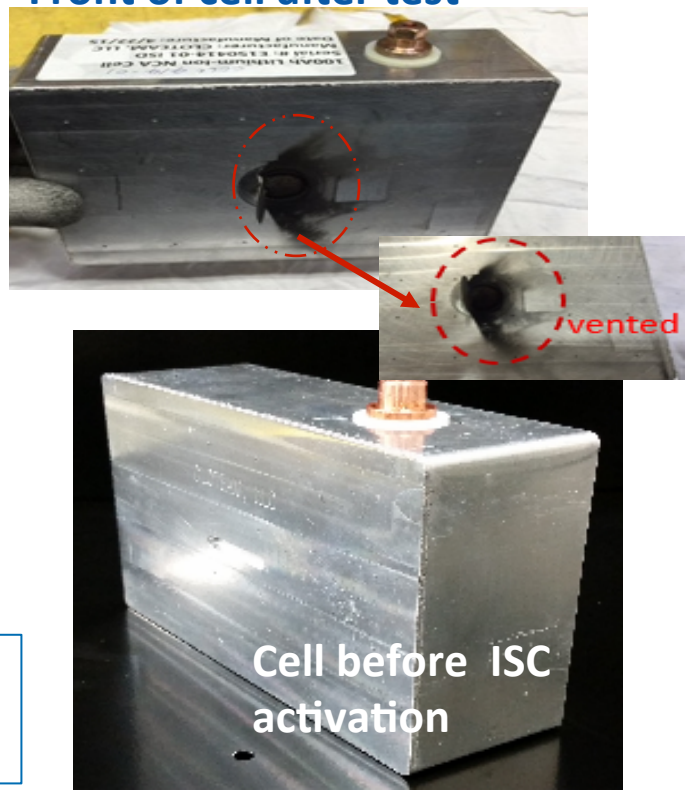


The cell only vented with a max measured cell surface temperature less than 138°C.

Experiments Showed No Cascading TR
in the 90 Ah cell after initiating the ISC (NCA)



Front of cell after test



The cell only vented with a max measured cell surface temperature less than 138°C.

Summary

- NREL has a portfolio of battery safety modeling to evaluate battery design ideas and propose safer designs
- NREL has developed an ISC Device to emulate internal short circuits in any cell format for four type of shorts
- ISC device as a research tool, but repeatable and with consistent results
  - Must be implanted when prototyping cells
  - Not suitable for post-production cells
  - Can be used for cell-to-cell thermal runaway propagation study
- ISC Device can be activated by heating of cell beyond melting point of wax (tunable between 40°C to 60°C)
- Our modeling have shown the safety of a new cell uniquely packaged by Cadenza Innovation and ISC device proven its safety

Thank You!

http://www.nrel.gov/transportation/energystorage/

- Funding for ISC Device and Model Development provided by DOE Vehicle Technologies Office

- Funding for project with Cadenza Innovations provided by DOE ARPA-E RANGE Program

- Appreciate the support by Cadenza Innovation