	NASA Battery Workshop 2014	Presenter R. Button
		Date Nov 19, 2014

NASA Perspective and Modeling of Thermal Runaway Propagation Mitigation in Aerospace Batteries

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November 19, 2014

	Background	Presenter R. Button Date Nov 19, 2014

- High profile Boeing 787 failures of lithium ion batteries in Jan 2013
  - Prompted NASA assessments in their use
- NESC Assessment of NASA's Risk of Thermal Runaway Failures in Lithium Ion Battery Deployments (May 2013)

  - Current ISS use
    - Small OEM batteries – cameras, laptops, etc.
    - EVA suit main power – 20V/40Ah
    - Planned ISS Main Batteries – 120V/GSY 134Ahr
    - ISS Cargo ships – HTV and SpaceX
  - Conclusion
    - Extensive use of supply chain management and cell acceptance screening results in very low probability of thermal runaway.
    - Future batteries should attempt to improve "tolerance" to single cell TR within battery

	Background	Presenter R. Button

- NESC re-assessment of the EVA suit main battery (Summer 2013)

- Relevant Findings

  - Cell screening and acceptance testing significantly exceeded 787 protocols

  - Use conditions and environments significantly less taxing than 787.

  - However, some similarities

    - Limited instrumentation during use

    - No interlocks for low temperature charging

    - No *single cell* thermal runaway test or analysis performed.

	Background	Presenter R. Button

- Crewed Battery Safety Reqt (JSC-20793 Rev C) Feb 2014
  - Major re-organization and re-formatting to evolve from "handbook" to a "standard". Reduced "shall" statements from ~375 to ~100
  - Focused on larger batteries with catastrophic hazards, and allowed tailoring for smaller, OEM batteries
  - Reinforced NASA strengths
    - Cell screening processes
    - Sample qualification testing and battery acceptance processes
  - Added lessons learned from 787 failures
    - Cell monitoring requirements
    - Integrity of electrical connections
    - Single cell thermal runaway propagation assessments

	New Thermal Runaway Propagation Requirements	Presenter R. Button
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- 5.1.5.1 Requirements – Thermal Runaway Propagation
  - A. For battery designs greater than a 80-Wh energy employing high specific energy cells (greater than 80 watt-hours/kg, for example, lithium-ion chemistries) with catastrophic failure modes, the battery shall be evaluated to ascertain the severity of a worst-case single-cell thermal runaway event and the propensity of the design to demonstrate cell-to-cell propagation in the intended application and environment.
  - B. The evaluation shall include all necessary analysis and test to quantify the severity (consequence) of the event in the intended application and environment as well as to identify design modifications to the battery or the system that could appreciably reduce that severity.

Note – Batteries are not ***required*** to be propagation resistant

	Background Summary	Presenter R. Button
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- Boeing 787 assessments prompted self-reflection on current Lithium-ion deployment strategy within NASA

- Typical NASA paradigm had been to emphasize prevention protocols to reduce likelihood of a TR event in lieu of severity reducing design measures.
  - 787 failures **and subsequent design changes** underscored that screening can be imperfect _and_ that there are often reasonable design measures that can greatly reduce severity.

- NASA Battery specialists believed that TR propagation was a foregone conclusion in the high energy density batteries required by NASA missions
  - Projects were accepting the risk, without fully quantifying

- However, new commercial and DOD batteries were being developed that purported to be TR propagation resistant.

PAST STRATEGY

values are notional

FUTURE STRATEGY

- NESC assessment 14-00942 (March 2014) involves both analysis and test elements, and is intended to accomplish three primary goals:
  - Serve as a **pathfinder** for future manned spaceflight battery deployments on how to analyze TR within lithium-ion batteries, how to consider and select severity mitigation strategies, and how to conduct a sufficient test protocol to verify the effectiveness of the strategies selected.
  - Establish NASA "best-practice" battery design features so future, "clean-sheet" battery designs will be more tolerant to single cell thermal runaway.
  - Provide immediate assessment of _four specific battery applications_ within NASA's ISS Program and EVA Project Office and assess possible strategies to reduce TR severity in each specific battery design. The batteries under consideration include:
    - Lithium-ion Rechargeable EVA Battery Assembly (LREBA)
    - Lithium-ion Pistol Grip Tool (LPGT), and
    - The Main EVA Suit Long-Life Battery (LLB).
    - The ISS main battery lithium-ion battery replacement.

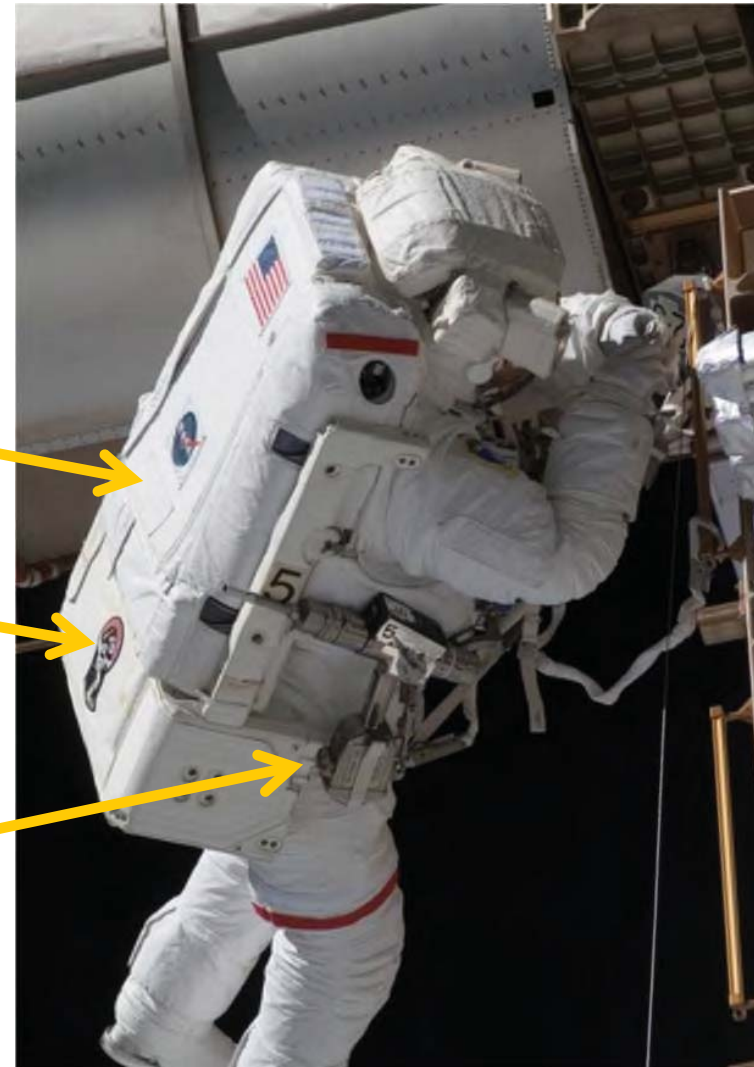|	**EVA Battery Overview**	Presenter R. Button
		Date Nov 19, 2014

EVA Batteries addressed are:

LLB – 650 Wh
Long-life Battery: primary power
for EMU life support, data, comm
80 Cells: 16P-5S config

LREBA – 400 Wh
Li Rechargeable EVA Battery:
glove heaters, lights, camera, etc.
45 Cells: 9P-5S config

LPGT - 89 Wh
Li Pistol Grip Tool
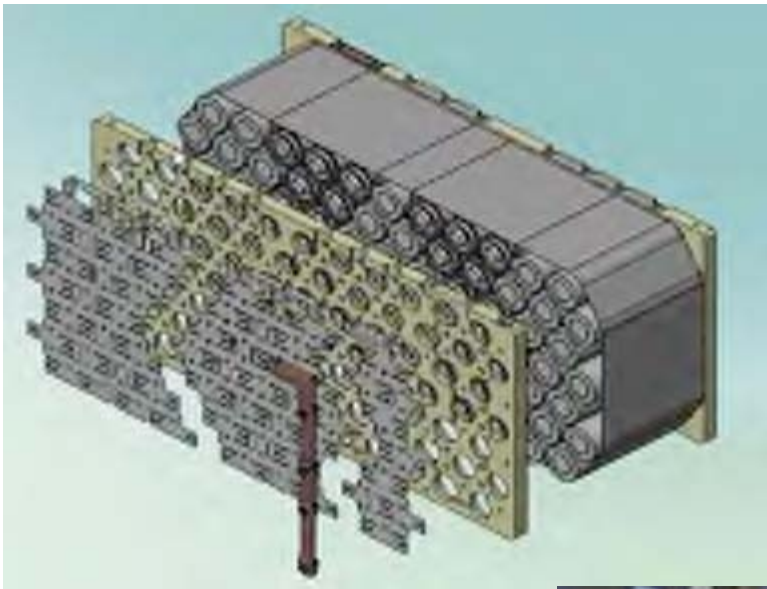10 Cells: 10S config in use
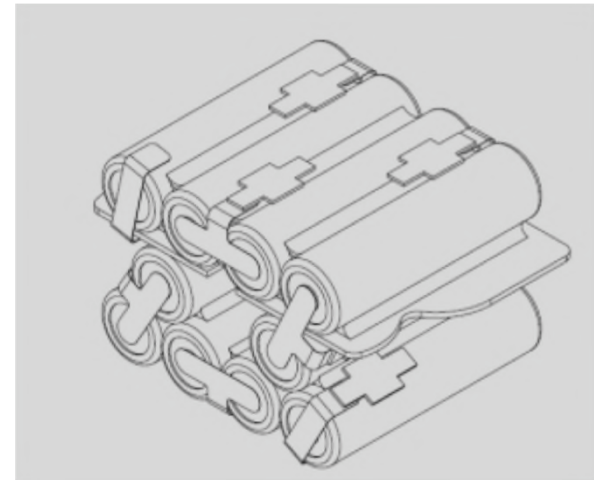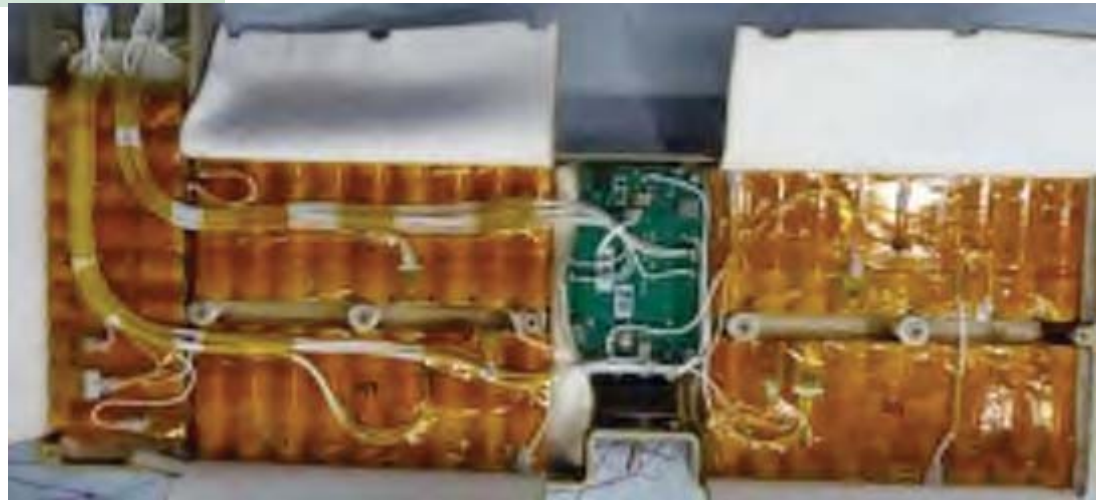   2P-5S charging

Baseline Designs

LPGT – Loose Brick

LLB – Dense Brick

LREBA – Planar Sub-banks

	Thermal Analysis	Presenter
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- A Thermal analysis sub-team has conducted considerable thermal analysis, in concert with testing, to understand heat generated within a failed cell, and estimate heat transport via conduction, convection, and radiation within a network of cells in a battery.

- Internal cell thermal analysis and calorimetry testing has provided insight on the potential for heat generation, however, measuring heat released through venting has been problematic.

- The eventual goal is for the thermal model to become predictive and a tool to explore mitigation measures prior to testing.

- Analysis Team
  - Battery level analysis and mitigations -- Steve Rickman
  - Internal cell models -- Dr. Ralph White
  - Analysis of ARC data and mitigations -- Bob Christie
  - Boeing 787 batteries lessons learned -- Dr. Bruce Drolen

The thermal runaway equations

SEI decomposition

$$\frac{dc_{sei}^*}{dt} = -A_{sei} \exp\left(-\frac{E_{a,sei}}{RT}\right) c_{sei}^*$$

$$Q_{sei} = H_{sei} W_{sei} A_{sei} \exp\left(-\frac{E_{a,sei}}{RT}\right) c_{sei}^*$$

Anode-electrolyte reactions

$$\frac{dc_n^*}{dt} = -A_n \exp\left(-\frac{z}{z^0}\right) \exp\left(-\frac{E_{a,n}}{RT}\right) c_n^*$$

$$\frac{dz}{dt} = A_n \exp\left(-\frac{z}{z^0}\right) \exp\left(-\frac{E_{a,n}}{RT}\right) c_n^*$$

$$Q_n = H_n W_n A_n \exp\left(-\frac{z}{z^0}\right) \exp\left(-\frac{E_{a,n}}{RT}\right) c_n^*$$

Cathode-electrolyte reactions

$$\frac{d\alpha}{dt} = -A_p \alpha (1-\alpha) \exp\left(-\frac{E_{a,p}}{RT}\right)$$

$$Q_p = H_p W_p A_p \alpha (1-\alpha) \exp\left(-\frac{E_{a,p}}{RT}\right)$$

Electrolyte decomposition

$$\frac{dc_e^*}{dt} = -A_e \exp\left(-\frac{E_{a,e}}{RT}\right) c_e^*$$

$$Q_e = H_e W_e A_e \exp\left(-\frac{E_{a,e}}{RT}\right) c_e^*$$

The general energy balance

$$Q_{total} = Q_{ech} + Q_{sei} + Q_n + Q_p + Q_e$$

$$\rho C_p \frac{dT}{dt} = Q_{total} - \frac{h(T - T_{amb})}{l_p + l_s + l_n}$$

Reference

Chiu, Kuan-Cheng, et al. "An electrochemical modeling of lithium-ion battery nail penetration." *Journal of Power Sources* 251 (2014): 254-263.
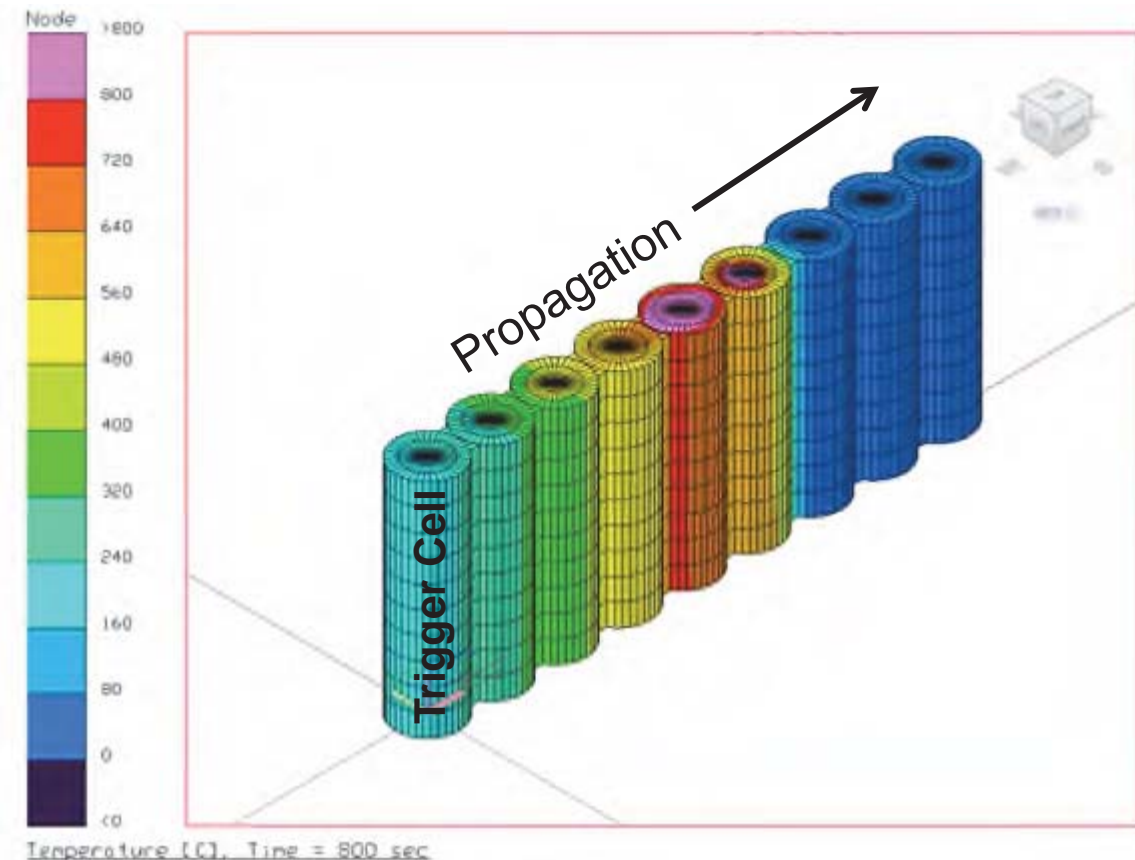
Numerous iterations of battery-level thermal models have been studied.

Early models focused on original 9P "picket fence" configuration with adjacent cells in direct contact via an adhesive fillet.

Analysis indicated heating was sufficient to trigger adjacent cells into thermal runaway.

Led to separation of cells using capture plates.

Early Thermal Model of 9P Picket Fence Configuration with EndCell Trigger: Assumes All Heating Through Cell Can, Radiative and Convective Relief

Most recent version correlated to test run 53 in an LREBA enclosure with open vent holes.

Model represents a segment of LREBA enclosure and includes:
- internal heat generation
- triggering based on jellyroll temperature
- mass loss on venting
- heat generation due to I^2R + chemical reactions due to decomposition (scaled from cell internal models)
- internal air conduction
- external convection
- internal and external thermal radiation.

Correlation is very good in some areas and in need of improvement in others.
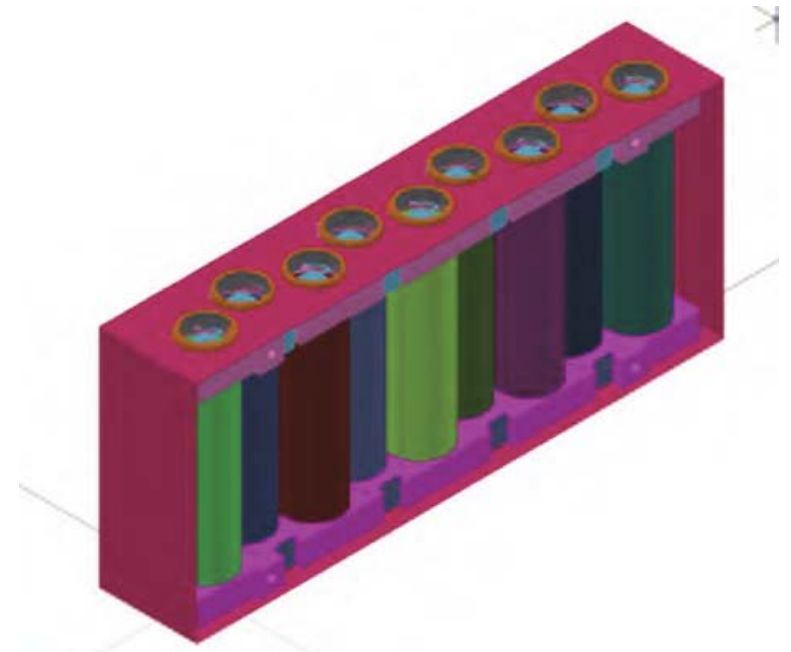
Detailed Thermal Model of (a representative segment of) the Lithium Reusable Battery (enclosure front cover removed)
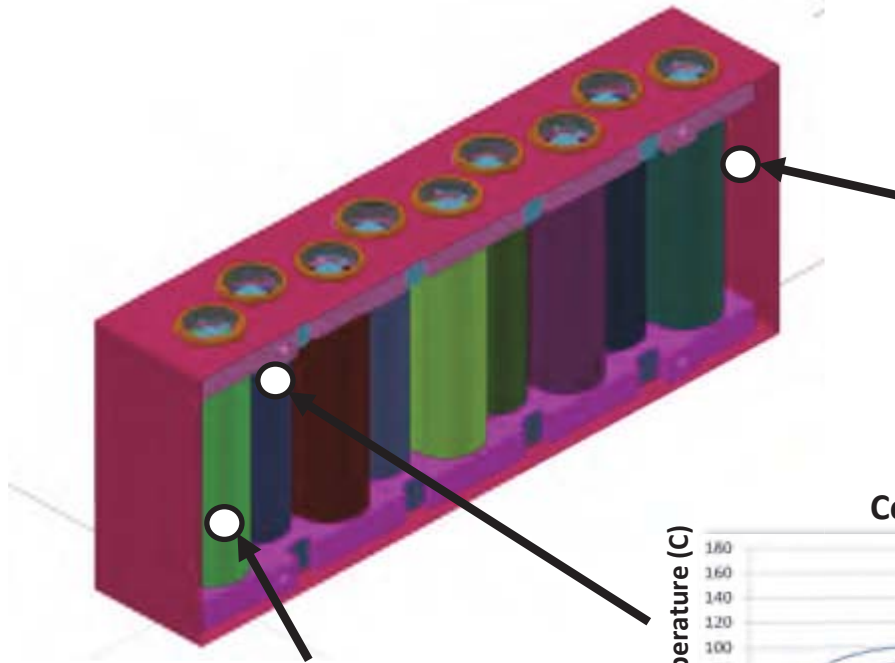
Free Air, Dog Leg End

Temperature (C)

Time (s)

Cell 2, Top

Temperature (C)

Time (s)

Trigger Cell, Bottom

Temperature (C)

Time (s)

Key

Test Data ——

Analysis ——

	Battery Thermal Model Preliminary Results	Presenter
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Temperature [C], Time = 350 sec
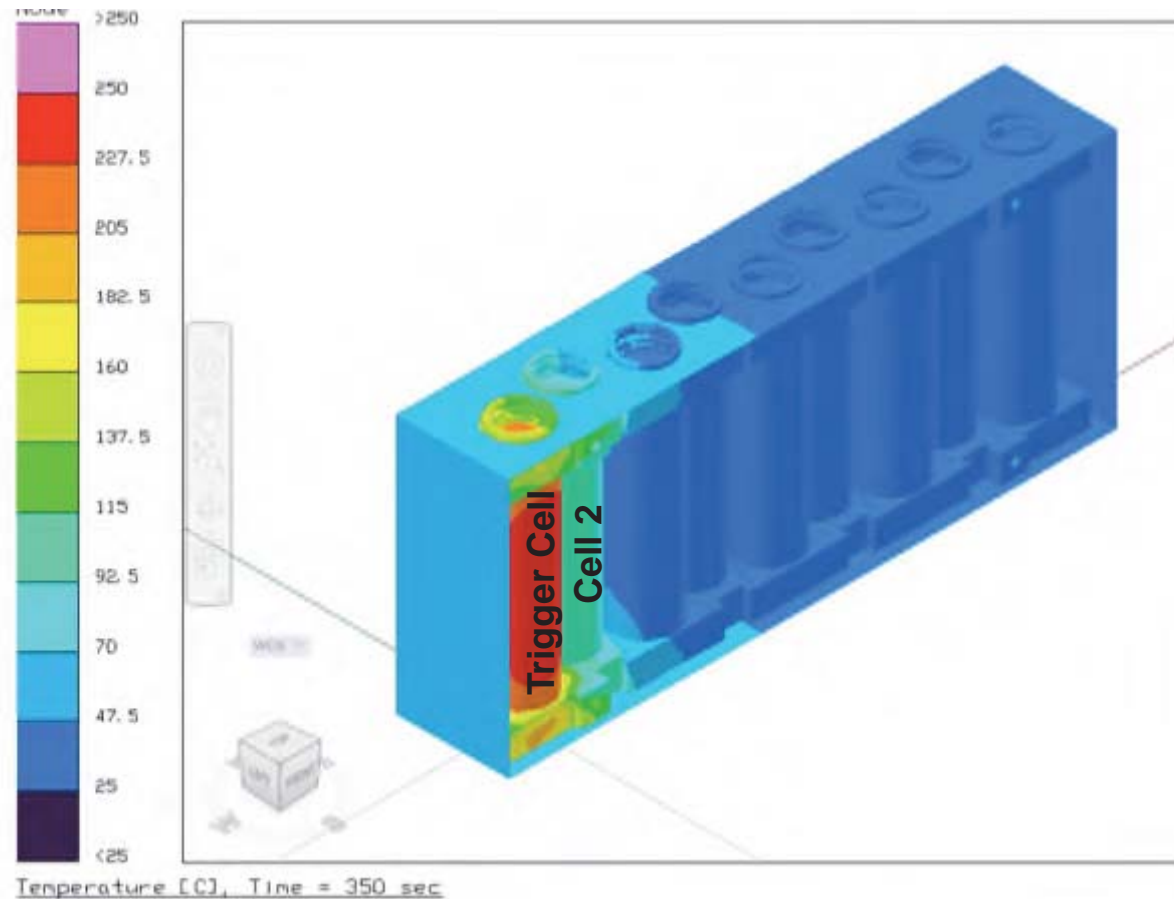
Run 53 correlated LREBA segment thermal model at approximate time of maximum Cell 2 temperature -- no TR propagation.

Adiabatic Chamber

Test battery in holder

ARC testing is used to measure heat release from cells during TR

	ARC Test Summary	Presenter R. Button
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- Self-heating typically began at ~140 °C.

- The energy required to raise the average temperature of the cell to the observed maximum temperature was on the order of 13.6 kJ.

- Stored electrical energy in cell

  - 2.4 A-hr * 3.75V average = 9.0 W-hr * 3,600 s/hr = 32.4 kJ

ARC testing and analysis indicate that a fraction of theoretical energy is conducted thru the cell can. More work is needed to quantify energy released during venting.

SOC	ΔE (kJ) w.r.t initial mC_p	*T_{SH} (C)	Mass Loss (%)
50%	10.5	153	42.4%
80%	15.8	135	49.5%
100%	16.1	151	50.4%
110%	12.2	136	80.4%

ARC run data

To date, the analysis, in conjunction with corroborating tests, has informed the team on the following:

- Direct cell-to-cell contact can lead to propagation of TR via heat conduction through the adhesive joining the cells in the cell array.

- Effluents from cell venting carry sufficient energy to promote propagation of TR; when combustion of the effluents occur, this problem is exacerbated.

- Heat transfer through any atmosphere present in the LREBA battery enclosure is primarily via gas conduction, as characteristic dimensions within the enclosure are too small to sustain convective heat transfer.

- Heat generated through cell TR that conducts through the cell can is on the order of one-half of the cell's total I^2R heating; this is supported by model correlation, correlation to ARC testing, and examination of cell carcass materials posttest.

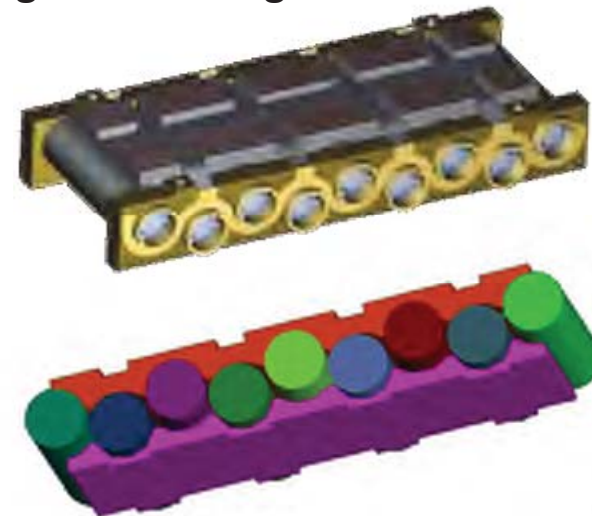|	**Mitigations**	Presenter
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Analysis and subsequent testing has shown that TR may be mitigated by eliminating direct thermal contact between cells and by <u>removing vented cell effluents from the battery enclosure</u>.

While these design modifications have been shown to prevent propagation of thermal runaway to adjacent cells, additional temperature margin is desired.

The thermal sub-team evaluated various mitigation strategies:

- Aluminum spreader -- spreads heat from trigger cell wall to a larger thermal mass and distributes the energy around the enclosure.
- Phase change interstitial material

Aluminum Heat Spreader Concept and Implementation in LREBA Segment 9P Thermal Model (partial)
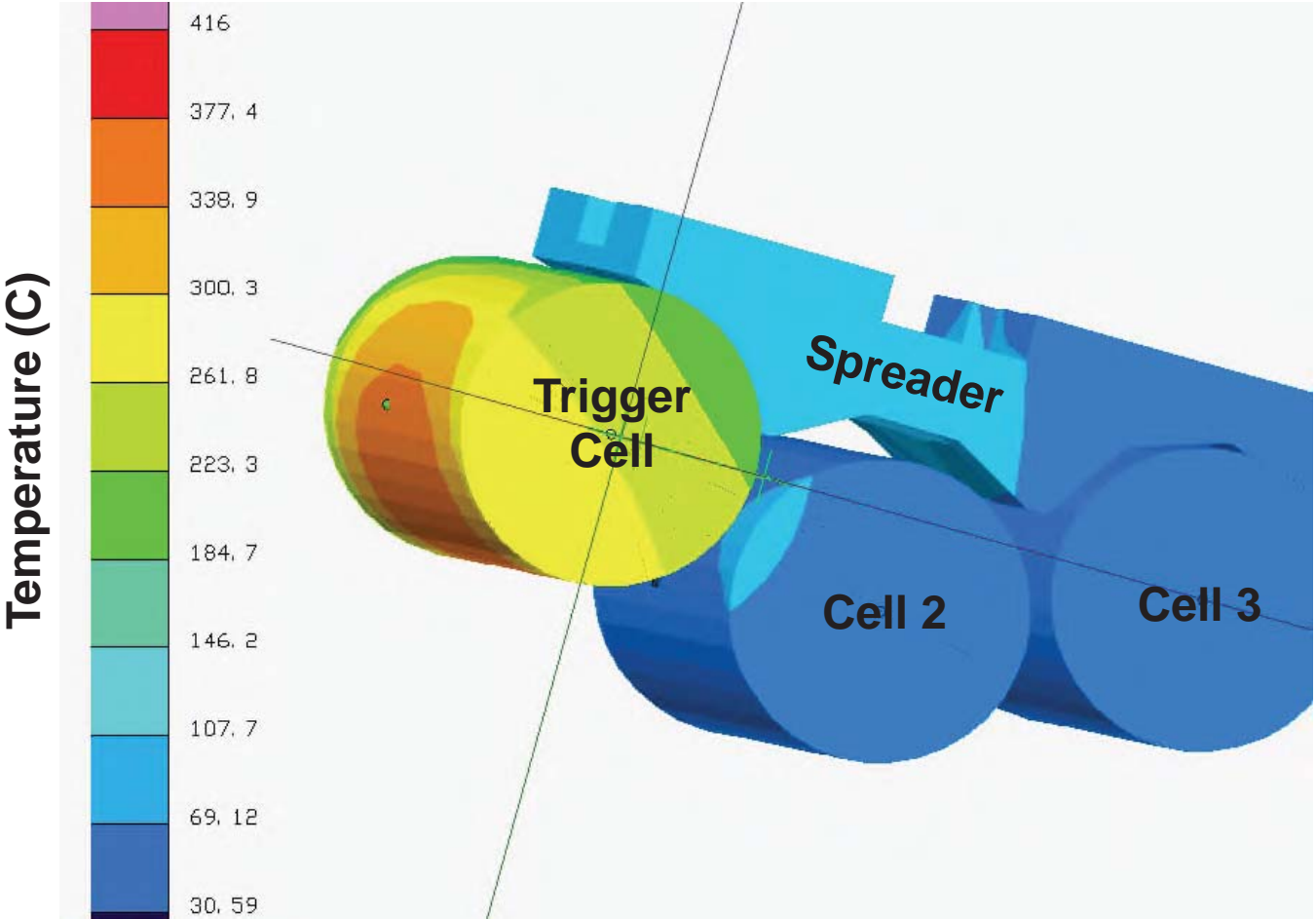
Temperature (C)

	416
	377, 4
	338, 9
	300, 3
	261, 8
	223, 3
	184, 7
	146, 2
	107, 7
	69, 12
	30, 59

Spreader

Trigger Cell

Cell 2

Cell 3

Preliminary Thermal Analysis Depicting Effect of Aluminum Heat Spreader Added to the Correlated Thermal Model (partial geometry shown)

- Development of analytical models for LPGT and LLB and associated TR mitigations.

- Analytical support for future ARC tests to quantify heat released on venting.

- Determine if CFD analysis can be added to the model to inform energy distribution when TR vented products are not directly vented outside the battery enclosure.

	Final Thoughts	Presenter
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		Date
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- Industry experience caused a paradigm shift at NASA
  - No longer acceptable to rely solely on likelihood reductions to address catastrophic hazards.
  - Steps must be taken to assess severity reduction as well.

- NESC pathfinder work
  - Determine whether combination of <u>analysis and test</u> and/or <u>reference design standards</u> best meet these new goals.
  - Learn from ISS/EVA test cases to understand real impacts to cost/schedule/performance.
  - If impacts are low, include severity reduction as a new requirement and elevate to an Agency Standard.
  - Some design features would also benefit unmanned programs and improve probability of mission success.