Can Cell-to-Cell Thermal Runaway Propagation in Li-ion Modules Be Prevented?

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Background

Lithium-ion batteries have a very high energy density but have catastrophic consequences such as fire and thermal runaway associated with them- as observed by the incidents in the commercial electronics and aerospace industry.

New requirement in NASA-Battery Safety Requirements document: JSC 20793 RevC

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.

Cell Specifications

Spec.	Cond.	LG18650B4	LG18650C2	BP 5300
Capacity	Nominal	2.6 Ah	2.8 Ah	5.3 Ah
Voltage	Nominal	3.7	3.72 V	3.65 V
Std. Charge	CC/CV Cut off	0.5C 4.2 V 50 mA	0.5C 4.3 V 50 mA	0.7C 4.2 V 50 mA
Std. Discharge	CC Cut off	0.2C 2.75 V	0.2C 3.0 V	0.2C 2.75 V
Weight	Max	48.0 g	53.0 g	93.5 g
Operating Temperature	Charge Discharge	0 to 45 °C -20 to 60 °C	0 to 45 °C -20 to 60 °C	-20 to 60 °C -40 to 70 °C
Vent Location		Header	Header	2 on flat side

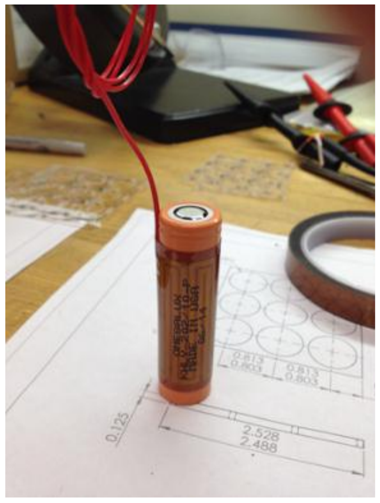
Boston Power (BP)

LG18650 B4

LG18650 C2

Thermal Runaway Trigger Method

- 2-inch square Kapton heater elements (40W)
- Pressure sensitive adhesive (PSA) on backside
- 20W (20V @ 1A) heater power applied
- 3-5 °C/min desired heating rate
- All tests were performed inside an abuse test chamber
- 5-min N_2 purge was performed before start of test & after test



Omega KHLV-202/40-P

Test Matrix

Test #	Cell Type	Configuration	SOC	Cell Arrangement	Intercell space Material
1	BP5300	9S	100%	3x3, 2mm	Air
2	LGB4	9S	100%	3x3, 2mm	Air
3	LGB4	9S	100%	3x3, 4mm	Air
4	BP5300	4S	100%	2x2,	Radiant Barrier
5	LGC2	9P, Fork-tabs	100%	3x3, 4mm	Air
6	LGC2	9P, Fork-tabs	100%	3x3, 2mm	Air
7	BP5300	4P, Fork-tabs	100%	2x2,	Radiant Barrier
8	BP5300	9P, Fork-tabs	50%	2x2,	Radiant Barrier
9	LGC2	9P, Fork-tabs	100%	3x3, 1mm	Air
10	LGC2	9P, Serpentine (S) tabs	100%	3x3, 1mm	Air
11	LGC2	9P, S-tabs	100%	3x3, 2mm	Air
12	BP5300	4P, S-tabs	50%	2x2,	Radiant Barrier
13	LFP/SKC	14P, (2.2 Ah) Fork Tabs (10A fuse)	100%	5X5X4	Air
14	LFP/SKC	14P, (2.0 Ah) Fork tabs (10A fuse)	100%	5X5X4	Air
15	BP5300	9P	100%	3x3, 2mm	Intuplas
16	LGC2	9P	100%	3X3, 2mm	Intuplas
17-20	BP/LG	9P	100% & 50%	3X3, 4mm	Intuplas

Tests

- **Preliminary Runs:**
  - BP 5300 & LG B4 cell tests with 2-mm (air) spacing; series configuration; 100% SOC

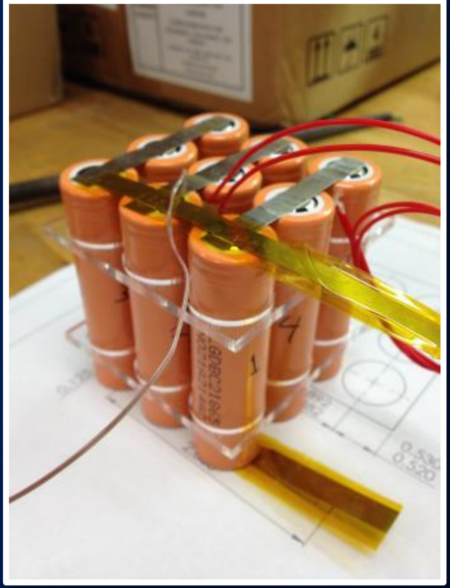
- **Cell-to-cell Spacing – LG C2 cells:**
  - 1-, 2-, & 4-mm spacing; 100% SOC; 9P (Fork & Serpentine)

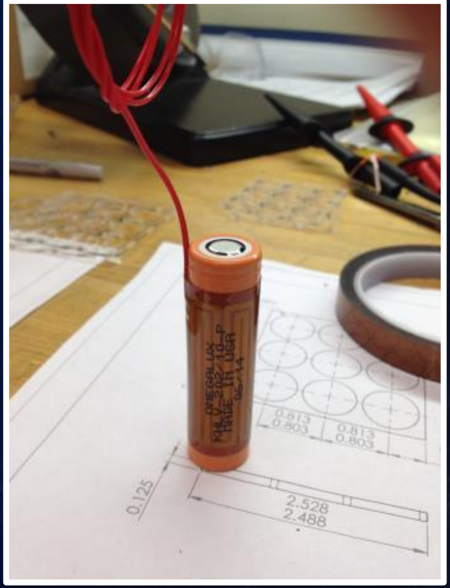
- **Radiant Barrier – BP cells:**
  - Folded radiant barrier sample; 100% & 50% SOC; 4P

- **Intuplas – LG C2 & BP cells:**
  - 2-, -4 mm; 100% SOC; 9P (Fork)

Cell-to-Cell Space LG C2 Cell Tests

- 1-, 2-, & 4-mm spacing between cells
- LG 18650 C2 (2.8 Ah) in 9P configuration

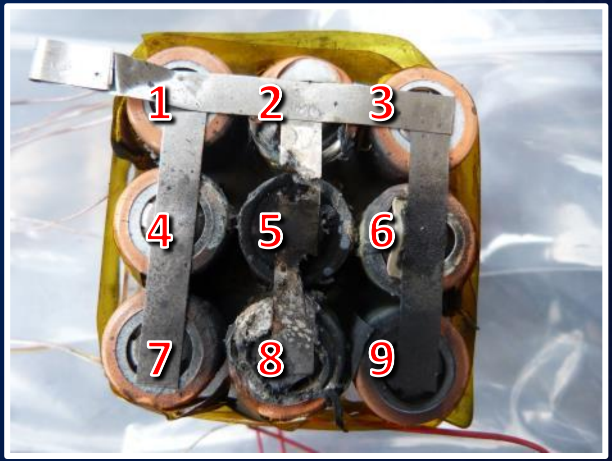


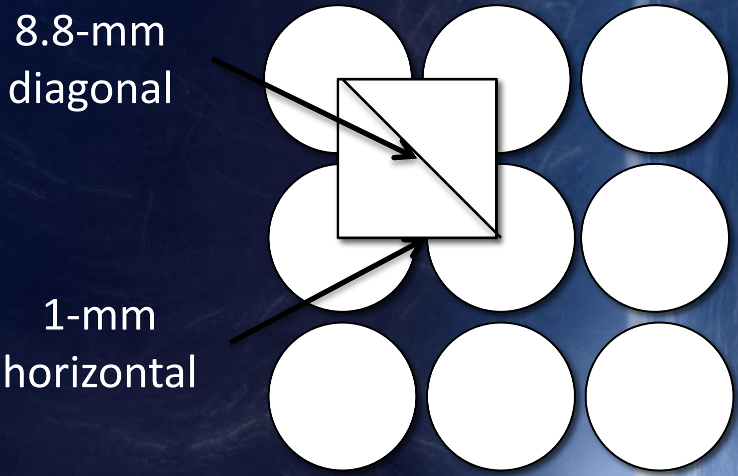


LG C2 – 1-mm Space 9P Fork Config. 100% SOC

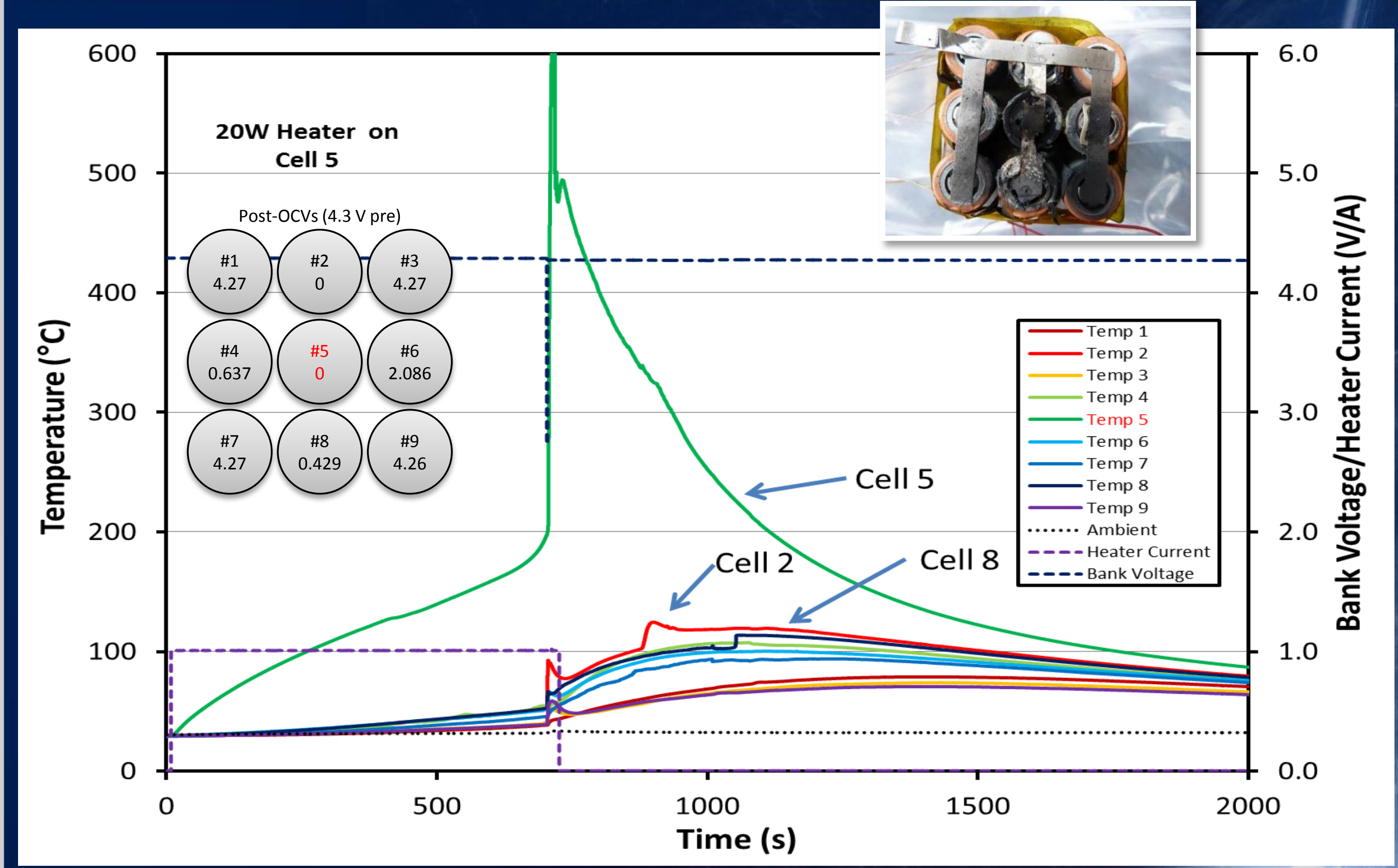
- Propagation to adjacent cells
- No propagation to diagonal cells
- Voltage/capacity drain observed
- No crimp opening or extrusion of electrode roll
- Elevated adjacent cell temperatures (120 °C)

Fork Pattern



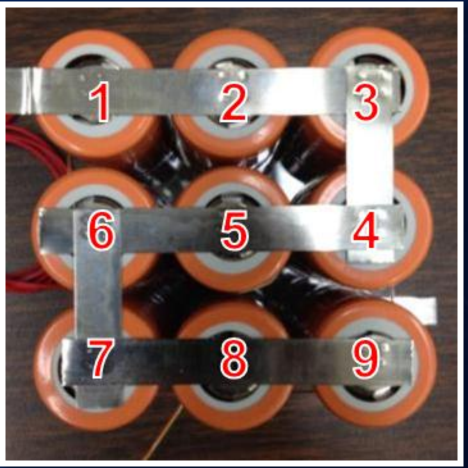


LG C2 – 1-mm Space 9P Fork Config. 100% SOC

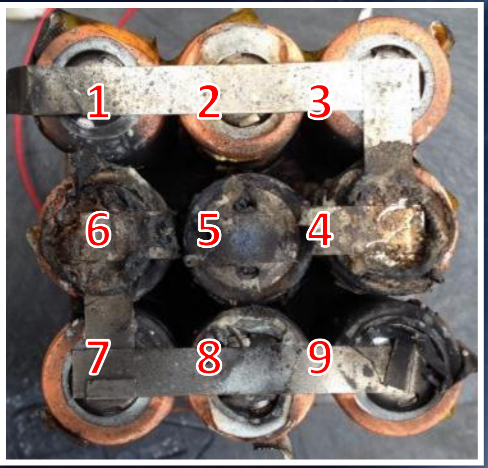


LG C2 – 1-mm Space 9P Serpentine Config. 100% SOC

- Significant damage to adjacent cells
- No propagation to all diagonal cells
- Post-test OCVs all 0 V
- No extrusion of electrode roll
- Adjacent cell temperatures were elevated (120-150 °C)

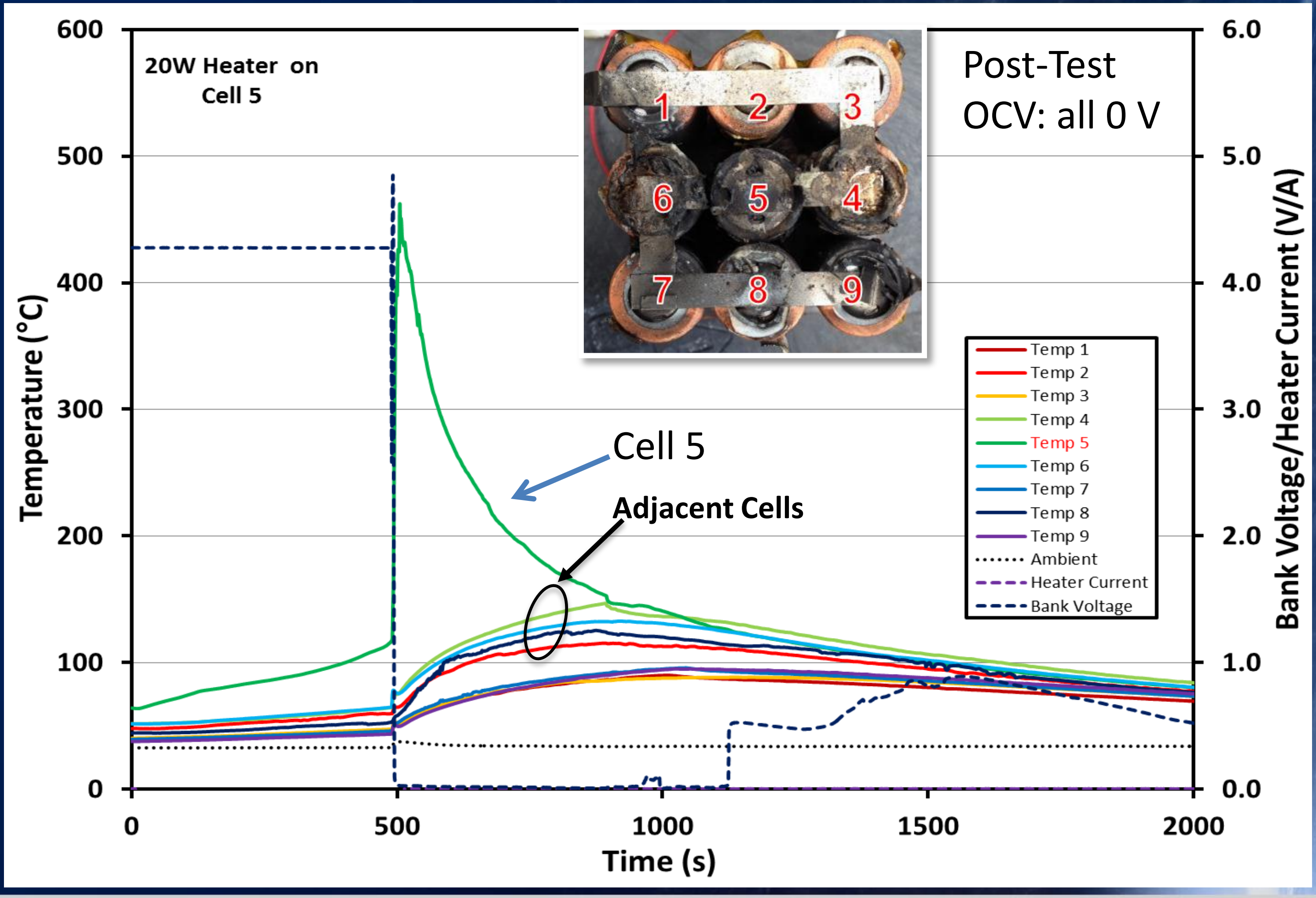


Pre-test



Post-test

LG C2 – 1-mm Space 9P Serpentine Config. 100% SOC

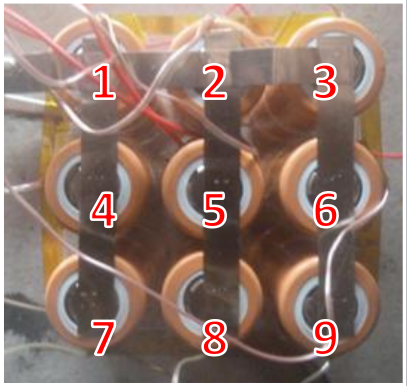


LG C2 – 2-mm Space 9P Configurations 100% SOC

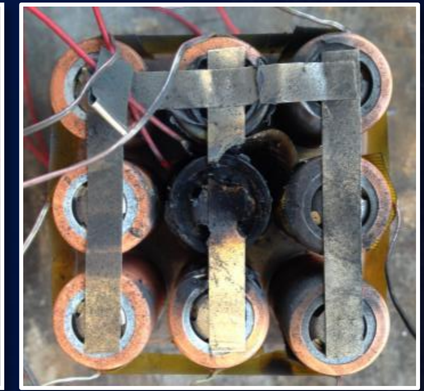
9P Fork

- Complete thermal runaway of cell 5
- Thermocouple wire melted from venting
- Observed voltage/capacity drain from adjacent cells 2, 6, & 8
- No crimp opening or extrusion of electrode roll
- Elevated adjacent cell temperatures (100 °C)

Pre-Test



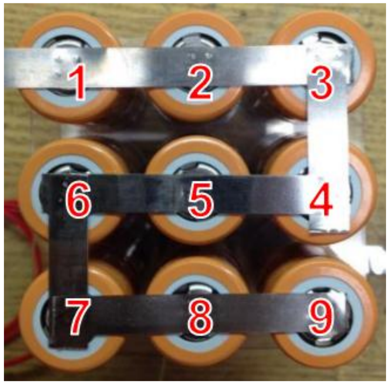
Post-Test



9P Serpentine

- Complete TR of cell 5
- Some damage to cell 4
- Post-test OCVs all 0V
- No extrusion of electrode roll
- Elevated adjacent cell temperatures (100 °C)

Pre-Test

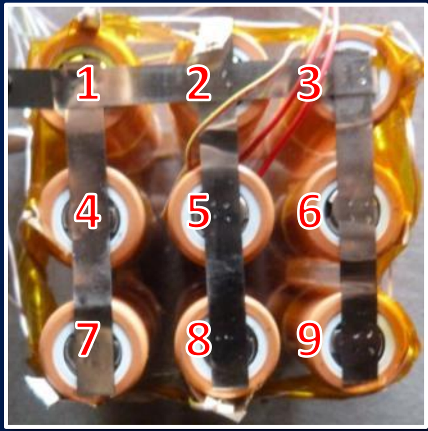


Post-Test

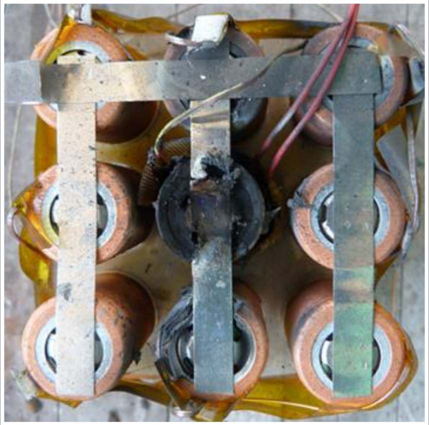
LG C2 – 4-mm Space 9P Fork Config. 100% SOC

- Complete thermal runaway of cell 5
- No propagation
- Capacity/voltage drain observed on adjacent cells 2 & 8
- No crimp opening or extrusion of electrode roll

Pre-Test

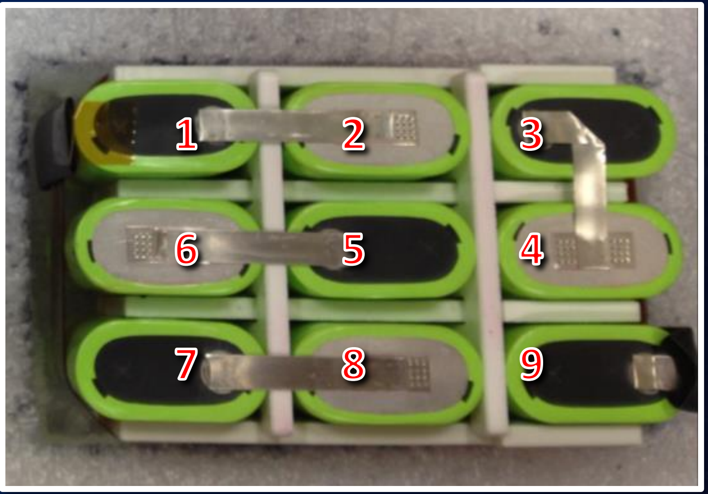


Post-Test

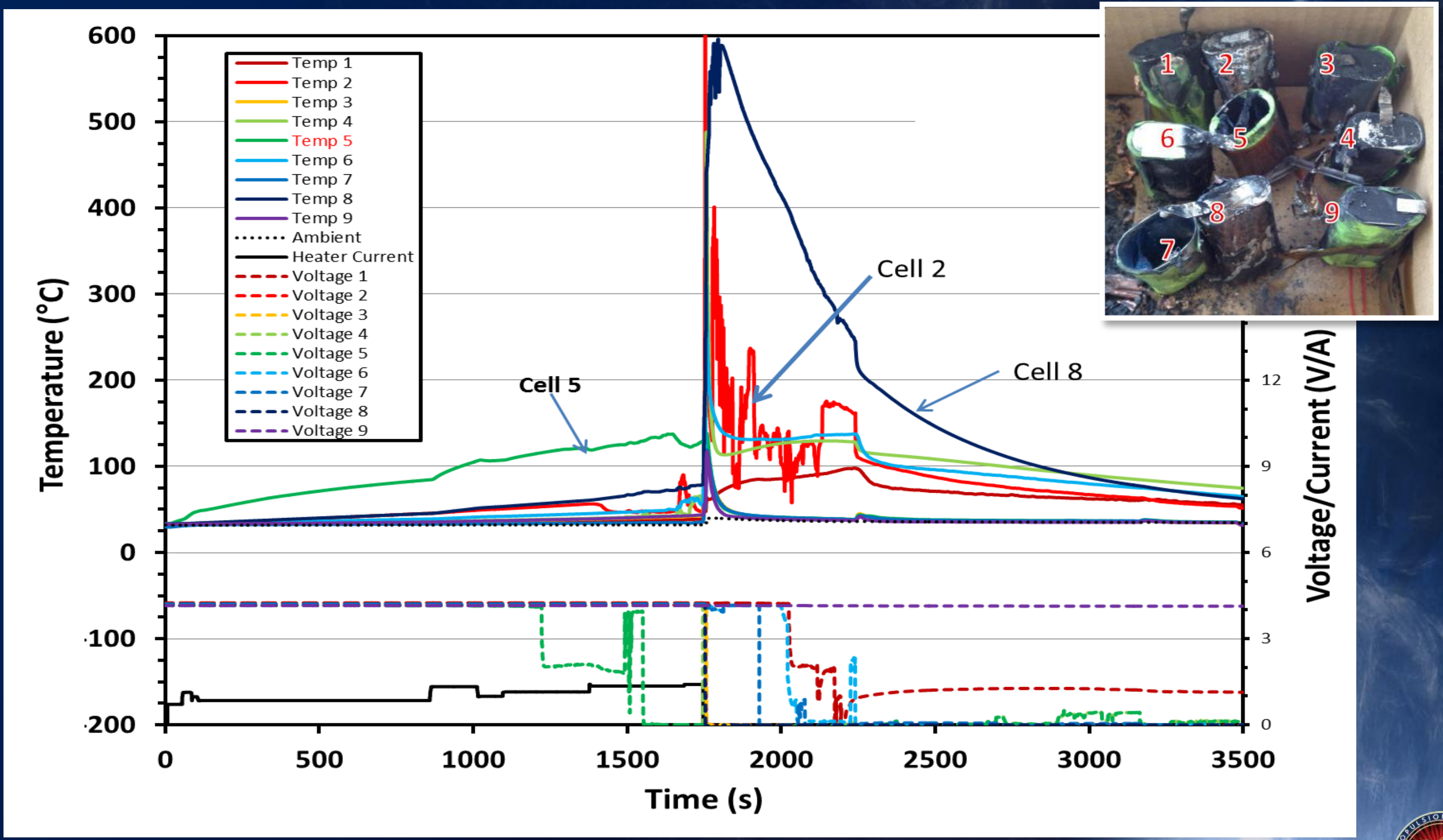


BP5300 2-mm Space at 100% SOC (9S Config.)

- Complete thermal runaway of cell 5
- Propagation to cell 2 (in vent path), & cell 8 (adjacent to heater)
- Contents ejected from cells 5 & 7
- Heater power 20W (1A at 20V)
- Spacers (in left picture below) removed before test

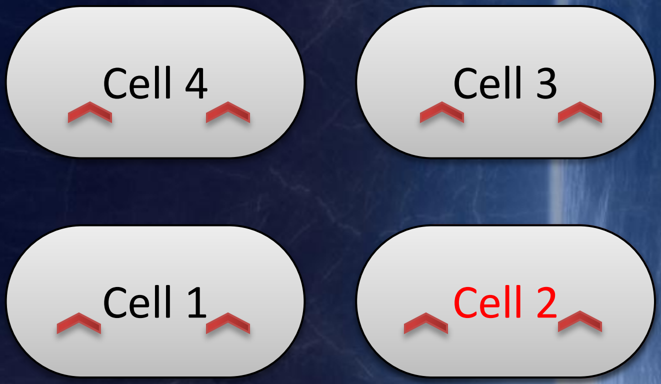


BP500 2-mm Space 9S 100% SOC



Radiant Barrier

- **To mitigate radiation heat transfer & protect against direct flame from side vents in BP cells**
- **Radiant barrier description per Boeing donor:**
  - Outer layers are quartz cloth
  - Five nickel foil layers inside with Linoweave (open mesh quartz cloth) separator layers between the nickel foil layers

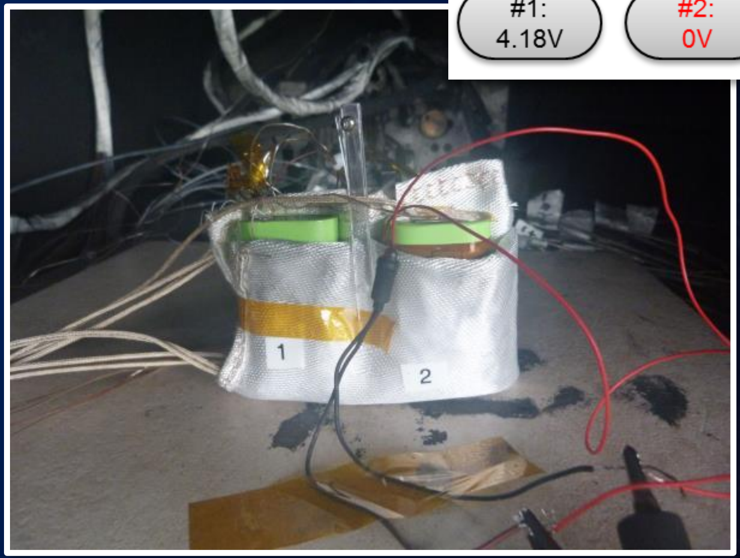


BP5300 at 100% SOC with Radiant Barrier (4S and 4P Config.)

- Identical Results
- Can ruptured & contents ejected from triggered cell
- No propagation

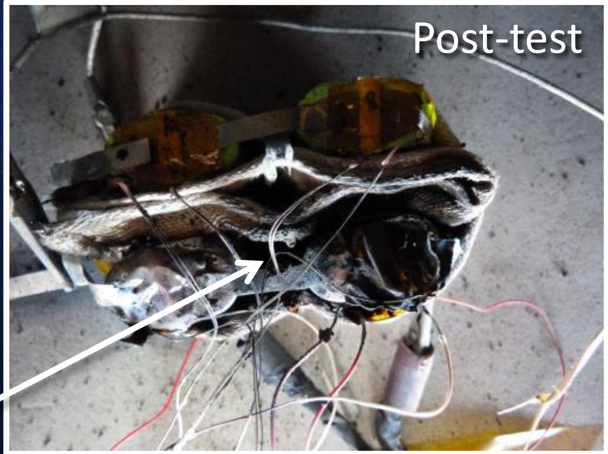
Post-OCVs (4.2 V pre)

#4: 4.18V	#3: 4.18V
#1: 4.18V	#2: 0V

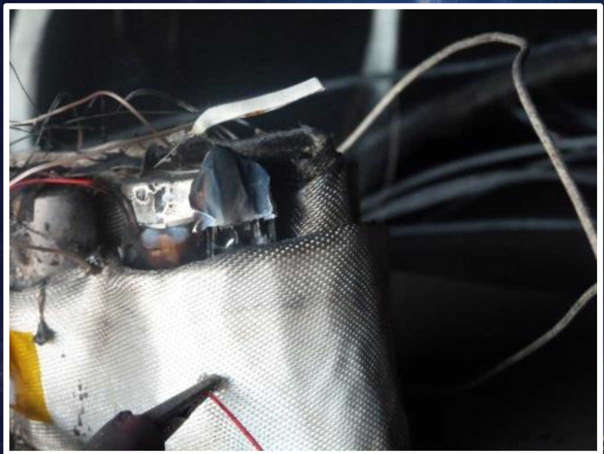


BP5300 at 50% SOC with Radiant Barrier (4P Config.)

- No expulsion of contents
- Fire started through vent opening & spread to adjacent cell
- Heat transferred from cell 2 to cell 1
- Cells 3 & 4 displayed capacity/voltage drain

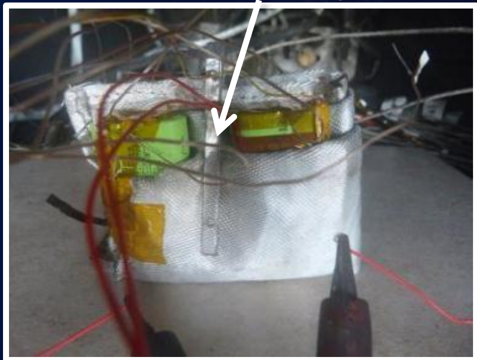


Gap in barrier w/melting of restraint clip



Restraint Clip

Pre-test



Post-OCVs (4.2 V pre)	
#4: 0.28V	#3: 1.5V
#1: 0V	#2: 0V

Intumescent Material

- **Intuplas:**
  - Nanocomposite consisting of thermoplastic carrier & inorganic intumescent activator
  - Activates at 200 °C to form a dense, insulating ash
  - 2-hour fire rating with ASTM E119
  - Manufactured by Pyrophobic Systems Ltd.

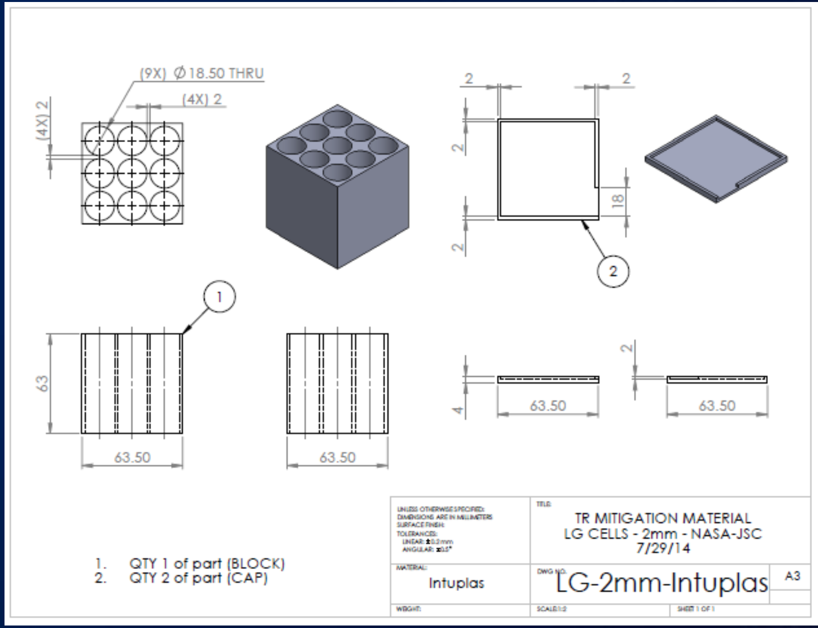
- **WSTF Testing:**
  - Flame propagation
  - Off-gassed products
  - Tested to NASA-STD-6001
  - Material passed flame propagation & off-gas test

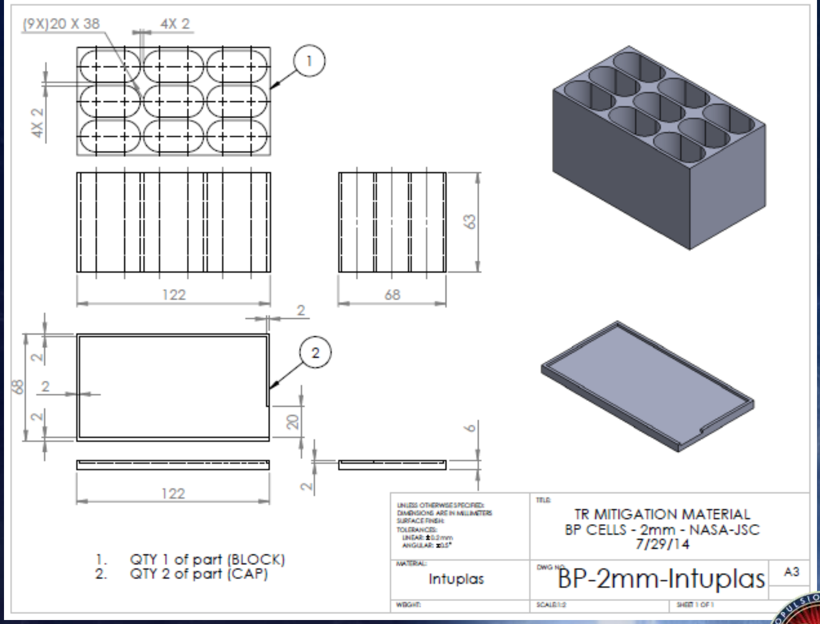
(Courtesy: Mike Fowler)

Intuplas Modules

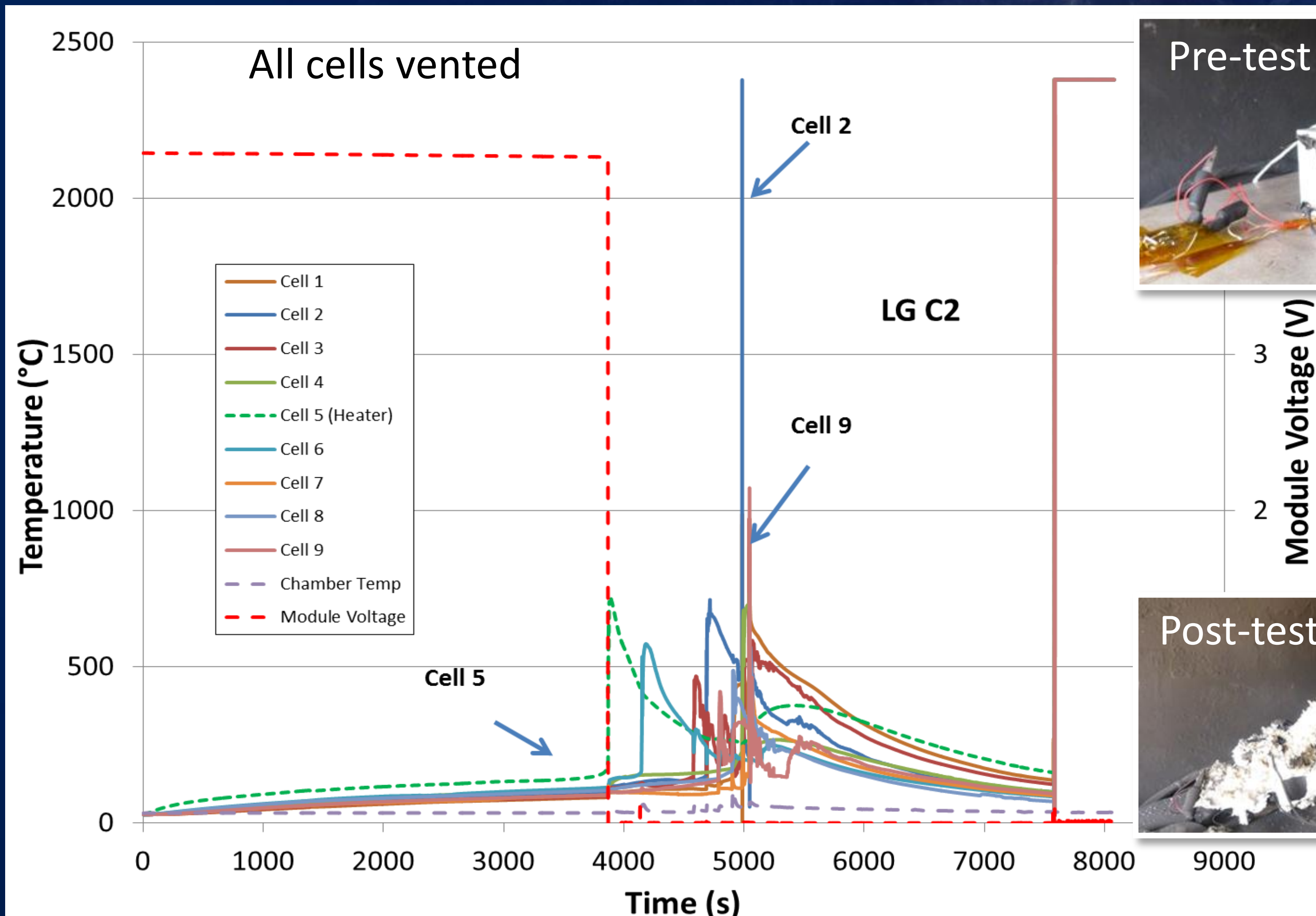
Three each of 2-mm, 4-mm spacing for BP & LG cells designs

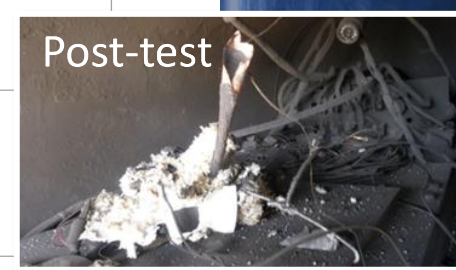
QTY	Form Factor	Layout	Spacing
3	BP5300	3x3	2mm
3	BP5300	3x3	4mm
3	18650	3x3	2mm
3	18650	3x3	4mm





LG C2 at 100% SOC with 2-mm Intuplas (9P Config.)

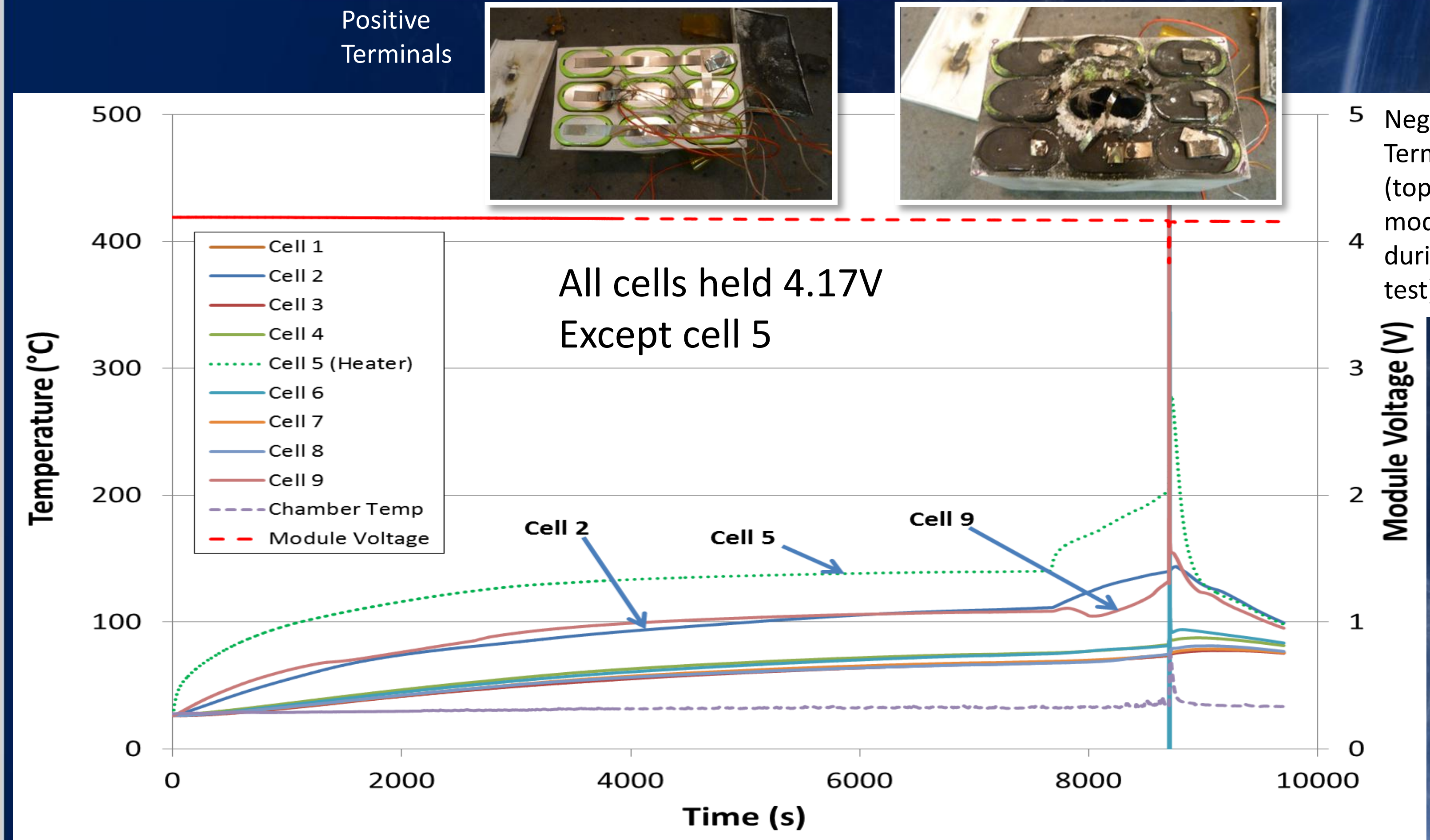




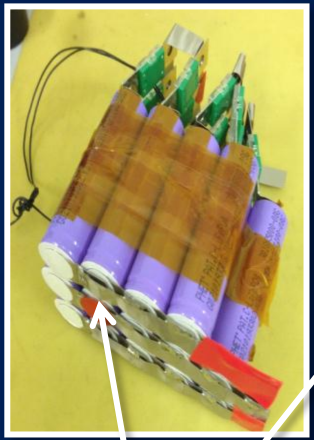
BP5300 at 100% SOC with 2-mm Intuplas (9P Config.)

Positive Terminals

Negative Terminals (top of module during test)

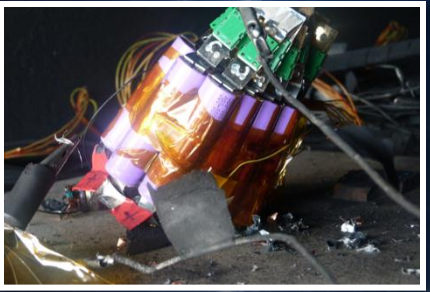


SKC LFP 14.7 Ah 14P Module 2
100% SOC

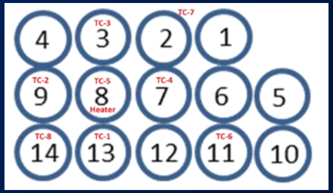


50 W heater

Cell positive terminals

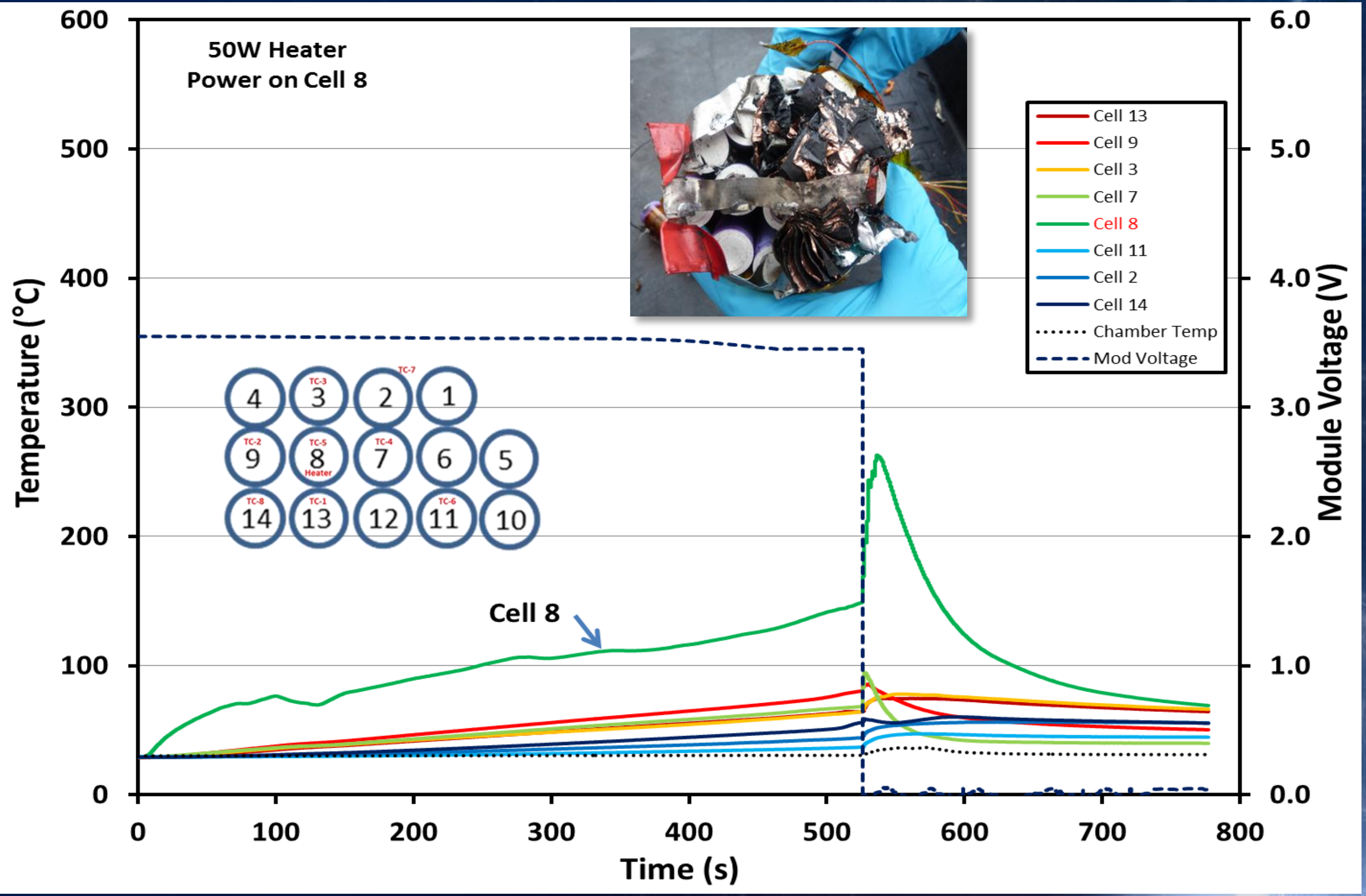


LFP: Lithium Iron Phosphate



7 deg. C/min. heating rate

SKC LFP 14.7 Ah 14P Module 2
100 % SOC



Thermal Propagation Analysis

- Convection negligible in space
- Conduction dominates at T < 500 °C
- Radiation exponentially increases with temperature
- Increasing spacing significantly decreases heat transfer
- Fire because of electrolyte venting in the presence of high temperatures can cause significant propagation

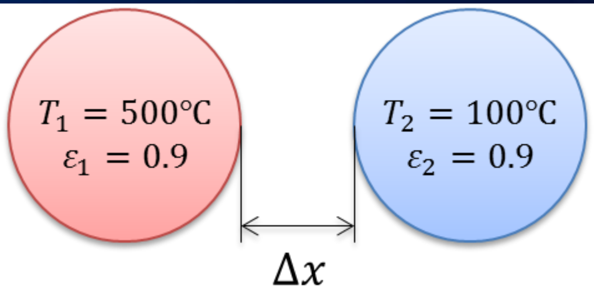
$$Q_{cond} = kA\frac{T_1 - T_2}{\Delta x}$$

$$Q_{rad} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{\boldsymbol{F_{12}}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$

$$\boldsymbol{F_{12}} = \frac{1}{2\pi}\left\{\pi + \sqrt{\boldsymbol{C}^2 - 2^2} - \boldsymbol{C} - 2\cos^{-1}\left[{}^{2}/_{\boldsymbol{C}}\right]\right\}$$

$$\boldsymbol{C} = 1 + {}^{\boldsymbol{\Delta x}}/_{\boldsymbol{r}}$$

(Calculations by Carlos Lopez)



Radiation view factor, $\mathbf{F_{12}}$

Spacing	Rate of Heat Transfer		
Δx (mm)	Q_{rad} (W)	Q_{cond} (W)	Total (W)
1	5.69	18.06	**23.76**
2	5.34	9.03	**14.37**
4	4.77	4.52	**9.28**

Summary

- **<u>Increasing cell spacing decreased adjacent cell damage</u>**
- Electrically connected adjacent cells drained more than physically adjacent cells
- **<u>Radiant barrier prevents propagation when fully installed between BP cells</u>**
- BP cells vent rapidly & expel contents at 100% SOC:
  - Slower vent with flame/smoke at 50%
  - Thermal runaway event typically occurs at 160 °C
- LG cells vent, but do not expel contents:
  - Thermal runaway event typically occurs at 200 °C
- SKC LFP modules did not propagate; **<u>fuses on negative terminal of cell (away from cell vents)</u>** may benefit in reducing cell-to-cell damage propagation

Future Work

- Optimize materials and designs that will completely eliminate the cell-to-cell propagation
- Look at design solutions that may extinguish a fire in the battery
- Develop inherent cell safety through chemical modifications to cell components

Acknowledgments

- NASA-JSC Test Area Team
- Pyrophobic Systems Team
- Bruce Drolen – Boeing Seattle

Backup Slides

Acronym List

BP	Boston Power
LFP	Lithium iron phosphate
mm	millimeter
OCV	Open Circuit Voltage
P	Cells in parallel (bank)
S	Cells in series (String)
SOC	State of Charge
V	Voltage
W	Watts
WSTF	White Sands Test Facility

Test Chamber Setup

- **Buckeye pressure vessel**
- **Nitrogen pre- and post-purge**
- **Data acquisition:**
  - K-type thermocouples
  - Voltage sense
  - Dual video feeds
  - 1 sample/sec.
- **Heater voltage & current**