Can Cell to Cell Thermal Runaway Propagation be Prevented in a Li-ion Battery Module?

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Background

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

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.**

NASA has traditionally addressed the threat of thermal runaway incidents in its battery deployments through comprehensive prevention protocols. This prevention-centered approach has included extensive screening for manufacturing defects, as well as robust battery management controls that prevent abuse-induced runaway even in the face of multiple system failures. This focused strategy has made the likelihood of occurrence of such an event highly improbable.

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.**

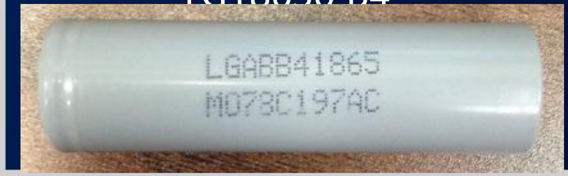
In addition to prevention protocols, programs developing battery designs with catastrophic failure modes should take the steps necessary to assess the severity of a possible thermal runaway event. Programs should assess whether there are reasonable design changes that could appreciably affect the severity of the outcome.

Evaluation should include environmental effects to surrounding hardware (i.e., temperature, pressure, shock), contamination effects due to any expelled contaminates, and venting propulsive effects when venting overboard.

Cell Specifications

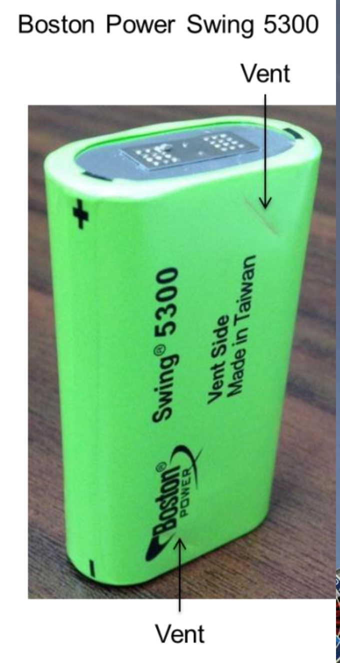
Spec.	Cond.	LG18650B4	LG18650C2	BP 5300
Capacity	Nominal	2.6 Ah	2.8 Ah	5.3 Ah
Voltage	Nominal	3.7	3.72 V	3.65 V
Std. Charge	CC/CV Cut off	0.5C 4.2 V 50 mA	0.5C 4.3 V 50 mA	0.7C 4.2 V 50 mA
Std. Discharge	CC Cut off	0.2C 2.75 V	0.2C 3.0 V	0.2C 2.75 V
Weight	Max	48.0 g	53.0 g	93.5 g
Operating Temperature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

LG18650 B4


LGABB41865
M078C197AC

LG18650 C2

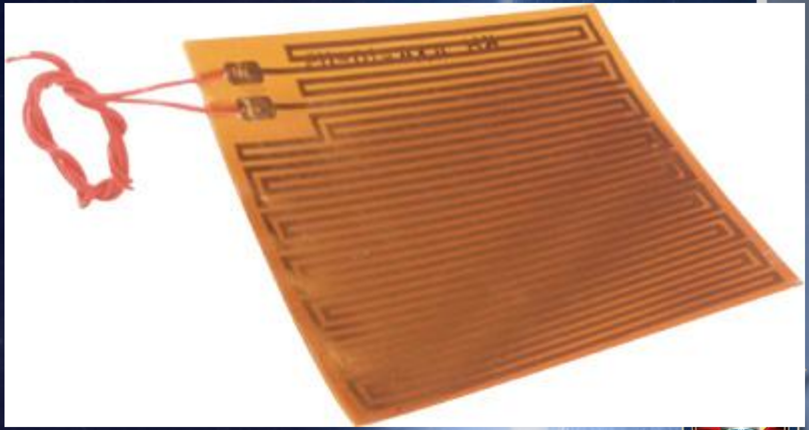
LGDBC21865
N021A214A2


Boston Power Swing 5300
Vent
Swing® 5300
Vent Side
Made in Taiwan
Boston POWER
Vent

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 carried out inside an abuse test chamber
- A 5 minute N_2 purge was carried out before start of test and after test.

Omega KHLV-202/40-P



Test Matrix

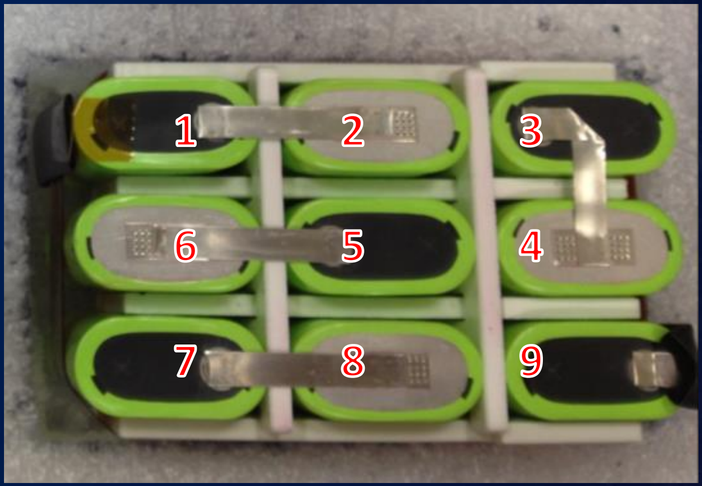
Test #	Cell Type	Configuration	SOC	Cell Arrangement	Intercell space Material
1	BP5300	9S	100%	3x3, 2mm	Air
2	LGB4	9S	100%	3x3, 2mm	Air
3	LGB4	9S	100%	3x3, 4mm	Air
4	BP5300	4S	100%	2x2,	Radiant Barrier
5	LGC2	9P, Fork-tabs	100%	3x3, 4mm	Air
6	LGC2	9P, Fork-tabs	100%	3x3, 2mm	Air
7	BP5300	4P, Fork-tabs	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, 4 mm	Intuplas

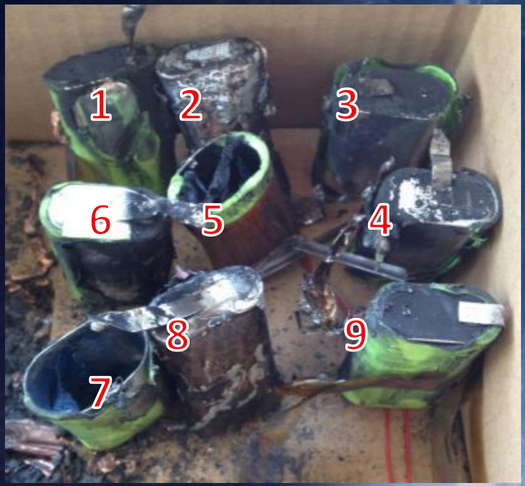
Tests

- Preliminary Runs
  - BP 5300 and LG B4cell tests with 2mm (air) spacing; Series configuration; 100% SOC
- Cell-to-cell Spacing –LG C2
  - 1, 2, and 4mm spacing; 100% SOC; 9P (Fork and Serpentine)
- Radiant Barrier - BP
  - Folded radiant barrier sample; 100% and 50% SOC; 4P
- Intuplas – LG and BP
  - 2 mm; 100% SOC; 9P (Fork)

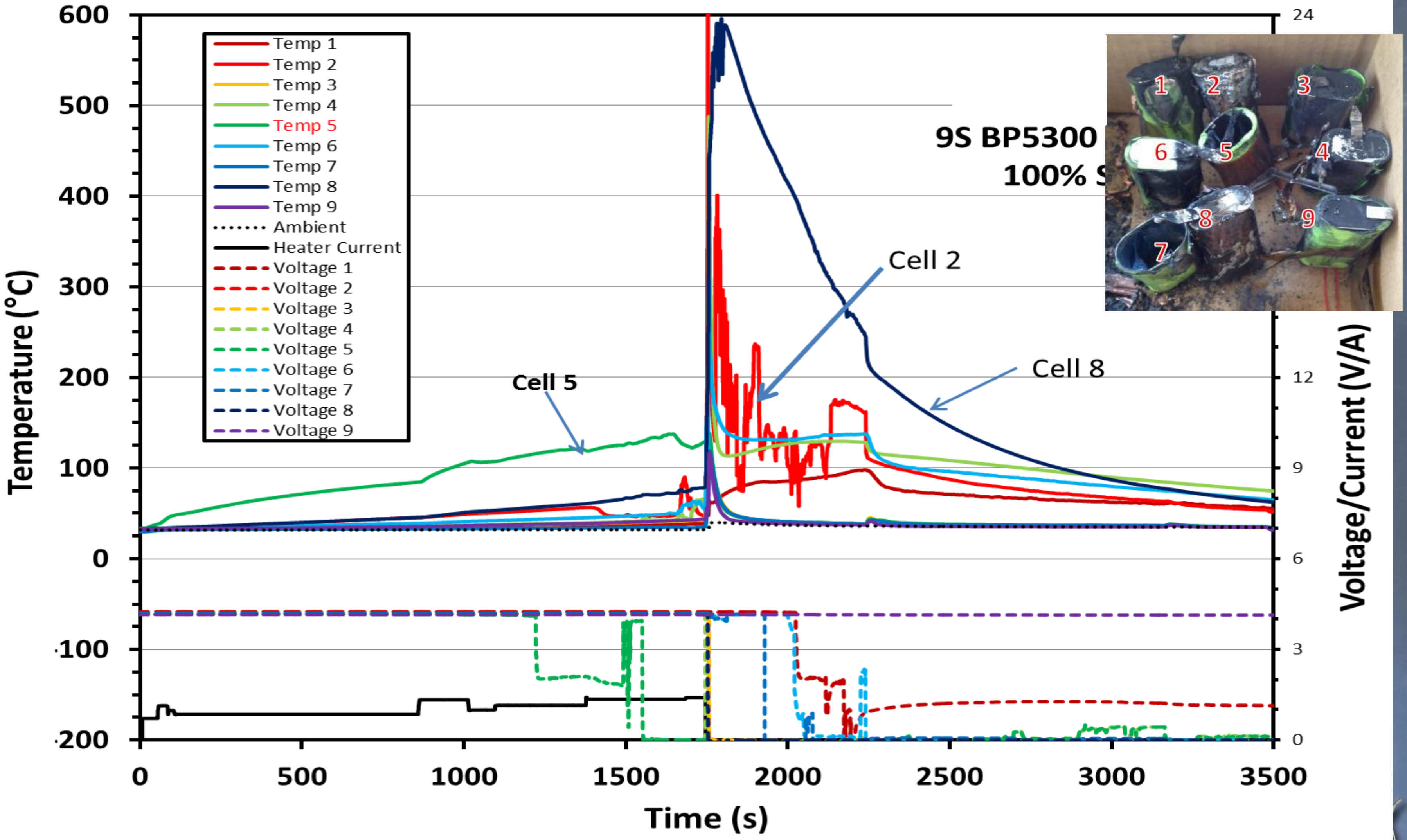
BP5300 2mm Air Space at 100% SOC (9S config.)

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



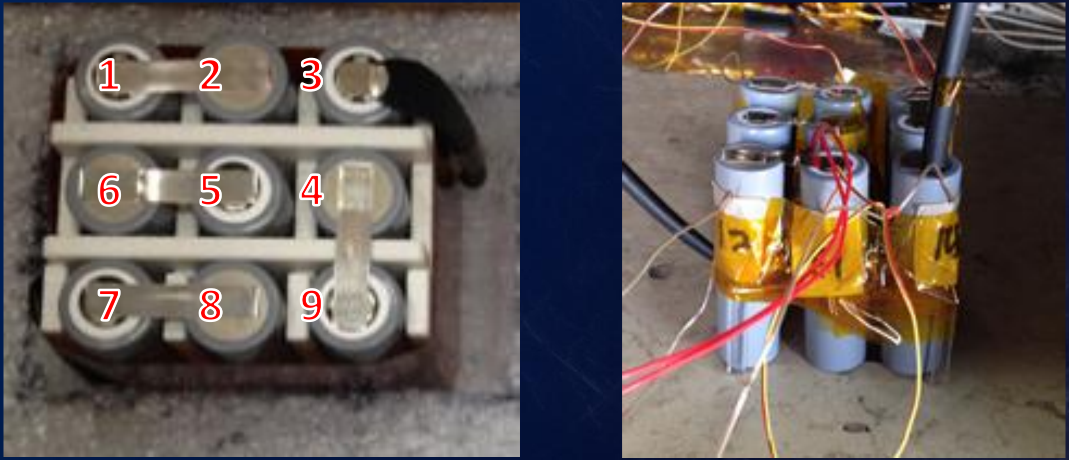


BP5300 2mm Air Space 9S 100% SOC



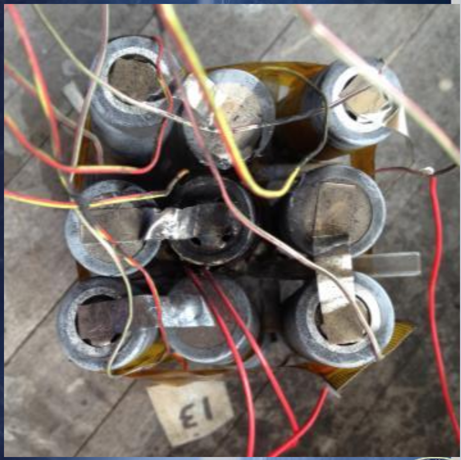
LG B4 4mm Cell-to-Cell Space at 100% SOC 9S config.

- Thermal runaway observed in trigger cell 5
- No propagation
- All other voltages held at 4.19V

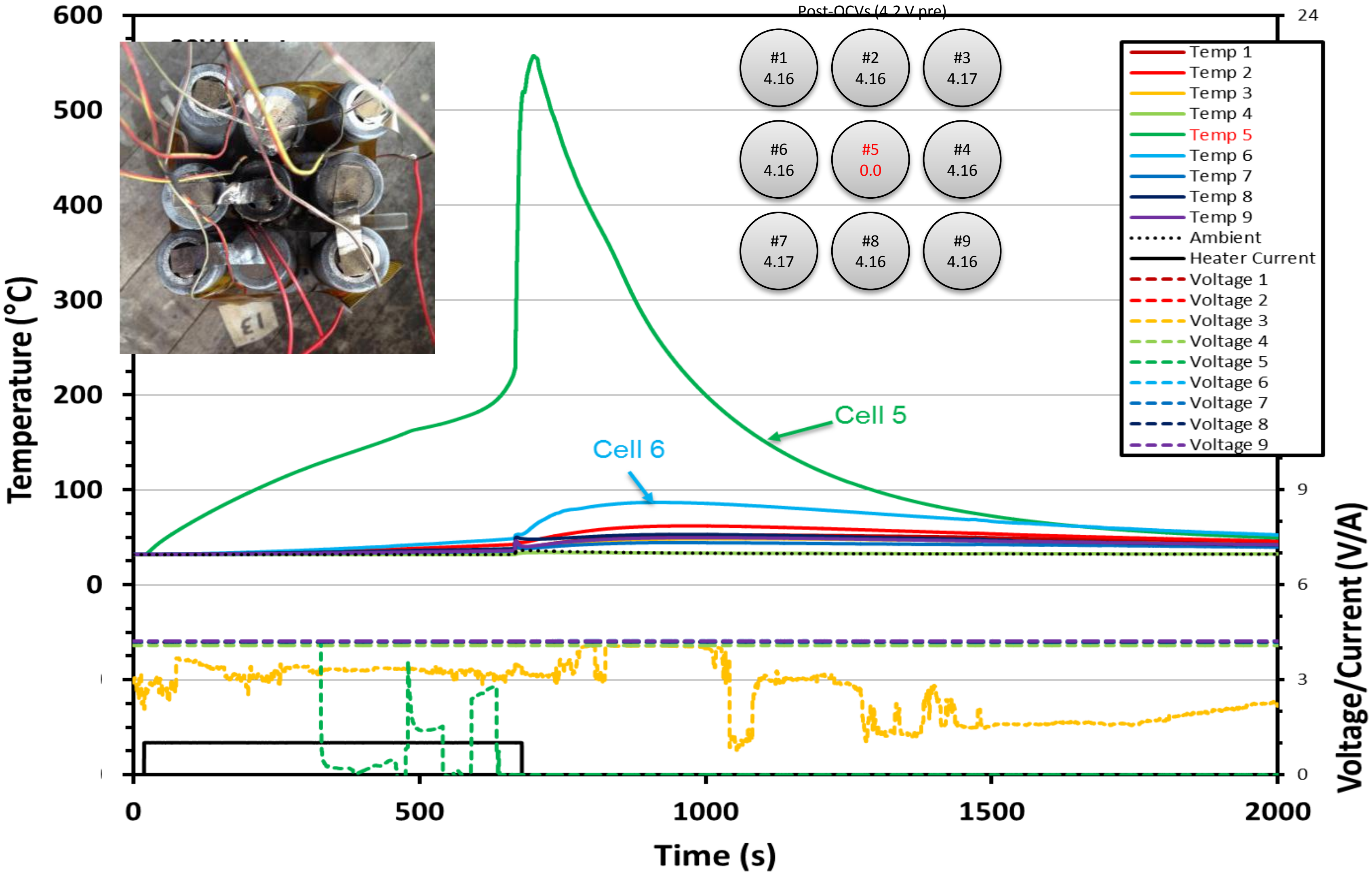


Pre-test 9S-LGB4

Post-test 9S-LGB4



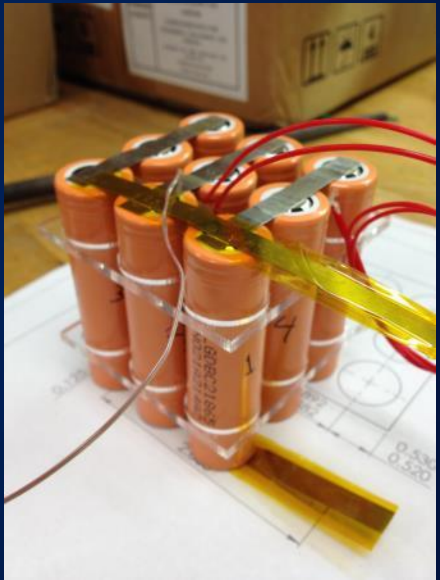
LG B4 4mm Space at 100% SOC (9S config.)



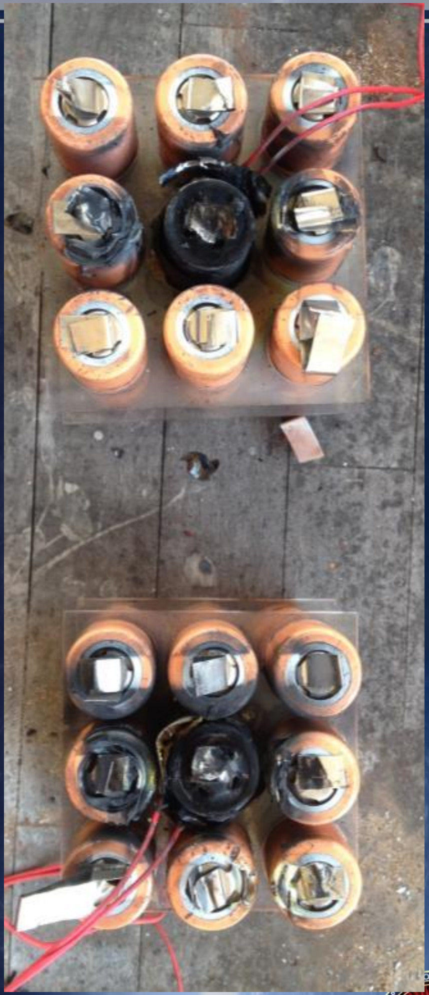
Cell-to-Cell Space LG C2 Cell Tests

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

configuration



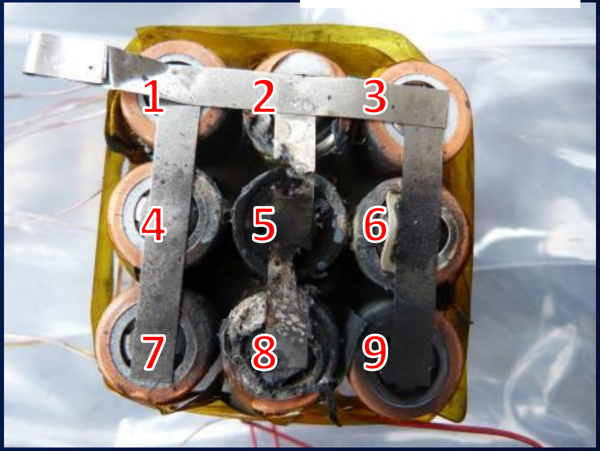
0.813
0.803
0.813
0.803
0.125
2.528
2.488

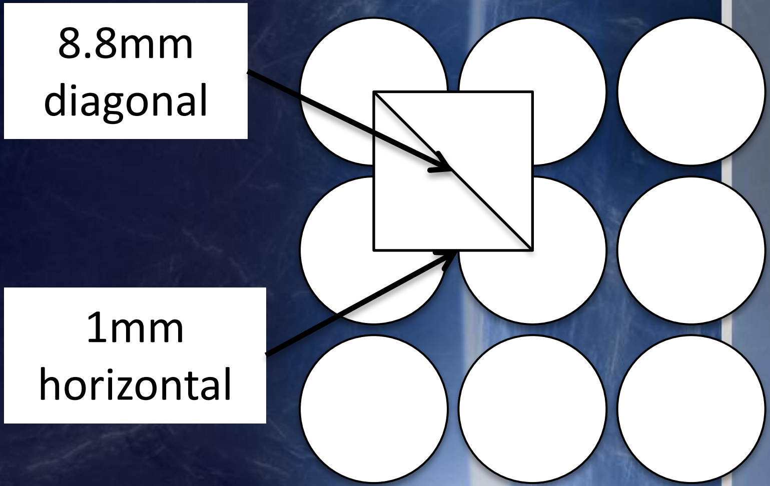


LG C2 – 1mm Space 9P Fork Config. 100% SOC

- 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)

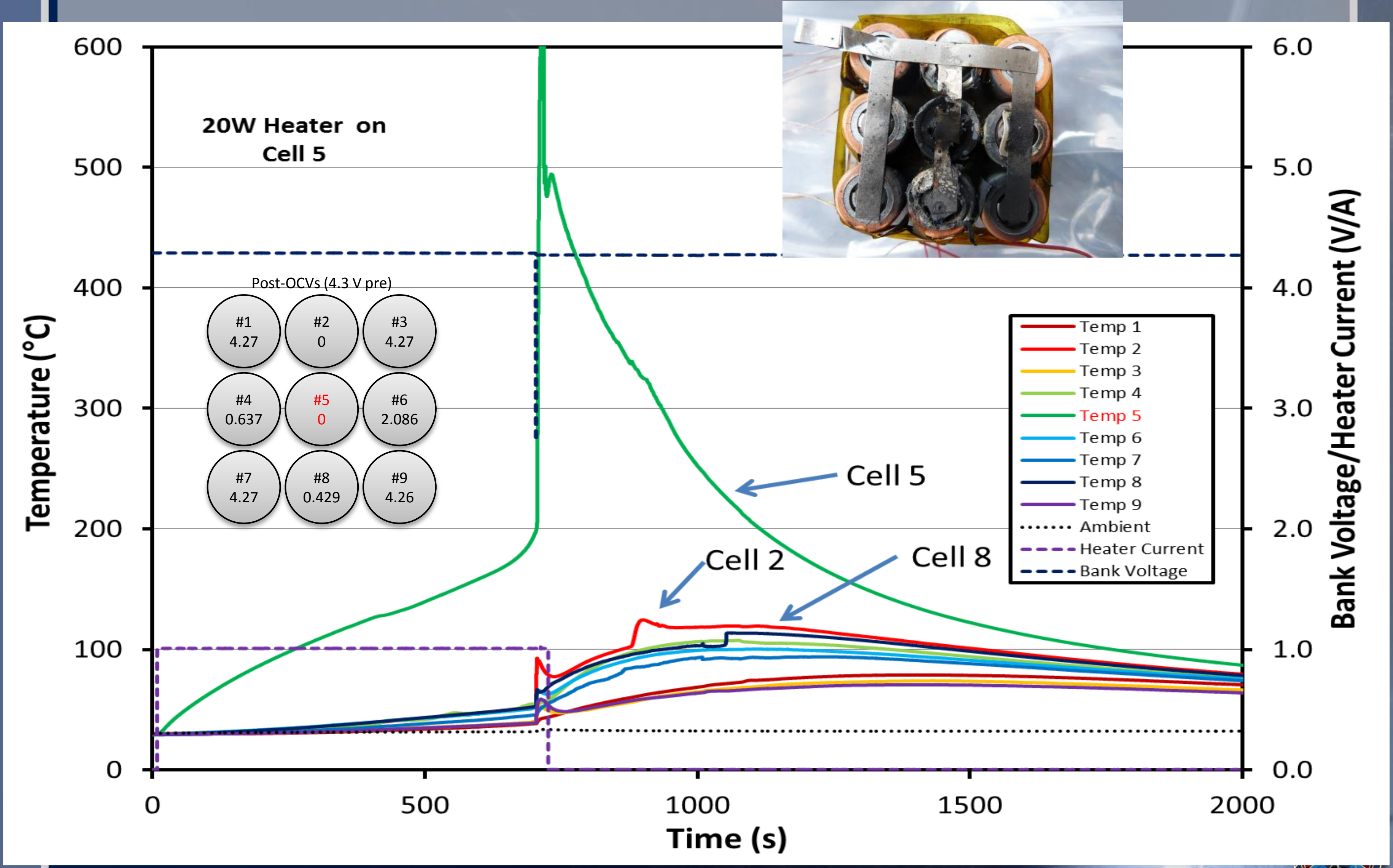
Fork Pattern




8.8mm diagonal

1mm horizontal

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

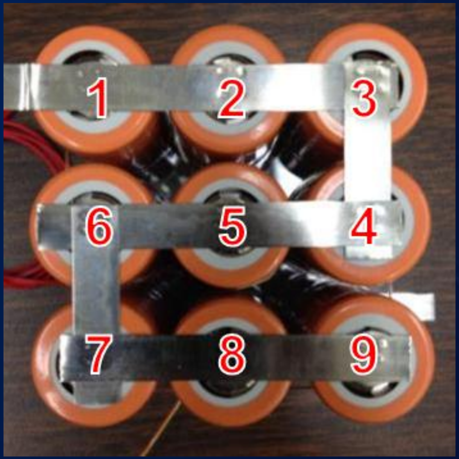


Post-OCVs (4.3 V pre)

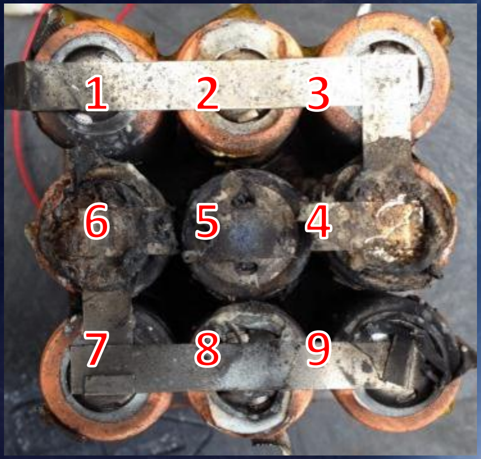
#1 4.27	#2 0	#3 4.27
#4 0.637	#5 0	#6 2.086
#7 4.27	#8 0.429	#9 4.26

LG C2 – 1mm Air Space 9P Serpentine (S-type) 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
- Elevated adjacent cell temperatures (120-150 °C)



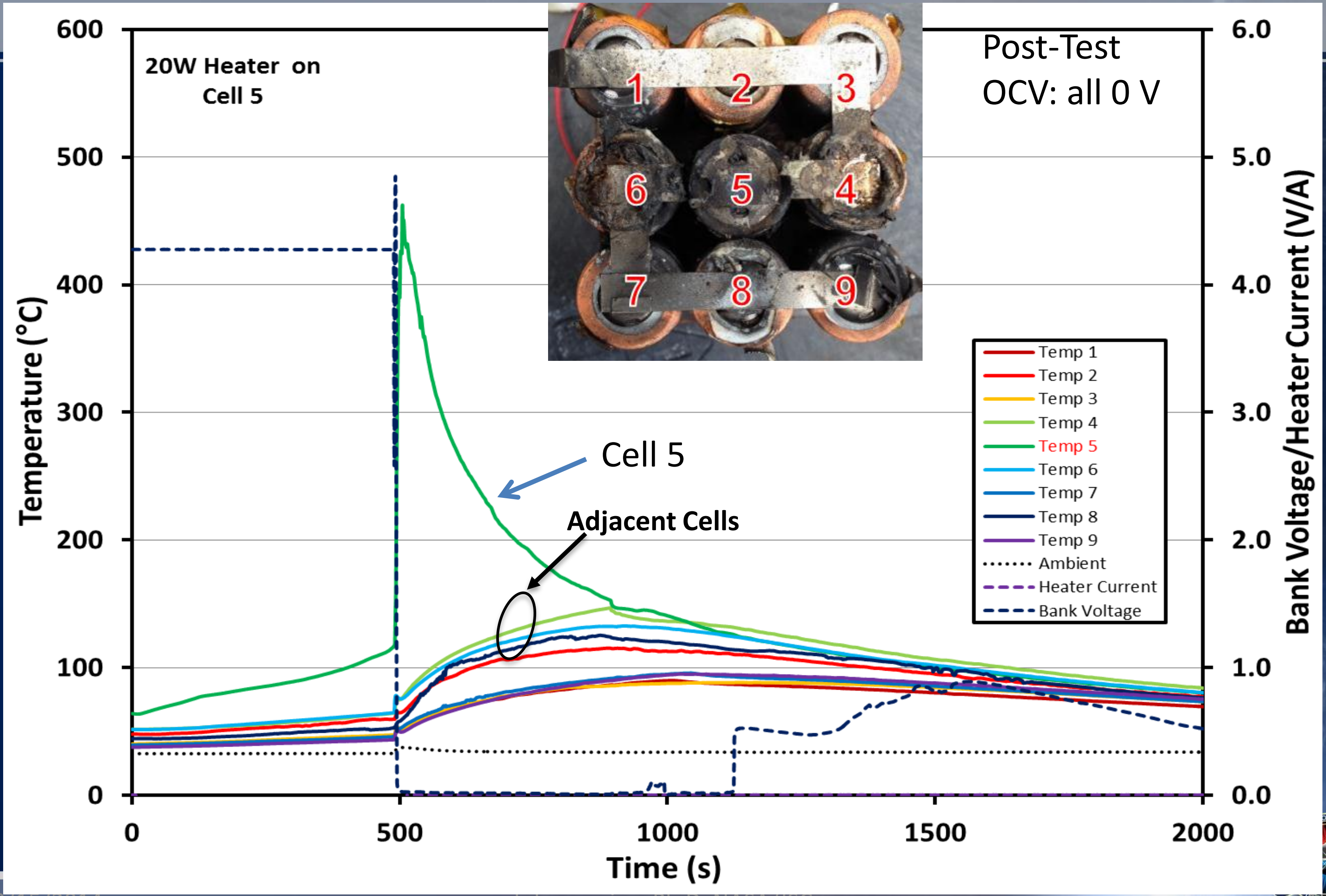
Pre-test



Post-test

LG C2 – 1mm Air Space 9P Serpentine (S-type) Config.

100% SOC



20W Heater on Cell 5

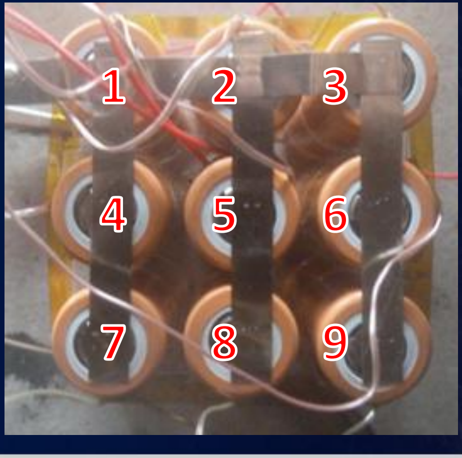
Post-Test OCV: all 0 V

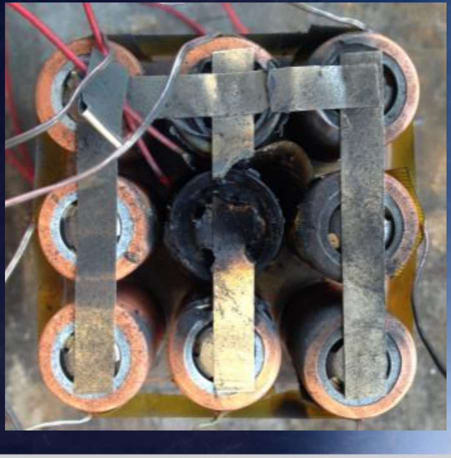
Cell 5

Adjacent Cells

LG C2 – 2mm Air Space 9P Fork Config. 100% SOC

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

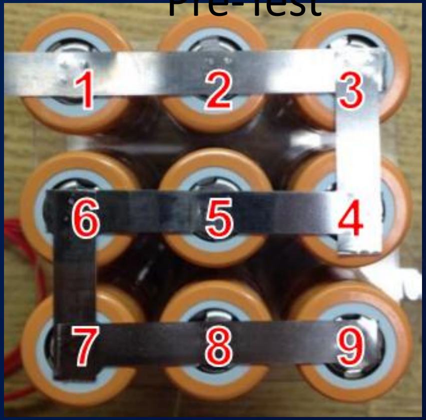




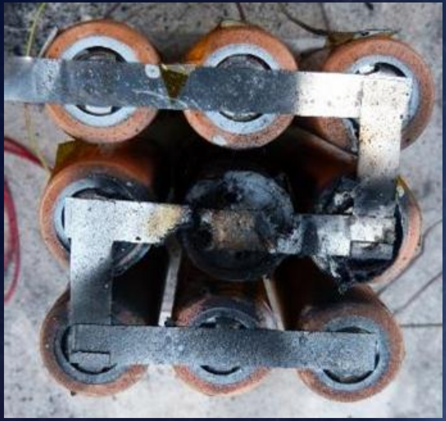
LG C2 – 2mm Air Space 9P Serpentine (S-type) Config. 100% SOC

- 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

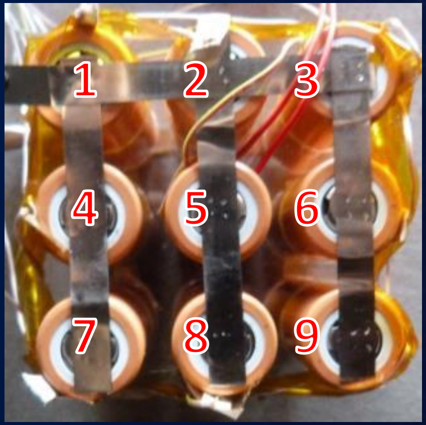


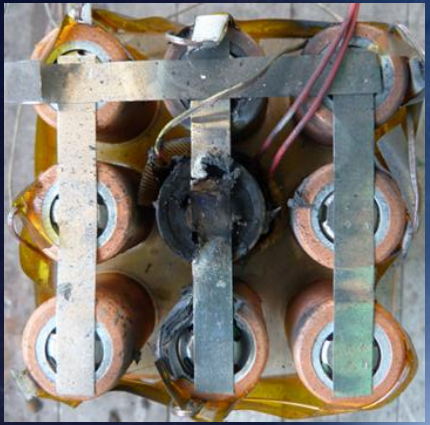
Post-Test



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

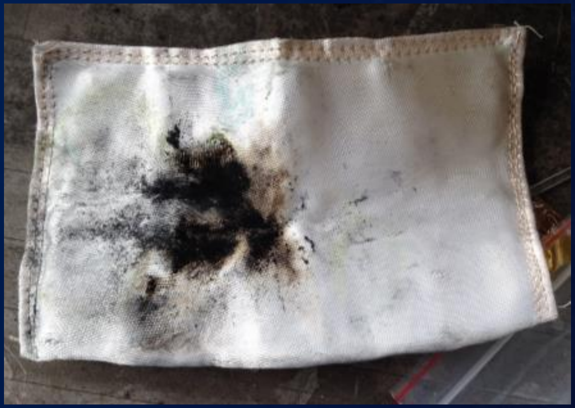
- Complete thermal runaway of cell 5
- No propagation
- Capacity/Voltage drain observed on adjacent cells 2 and 8
- No crimp opening or extrusion of electrode roll

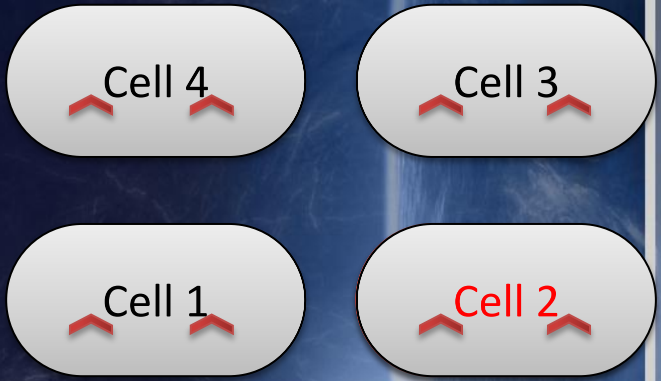




Radiant Barrier

- To mitigate radiation heat transfer and protect against direct flame from side vents in BP cells
- Per Boeing donor
  - Outer layers are quartz cloth,
  - there are 5 nickel foil layers inside with Linoweave (open mesh quartz cloth) separator layers between the nickel foil layers.





Cell 4

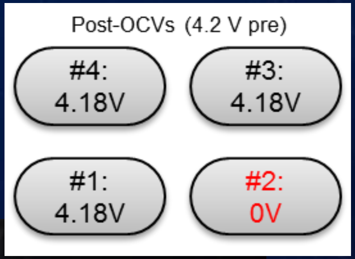
Cell 3

Cell 1

Cell 2

BP5300 at 100% SOC with Radiant Barrier (4S config.)

- Can ruptured and contents ejected from triggered cell
- No propagation



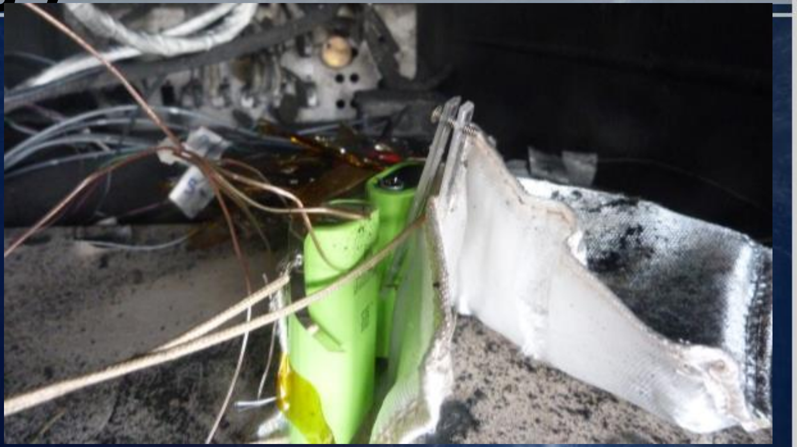
Post-OCVs (4.2 V pre)

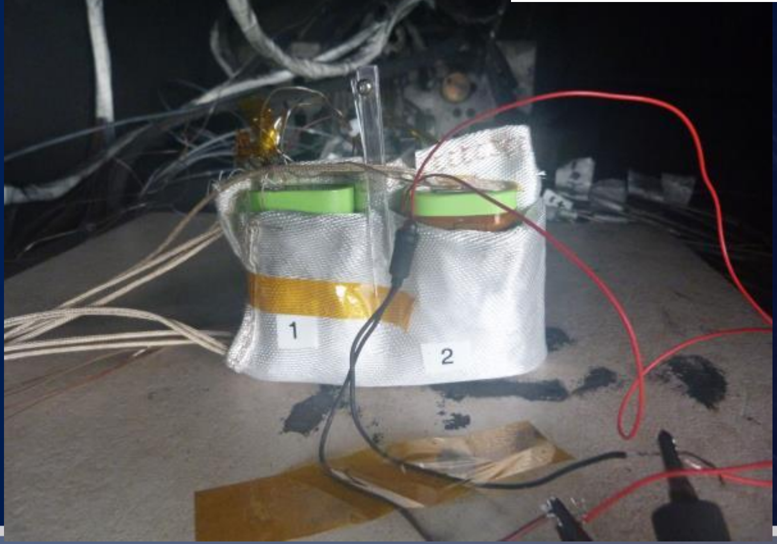
#4: 4.18V

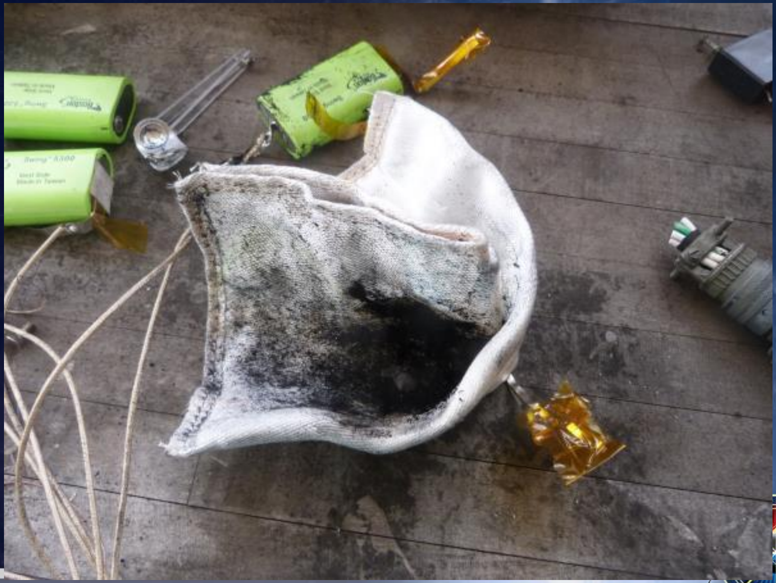
#3: 4.18V

#1: 4.18V

#2: 0V





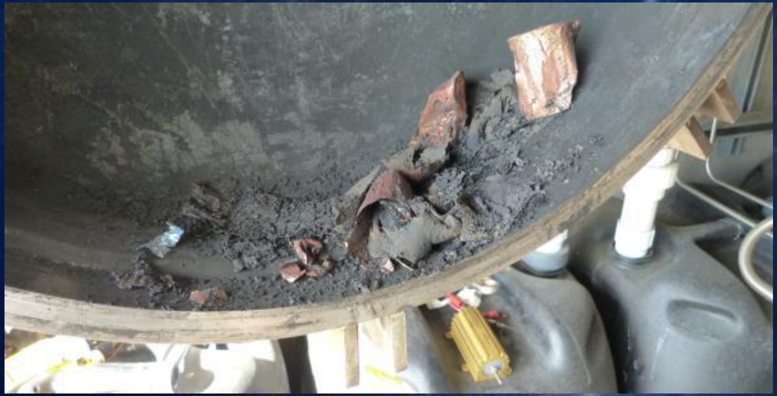


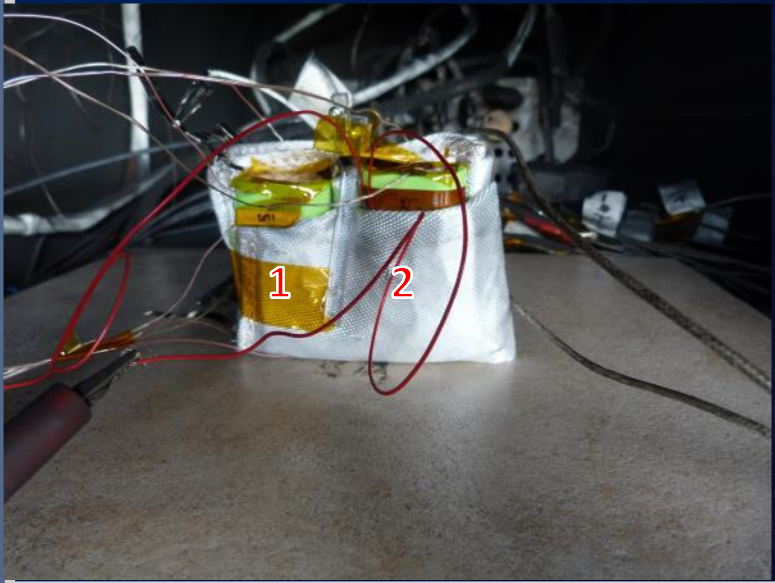
BP5300 at 100% SOC with Radiant Barrier (4P config.)

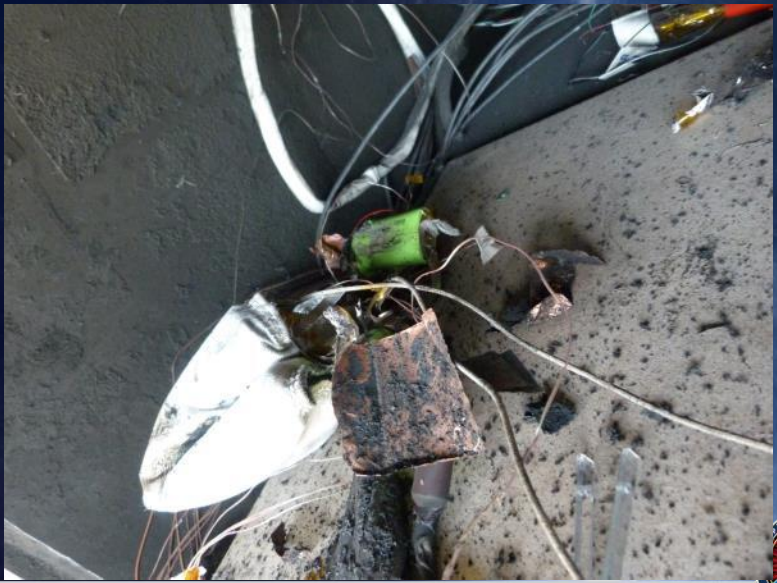
- Can ruptured and contents ejected from triggered cell
- No propagation

Post-OCVs (4.2 V pre)

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



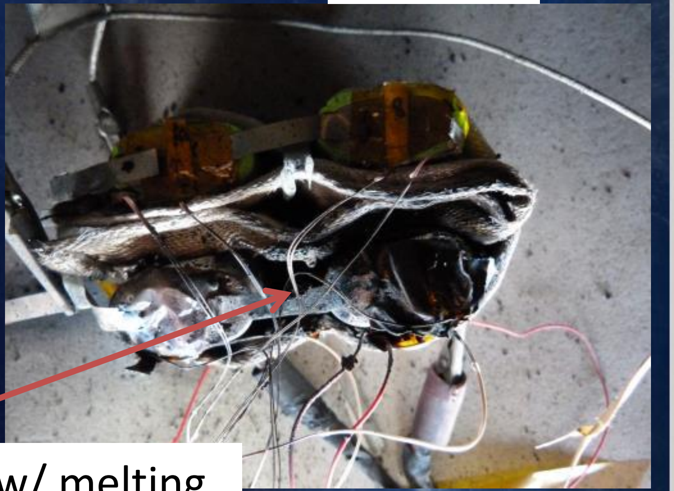




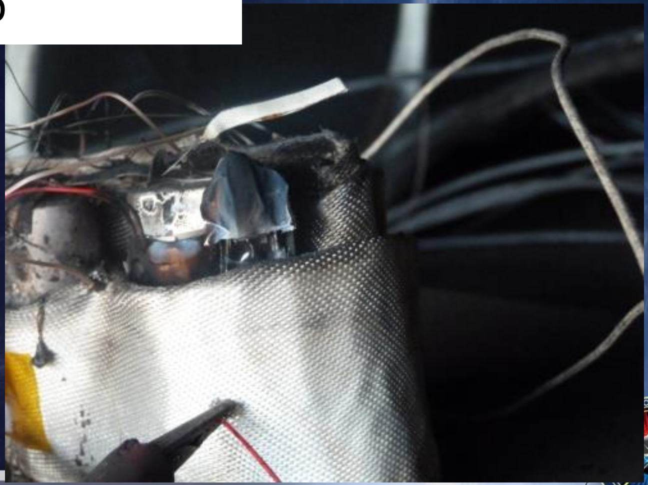
BP5300 at 50% SOC with Radiant Barrier (4P config.)

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

Post-test

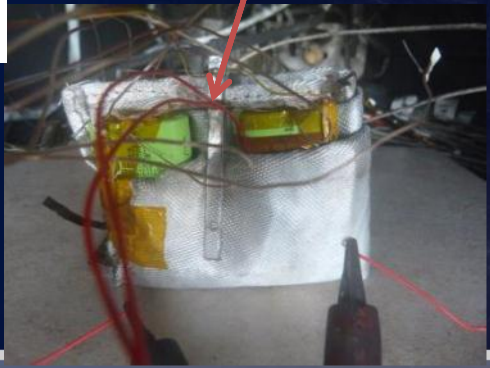


Gap in barrier w/ melting of restraint clip



Restraint Clip

Pre-test

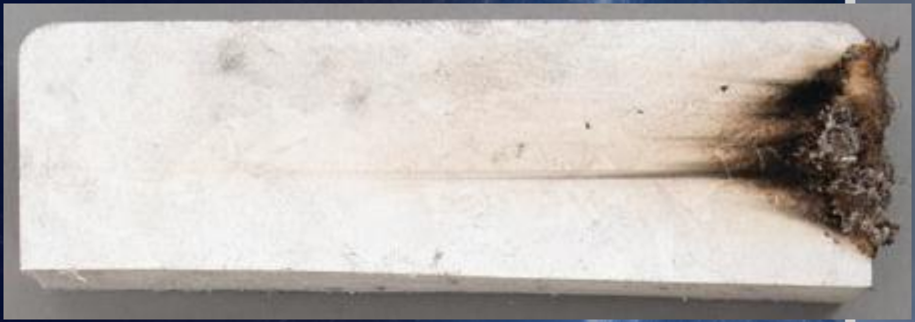


Post-OCVs (4.2 V pre)

#4: 0.28V	#3: 1.5V
#1: 0V	#2: 0V

Intumescent Material

- Intuplas
  - Nanocomposite consisting of thermoplastic carrier and 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.



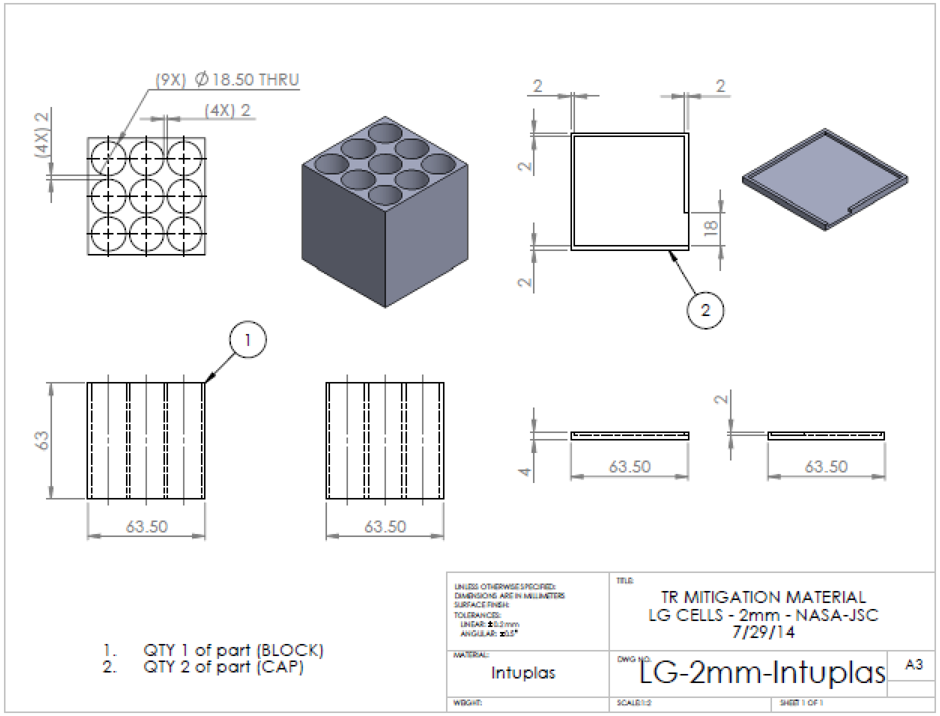
- WSTF Testing
  - Flame propagation
  - Off-gassed products
  - Tested to NASA-STD-6001
  - Material passed flame propagation and off-gas test

(Courtesy: Mike Fowler)

Intuplas Modules

3 each of 2 mm, 4mm spacing for BP and LG cells designs

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


(9X) Ø 18.50 THRU
(4X) 2
(4X) 2
2
2
2
18
2
2
1
63
63.50
63.50
4
63.50
2
63.50

1. QTY 1 of part (BLOCK)
2. QTY 2 of part (CAP)

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR: ±0.2mm
ANGULAR: ±0.5°

TITLE:
TR MITIGATION MATERIAL
LG CELLS - 2mm - NASA-JSC
7/29/14

MATERIAL: Intuplas

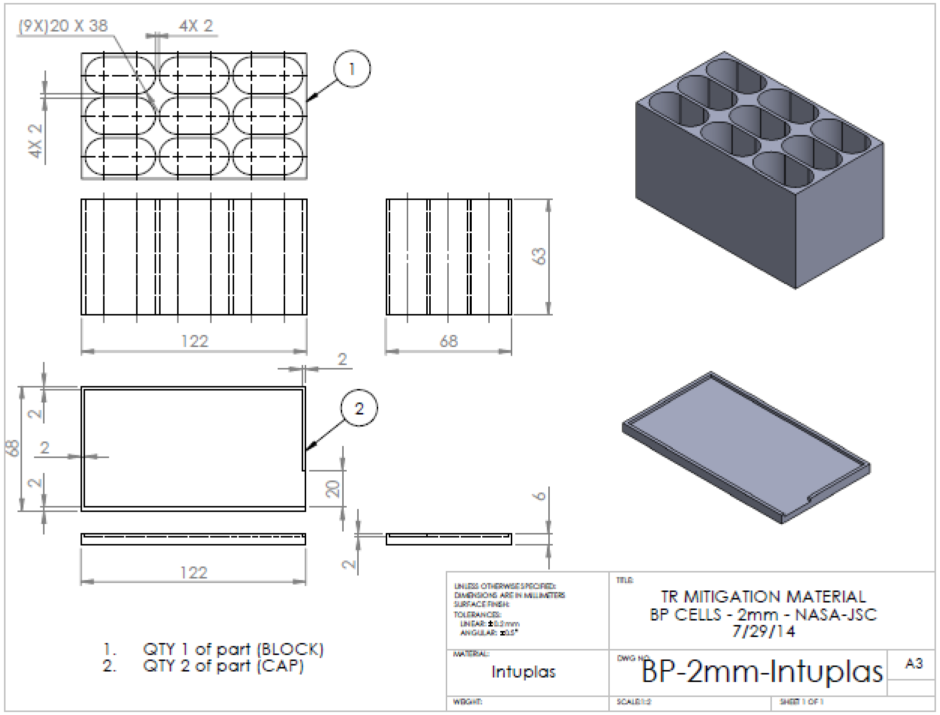
DWG NO. LG-2mm-Intuplas

A3

WEIGHT:

SCALE:1:2

SHEET 1 OF 1


(9X)20 X 38
4X 2
1
4X 2
122
68
63
2
2
68
2
2
2
20
122
6
2

1. QTY 1 of part (BLOCK)
2. QTY 2 of part (CAP)

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR: ±0.2mm
ANGULAR: ±0.5°

TITLE:
TR MITIGATION MATERIAL
BP CELLS - 2mm - NASA-JSC
7/29/14

MATERIAL: Intuplas

DWG NO. BP-2mm-Intuplas

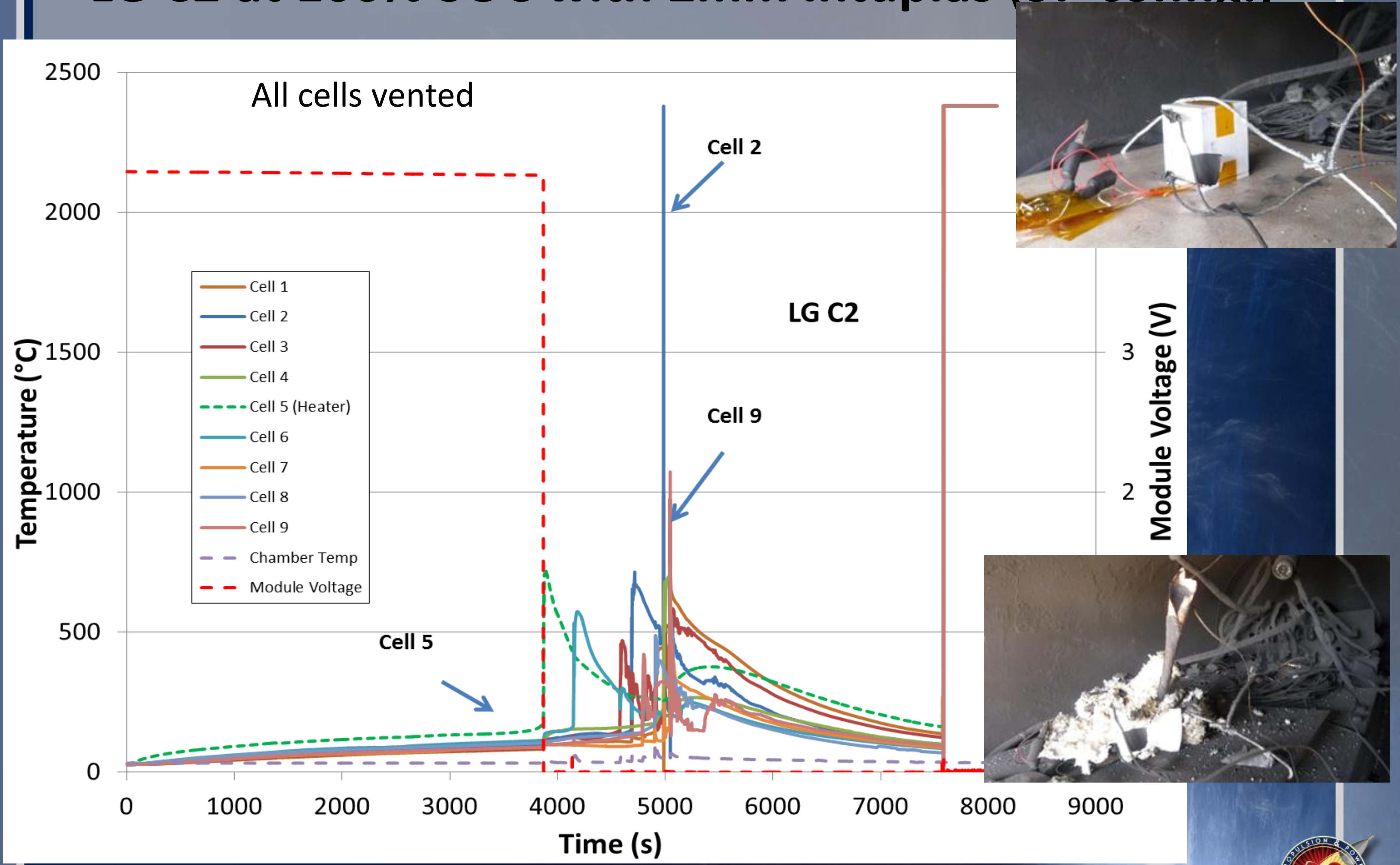
A3

WEIGHT:

SCALE:1:2

SHEET 1 OF 1

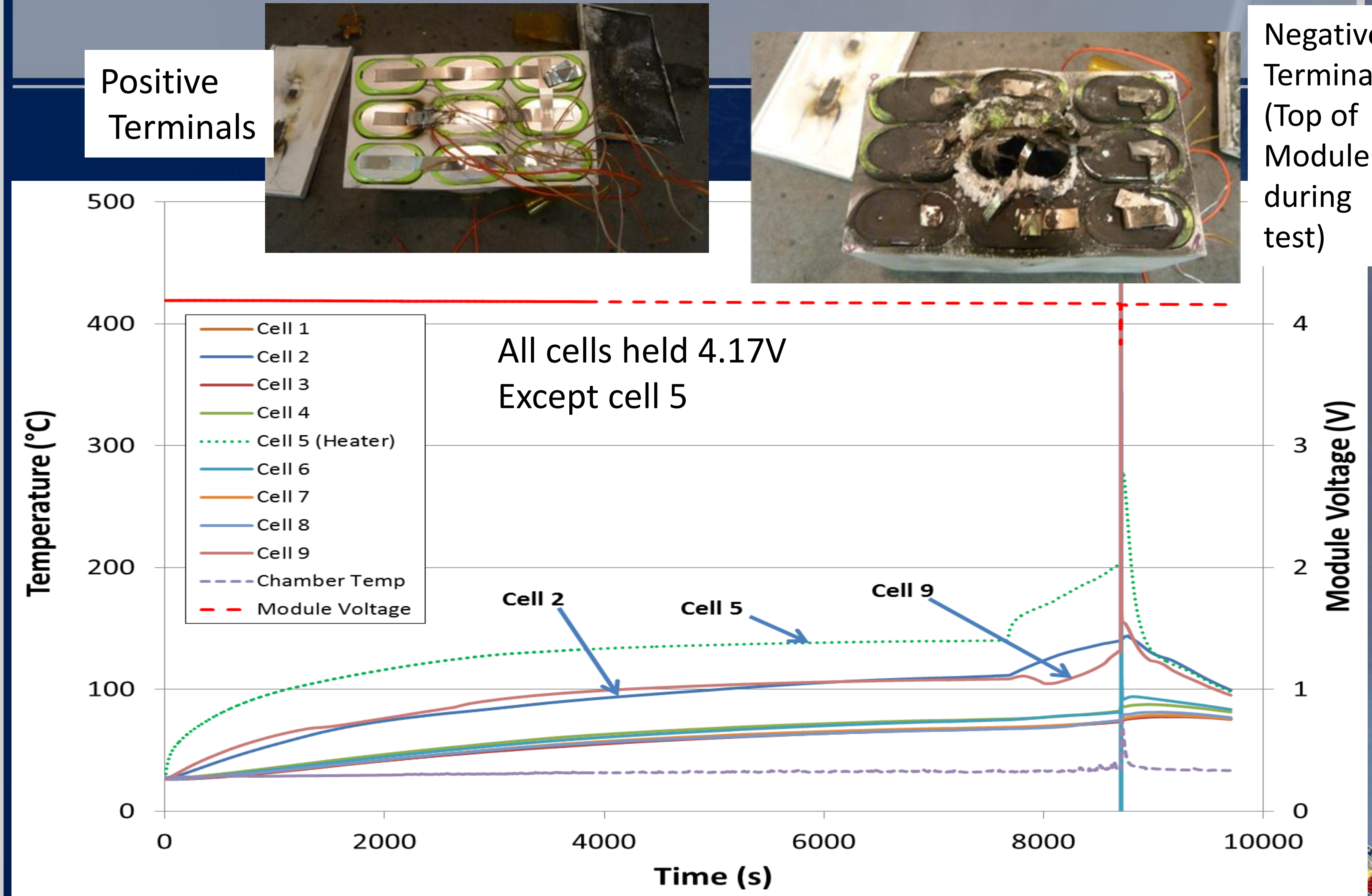
LG C2 at 100% SOC with 2mm Intuplas (9P config.)



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

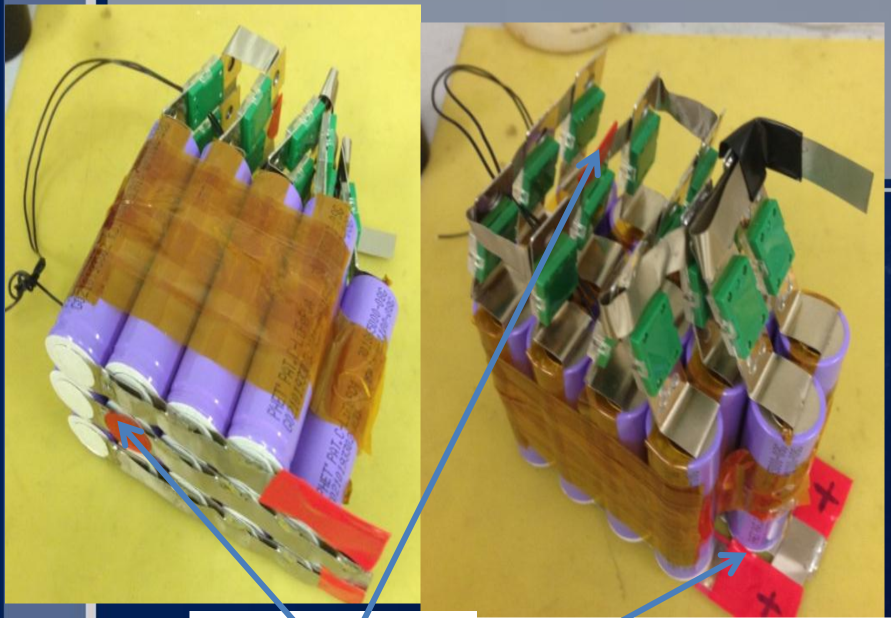
Positive Terminals

Negative Terminals (Top of Module during test)



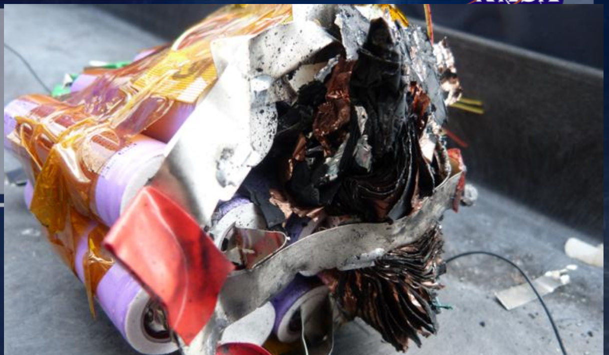
All cells held 4.17V
Except cell 5

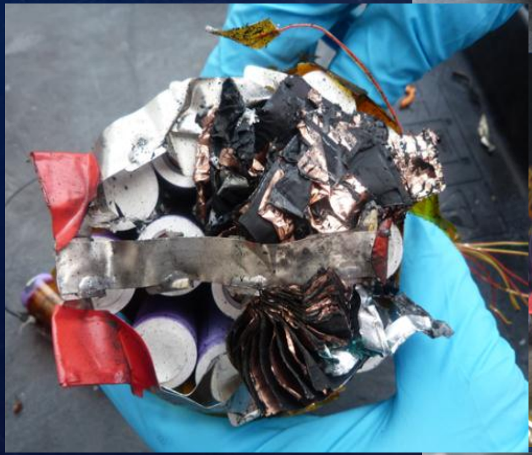
SKC LFP 14.7 Ah 14P Module 2-100 % SOC

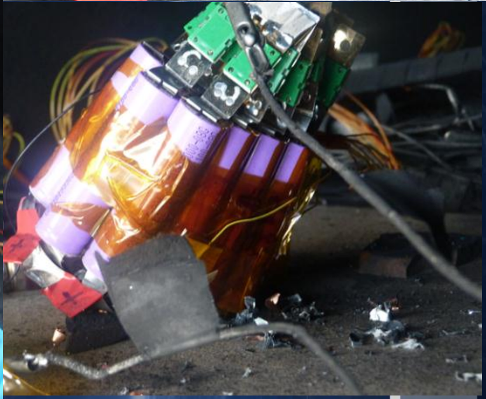


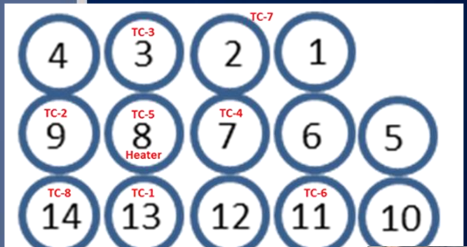
50 W Heater

Cell positive terminals

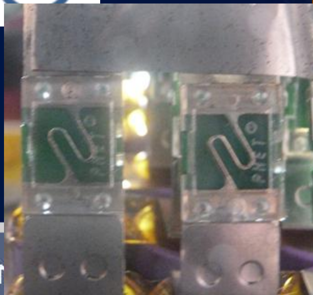


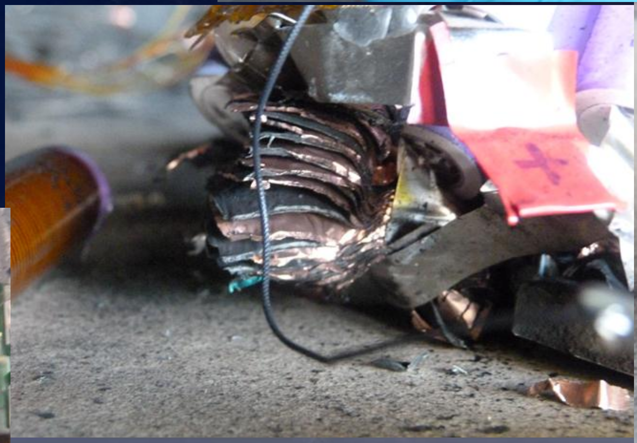


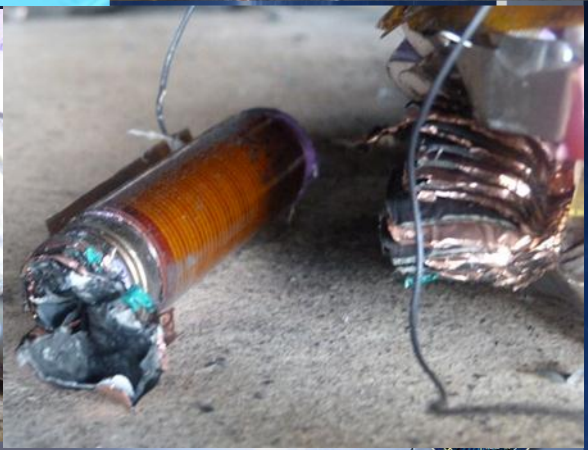



4
TC-3
3
TC-7
2
1
TC-2
9
TC-5
8
Heater
TC-4
7
6
5
TC-8
14
TC-1
13
12
TC-6
11
10

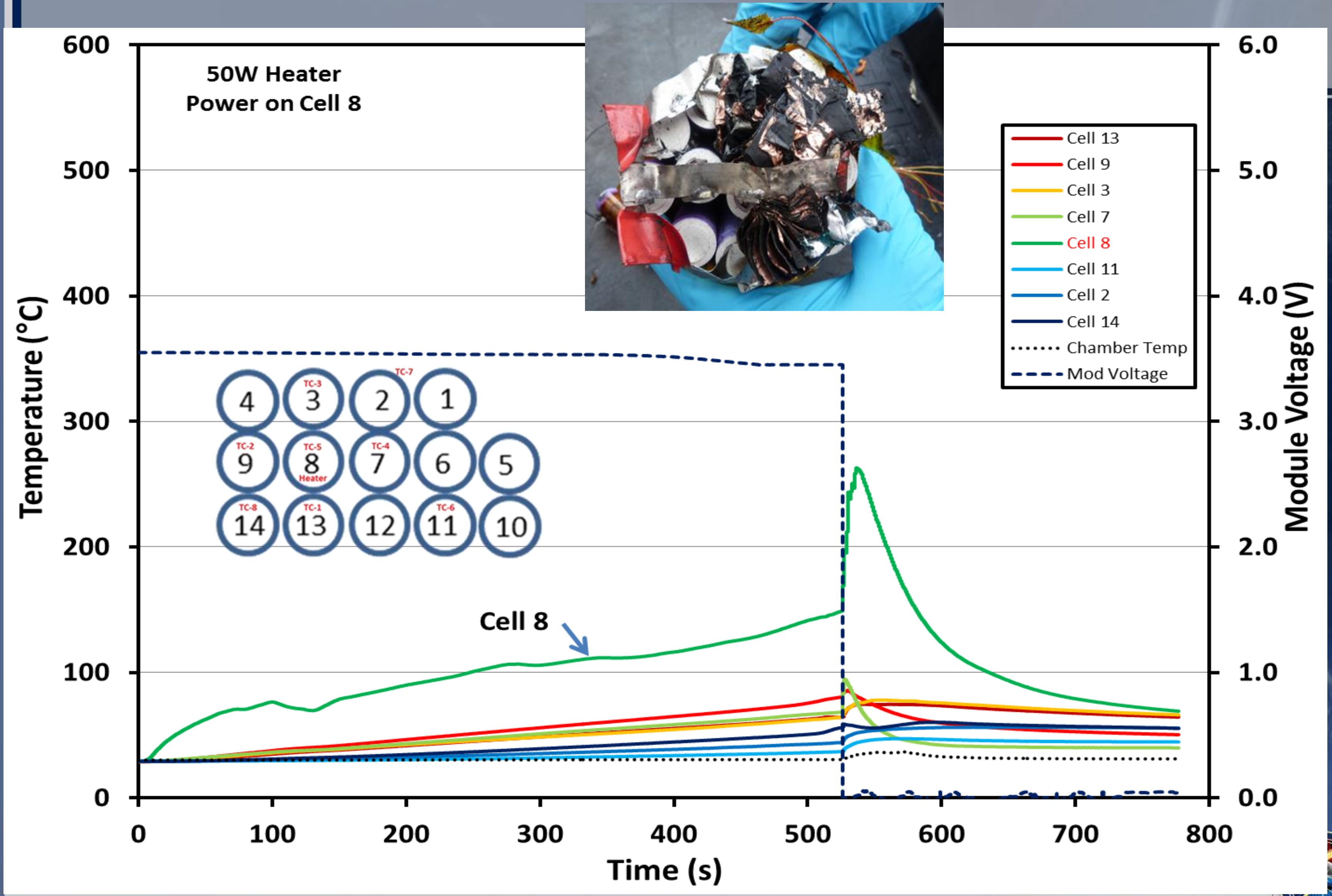
7 deg C / min.
Heating rate







SKC LFP 14.7 Ah 14P Module 2-100 % SOC



Thermal Propagation Analysis

(Calculations by Carlos Lopez)

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

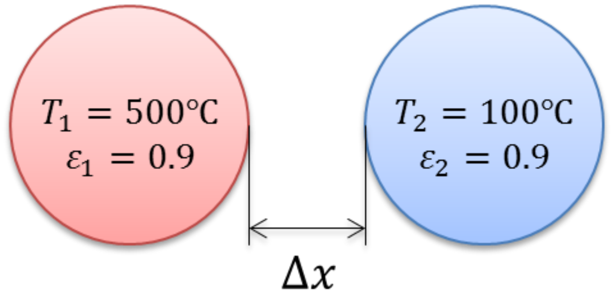
$$Q_{rad} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{\boldsymbol{F}_{\boldsymbol{12}}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$

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

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

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

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**



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

Summary

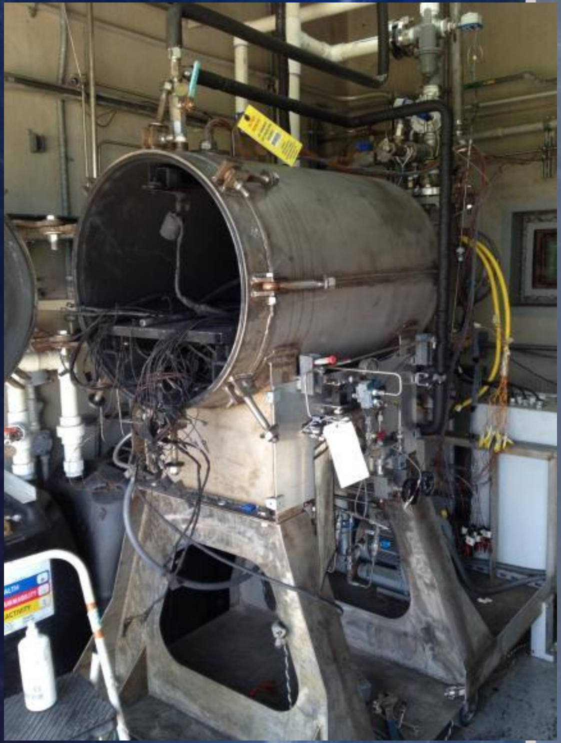
- Increasing cell spacing decreased adjacent cell damage
- Electrically connected adjacent cells drained more than physically adjacent cells
- Radiant barrier prevents propagation when fully installed between BP cells
- BP cells vent rapidly and expel contents at 100% SOC
  - Slower vent with flame/smoke 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; fuses on negative terminal of cell may provide a benefit in reducing cell to cell damage propagation.

Acknowledgment

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

Backup Slides

Test Chamber Setup

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