Battery Design Implications on Thermal Runaway Severity:
NASA ISS SAFER Battery Safety Assessment

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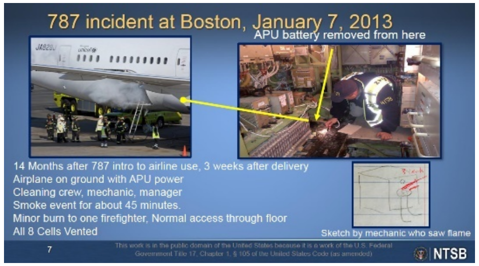
(d). Battery Safety Consulting, Inc. (Albuquerque, NM, USA);
(e). Naval Surface Warfare Center (Crane, IN, USA).

Agenda

- Background
  - Battery Design
- Test Approach and Results
  - Single-Cell Trigger
  - SAFER Battery TR
- Summary

Background

- 2013 Commercial Aviation Li-Battery Incidents
  - Three (3) rechargeable lithium-ion battery (LIB)[1]
  - *One (1) non-rechargeable lithium battery* [2]
- Industry Impacts – Risk Mitigation
  - Severity of Thermal Runaway (TR) Event
    - Energetic cell internal short
    - Other causes
  - Consequences of TR Event
    - Effects of cell-to-cell propagation
  - Standards and Legislation - Ongoing
    - Revisions to industry LIB safety standards
    - New test protocols and compliance methods



Ref:

1. Bauer, M., Swain, R., Jeevarajan, J., "*Findings and Lessons Learned from The Boeing 787 Investigations*", 2015 Space Power Workshop, May 11-14, Manhattan Beach, CA, USA.
2. Air Accidents Investigation Branch (AAIB), "*Report on the serious incident to Boeing B-787-8, ET-AOP London Heathrow Airport on 12 July 2013*", Air Accident Report 2/2015, August 19, 2015.

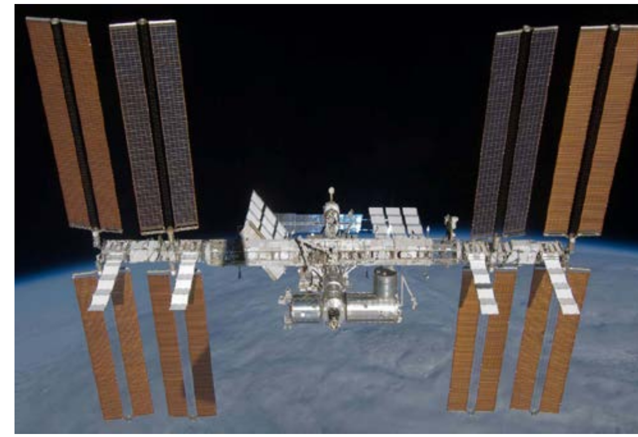
Impacts To NASA Programs

- Goals & Objectives
  - Implementation of NASA Engineering Safety Center (NESC)-sponsored risk assessments
  - Independent reviews of deployed and new lithium batteries
    - ISS Main LIB Orbital Replacement Unit (ORU)
    - ***Extravehicular Mobility Unit (EMU)***
- Approach
  - Critical independent reviews of TR hazards
  - Perceptive relevant testing to determine TR hazards risk

Risk α [Severity x Consequences]

  - Implementation of new design solutions to reduce safety risk, if necessary

NASA/ISS Transition from Ni-H_2 to LIB ORU

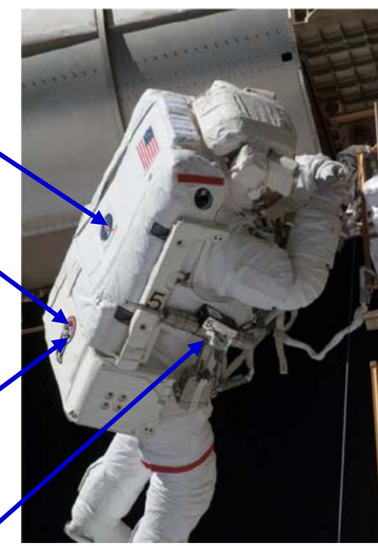


Long Life Li-Ion Battery (LLB)

Li-Ion Rechargeable EVA Battery (LREBA)

Simplified Aid For EVA Rescue (SAFER) Battery – Non-rechargeable Li Battery

Li-Ion Pistol Grip Tool (LPGT)



NESC Project Objective and Approach

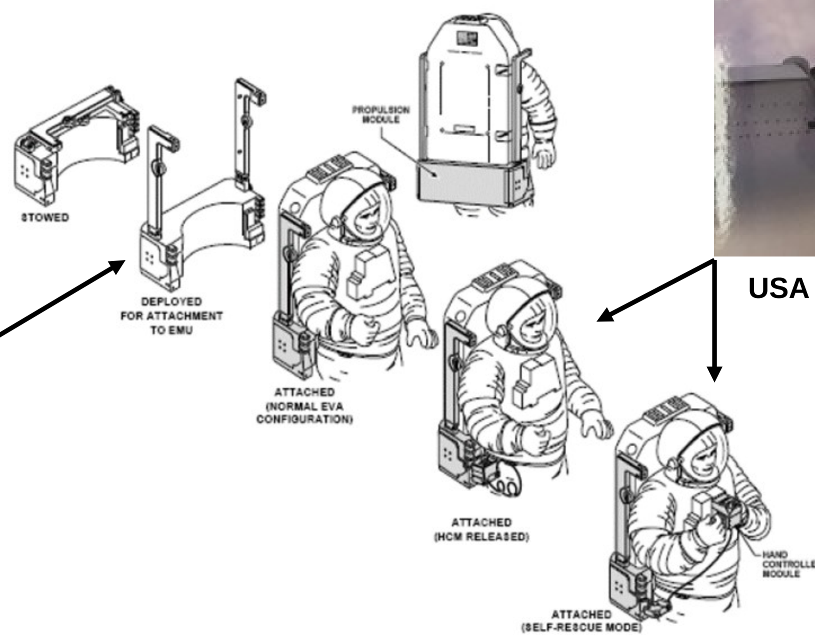
- Objective
  - Assess the severity of a TR event in the SAFER non-rechargeable lithium battery
- Approach
  - Conduct credible *worst-case* SAFER battery safety tests designed to quantify the severity of a TR condition which may result in cell-to-cell propagation
    - Utilize relevant flight configuration
    - Employ relevant flight environment

Conservative assumption that likelihood of single-cell TR event is non-zero

ISS EMU SAFER System Unit: Brief Intro

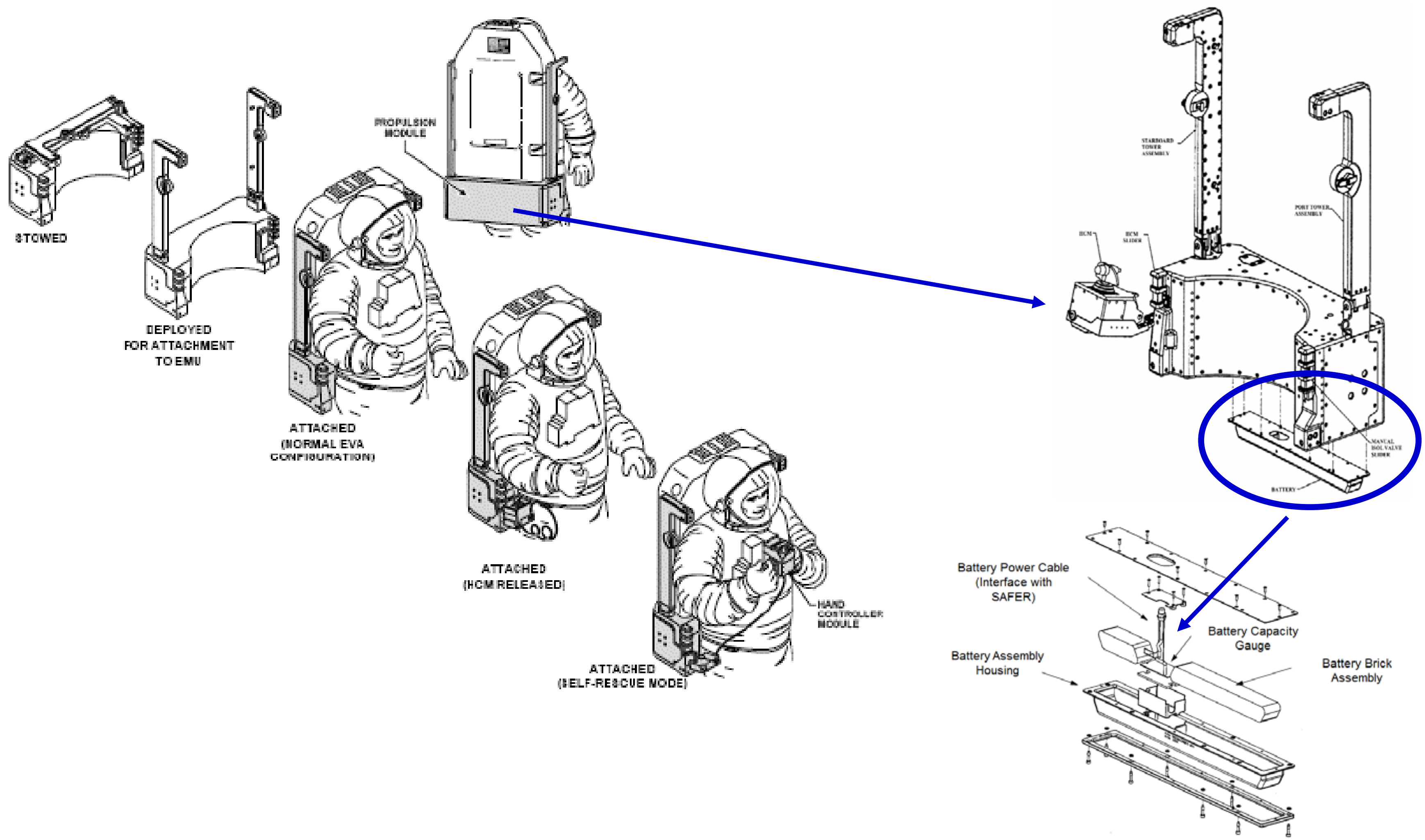
- Purpose
  - Self-contained, 24-jet free flyer “jet pack” system that provides capability for EVA crewmember self-rescue
    - SAFER Battery provides all SAFER system unit power
  - Jetpack operation is for contingency use in case astronaut becomes un-tethered from ISS
  - Worn by USA astronauts on EVA since 1994

ISS SAFER System Unit



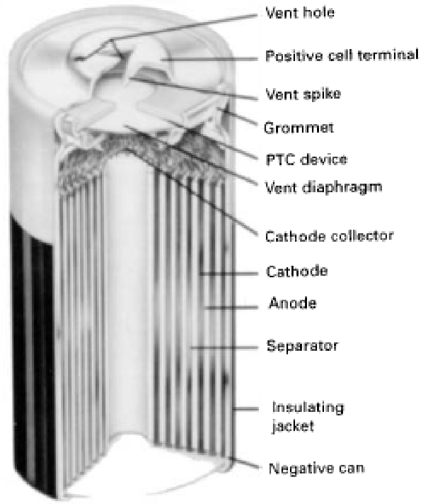
USA Astronaut on EVA with SAFER attached to EMU

ISS EMU SAFER System Integration



Battery and COTS Cell Design

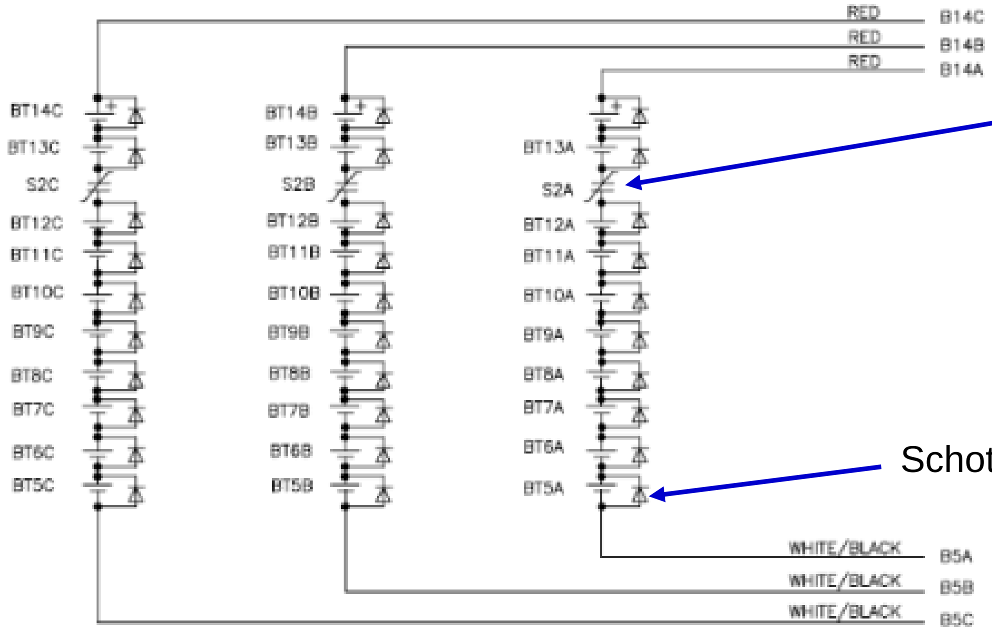
- Battery Design
  - ***Non-rechargeable***
  - ORU refurb schedule = Every 3.5-yr.
  - 14S-3P topology **(4S+10S=14S)**
  - Mass = 1.99kg
  - Nominal Voltage = 40V
  - Nominal Capacity = 3.75Ah
  - Operating Temp = -20ºC to +58ºC
  - Duracell® Ultra CR123 (2/3A size; Li-MnO_2)
  - **Safety Devices**
    - **Individual cell Schottky bypass diodes**
    - **Bundle-level PTC's**
- Cell Design
  - ***Non-rechargeable***
  - Mass = 17g
  - Nominal Voltage = 3.00V
  - Nominal Capacity = 1.5Ah
  - Operating Temp = -20ºC to +75ºC
  - **Safety Devices**
    - **Internal PTC**
    - **External Vent**



Ref: Duracell® Lithium Technical Bulletin (www.duracell.com)

Cross-sectional view of Duracell® Ultra 123 Li/MnO_2 spiral-wound cell.

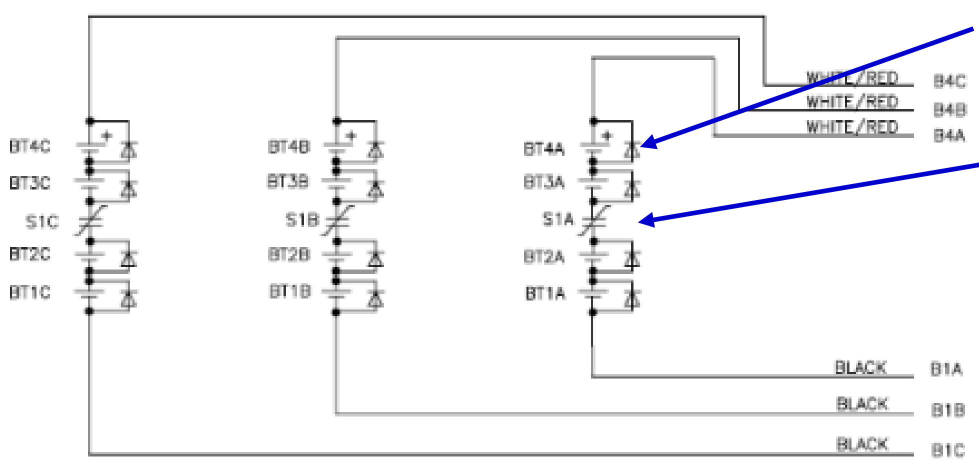
ISS SAFER 4S/10S Battery: Bundle Electrical Design



10-Cell (10S) Bundle PTC
(Positive Temperature Coefficient)

Schematic Diagram
10-Cell (10S) Bundles

Schottky Diode

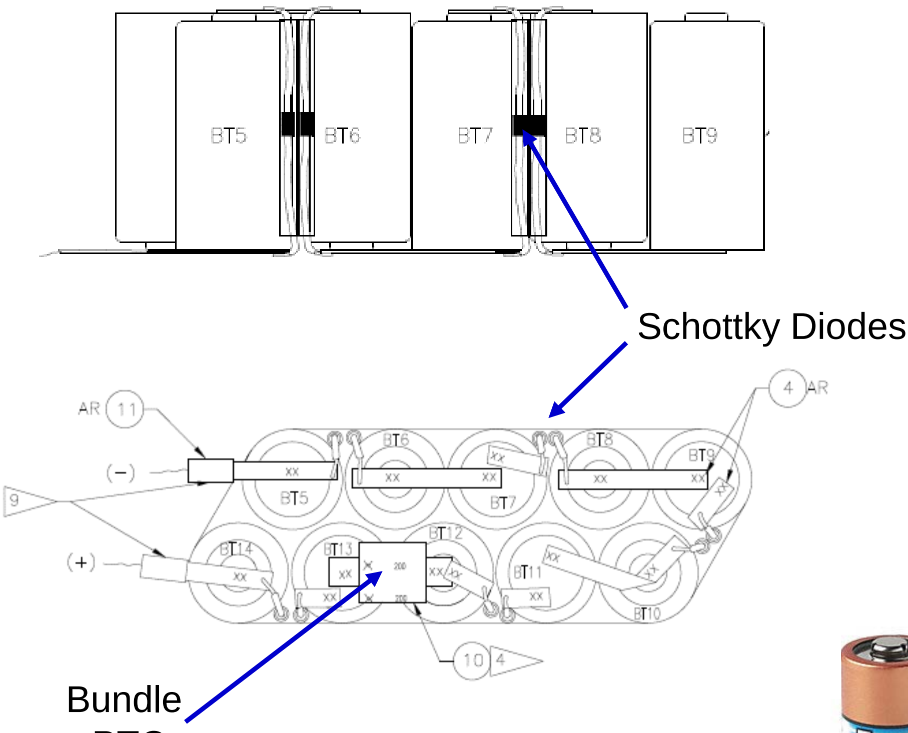


Schottky Diode

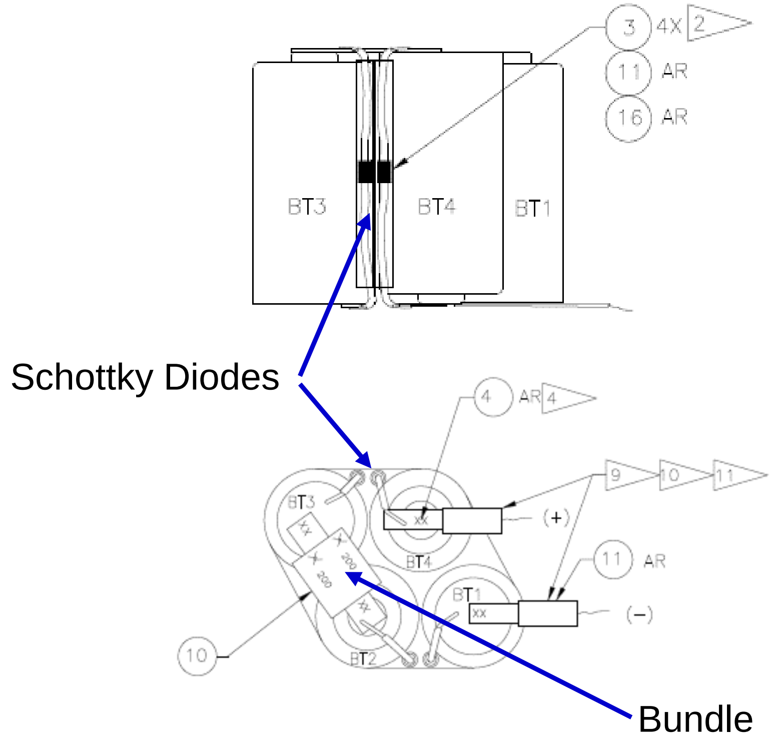
4-Cell (4S) Bundle PTC

Schematic Diagram
4-Cell (4S) Bundles

ISS SAFER Battery: 4S/10S-Cell Bundle Safety Devices



10-Cell (10S) Bundle



4-Cell (4S) Bundle

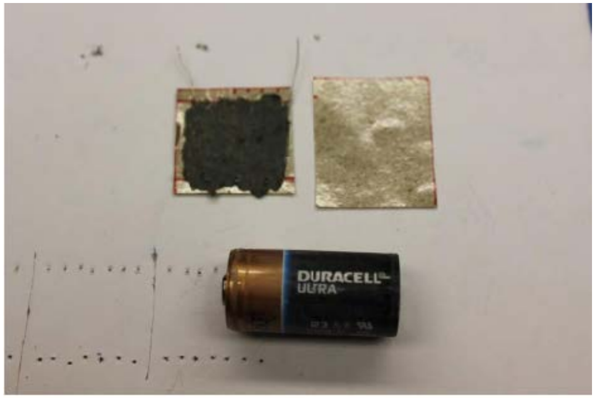
Single-Cell TR Trigger Testing

Single-Cell TR Trigger Test Matrix Results

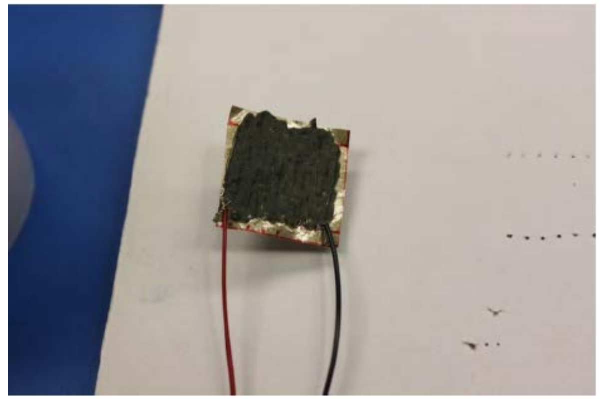
Trial Run	Cell ID	Heater Power (W)	Heater Location	Cell Temp (°C)	Time to TR (min)	Cell Jacket Temp at Start of TR (°C)	Max Cell Jacket Temp (°C)	Max Positive Terminal Probe Temp (°C)	Comments
1	53	15	Bottom	Ambient	-	-	~ 161	N/A	No thermal runaway after 44 min
1	70	15	Bottom	Ambient	~ 22	~ 199	~ 575	N/A	
2	44	15	Side	Ambient	~ 11	~ 180	~ 733	N/A	
2	50	15	Side	Ambient	~ 9	~ 158	~ 518	N/A	
3	119	10	Bottom	Ambient	-	-	~ 120	-	No thermal runaway after 1 hr
3	123	10	Bottom	Ambient	-	-	~ 119	-	No thermal runaway after 1 hr
4	129	10	Side	Ambient	-	-	~ 143	-	No thermal runaway after 1 hr
4	133	10	Side	Ambient	-	-	~ 162	-	No thermal runaway after 1 hr
5	142	20	Bottom	Ambient	~ 8.5	~175	~ 621	~632	
5	167	20	Bottom	Ambient	~ 8.3	~172	~ 645	~882	
6	169	20	Side	Ambient	~ 5.7	~209	~ 734	~409	
6	175	20	Side	Ambient	~ 6.5	~204	~ 684	~532	
7	406	25	Bottom	Ambient	~ 7	~155	~ 661	~ 275	
7	419	25	Bottom	Ambient	~ 6.3	~ 177	~649	~ 1158	Heater power unstable
8	208	25	Side	Ambient	~ 4.7	~ 182	~ 582	~ 340	
8	402	25	Side	Ambient	~ 5	~ 176	~ 608	~ 437	
12	216	15	Side	49	~ 9:31	~ 250	~ 746	~ 690	False start @ < 00:00; Heater not connected
12	246	15	Side	49	~ 7:19	~ 198	~ 569	~ 430	Clamp TC faulty
16	252	20	Side	49	~ 5:23	~ 178	~ 735	~562	
16	308	20	Side	49	~ 6:10	~ 178	~ 585	~ 652	
18	312	25	Side	49	~ 4:16	~ 170	~ 577	~ 502	
18	318	25	Side	49	~ 3:51	~ 228	~ 717	~ 552	False start @ < 00:00; Heater not connected
22a	251	35	Side	Ambient	~ 2:26	~ 186	~ 700	N/A	
22a	522	35	Side	Ambient	~ 2:45	~ 173	N/A	N/A	Heater appears to have shorted
23a	579	40	Side	Ambient	~ 2:22	~ 216	N/A	N/A	Lost jacket temp after ~ 230°C
23a	839	40	Side	Ambient	~ 1:54	~ 170	~ 730	N/A	Heater appears to have shorted
S12	17	35	Side	Ambient	~ 2:18	~ 134.8	~ 851	N/A	Spare cell; Ceramic heater (6.526 Ω DMM, 6.8 Ω data); TC on cell jacket
S13	135	35	Side	Ambient	~ 2:14	~ 170.2	~ 694	N/A	Spare cell; Ceramic heater (6.417 Ω DMM, 6.5 Ω data); TC on cell jacket
S14	25	35	Side	Ambient	~ 3:10	~ 155	~ 668	N/A	Spare cell; Ceramic heater (12.47 Ω DMM, 7.2 Ω data); TC on cell can; Op Error
S15	78	35	Side	Ambient	~ 2:48	~ 146.9	~ 599	N/A	Spare cell; Ceramic heater (7.49 Ω DMM, 7.2 Ω data); TC on cell can
22b	128	35	Side	Ambient	~ 2:47	~ 348	~ 492	N/A	Ceramic heater (6.56 Ω DMM, 6.4 Ω data); TC on cell can; Cell can TC too close to heater
22b	315	35	Side	Ambient	~ 2:06	~ 169	~ 1280	N/A	Ceramic heater (6.713 Ω DMM, 6.6 Ω data); TC on cell can
23b	381	40	Side	Ambient	~ 2:07	~ 130	~ 622	N/A	Ceramic heater (6.88 Ω DMM, 6.8 Ω data); TC on cell can
23b	706	40	Side	Ambient	~ 2:07	~ 175	~ 827	N/A	Ceramic heater (9.89 Ω DMM, 7.0 Ω data); TC on cell can
22c	26	35	Side	Ambient	~ 2:27	~ 173	~ 655	~ 375	Ceramic heater (7.1 Ω DMM, 6.9 Ω data); TC on cell can
22c	266	35	Side	Ambient	~ 2:18	~ 125	~ 551	~ 619	Ceramic heater (6.8 Ω DMM, 6.9 Ω data); TC on cell can
23c	486	40	Side	Ambient	~ 2:00	~ 163	~ 700	~ 216	Ceramic heater (6.9 Ω DMM, 6.9 Ω data); TC on cell can
23c	740	40	Side	Ambient	~1:40	~ 110	~ 213	~ 605	Ceramic heater (7.2 Ω DMM, 7.0 Ω data); TC on cell can; Cell OCV 3.02 V (low); Heater Current = ~ 5A startup then ~ 2.3A

35W heater power chosen for battery-level TR testing

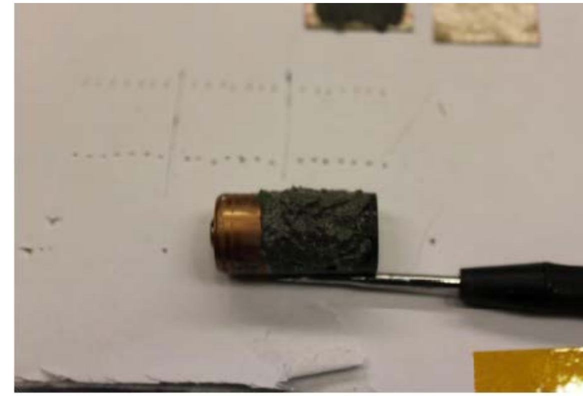
Ceramic Patch Heater: Design & Installation



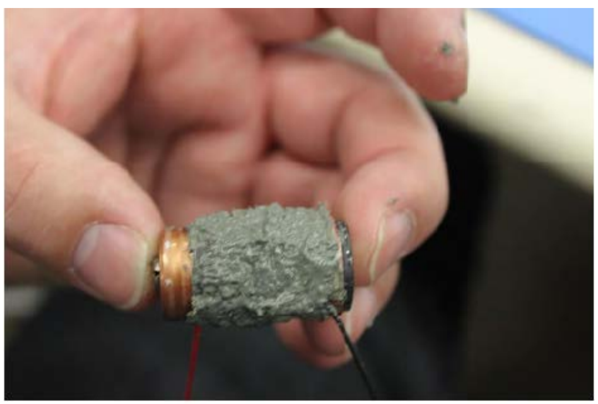
SAFER Cell



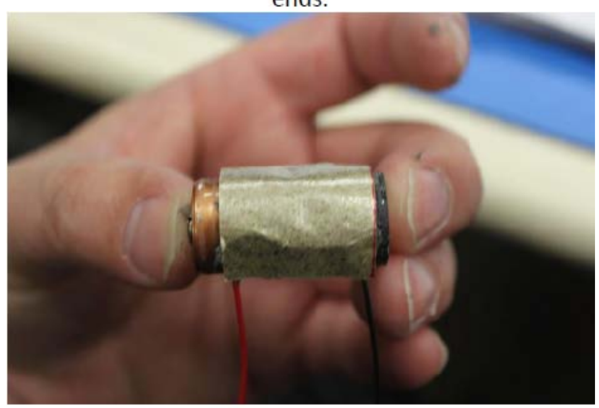
Twist insulated copper wires onto Nichrome wire ends.



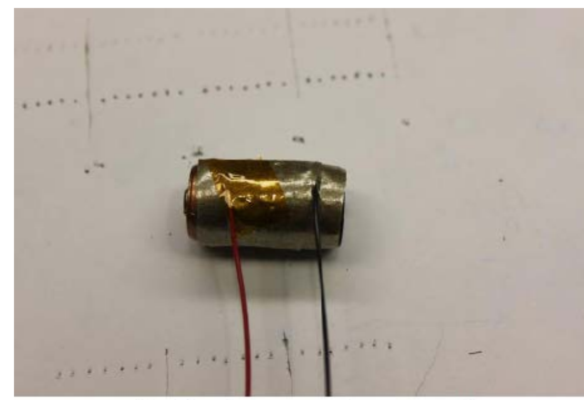
Apply putty directly on cell.



Install heater, wire-side up, on putty-coated side of cell. Apply new coat of putty to fill in any cracks.

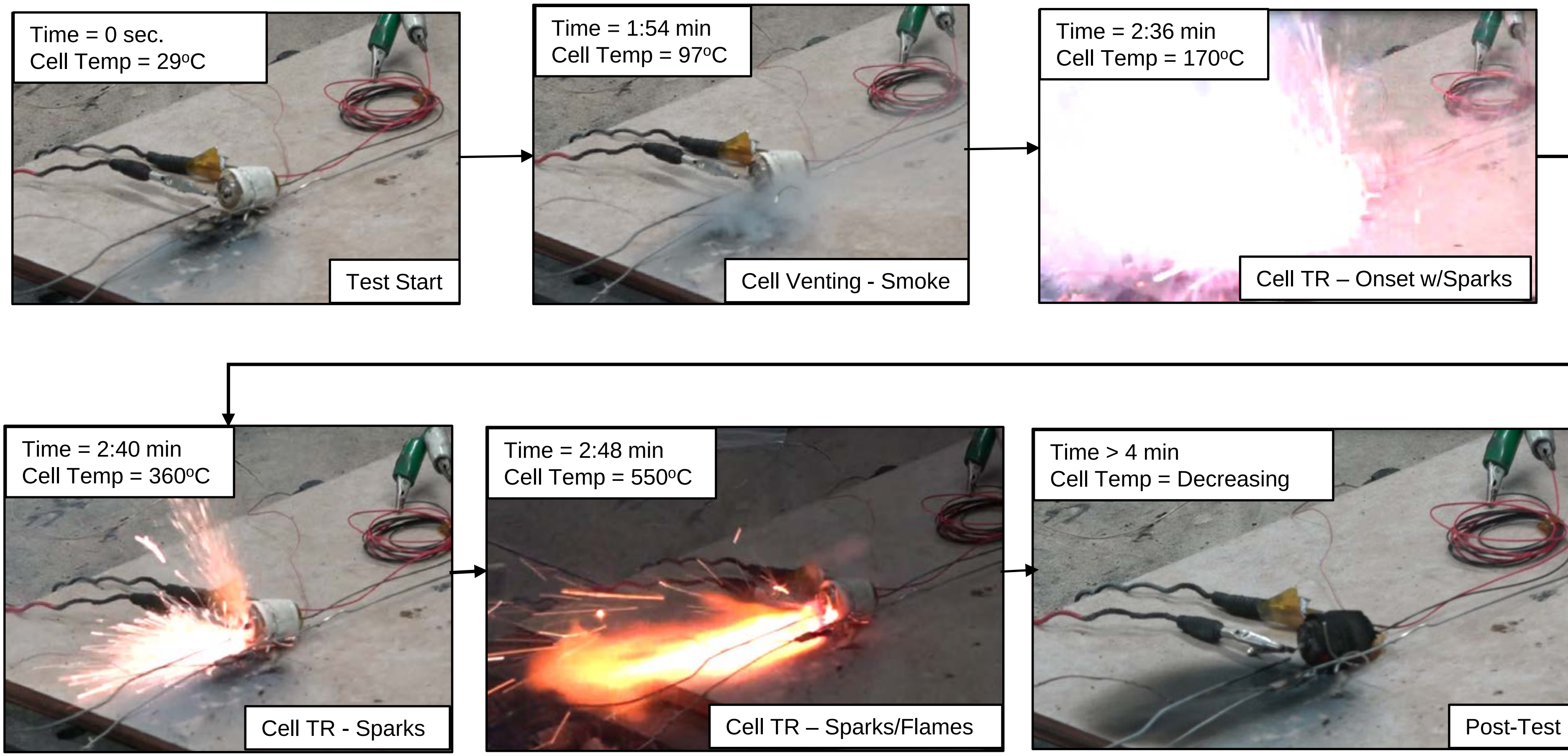


Cover heater with the slightly larger piece of mica paper.



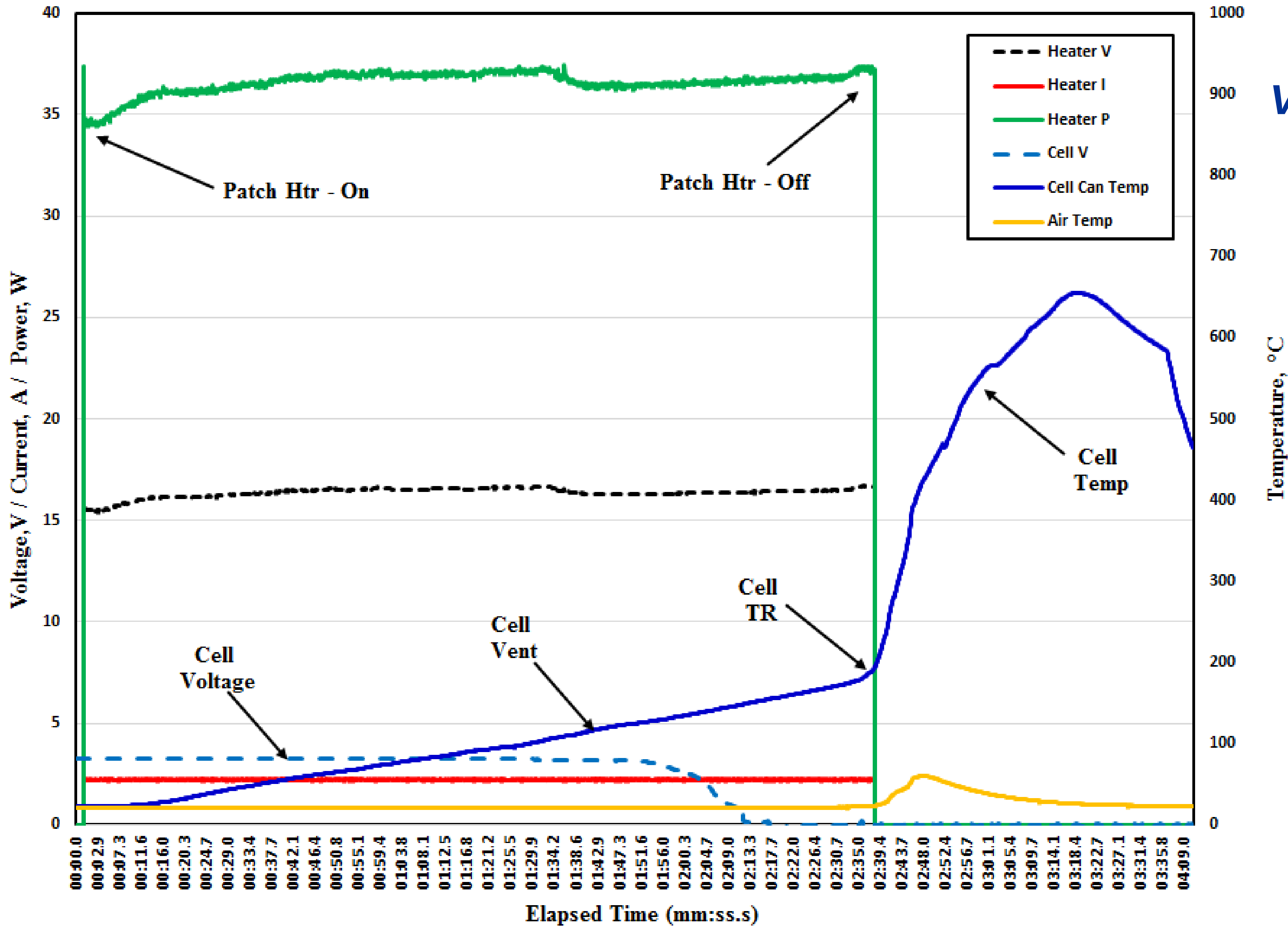
Wrap cell with mica tape and secure with Kapton tape. Allow to dry for 12 hrs. for total of 24 hrs.

Internal Short Circuit Simulation - Single Cell Heater Trigger Test – Sequence of Events (Trial Run @ 35W)

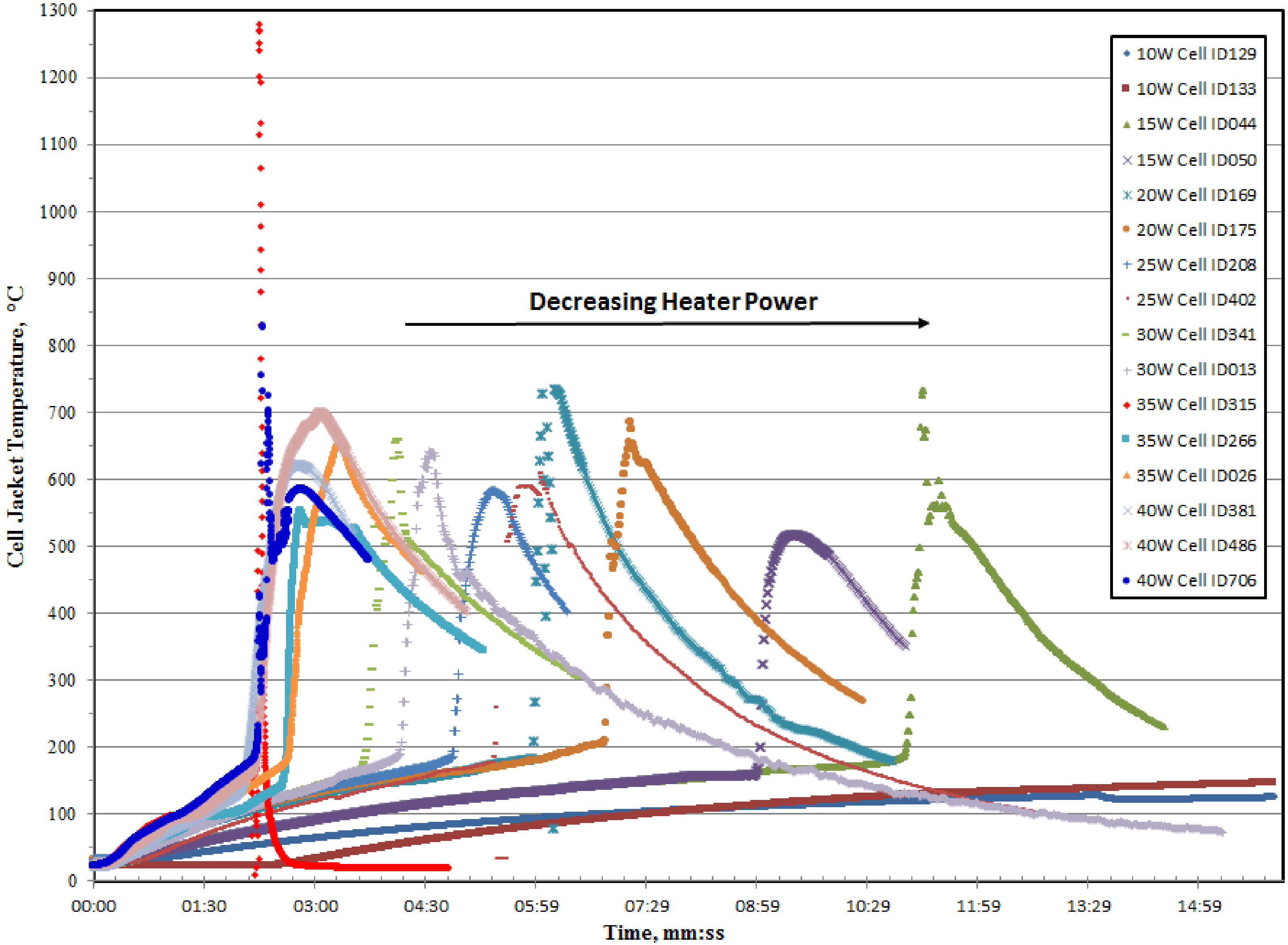


Single-Cell TR Trigger Test – 35W Heater Pwr

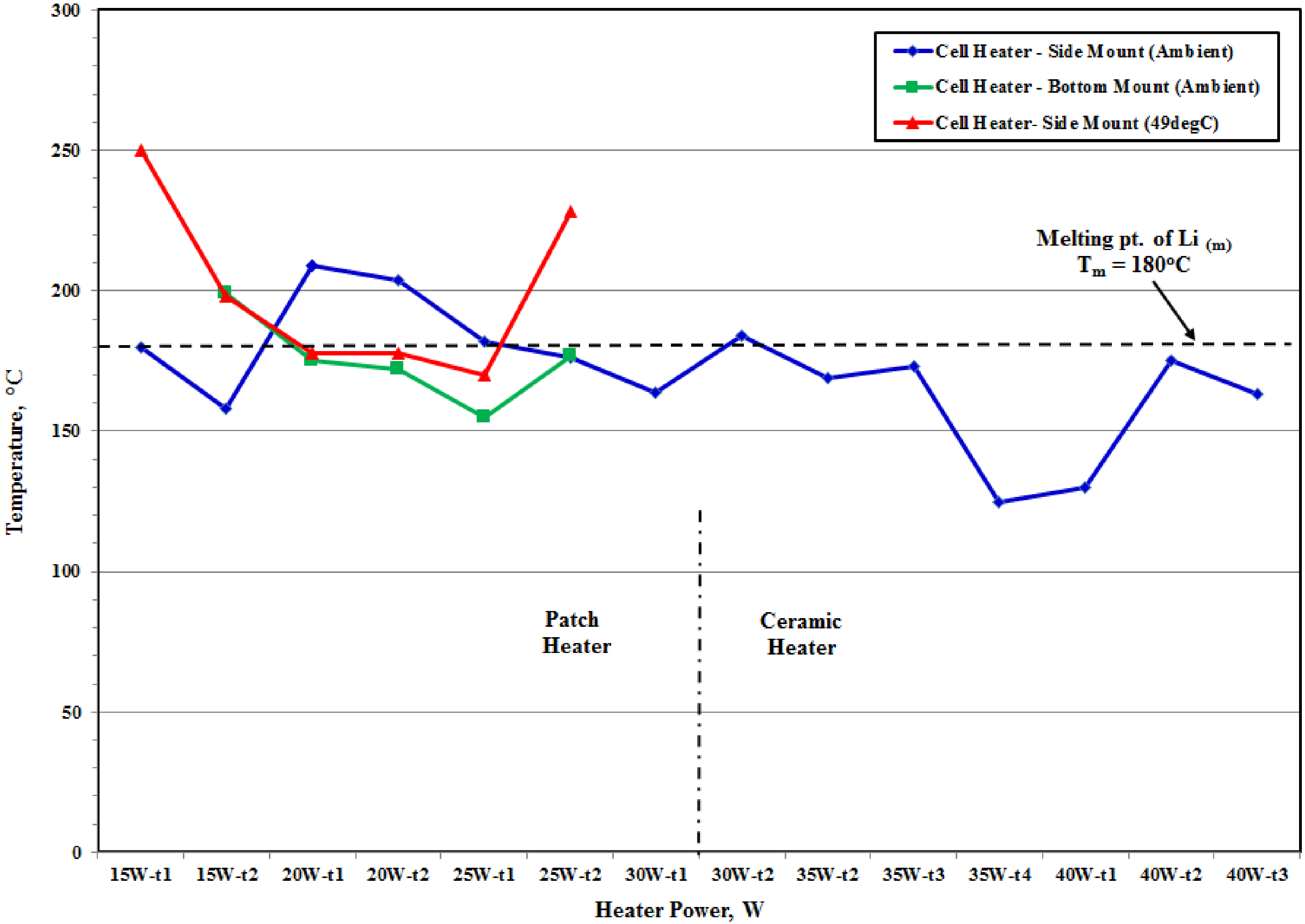
Video



Effect of Heater Power on Time-To-Cell TR



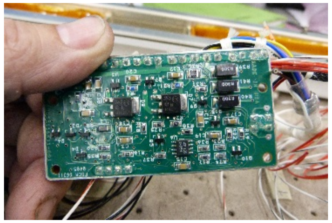
Effect of Heater Power on Cell TR Temperature



Battery-Level TR Testing

“Flight Like” SAFER Battery Test Article: Build Quality Details

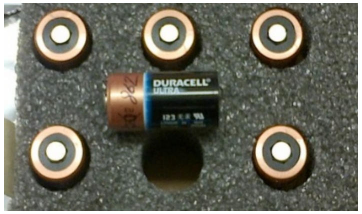
Gauge Board Insert



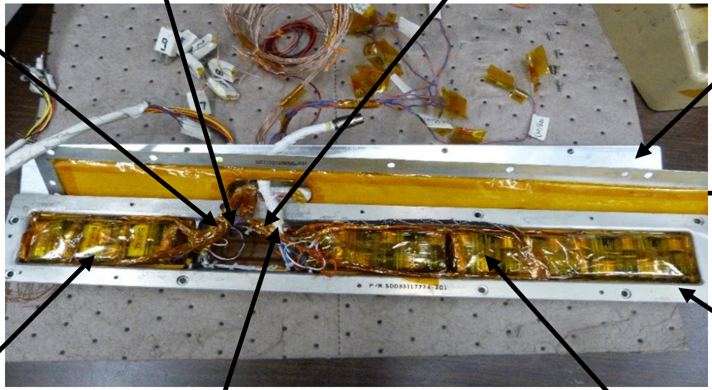
Gauge Board

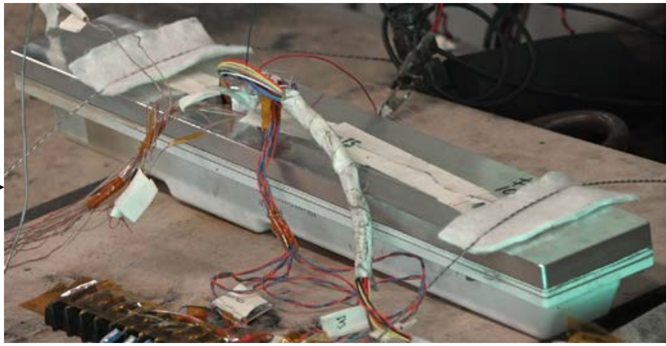
Gauge Board Cover

SAFER Unit Mass Simulator



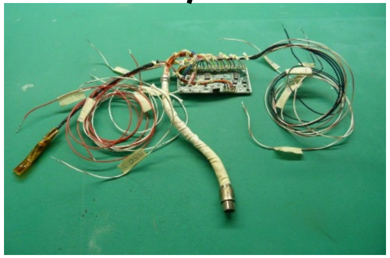
Non-rechargeable COTS Lithium cells (42 cells per battery)





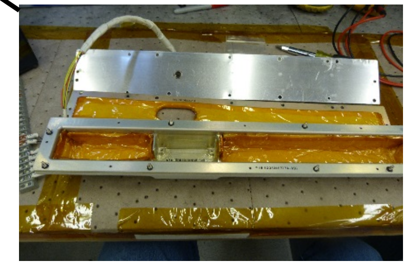
Flight-Like SAFER Battery Test Article

4S Cell Bundle (3 per battery) w/Htr Harness



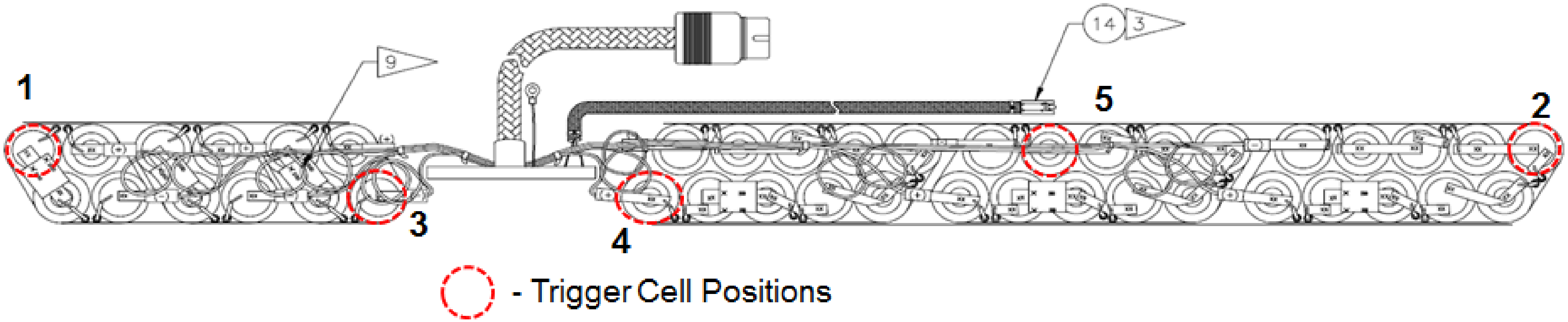
Test Instrumentation Harness

10S Cell Bundles (3 per battery)



SAFER Battery Chassis

SAFER Battery Heater Trigger TR Test – Worst-Case Trigger Cell Location Map

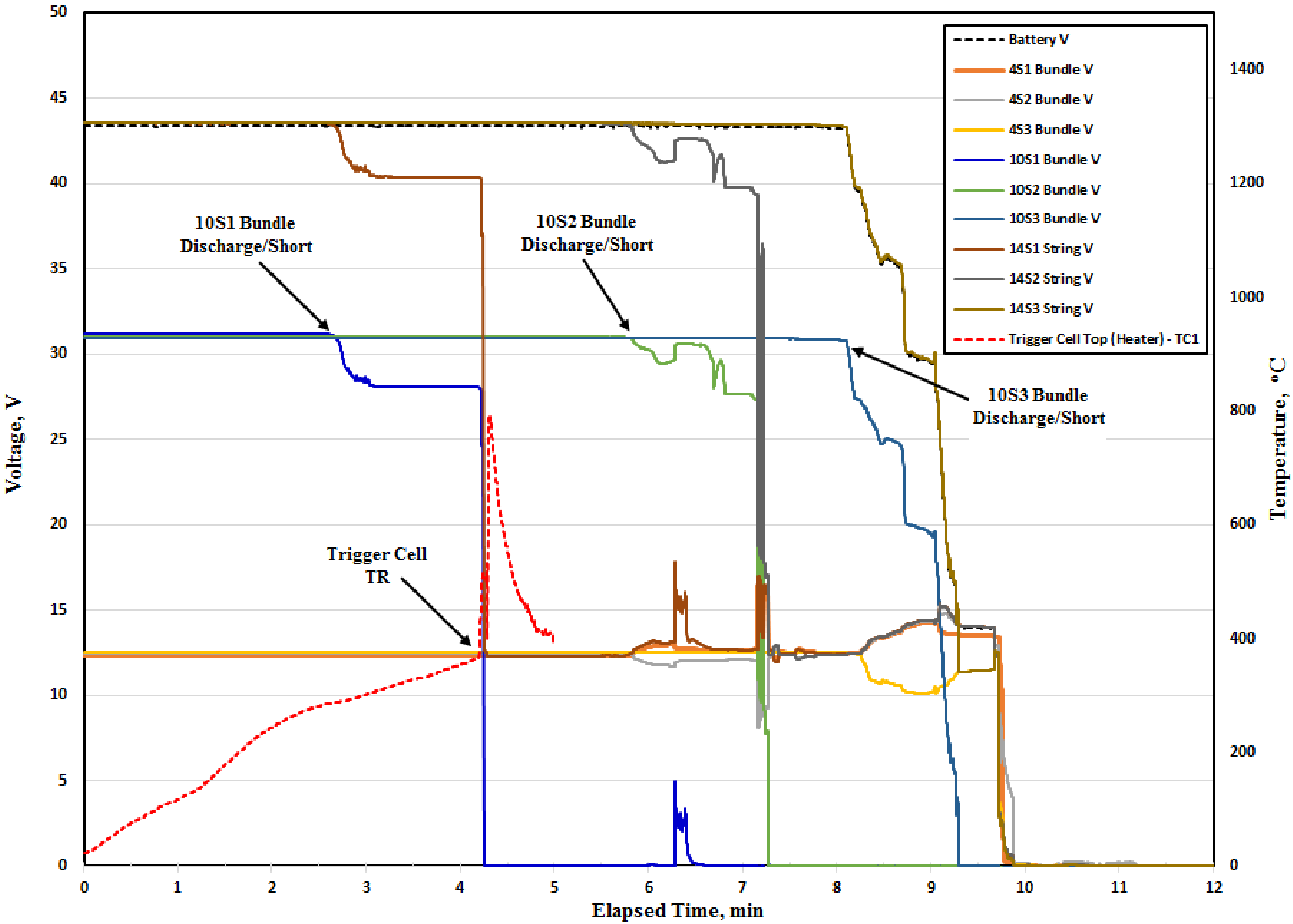


Trigger Cell "**Worst-Case**" Location Selection Rationale:

1. Choose trigger cells in both 4S and 10S sides of battery.
2. Choose trigger cell(s) with fewest adjacent cells (Positions #1, #2, #3, & #4).
3. Positions #3 and #4 are nearest to gauge board.
4. Choose 1 trigger cell location closest to heritage temp sensor location (Position #5).

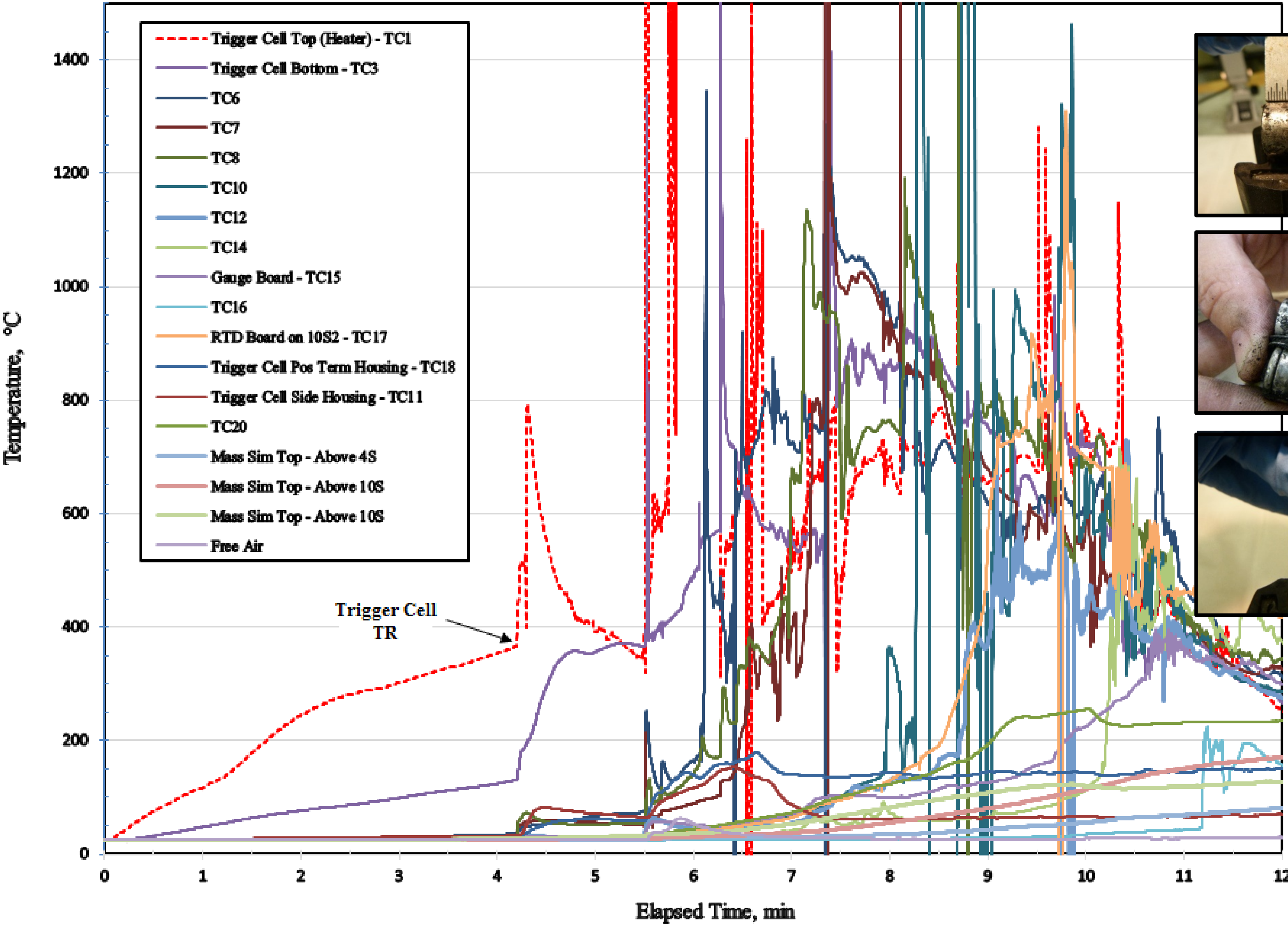
Fewer adjacent cell(s) reduces likelihood of thermal biasing (over-test) test condition

SAFER Battery Heater Trigger TR Test : 35W; Pos. #2

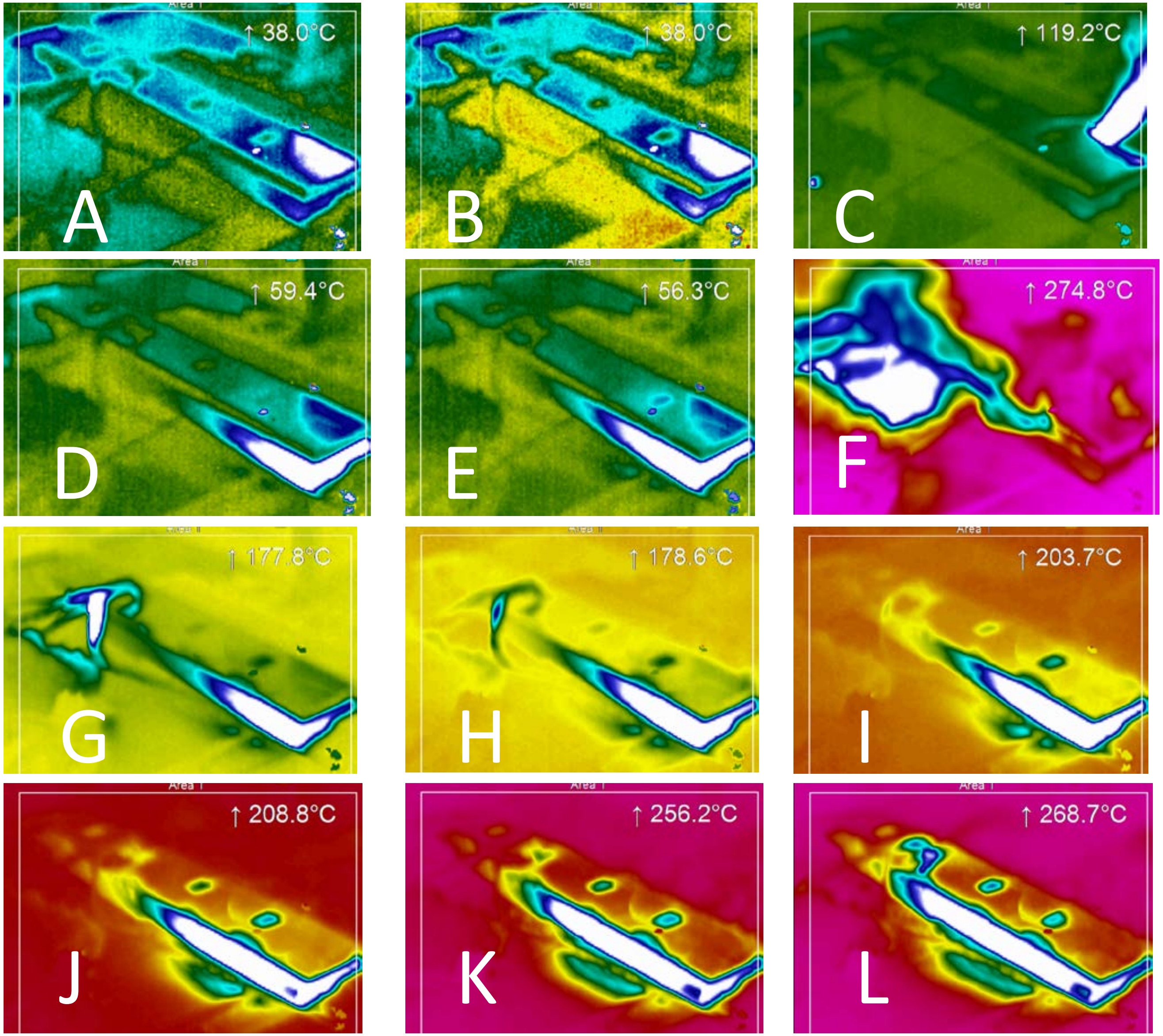


Video

SAFER Battery Heater Trigger TR Test : 35W; Pos. #2



SAFER Battery TR: Cell-To-Cell Propagation IR Images



Battery 4S & 10S-Side TR Test Results: Post-Test Forensics

Test #3
(35W; Pos. #1)

Cell-to-cell propagation

Test #4
(35W; Pos. #2)

Video

Project Summary

- Experimental Results
  - Worst-case single-cell TR results in catastrophic cell-to-cell TR propagation
    - Heritage cell bundle packaging design facilitates TR propagation
    - Gauge board "spacing" mitigates TR across entire SAFER battery pack
    - Ambient oxygen sources increases severity of SAFER battery TR consequences.
- Flight Status
  - Near-term continued use for ISS EVA's **<u>is acceptable</u>**
    - Likelihood of catastrophic TR event deemed to be low
- **Next Steps**
  - Project currently evaluating options for SAFER battery re-design
    - Battery chassis vent capability
    - Cell packaging
    - Other

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  - Dr. Eric Darcy
- **The Boeing Co. Satellite Development Ctr** – El Segundo, CA, USA
  - Ms. Amalia Aviles
- **The Aerospace Corporation** – El Segundo, CA, USA
  - Dr. Boyd Carter

Thanks for your attention!