

	Space Power Workshop	Presenter
		Jason Graika
		Date
		4/27/2017

Assessment of International Space Station (ISS) Lithium-ion Battery Thermal Runaway (TR)

Jason Graika

4/27/2017

Project Background

Presenter

Jason Graika

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- This task was developed in the wake of the Boeing 787 Dreamliner lithium-ion battery TR incidents of January 2013 and January 2014.
 - The Electrical Power Technical Discipline Team supported the Dreamliner investigations and has followed up by applying lessons learned to conduct an introspective evaluation of NASA's risk of similar incidents in its own lithium-ion battery deployments.
 - This activity has demonstrated that historically NASA, like Boeing and others in the aerospace industry, has emphasized the prevention of TR in a single cell within the battery (e.g., cell screening) but has not considered TR severity-reducing measures in the event of a single-cell TR event.
 - In the recent update of the battery safety standard (JSC 20793) to address this paradigm shift, the NASA community included requirements for assessing TR severity and identifying simple, low-cost severity reduction measures.
 - This task will serve as a pathfinder for meeting those requirements and will specifically look at a number of different lithium-ion batteries currently in the design pipeline within the ISS Program batteries that, should they fail in a Dreamliner-like incident, could result in catastrophic consequences.
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Test Objective

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- This test is an abuse test to understand the heat transfer properties of the cell and ORU in thermal runaway, with radiant barriers in place in a flight like test in on orbit conditions. This includes studying the heat flow and distribution in the ORU. This data will be used to validate the thermal runaway analysis. This test does not cover the ambient pressure case.
 - **There is no pass/ fail criteria for this test**
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Assessment Timeline

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- November 2014 Project Start
 - Accelerated Rate Calorimetry (ARC) test complete at THT in England 8-14-2015
 - August 15- January 16 Project Pause
 - Test article procurements continued to occur during this time
 - 3/16 – 7/16 Trigger method testing at ESTA
 - 2/16 – 8/16 Test unit build up at ESTA
 - Propagation test complete at WSTF 10-26-2016
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ISS Main battery background

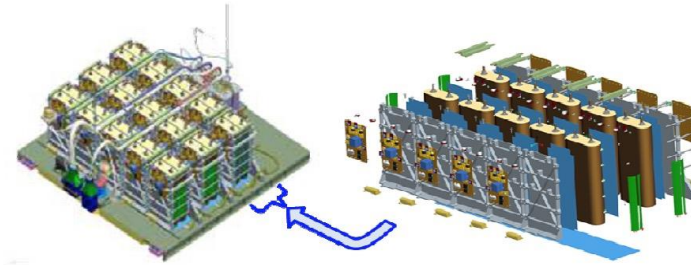
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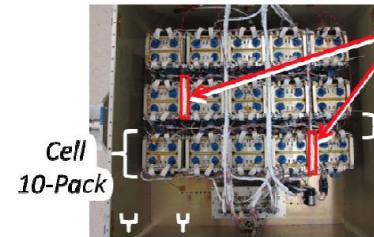
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- Designed by Boeing
- Large format Lithium – Ion designed to replace existing NI-H2 batteries on Station
- 2 Ni-H2 ORUs can be replaced with a single Li-ion ORU and adapter plate
 - 48 Ni-H2 ORUs to be replaced with 24 Li-ion ORUs
- 30 cells arranged into 10 packs per battery
- Finned baseplate and Cooling plate directly below ORU



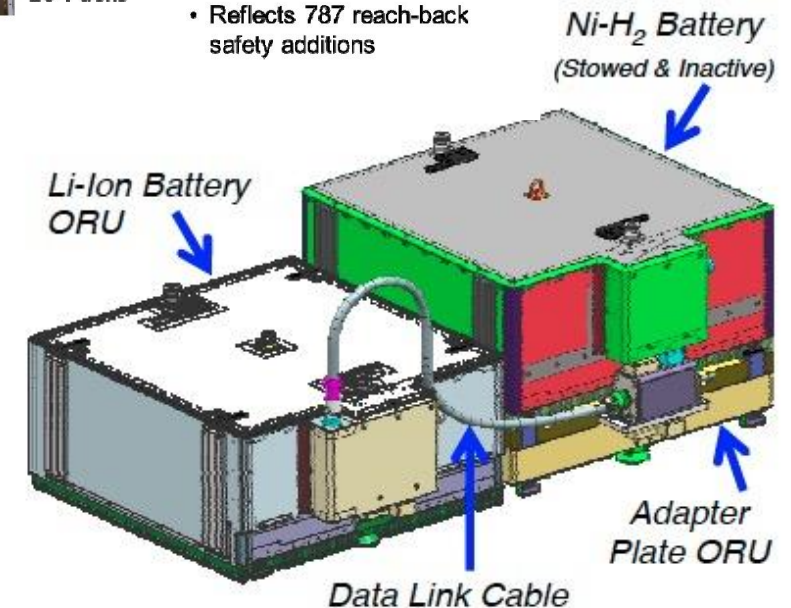
- ORU Layout – 3 Cell "10-Packs" and 12 Radiant Barriers



~2" ~1" Spacing
Spacing between cell pairs

Radiant Heat Barrier (12 per ORU)

- Higher margin against thermal runaway propagation
- 1 barrier between each cell pair
- Reflects 787 reach-back safety additions



Cell Information

Presenter

Jason Graika

Date

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Manufacturer and Part Number	GS-Yuasa LSE134-101
Chemistry	Lithium Cobalt Oxide
Performance	
Capacity (nameplate)	134 A-hr
Energy (nameplate)	496 W-hr
Energy Density at BOL	349 Wh/L
Specific Energy at BOL	155 Wh/kg
Temperature Range	
Charge	+10 to +35C
Discharge	-10 to + 35C
Mechanical	
Dimension (WxDxH) excluding terminals	130 x 50 x 271 mm
Weight	3.53 kg

ARC testing

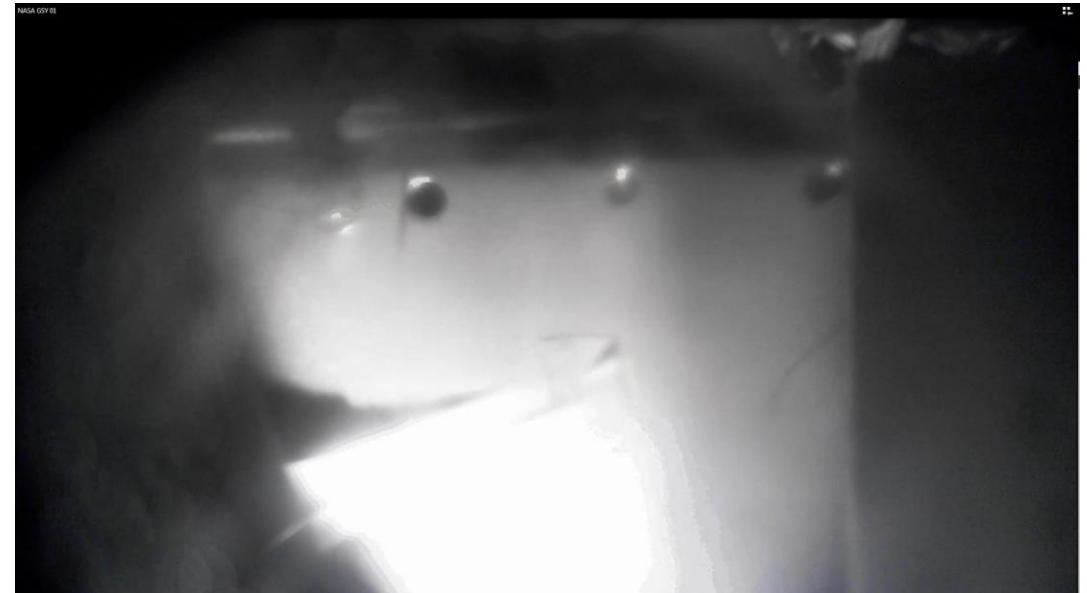
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- An ARC test was completed at THT in England on 8-14-2015
 - Test was conducted in chamber open configuration
 - We were unable to complete test in chamber closed configuration due to size of cell and gas released
 - Closed chamber configuration helps to understand total heat released as gas affluent



ARC testing

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- Several methods were used to try to calculate total energy released
 - The THT report assumed $\Delta T_{ab} = 236 \text{ }^\circ\text{C}$ which yields a total energy release of 1.99 MJ.
 - Re-performing the calculation based on the maximum temperature experienced by the cell ($\Delta T_{ab} = 253 \text{ }^\circ\text{C}$) results in a total energy release of 2.13 MJ³
 - Scaling from 18650 data gives minimum energy released of 1.58 MJ, average energy release of 2.2 MJ and a maximum energy release of 2.5 MJ.
 - The stored energy for the thermal runaway of a single cell is 2.72 MJ in original Boeing Model
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Single cell TR initiation testing

Presenter

Jason Graika

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Effort was put into developing a way to initiate thermal runaway in a single cell. The goals for this testing were:

- Reliable in initiating thermal runaway,
 - Capable of being integrated with the ORU test article in the relevant environment including vacuum,
 - Realistic as possible to an event that would be caused by an internal short circuit, and
 - Failure initiation method should result in minimal biasing of adjacent cells such that it didn't significantly impact the outcome of the propagation testing.
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Single cell Quallion heater testing

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- Initial heater testing was run of Aluminum mass simulators and Quallion 75-A-hr cells due to limited number of GS Yuasa LSE 134 cells
- 3 trigger method tests were run on Quallion cells utilizing Ni-Chrome wire heaters



Heater test of a single Quallion cell

Single cell Quallion heater testing

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<u>Qualion</u> cell Ni-chrome wire testing	Test 1	Test 2 6-3-2015	Test 3 9-23-2015
Heater power	~130 W	~330 W	~380 W
Time to cell vent	N/A	207 Seconds	210 Seconds
Max temperature	38C	712C	935C
Heater design	120" of 30 AWG Ni-chrome wire packaged into 3" X 5"	56" of 22 AWG Ni-chrome wire packaged into 2" X 3"	22 AWG Ni-chrome wire packaged in whole length of cell side
Heater Resistance Front	30.3 Ω	5.261 Ω	7.68 Ω
Heater Resistance Back	30.9 Ω	5.31 Ω	N/A
Note:	Heater broke and no thermal runaway achieved		

Heater test AI mass Simulator

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- Heater tests were run on mass simulators of equivalent size and thermal capacitance of GS Yuasa LSE 134 cells
- Allowed for testing of different heater configurations including different form factors, materials and ni chrome wire gauges



Heater test AI mass Simulator

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- It was found that the mass simulators were likely a better test than heater of Quallion cells for several reasons
 - Found to have very similar heating profile to GS Yuasa LSE 134 cells
 - Quallion cell is housed in a steel can, while the GS Yuasa LSE134 has an aluminum can
 - Aluminum is a much better thermal conductor
 - Quallion cell is a true prismatic cell made up of paralleled anode/cathode sheets, while the GS Yuasa cell has a flattened, spirally wound jelly roll construction
-

Single cell GS Yuasa heater testing

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- Conducted of 4/16/2016
 - Heater composed of 20 AWG Ni-chrome on each curved surface
 - Ran heater at ~800 watts on one side for 15 minutes
 - After 15 minutes decision was made to utilize second heater
 - After 5 more minutes thermal runaway was achieved
 - Entire jelly roll was ejected shortly after thermal runaway was achieved
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Single cell GS Yuasa heater testing

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Progression of test of GS Yuasa heater test

Single cell GS Yuasa heater testing

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Single cell GS Yuasa heater testing

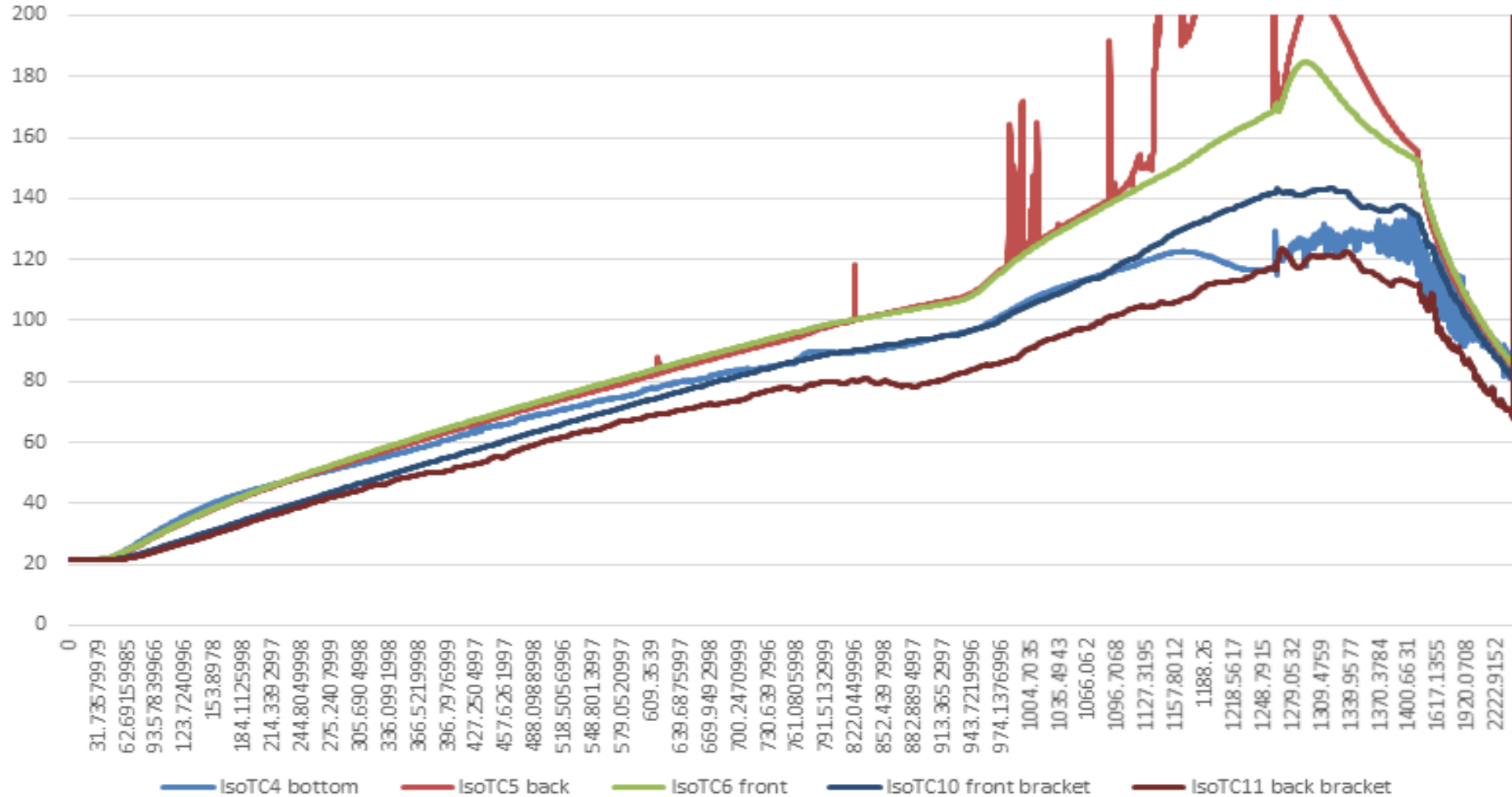
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Cell temps GS Yuasa trigger test 4-13-16



Single Cell Quallion Drill Testing

Presenter

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- 4 Drill penetration tests were run on Quallion cells charged to 3.95V
 - All showed TR achieved quickly after breaching side wall
 - No Jelly roll ejection was observed



Trigger Method testing on Quallion Cells – Left two are of cell in TR, Middle two are cell venting, Right two are post test pics

Single Cell Quallion Drill Testing

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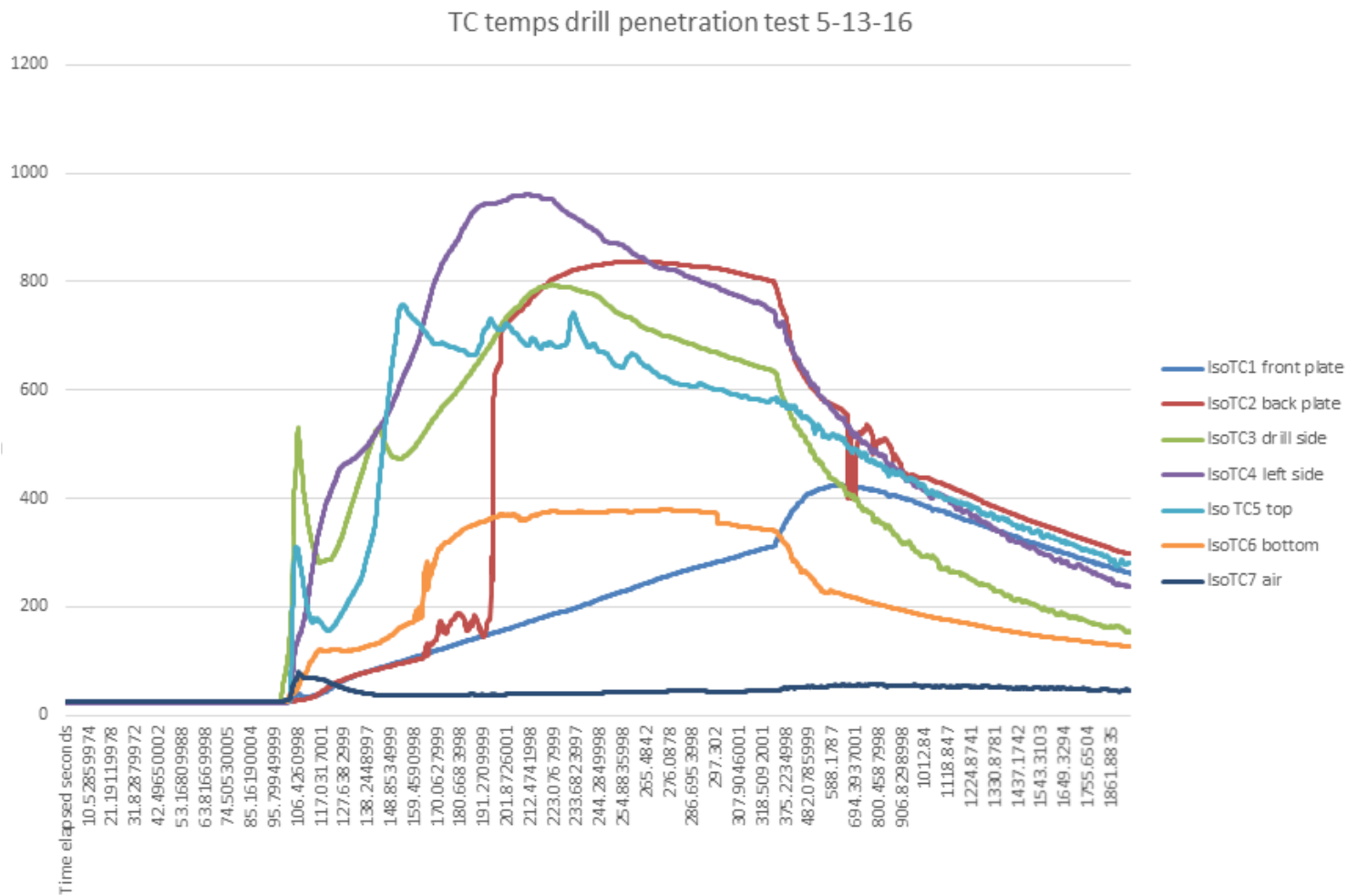
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Single Cell Quallion Drill Testing

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Single cell GS Yuasa Drill Testing

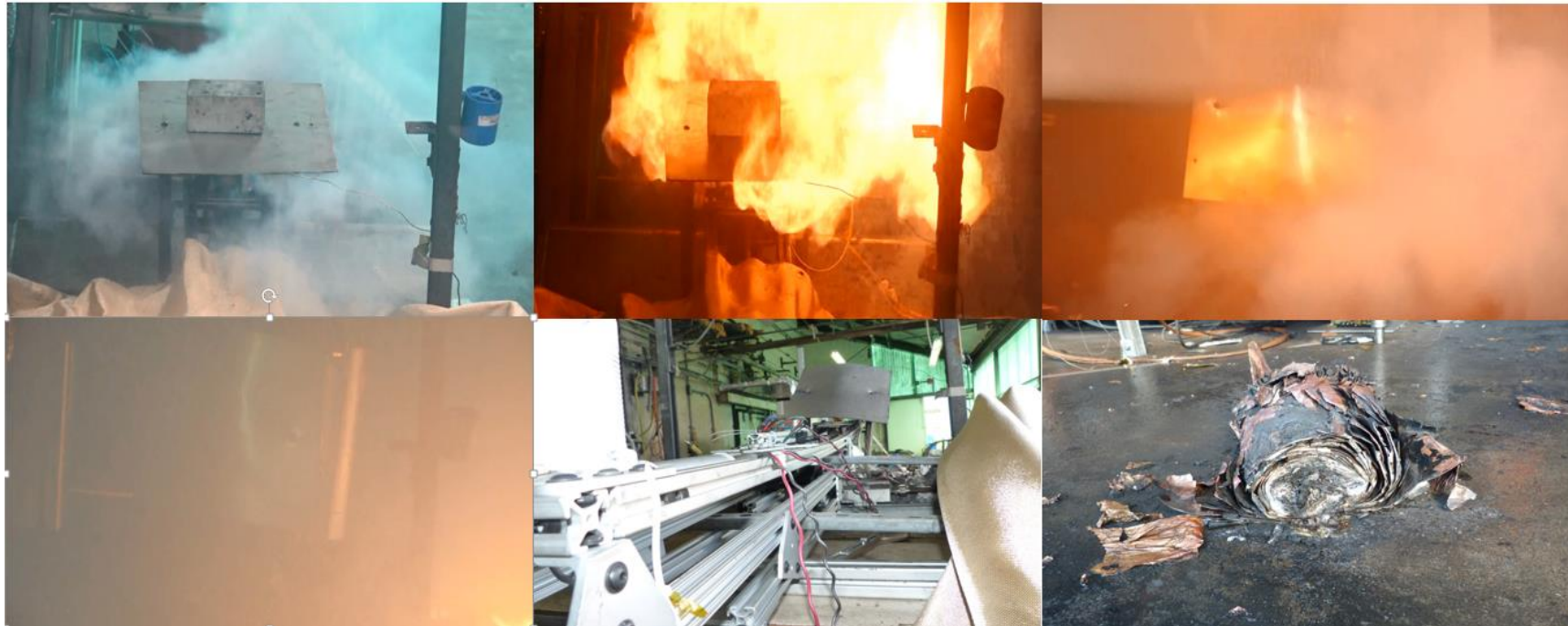
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- One drill penetration test was run on a single GS Yuasa LSE 134A-hr cell charged to 3.95V
 - Cell contents did eject shortly after thermal runaway was achieved



Pictures show progression of test. First is cell venting. Second is undergoing TR. Third and fourth show smoke post ejection. Fifth shows damage to test assembly and 6th shows jelly roll that was ejected from cell.

Single Cell GS Yuasa Drill Testing in Enclosure

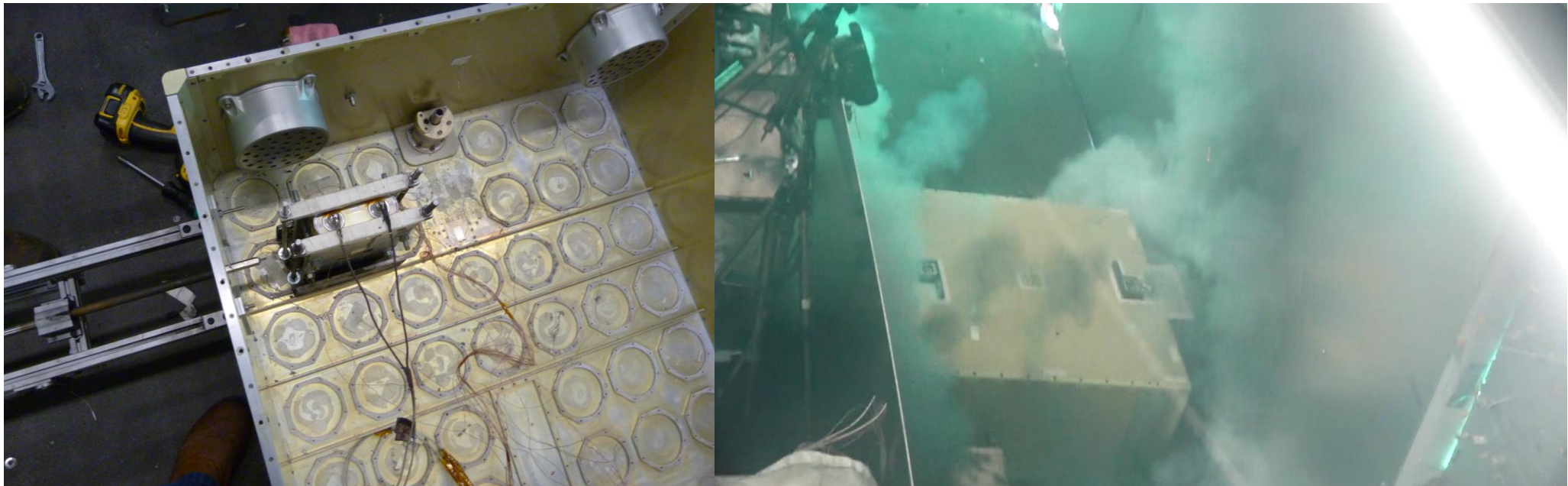
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- Two drill penetration tests were run on a single GS Yuasa LSE 134A-hr cell charged to 3.95V inside a Ni-H2 enclosure
 - No MMOD pillow was installed on underside of lid
 - Performed twice on same enclosure



Single Cell GS Yuasa Drill Testing in Enclosure

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- Both test had a forceful jelly roll ejection from cell
 - Both instances left a visible dent in cover but jelly roll remained inside ORU
 - ~5 inches of jelly roll were ejected from cell then stopped by lid



Different Drill/ Penetrators Used

Presenter

Jason Graika

Date

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Test	Drill/ Screw penetrator used
Quallion drill penetration #1	5/16" screw Steel
Quallion drill penetration #2	¼" screw Steel
Quallion drill penetration #3	¼" screw Steel
GS Yuasa Drill Penetration 6-6-16	¼" screw Steel
GS Yuasa Drill Penetration with enclosure 6-22-16	.1285" 5/16" flute length drill bit Cobalt
GS Yuasa Drill Penetration with enclosure 7-13-16	.1285" 4/16" flute length drill bit Cobalt

Full Scale Propagation test

Presenter

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- A full scale propagation test was run at White Sands Test Facility (WSTF) Remote Hypervelocity Chamber on 10-26-2016



Full Scale Propagation test

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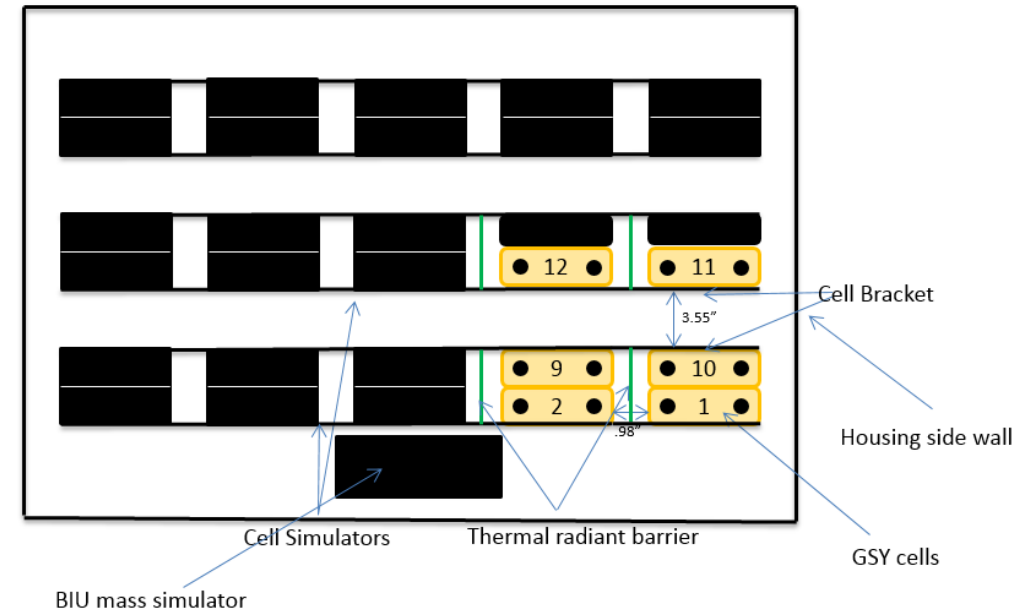
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- Details of this test

- Drill Penetration method used to puncture side of cell
- 6 live cells and 24 aluminum mass simulators
- Battery Interface Unit (BIU) replaced with aluminum mass simulator
- All cells charged to 3.95V
- Vacuum (minimum 1 Tor) held during test
- Cell 1 triggered and underwent thermal runaway by drill penetration method
- 4 thermal radiant barriers installed
- Cooling loop underneath ORU
- Heater circuit on each cell



	<h1>Test Initial Conditions</h1>	Presenter Jason Graika
		Date 4/27/2017

- Great effort was put into making sure the initial conditions for this test would be flight like. This included:
 - Coolant temperature of 40F
 - Cell and mass simulator temperatures of 77F
 - Coldplate painted black for correct emissivity
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	Propagation Test Results	Presenter
		Jason Graika
		Date
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- Cell underwent thermal runaway shortly after being penetrated by the drill assembly
 - Jelly roll was ejected shortly after thermal runaway was achieved
 - No cell to cell propagation was observed with significant margin
 - Neighboring cells retained voltage throughout test
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Propagation Test Results

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JSC WSTF RHTL LI001

Pre Test



JSC WSTF RHTL LI001

Post Test

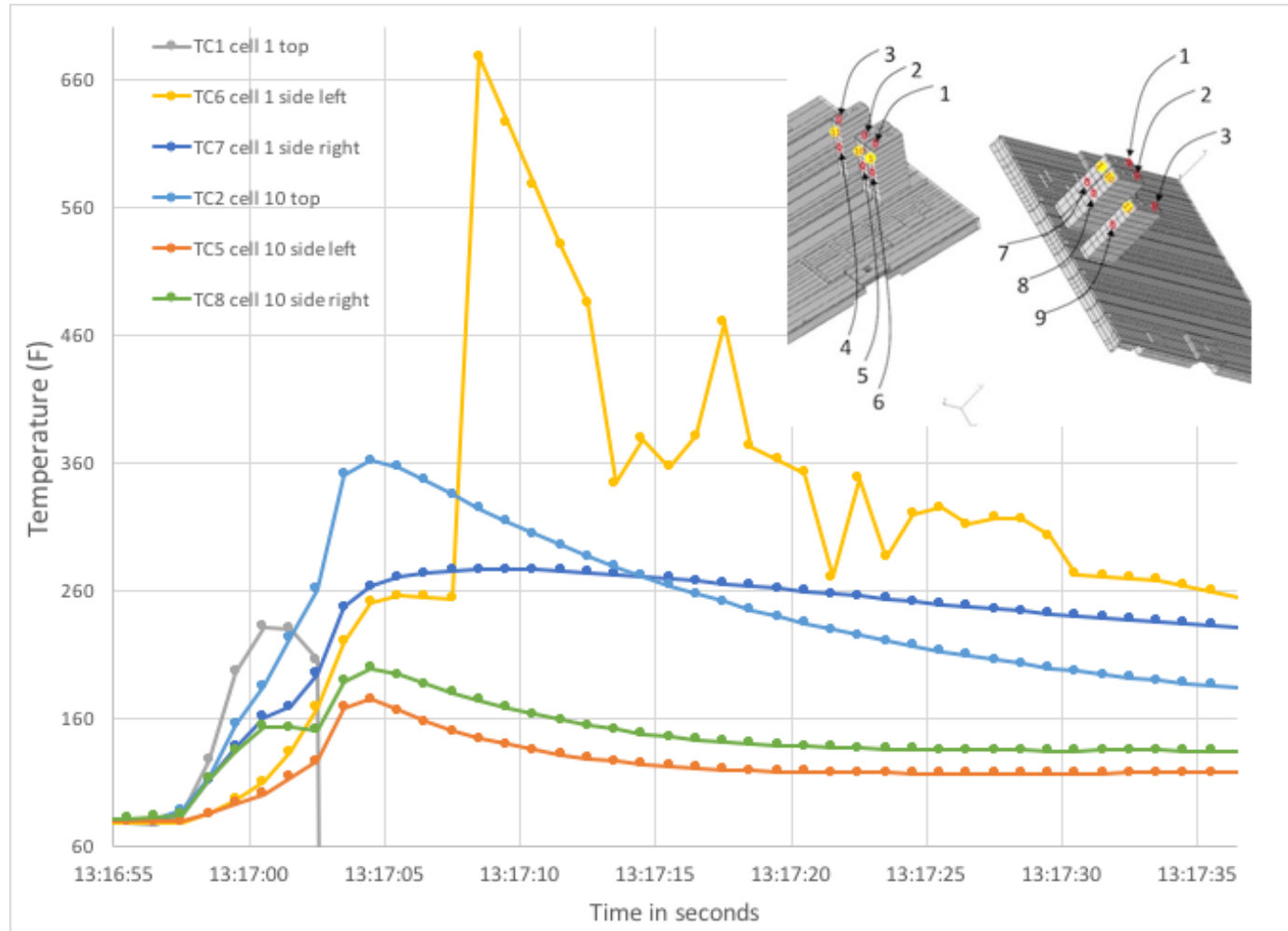
Propagation Test Results

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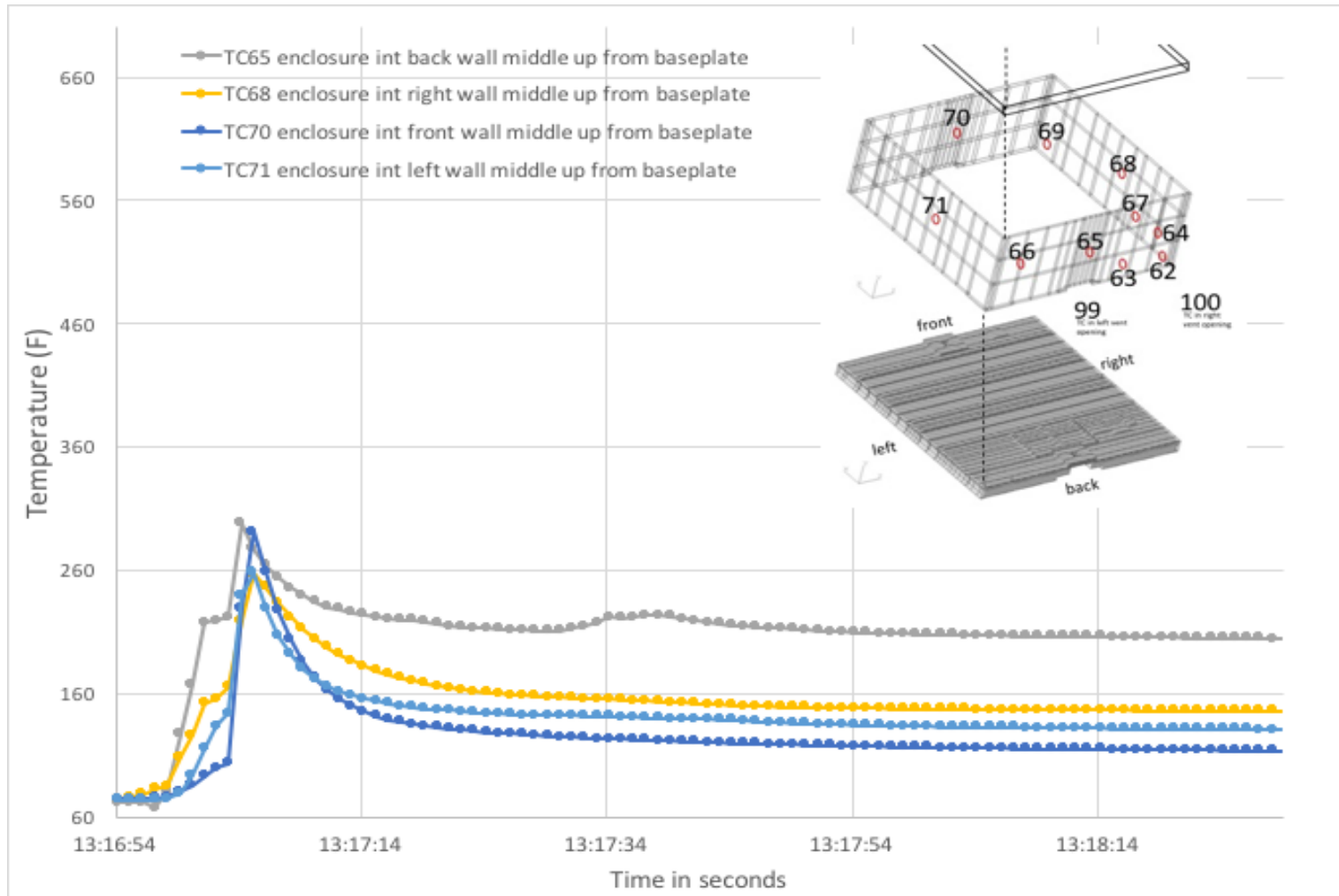
Propagation Test Results

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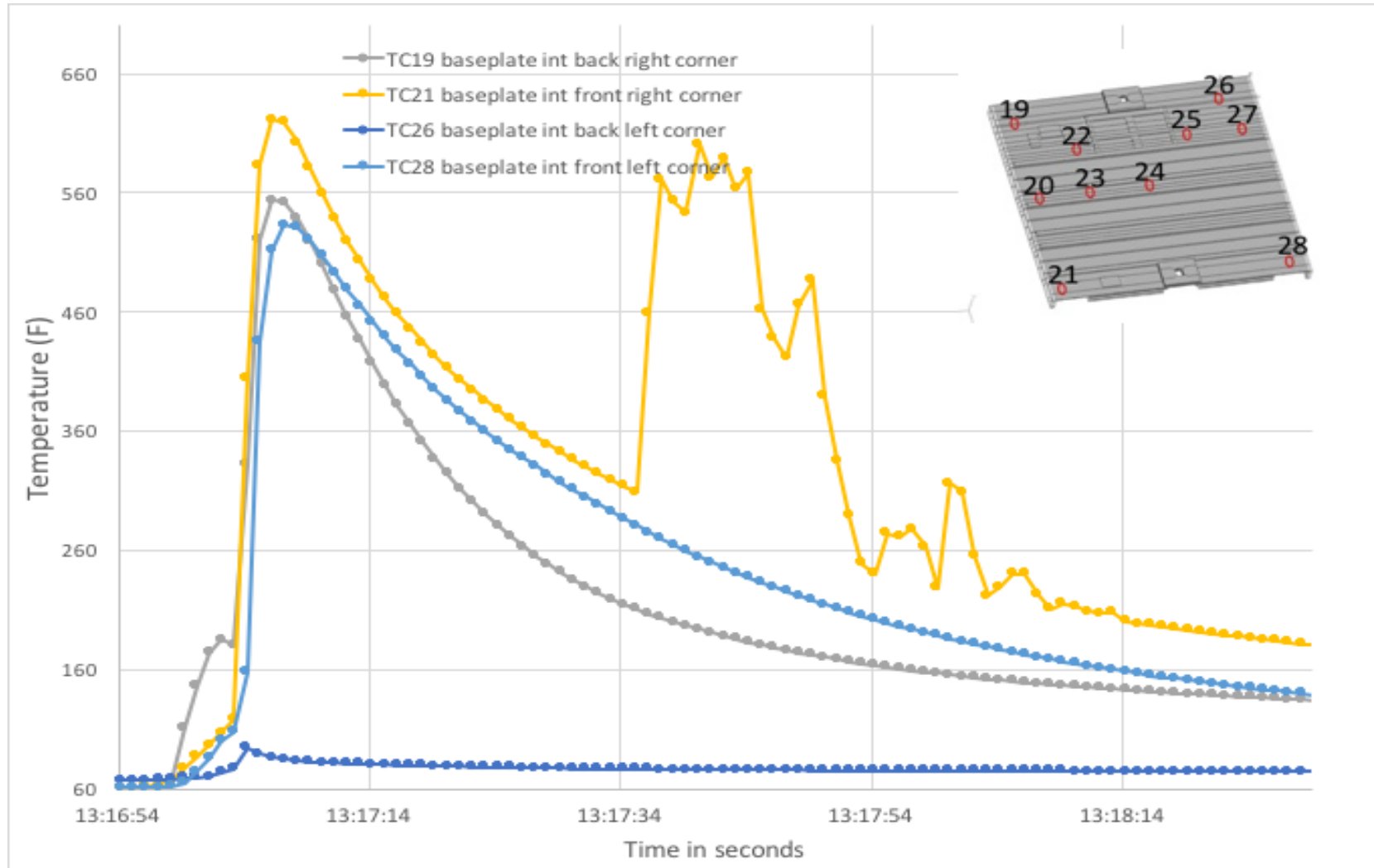
Propagation Test Results

Presenter

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Findings

Presenter

Jason Graika

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1. A review of the Boeing detailed thermal model found that the model was likely to be overly conservative in predicting thermal runaway propagation. There were numerous over-estimations of energy available to drive TR propagation. These include:
 - a. Very conservative calculations of total energy generated during thermal runaway of a single LSE-134 cell.
 - b. Assumptions that the vast majority of TR energy would remain with the cell and be available for conduction and radiation to neighboring cells.
 - c. Thermal model logic that assumed that any cell node reaching a trigger temperature would result in TR of that cell.
 - d. Because the test did not duplicate the model simulation, the assessment was unable to determine whether the approach taken to account for effluent energy in the thermal model is effective in terms of point of delivery, amount, and rate.
 2. The GS Yuasa LSE-134 cells and the ISS battery design precludes the effective use of the in-house patch heaters to trigger thermal runaway.
 - a. Aluminum cell case preferentially conducts heat through the cell case, rather than into the cell winding to create an internal short circuit.
 - b. Large aluminum cell bracket structures with high thermal conductivity contact to the cell case.
 - c. Cell pairs thermally connected to one another with high thermal conductivity materials.
 - d. A large aluminum baseplate with an active thermal control system drawing excess heat away from cells.
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Findings

Presenter

Jason Graika

Date

4/27/2017

3. A screw penetration apparatus/method was very successful in quickly creating full thermal runaway in large format cells without thermally biasing any neighboring cells or other battery components.
 - a. Five (5) Quallion 75 A-hr cells were successfully triggered into TR using this method, with no cell winding ejections.
 - b. Four (4) GS Yuasa LSE-134 were successfully triggered into TR using this method.
 4. Five (5) GS Yuasa LSE-134 cells were driven into TR using a variety of methods, and all instances resulted in a full, energetic ejection of the cell windings from the cell case. No cell winding ejection were observed in any of the Quallion 75 A-hr cells that were used to initially validate cell trigger methods.
 - a. One (1) high flux cell heater method used on an LSE-134 cell.
 - b. Four (4) screw penetration method used on LSE-134 cells, including the full scale test.
 5. An enclosure design with multiple vent ports is important in a battery using large format cells. Large, solid particles venting from the cell during thermal runaway partially blocked the nearest vent port, so having a redundant path for effluents and gas to escape is important to prevent over-pressurization of the battery enclosure.
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Findings

Presenter

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6. Cell winding ejection was found to impede thermal runaway propagation. The free space within the enclosure allowed the thermal mass and energy to move away from the cell and limit the energy available for conduction/radiation to neighboring cells. This result agrees with ISS battery development testing where two failure tests (MMOD penetration) were conducted with pairs of LSE-134 cells.
 - a. In one test the cell winding stayed in the case and the neighbor cell was triggered into TR.
 - b. In the other test, the cell winding partially ejected, and the neighbor cell was not triggered into TR.
 7. The battery enclosure design was effective in keeping the energetic cell winding ejection within the enclosure.
 - a. The lightweight, sandwiched, aluminum honeycomb lid was able to contain the cell winding ejection.
 - b. The MMOD pillow significantly decreased the impact of cell winding ejection on the enclosure lid, and also provided thermal protection from TR effluent.
 8. A full-scale test of an ISS Main Battery representative test article was successfully conducted in flight-like conditions (vacuum and temperature). A single cell was triggered into thermal runaway, and no sparks or flames visibly exited the battery enclosure. Post-test analysis showed that all neighboring live cells maintained voltage, were still functional, did not vent/lose mass, and didn't experience TR failure.
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Team list

Presenter

Jason Graika

Date

4/27/2017

Name	Discipline	Organization
ISS Battery Team		
Jason Graika	Team Lead and Test Engineer	JSC
Timothy North	ISS Battery Project Technical Lead	The Boeing Company
Matthew Jurick	Thermal	The Boeing Company
Eugene Ungar	Thermal	JSC
Eugene Schwanbeck	ISS Battery Project Lead	JSC
Penni Dalton	ISS Battery Subsystem Manager	GRC
Marcus Sandy	Test Engineering	WSTF
Donald Henderson	Test Engineering	WSTF
Arturo Pardo	Test Engineering	WSTF
Richard Fair	Test Engineering	WSTF
Karen Rodriguez	Test Engineering	WSTF
Bruce Drolen	Battery Specialist	The Boeing Company
Dereck Lenoir	Test Engineer	Jacobs Engineering
Oscar Huerta	Test Unit Assembly and Test	Jacobs Engineering
Yaramy Trevino	Test Engineer	Jacobs Engineering
Pete Sanchez	Test Unit Assembly and Test	Jacobs Engineering
Tony Parish	Test Unit Assembly and Test	Jacobs Engineering
Henrey Bravo	Test Unit Assembly and Test	Jacobs Engineering
Adan Garza	Test Unit Assembly and Test	Jacobs Engineering
Brianne DeMattia	Battery Specialist	GRC