International Space Station Lithium-Ion Main Battery Thermal Runaway Propagation Test

NASA Battery Workshop
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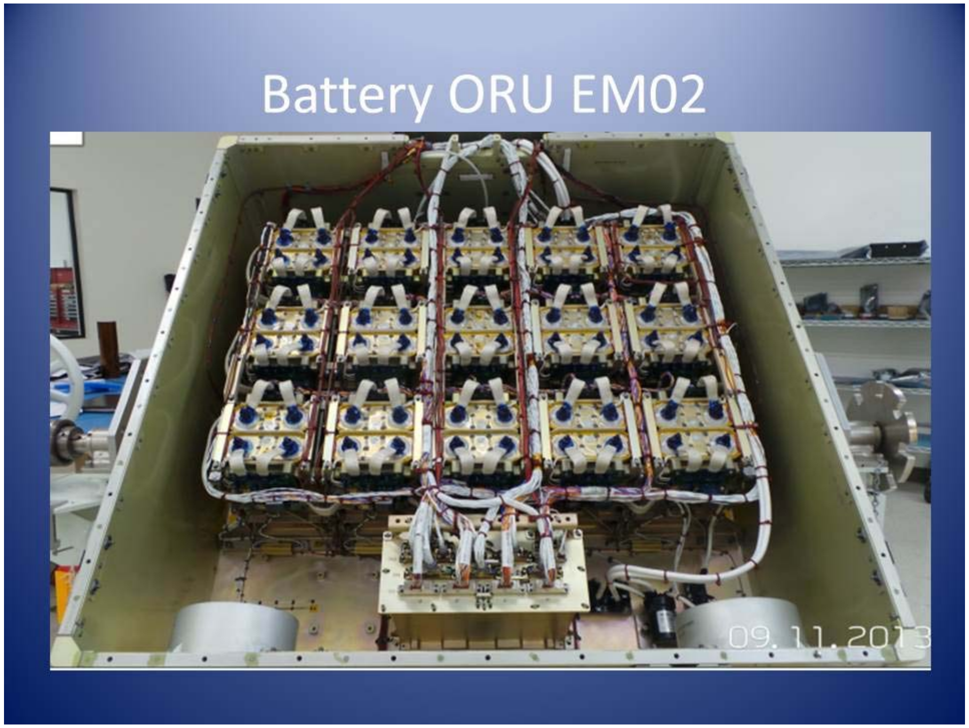
Background & Overview

- NASA Engineering and Safety Center (NESC) funded a task to evaluate thermal runaway (TR) propagation of Li-Ion batteries on the International Space Station (ISS)
  - Response to Boeing 787 Li-Ion thermal runaway (TR) events of 2013
- ISS Main EPS Li-Ion battery used analysis to show that the design would not propagate beyond battery to damage ISS
  - Requirement to verify this via test not levied on the project
  - NESC assessment of ISS Analysis indicated conservative approach
- NESC funded TR test with intent to verify the analysis results
  - Test Article ORU build February – August 2016
  - Trigger method testing in March - July 2016
    - Space Power Workshop, 4/27/17, "ISS Main Battery Large Cell Thermal Runaway Propagation Testing", Jason Graika
  - White Sand Test Bed Integration September – October 2016
  - White Sands Battery Propagation Test in October 2016
  - Post Test analysis in November - December 2016

Outline

- Battery ORU and Safety Features
- Battery ORU Test Article
- Battery TR Propagation Test Bed
- Battery TR Propagation Test
- Results and Findings

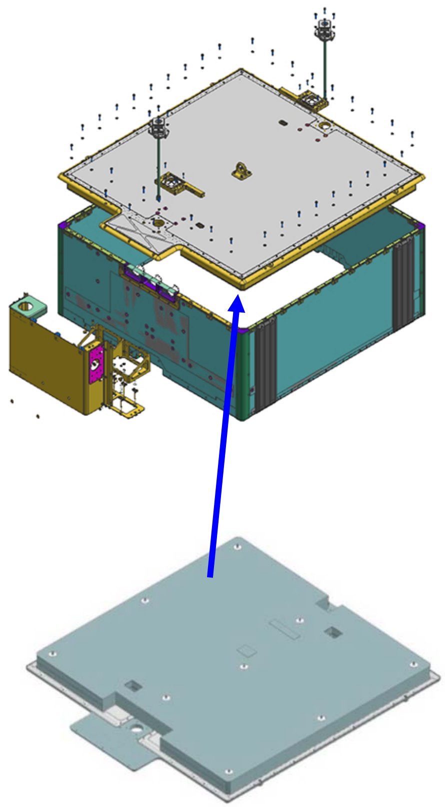
ISS Li-Ion ORU



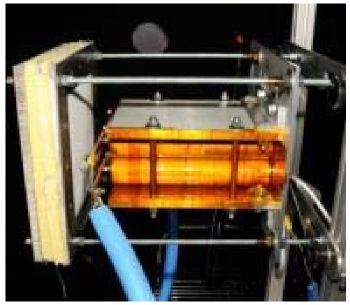
- 30 GS Yuasa LSE134-101 cells in series
  - Arranged in three "10 packs"
- 3.95 V/cell End of Charge Voltage
- ~15 Kwh
- Low Earth Orbit ~35 min discharge & 55 min charge
- 10 year (60,000 cycles) life

GS Yuasa 134 A-hr cell

ORU Safety Features
MMOD Shielding



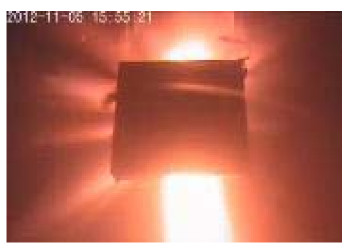
MMOD Shield

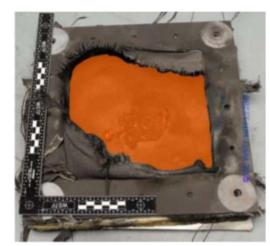


MMOD test setup

Ballistic Limit Testing

Over Match - Penetration testing
10 mm 2017-T4 Aluminum Sphere @ 6.86 km/s





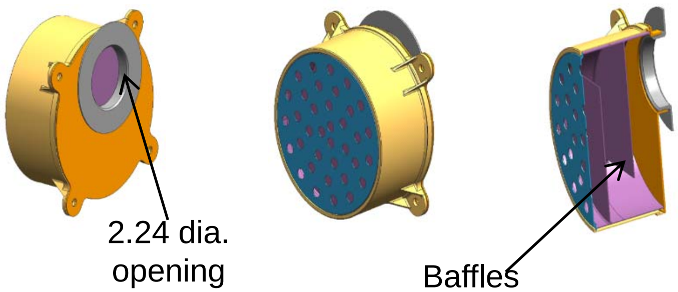
Overcharge Containment Testing

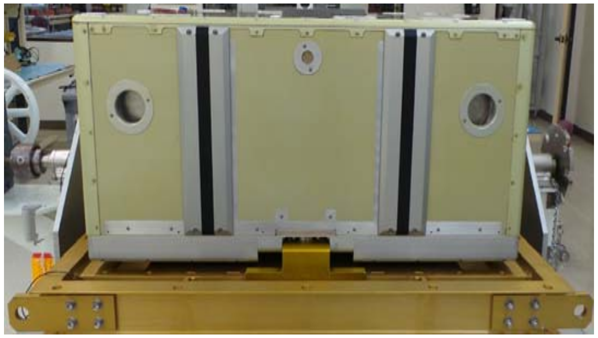
Note: Existing Ni-H_2 batteries do not have MMOD (Micro-Meteoroid Orbital Debris) protection

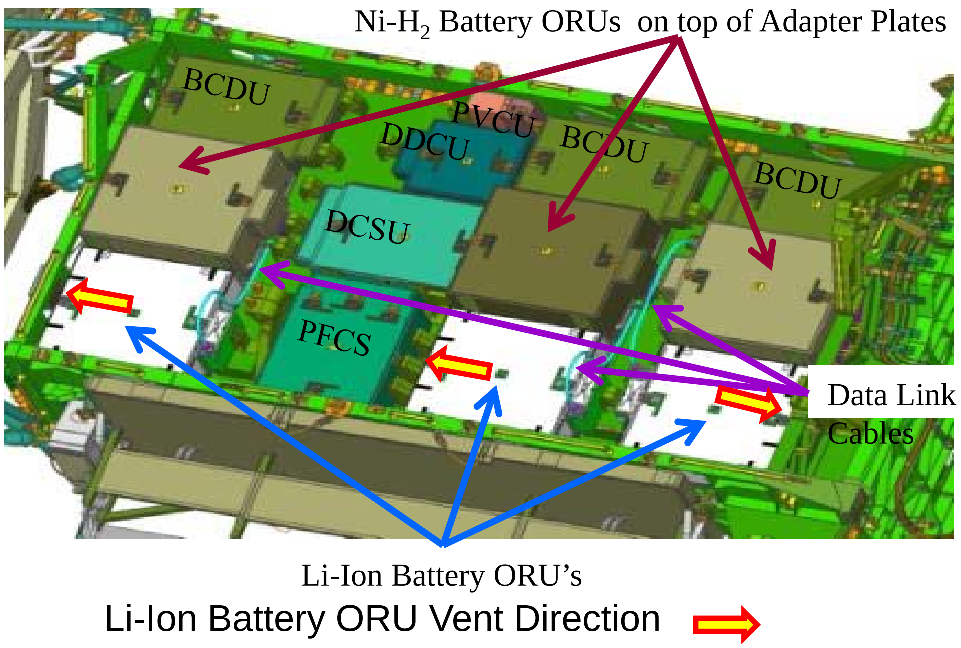
ORU Safety Features
Flame Trap Pressure Relief Assemblies

- Allows ORU vent gas pressure relief
- Prevent Flames from escaping the ORU
- Baffles made of 300 series CRES (Stainless Steel)
- Directs vent effluent away from EVA crew member during Installation
- Once installed on ISS, vent ports face structure or adjacent ORUs, thus limiting effluent flow to EVA accessible areas

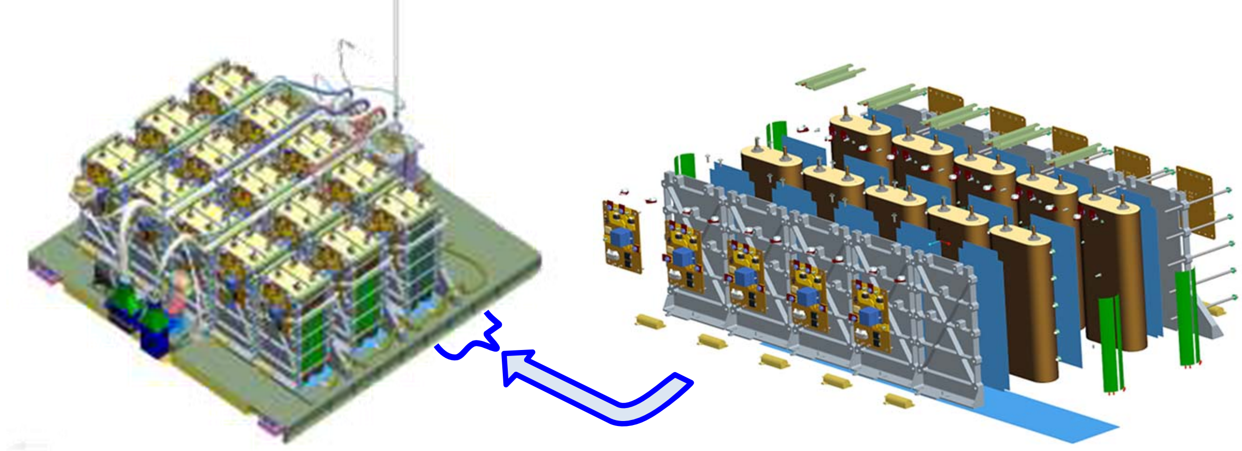
Note: Cell vents face up toward MMOD shielding – away from cold plate, adjacent cells, and IEA hardware



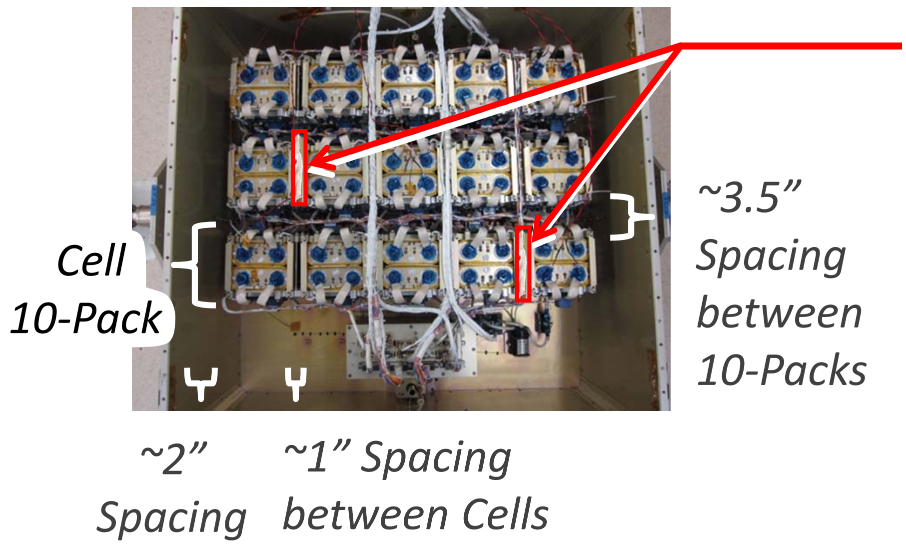




ORU Safety Features
Radiant Heat Barriers & Cell Spacing



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

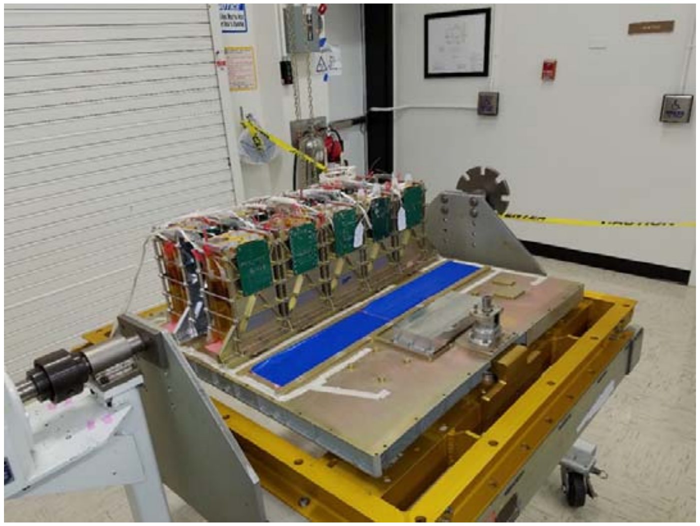


Radiant Heat Barrier (12 per ORU)

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

ISS Li-Ion ORU Test Article

- As Flight Like as possible within cost and schedule constraints
  - Finned baseplate, enclosure, MMOD shield, flame trap vent assemblies, cell holding fixtures, thermal gaskets, radiant barriers, insulation, etc.
- Six live cells, 24 cell mass simulators
  - Live cells at and adjacent to initiating TR cell locations.
- Battery Interface Unit mass simulator
- Cable runs similar to flight configuration
- Additional Thermal Couple Instrumentation
- Enclosure modified to accommodate drill penetration apparatus



First two rows of cells on baseplate

Six live cells, 24 cell simulators

Trigger Method

- Patch Heater Method
  - Developmental tests on cells and mass simulators
  - Tested 800W heaters on a ISS cell
  - 1.2 MJ over 20 minutes to achieve TR
  - Resulted *in TR with JR ejection*
  - Too large of an initial temperature bias on battery and adjacent cells for implement on ORU TR test

- Drill Penetration Method
  - All resulted *in TR within seconds with JR ejection*
  - No temperature bias on adjacent cells, but requires breach of cell can prior to TR
- **Drill Penetration Method selected for ORU TR test**

- For further details reference
  - Space Power Workshop, 4/27/17, “ISS Main Battery Large Cell Thermal Runaway Propagation Testing”, Jason Graika

ISS Li-Ion ORU TR Propagation Test Bed

White Sands Thermal Runaway Propagation Test Bed

- Flight-like finned active cooling loop from ORU manufacturer, painted black over anodized gold coating for proper emissivity
- Affinity chiller selected for circulation of cooling fluid
  - Dynalene HC-10 fluid, on-orbit uses ammonia
  - Thermal analysis determined that differences were acceptable
- Two cameras, one inside test article, one inside chamber
- Drill Penetration Apparatus installed

Cell 1

Drill penetration apparatus

ISS Li-Ion ORU TR Propagation Test

- ORU TR Test Execution – October 26, 2016
    - Cells charged to 3.95 V at C/6 prior to test start (on-orbit EOCV)
    - Chamber <1 torr
    - Chiller temp ~40 deg F and average cell temp 75 deg F
    - Heaters turned off, cameras began recording, drill actuated
    - TR initiated in Cell 1, lower area of the curved side
        - Drill stopped when sparks & electrolyte release were observed
        - Drill re-started after 14 seconds, run until full TR observed (see video)
    - Chamber camera captured cell venting (see video)
    - Continued monitoring temperatures & voltages post-TR
    - No propagation of TR to adjacent cells
    - 5 intact live cells discharged at C/6 prior to opening chamber
    - Test article shipped to JSC for destructive physical analysis

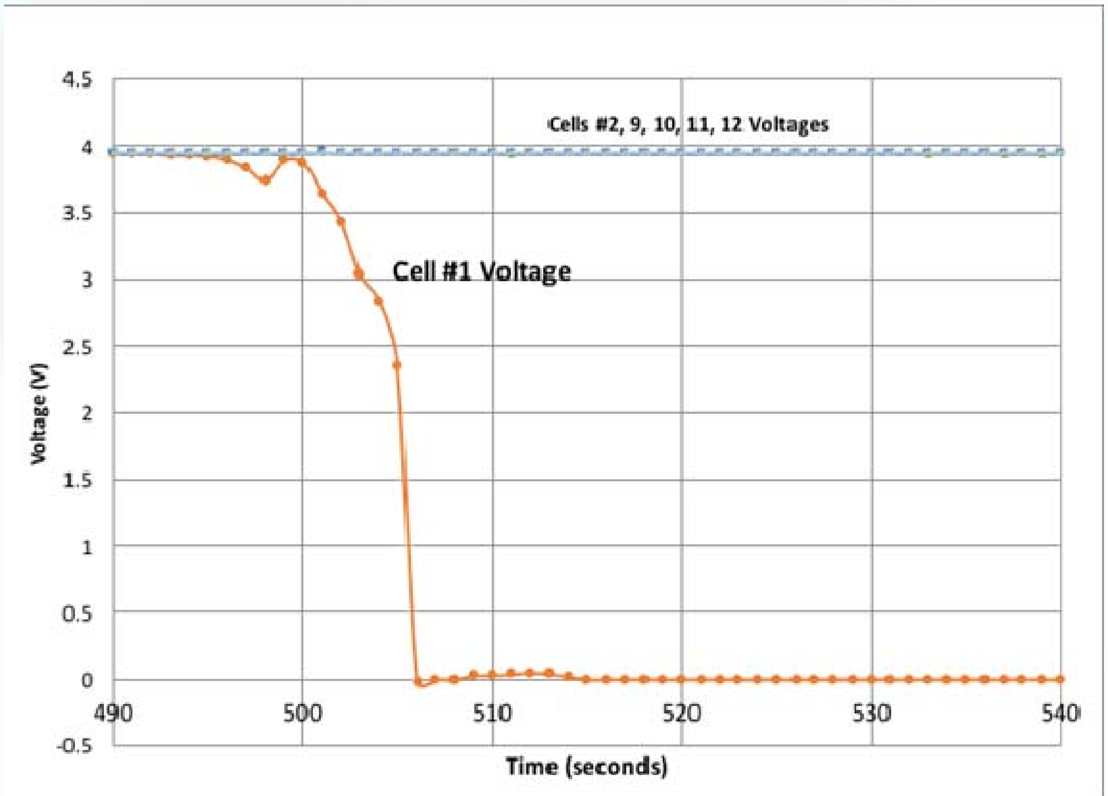
ISS Li-Ion ORU TR Propagation Test Videos

USB Camera inside Test Article

USB Camera outside Test Article

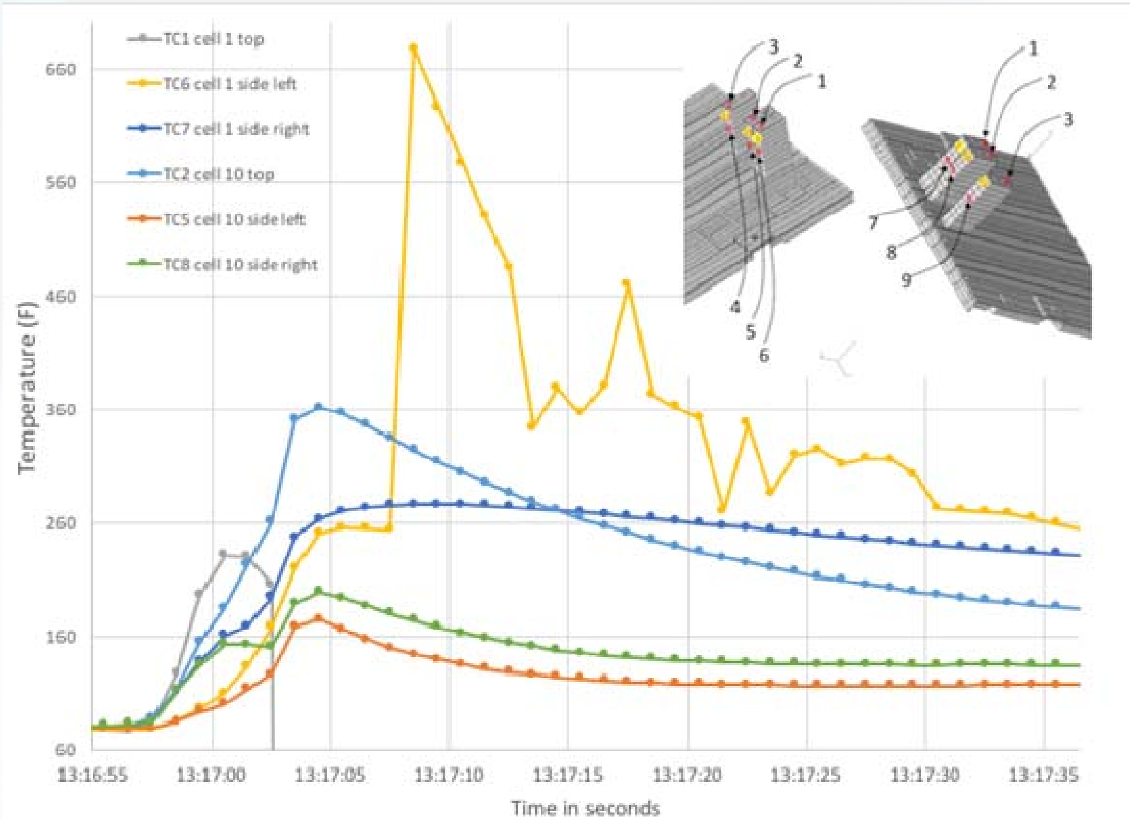
ISS Li-Ion ORU TR Propagation Test

- Test Summary – Cell Voltages



ISS Li-Ion ORU TR Propagation Test

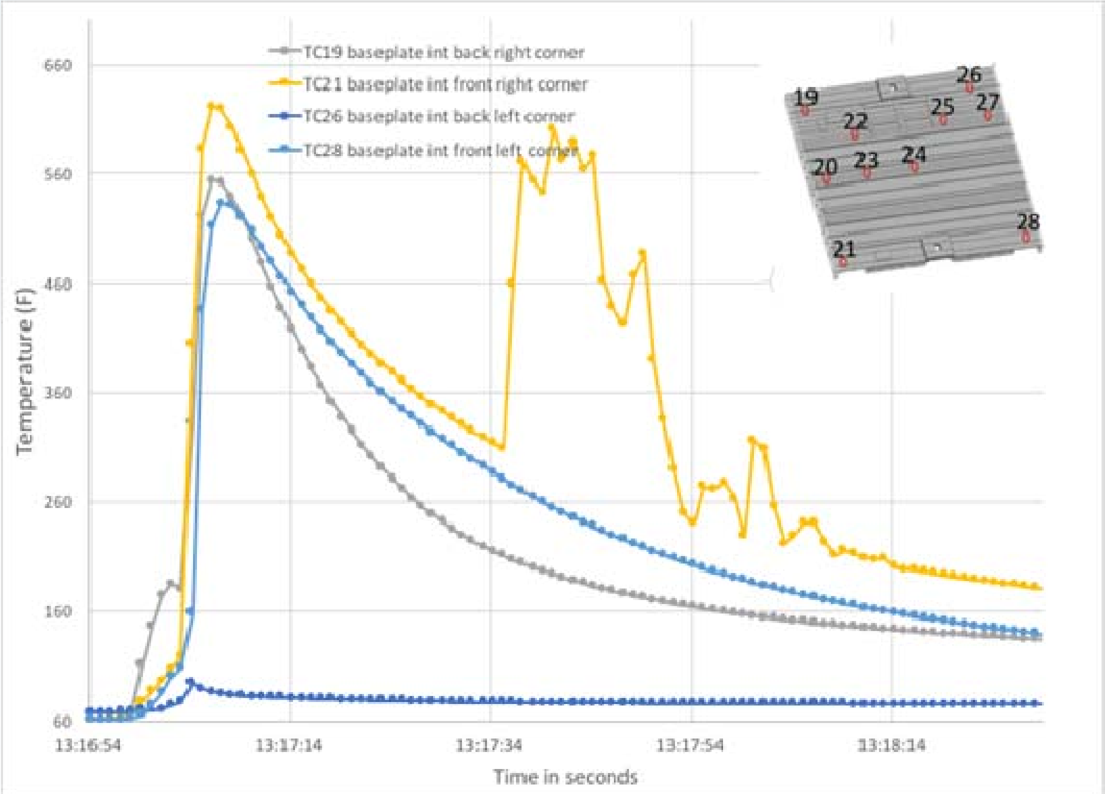
- Test Summary – Cell 1 and Cell 10 Temperatures



Note: TC 1 failure, erratic readings on TC6 due to intermittent contact with the cell case

ISS Li-Ion ORU TR Propagation Test

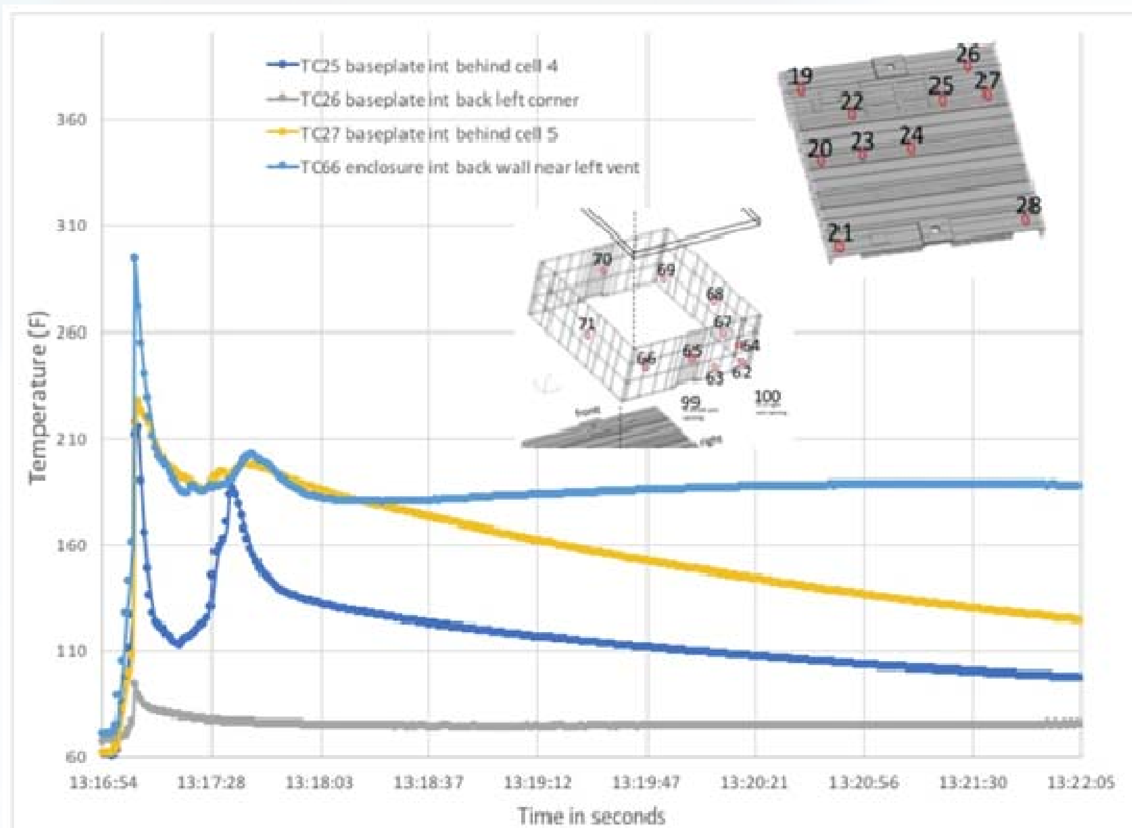
- Test Summary – Baseplate Corner Temperatures



Note: Erratic readings on TC21 due to intermittent contact with the cell case

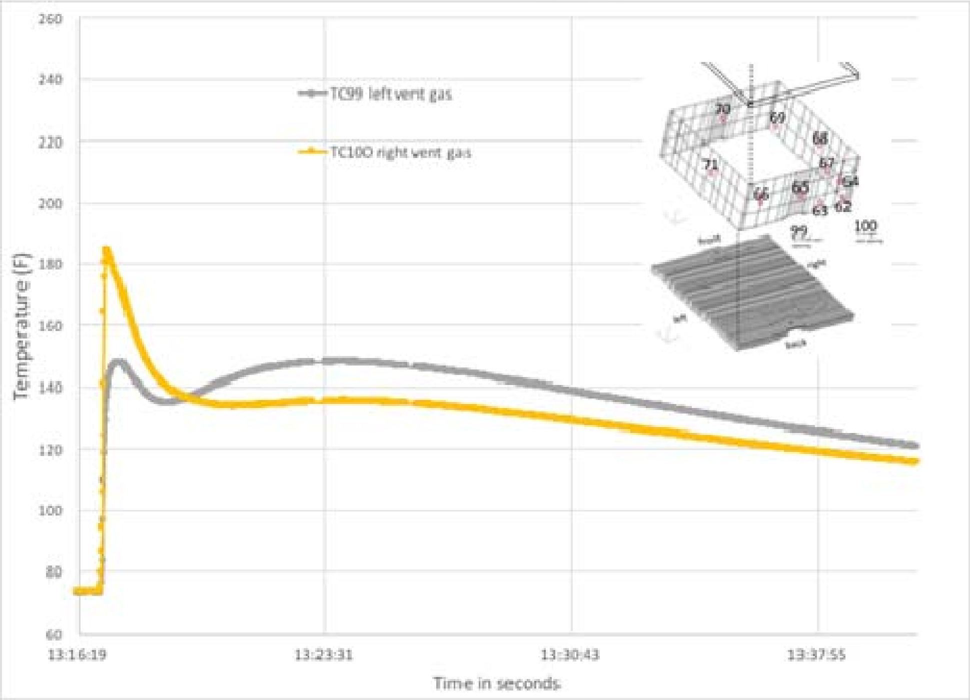
ISS Li-Ion ORU TR Propagation Test

- Test Summary – Baseplate Corner near jelly roll winding final location



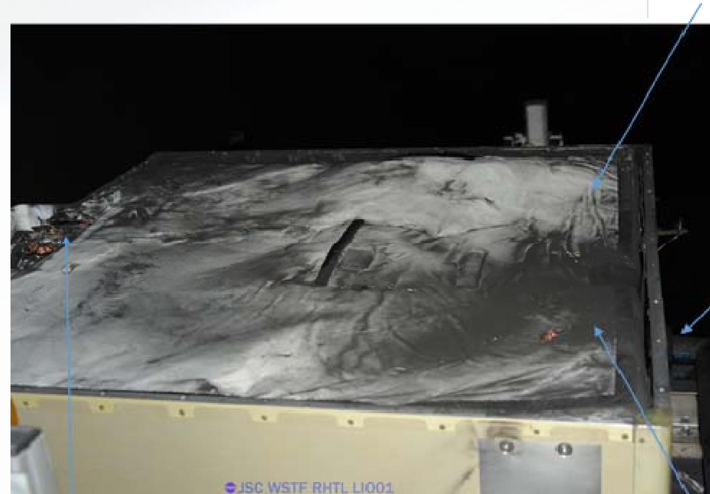
ISS Li-Ion ORU TR Propagation Test

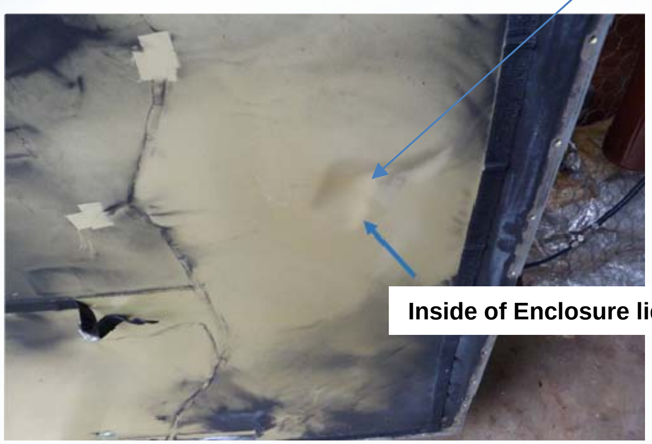
- Test Summary – Flame Trap Exit Temperatures



ISS Li-Ion ORU TR Propagation Test

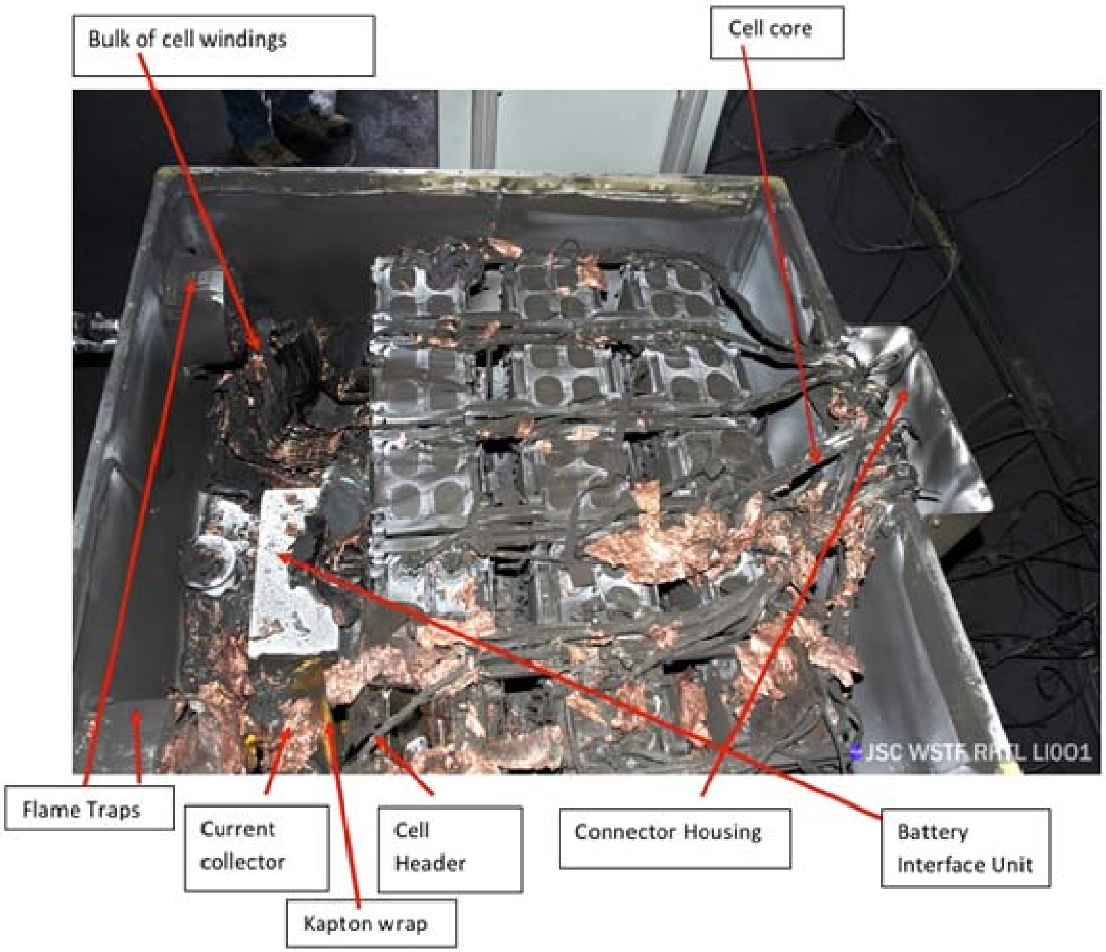
- Post-test Destructive Physical Analysis at JSC– Minimal Enclosure or MMOD shield damage





ISS Li-Ion ORU TR Propagation Test

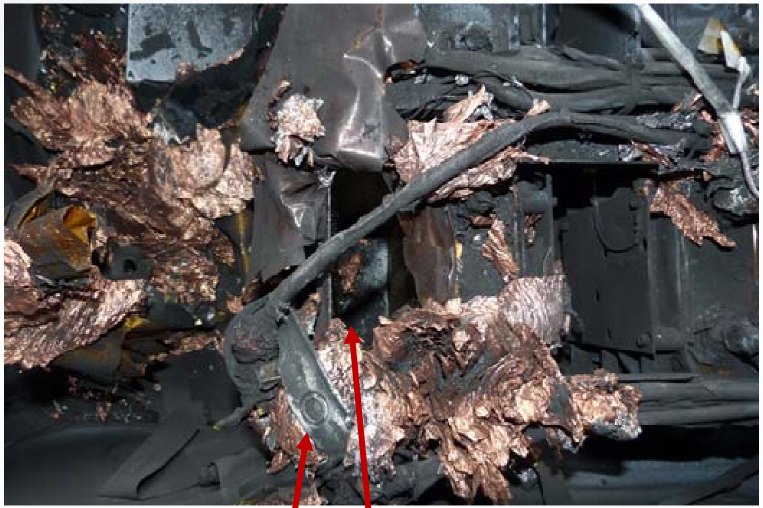
- Post-test Destructive Physical Analysis at JSC



Location	Mass (g)
Cell Winding	470
Cell #1 remains	*328*
Front corner near cell 1	165
Front corner near cell 5	157
Cell Header	157
Baseplate cell 30 row	128
Top of live cells	86
Current collector	44
Top of mass simulator plus doghouse	31
In Flame Trap near cell 1	30
Between Cell Rows 1-2	28
Between Cell Rows 2-3	18
Cell Core	16
Cell 5 and 6 area	10
Outside ORU under doghouse	3
TOTAL	1671
Pretest Mass	3526
Missing Mass	1855

ISS Li-Ion ORU TR Propagation Test

- Post-test Destructive Physical Analysis at JSC – Flame Trap, Cell 1, and Header



Flame Trap

Cell Header

Cell 1

ISS Li-Ion ORU TR Propagation Test

- Test Results
  - Trigger cell vented, achieved TR, followed by cell winding ejection
  - Battery enclosure contained TR products, including flames
    - Minimal damage to enclosure, MMOD shield, or radiant barriers
    - Gases vented and exited from enclosure
  - No propagation to neighboring cells
    - All 5 live cells maintained their pre-test Open Circuit Voltages
- Test Findings
  - Full-scale test did not propagate or damage adjacent cells
    - Cell winding ejection resulted in a suspected under-test condition
      - Limited ability to fully verify thermal model results
  - Battery design precluded effective use of patch heaters for TR trigger
    - Recommend development of TR trigger method that limits thermal bias
- Forward Work
  - NESC is pursuing further work on trigger method
    - Once developed, consider repeat the full-scale test
    - Use results to further assess thermal model predictions

Acknowledgements

- Thanks to the NASA Engineering and Safety Center for funding the test, ISS Li-Ion Project (Boeing and NASA) for supporting the development of the test, JSC for the build up and DPA of the test article, and White Sand Test Facility for performing the test