Testing of Thermal Runaway Tolerant Designs Utilizing High Energy Density 18650 Lithium Ion Cells

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Overview

- Reason for thermal runaway testing
  - TR failures are rare, but can be catastrophic
  - Manned spaceflight fault tolerance
- Review ABSL test results from 2016 designs using HCM and Moli C
- New results single cell and battery-level MJ1 tests
  - Test methodology
  - Design validation

Background

- Testing completed in 2016 for two separate ABSL manned spaceflight battery designs

- Cell types tested:

	Sony 18650HCM	Molicel IHR-18650C (Moli C)
Discharge Capacity (Datasheet)	1.5 Ah	2.0 Ah
Specific Energy	133 Wh/kg	157 Wh/kg
Energy Density	326 Wh/L	418 Wh/L

Single Cell Test Method

- Single cell tests used nichrome heater attached with Kapton tape, driven at 30-50W

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HCM (1.5 Ah) Single Cell TR Test Results

- As the HCM approaches thermal runaway, it begins to vent a small amount of smoke
  - Typically lasted 10-15 seconds before full TR

- At the time of TR initiation, a jet of flames, sparks and smoke are emitted through the center of the cathode assembly
  - Typically lasted 2-3 seconds

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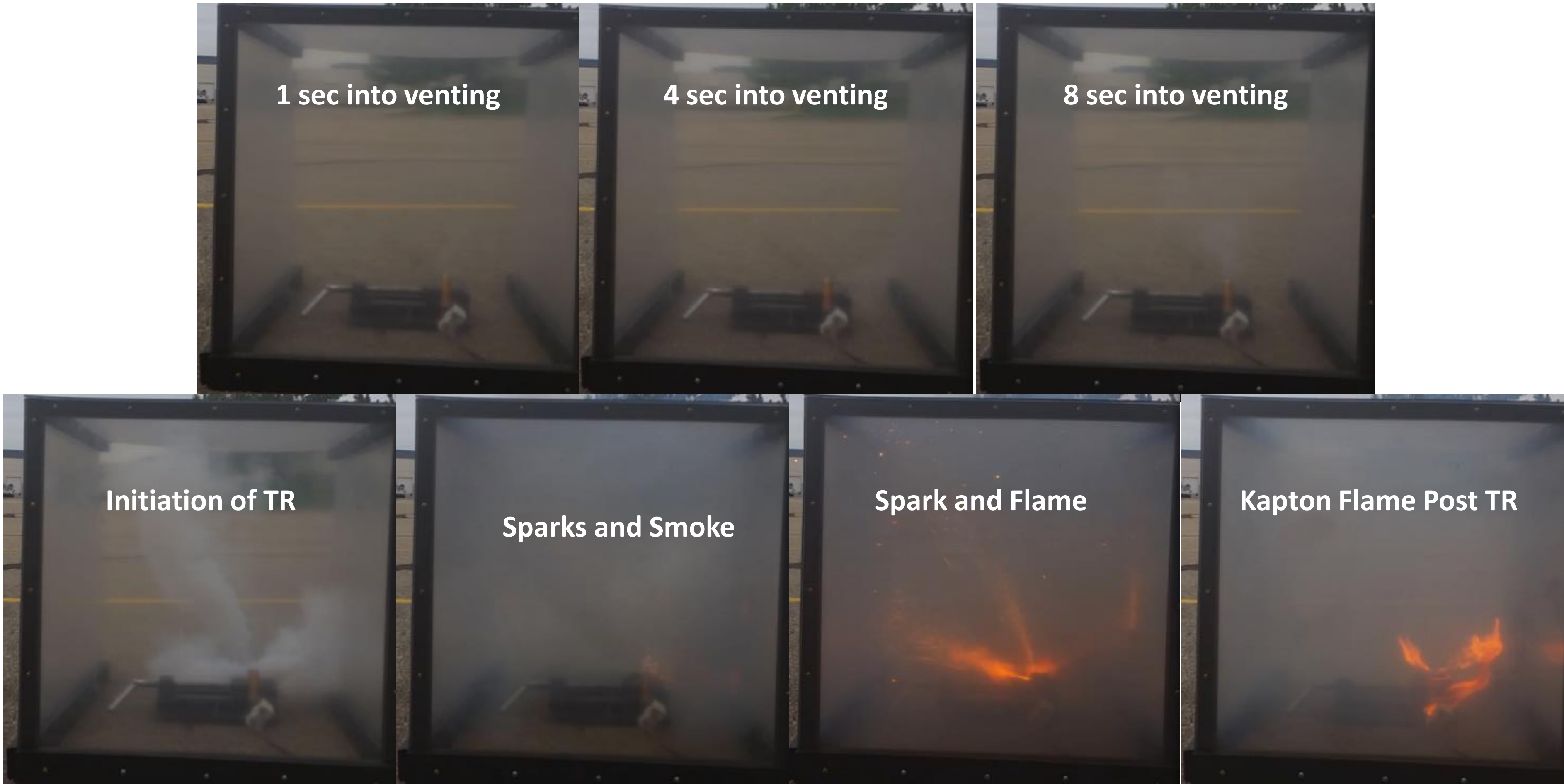
HCM (1.5 Ah) Single Cell TR Test Results



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HCM (1.5 Ah) Single Cell TR Test Results

- Cathode assembly remained intact
  - TR jet pierced burst disk and cathode top cap
- No signs of side wall rupture
- Heat discoloration of the cell can

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Moli C (2.0 Ah) Single Cell Test Results

- As the Moli C approaches TR initiation, it is much less consistent than the HCM cell
  - Some cells would vent a significant amount of smoke, others would vent no smoke
- TR failure mode was failure of the cathode assembly
  - Cathode assembly blown out of the cell entirely, along with jelly roll
- Fundamentally different TR event
  - Duration is much shorter than HCM
  - No flames observed coming out of cell

Moli C (2.0 Ah) Single Cell Test Results

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Moli C (2.0 Ah) Single Cell Test Results

- Cathode and jelly roll ejected
- No signs of side wall rupture in the anode, but significant bulging from internal pressure
- Cell can heat discoloration

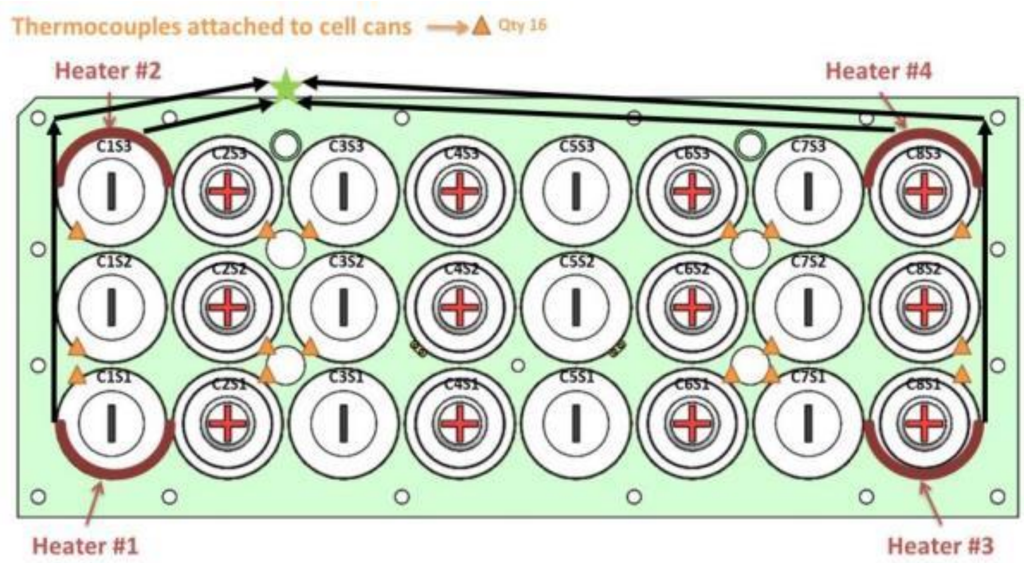
Battery-Level TR Testing

- At battery level, the concern becomes that the single cell TR will heat neighboring cells to the point of TR, resulting in propagation

- Failure of battery housing structure due to heating, jet impingement, and/or housing pressurization would also be catastrophic

HCM Battery-Level Test Method

- Flight-like 3p8s was built, with integrated heaters and additional thermocouples
  - Heaters installed on four corner cells

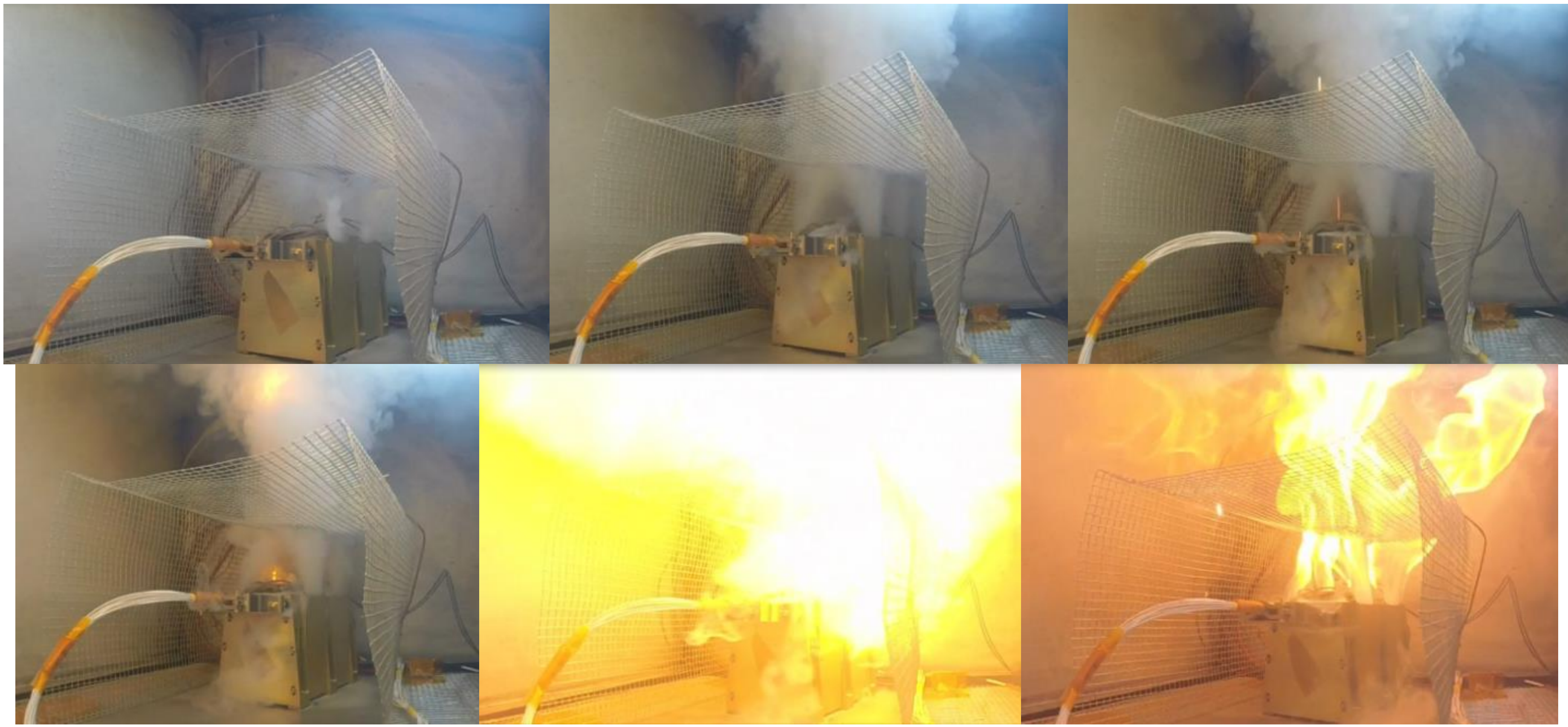


HCM Battery-Level Test Results

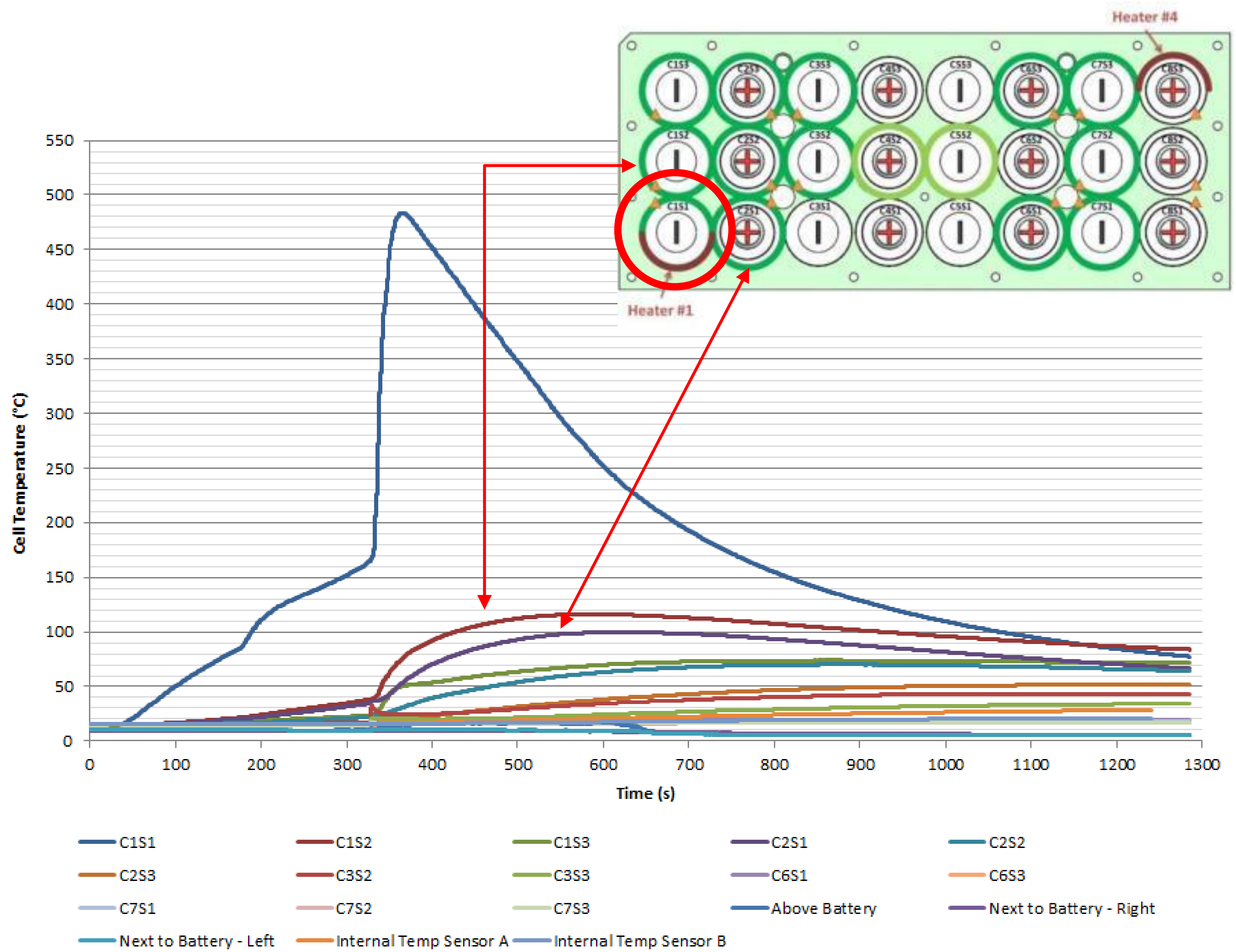
- Trigger cell went into TR as expected, ~160°C
- No propagation of TR
- Battery maintained structural integrity
  - No signs of structural damage on the outside of the housing

HCM Battery-Level TR Test #1

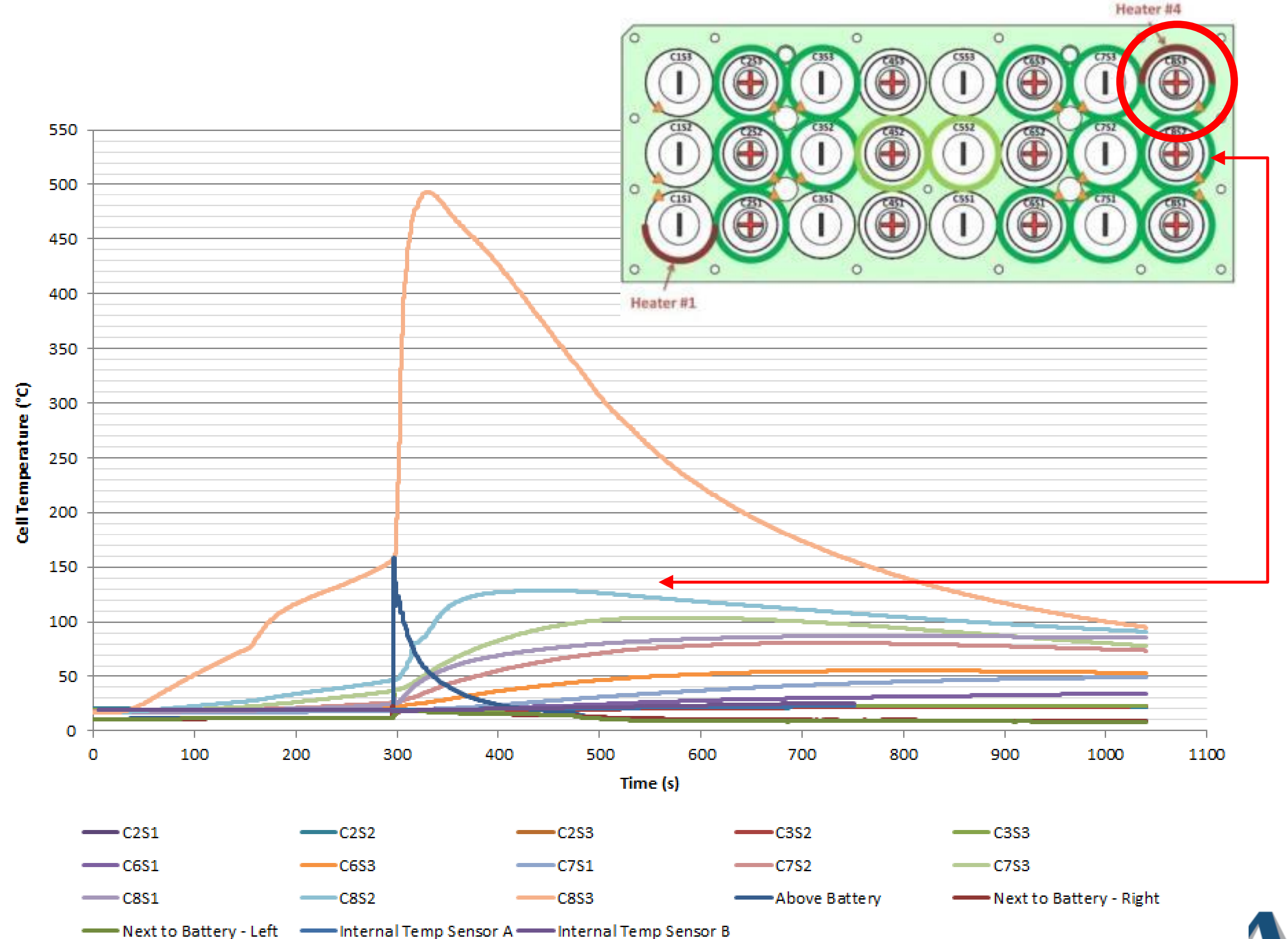
HCM Battery-Level TR Test #2



HCM Battery-Level TR Test #1



HCM Battery-Level TR Test #2



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Moli C Battery-Level Test Method

- **Configuration 1:** 24 individual cells in chassis similar to HCM
  - Cells not connected electrically

- **Configuration 2:** Four 6p1s virtual cells
  - No chassis, but added deflector plate and vent chimney

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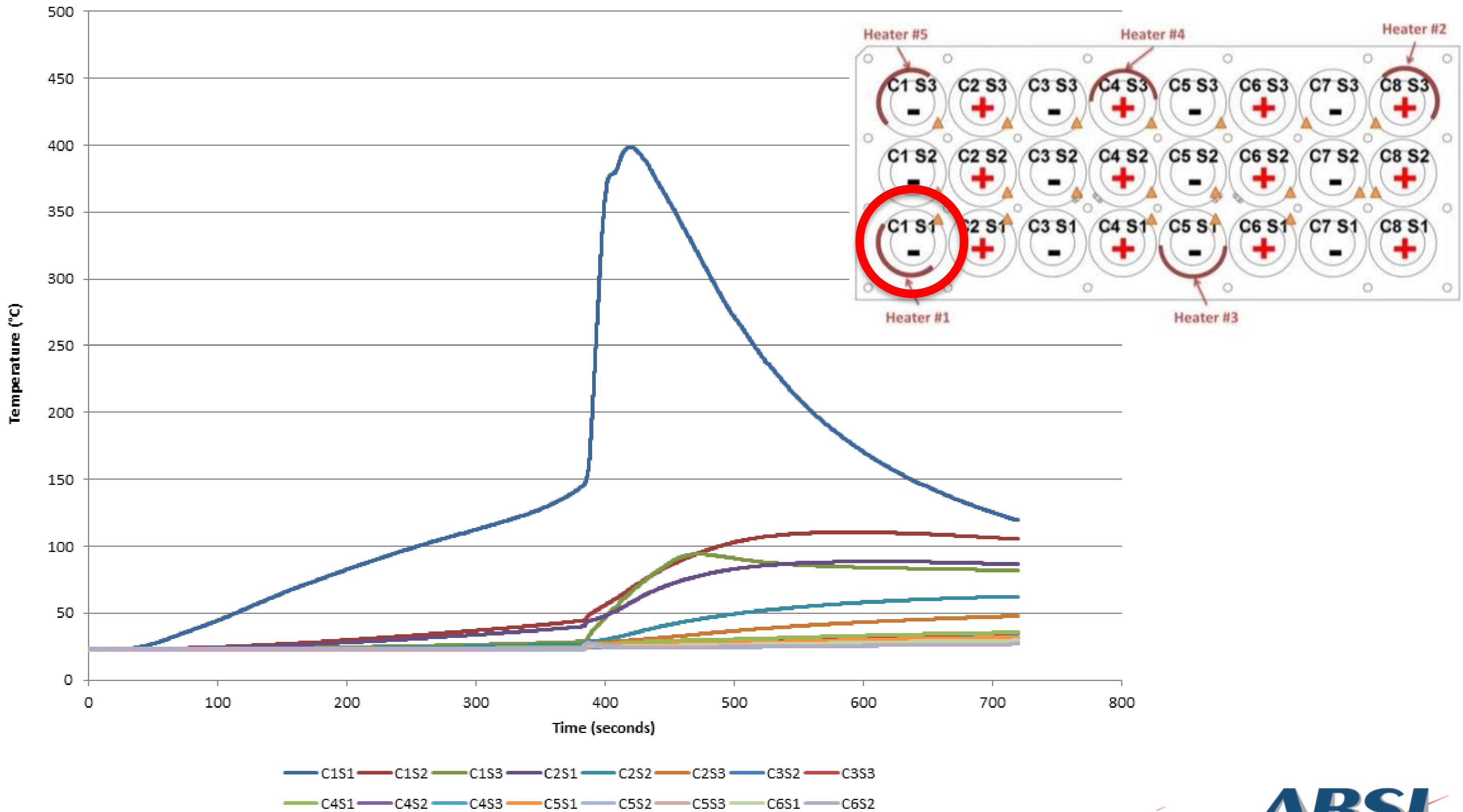
Moli C Battery-Level TR Test #1

Moli C Battery-Level TR Test #1



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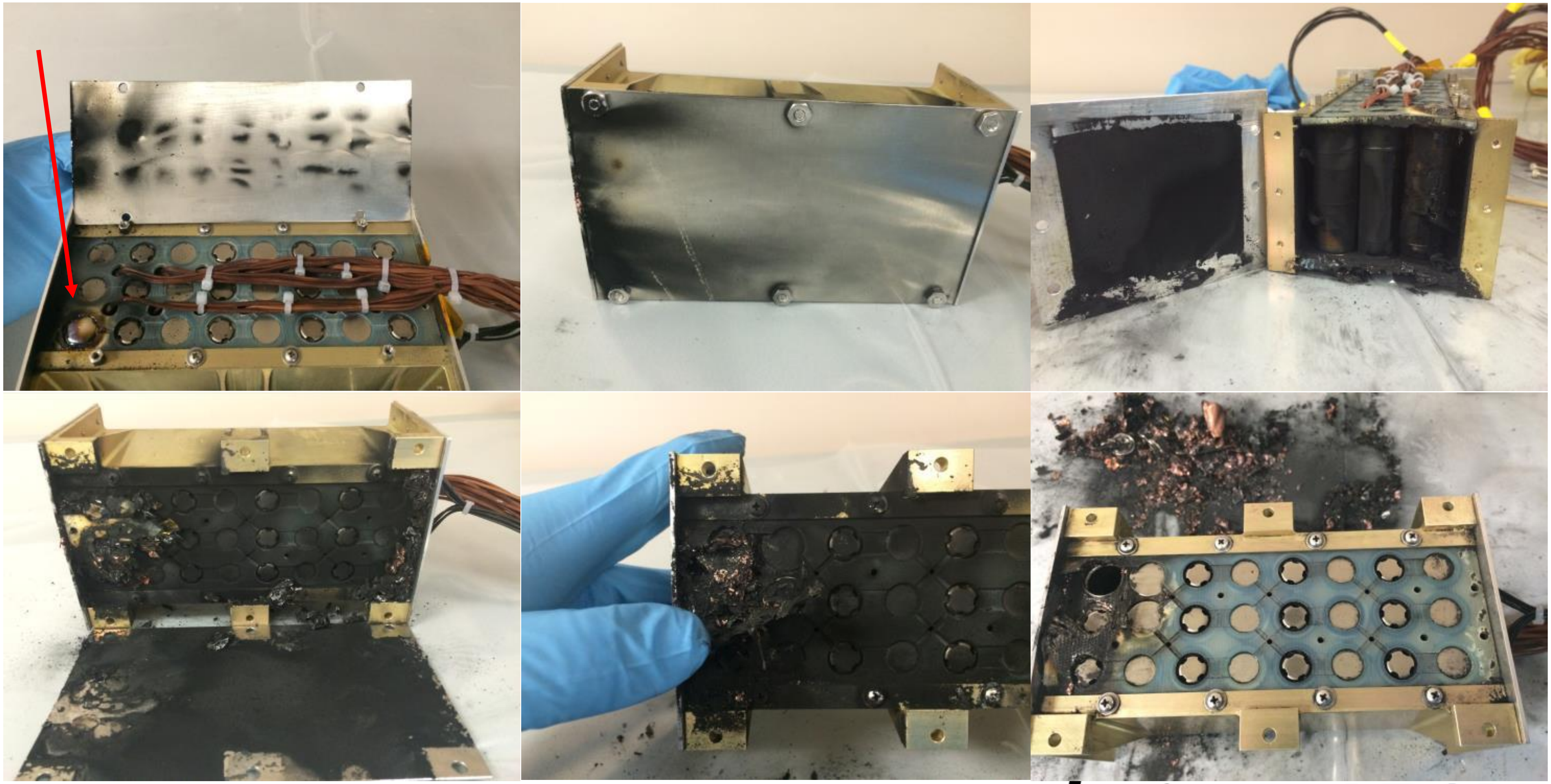
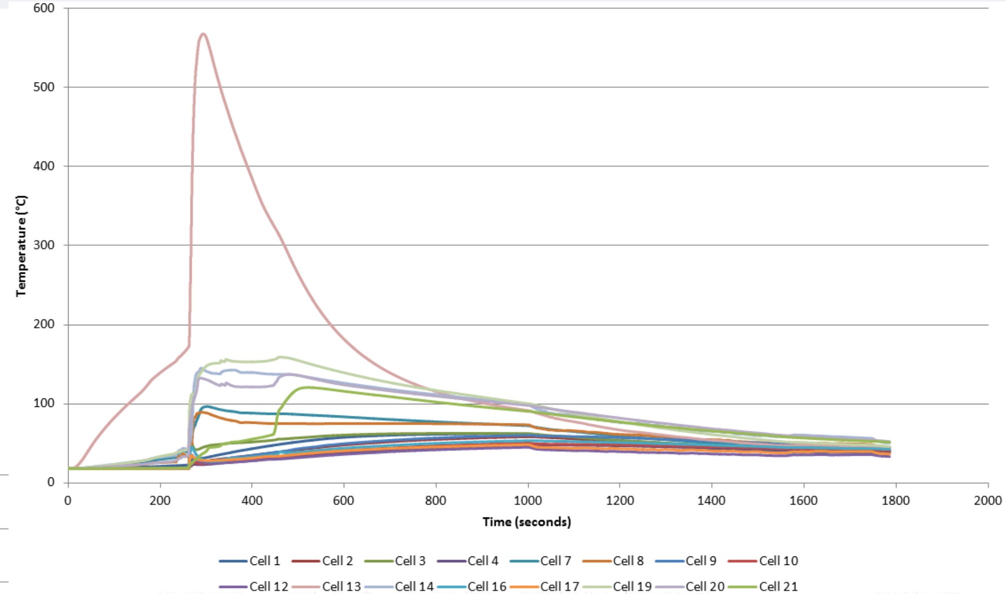
Moli C Battery-Level TR Test #1

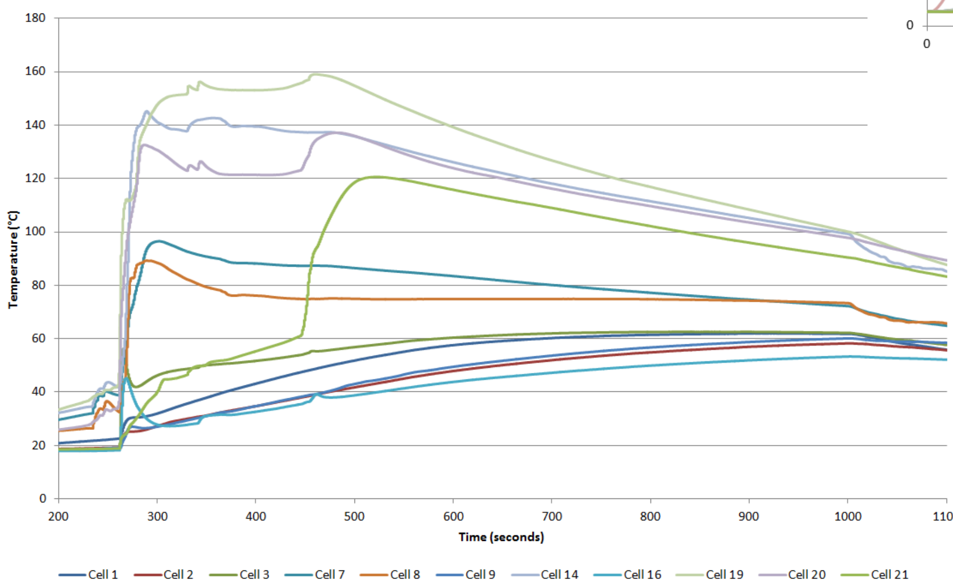


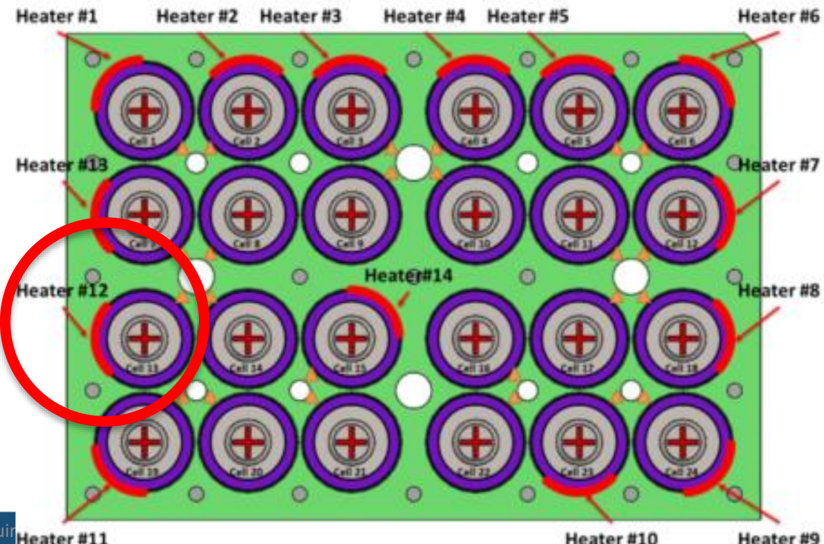
Moli C Battery-Level TR Test #2

Moli C Battery-Level TR Test #2

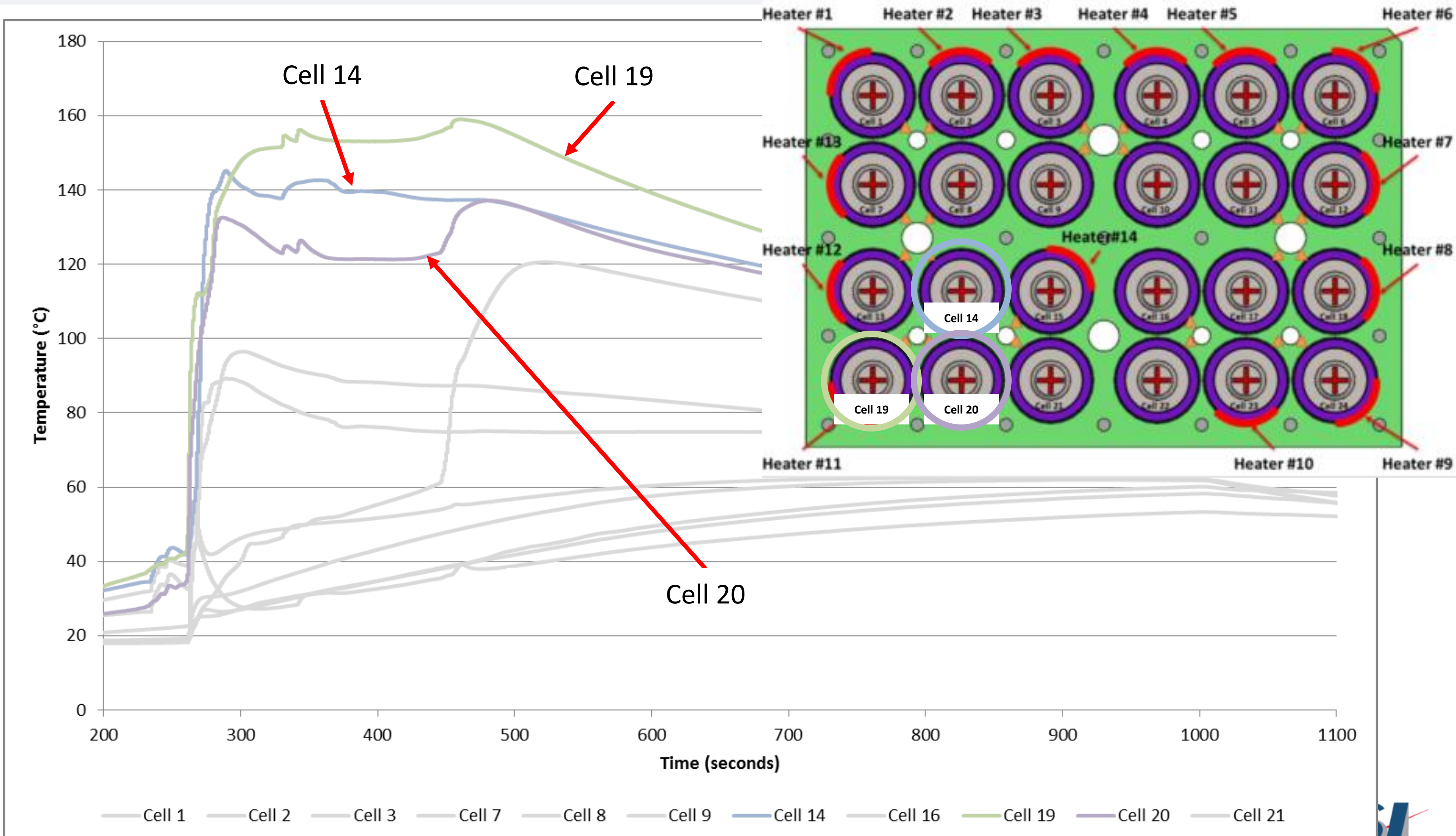
- TR initiated on the trigger cell at approximately 170°C
- Maximum temperature of neighbor cells was approximately 160°C



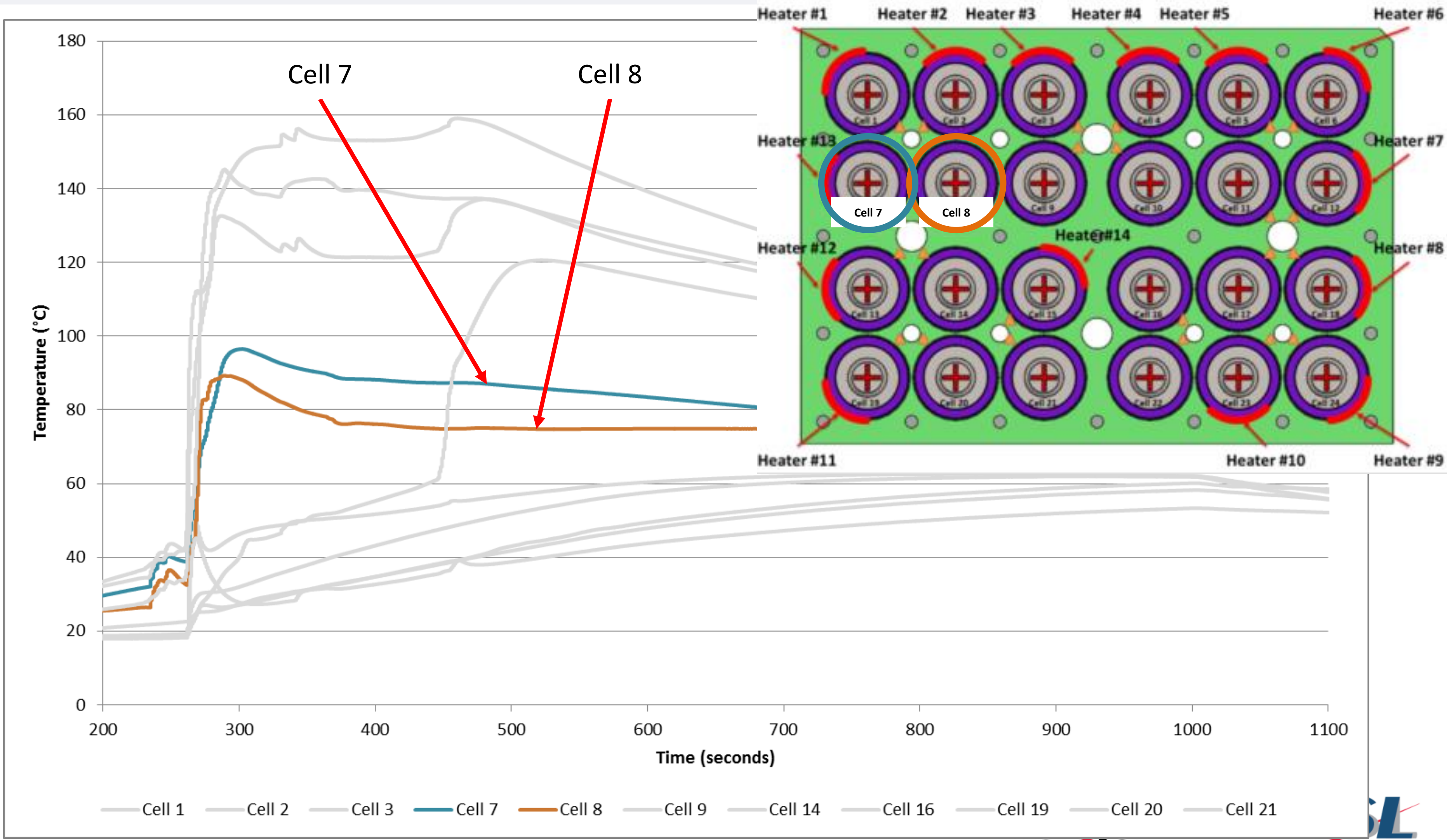




Moli C Battery-Level TR Test #2



Moli C Battery-Level TR Test #2



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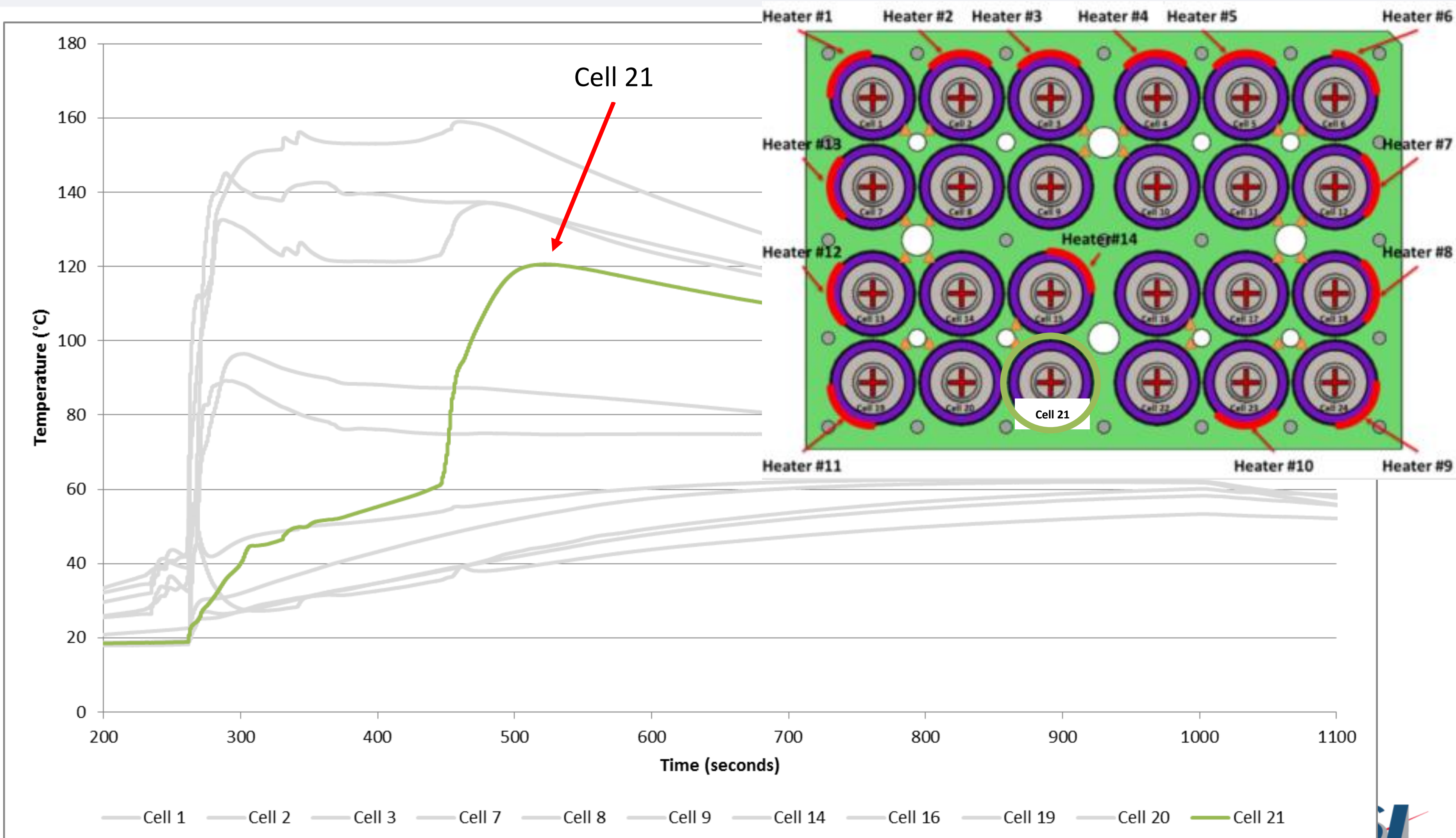
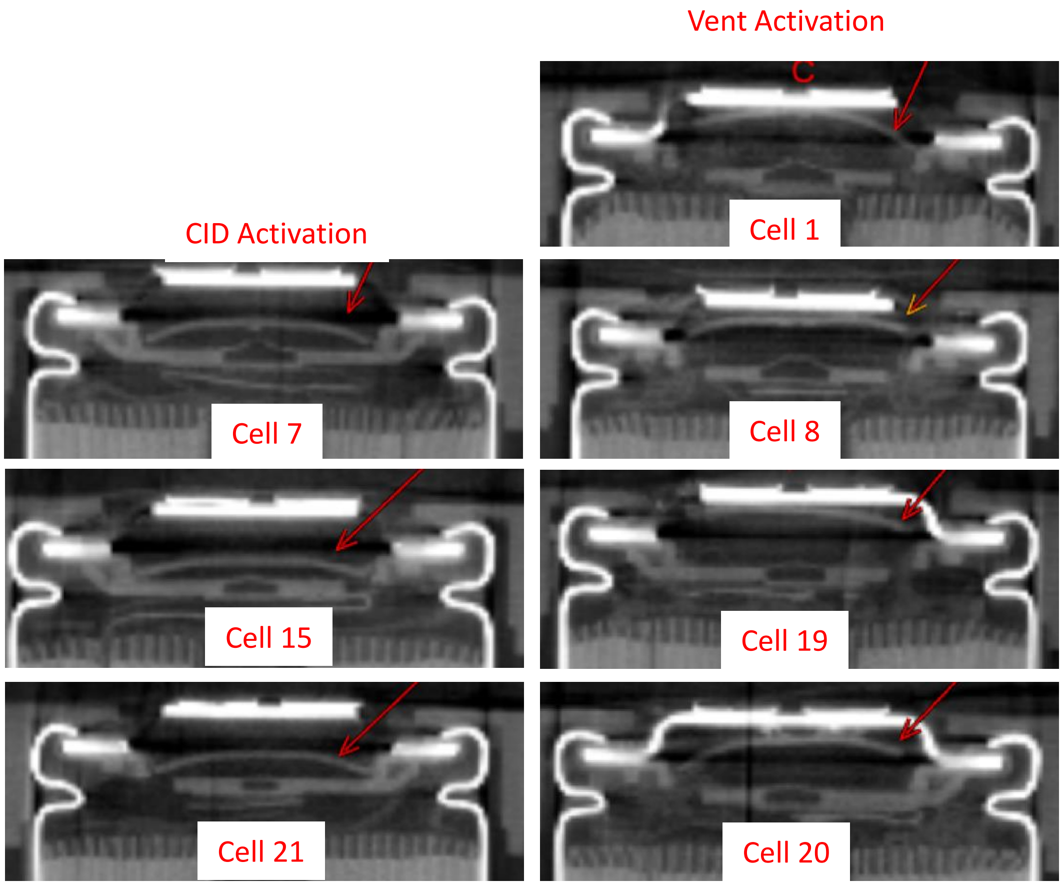
Moli C Battery-Level TR Test #2



Moli C Battery-Level TR Test #2

- No sidewall ruptures or other gross failures of trigger cells, or neighbor cells
- GRP damage around trigger cells
- Neighbor cell normal safety device activation
  - Three CID activation
  - Four vent activation



Increasing Energy Density

- HCM and Moli C battery-level tests validated design requirements
  - No propagation of TR to other cells
  - Battery housing maintains structural integrity

- Margin to propagation can be improved
  - Neighbor cell temperatures 100°C – 130°C
  - Safety devices activating means more capacity loss than just single cell

Increasing Energy Density

- Effects on neighbor cells are expected to be more pronounced with increasing energy density
  - Moli C was ~20% higher than HCM
  - MJ1 is ~100% higher than HCM
- Different chemistries also effect thermal runaway behavior
  - In addition to energy content effect

	Sony 18650HCM	Molicel IHR-18650C (Moli C)	Panasonic NCR18650A (Pan A)	LG Chem INR18650MJ1 (MJ1)
Discharge Capacity (Datasheet)	1.5 Ah	2.0 Ah	2.9 Ah	3.4 Ah
Specific Energy	133 Wh/kg	157 Wh/kg	225 Wh/kg	252 Wh/kg
Energy Density	326 Wh/L	418 Wh/L	620 Wh/L	705 Wh/L

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Increasing Energy Density

- Increased risk of sidewall ruptures
  – Some manufacturers increase energy density by reducing can wall thickness

Image credit: Safe, High Performing Li-ion Battery Designs: Summary of 2015 Findings, Eric Darcy and Stephanie Scharf, 2015 NASA Aerospace Battery Workshop

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MJ1 Single Cell Testing

- New heater design – eliminate Kapton burning during test, more evenly heat can circumference

MJ1 Single Cell – Unsupported

- Cells charged to various SOCs from 4.0-4.2V
  - Preliminary tests at 3.0V showed more benign reaction despite much higher initiation temps – high SOC is worst case

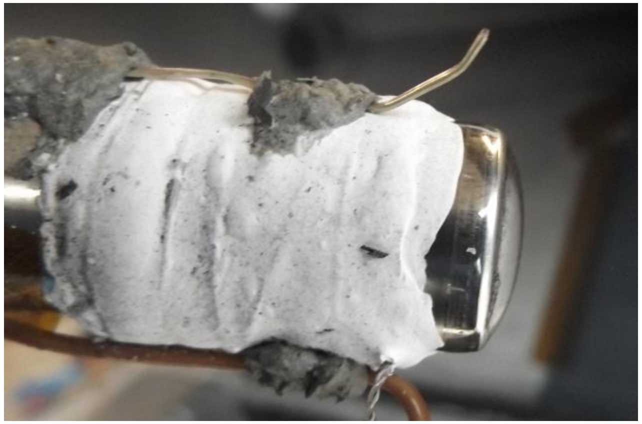
- One test at 100W; seven at 45W
  - High heat rate resulted in unrealistic failure mode

MJ1 Single Cell – Unsupported

- 1/7 “explosion” failure mode

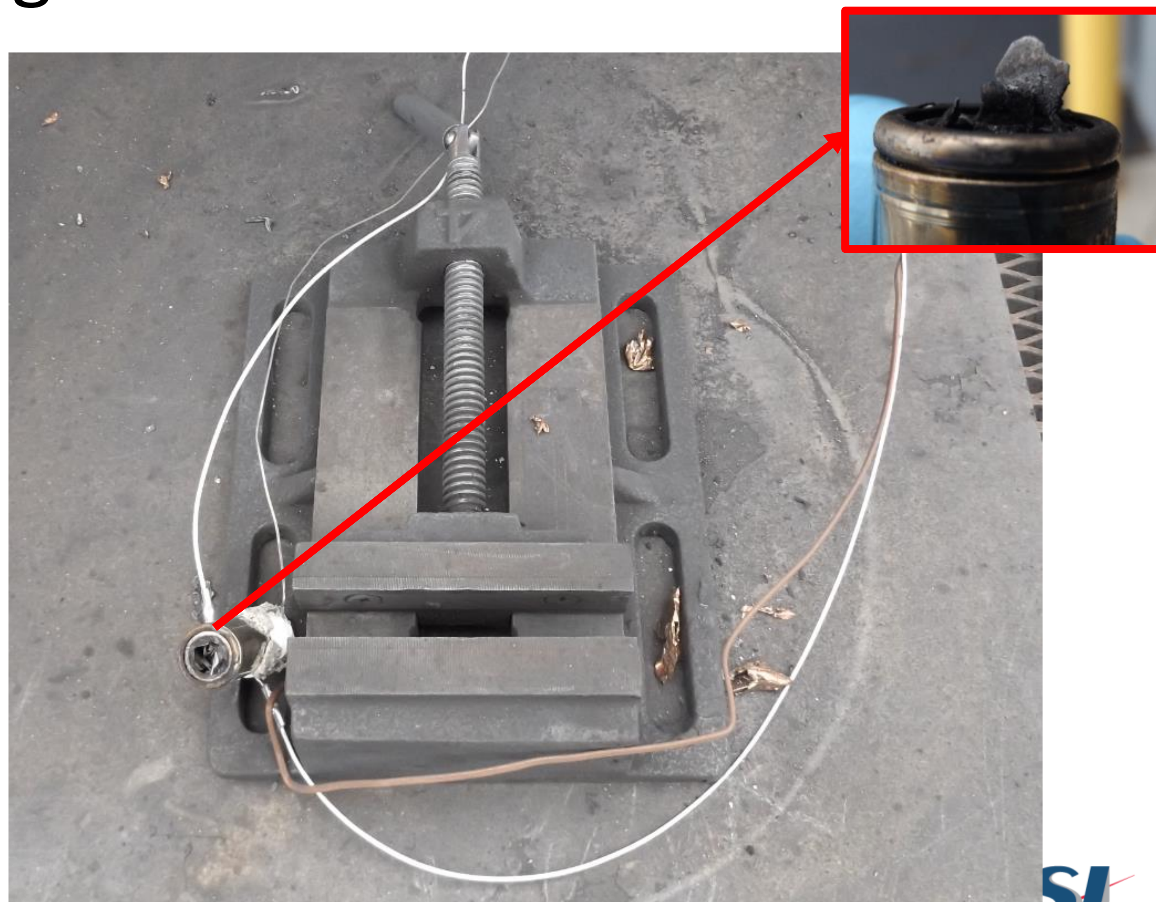
MJ1 Single Cell – Unsupported

- 1/7 “crimp unfurl” failure mode



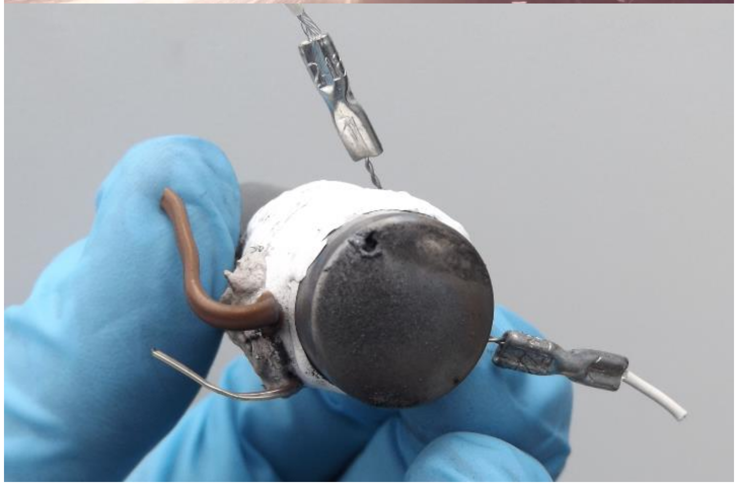
MJ1 Single Cell – Unsupported

- 5/7 “blast through” failure mode…



MJ1 Single Cell – Unsupported

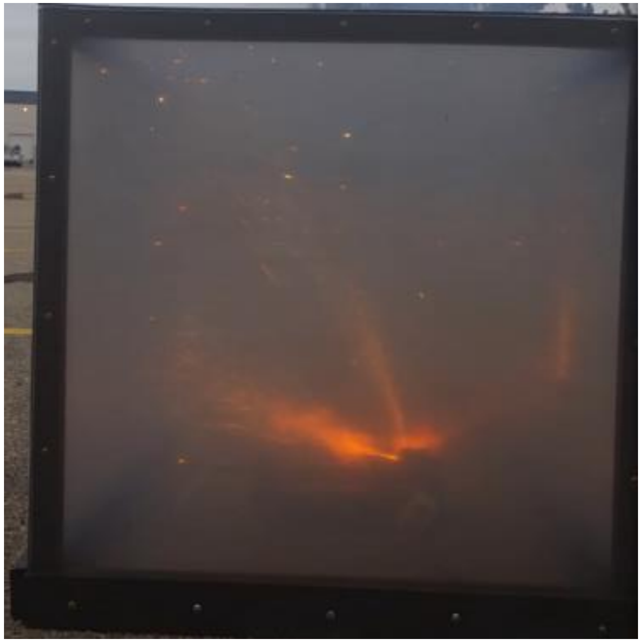
- … but two of these also had anode breaches



MJ1 Unsupported Cell Conclusions

- Empirically, MJ1 single cell TR more energetic than HCM or Moli C

HCM



Moli C

MJ1

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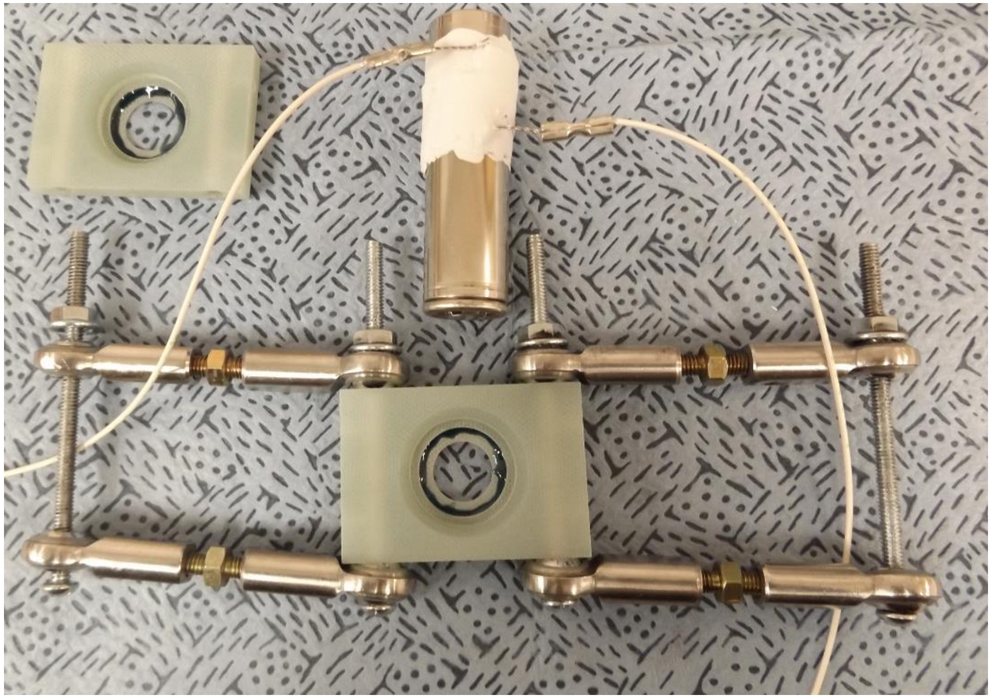
MJ1 Unsupported Cell Conclusions

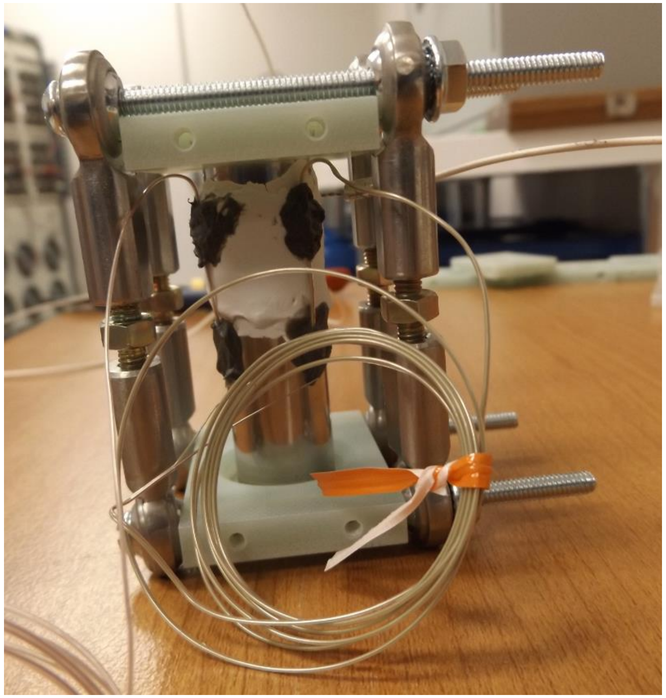
- “Blast through” failure mode was most consistent
- Other failure modes may be related to unsupported configuration
  - Unfurl – no capture plate restraint at cathode crimp
  - Anode hole – physically sitting on vise edge, and pressed into edge during TR event

Anode dented where resting on vise

MJ1 Single Cell – Supported

- Five tests clamped into GRP, plus three bonded
  - Clamped vs. bonded had no effect failure modes





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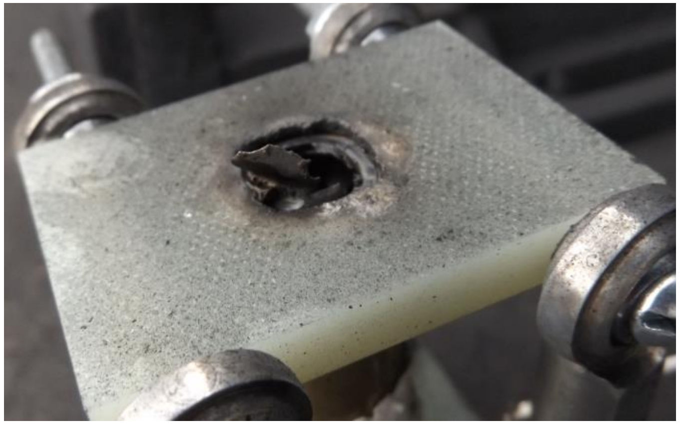
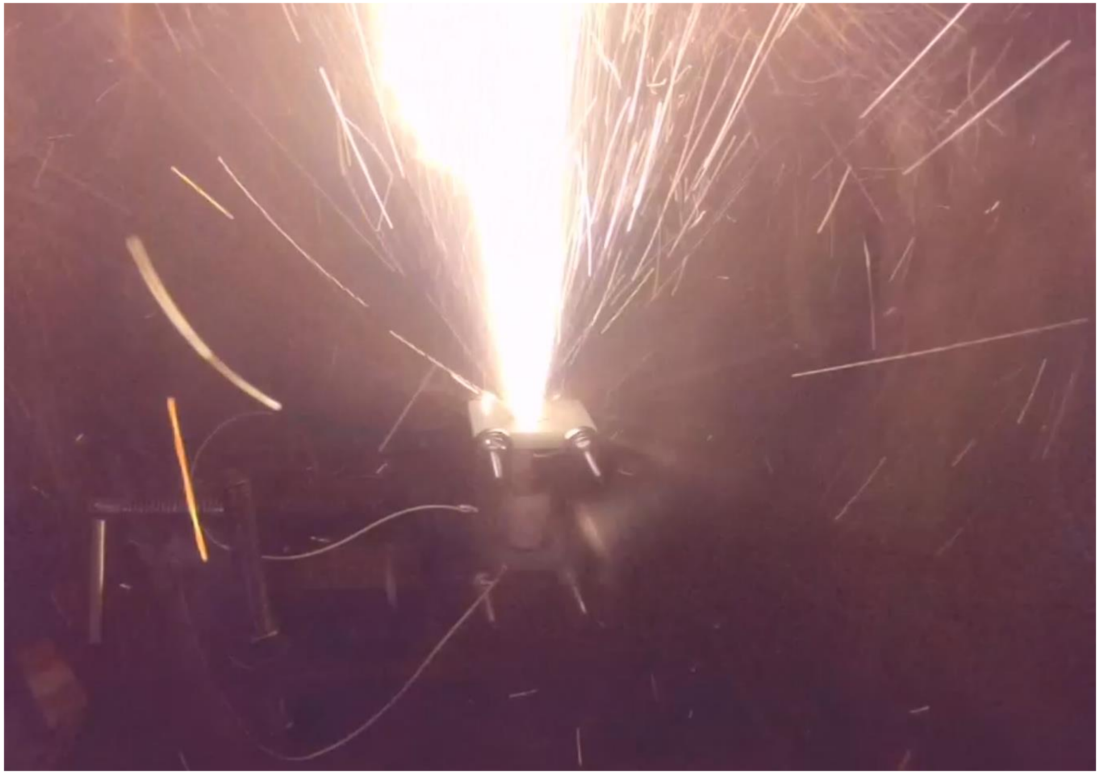
MJ1 Single Cell – Supported

- 4/8 "blast through" failure mode





MJ1 Single Cell – Supported

- 4/8 “stuck in GRP” failure mode

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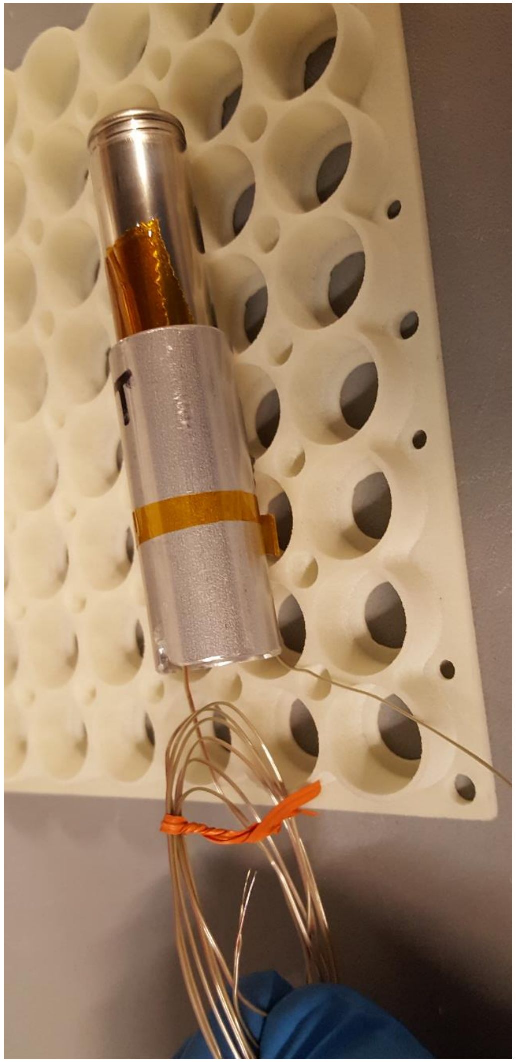
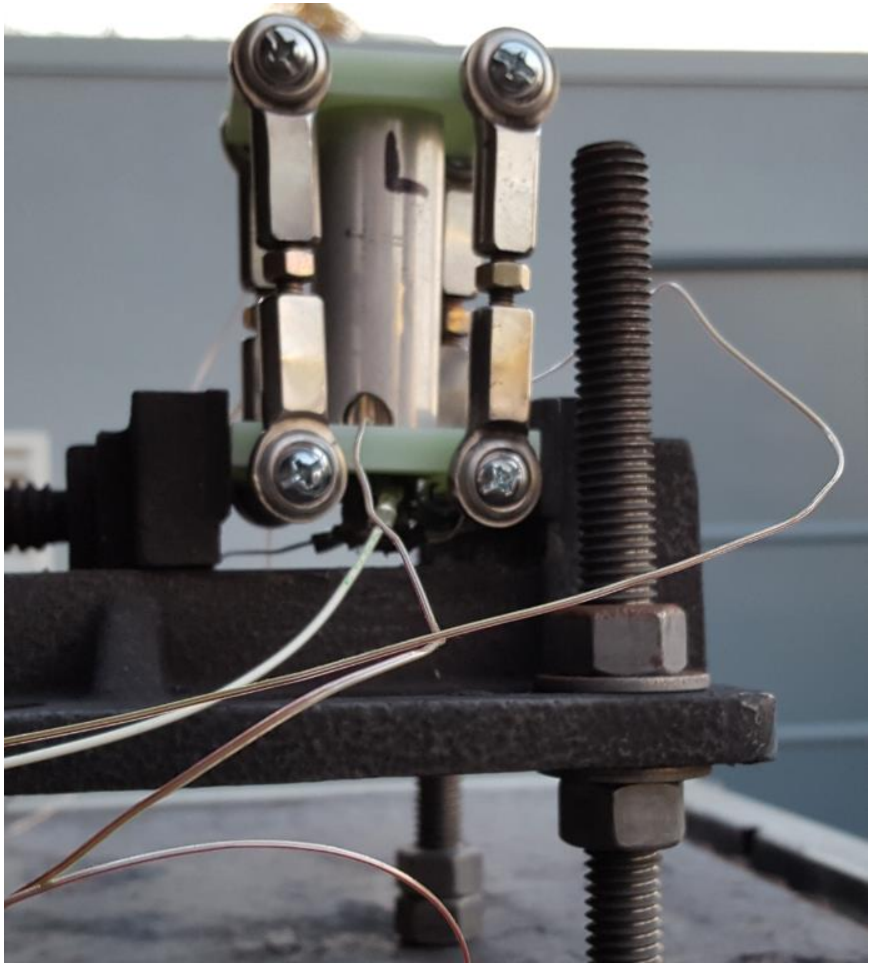
MJ1 Single Cell – Reinforced

- Third configuration – sleeve, anode heater
  - Eliminate potential stress concentration on can wall due to heater coil and/or adhesive boundary
  - Reinforce side walls per flight design
  - Move heat source further from vents to reduce insulator melting and clogging

- First test at 45W – anode heater fused open
  - Subsequent tests at 25-35W

MJ1 Single Cell – Reinforced





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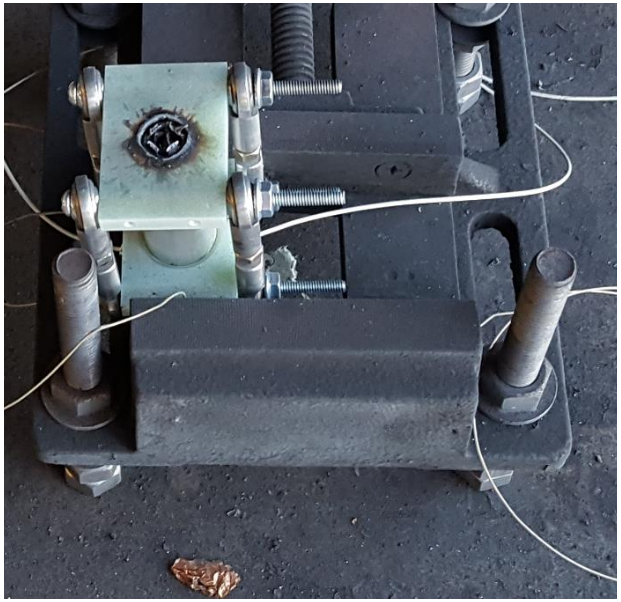
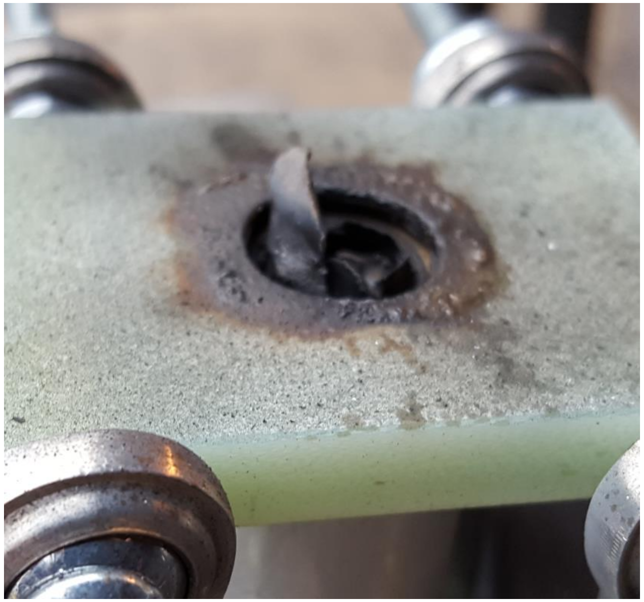
MJ1 Single Cell – Reinforced

- 3/3 "blast through" failure mode
  - Video and post-test evidence of insulator melting through vent holes





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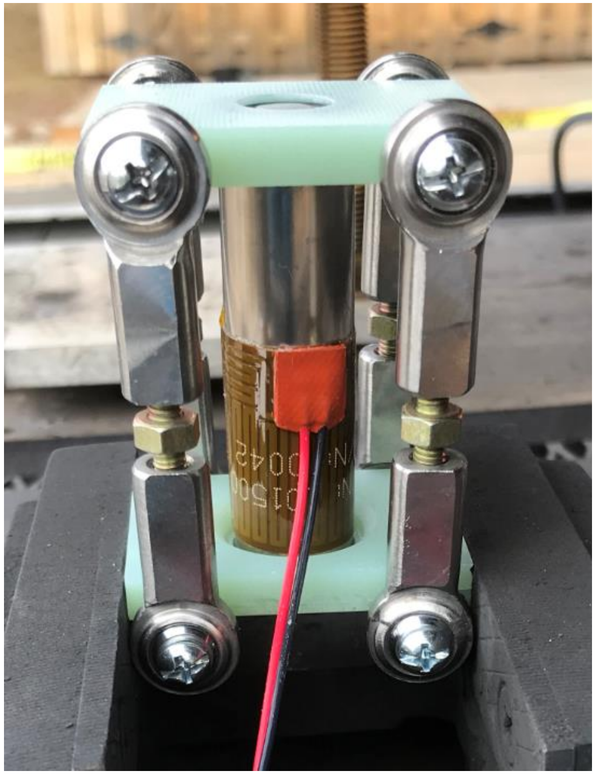
MJ1 Single Cell – Patch Heater

- Three unsupported, three in GRP



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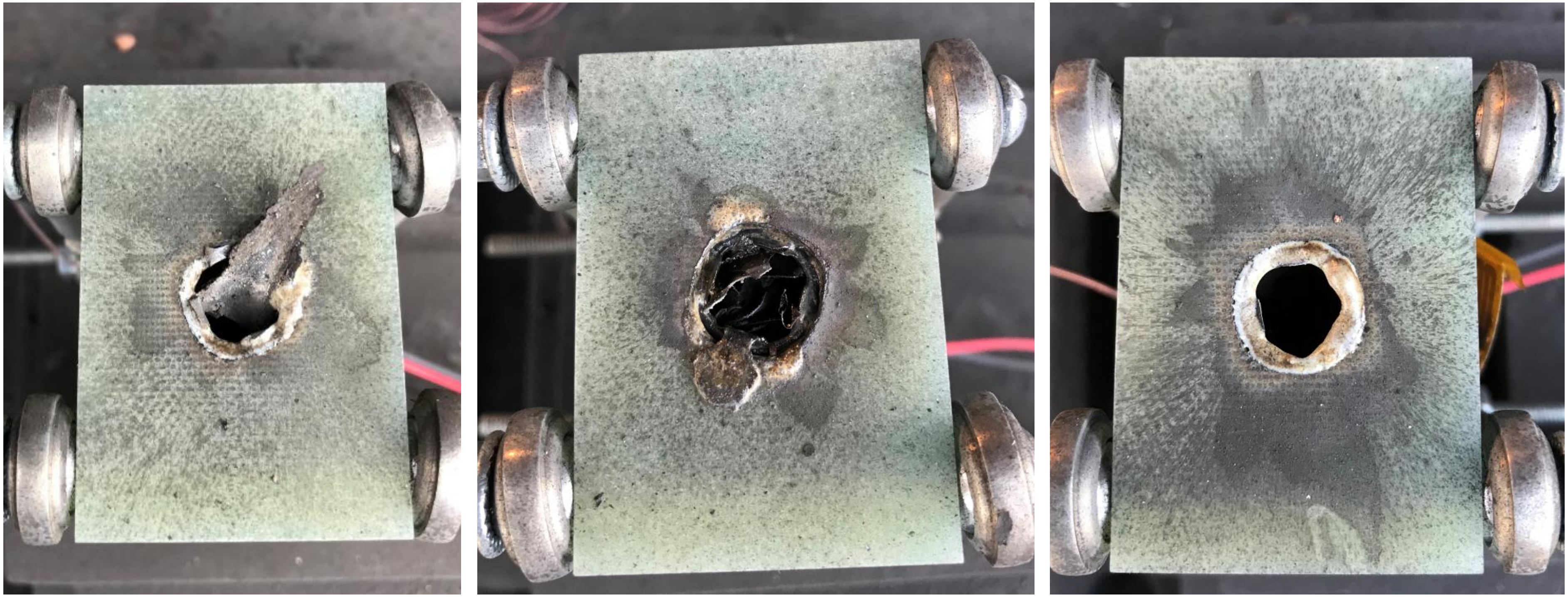
Patch Heater, Unsupported

- 1/3 “blast through” failure mode
- 2/3 “explode” failure mode

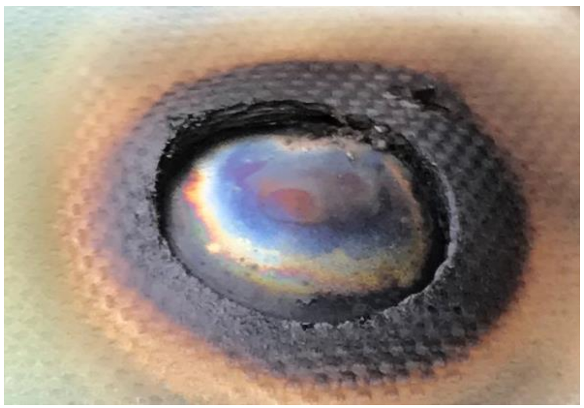
Patch Heater, Supported

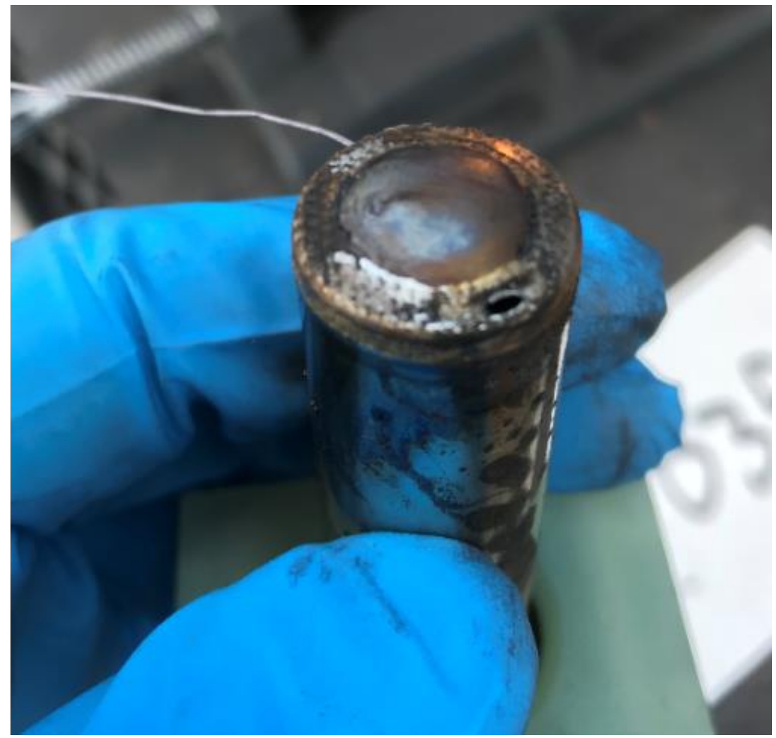
- 3/3 “blast through” (with insulator melting)…



Patch Heater, Supported

- … but 2/3 with anode hole





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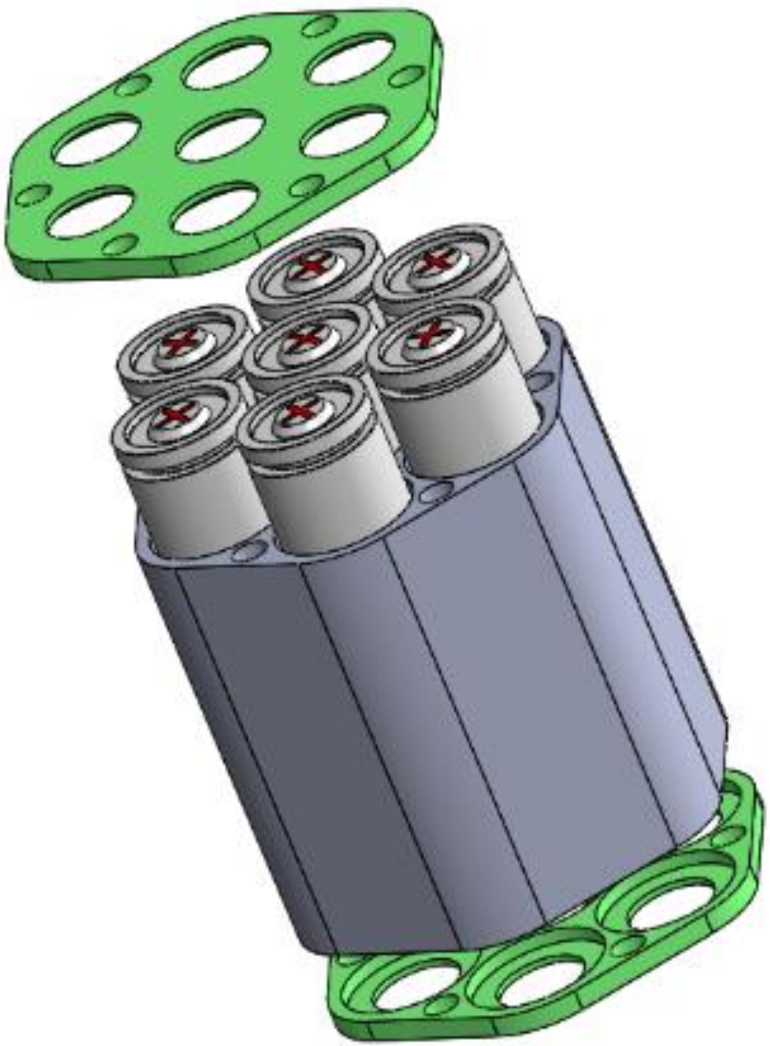
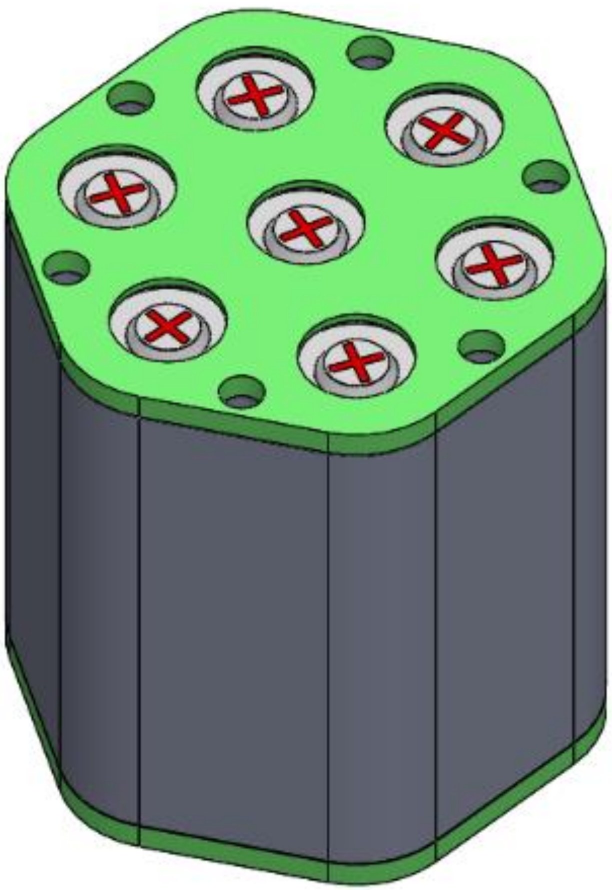
MJ1 7X Submodule



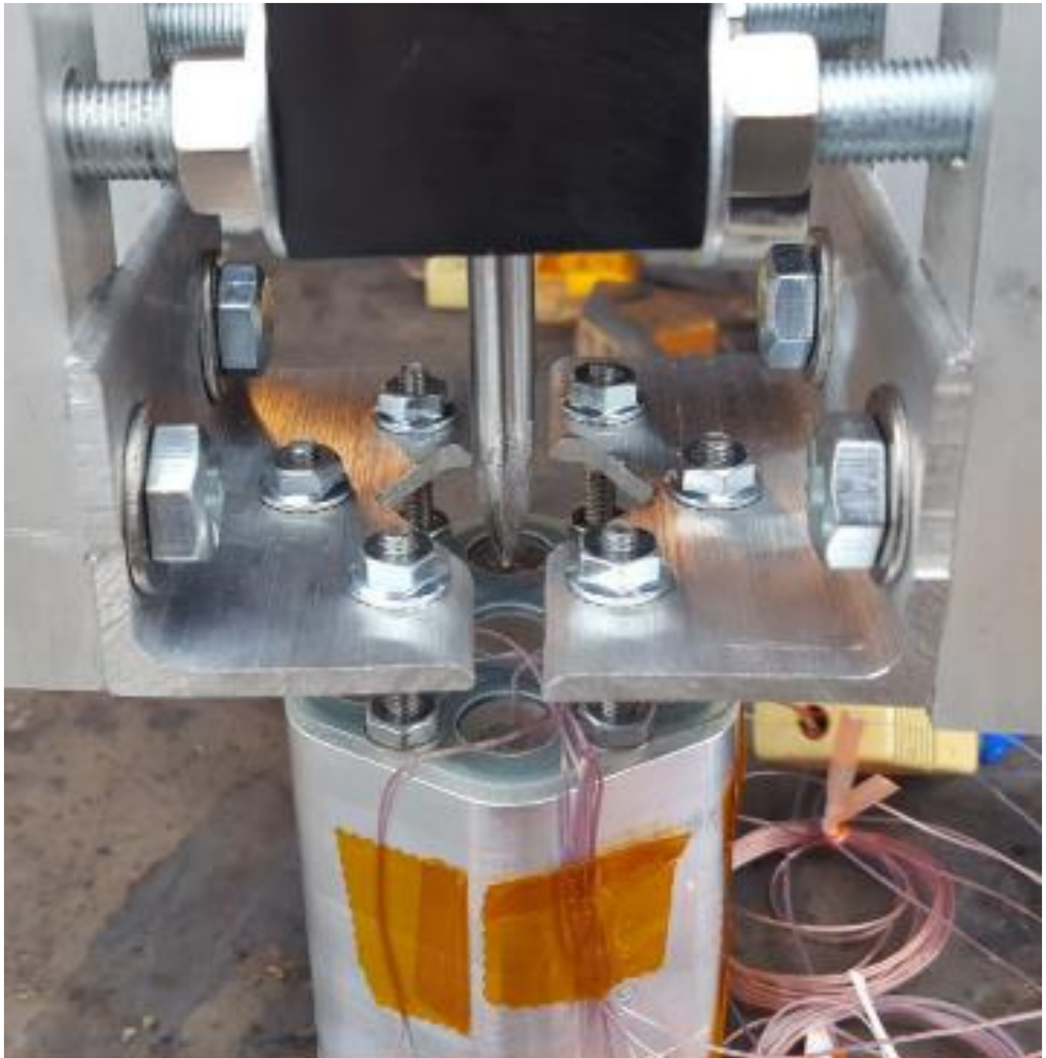


MJ1 7X Submodule – TR Initiation

- Tried anode heater, but found temperatures in neighbor cells would be biased to >100°C by the initiation of TR
  - Unacceptable – creates unrealistic risk of propagation

- Nail penetration gives advantages beyond avoiding neighbor cell temperature bias
  - More closely represents internal short failure mode
  - Avoids insulator melting by TR initiation temp and clogging vents

MJ1 7X Submodule – Test Setup



MJ1 7X Submodule – Typical Result

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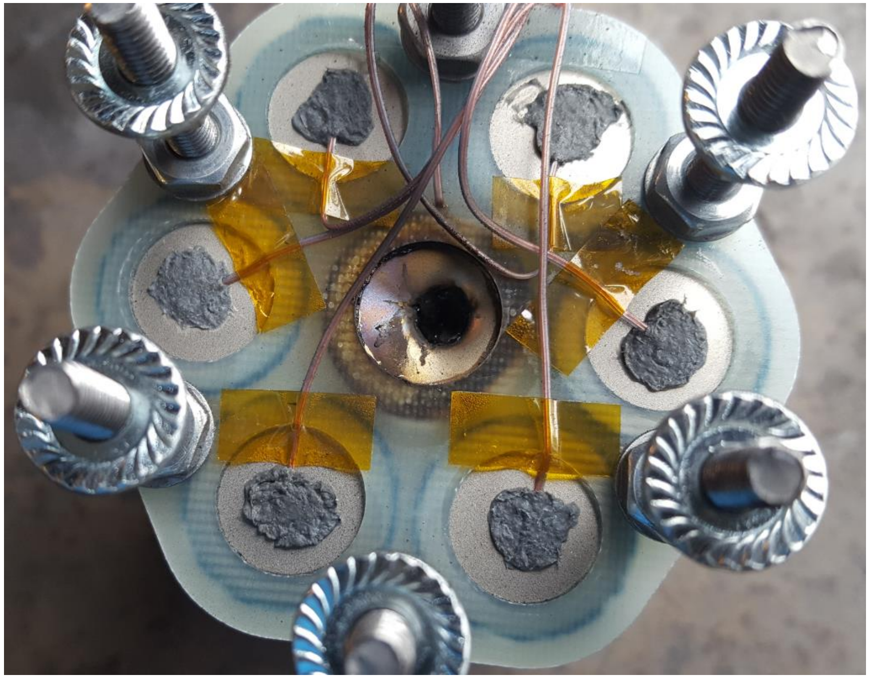
MJ1 7X Submodule

- Seven tests completed successfully
  - 7/7 “blast through” failure mode with ~4 seconds of sparks
  - No evidence of cell can failures, but submodules could not be disassembled due to epoxy bond



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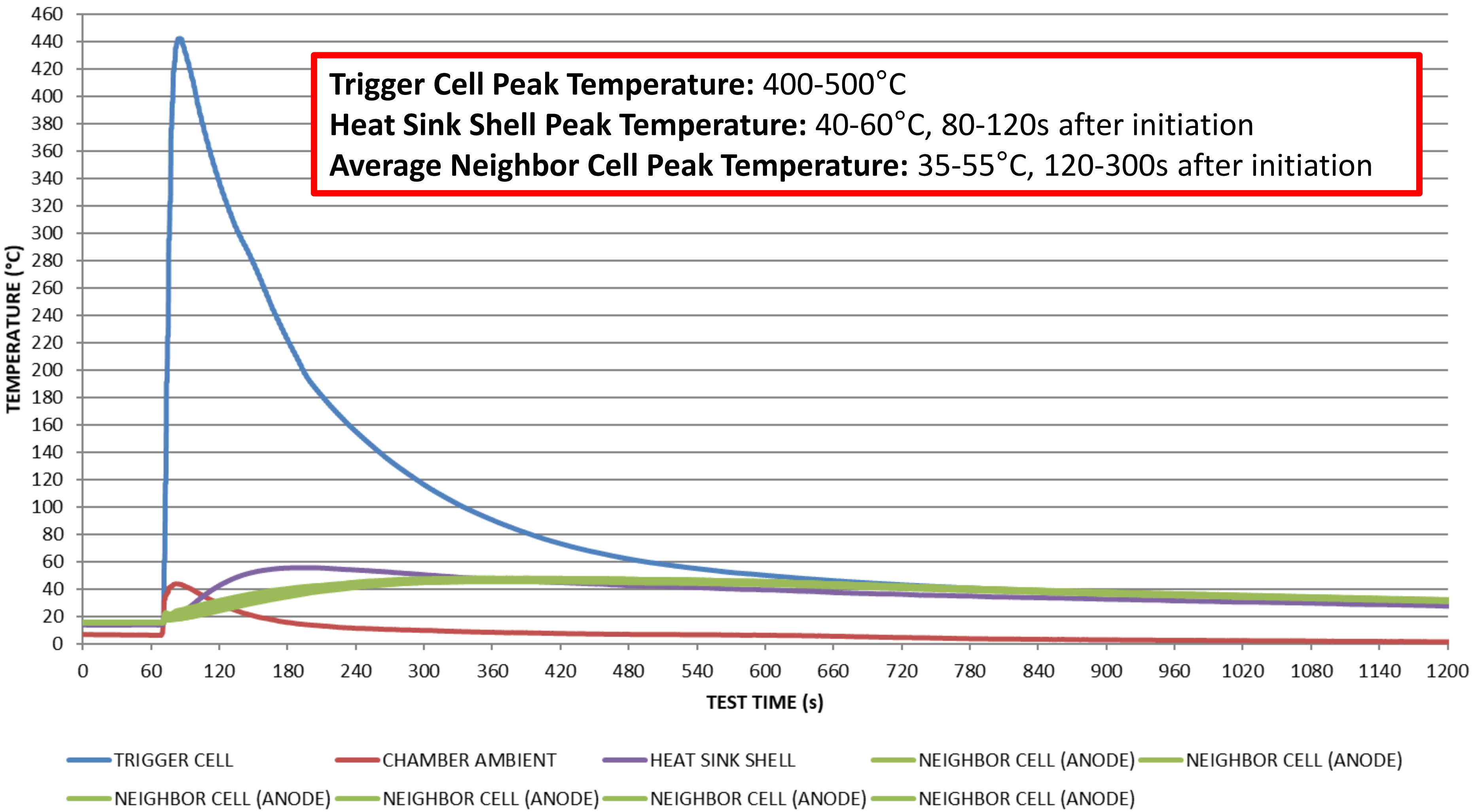
MJ1 7X Submodule – Typical Results



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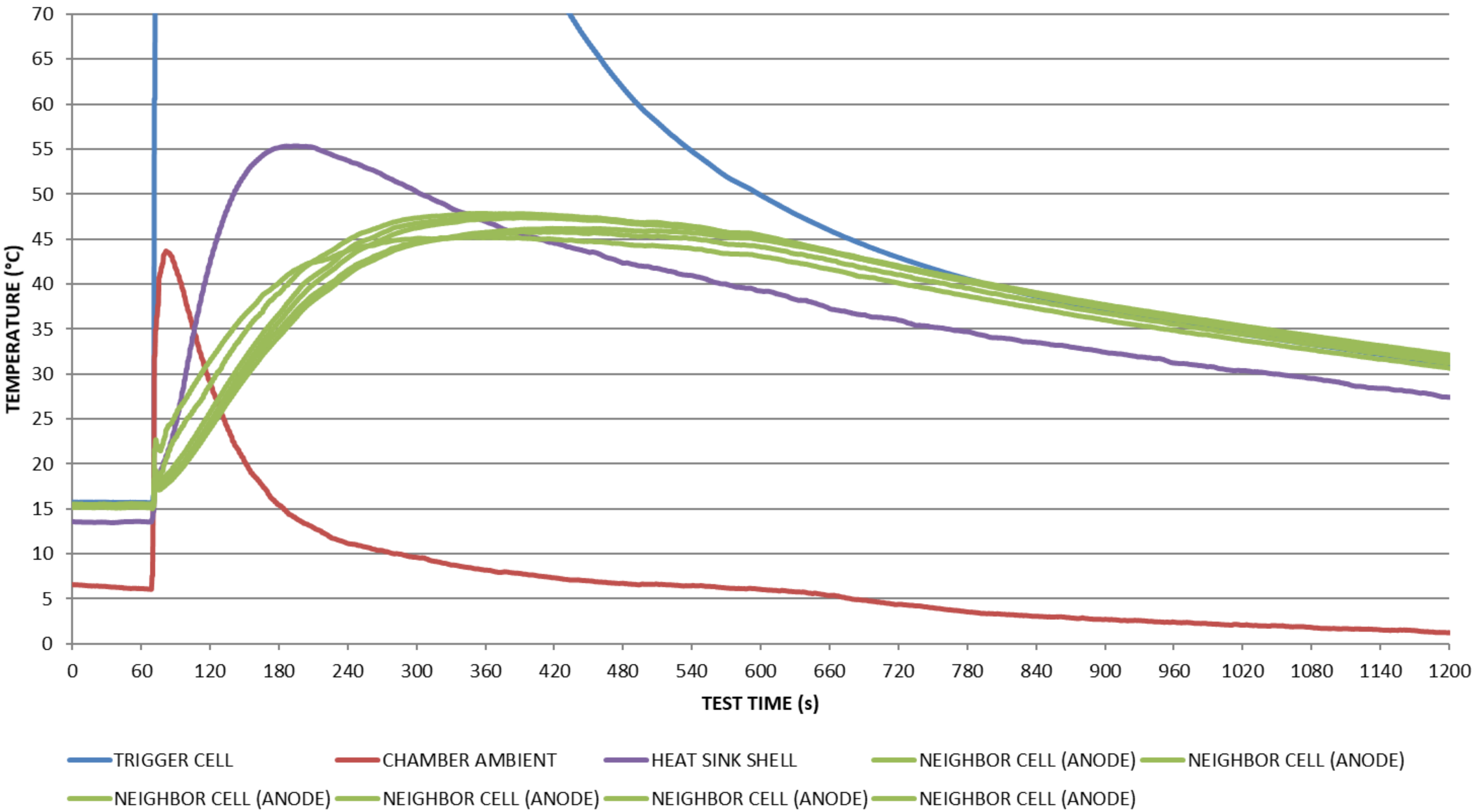
MJ1 7X Submodule – Typical Results



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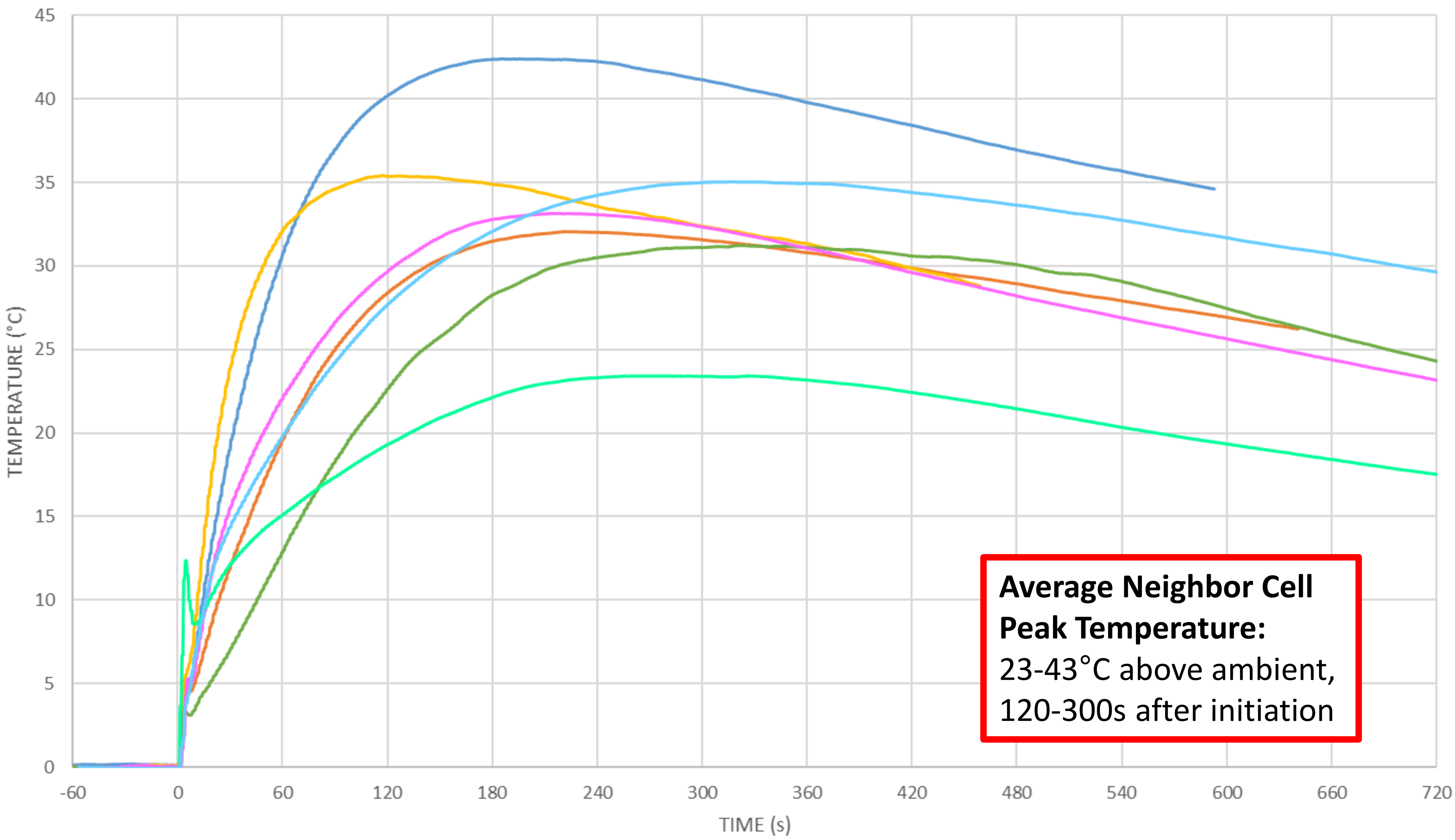
MJ1 7X Submodule – All Tests, Normalized

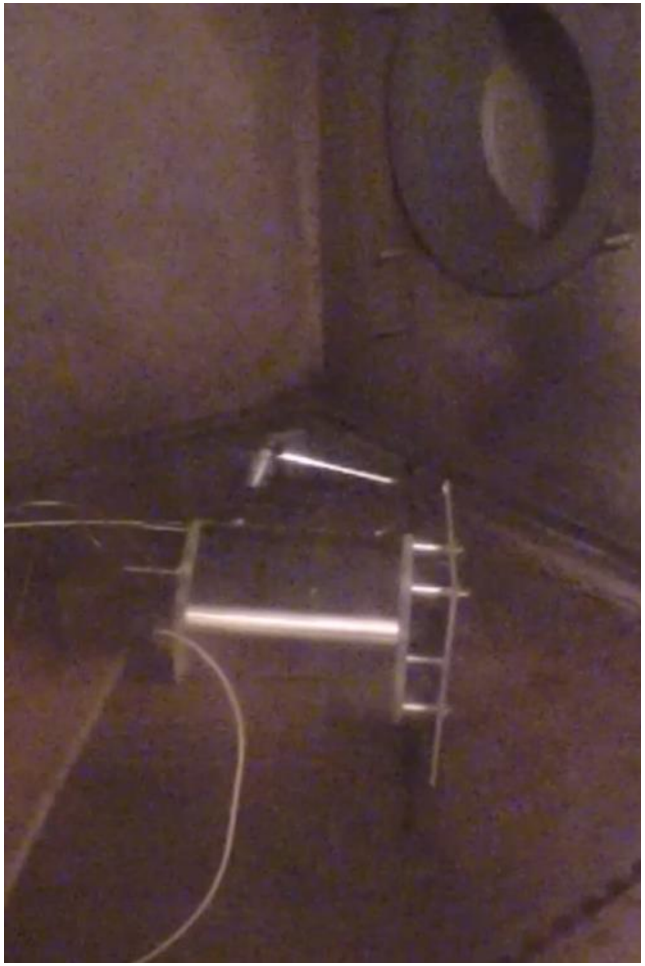


M36 Trigger Cell Validation

- 7X test hardware was used to perform validation run of M36 ISC trigger cell – goals:
  - Verify anode heater triggers ISC appropriately
  - Minimal neighbor cell bias due to anode heater
  - M36 ISC temperature response and failure mode consistent with MJ1 nail penetration

- Also added flight-like blast plate

7X Submodule – M36 Trigger Cell



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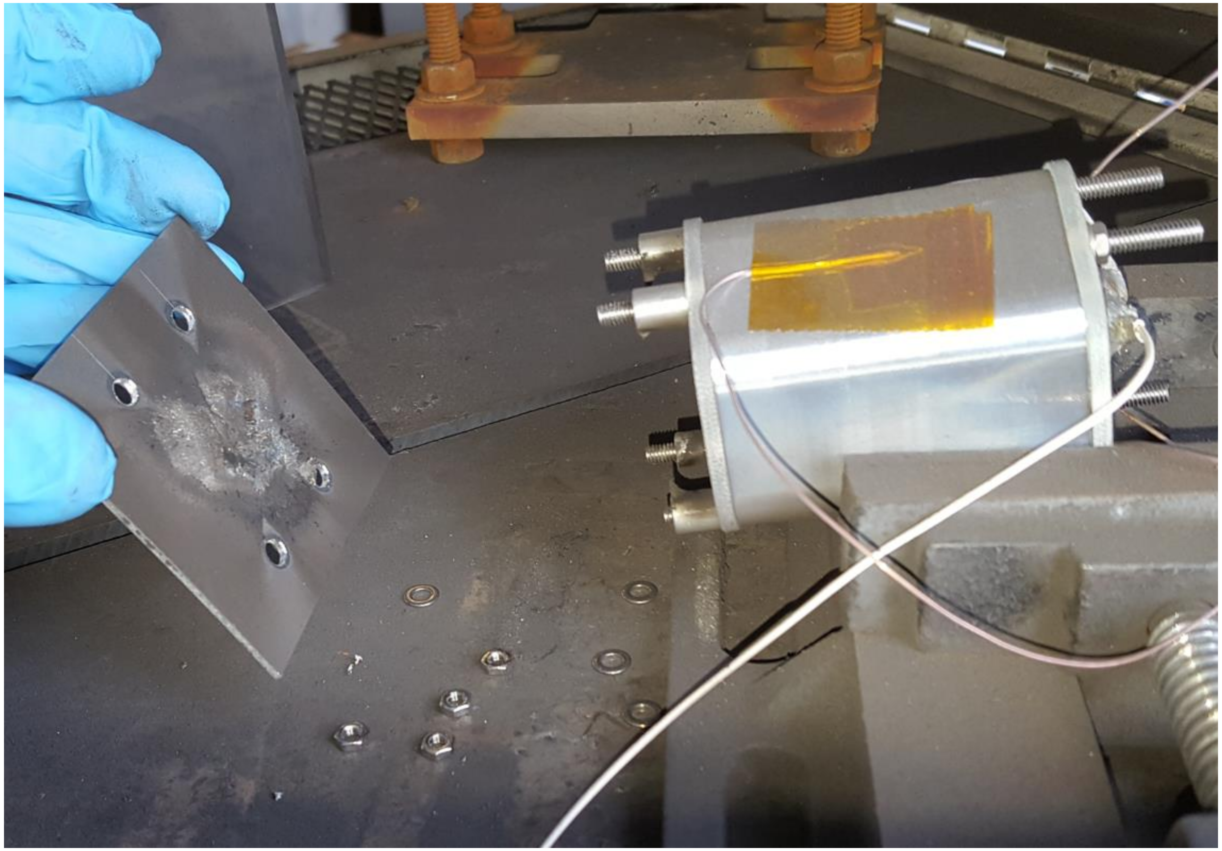
7X Submodule – M36 Trigger Cell

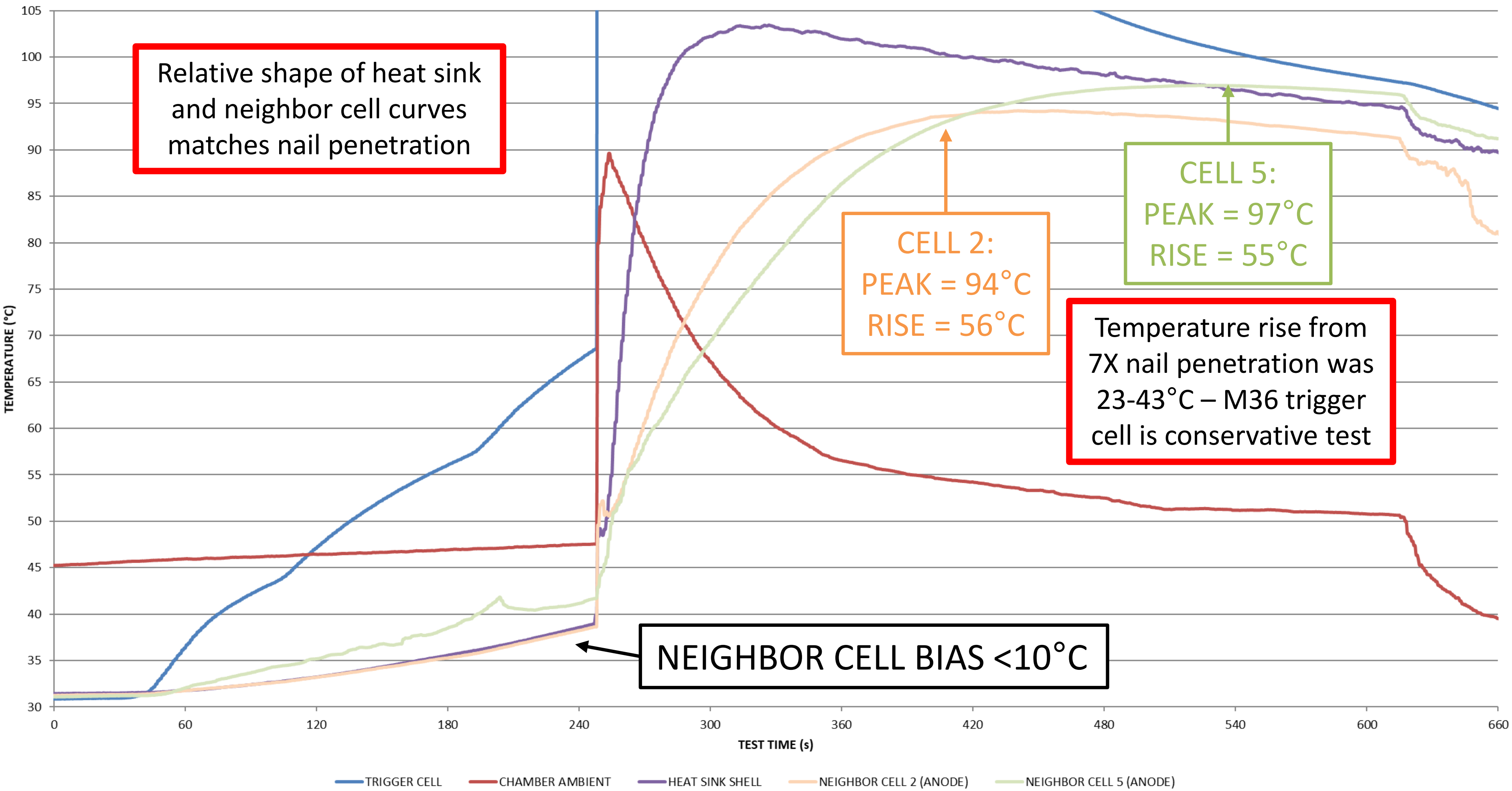
- Confirmed "blast through" failure mode (like MJ1)
  - Ejecta deposited on blast plate, GRP



7X Submodule – M36 Trigger Cell

- Blast plate deformed, but contained TR

7X Submodule – M36 Trigger Cell



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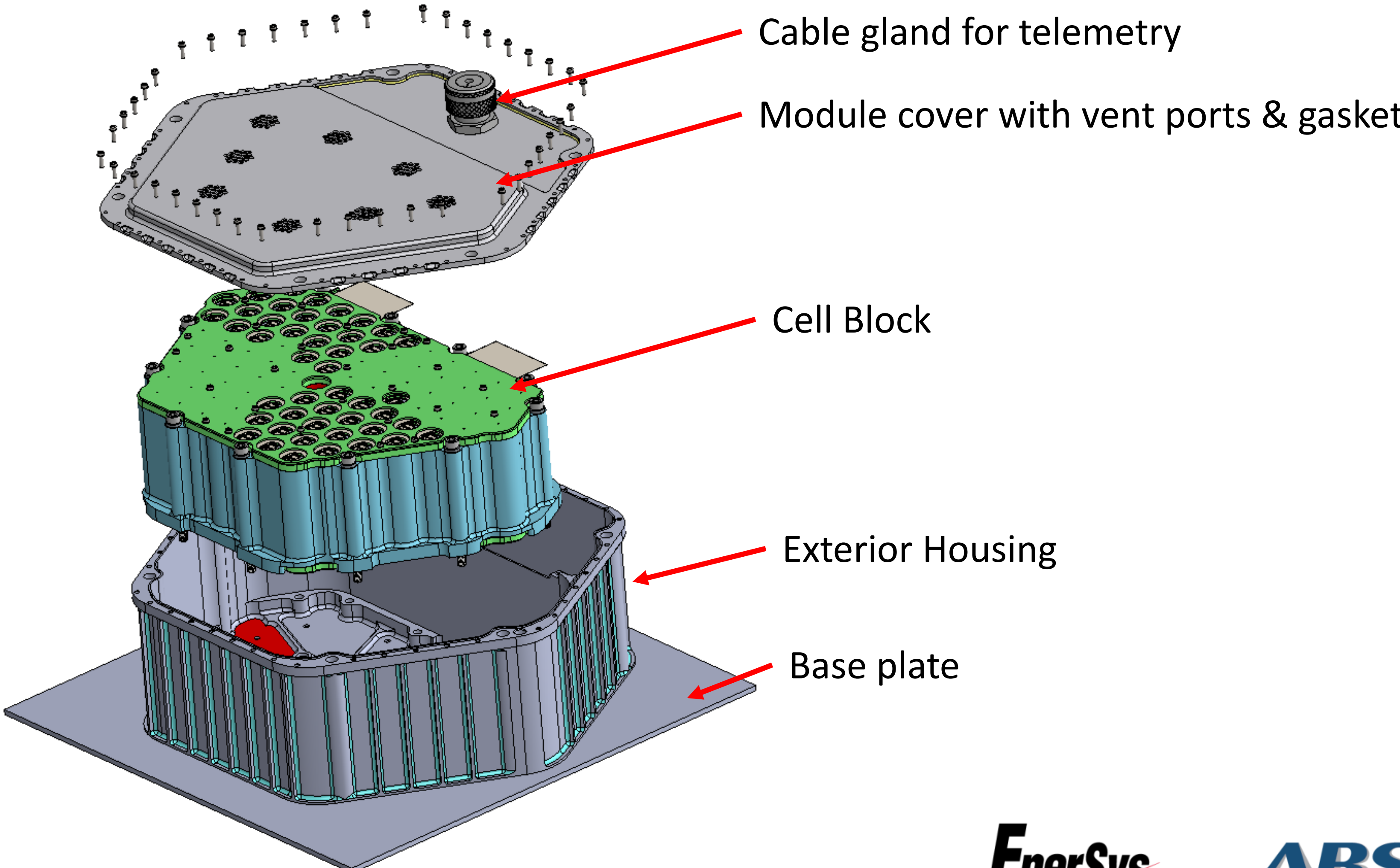
MJ1 23p2s Submodule

- Flight battery design is two 23p4s cell blocks
  - Interstitial and capture plates utilize design input from 7X experiments – minimize mass penalty
- Three submodule tests with 2/4 virtual cells populated and interconnected
  - Anode heater designed to avoid interference with fusible link element

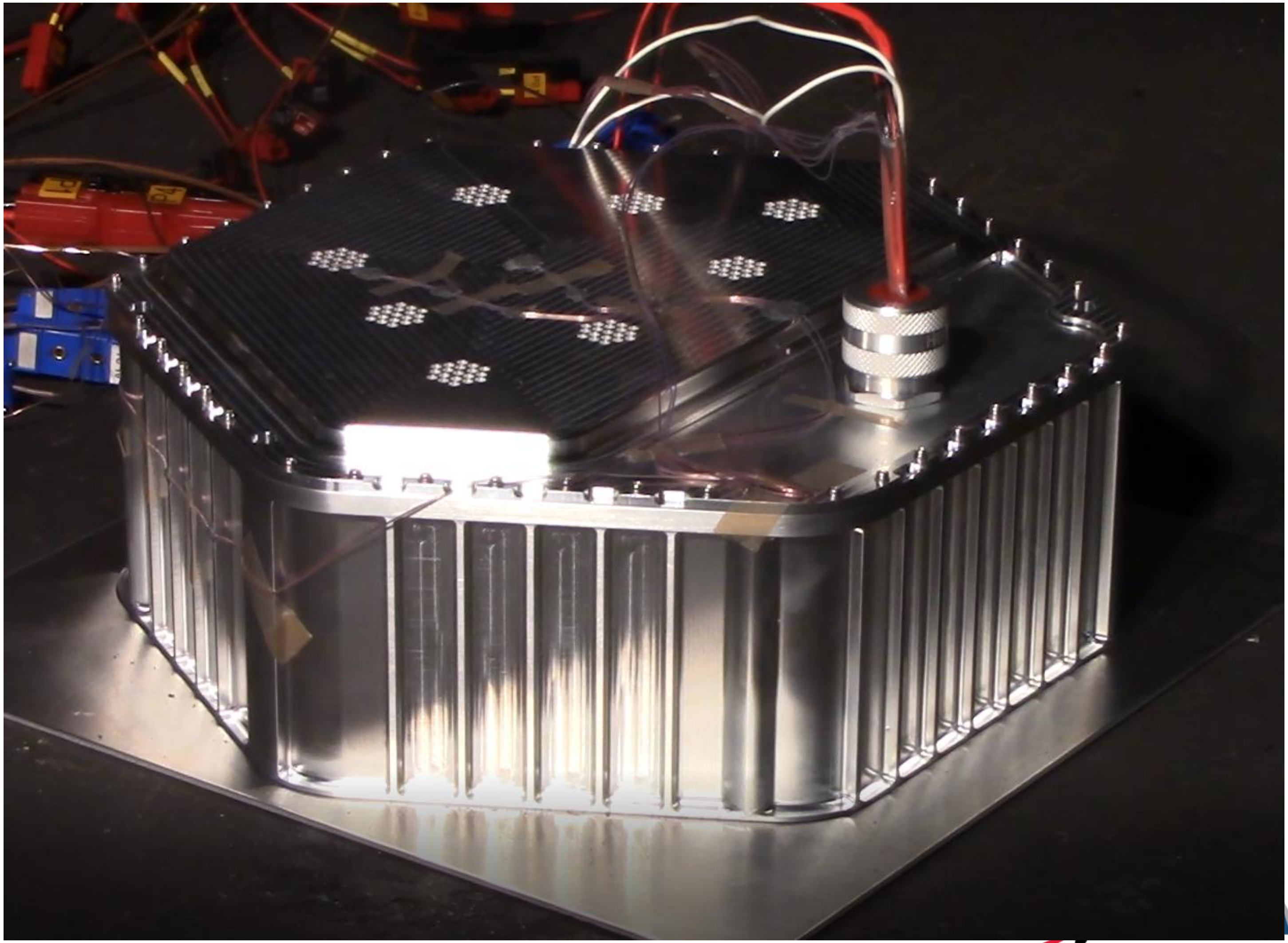
MJ1 23p2s Submodule



MJ1 23p2s Submodule Configurations

Test Name	Cell Configuration	Trigger Cell Location	Trigger Cell VC	Cathode (Vent) Direction
SM #1	23p2s	Edge	1	Up
SM #2	23p2s	Center	1	Up
SM #3	23p2s	Center Edge	1	Down

MJ1 23p2s Submodule – Typical Result



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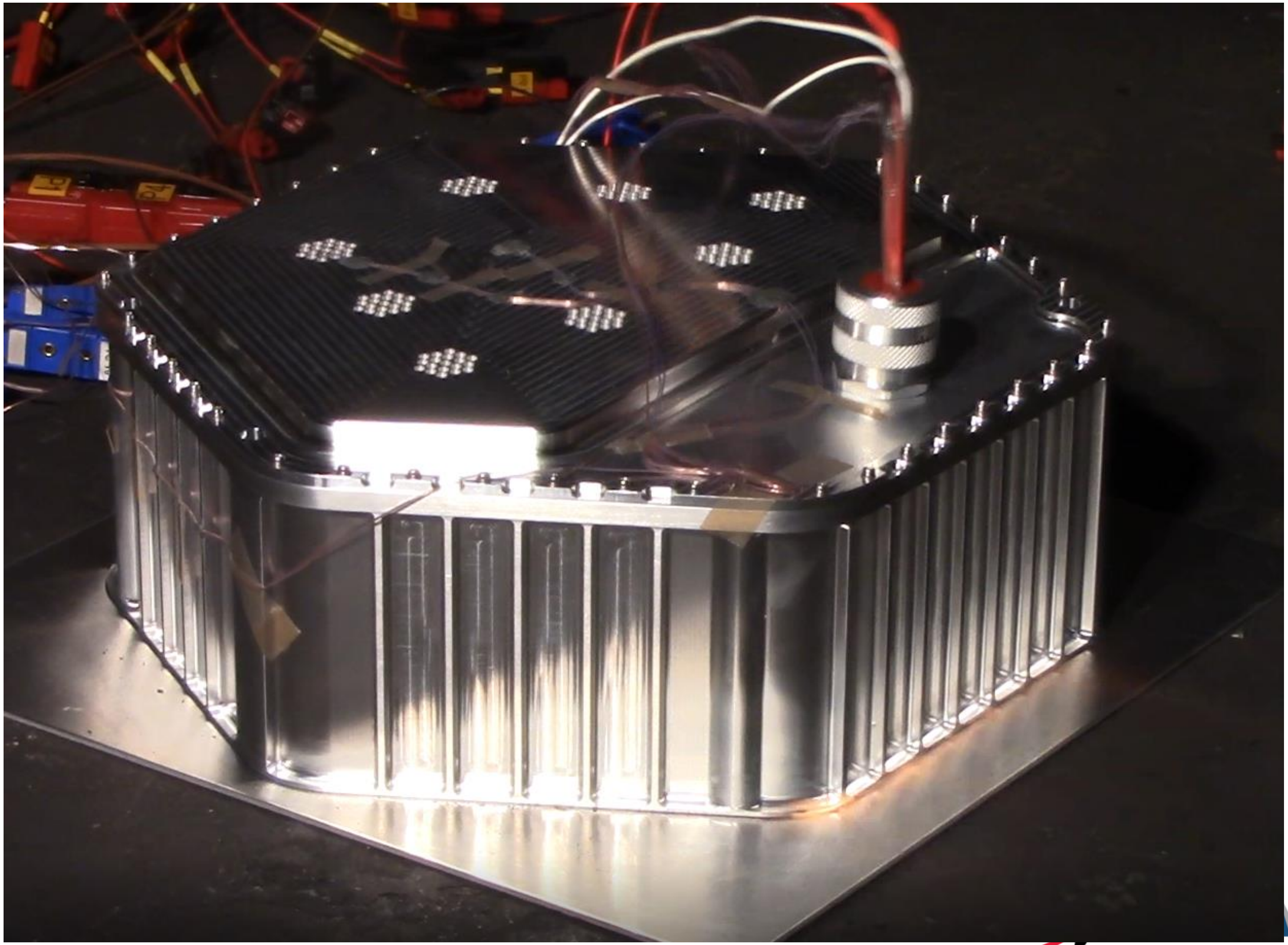
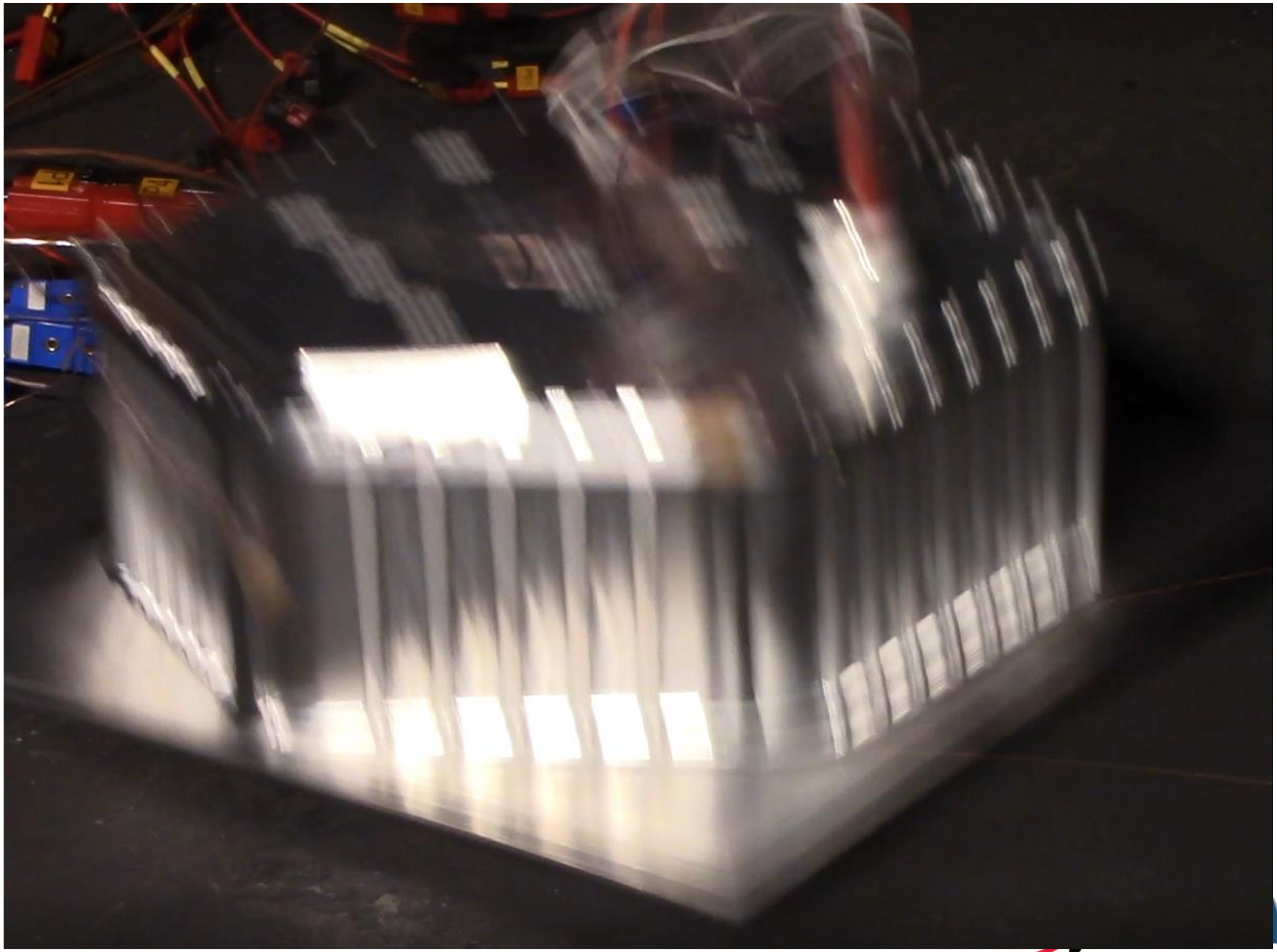
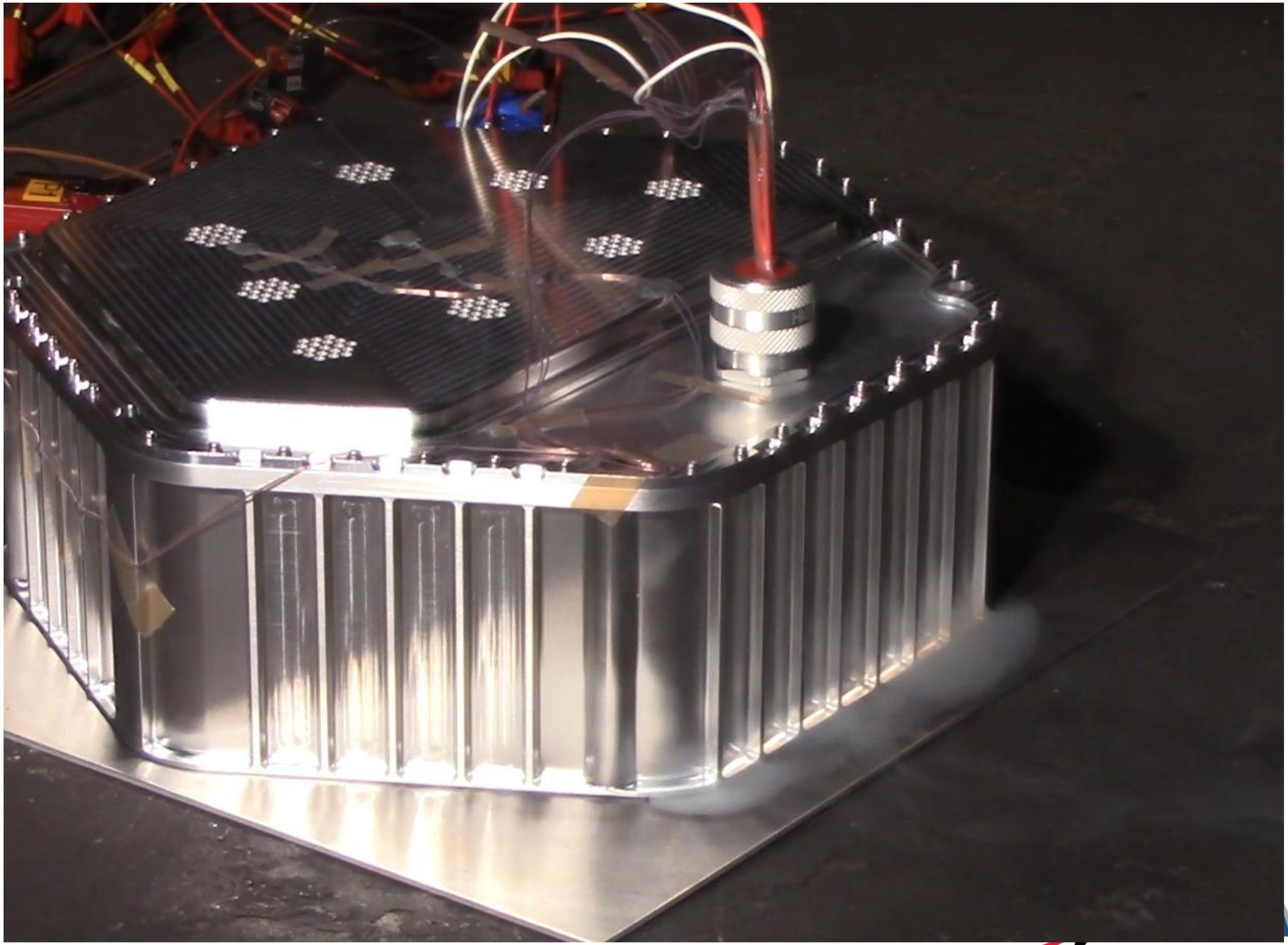
MJ1 23p2s Submodule – Typical Result



MJ1 23p2s Submodule – Typical Result



MJ1 23p2s Submodule – Typical Result



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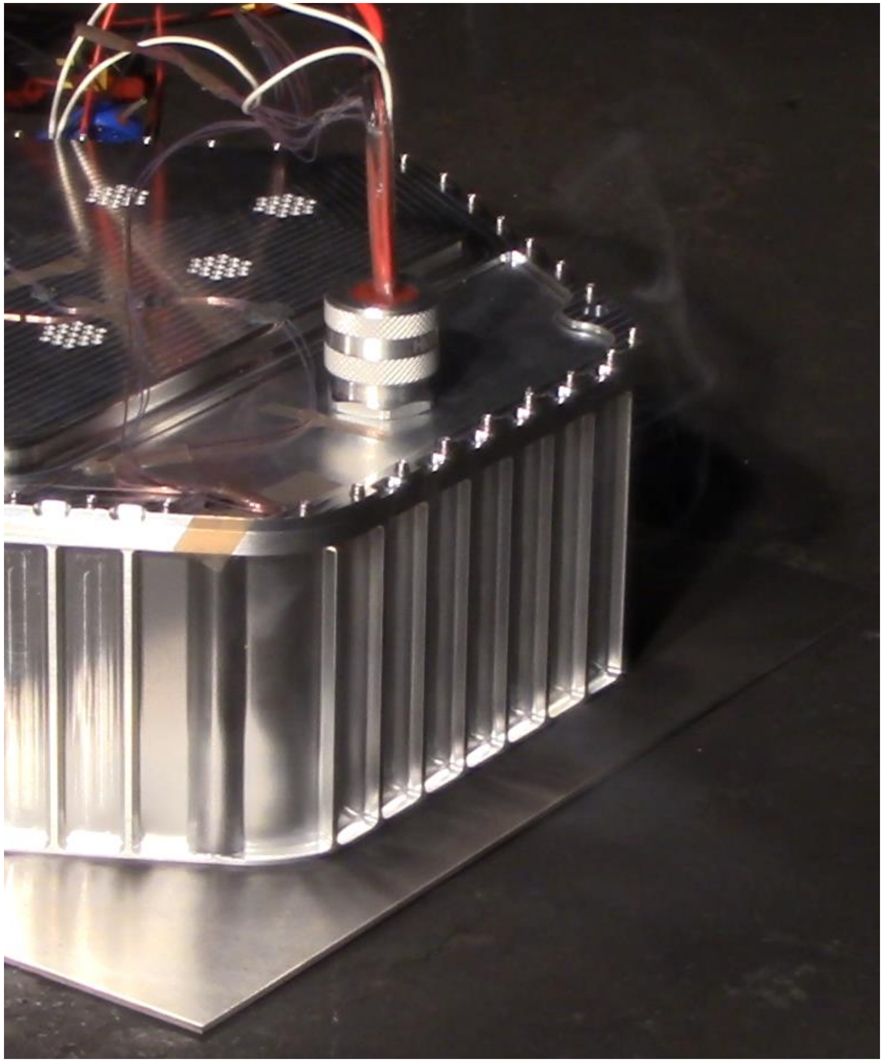
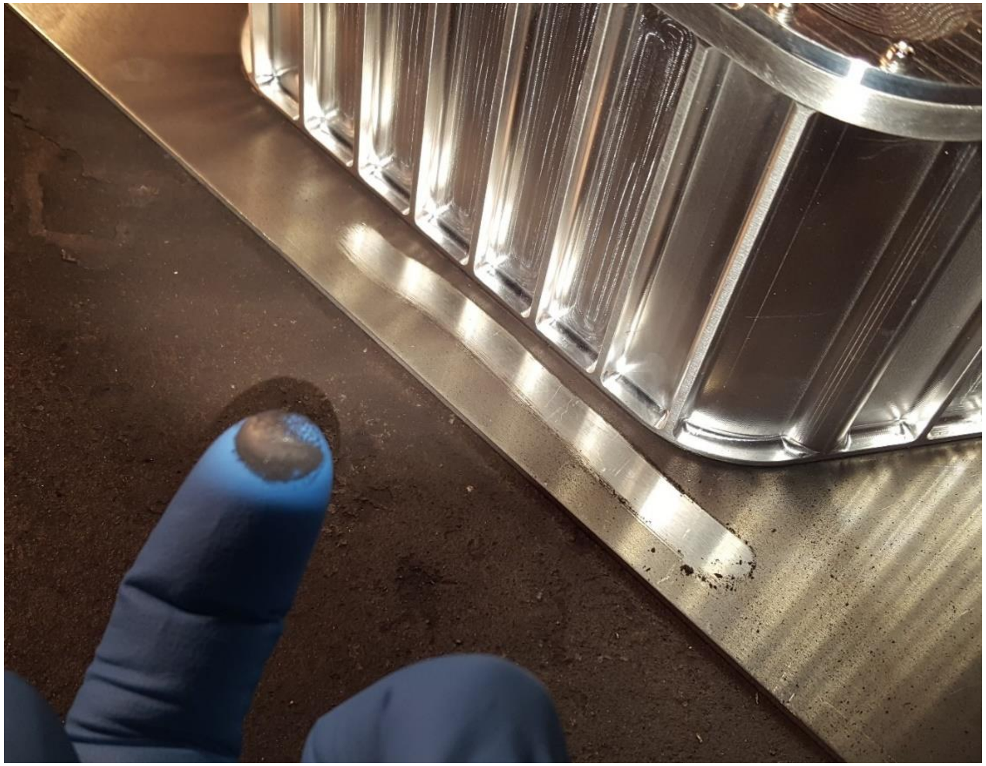
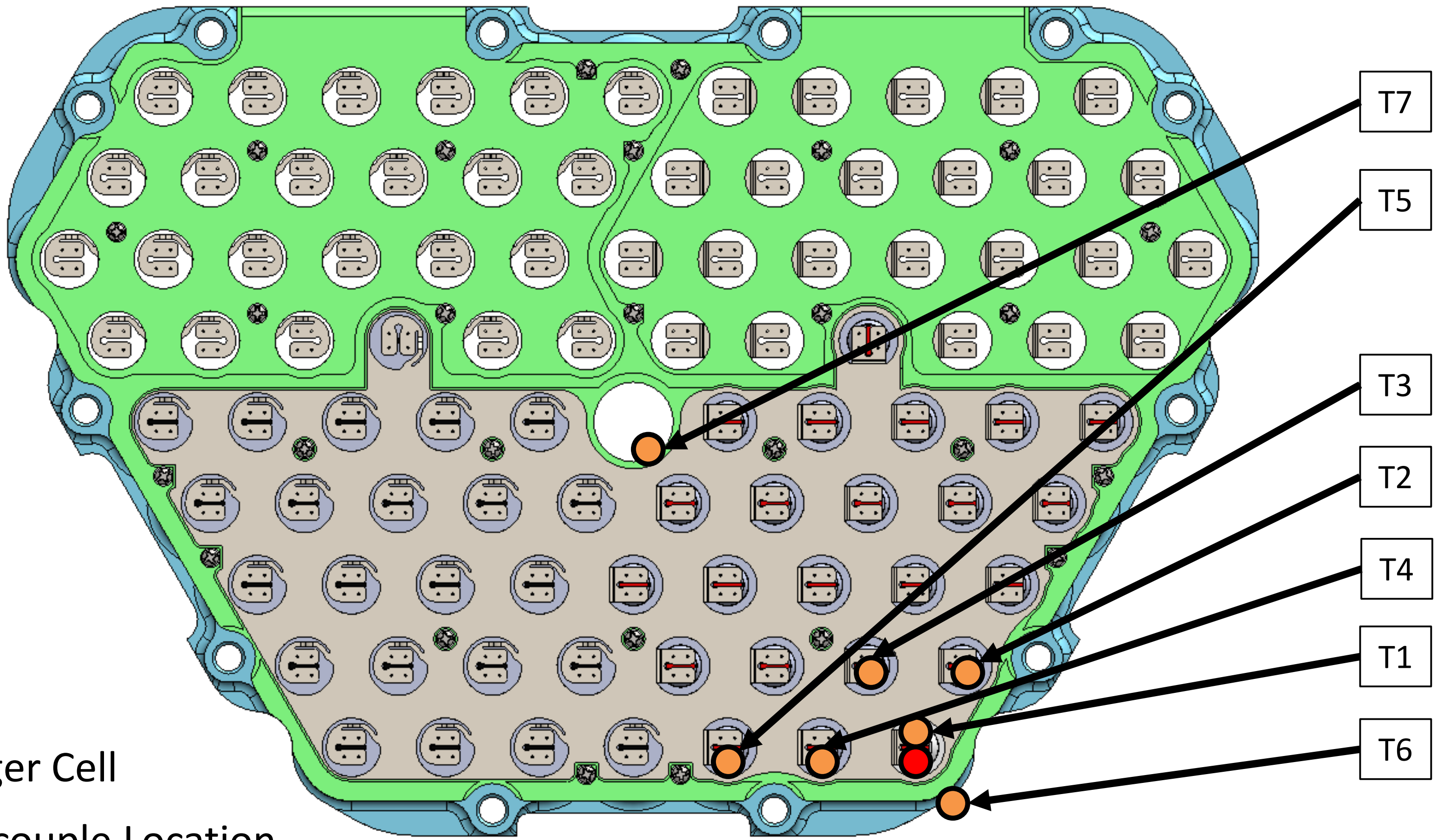
MJ1 23p2s Submodule – Typical Result





MJ1 23p2s Submodule #1



● ISC Trigger Cell

● Thermocouple Location (anode if on cell)

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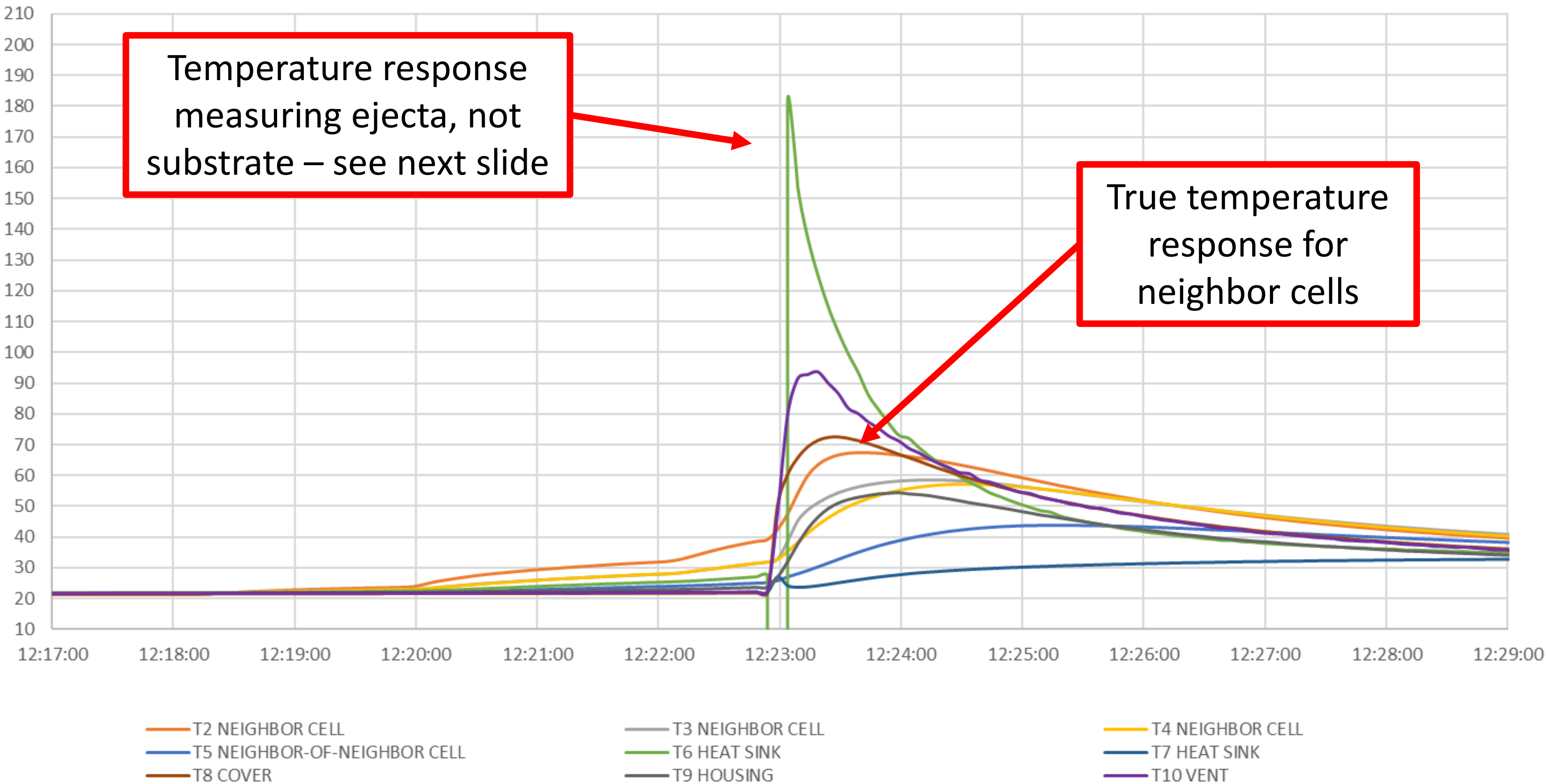
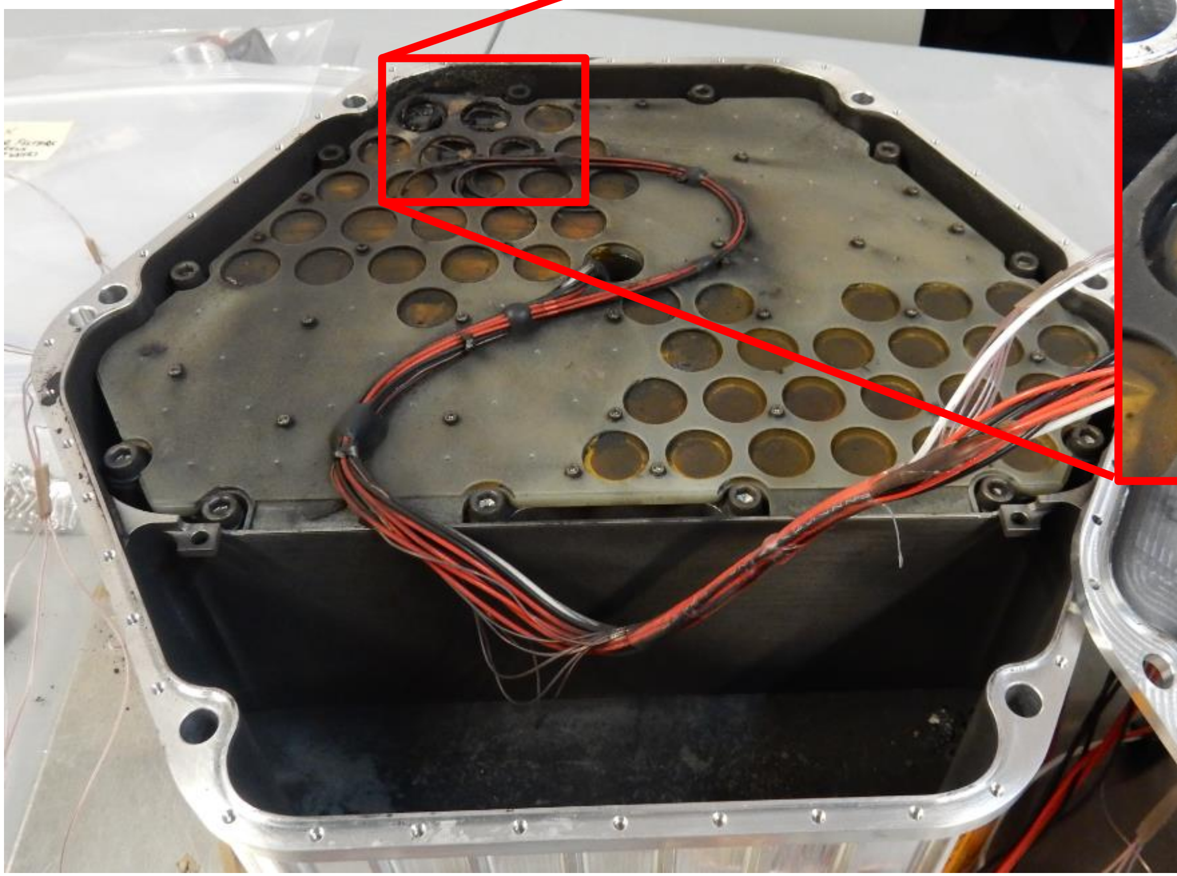
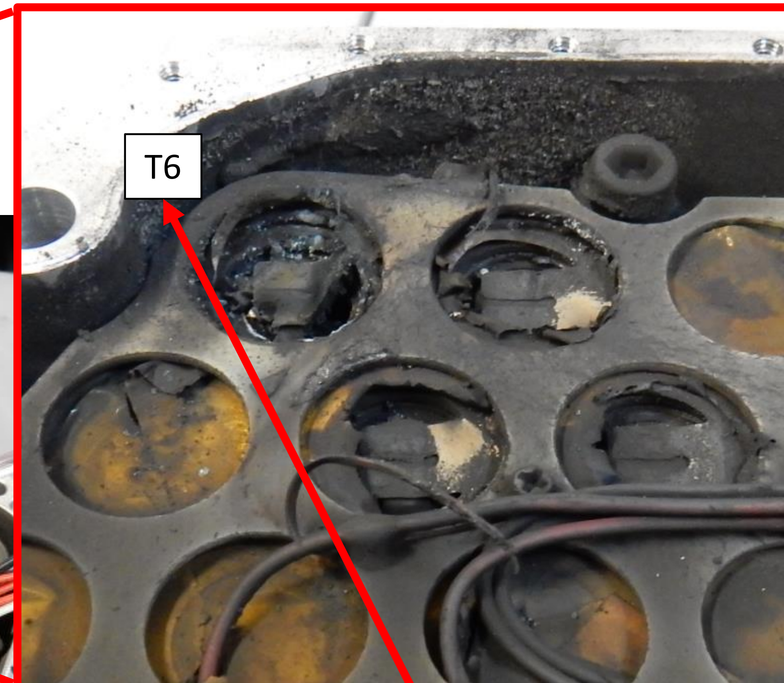
MJ1 23p2s Submodule #1



MJ1 23p2s Submodule #1





T6 between interstitial and housing wall – exposed to ejecta deflected back from cover

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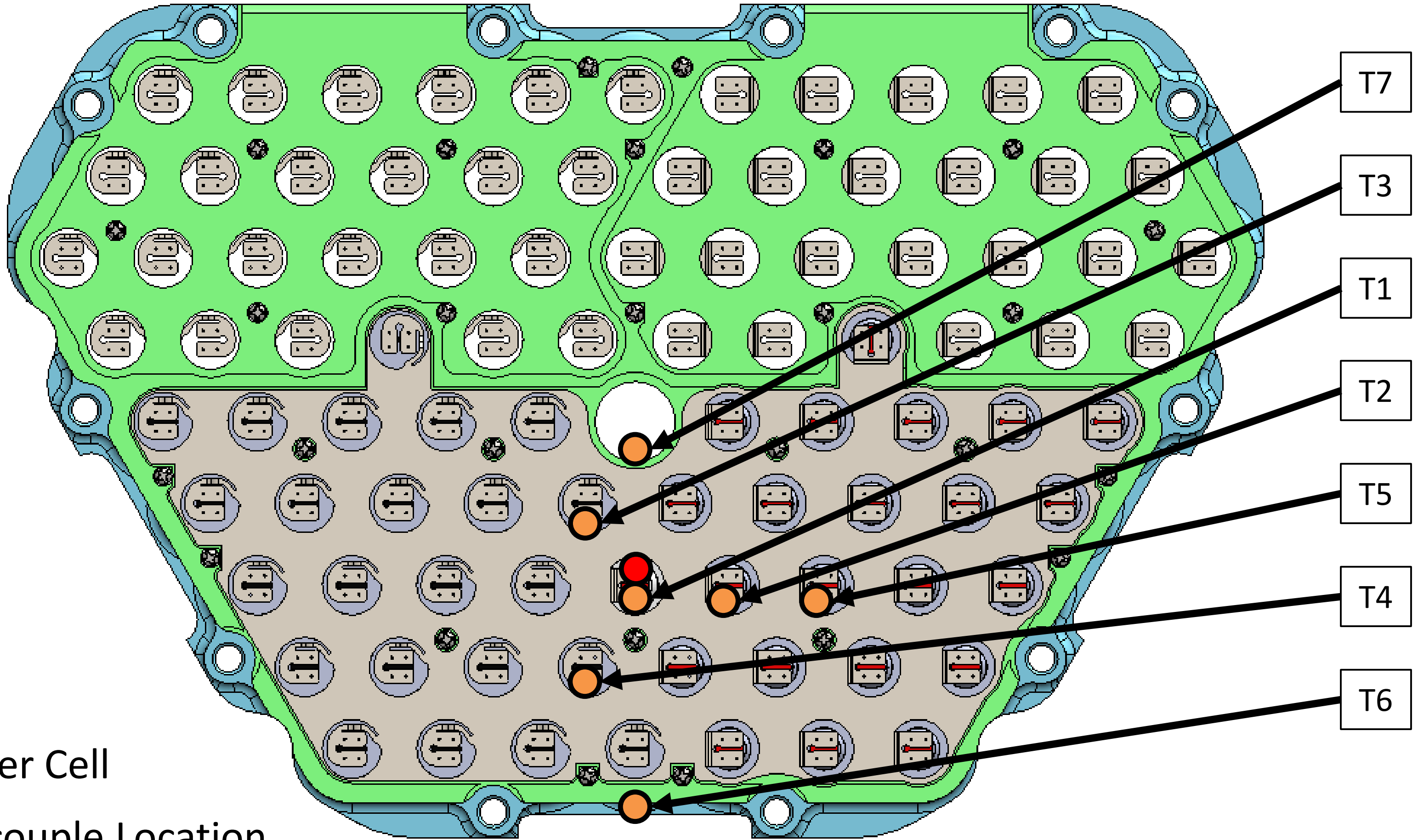
MJ1 23p2s Submodule #2



ISC Trigger Cell

Thermocouple Location (anode if on cell)

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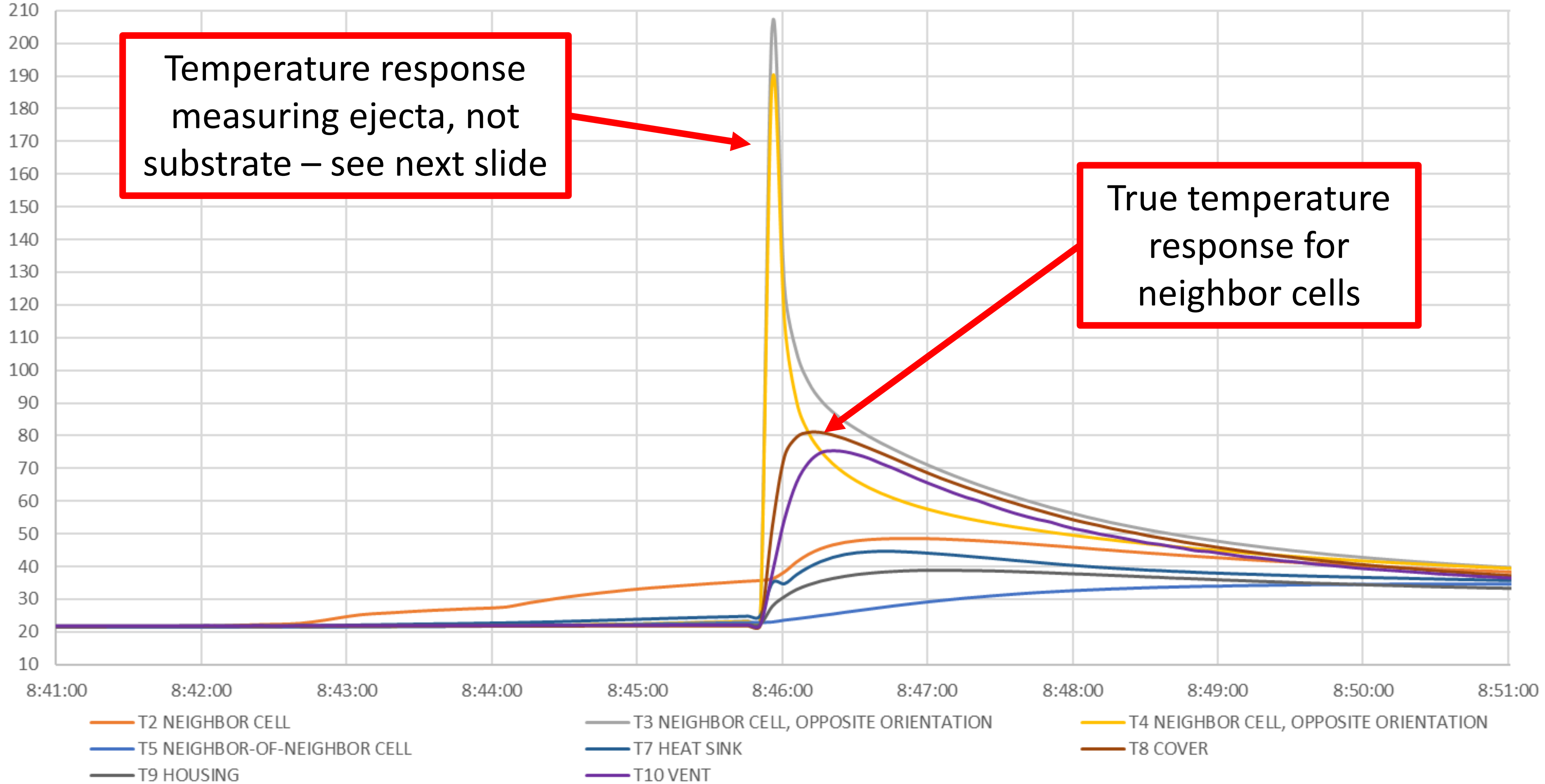
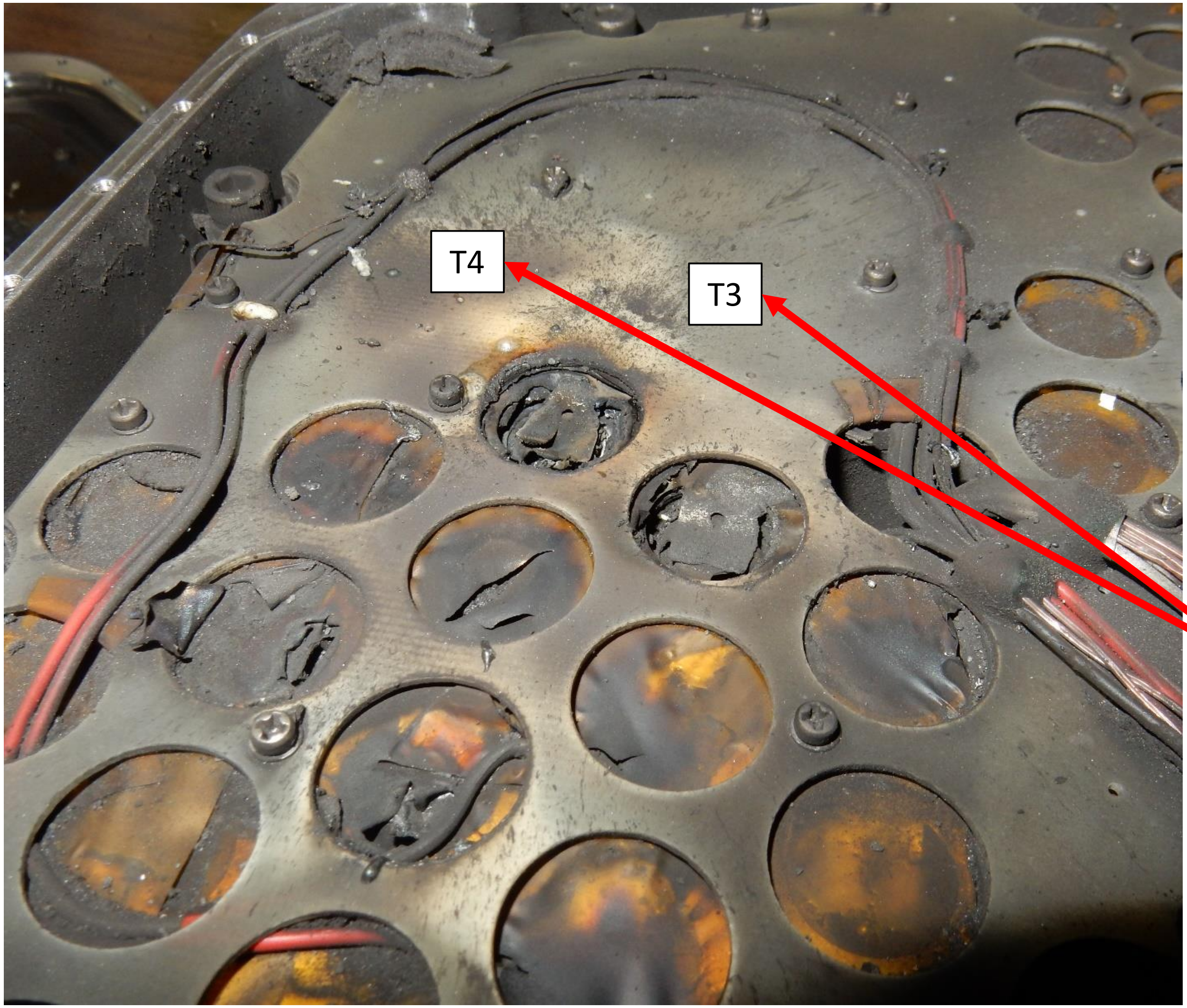
MJ1 23p2s Submodule #2

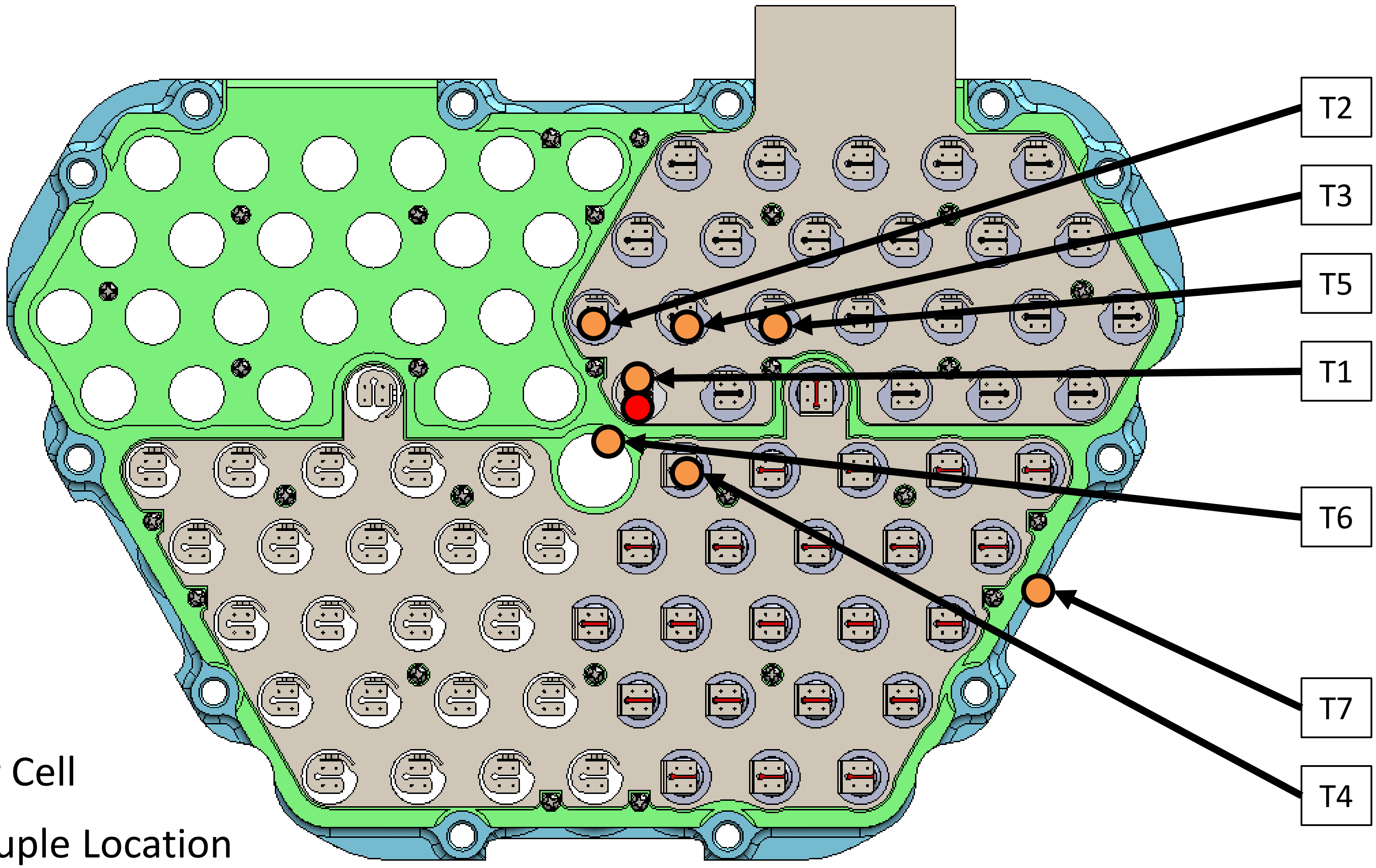


MJ1 23p2s Submodule #2



Neighbors T3 and T4 measured on anodes directly underneath GRP plate – note deflected ejecta deposits and heat discoloration on this surface

MJ1 23p2s Submodule #3



ISC Trigger Cell

Thermocouple Location
(anode if on cell)

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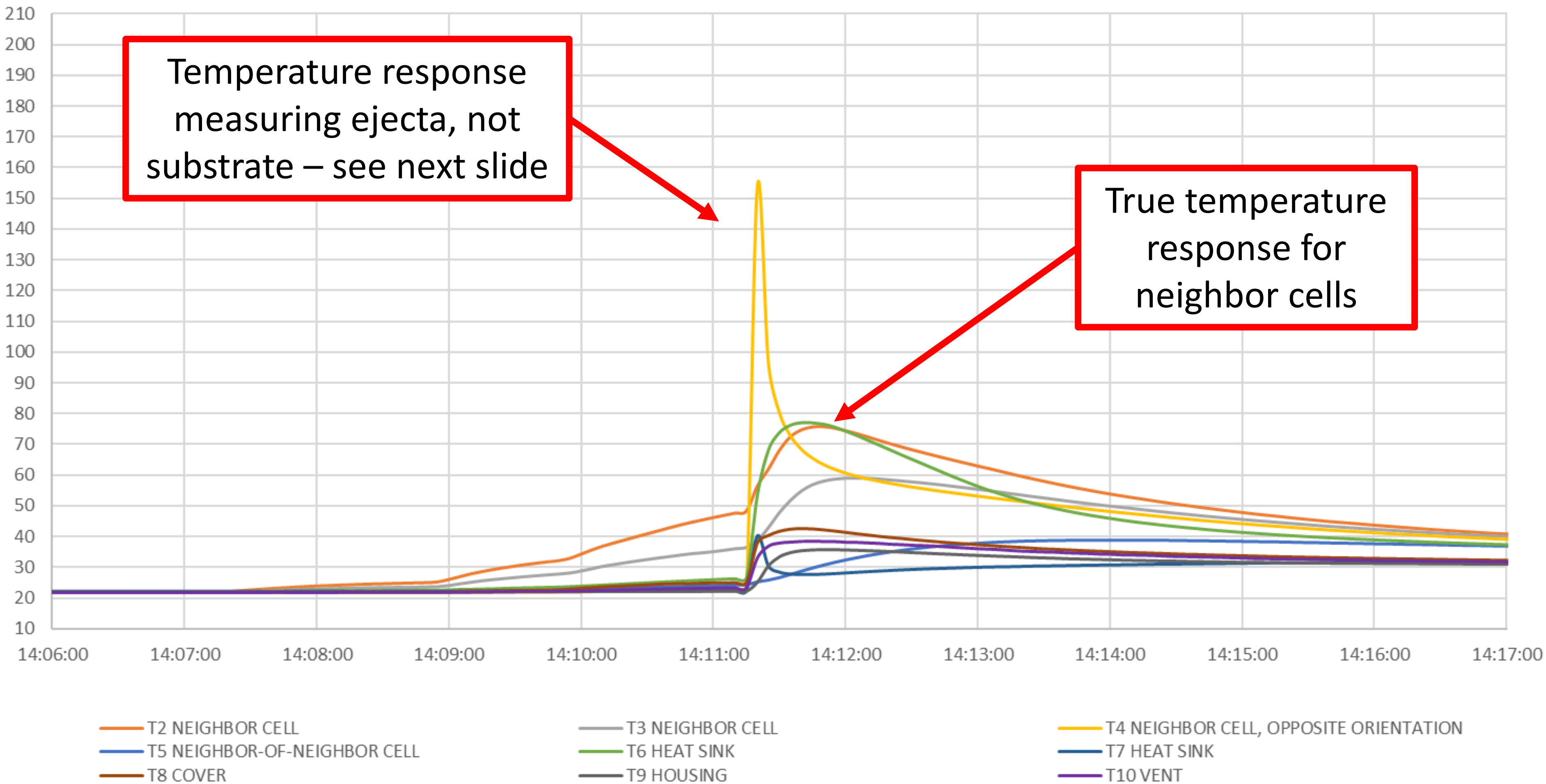
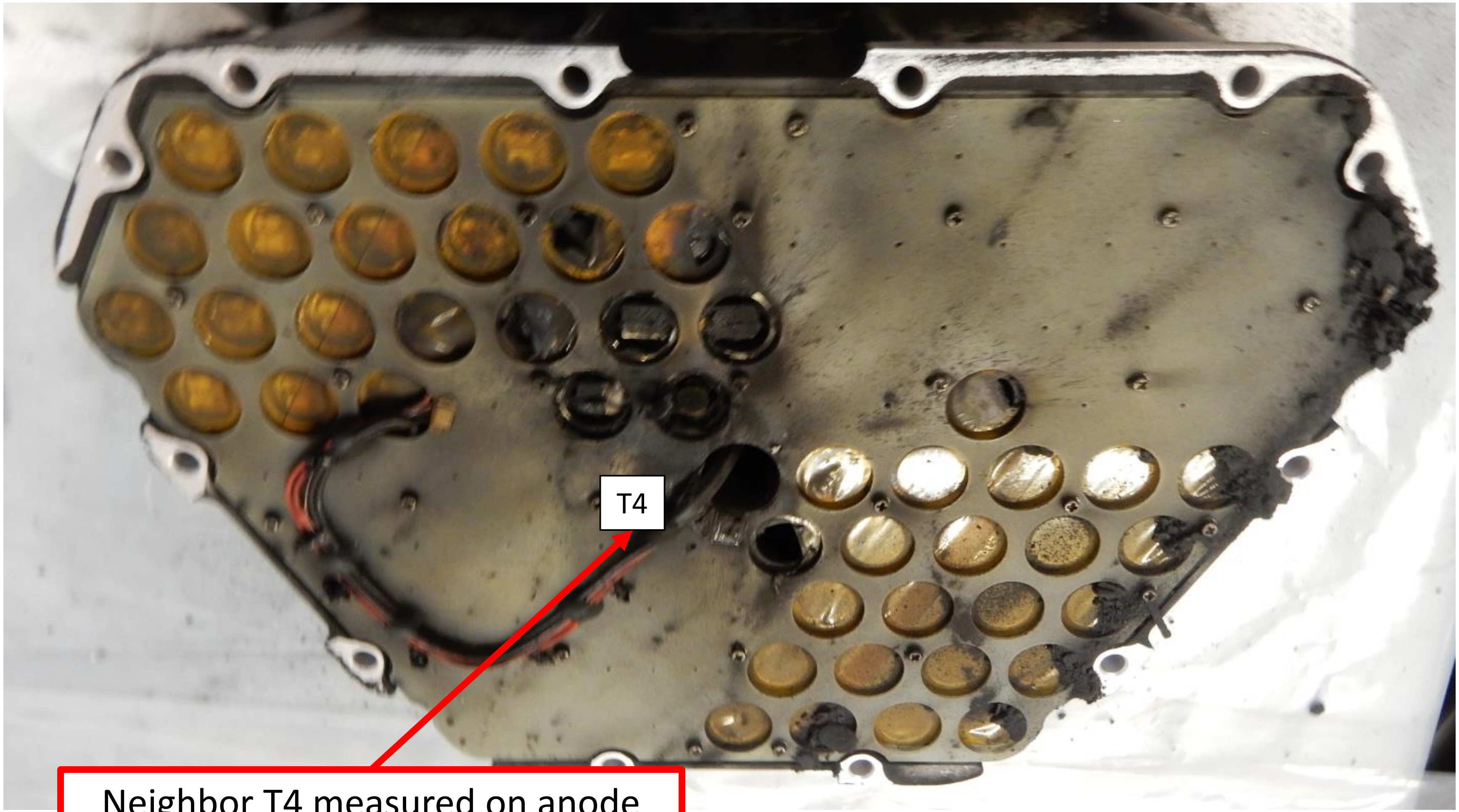
MJ1 23p2s Submodule #3

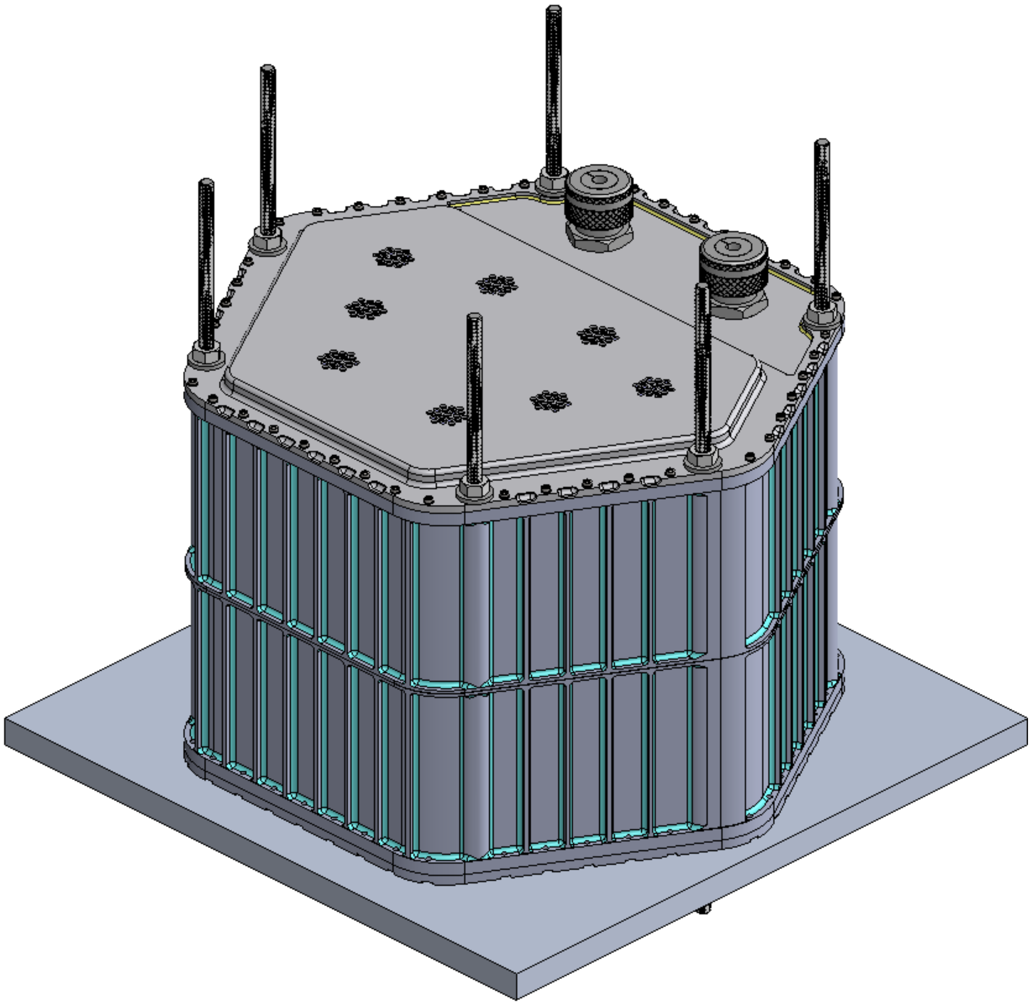


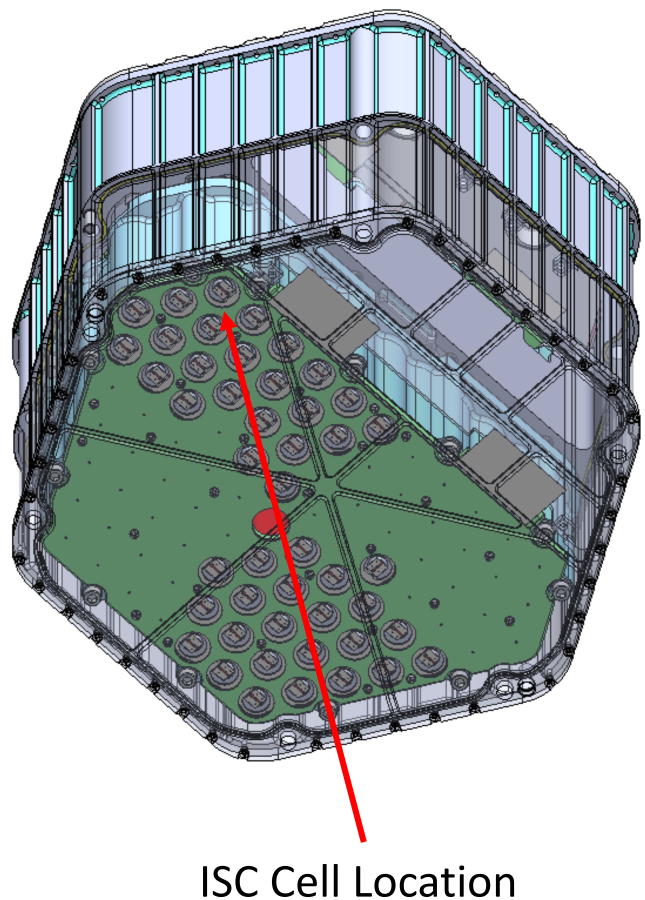
MJ1 23p2s Submodule #3



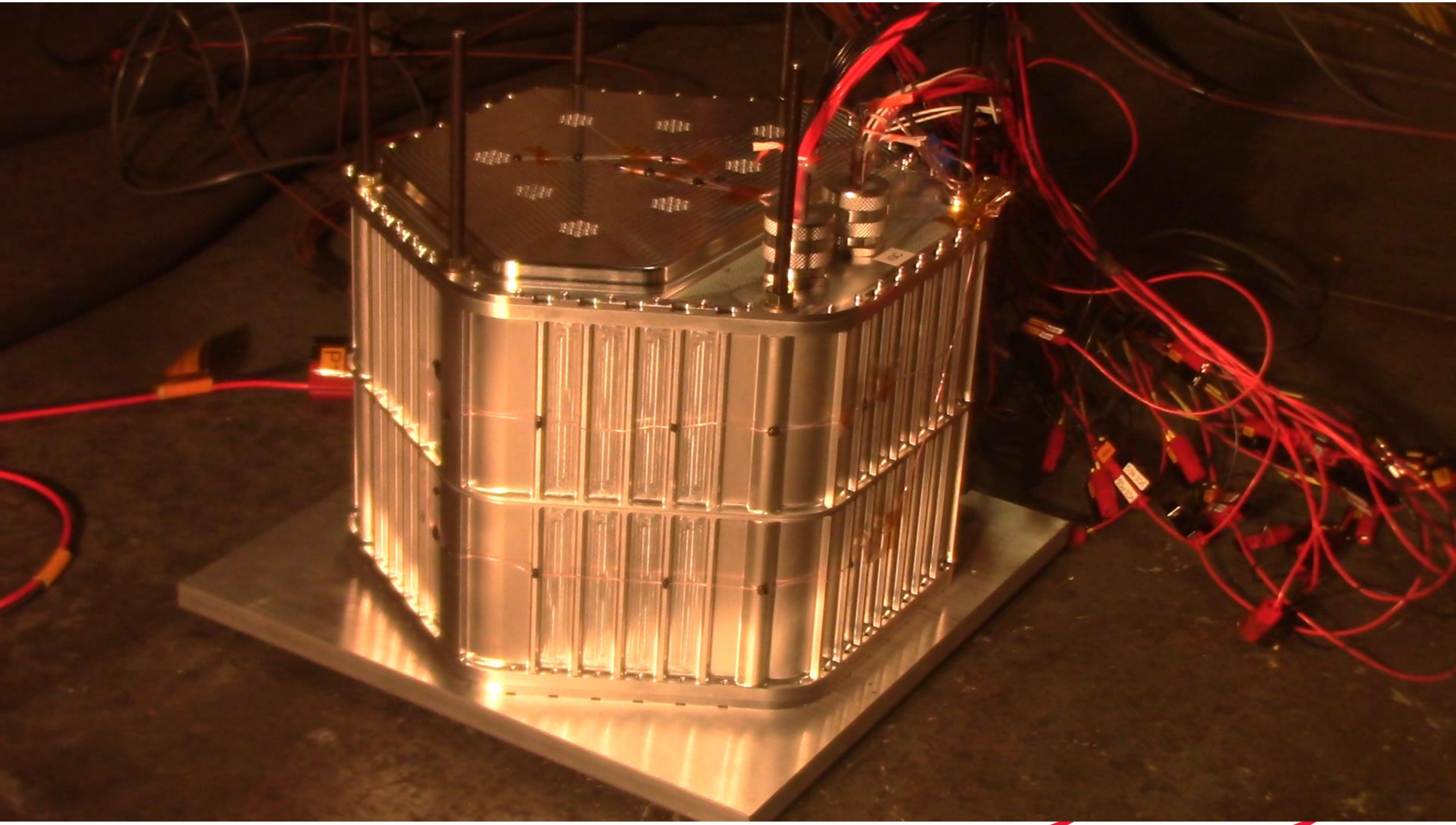
Neighbor T4 measured on anode directly underneath GRP plate

MJ1 23p8s Module

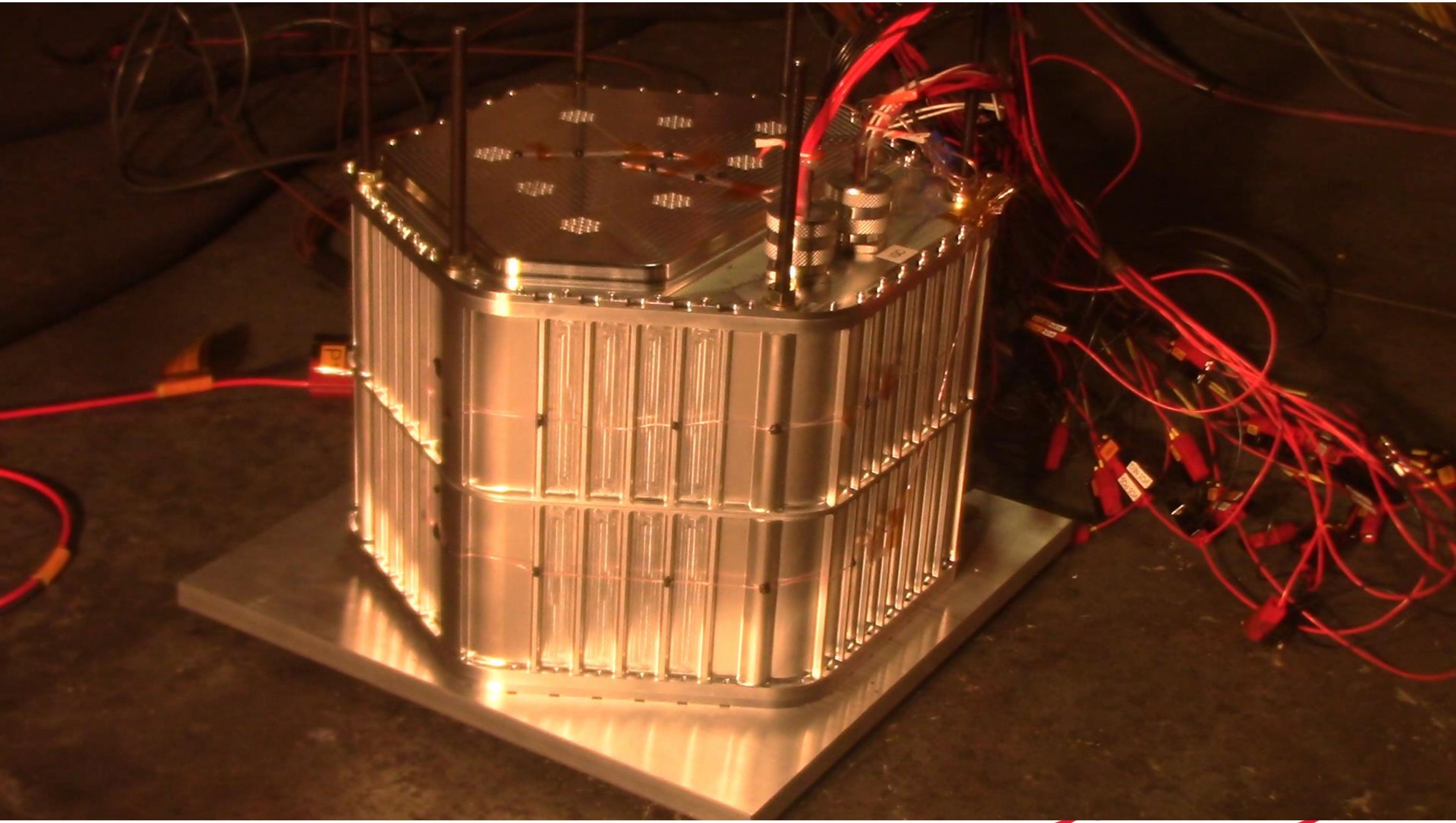




Video Screenshot – Pre Initiation



Video Screenshot – Initiation



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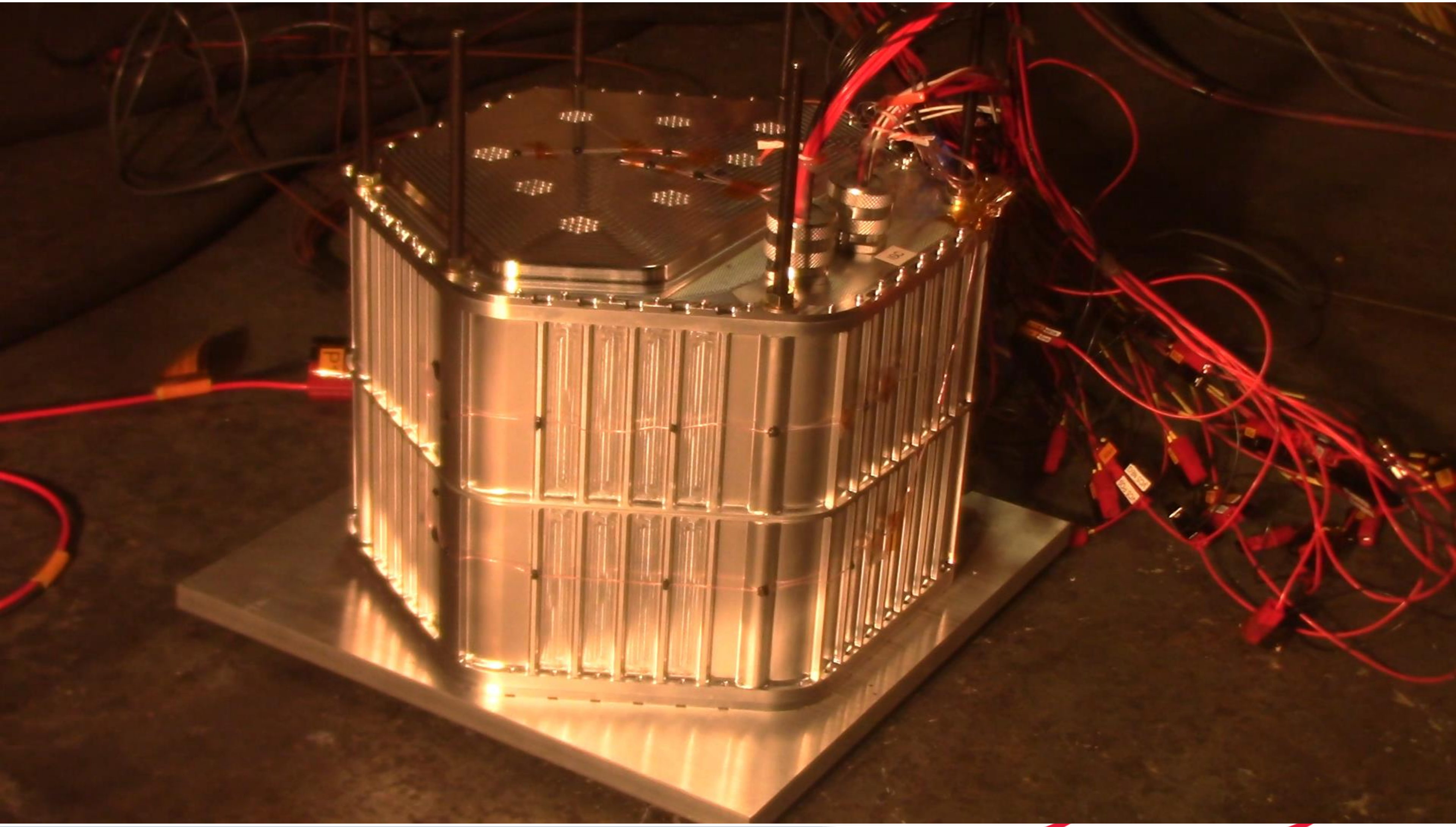
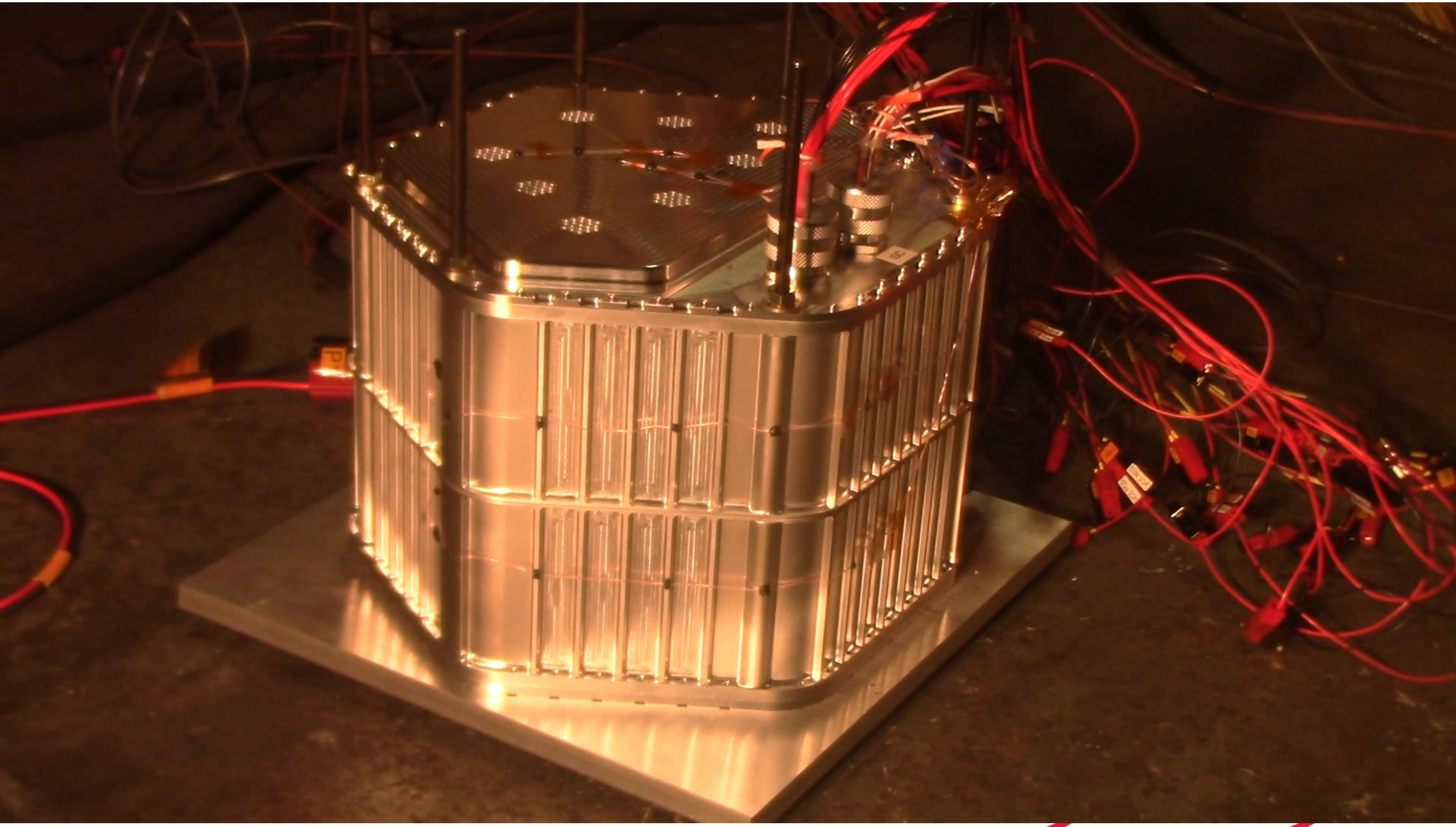
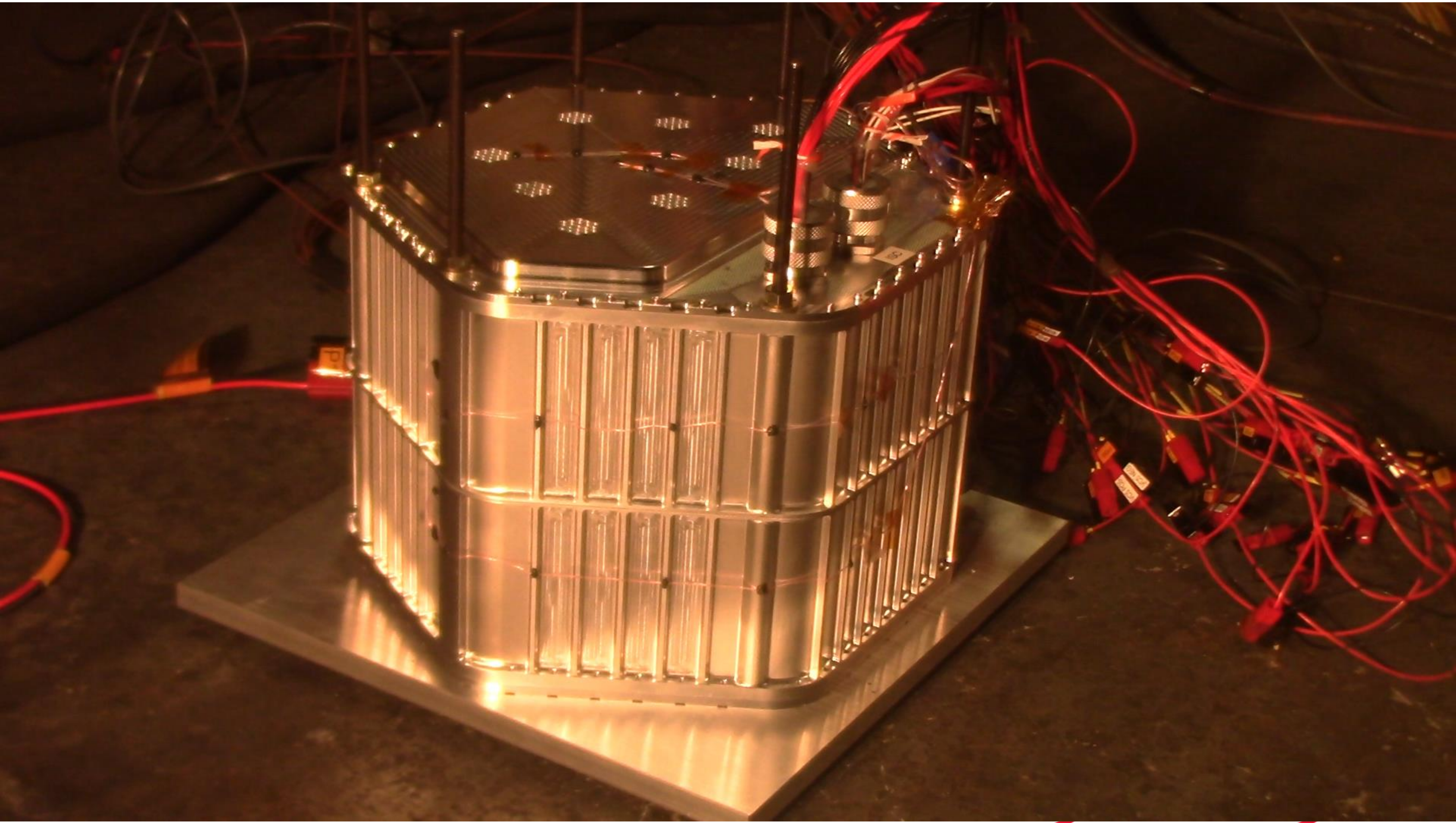
Video Screenshot – Initiation +1s



Video Screenshot – Initiation +2s



Video Screenshot – Initiation +5s



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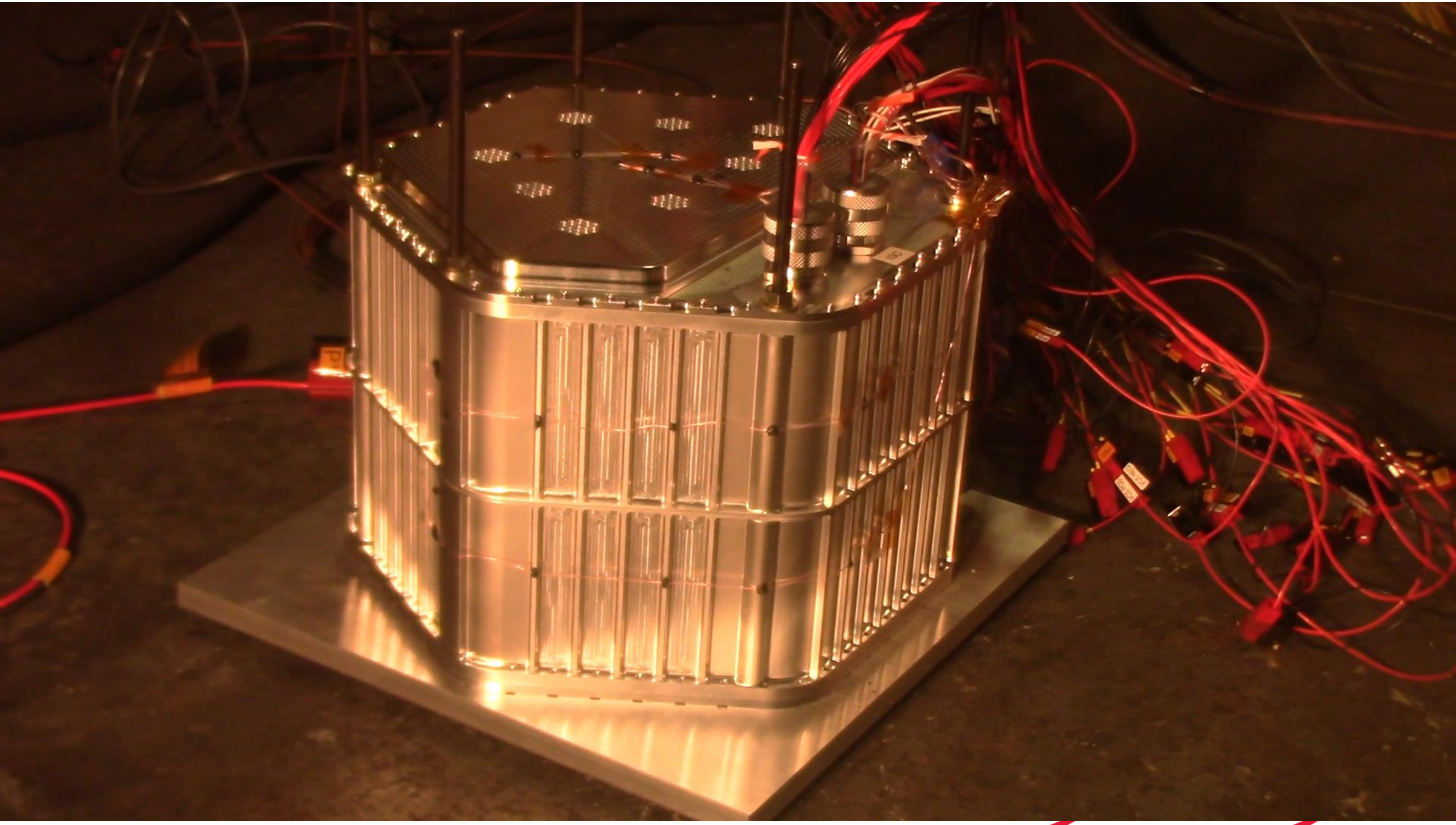
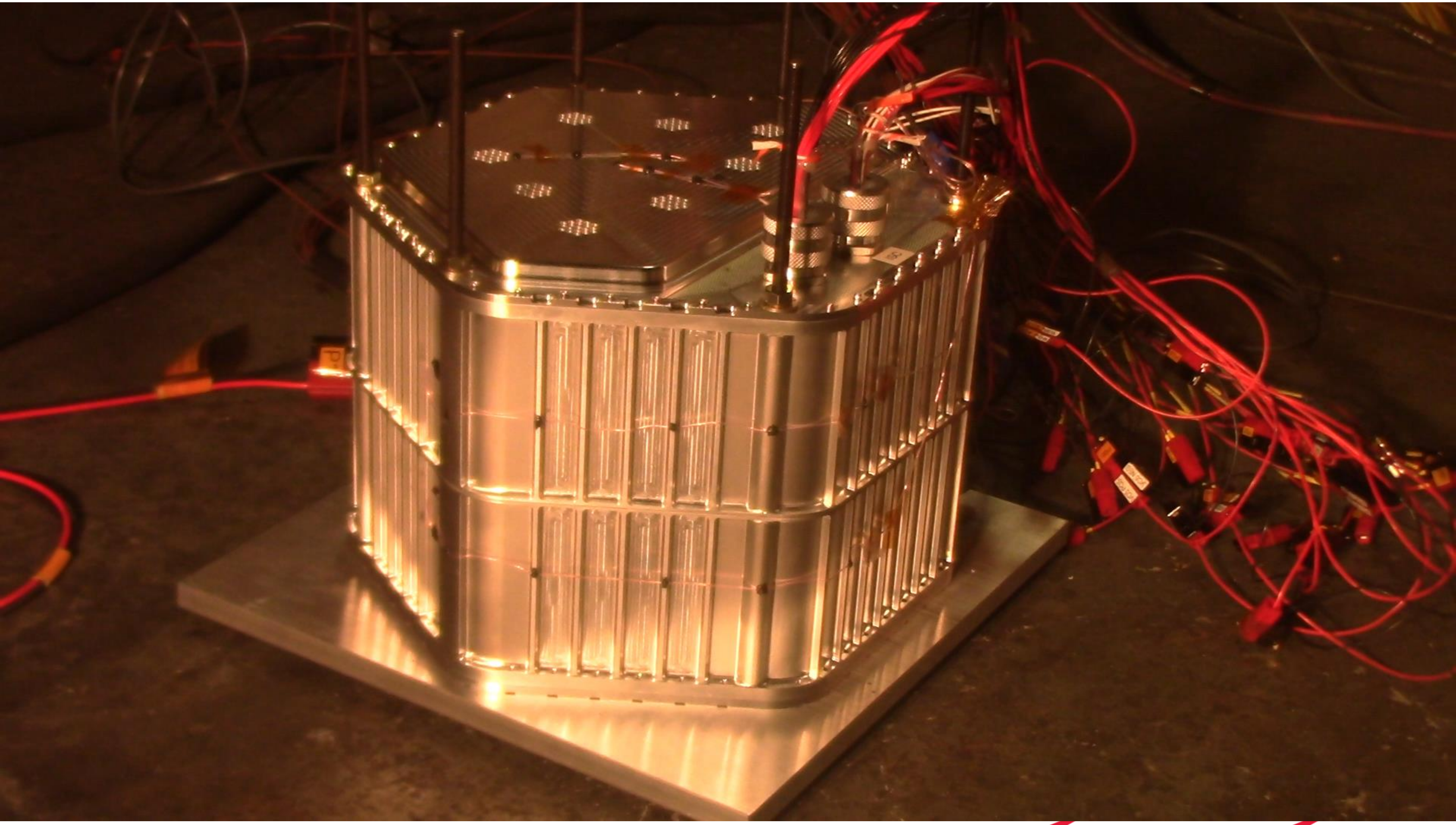
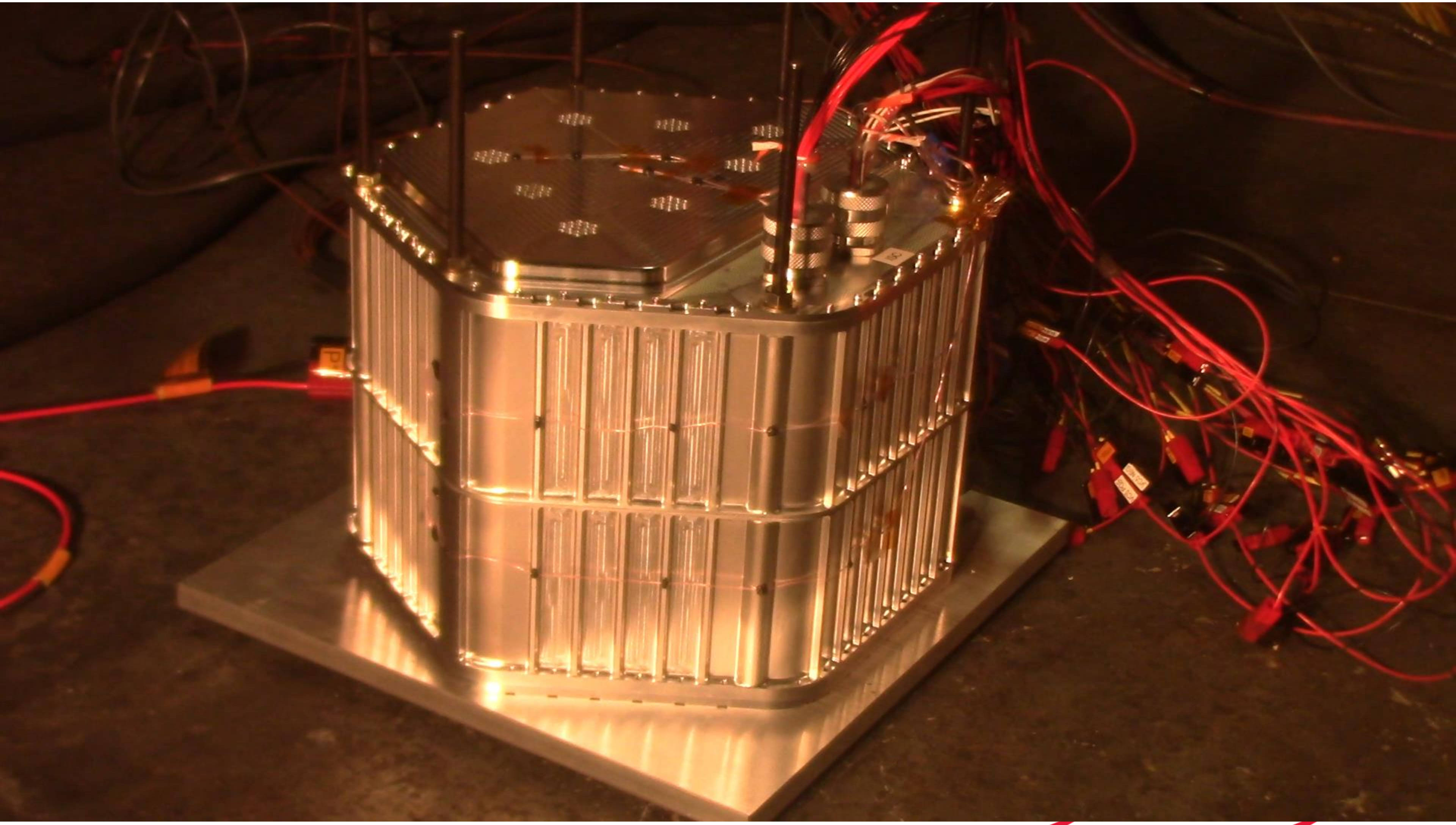
Video Screenshot – Initiation +10s



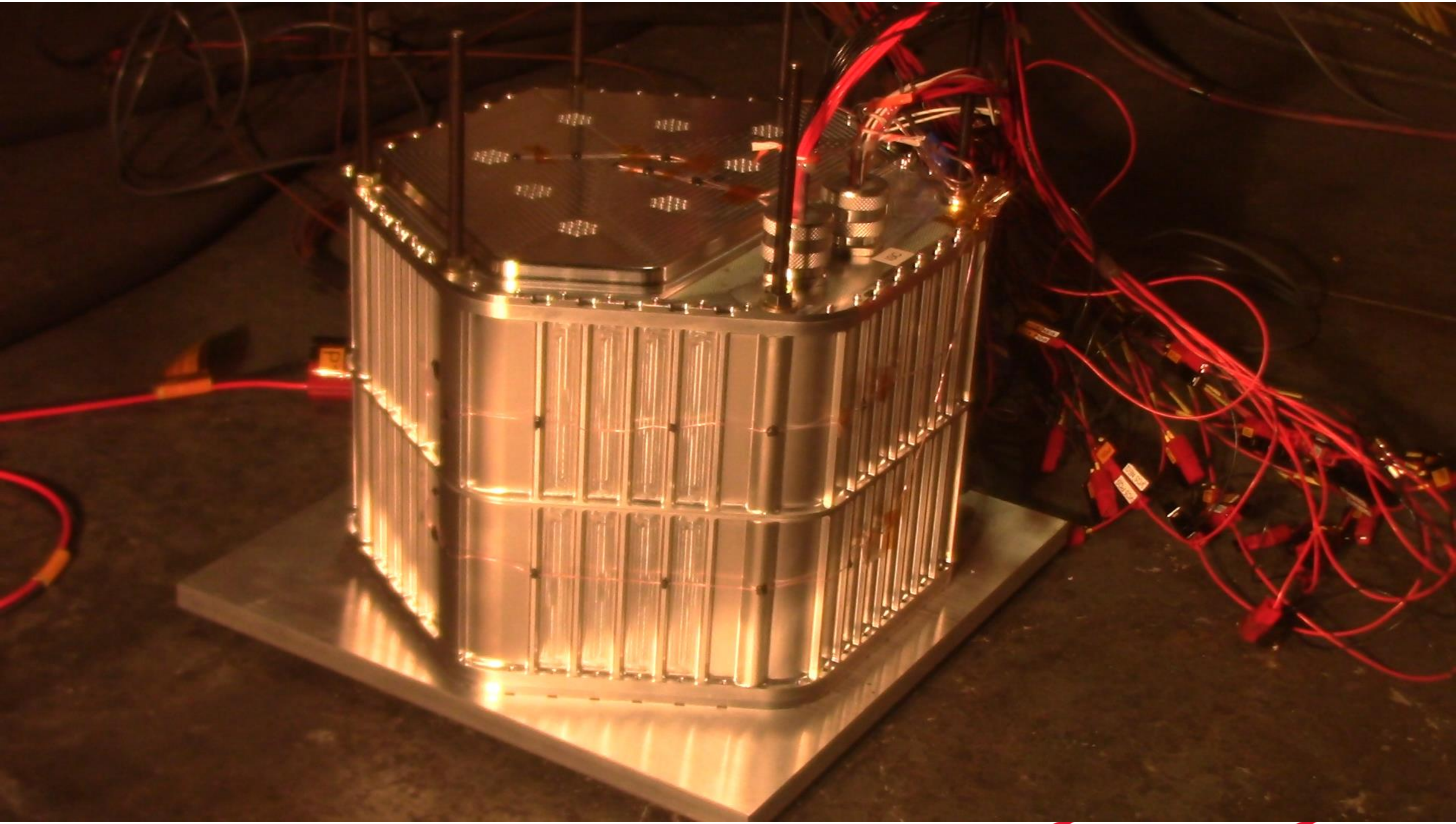
Video Screenshot – Initiation +20s



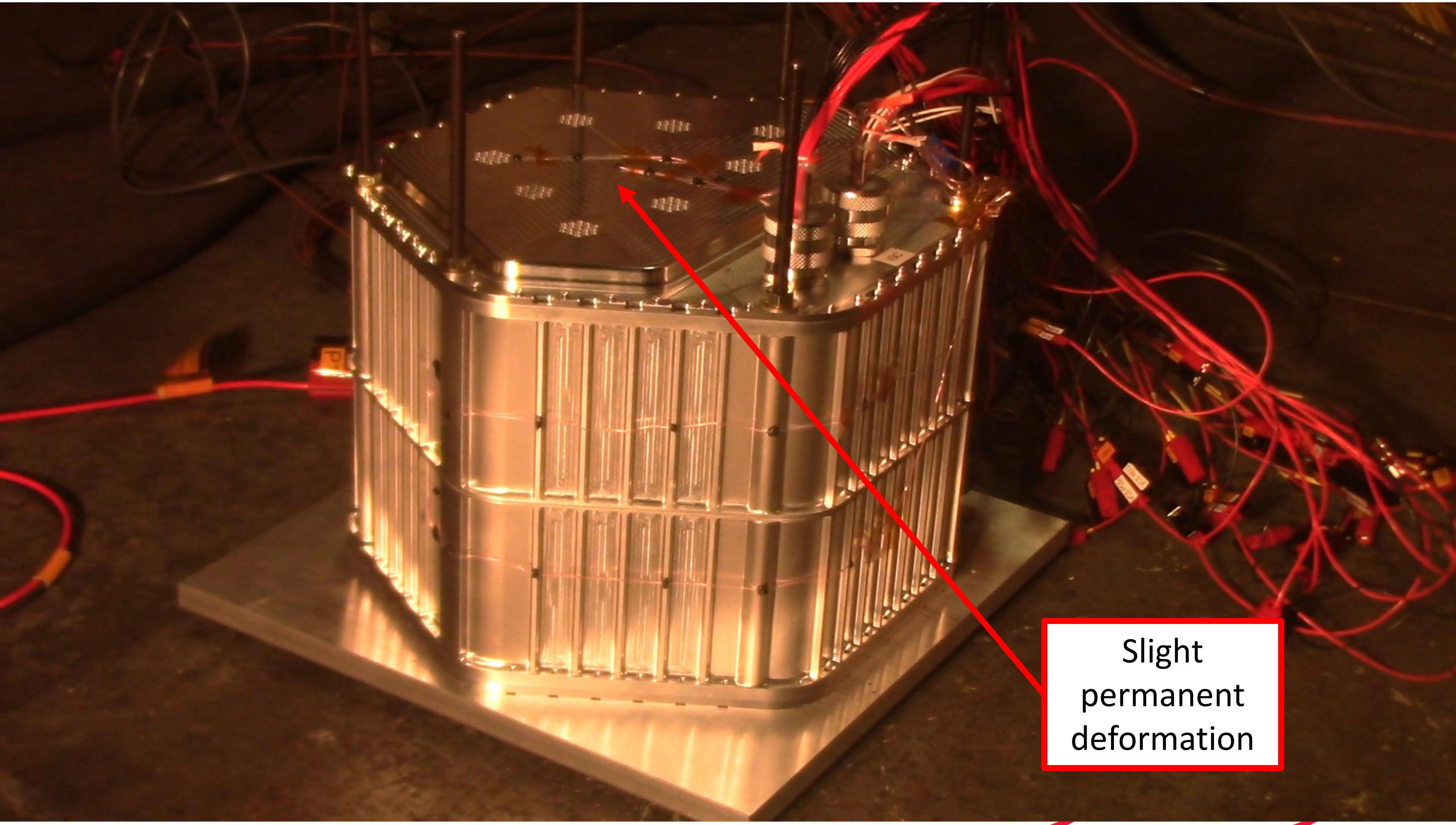
Video Screenshot – Initiation +60s



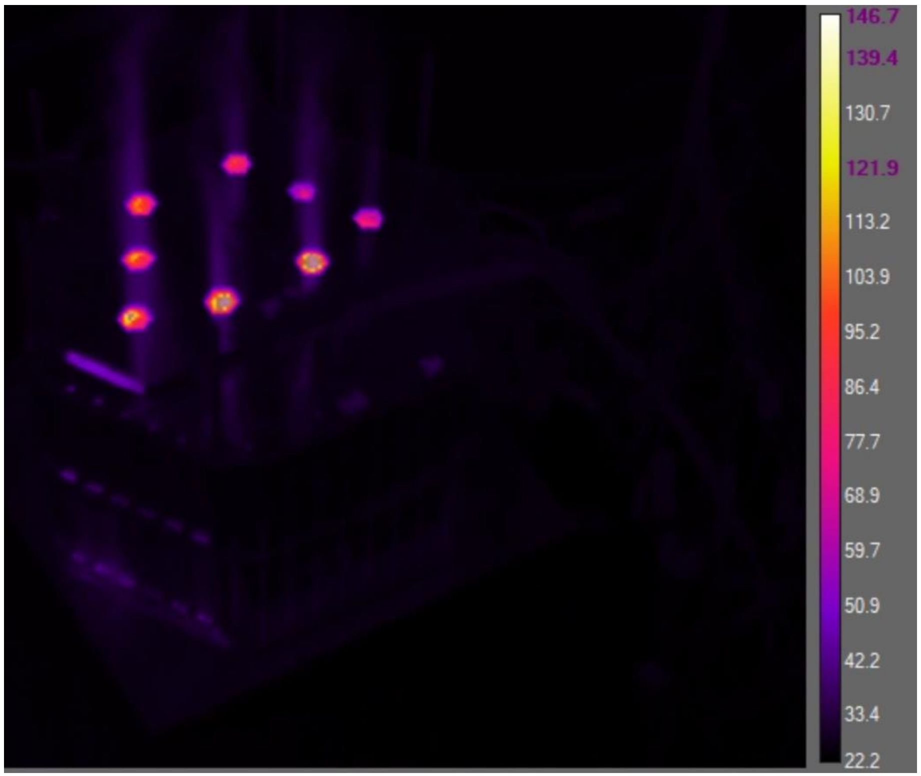
Video Screenshot – Initiation +180s



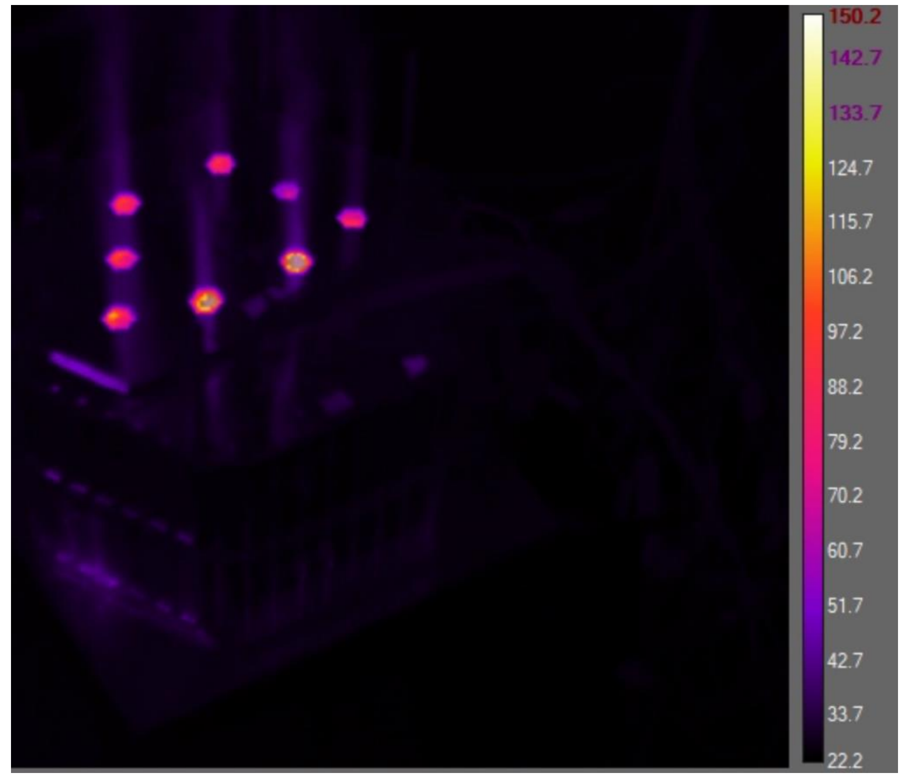
Video Screenshot – Pre Initiation



Thermal Camera Screenshots



1 second elapsed



2 seconds elapsed

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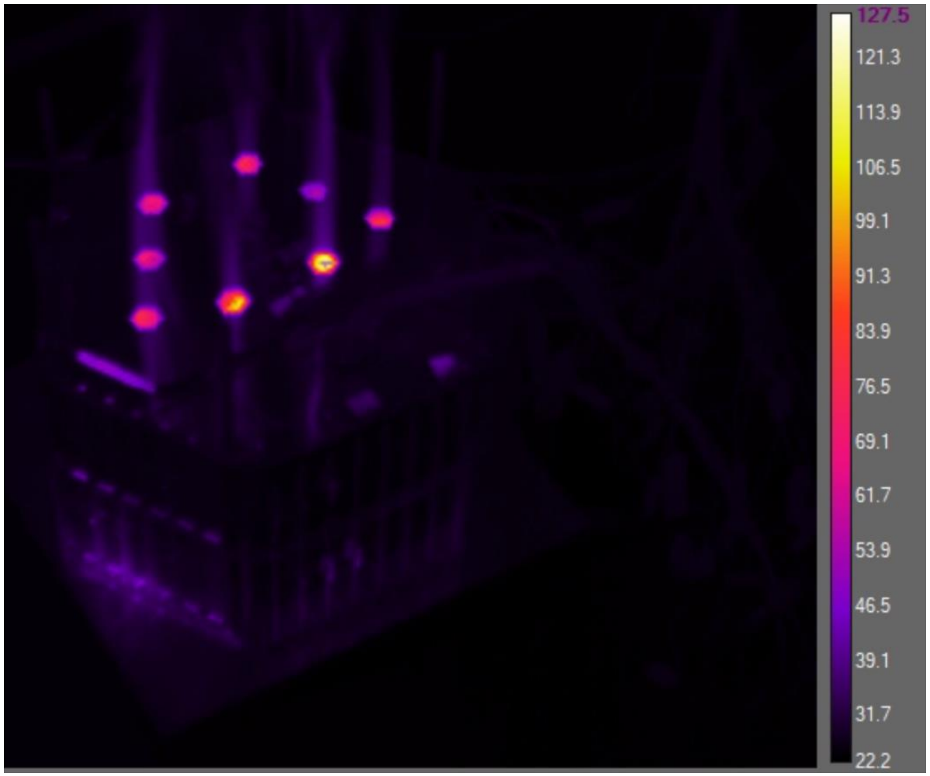
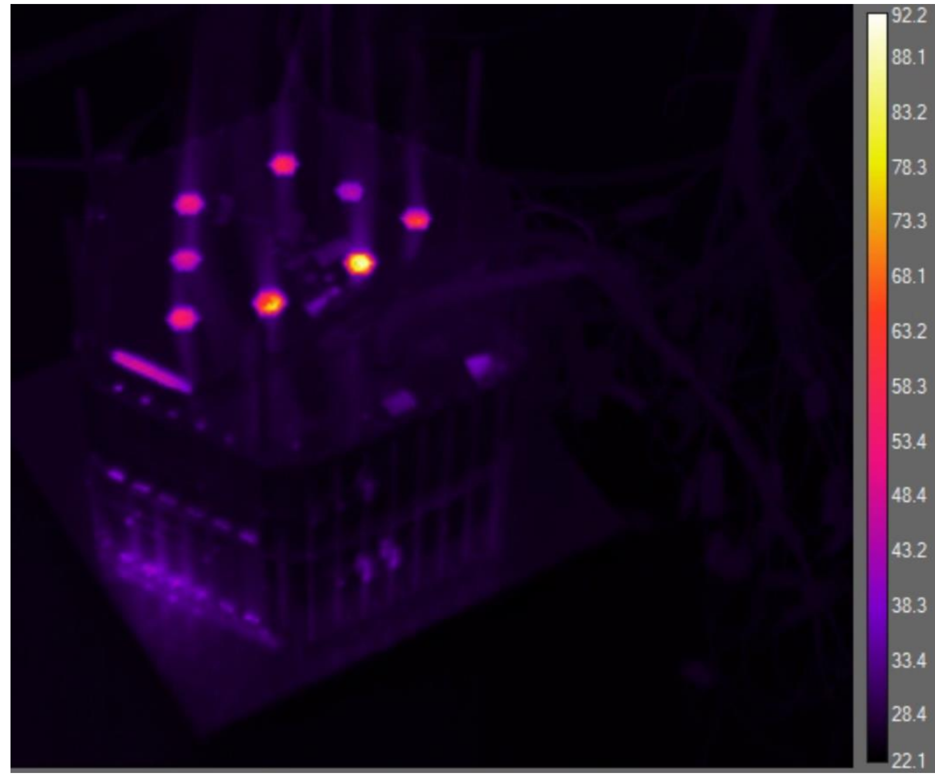
Thermal Camera Screenshots



5 seconds elapsed



10 seconds elapsed

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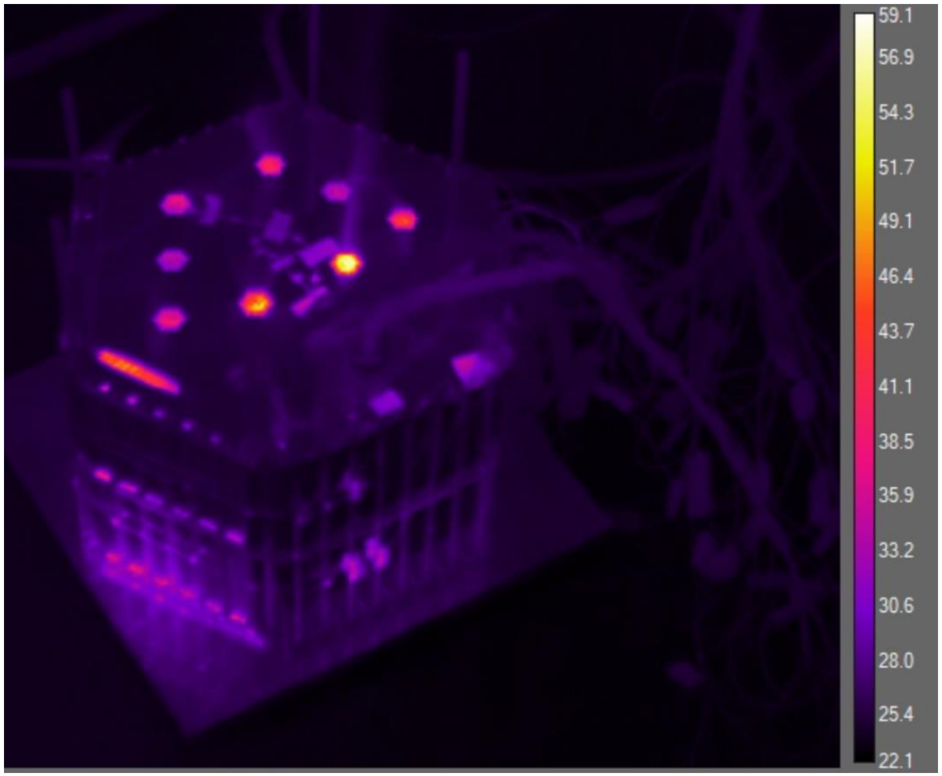
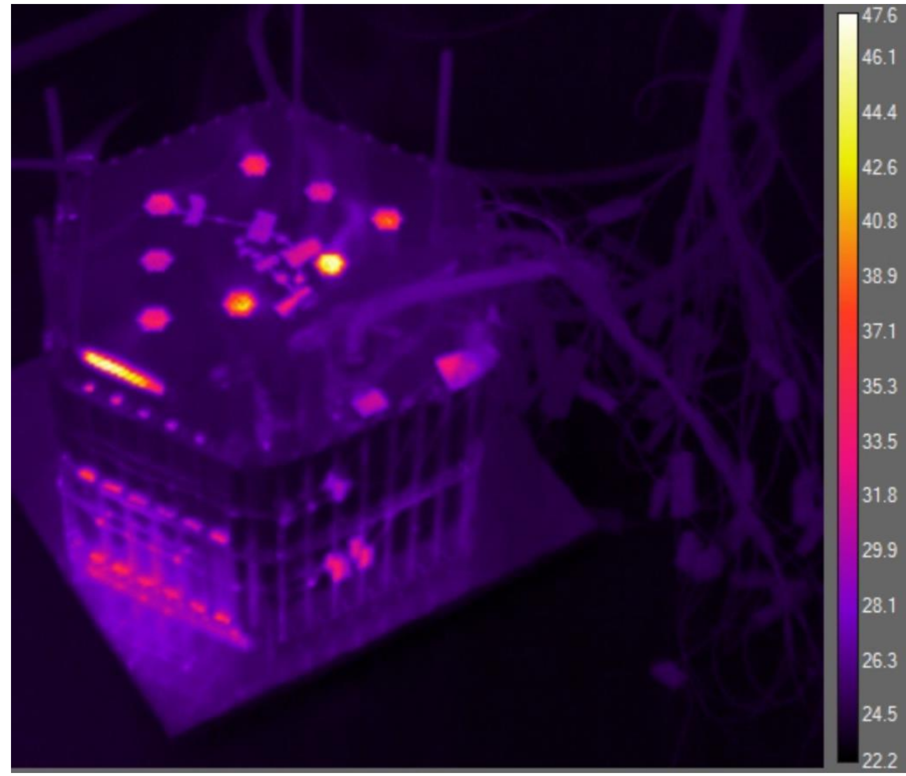
Thermal Camera Screenshots

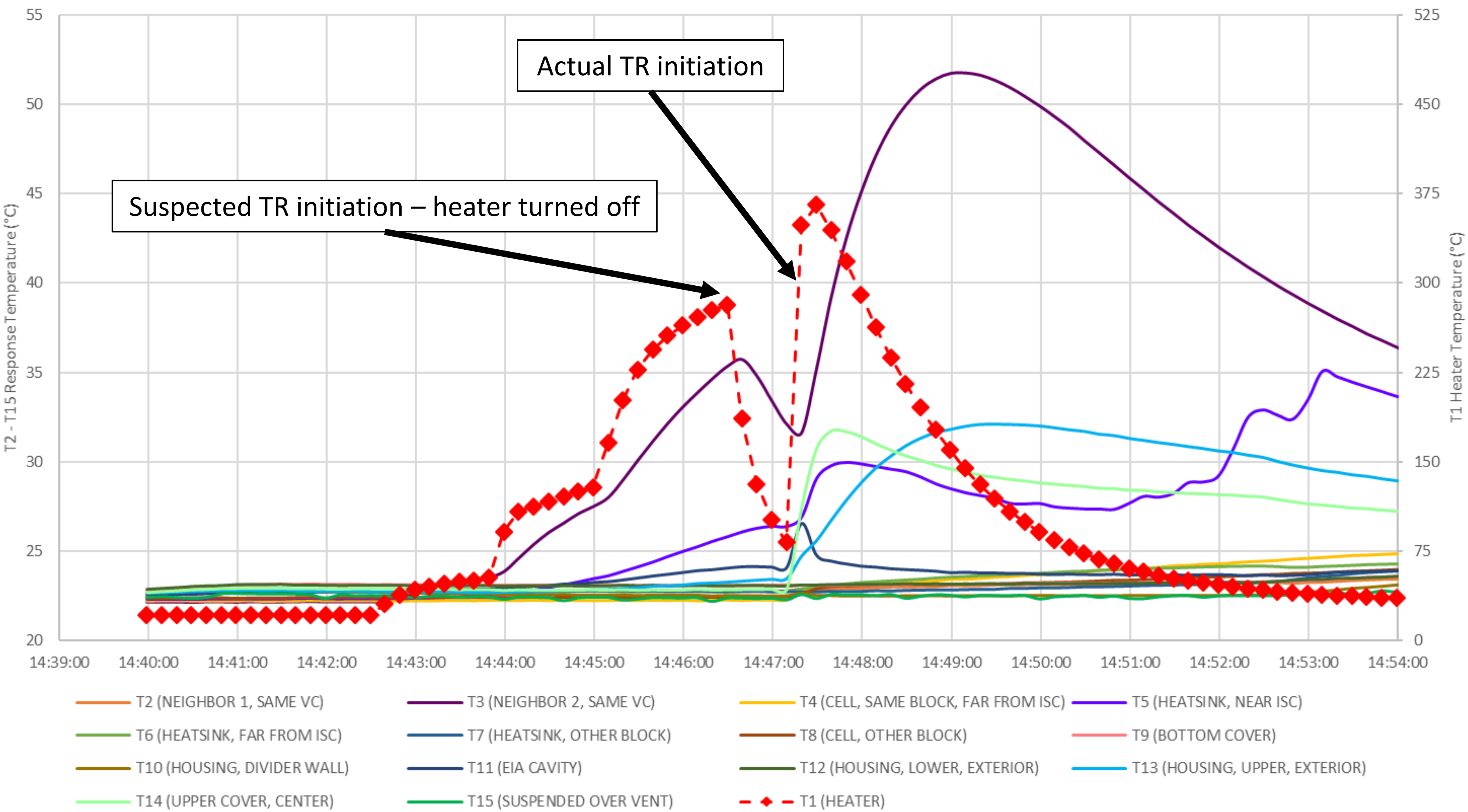


20 seconds elapsed

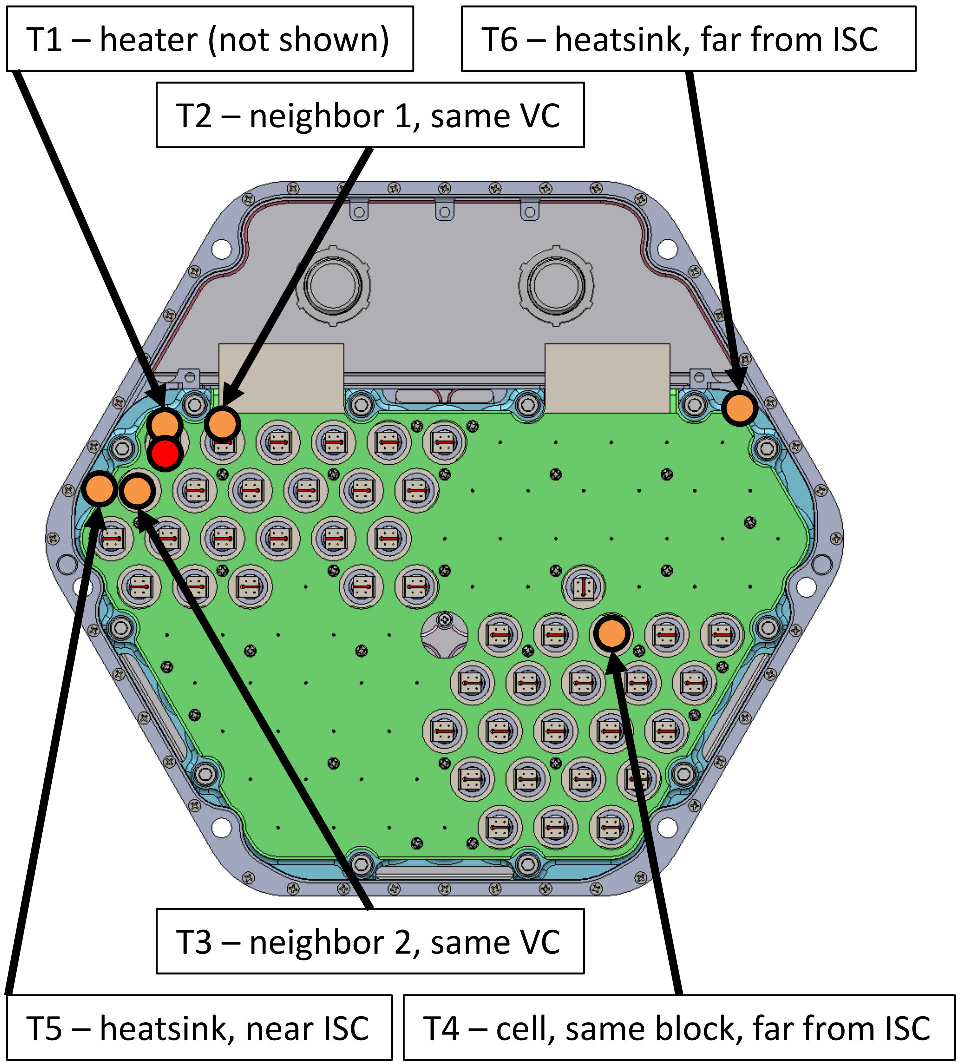


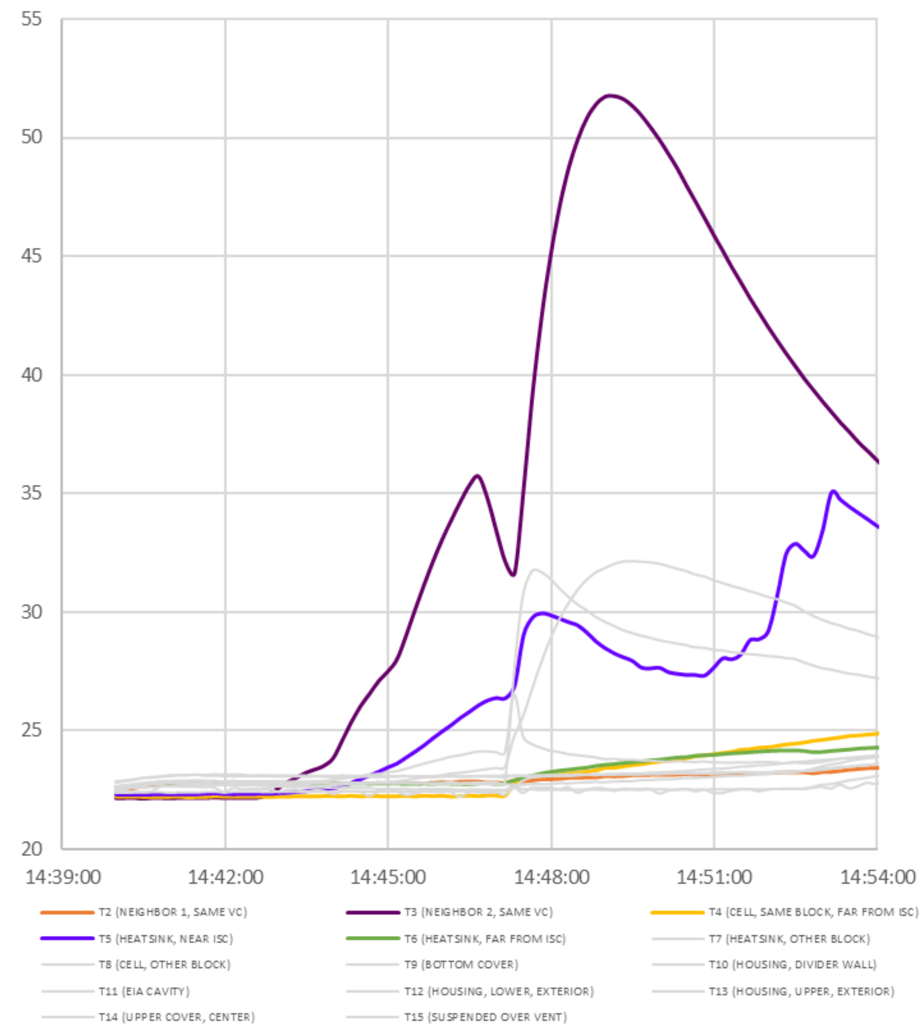
30 seconds elapsed

MJ1 23p8s Module



MJ1 23p8s Module





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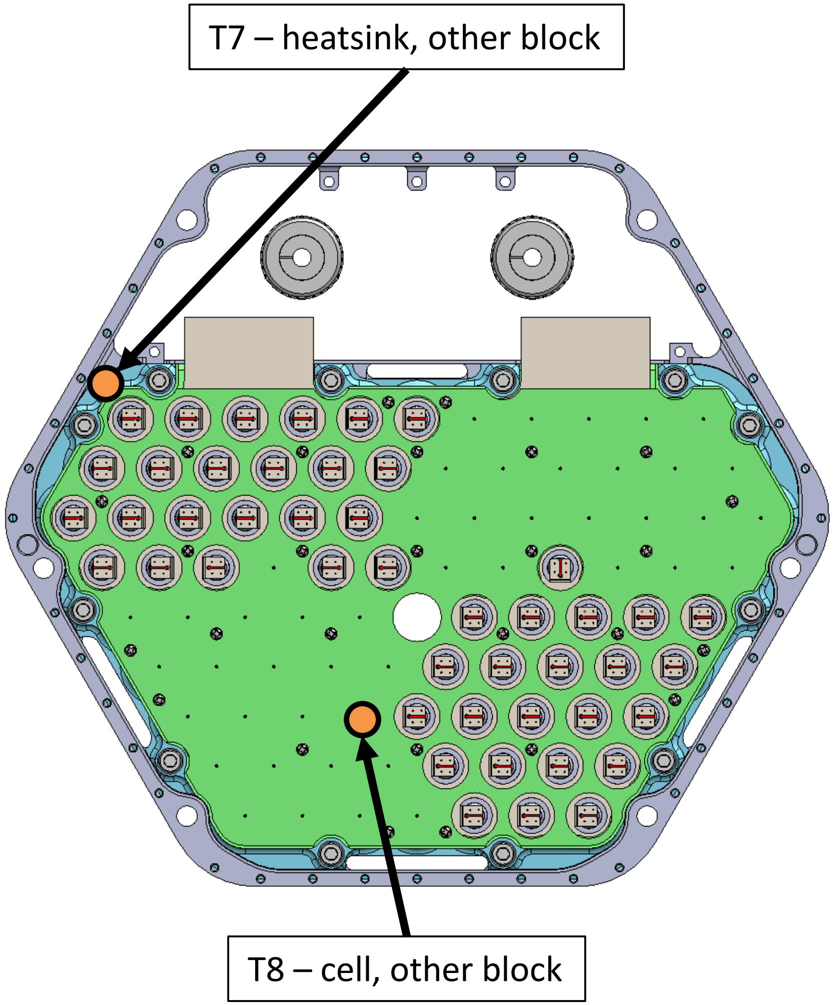
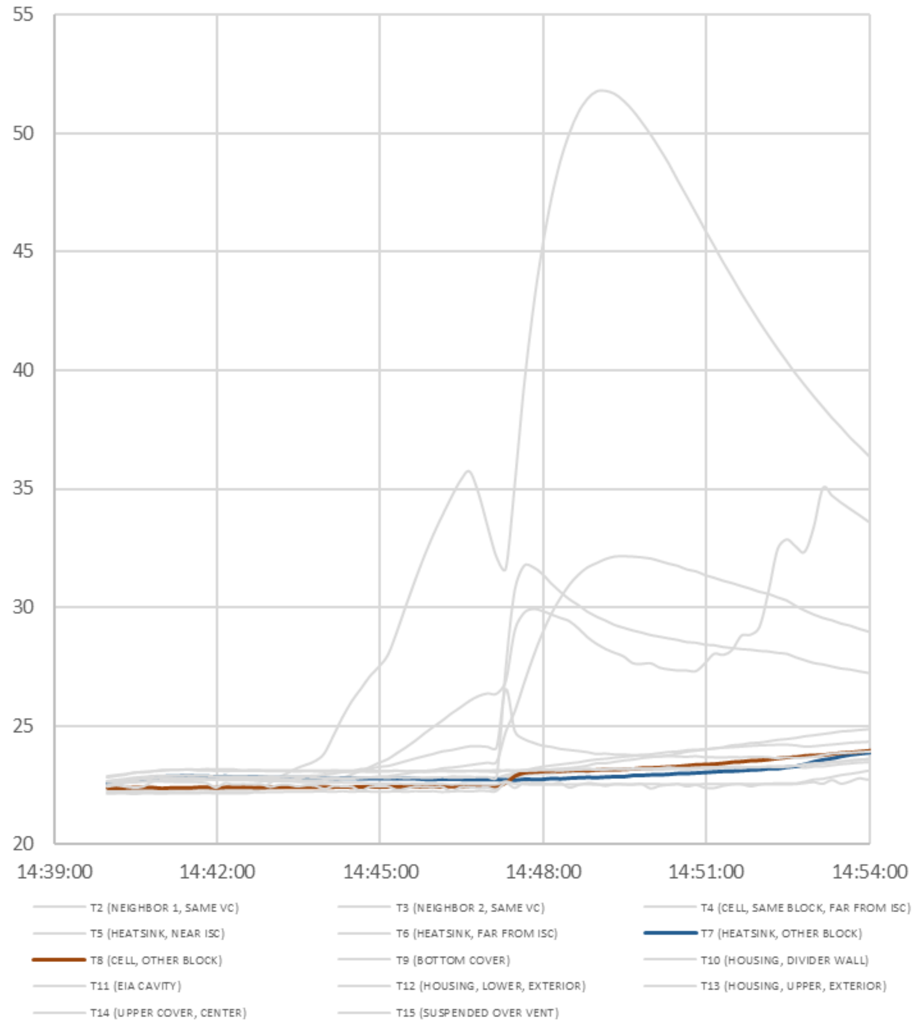
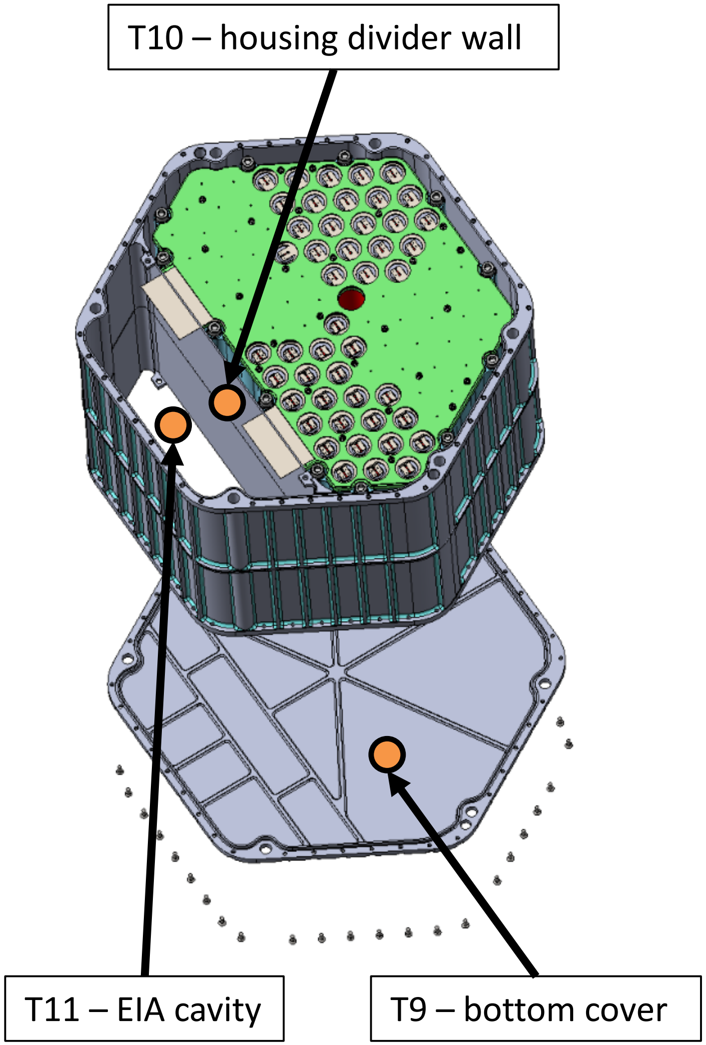
MJ1 23p8s Module

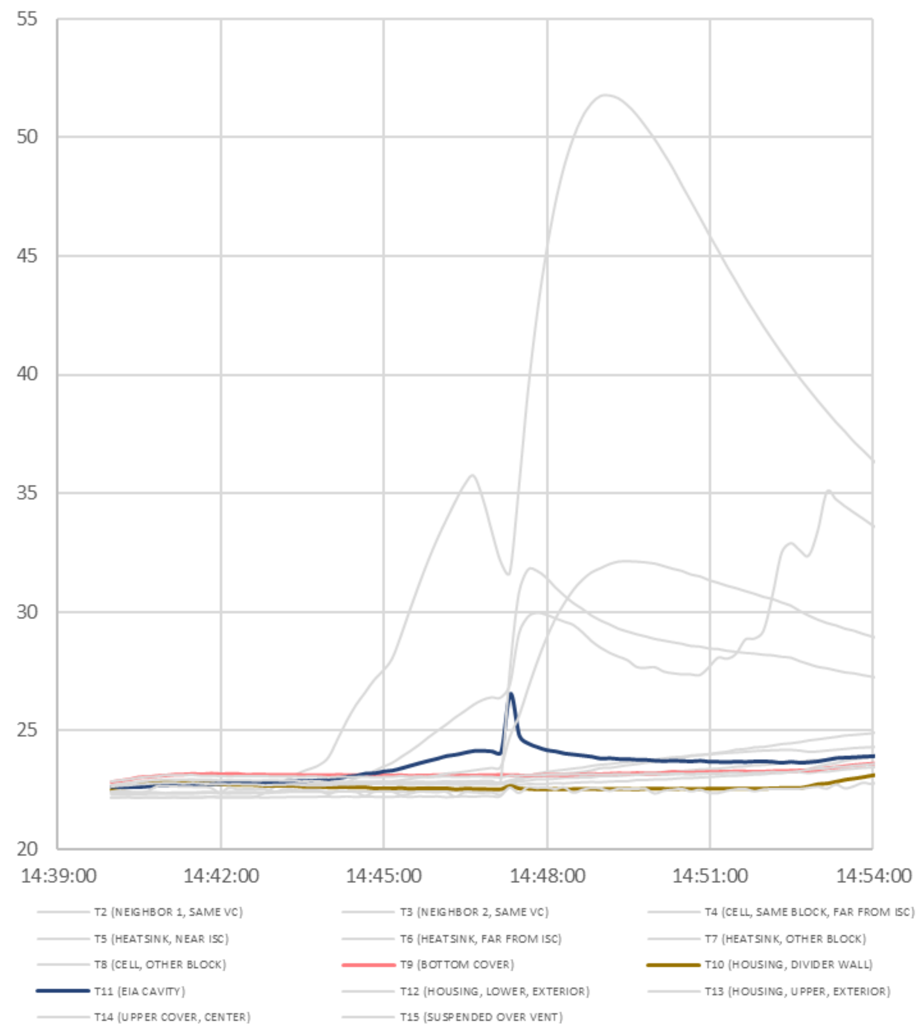




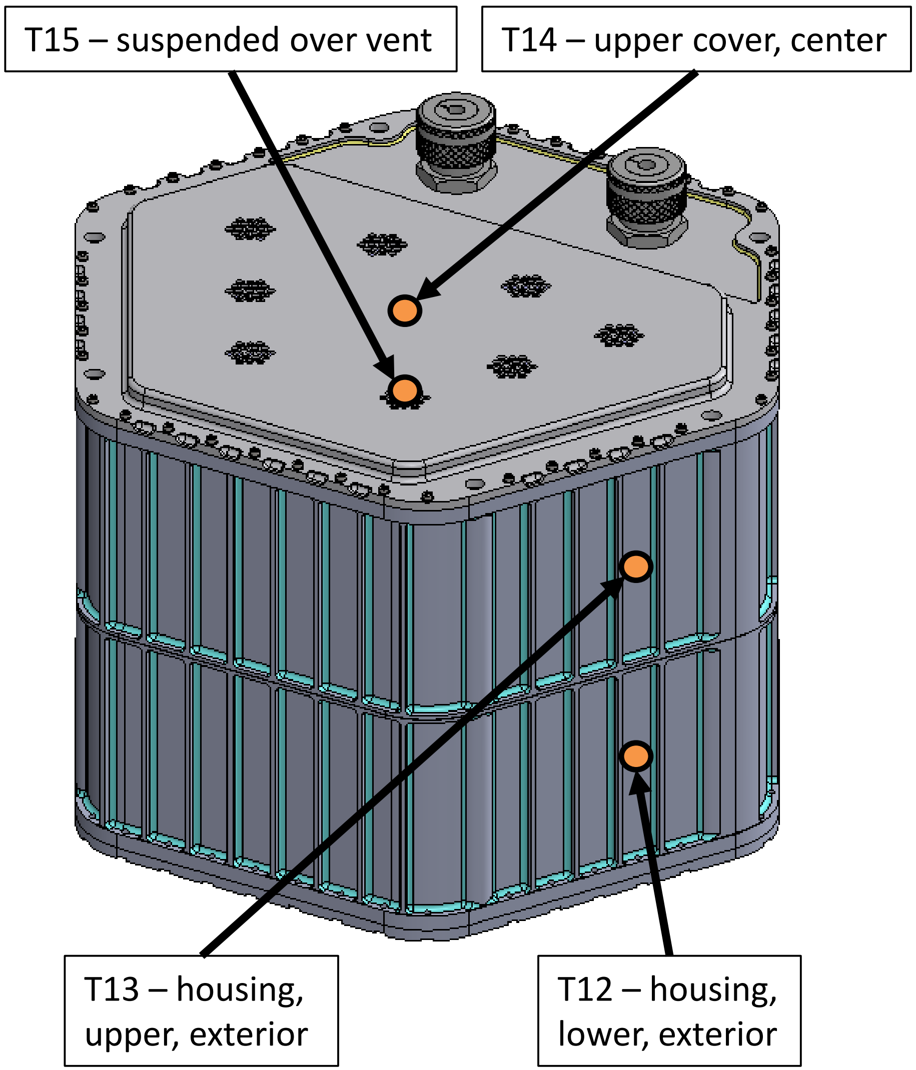
Power/Full Solutions

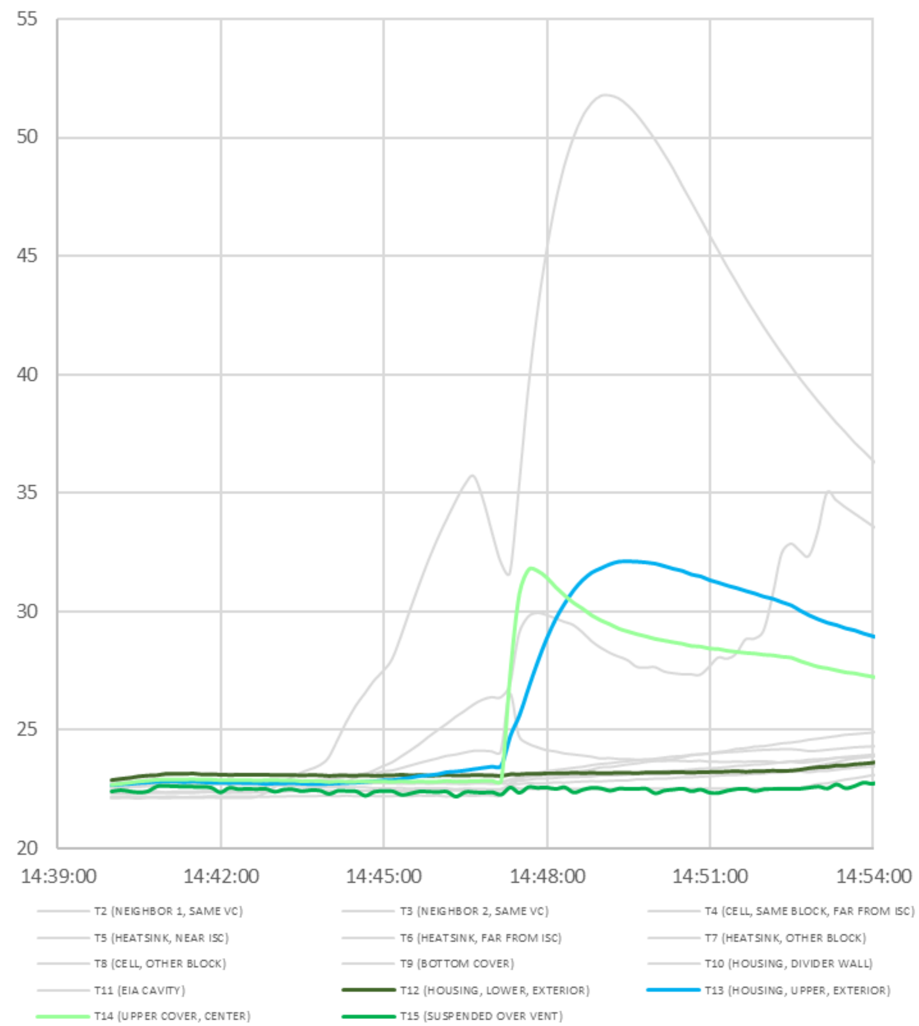
MJ1 23p8s Module





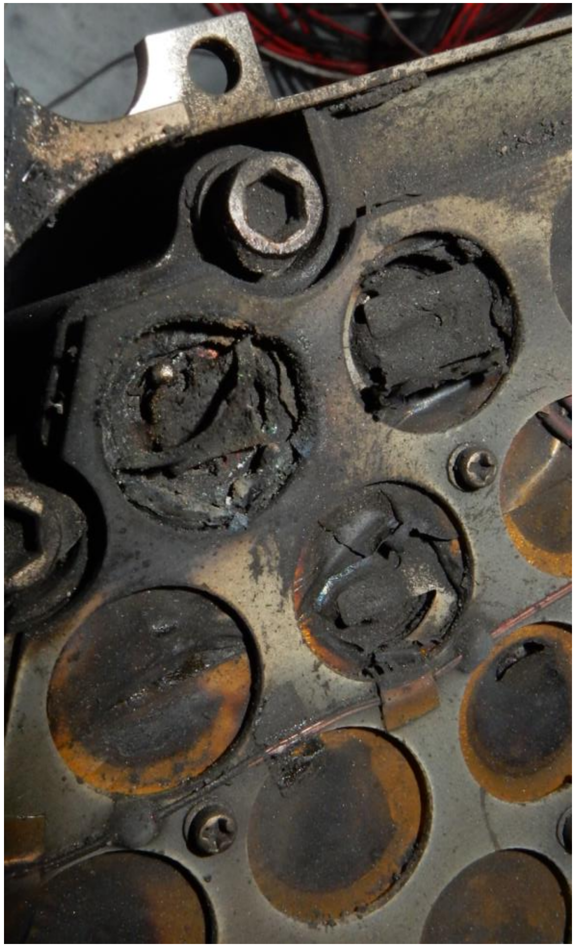
MJ1 23p8s Module



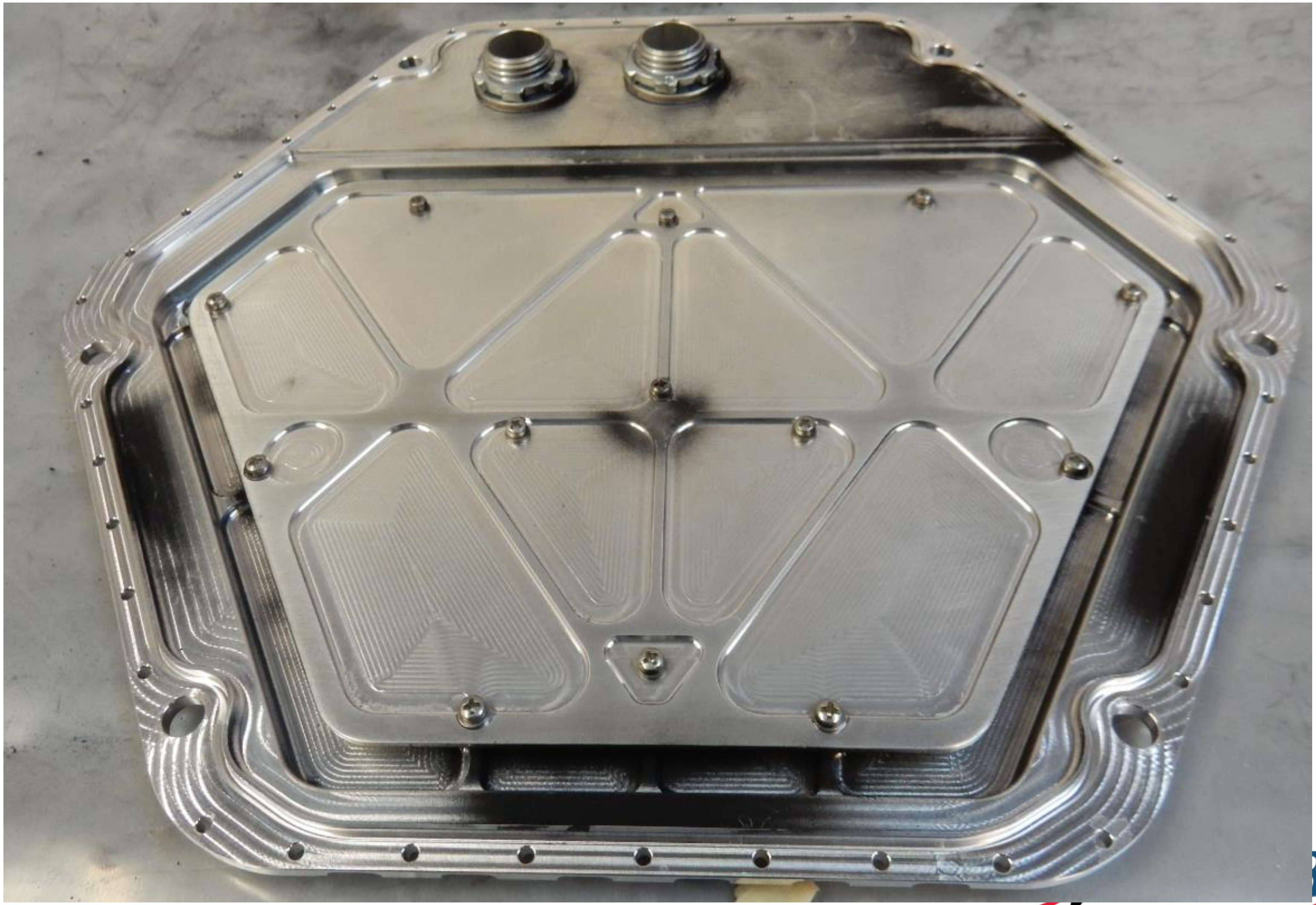


Power/Full Solutions

MJ1 23p8s Module

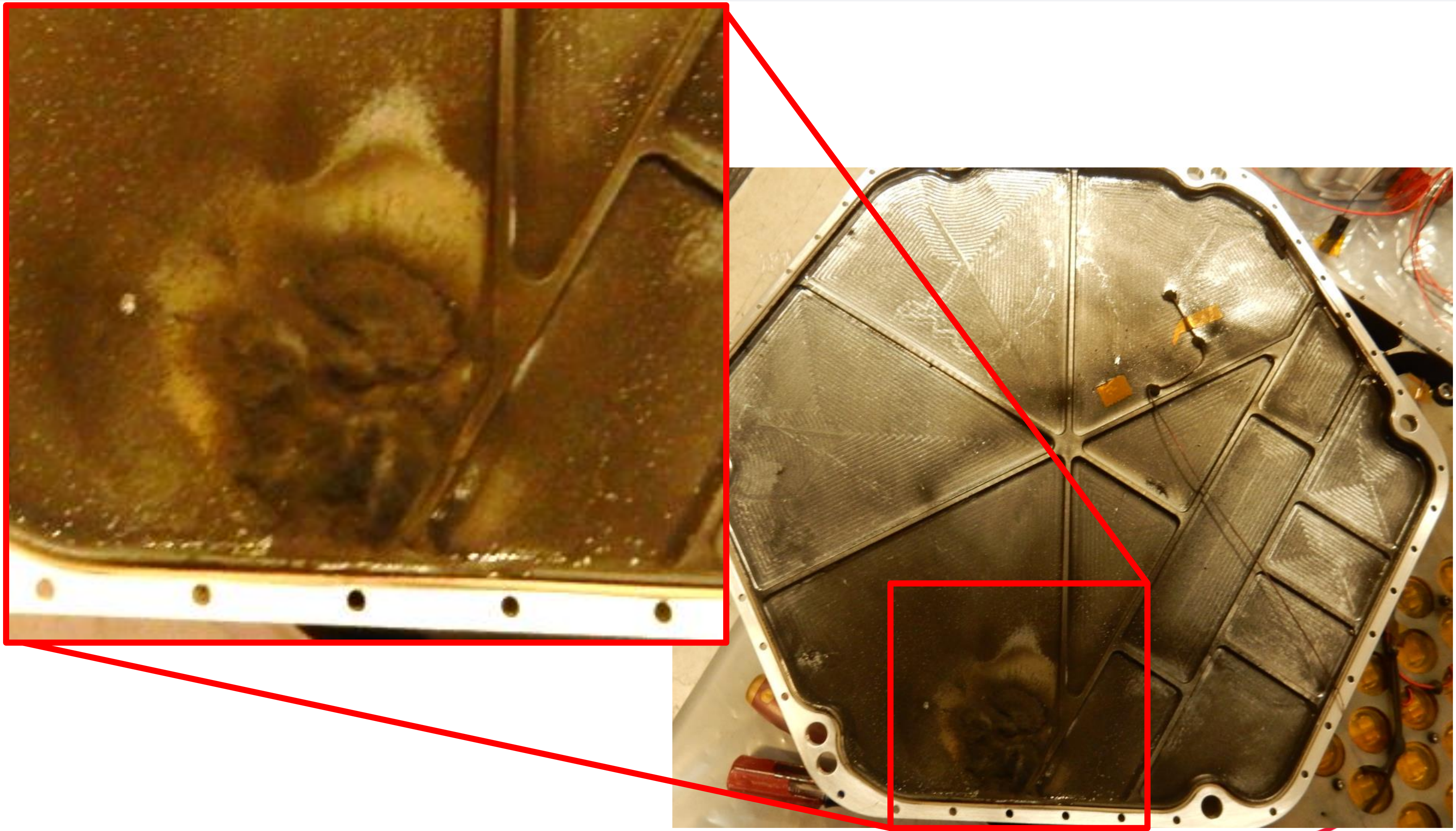


MJ1 23p8s Module



Power/Full Solutions

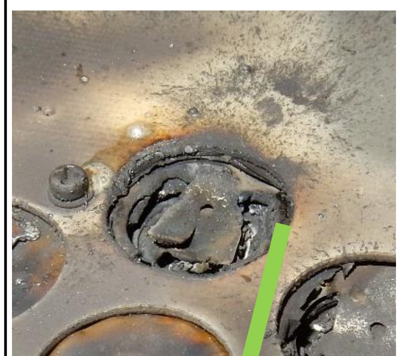
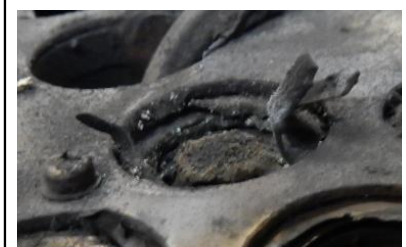
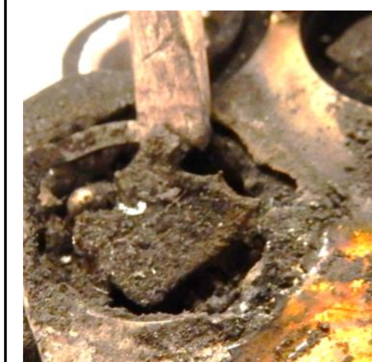
MJ1 23p8s Module



Power/Full Solutions

MJ1 23p8s Module

- Fusible link is effective in electrically isolating TR cell
  - In cases where cathode tag is not already severed by TR event

	SM1	SM2	SM3	Full Module
Cathode				
Anode				

MJ1 23p8s Module

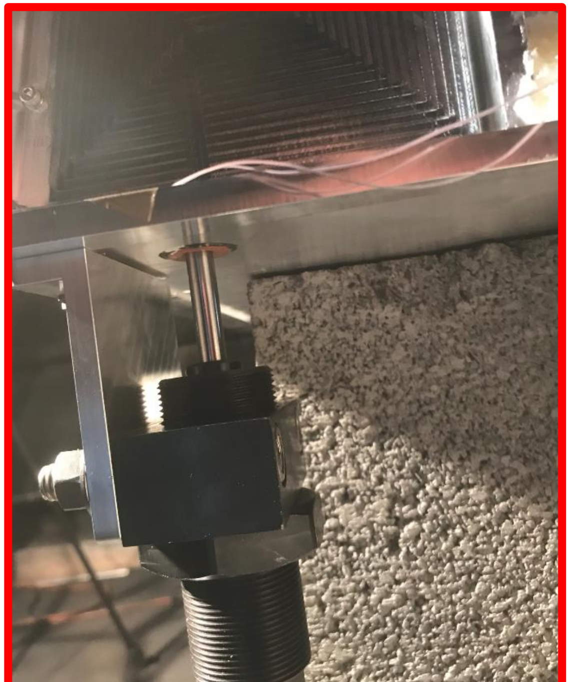
- Discharge capacity of all virtual cells was measured before and after TR test
  - Confirmed that only trigger cell was open circuit – i.e. no CID/vent in neighbors, in same virtual cell or others
  - No propagation of thermal runaway

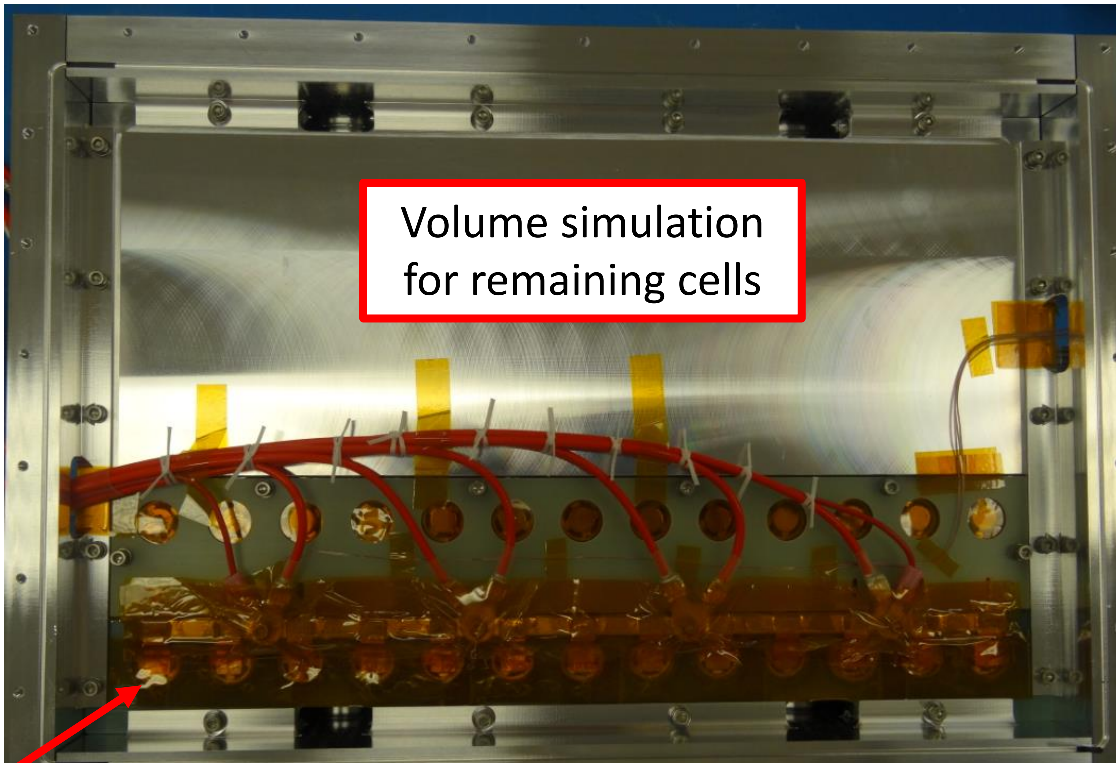
- Battery design is effective for preventing flames exiting
  - Internal vent pathway
  - Flame arrestors at vent

- Vent design is effective for preventing particulate exiting

MJ1 13p3s Submodule

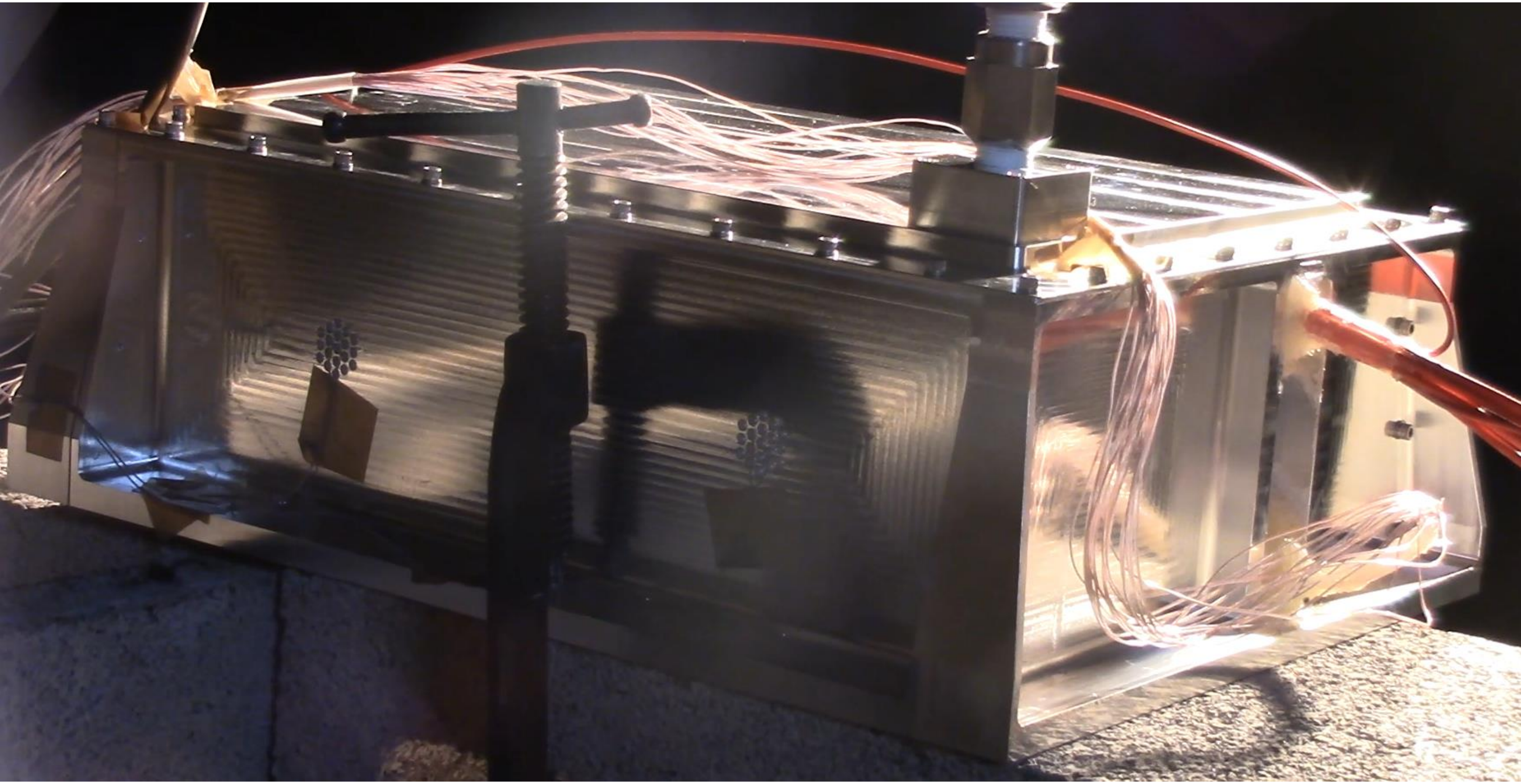
- Another ABSL program – 13p8s flight design



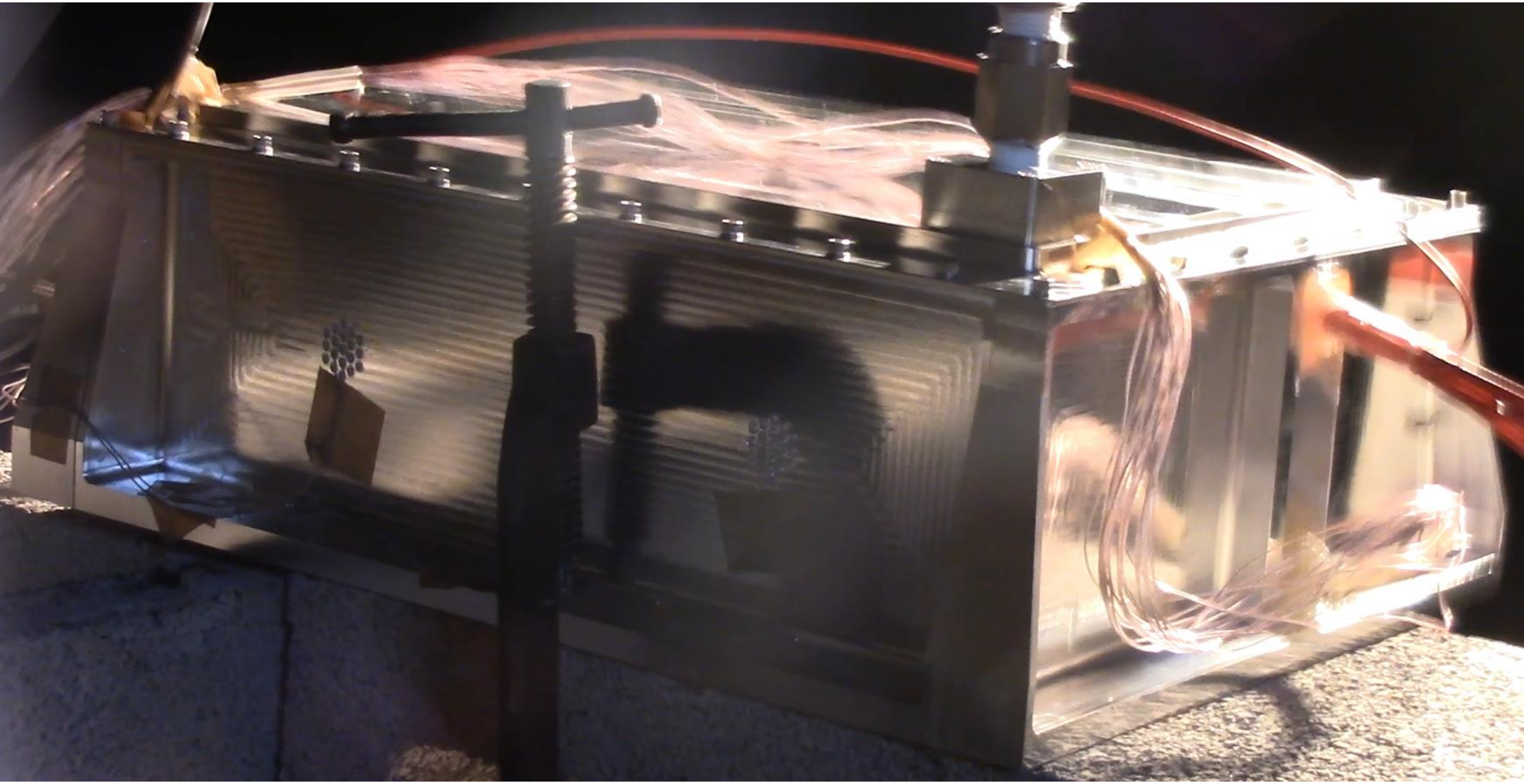


Nail penetration,
anode of corner cell

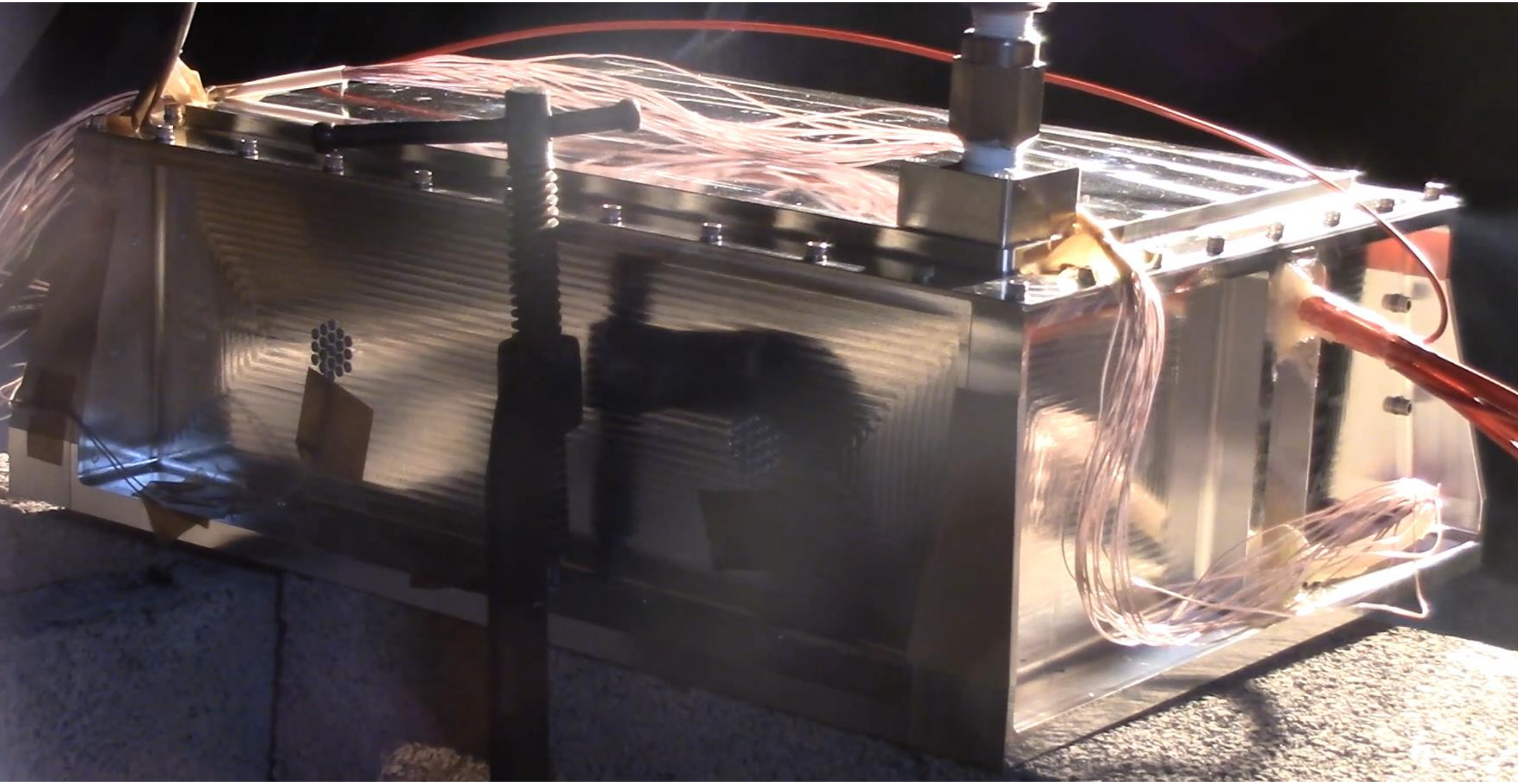
Video Screenshot – Pre Initiation



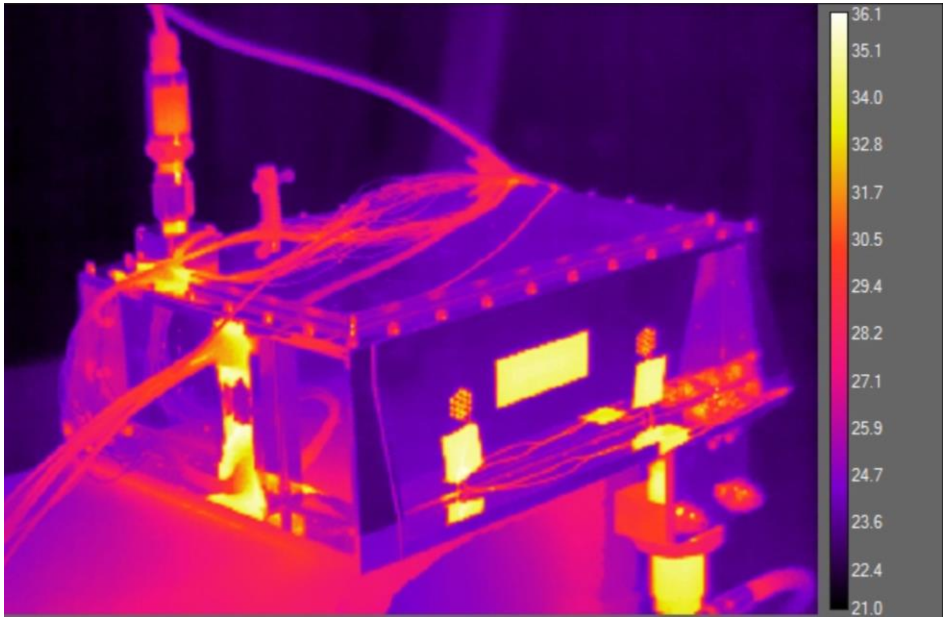
Video Screenshot – Initiation



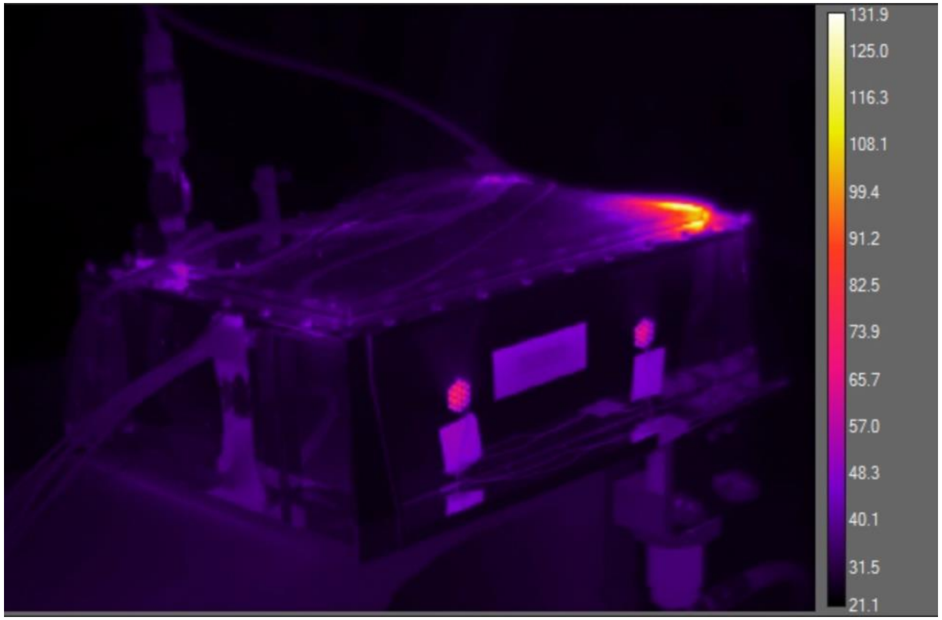
Video Screenshot – Initiation +2s



Thermal Camera Screenshots

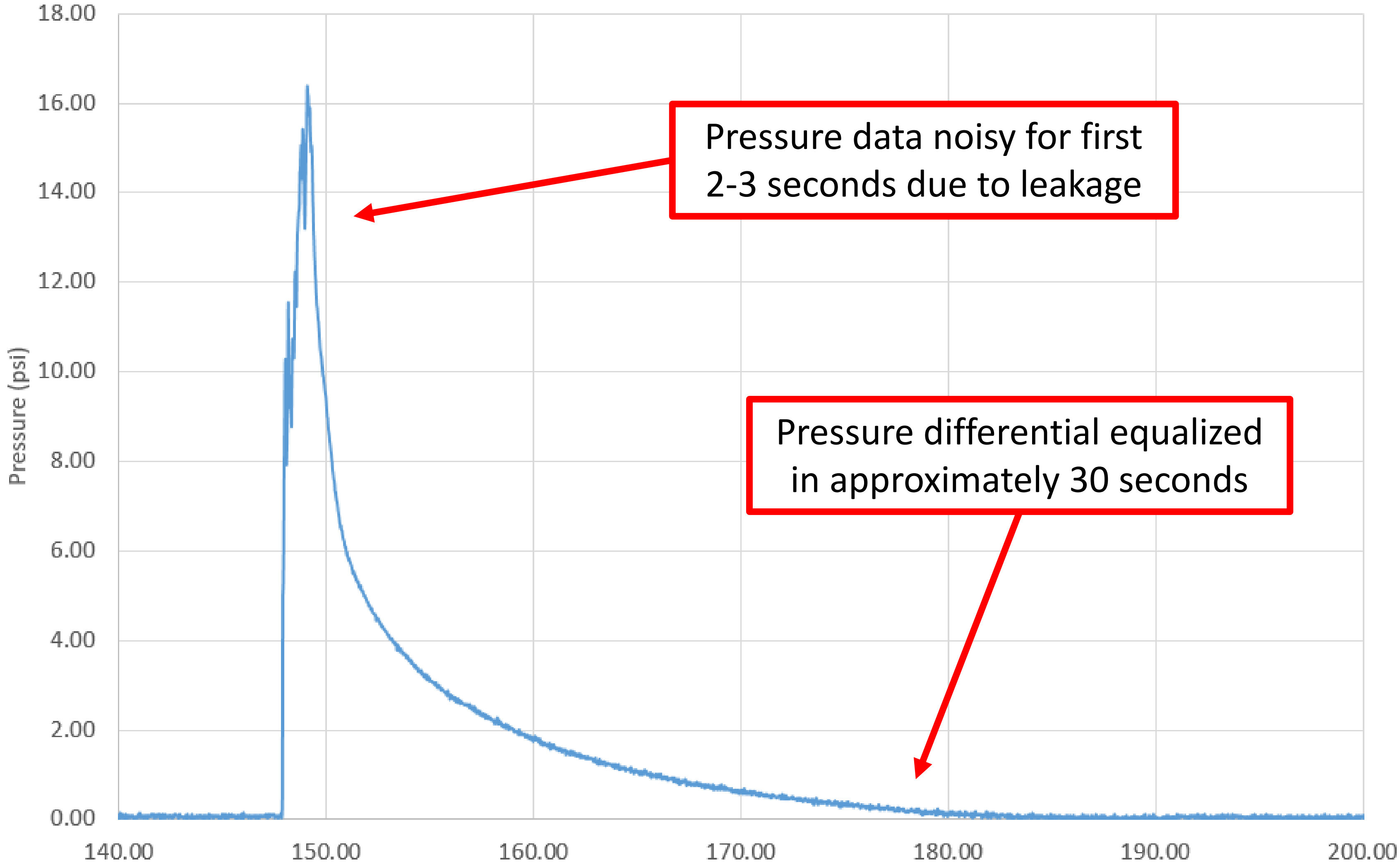


Before Initiation



Immediately After Initiation

MJ1 13p3s Submodule – Internal Pressure



Power/Full Solutions

Next Steps

- 23p8s battery design is heading toward CDR closure next week
  - Design achieves >135 Wh/kg
    - Compare to 107 Wh/kg for reference HCM design, with similar fraction of internal electronics
    - Compare to 70 Wh/kg for 2016 TR-tolerant HCM
  - Three pre-MRR design validation tests upcoming
    - Will demonstrate compliance to JSC 20793 rev D

- 13p8s battery design is past PDR

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Questions?