Design Safety Used in NASA's Human-rated Primary Lithium Batteries

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The 2013 NASA Battery Workshop

Huntsville, AL

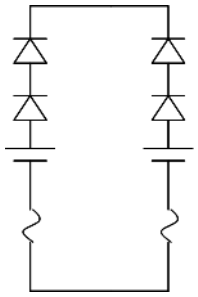
November, 2013

Safety Requirements

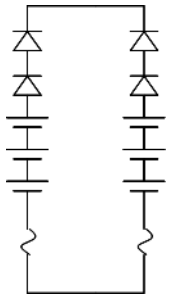
- NASA's human-rated safety requirements
  - Two-failure tolerance to catastrophic failures (JSC 20793)
- Catastrophic for human-rating requires
  - No electrolyte venting that would cause permanent injury to crew or loss of vehicle or mission
  - Electrolytes that can cause permanent injury are rated as Toxicology level 2 for NASA human-rated missions
    - Lithium primary with an organic electrolyte and li-ion with organic electrolytes have a salt that is an irritant and corrrosive giving these electrolytes a Tox2 rating
- The requirement therefore dictates that two-failure tolerance should be provided for all hazards that can lead to venting (electrolyte liquid), fire and thermal runaway.
  - For primary batteries this translates to two-failure tolerance to inadvertent charge, overdischarge into reversal, external and internal shorts, extreme temperatures especially high temps
  - Since no external controls exist for internal shorts, a design for minimum risk approach is used to mitigate that hazard.

Recommendations for Protective Features to Prevent Catastrophic Failures

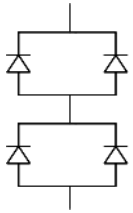
- Inadvertent charge shall be prevented
  - Between parallel primary lithium cells/cell strings
  - Between primary lithium cells and other charging sources



Cells in parallel

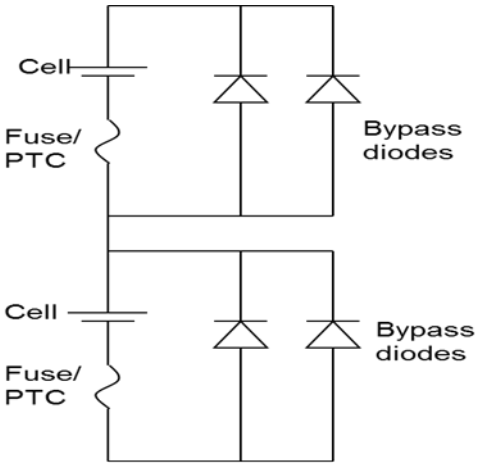


Cell strings in parallel



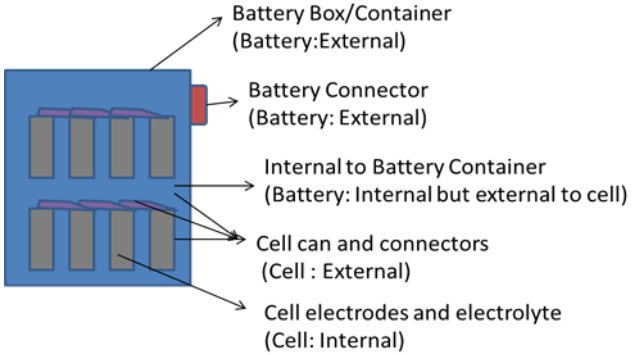
Redundancy in the case of mission critical applications

- Overdischarge into reversal
  - Prevent unbalanced cell condition (need for cell matching)
  - Prevent taking cells into low voltages and/ or reversal



Recommendations for Protective Features to Prevent Catastrophic Failures

- External Shorts
  - High and low impedance short protection required
  - Fuses, PTCs, polyswitches, etc. shall be rated for the voltage, current and temperature of battery design and application as well as environment



- Internal Short
  - Stringent cell and battery level screening (OCV, CCV, dimensions, mass, R_e)
  - Cell matching
  - Rigorous battery flight acceptance testing that includes (vacuum) leak check and vibration screening with stringent pass/fail criteria for OCV, CCV (R_e) and mass

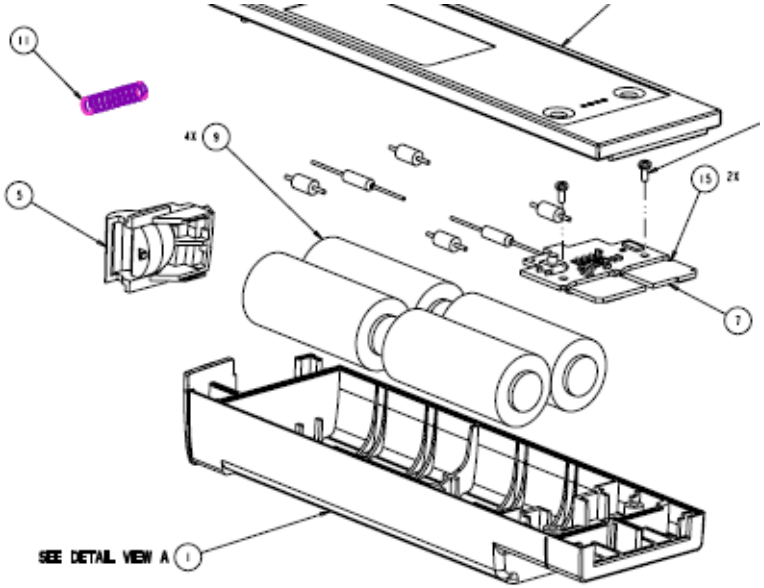
AED $LiMnO_2$ battery

AED for International Space Station (ISS) Human-rated Application (Flown in 2008 and has been on-orbit since)

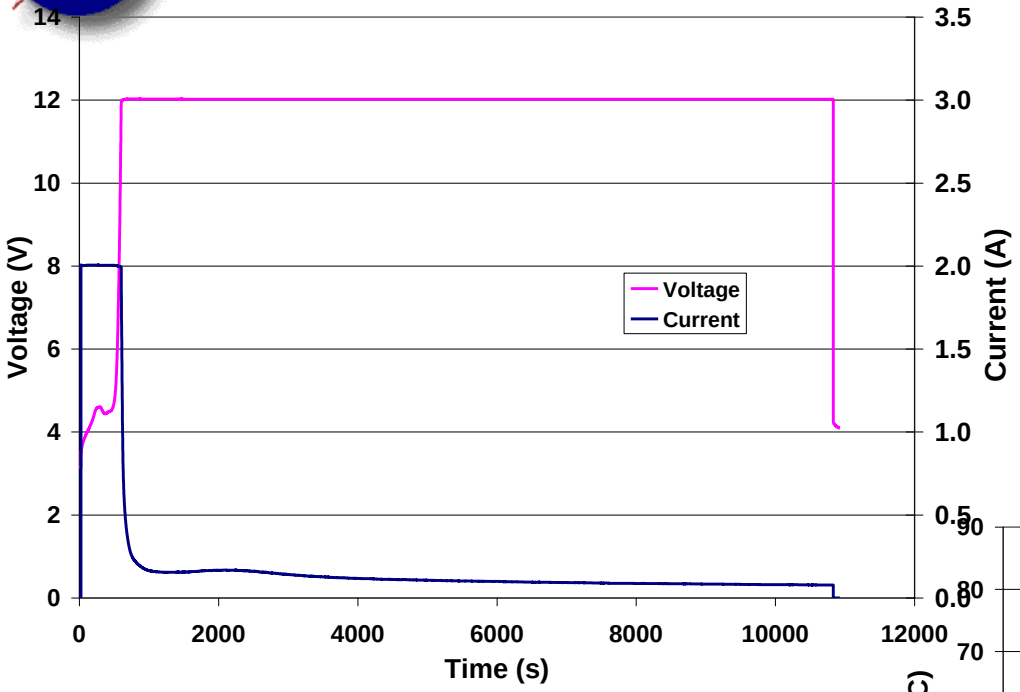
Original Design: Ultralife 5/4 C (U10021) high-rate cells; 4 in series; 1 diode in parallel to each cell; 2 TCOs one between cells 1 & 2 and one between cells 3 & 4

12 V; 6.2 Ah

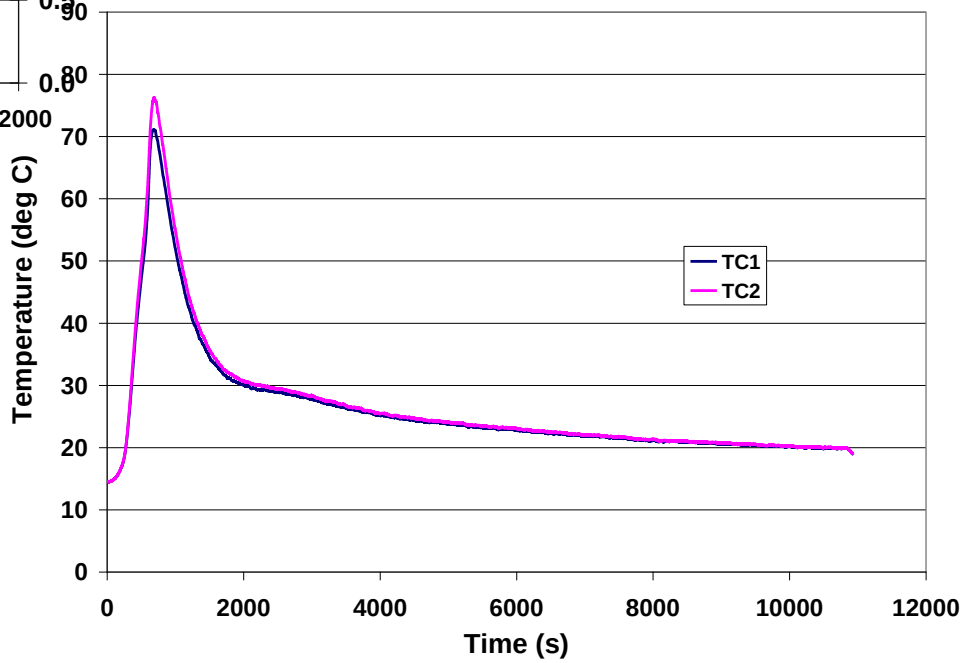
Original AED Battery Design



Inadvertent Charge on Single Cell



Charge Current: 2.0A
Duration: 6 hours
Limit: 12 V



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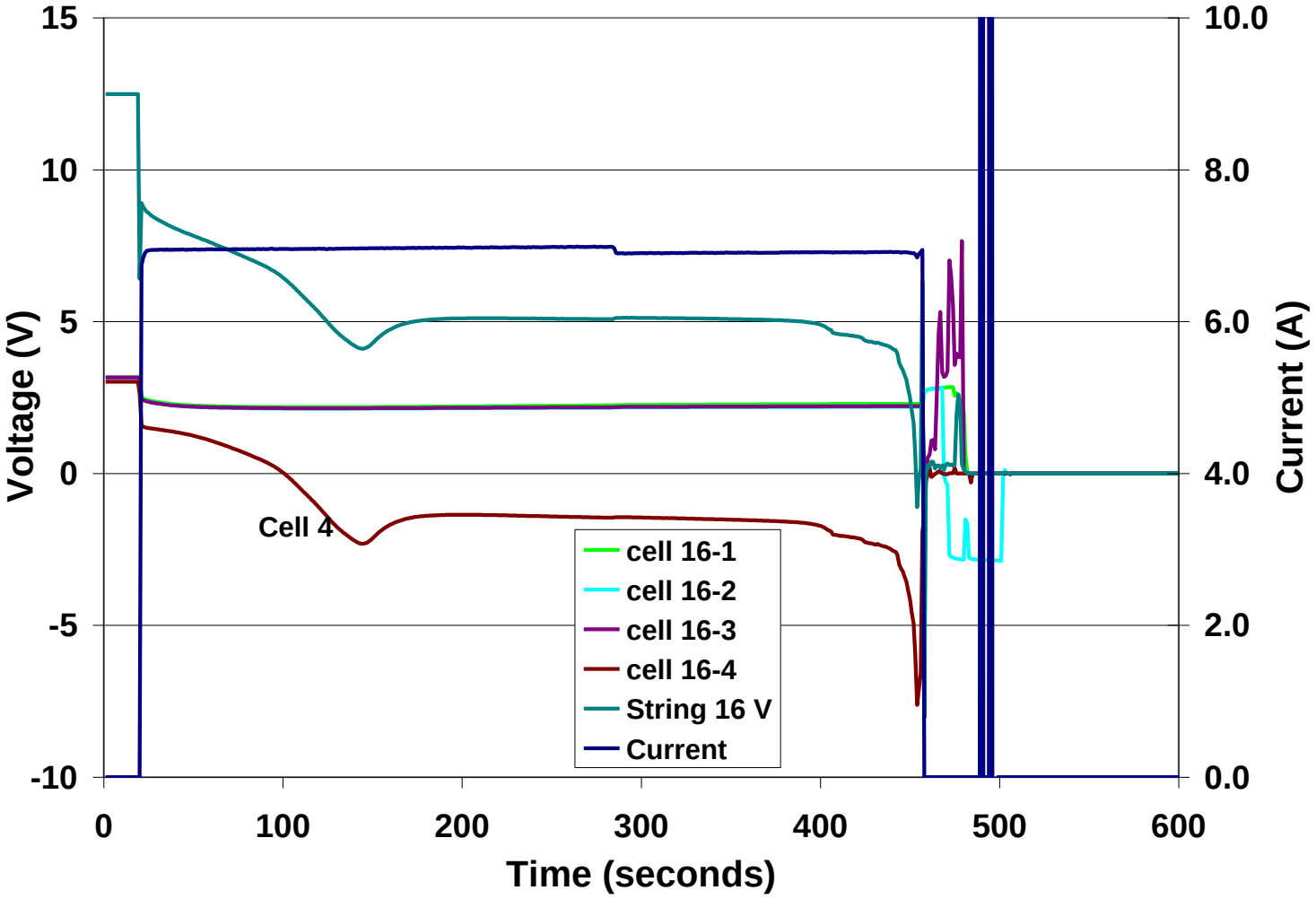
Overdischarge of Unbalanced String of Four Cells

Load: 6.9 A



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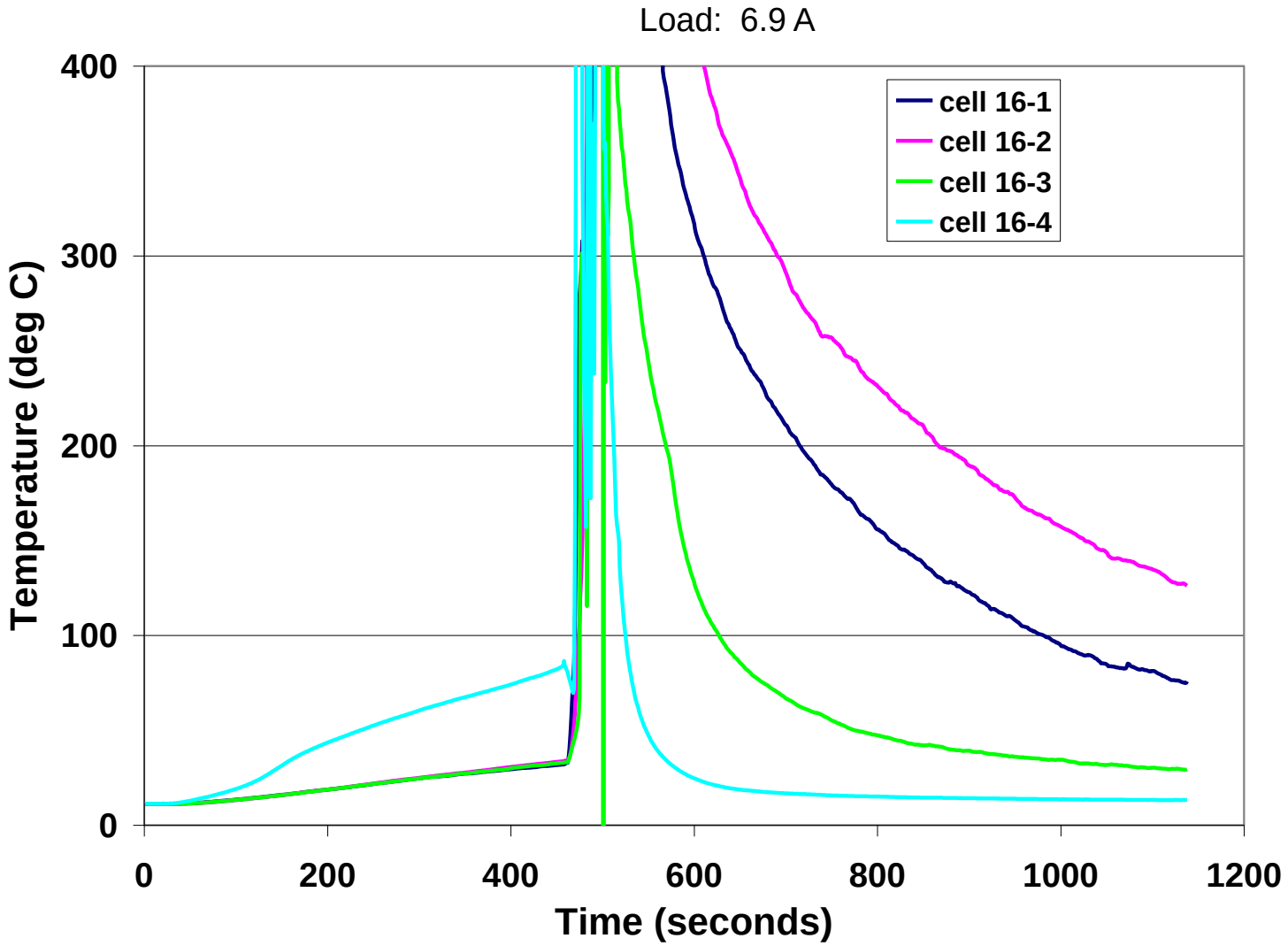
Overdischarge of Unbalanced String of Four Cells



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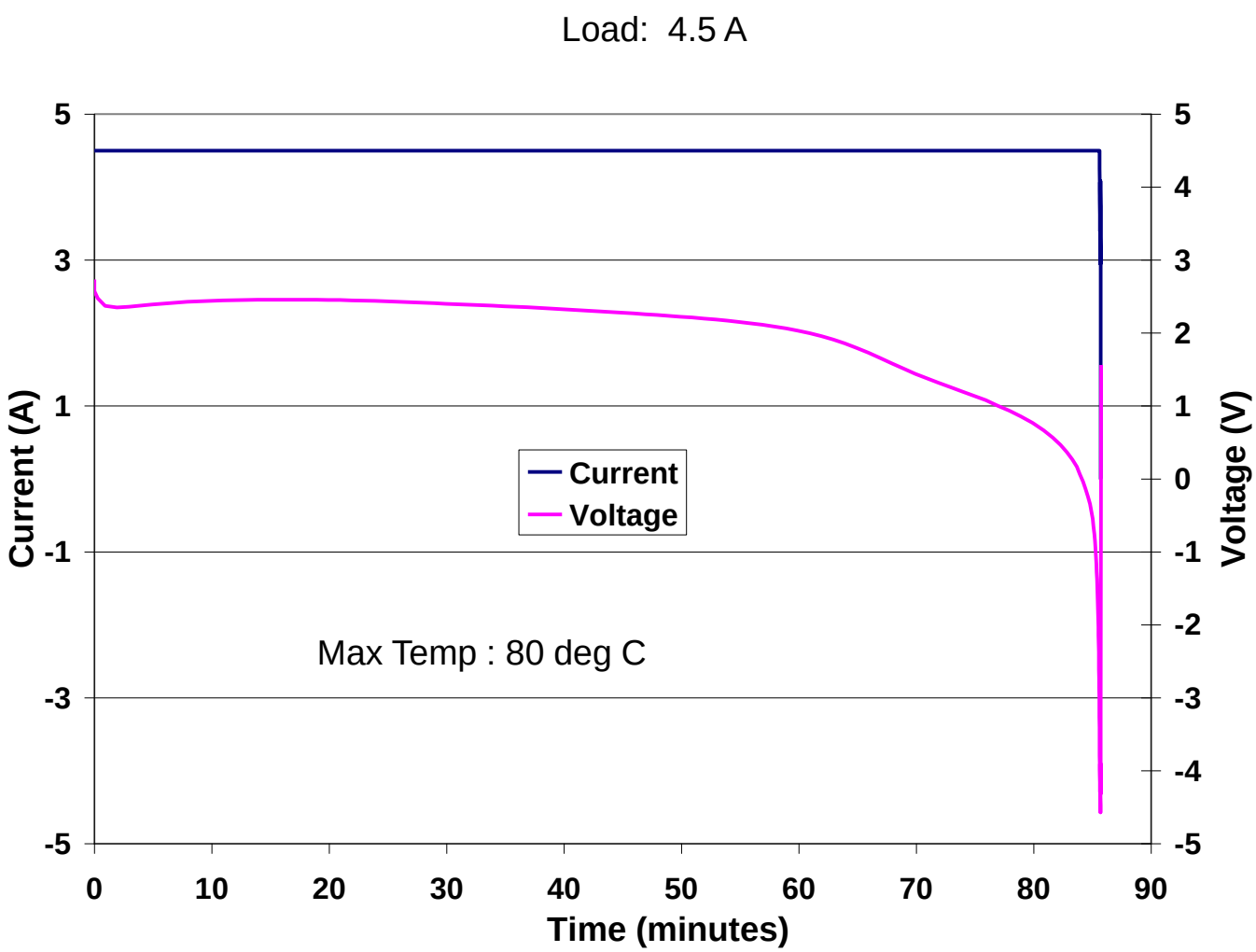
Overdischarge Into Reversal of Single Cell



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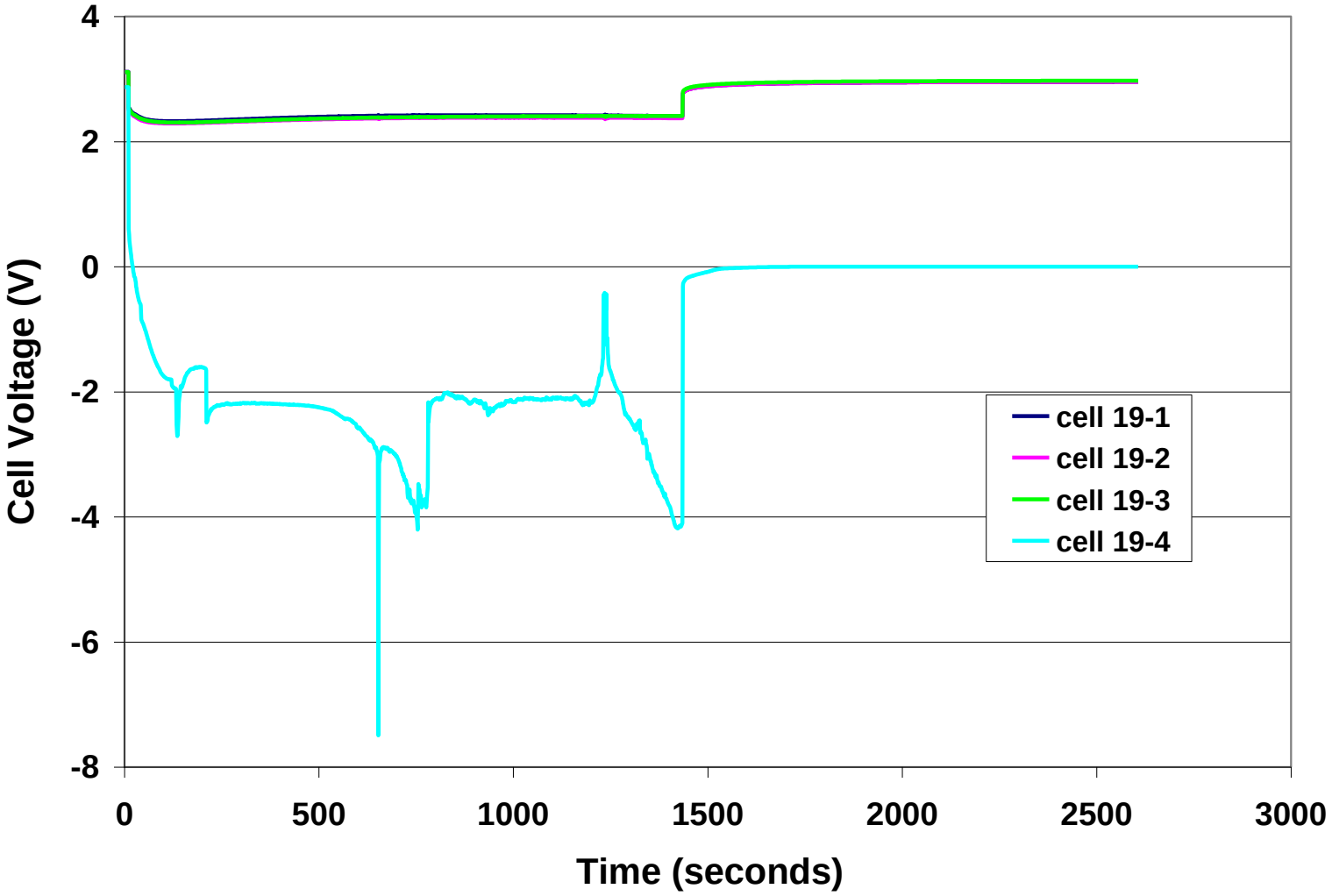
Overdischarge of Unbalanced String of Four Cells

Load: 4.5 A



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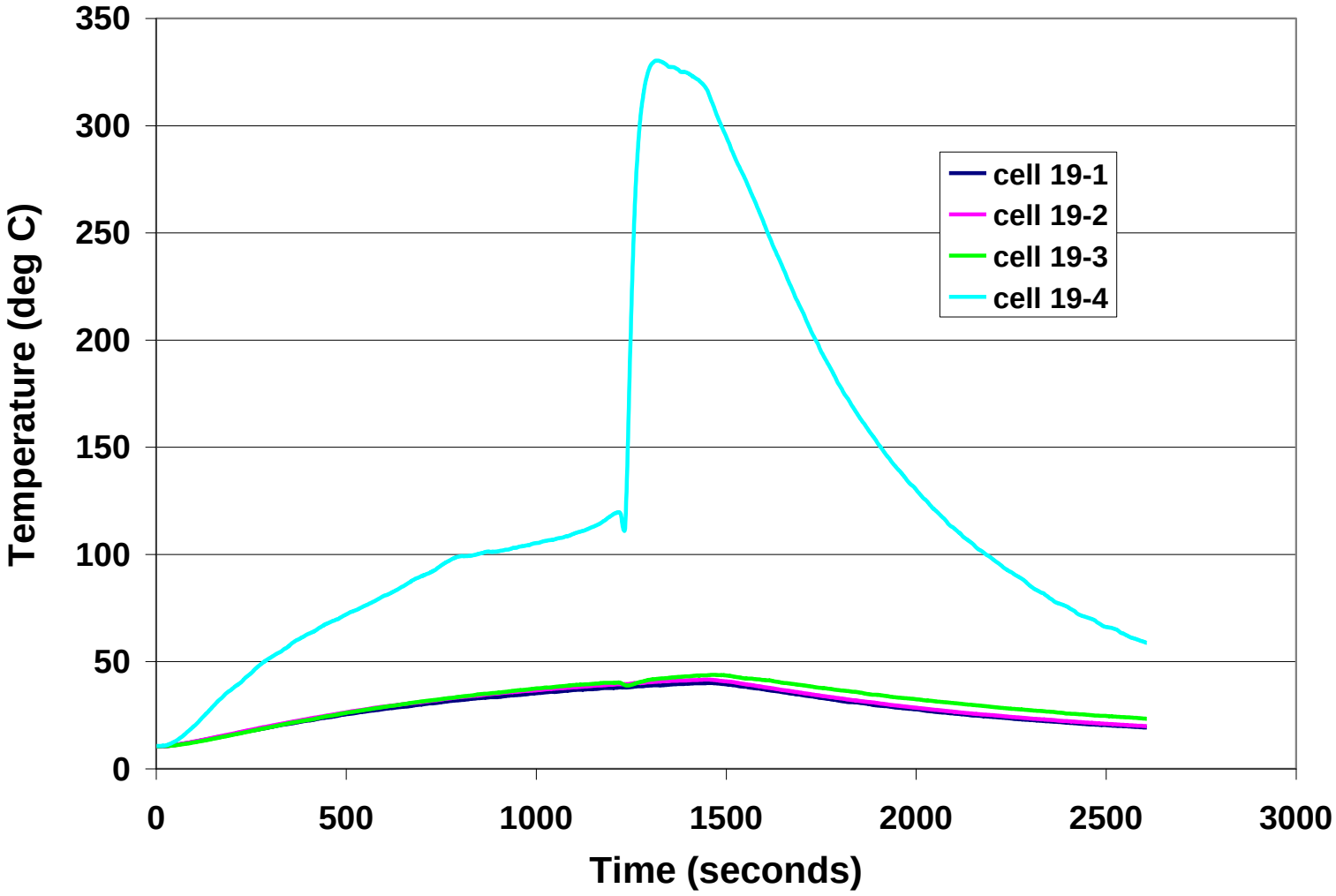
Overdischarge of Unbalanced String of Four Cells

Load: 4.5 A



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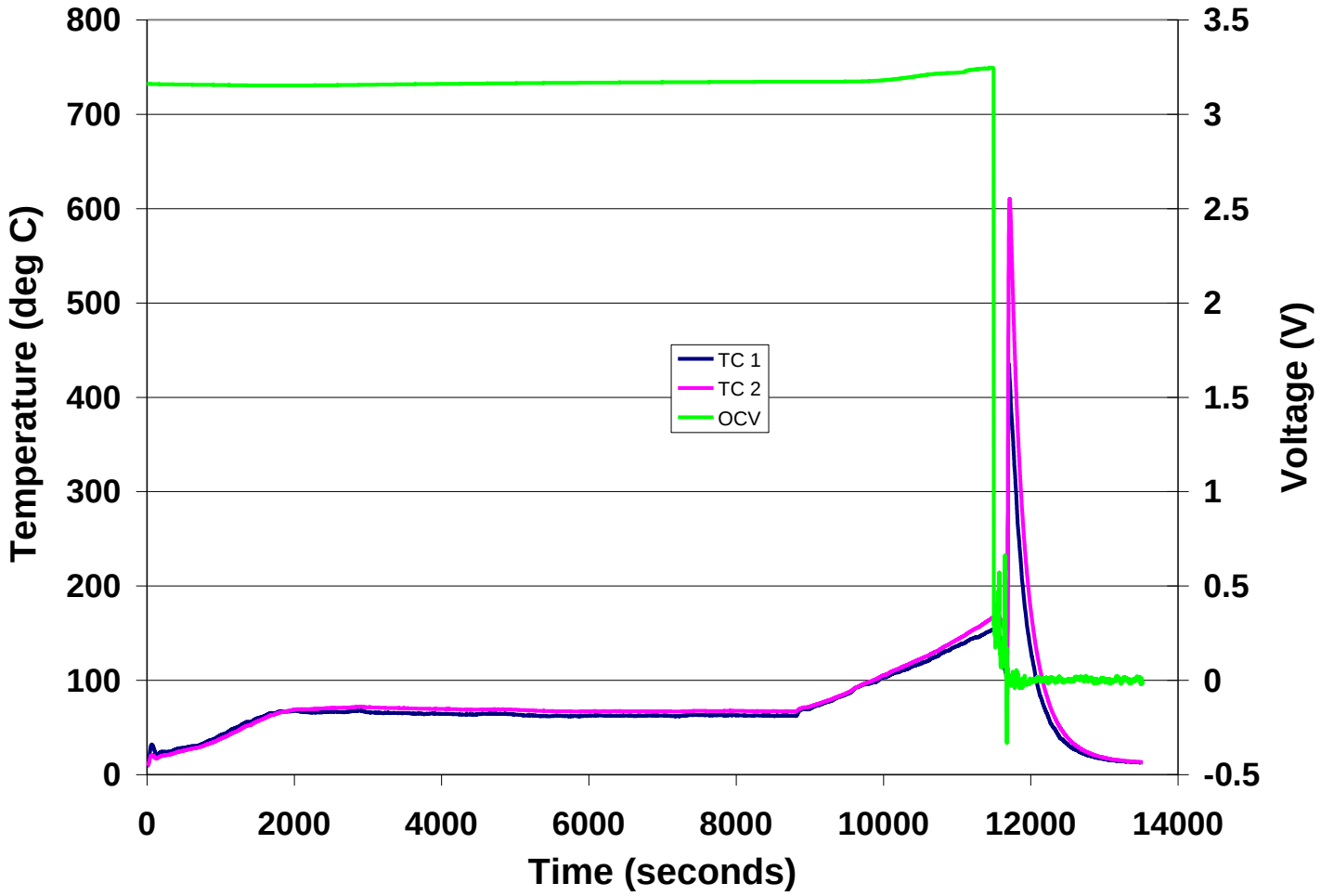
Heat-to-Vent Test on Single $LiMnO_2$ AED Cell



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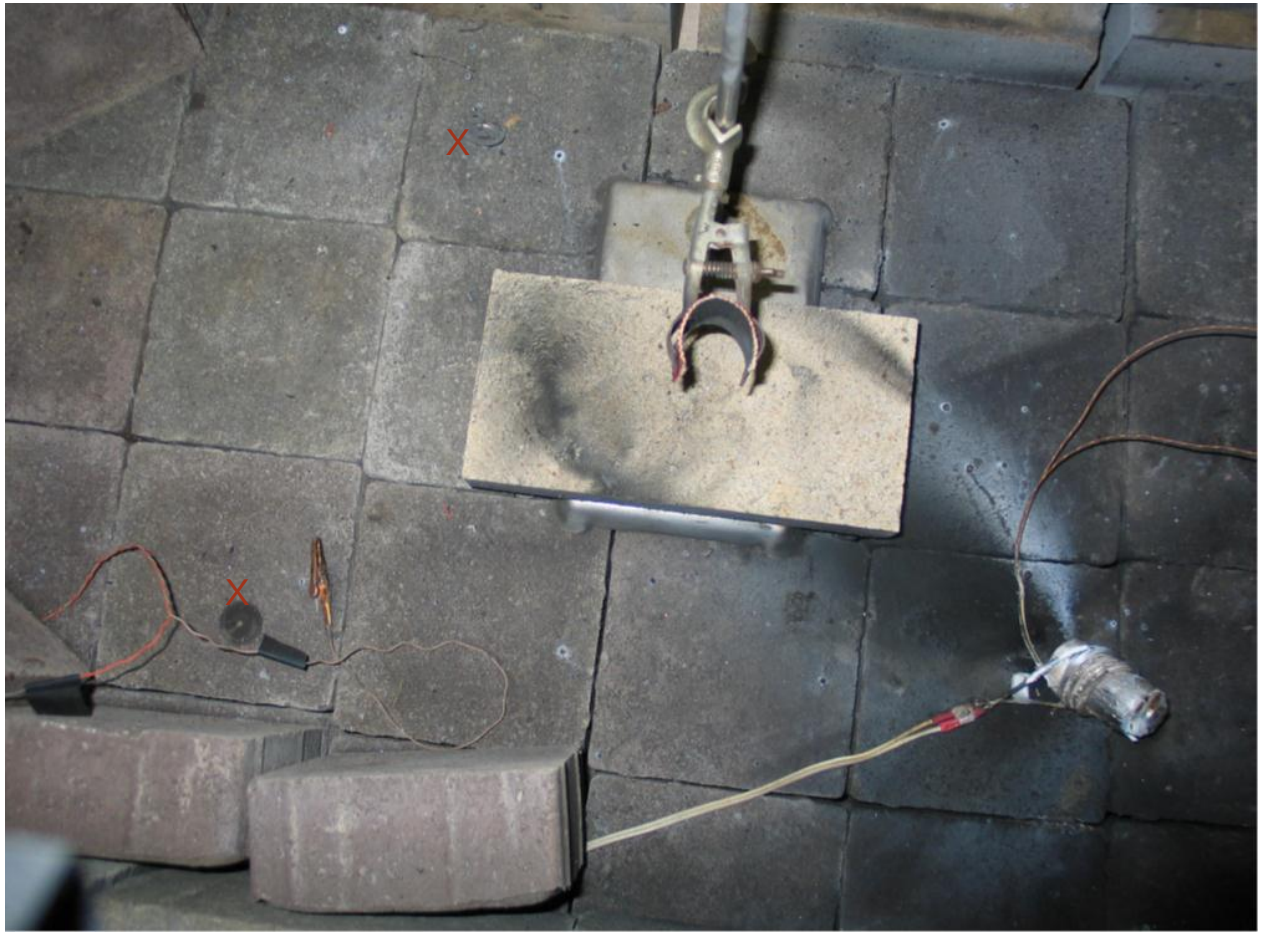
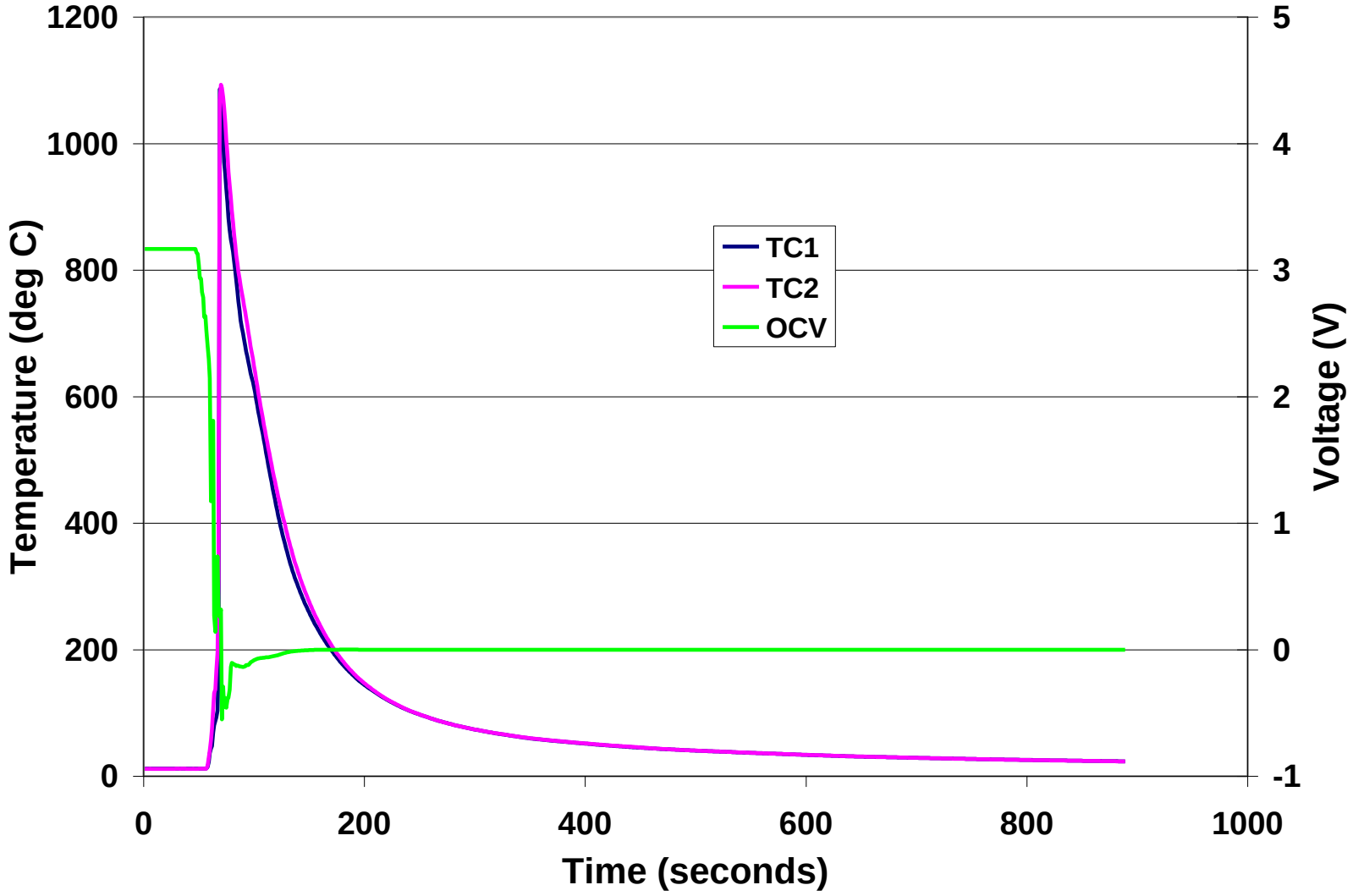
Heat-to-Vent of Single Cell



- **Originally, the cell was in the clamp on the ring stand.**
- **the cell went to the right, the feedthrough went towards the top to the left,**
- **the false cover went to the bottom left,**
- **the brick on the lower center was in alignment with the brick next to it (the bricks are 5 1/2 x 5 1/2 x 2 3/8 in.(14 x 14 x 6 cm) and weigh 5.8 lb (2.6 kg))**

Simulated Internal Short (Crush) on Single Cell



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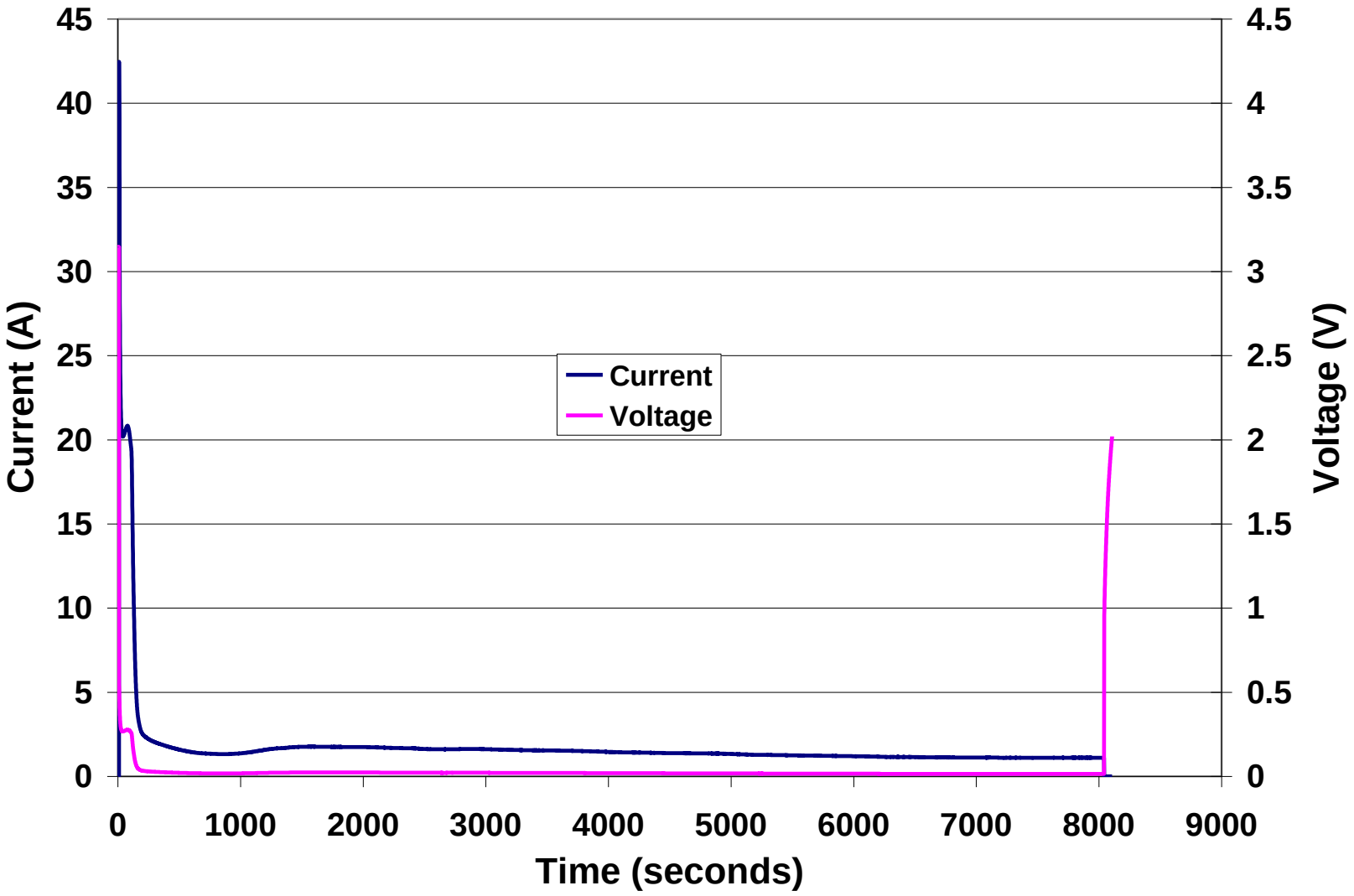
External Short Circuit Test on a Single Cell

Load : 50 mohm



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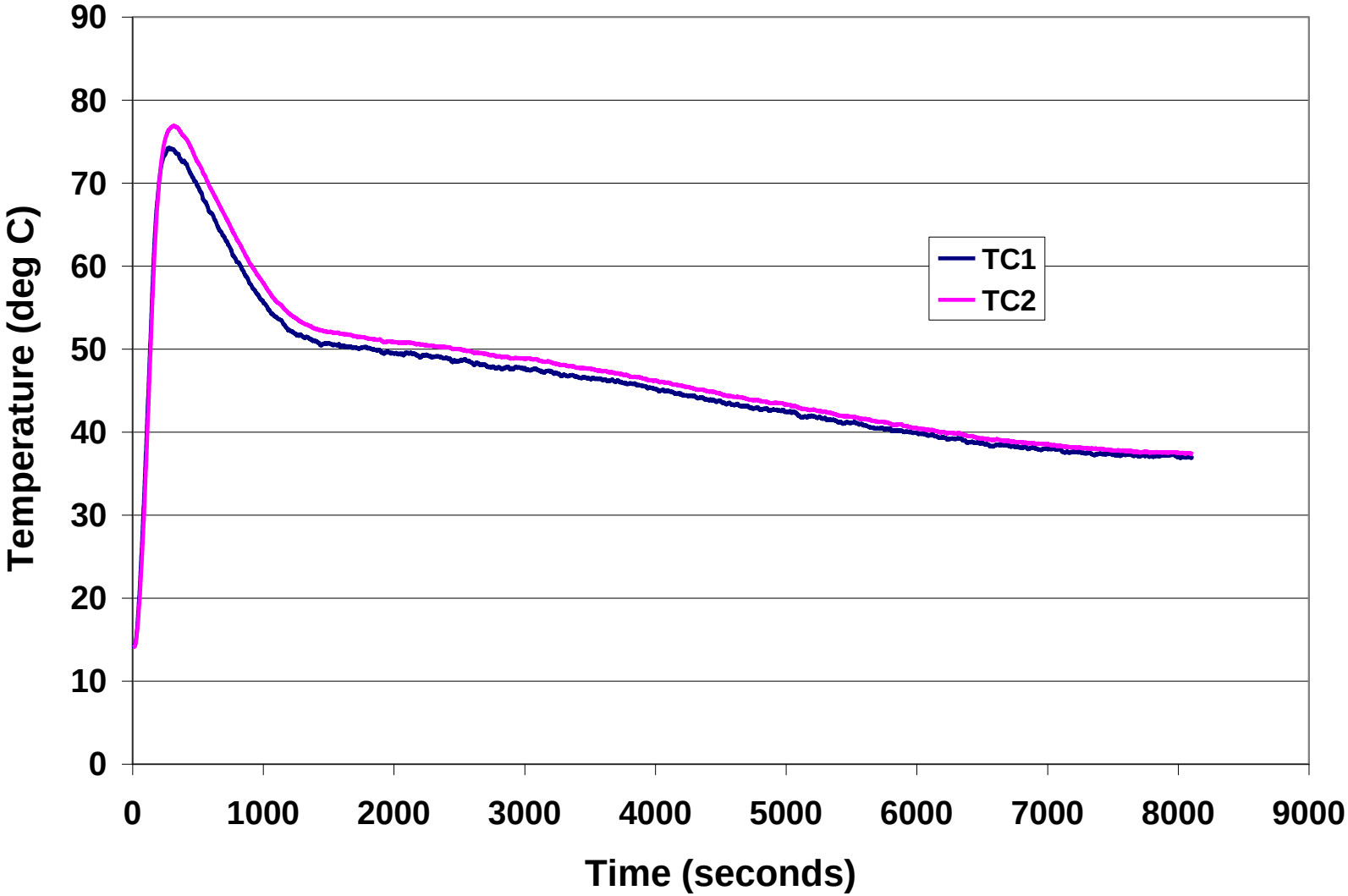
External Short Circuit Test on a Single Cell



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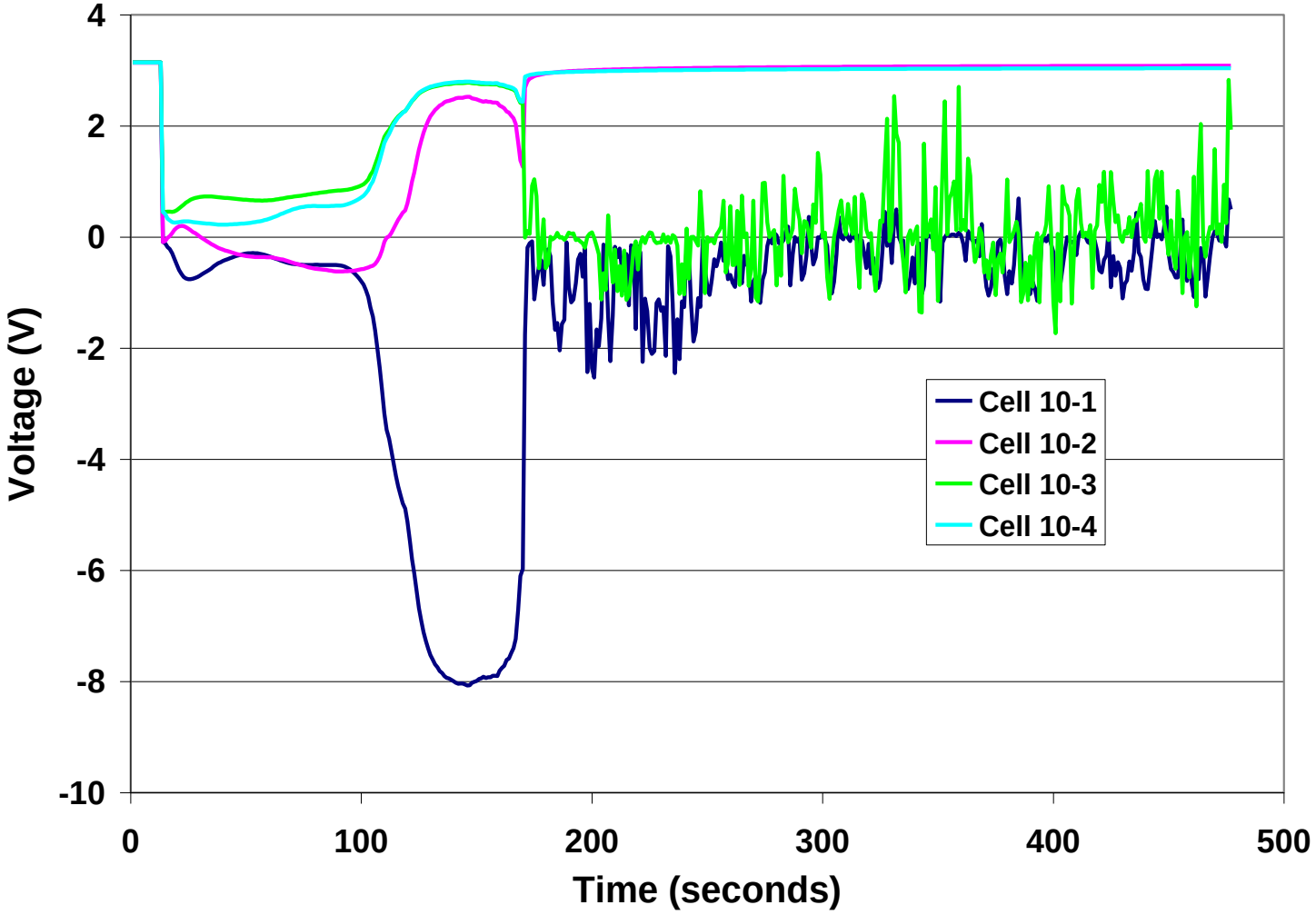
External Short on a String of Four Cells



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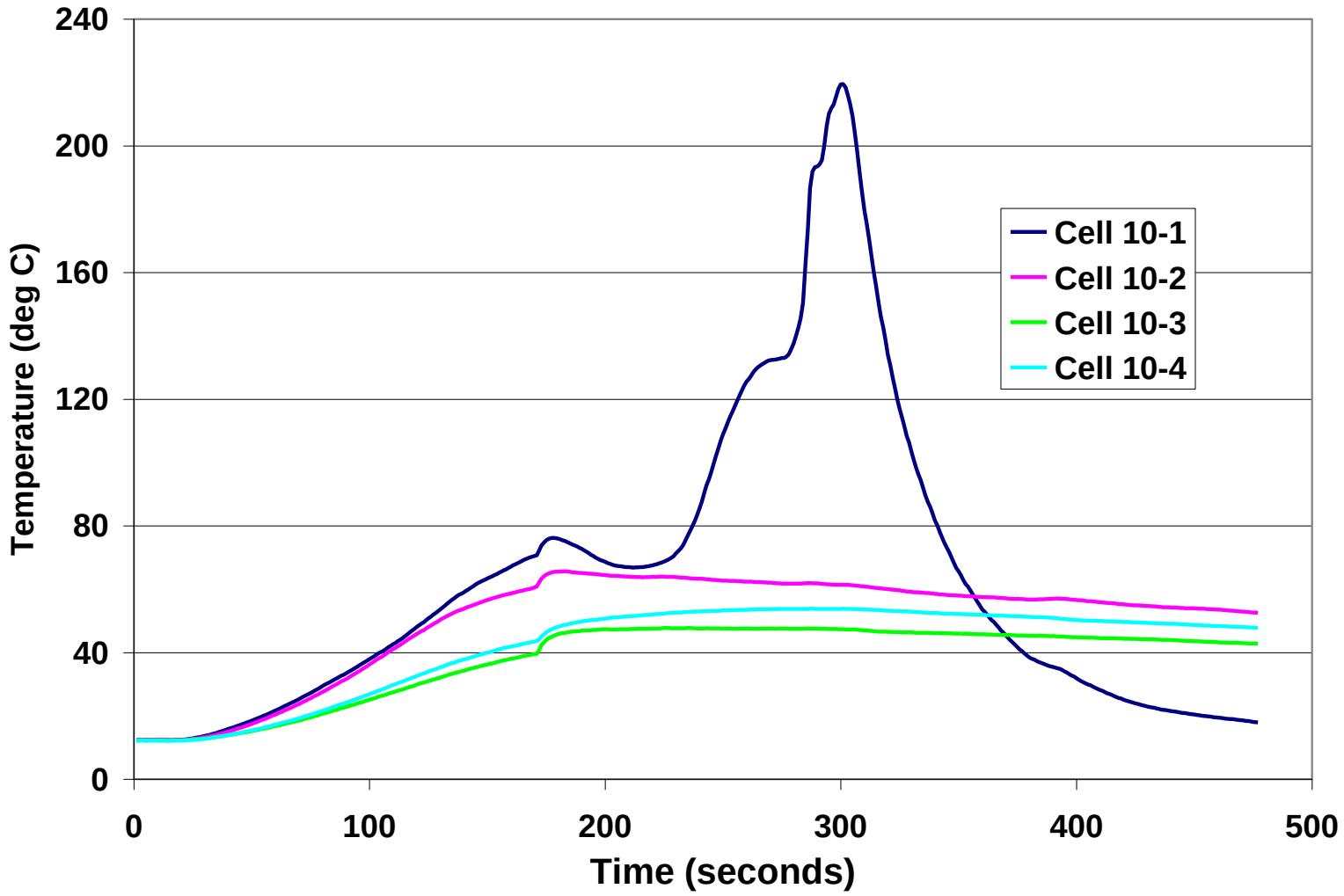

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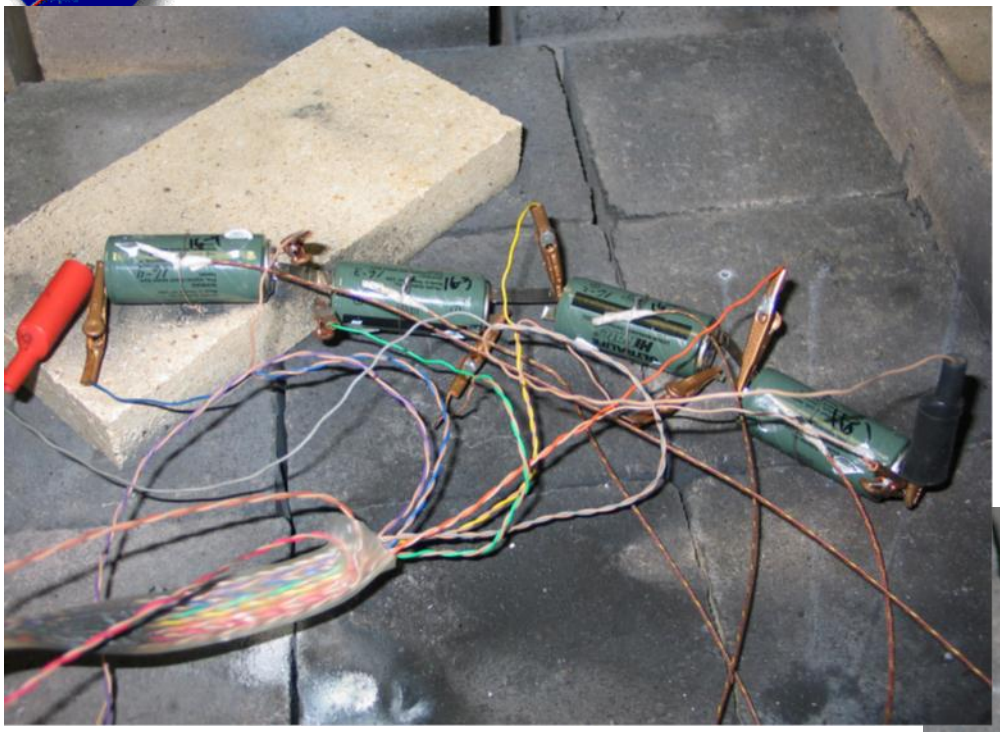
External Short on a String of Four Cells



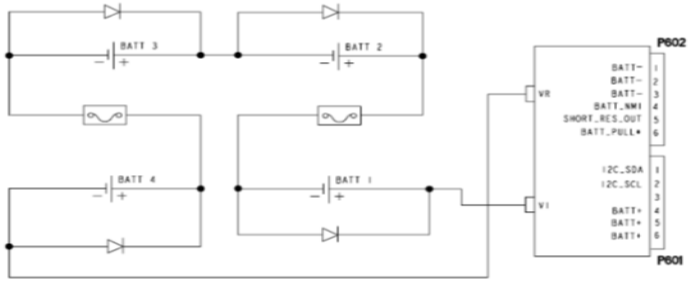
Summary of Test Results

- Single cell tests were benign for external short, inadvertent charge and overdischarge into reversal up to 4.5 A.
  - At lower current loads cells die (may be due to excessive dendrite formation) benignly.
- String level external short circuits lead to an unbalanced overdischarge, with one cell going into reversal. The result is catastrophic violent venting.
- Unbalanced string overdischarges at different currents causes catastrophic violent venting also.
- Heat-to-vent is very dramatic displaying violent venting
- Simulated internal short is also catastrophic and displays violent venting.

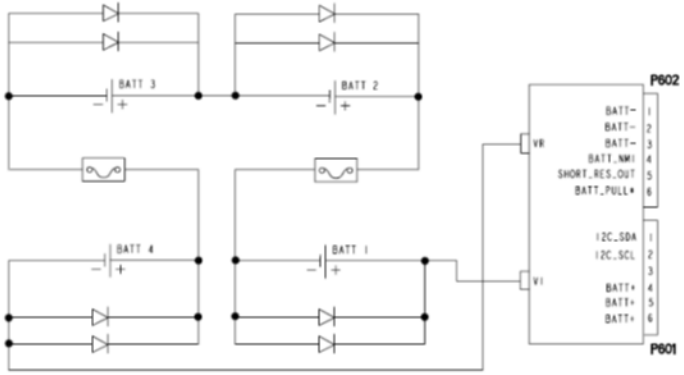
- Battery is not UL-rated; hence does not have dual-fault tolerance or tolerance to inherent cell tolerance to failures

Design Change as Recommended by NASA Battery Safety

Original AED Battery Design



NASA JSC AED Battery Design (currently on ISS)



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Summary and Conclusions

- Single cell tests were benign for external short, inadvertent charge and overdischarge into reversal up to 4.5 A.
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- Heat-to-vent is very dramatic displaying violent venting
- Simulated internal short is also catastrophic and displays violent venting.

- Battery is not UL-rated; hence does not have dual-fault tolerance or tolerance to inherent cell tolerance to failures
- Battery Design for NASA JSC's human-rated application for use on ISS was changed to include two bypass diodes per cell to provide for two-failure tolerance to overdischarge into reversal (and external short) hazards.

Acknowledgment

- Applied Power International
- Space and Life Sciences Directorate, NASA-JSC