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

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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 corrosive 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.

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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

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

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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

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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
Inadvertent Charge on Single Cell

Charge Current: 2.0A
Duration: 6 hours
Limit: 12 V
Overdischarge of Unbalanced String of Four Cells

Load: 6.9 A

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Overdischarge of Unbalanced String of Four Cells

Load: 6.9 A

Time (seconds)

Temperature (deg C)

- cell 16-1
- cell 16-2
- cell 16-3
- cell 16-4

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Overdischarge Into Reversal of Single Cell

Load: 4.5 A

Max Temp: 80 deg C

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Overdischarge of Unbalanced String of Four Cells

Load: 4.5 A
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
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))

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Simulated Internal Short (Crush) on Single Cell

Temperature (deg C)

Voltage (V)

Time (seconds)

TC1
TC2
OCV

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External Short Circuit Test on a Single Cell

Load: 50 mohm

- Current (A)
- Voltage (V)

Time (seconds)
External Short Circuit Test on a Single Cell
External Short on a String of Four Cells

![Graph showing voltage over time for four cells.](image-url)

Cells 10-1 to 10-4 are plotted against time in seconds. The graph displays the voltage changes over time for each cell, with distinct lines for each cell type.
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)
Summary and Conclusions

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  - At lower current loads cells die (may be due to excessive dendrite formation) benignly.
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- 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
- 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.

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