Battery Safety
Requirements and Approach

and

Revisions to JSC 20793

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Battery Requirements Documents

Be familiar with the two battery requirements documents:

- JSC 20793 Crewed Space Vehicle Battery Requirements
  - Current official version is Rev B, Rev C will be official by early December (accepted by Commercial Crew and Cargo; CR almost complete for ISS)

and

- JWI 8705.3 Battery Processing

Energy and Toxicity

Two main factors that categorize safety

- Energy provided in Wh/kg or Wh/L – categorization and waivers provided under each chemistry
- Toxicity – based on electrolyte (vapors, decomposition products, etc.)

- General Tox information. Tox memo should be obtained from the toxicologist who makes the final decision.
- KOH: alkaline, NiCd, NiMH, AgZn – caustic and corrosive- will burn skin and eyes. Typically Tox 2.
- H_2SO_4: Lead acid- acidic and corrosive, will create acid fumes that can damage throat and lungs. Typically Tox 2 unless the amount is significantly large.
- $SOCl_2$: $LiSOCl_2$ and BCX- burn skin, eyes, damage throat and lungs to a higher degree than above and can be lethal. Tox 4; could be lower if electrolyte quantity is negligible.
- $Li(CF)_x$, $LiMnO_2$, $LiFeS_2$, Li-ion: affects skin and eyes on contact; electrolyte is flammable and can cause fire in the presence of an ignition source. Tox 2 depending on nature of salt in electrolyte.

Fault- Tolerance

- Failure tolerance is the basis of the NASA safety approach. This method is applied in all safety evaluations unless it can be proven that a failure tolerance approach is not feasible.

  a. Battery systems for crewed spacecraft shall implement failure tolerance as the preferred approach to control all catastrophic hazard causes.

  b. The level of failure tolerance shall be the product of an integrated design and safety analysis but be a minimum of one (Rev B required two-fault tolerance approach)

Following NASA Procedural Requirements (NPR) 8705.2B

- Some potentially catastrophic hazards cannot practically be controlled using failure tolerance and are exempted from the tolerance requirement provided the risk they pose is mitigated to the maximum practical extent through a defined process in which approved standards and margins are implemented to account for the absence of failure tolerance. Herein, this process is called DFMR.

  a. The DFMR approach shall be used to address catastrophic battery hazards that cannot practically be controlled by a failure tolerance approach.

Following NASA Procedural Requirements (NPR) 8705.2B

Typical Failure Modes & Controls or Mitigation Measures for Battery Designs

Overcharge (for rechargeables) or Inadvertent Charge (for non-rechargeables)
Min. 3 controls verified by test
*Manuf. spec

Overdischarge into Reversal (for Primaries) or Repeated Overdischarge or Overdischarge followed by charge
Min. 3 controls verified by test
*Manuf. Spec.

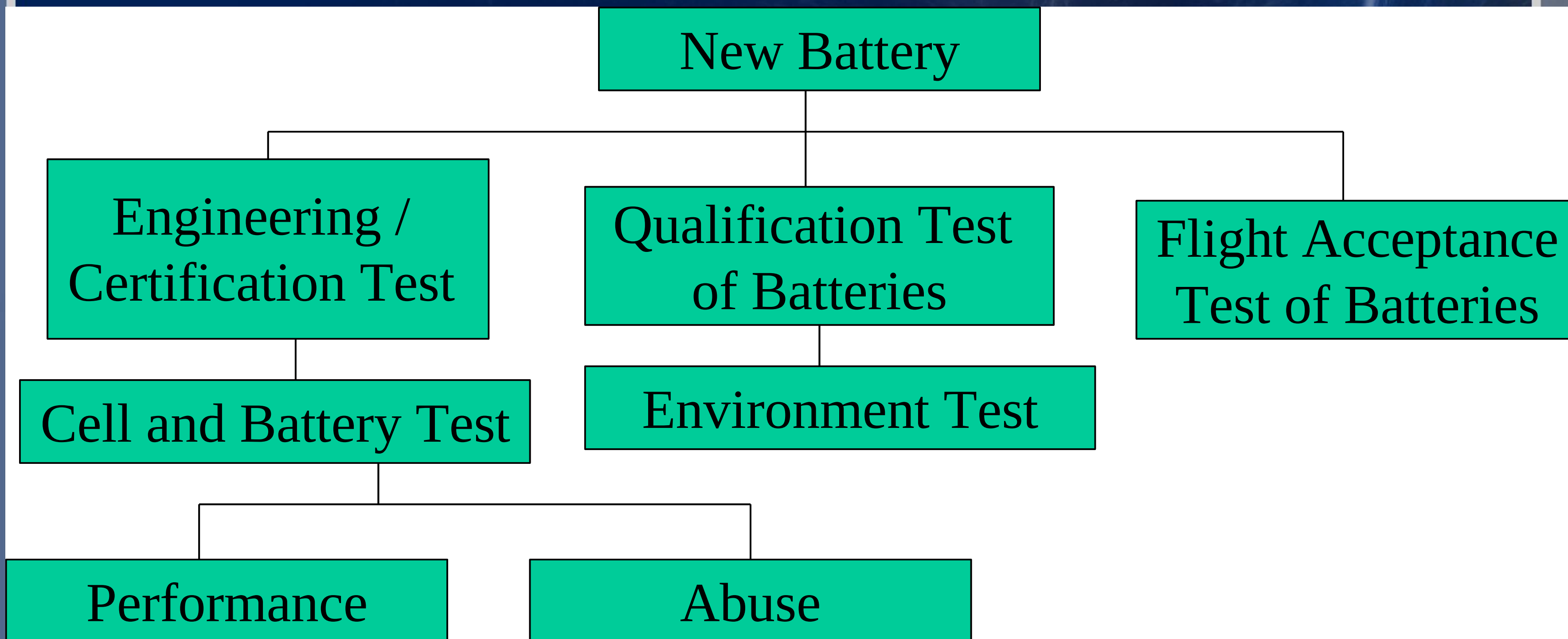
High temperatures/High Thermal Environments
*Thermal analysis leading to appropriate thermal sensing; 3 Controls; Verified by test
Design qualified to extreme temps *Manuf. Spec.

External Shorts:
High and Low Impedance
Combination of Controls and Design for Minimum Risk
Verified by test;
*heat dissipation

Internal Short
Design for Minimum Risk
Stringent testing and screening of flight cells;
Usage within manufac. spec. (latent defects, field failures)
•Impeccable cell quality, cell uniformity; manuf. facility audits

- Test at appropriate level (cell/module/battery/system) to determine safety characteristics and tolerance to any hazardous condition
- Analysis and modeling (high fidelity) with testing to confirm results from analysis

Battery Flight Certification Process



Process for a New Lot of Certified Batteries

New Lot / Batch of Batteries

Lot Sample Test
3 to 6 % of every lot

Flight Test
(100 % of flight batteries)

To verify critical qualification tests and safety controls in battery /cell designs (Tests that are critical especially those that are considered to be safety controls)

Non-COTS Battery Certification Process

Cell Selection (after trade study/testing)

Test – functional, relevant environment, safety

Battery Design and Assembly

Battery Engineering/Certification Test (cell, module and battery level)

Battery Qualification Test (flight environment with margin)

Flight Acceptance Test (includes cell screening, matching, module and battery assembly and tests)

Exemptions to Extensive Testing

- Button cells of Li primary types ($LiCF_x$, $LiMnO_2$, $LiFeS_2$, LiV_2O_5, Li-iodine, etc.), Li rechargeables (includes all li-ion, LiV_2O_5, $LiMnO_2$, etc.), NiMH, NiCd, Ag/Zn, of 300 mAh or less.
  - All (100%) flight cells and batteries should pass acceptance tests that include visual examination, OCV, CCV/functional check, vacuum leak check (0.1 psia for 6 hours)
  - Form-03 should be completed and submitted for review.
  - Protective circuit schematic to be provided wherever possible; UL data can also be provided for review.
  - Above acceptance testing for button cells which are soldered to a circuit board in commercial equipment (not applicable to those button cells in a spring-loaded clip) is limited to a functional check of the equipment utilizing the subject battery.

Cat 1 in 907

Exemptions to Extensive Testing

- Alkalines : 12 V and 60 Wh; only in series or only in parallel; no combinations of series-parallel, no gastight battery compartment
  - All (100%) flight cells and batteries should pass acceptance tests that include visual examination, OCV, CCV/functional check, vacuum leak check (0.1 psia for 6 hours)
  - Form-03 to be completed and submitted for review.

Need for Vented Battery Compartment:

Energy Content: Water: KOH electrolyte is 30 -45 % weight in water. KOH is electrolyte in alkaline cells. If electrolyzed by inadvertent charge or overdischarge, it yields a H_2/O_2 mixture that has an equivalent of 5783 Btu/lb (Oxygen is non-flammable but supports and vigorously accelerates combustion of flammables; hydrogen is in itself a fuel).

Note: D cell is 18 Ah capacity

Cat 1 in 907

Wh: V x Ah (Voltage x Capacity)

Exemptions / Reduced Testing

- COTS NiMH, NiCd and Ag/Zn cells and batteries for IVA use up to 20 V and 60 Wh
  - Cells and batteries purchased in one lot; pass acceptance tests that include loaded and open circuit voltage measurements, visual examination, leakage check under vacuum (e.g 6 hours at 0.1psia) and vibration to workmanship levels with functional checks which include charge/discharge cycles before and after each environmental test.
  - Require the use of Form-03 for the approval process. Manufacturer's specification, battery protective features and charger schematic shall be provided for review.

Cat 1 in 907

Exemptions / Reduced Testing

- COTS Li-ion batteries up to 10 V and 60 Wh for IVA use
  - Batteries shall be from a single lot; COTS chargers shall be from a single lot.
  - Batteries shall show one-fault tolerance at battery level and shall pass acceptance tests that include loaded and open circuit voltage measurements, visual examination, leakage check under vacuum (e.g 6 hours at 0.1psia) and vibration to environment or double the workmanship level, whichever is higher; and functional checks which include charge/discharge cycles between each of the environmental tests.
  - Require the use of Form-03 for the approval process. Battery protective features and charger schematic shall be provided for review.

Note: Other levels of control shall be from hardware using battery, and/or in the charger; heritage cell test data, and crew procedures in the event of an emergency

Cat 1 in 907

New Requirement (JSC 20793 Rev C)

5.1.5.1 Requirements – Thermal Runaway Propagation

a. For battery designs greater than a 80-Wh energy employing high specific energy cells (greater than 80 watt-hours/kg, for example, lithium-ion chemistries) with catastrophic failure modes, the battery shall be evaluated to ascertain the severity of a worst-case single-cell thermal runaway event and the propensity of the design to demonstrate cell-to-cell propagation in the intended application and environment.

b. The evaluation shall include all necessary analysis and test to quantify the severity (consequence) of the event in the intended application and environment as well as to identify design modifications to the battery or the system that could appreciably reduce that severity.

Test Details for Cells and Batteries

- Test Details can be obtained from the JSC 20793 Rev C (engineering, qualification and flight acceptance test sections as well as from Chapter 6 which has the chemistry sections)

- In addition to that, the following documents were written specifically for certain types of hardware:
  - JSC 66548 (Requirements for Flight Certification and Acceptance of COTS Li-ion Batteries)
  - EP-WI-032 (Statement of Work- Engineering Evaluation, Qualification and Flight Acceptance Tests for Li-ion Cells and Battery Packs for Small Satellite Systems)
  - Other specific ones:
    - EP-WI-23 (Spec for lot testing and flight screening of Energizer AA LiFeS2 Batteries)
    - JSC 66217 (Spec for Lot Testing and Flight Screening of Canon BP 927 and BP 930 Li-ion Batteries)
    - EP-WI-14 (Spec for Acceptance Testing of Commercial NiMH and NiCd Cells)
    - JSC 62618 (Flight Acceptance Tests for the Kodak DCS760 NiMH Batteries)
    - JSC 62863 (Flight Acceptance Tests for the IBM Thinkpad A31P Batteries)

- If new hardware, that does not fall under any of these established documents, is to be flown, hardware owners can work with EP5 battery team to work out a plan to complete safety certification and flight acceptance testing of the batteries
- Past Experience with flying: COTS batteries with COTS hardware; COTS batteries with custom-designed hardware; COTS batteries used for portable equipment used with other COTS hardware; custom batteries with custom hardware.

Revisions to the Crewed Space Vehicle Battery Safety Requirements JSC 20793

Background

- Crewed Space Vehicle Battery Safety Requirements, JSC 20793
  - Began as a Handbook in '85; Used widely throughout Agency in handbook form
  - Converted to requirements document (standard) in 2005
  - Current version is Rev B. (2006)
  - Only battery safety standard within the Agency

- The need for an update to JSC 20793 was required for the following reasons
  - NASA battery teams have learned a lot (internal and external test data) since the document was last updated especially on chemistries such as li-ion
  - After NASA support to the Boeing Dreamliner 787, the NASA battery technical team confirmed the need to revise the standard bringing it up to date and incorporating lessons learned from the 787
  - The extensive use of high voltage and high capacity Li-ion batteries
  - Use of new battery chemistries like Li-S as well as others like thermal batteries for commercial crew and cargo and Orion launch systems
  - Introduction of Supercapacitors in the place of batteries, etc.

- The format was revised to follow NASA standards template
  - Requirement based format with italicized text included explanatory, best practice, and rationale information

Major Changes

- High Level requirements with a single shall in each and suggested best practice
- Rev C is less prescriptive on "how to" and is more objective oriented
- Shall statements localized to sections 4 and 5 with each of these sections receiving a major format revision
  - Section 4 now contains all of the general battery requirements such as test protocols and FT requirements
  - Section 5 focuses on the catastrophic hazards at the top level and then calls out the controls for each and is hence more aligned with a typical hazard report.
- Added glossary, definitions, and numerous appendices (qual testing, requirements matrix, approval process, etc.)
- Examples and details of change are provided in the next few pages.

JSC 20793 Updates and Changes

JSC 20793 Rev B

1. Introduction (Purpose/Scope, responsibility)
2. Applicable/Reference Documents
3. Battery Requirements
   - 3.1 Battery Design eval and approval
   - 3.2 Fault Tolerance (critical *vs* catastrophic
   - 3.3 Risk
   - 3.4 Hazard Controls
   - 3.5 Flight Cell and Battery Pack Testing
   - 3.6 On-orbit Usage
   - 3.7 Post-flight Cell and Batt processing

JSC 20793 Rev C

1. Introduction (Purpose/Scope, responsibility, battery design evaluation and approval)
2. Applicable/Reference documents
3. Acronyms and Definitions
4. General Battery Requirements
   - 4.1 Methodologies Used in Ensuring Safe Outcomes (Failure tolerance and design for minimum risk)
   - 4.2 Key Aspects of Engineering Evaluation, Qualification and Acceptance Testing
   - 4.3 Manufacturing Quality (configuration control, lot testing)
   - 4.4 General Design Requirements (electrical interconnects, wiring, li-ion battery and cell monitoring, cell matching, dissimilar controls)
   - 4.5 Mission Usage
   - 4.6 Post-flight cell and pack evaluation
   - 4.7 Ground Processing Requirements
   - 4.8 Shelf and service life related requirements

Changes/additions are represented in red

SAA: Same as above

JSC 20793 Updates/Changes (contd..)

JSC 20793 Rev B

4. General Hazards and Controls
   - –4.1 Structural (Sources, hazards and controls)
   - –4.2 Battery Gases (SAA)
   - –4.3 Pressure (SAA)
   - –4.4 Electrolyte Leakage (SAA)
   - –4.5 Short Circuits (SAA and contains internal and external short hazard causes)
   - –4.6 Circulating Currents (SAA)
   - –4.7 High Temperature (SAA)
   - –4.8 Charging (SAA)
   - –4.9 Overdischarge into Reversal (SAA)

JSC 20793 Rev C

5. General Battery Hazards and Controls
   - –5.1 Fire/Explosion Hazard (Sources: chemical reaction, overcharge failure/overdischarge failure, external short circuit, internal short circuit, thermal runaway propagation)
   - –5.2 Chemical Exposure Hazards (mechanical failure, seals and vents)
   - –5.3 Electrical Hazards (Electrical shock, corona, arc-flash)
   - –5.4 Extreme Temperature Hazards (sources and requirements)

Changes/additions are represented in red

SAA: Same as above

JSC 20793 Updates/Changes (contd…)

JSC 20793 Rev B

5. Safety Relevant to Specific Battery Chemistries (Has Shalls/requirements)

- 5.1 Alkaline Primary Batteries (Definition, Hazard sources, controls/process requirements)
- 5.2 Alkaline Secondary Batteries (SAA)
- 5.3 Lead Acid Batteries (SAA)
- 5.4 Lithium-ion Secondary Batteries (SAA)
- 5.5 Lithium/Lithium-ion Polymer Secondary Batteries (SAA)
- 5.6 Lithium Primary Batteries (SAA)
- 5.7 Mercuric Oxide-Zinc Batteries (SAA)
- 5.8 Nickel-Cadmium Batteries (SAA)
- 5.9 Nickel-Hydrogen Batteries (SAA)
- 5.10 Nickel-Metal Hydride Batteries (SAA)
- 5.11 Silver-Zinc Batteries (SAA)
- 5.12 Zinc-Air Batteries (SAA)

6. Battery References

Changes/additions are represented in red

JSC 20793 Rev C

6. Safety Relevant to Specific Battery Chemistries (no shalls)

- 6.1 Alkaline Primary Batteries (Definition, Hazard sources, controls/process requirements)
- 6.2 Alkaline Secondary Batteries (SAA)
- 6.3 Lead Acid Batteries (SAA)
- 6.4 Lithium-ion Secondary Batteries (SAA; additional recommendations)
- 6.5 Lithium/Lithium-ion Polymer Sec. Batts (SAA)
- 6.6 Lithium Primary Batteries (SAA; UL data; prepackaged batteries)
- 6.7 Nickel-Cadmium Batteries (SAA)
- 6.8 Nickel-Hydrogen Batteries (SAA)
- 6.9 Nickel-Metal Hydride Batteries (SAA)
- 6.10 Silver-Zinc Batteries (SAA)
- 6.11 Zinc-Air Batteries (SAA)
- 6.12 Lithium-Sulfur
- 6.13 Thermal Batteries
- 6.14 Capacitors/Supercapacitors

7. Reference

SAA: Same as above

JSC 20793 Updates/Changes (contd…)

8. Appendices

A: Qualification and Flight Acceptance Vibration Tests (AVTs) for Batteries

B: Custom Cell Manufacturing Facility Audits

C: Shelf and Service Life for Various Cell/Battery Chemistries

D: Battery Design Evaluation and Approval

E: Requirements Matrix

Changes/additions are represented in red

Examples for format change

4.3.2 Subsequent Flight Lot Testing

Some applications could require additional lots of flight batteries/cells beyond the original lot that was acceptance tested, qualified, and approved for flight. Key safety features must be retested to be sure that the new cell lots are performing like the previous qualified lot.

a. Any new battery lot and/or cell date code shall be assumed to be a new design and require a repeat of all battery and/or cell lot qualification testing and mitigation measures specified in Section 4.2.2.

An exception can be made for COTS cell batches delivered with two date codes that represent consecutive days if it can be verified they are part of a single production run.

b. Subsequent flight cell lot destructive testing shall confirm that subsequent lot performance and safety features are the same as that of the original qualification lot.

A key purpose of this repetition is to gain confidence that configuration control of the manufacturing process is still effective and that the new cell lots are performing like the previous qualified lot. For example, if a cell internal fusible link is used as a control for external short circuit hazards, sample cells from each subsequent lot should be tested to confirm that the fusible link works as expected.

Lot sample testing is carried out to confirm that the safety tolerances of the cells/batteries remain the same compared with the original lot. A statistically significant number of cells/batteries should be randomly selected for lot sample testing and should be based on the flight program, the number of cells manufactured, the period between manufacturing of the lots, the original materials that go into the manufacturing of a single lot, etc. A 3- to 6-percent sample size has been used for past flight battery programs.

Subsequent flight lot destructive testing can consist of a reduced set of lot sample testing but should include computed tomography (CT)/DPA, capacity (primary), 100-percent depth of discharge (DoD) cycle life (rechargeable), ARC (lithium), short circuit, and overcharge (rechargeable).

ARC testing should be performed on cells and compared with baseline characterization of the thermal signature to evaluate consistency of subsequent lots.

Significant Additions

5.1.4.1 Requirements – Internal Short Circuit

b. Measures shall be taken to reduce the likelihood and/or severity of an internal short circuit event to a level acceptable to the program/project.

Best practices listed below are intended to minimize the likelihood of a cell internal short event occurring. Section 5.1.5 discusses steps to be taken when trying to minimize the consequence/severity of an internal short circuit event in a custom battery design.

1. Design mitigation measures

- *a. In the case of a custom battery design, only cell designs whose performance and safety have been sufficiently characterized to support safety assessment and validation of the abuse tolerance and where insight into the manufacturing control process is provided should be approved.*
- *b. In the case of COTS battery designs, only batteries whose performance and safety have been sufficiently characterized to support safety assessment and validation of the abuse tolerance should be approved.*
- *c. Batteries should be designed to perform well within the manufacturer's specifications for the cells used to build the battery.*
- *d. If a particular cell/battery is to be used in an application or environment that is beyond the manufacturer's specification, extensive testing with margin to predicted environments should be carried out to confirm that the battery design will not be driven into a catastrophic safety hazard.*
- *e. Battery designs should also have the required fault tolerance in place to prevent the cells from being subjected to off-nominal conditions that result in the formation of internal shorts.*
- *f. Cells or batteries used in space applications should not have any records of Consumer Product Safety Commission (CPSC) recalls.*

2. Manufacturing mitigation measures

- *a. For custom battery designs, cells should be selected from cell manufacturers with a mature production history.*
- *b. Cell lots should be defined for each battery system as all cells with a common date code made from the same continuous production run.*
- *c. In the case of a custom cell or custom battery design, a cell production line audit of the cell design should be conducted to evaluate how well contamination, humidity control, and cell defects are limited in all phases of cell production processes. High particle counts and poor contamination and humidity control are known to contribute to the high occurrence of cell failures.*

3. Test mitigation measures (details left out in this presentation)

4. Operation (details left out in this presentation)

Significant Additions

5.1.5.1 Requirements – Thermal Runaway Propagation

a. For battery designs greater than a 80-Wh energy employing high specific energy cells (greater than 80 watt-hours/kg, for example, lithium-ion chemistries) with catastrophic failure modes, the battery shall be evaluated to ascertain the severity of a worst-case single-cell thermal runaway event and the propensity of the design to demonstrate cell-to-cell propagation in the intended application and environment.

Worst-case thermal runaway events will include method and location of thermal runaway initiation and environmental conditions. Thermal analysis that considers ohmic and entropic heating should be performed and validated by test.

NASA has traditionally addressed the threat of thermal runaway incidents in its battery deployments through comprehensive prevention protocols. This prevention-centered approach has included extensive screening for manufacturing defects, as well as robust battery management controls that prevent abuse-induced runaway even in the face of multiple system failures. This focused strategy has made the likelihood of occurrence of such an event highly improbable.

This requirement focuses not on the likelihood of such an event but rather on understanding the severity of consequences in the intended application should this unlikely event occur. Understanding the consequences of an event allows an informed risk assessment and identifies potential mitigation via design or operations.

b. The evaluation shall include all necessary analysis and test to quantify the severity (consequence) of the event in the intended application and environment as well as to identify design modifications to the battery or the system that could appreciably reduce that severity.

In addition to prevention protocols, programs developing battery designs with catastrophic failure modes should take the steps necessary to assess the severity of a possible thermal runaway event. Programs should assess whether there are reasonable design changes that could appreciably affect the severity of the outcome.

Evaluation should include environmental effects to surrounding hardware (i.e., temperature, pressure, shock), contamination effects due to any expelled contaminates, and venting propulsive effects when venting overboard.

Example of Significant Change

4.2.2 Qualification Testing: This section addresses the qualification testing of the flight battery.

a. Qualification testing shall be performed to the worst-case relevant flight environments with margin.

The qualification sample of batteries should be randomly sampled from units from the flight lot that have passed acceptance testing.

b. Environmental tests shall include, at a minimum, extreme temperature exposures, vacuum, and vibration tests.

The margin used for qualification tests will be provided by the respective projects or programs or from SSP41172 for ISS environments. Appendix C may be used as a guideline for qualification vibration tests (QVTs) for cells and batteries if there are no project-provided environments. The margin proposed here should be consistent with the program's margining policies. In the event none are provided, as a guideline, 6 db above the maximum expected is typically used.

The qualification of the battery should include testing the batteries to environmental and vibration levels that are higher than the mission requirements. The number of flight missions that the batteries will be used for, along with the location of the battery in the spacecraft, should determine the period and level of vibration. As a minimum, the qualification test program should include the following:

1. *Functional baseline test (open circuit voltage (OCV), mass, capacity or load check, internal resistance, visual inspection).*
2. *Vibration to qualification levels.*
3. *Functional baseline test recheck.*
4. *Charge/discharge cycles (for rechargeable batteries) or a load test (for primary batteries) at 20 degrees Fahrenheit (°F) margin above and below worst-case hot and worst-case cold, respectively.*
5. *Functional baseline test recheck.*
6. *Vacuum (approx. 0.1 psi) or equivalent leak checks.*
7. *Functional baseline test recheck.*

For batteries used in a pressurized volume or environment, exposure to a vacuum environment (approximately 0.1 psi) for a minimum of 6 hours. For batteries used in an unpressurized volume or environment, thermal vacuum cycles must be performed with the deep vacuum levels of 1 × 10–5 Torr (instead of the 0.1 psi used for habitable volume/pressurized environments). Alternatively, the thermal cycles and vacuum environment tests can be performed independently.

If the acceptance test vibration levels and spectra used to screen cells for manufacturing defects are not enveloped by the mission vibration levels, a separate qualification for acceptance vibration test (AVT) should be performed to verify that the screening levels do not degrade cell reliability.

The qualification batteries should pass all cell and battery acceptance tests as described in Section 4.2.3 prior subjecting them to qualification tests.

For custom battery designs, safety (abuse) testing performed during engineering evaluation should be repeated at qualification with pass/fail criteria for the qualification tests determined based on information derived during engineering evaluation.

Summary

- Updated document is easy to read
- Has all the requirements upfront
- Number of requirements changed from 400 to 100 but with the information retained.
- Has a lot of recommendations on processes; Appendices are also very informative
- Provides flexibility to the hardware owner in designing their controls to meet the fault-tolerance or top level safety requirement.

Battery Team Participation for Updates

NASA

- Dr. Chris Iannello, NESC Power Technical Fellow, Lead, NASA KSC
- Rob Button, NASA GRC, Power Systems Specialist
- Tom Miller, NASA GRC, Battery Specialist,
- Concha Reid, NASA GRC, Battery Specialist
- Jeff Brewer, NASA MSFC Battery Specialist
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- Dr. Dan Doughty, Consultant, Battery Safety Specialist