



End User Acceptance:

Requirements or Specifications,
Certification, & Testing



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NTSB Li-ion Battery Forum

National Aeronautics and
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NASA Human-Rated Li-ion Battery Applications



Current: Flying Li-ion since 1999

- Government furnished equipment ~ 20 types (< 20V/ 10 Ah)
- Experiments/Payloads (55 to 60 types) up to 270 V (high energy, high power, capacity 2 to 20 Ah)
- Crew suit (main power) 20 V/ 40 Ah
- Space vehicles and Space Launch Systems
 - HTV (32 V / 174 and 100 Ah), SpaceX (28 V/ 200 Ah and 28 V/16.5 Ah)



Future (and in work):

- ISS Main Power (120 V / 134 Ah)
- Robonaut (106 V / 60 Ah)
- New Tools (18 V to 28 V / 8Ah)
- New Vehicles (Orion 120V/ 30Ah; Orion LAS 140V 10Ah, 28V 1Ah; Orbital, 28 V/190 Ah; Boeing, SNC, Blue Origin)
- Surface mobility systems (270 V / 60 Ah high power)
- Lunar Lander Platforms (varying); Habitats (\geq 28 V)



Uniqueness:

- Space, confined volume and human-rated with zero tolerance to fire
- pressurized and unpressurized environments



NASA Non-Human-Rated Li-ion Battery Applications



Deep Space Missions:

First Mission in 2002 (Maj. 20-70 Ah;
One at 120 Ah)

Current:

- Mars Exploration Rover (Spirit and Opportunity)
- Mars Phoenix Lander
- Juno (Jupiter Orbiter)
- Kepler
- NuStar
- GRAIL
- Aquarius
- Mars Science Laboratory
- SMAP (On-going) and

Future:

- Europa Orbiter
- Mars 2020 Rover
- Mars Insight (Lander)

Satellite Applications:

First Mission in 2006 (6 Ah to 134 Ah)

Current:

- Lunar Reconnaissance Orbiter (LRO)
- Solar Dynamics Observatory (SDO)
- Van Allen Probes (formerly RBSP Radiation Belt Storm Probes)
- Interstellar Boundary Explorer (IBEX)
- ST-5 (mission completed)

Future:

- **Global Precipitation Measurement (GPM) spacecraft**
- **Magnetospheric Multiscale (MMS) spacecrafts**
- **Mars Atmosphere and Volatile Evolution (MAVEN)**
- **DSCOVR (Triana) spacecraft**
- **James Webb Space Telescope (JWST)**
- **Joint Polar Satellite System-1 (JPSS-1)**
- **Solar Probe Plus**
- **Ice, Cloud and Land Elevation Satellite -2 (ICESAT-2)**
- **GeoStationary Operational Environmental Satellite (GOES-R)**



Current State for Safety of Li-ion Batteries



Although the chemistry is one that can provide very high energy density for rechargeable systems (significant weight advantage for NASA), it is not the safest due to the nature of the associated catastrophic failures such as

- electrolyte leakage (toxicity hazard in crewed environments),
- fire
- thermal runaway

Typical causes for catastrophic failures encountered in Li-ion cells/ batteries are

- Overcharge/overvoltage
- External shorts
- Repeated overdischarge; overdischarge with subsequent charge
- High thermal environments
- Internal Shorts

NASA human-rated safety requirement is **two-fault tolerance** to **catastrophic failures or design for minimum risk in cases where designing fault tolerance is impossible**

- Two-fault tolerance – three levels of control to all credible failures



Failure Modes & Controls or Mitigation Measures for Li-Ion Batteries



Overcharge

Min. 3 controls
Verified by test
*Manuf. spec

Repeated Overdischarge/ 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

Controls and Design for Minimum Risk
Verified by test;
*heat dissipation

Internal Short

Design for Minimum Risk
Stringent testing and screening of flight cells;
manuf. facility audits
•Impeccable cell quality, cell uniformity; Usage within manufac. Spec. (latent defects, field failures)
•Backup Slide 20

Stringent Monitoring and Control of

*Cell and battery voltage
*Battery current
*Temperature

Cell Balancing designed into a majority of applications



Concerns with Scaling & Testing: Cell to Module to Battery Level



- NASA Centers have carried out extensive testing on li-ion batteries in the past 15 years –for human and non-human rated missions
- NASA Centers have learned that **cell level controls do not necessarily translate to module or battery level controls** (Backup slides 15 and 16)
- NASA Centers have learned that all safety controls need to be verified by testing at the **appropriate level** and in the **relevant environment**
 - Hazards such as overcharge and external short have opposite outcomes in pressurized versus non-pressurized environments due to the difference in heat dissipation



Concerns with Scaling & Testing: Cell to Module to Battery Level



- Li-ion battery designs should have high fidelity thermal analysis to show that the battery design is safe under worst case environments (temperatures and pressures) and under all nominal and off-nominal conditions.
 - Results of thermal analysis should provide guidance on safe designs with very good heat dissipation paths.
 - Good thermal design increases safety as well as extends the life of the battery
- Li-ion battery management electronics should be robust
 - strike a balance in monitoring and control;
 - extensive testing of control electronics should be carried out on ground
 - For human-rated safety critical applications **insight into telemetry** should be appropriate for trouble-shooting off-nominal events.



NASA Standards & Certifications



"Human-Rating Requirements for Space Systems" NPR 8705.2B (2009)

Evolution of requirements occurs with rigorous testing (Backup Slide 17)

Human-Rated:

Crewed Space Vehicle Battery Safety Requirements, JSC 20793

- Manned Space Vehicle Battery Safety Handbook (since 1982) converted to Crewed Space Vehicle Battery Safety Requirements, current is Rev B. April 2006; working on Rev C now; in parallel AIAA battery safety document in preparation.
- Battery Processing, JWI 8705.3 and Battery Evaluation Forms (required for all batteries from button cells to large li-ion)

NASA NESC RP-08-75 "Database and Guidelines Document Developed for Lithium-ion Battery"

Non-Human Rated:

- Have tailored requirements based on programs/projects (as a minimum, need to meet Range safety and Launch readiness reviews and AFSPCMAN 91-710);
- safety requirements for ground processing, integration and launch are very similar to human-rated li-ion battery systems;
- on-orbit safety maybe reduced to one-fault tolerance in many cases.



Summary



- NASA follows top level safety requirement of two-failure tolerance (three levels of controls or design for minimum risk) to all catastrophic hazards in the design of safe li-ion batteries for space use
- Rigorous development testing at appropriate levels to credible off-nominal conditions and review of test data
- Implement robust design controls based on test results and test again to confirm safety at the appropriate levels
- Stringent testing of all (100%) flight batteries (from button cells to large batteries)





Back Up Charts



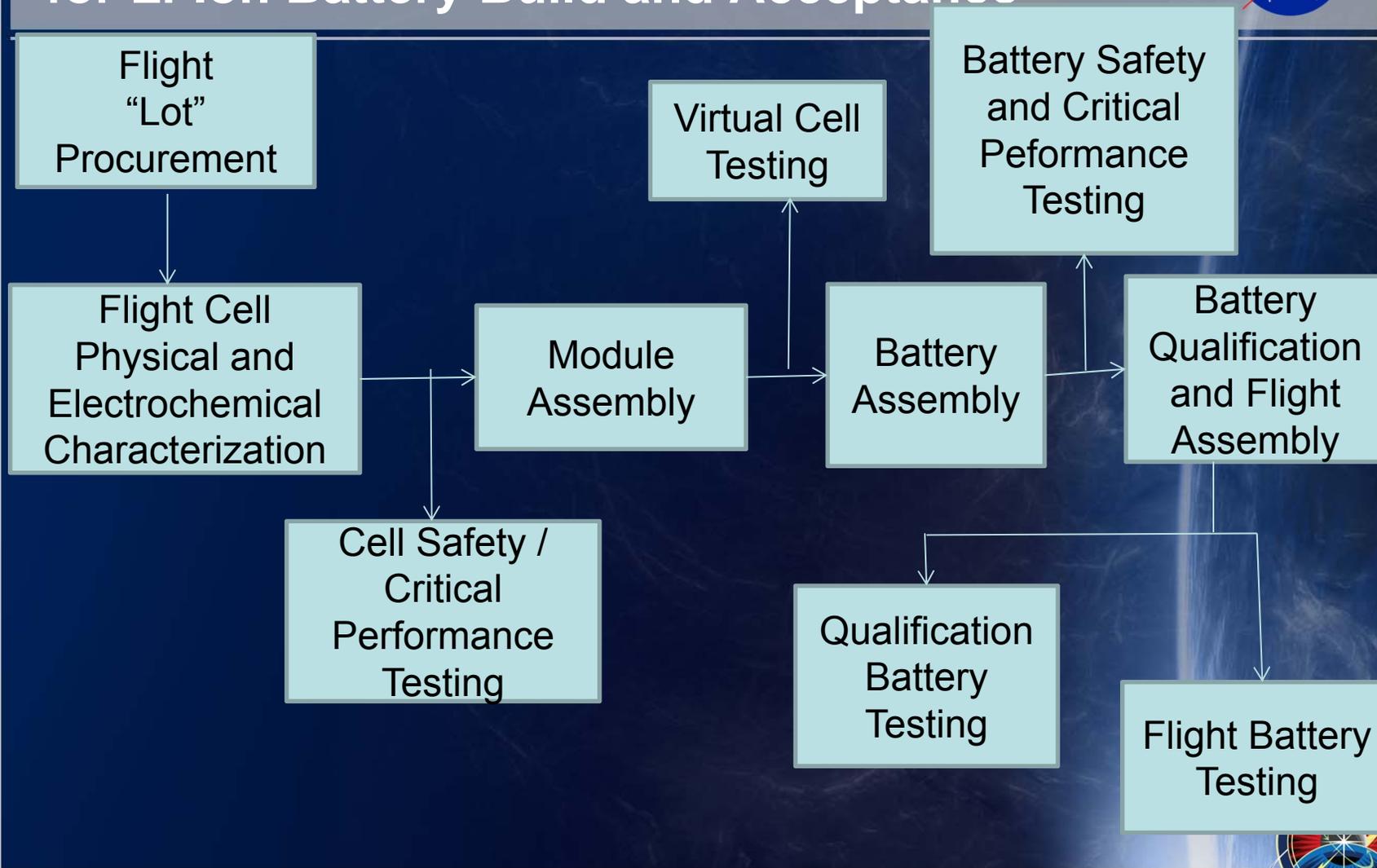
Li-Ion Battery Project & Safety Review Life Cycle



- **Systems Requirements Review (SRR)**
 - Project or Product Technical Requirements Specification (PTRS)
 - Outlines battery specifications, mission requirements for performance and safety, interfaces (mechanical, electrical, data, pressure, etc.) and unique requirements such as pressure variations, thermal extremes, vibration, shock, impact, water proofing, humidity, salt fog, etc.
- **Preliminary Design Review (PDR)**
 - Cell and Battery Design chosen at this point) (Phase 0/1 Safety Review)
- **Critical Design Review (CDR)**
 - Confirmed cell and battery design (Phase II Safety Review)
- **Manufacturing Readiness Review (MRR)**
 - Before start of cell manufacturing and/or battery manufacturing
- **Flight Readiness Review (FRR)**
 - Includes approved safety data packages (Phase III safety review and final approval)



Sample Flow Chart for Li-Ion Battery Build and Acceptance



Sample Li-Ion Qualification Tests



- Physical and Electrochemical Characterization (mass, dimensions, OCV, capacity, dc resistance/ac impedance,
- Charge/discharge cycles (typically with mission profile) at temperature extremes (+ /- 20 deg F of mission temperature range)
- Vibration to qualification levels (15 mins in each axis)

FREQ (Hz)	ASD (G ² /Hz)	dB/OCT	Grms
20.00	0.057600	*	*
40.00	0.057600	0.00	1.07
70.00	0.144000	4.93	2.02
700.00	0.144000	0.00	9.74
2000.00	0.037440	-3.86	13.65

- Charge/discharge cycles
- Vacuum leak Check (6 h exposure; 0.1 psi for pressurized; 10⁻⁵ Torr for those used in vacuum environments)
- Charge/discharge cycles

Pass/fail criteria is stringent with OCV (< 0.1 % change); capacity checks (1 to 5% depending on battery size) and mass checks (0.1 to 1% change depending on battery mass)



Sample Li-Ion Flight Battery Acceptance Tests



Cell Acceptance: As a minimum, physical and electrochemical characterization; 6 sigma range accepted; if more than 3% of lot fails, the entire lot is rejected

Cell Matching: As a minimum, from accepted cells, the cells are matched for modules (banks and strings) based on the following: OCV (0.1 % variance), capacity (less than 2%), dc resistance (10% variance)

Battery Flight Acceptance Testing:

- Physical and Electrochemical Characterization (mass, dimensions, OCV, capacity, dc resistance/ac impedance,
- Vibration to levels higher than workmanship (1 min per axis)

FREQ (Hz)	ASD (G ² /Hz)	dB/OCT	Grms
20.00	0.028800	*	*
40.00	0.028800	0.00	0.76
70.00	0.072000	4.93	1.43
700.00	0.072000	0.00	6.89
2000.00	0.018720	-3.86	9.65

- Charge/discharge cycles
- Vacuum leak Check (6 h exposure; 0.1 psi for pressurized; 10⁻⁵ Torr for those used in vacuum environments); thermal vacuum exposure tests for batteries to be used in unpressurized volume
- Charge/discharge cycles

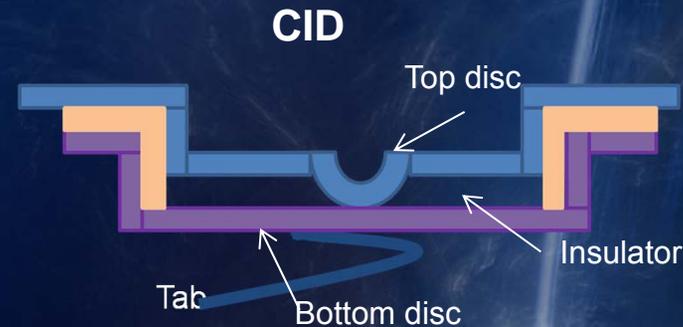
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Examples of Cell Protective Devices

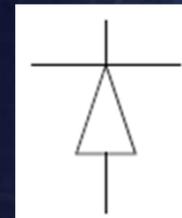


- Lithium-ion cells, whether cylindrical, prismatic, etc. irrespective of size, have different forms of internal protective devices
 - PTC
 - CID
 - Tab/lead meltdown (fusible link type)
 - Bimetallic disconnects
 - etc.



- External protective devices used in lithium-ion battery designs are
 - Diodes
 - PTC/polyswitch/contactors
 - Thermal fuses (hard blow or resettable)
 - Circuit boards with specialized wire traces
 - etc.

Diode



PTC Used inside Li-ion Cells

Although cell level protective devices protect cells and low voltage /low capacity batteries (less than 12 V and 60 Wh), extensive testing at NASA-JSC has shown that cell level protective devices do not always protect when the cells are used in batteries of high voltage and high capacity.



Examples Showing Cell Limitations in Multicell Configuration



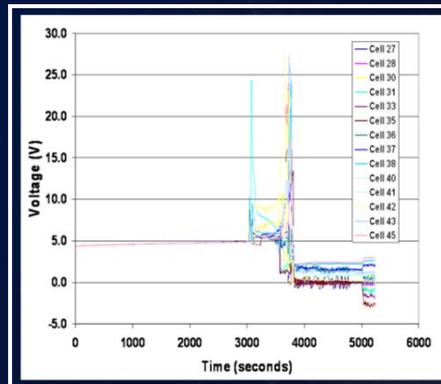
48V 6A Overcharge on 4P Battery



12V 6A Overcharge on 4P Battery



Photos show the limitations of 18650 size cells; These cells are only test vehicles; protective devices, internal and external to the cells, irrespective of cell size, should be fully characterized at all appropriate levels if used within the first three levels of safety control.



External Short on 8S5P Matrix Pack

Overcharge Test on a 14-Cell String



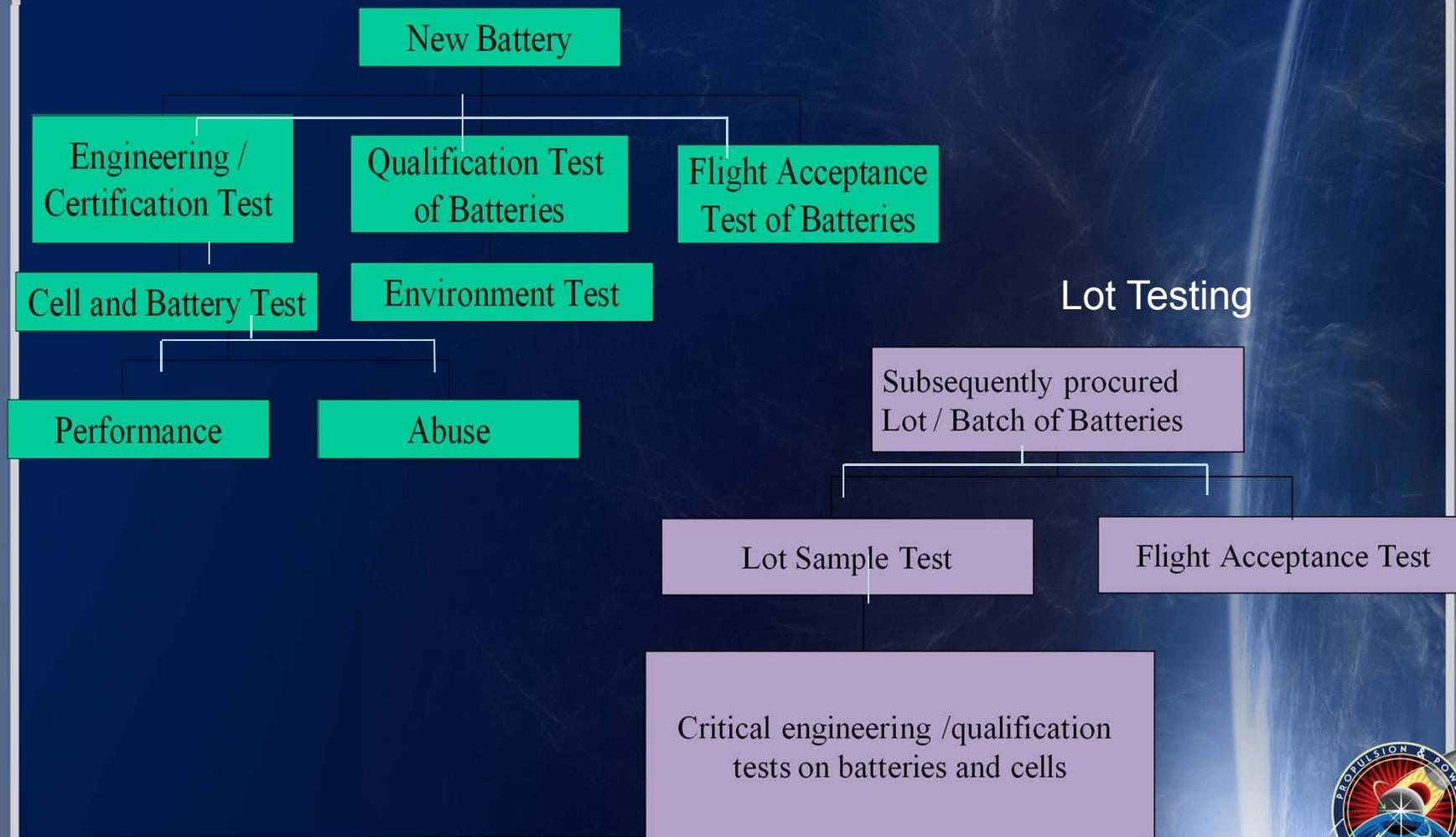
Studies In the Area of Lithium-Ion Technology



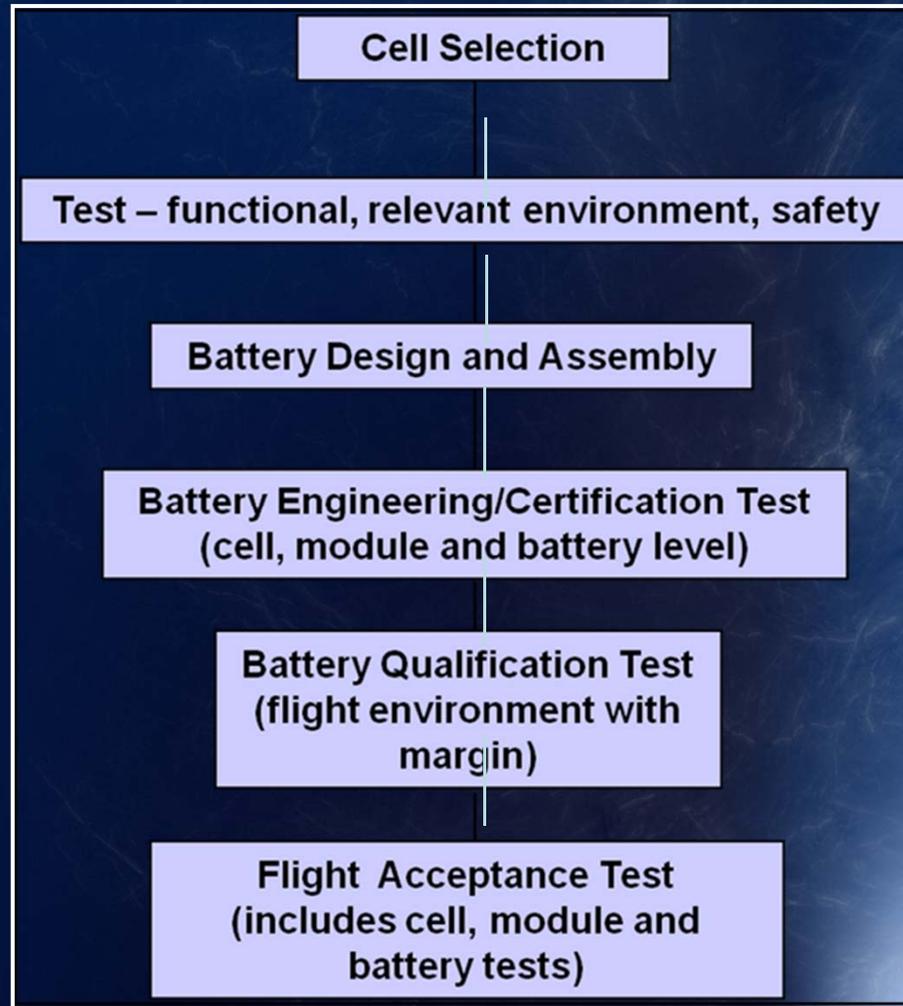
- Funding for surveillance task (more than 2 decades)
 - Previously Shuttle
 - Currently International Space Station, NASA Engineering Safety Committee (NESC), Office of Chief Technologist (OCT), Seed Funds from NASA HQ and Center Level Discretionary funds
- Types of Test Programs
 - State-of-the-art cell technology (commercial cells of increasing capacities, high energy and power density, pouch type, etc.) – performance and safety characterization
 - General issues faced by li-ion technology – limitations of cell internal protective devices, safety characteristics under different environmental conditions, overdischarge – cell mismatch study, matrix design performance and safety characterization, internal short test method standardization, implantable on-demand internal short circuit device
 - Technology improvements – safer electrolytes, electrode improvements – tested in ≥ 2 Ah to confirm safety



Sample Testing & Acceptance for COTS Li-Ion Batteries



Sample Testing & Acceptance Process for NASA / Custom Designed Li-Ion Batteries



Sample of Strong Correlation Between Soft Short Test Failures & Cell Defects

This slide was removed at the request of Dr. Judy Jeevarajan on July 31, 2013.

Please contact the presenter for more information on Soft Short Test Failures and Cell Defect correlations.