

Use of COTS batteries on ISS and Shuttle



PAYLOAD SAFETY & MISSION SUCCESS

Judith A. Jeevarajan, Ph.D

NASA-JSC, EP5

281-483-4528

judith.a.jeevarajan@nasa.gov

April 19-22, 2004

Cape Canaveral, Florida

Outline



- **Current Program Requirements**
- **Challenges with COTS Batteries**
- **Manned Vehicle COTS Methodology in Use**
- **List of Typical Flight COTS Batteries**
- **Energy Content and Toxicity**
- **Hazards, Failure Modes and Controls for Different Battery Chemistries**
- **JSC Test Details**
- **List of incidents from Consumer Protection Safety Commission**
- **Conclusions and Recommendations**

Current Program Requirements



Current Flight requirement: Two failure tolerance to catastrophic hazards.

- JSC 20793 “Manned Space Vehicle Battery Safety Handbook” is main reference/guideline for batteries.
- Payload Safety Requirements: NSTS 1700.7B Section 200.1b - Safety Policy and Requirements for Payloads using the STS
- Space Station Safety Requirements: SSP 50021 Section 3.3.6.1.1 – Safety Requirements Document for ISS
- Space Shuttle Safety Requirements: NSTS 22254 Section 1.6 - Methodology for Conduct of Space Shuttle Program Hazard Analyses and Section 1D201.6 of NHB 5300.4 (1D-2) – Safety, Reliability, Maintainability and Quality Provisions for the SSP.
- Space Station/Shuttle Safety Requirements: JSC 28484 Section 3.3.6 - Program Requirements Document for JSC Non-critical GFE.

Compliance to Requirements?



- **How can we comply with these established requirements and fly COTS batteries?**
- **Certificate of Compliance (C of C) from the vendor is insufficient for safety certification.**
- **Space Shuttle and ISS programs will not exempt payload COTS batteries from these safety requirements.**

Challenges with COTS Batteries



- Drawings for COTS batteries are difficult to obtain.
- Specifications for COTS batteries are obtained very rarely. Hence no information is available on the safety features in the battery.
- Information is proprietary or not shared due to trade secret aspects and high levels of competition. NASA must often conduct reverse engineering on samples from same lot to identify hazard controls.
- Import/export compliances sometimes prevent sharing of information.
- Lot-to-Lot variation exists in both performance and safety. Assumption of “lot” is already a risk in the COTS world.

Challenges with COTS Batteries (contd.)



- **Competition in the battery industry drives the efforts for continuous improvement.**
- **Improvement dictates more energy in same package leading to a high energy package.**
- **Users have no control or knowledge of these changes.**
- **Users have no control over the manufacturing line or the vendors supplying the active materials in the cells.**
- **Users also have no control over internal agreements that exist among manufacturers on the cell/label exchange that occurs due to high consumer demands.**

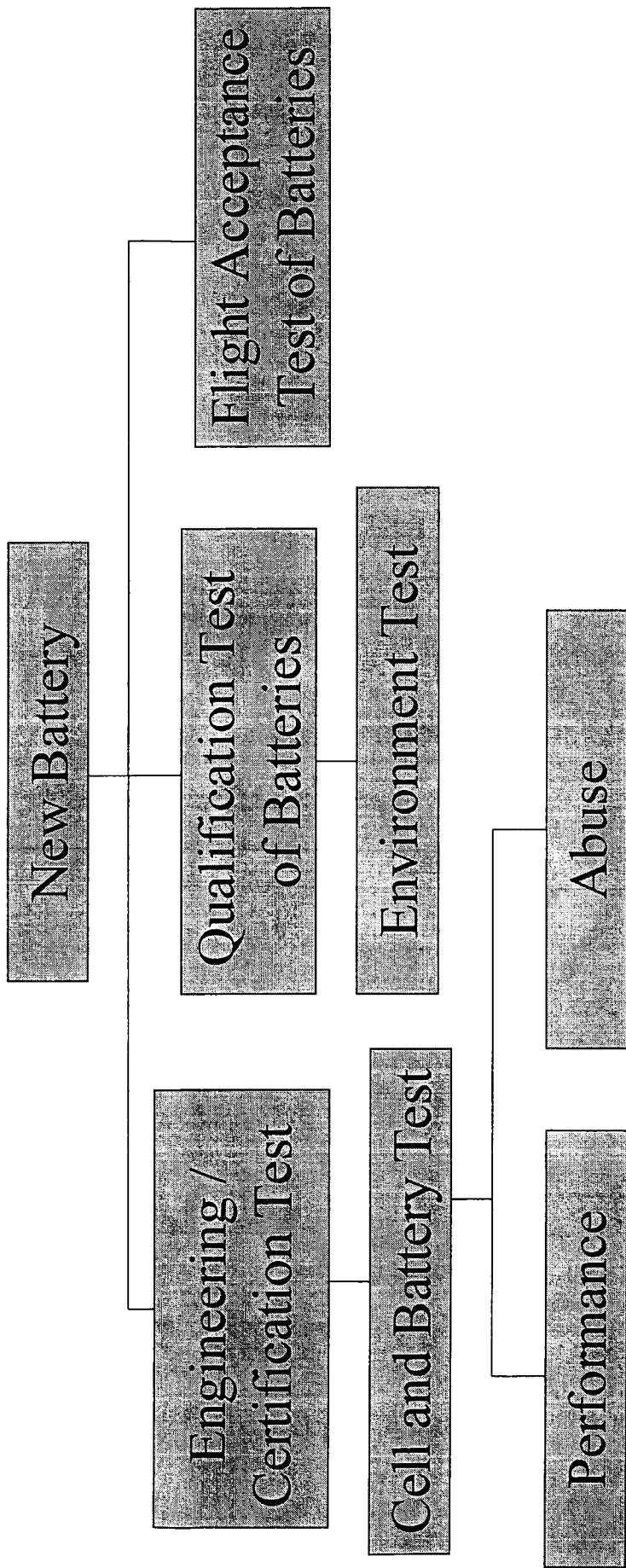
COTS Methodology

Currently in Use

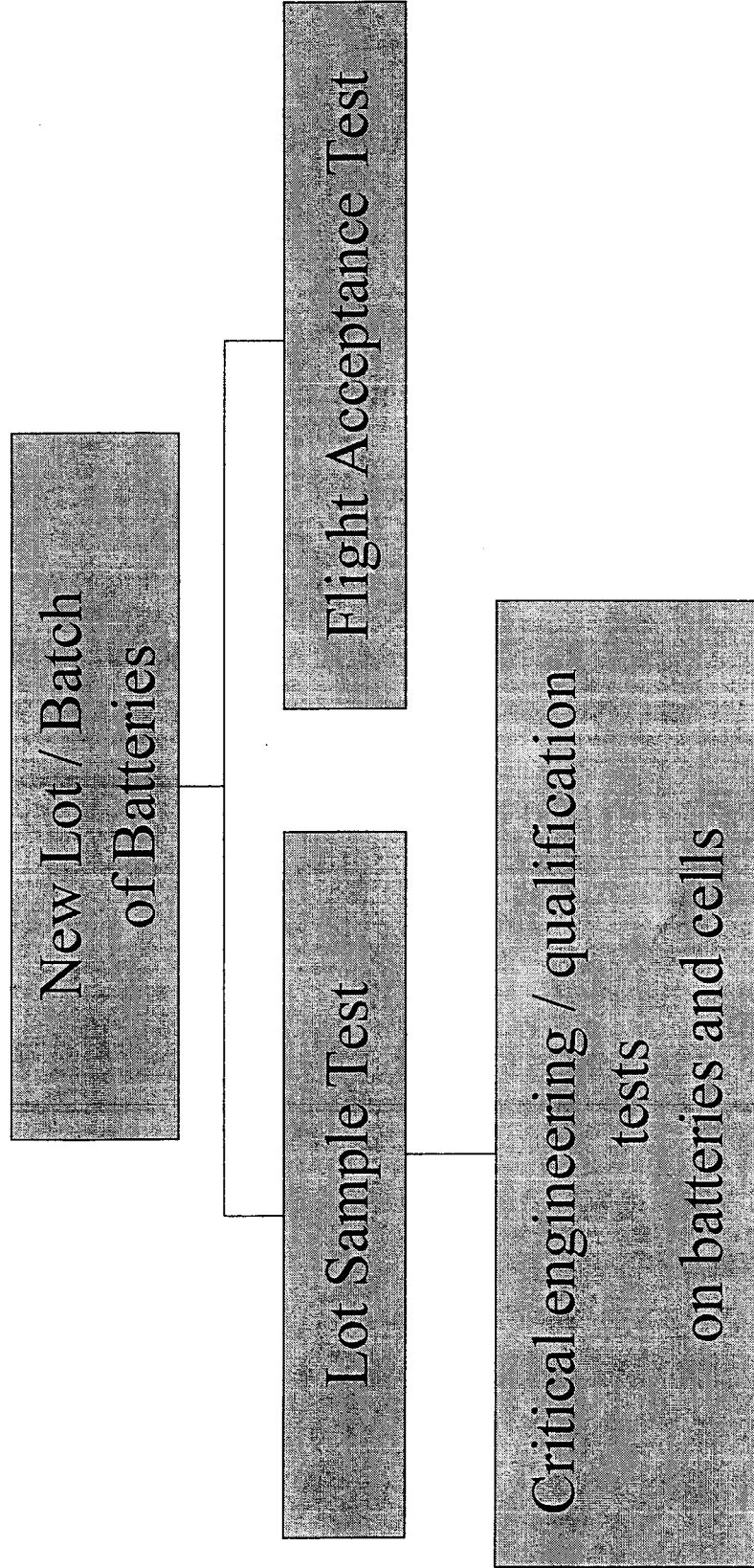


- Utilization of standard cells as building blocks:
- e.g. AA alkaline, 4/3 A & 2/3 A NiMH, 18650 li-ion, sub-C NiCd, etc.
- Use UL tested or recognized batteries - testing is paid for by cell manufacturer.
- Data Sharing:
- Battery Steering Committee (other NASA centers, JPL, AF, Navy, DoD, CIA, Aerospace Corp, etc)
- Lithium Battery Technical Safety Group (DoD, FBI, CIA, National Labs, other NASA centers)
- NASA Battery Workshop (Government and industry)

COTS Battery Test Process at JSC



Test Process for Each Successive Lot of Batteries



Energy Content



- **Energy Content of some materials used in the Shuttle:**
 - **Hydrazine – Shuttle APU- 1291 Btu/lb**
 - **TNT: 1929 Btu/lb**
 - **LiSOCl₂/LiBCX: 2000 Btu/lb**
 - **Water: KOH electrolyte is 30 -45 % weight in water. KOH used in alkaline, NiCd, NiMH, Ag-Zn, etc. If electrolyzed by overcharge or overdischarge, it yields a H₂/O₂ mixture that has an equivalent of 5783 Btu/lb**

Toxicity



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. Tox 2.
- **H₂SO₄:** Lead acid- acidic and corrosive, will create acid fumes that can damage throat and lungs. Tox 2
- **SOCl₂:** LiSOCl₂ and BCX- burn skin, eyes, damage throat and lungs to a higher degree than above and can be lethal. Tox 4
- **Li(CF)_x** and LiMnO₂: affects skin and eyes on contact; electrolytes is flammable and can cause fire in the presence of an ignition source. Tox 2 depending on nature of salt in electrolyte.

Lithium Primaries



Hazards:

- Electrolyte leakage-toxic and corrosive – harmful to lungs, eyes and skin, can be lethal.
- Explosion due to high temperatures

Failure Modes:

- Inadvertant charging, overdischarge, short circuit and high temperature exposure.

Controls:

- Lot testing to verify existing controls, 100 % ATP testing.
- Internal Short: demonstrate tolerance or use screening methods like vibration.
- Short circuit: Fuses, PTCs, thermostats, design.
- Overdischarge: demonstrate tolerance, redundant by-pass diodes with lot-by-lot verification, low-voltage device cutoff,
- Inadvertant charging: redundant blocking diodes on each parallel string, assure independence of other power sources.
- Overtemperature: good heat sinking, establish conservative operating temperature margins.
- Leakage: 100 % leak checks, good vent/burst ratio, pressure capability of specific cells used and of cell vents and pressure relief cases.

DoT Regulations



Lithium primaries:

**Transportation of lithium batteries must conform to the following:
If batteries meet special requirements and contain no more than
1.0 grams of lithium per cell or no more than 2.0 grams for a set of
batteries, they will be classified as “non-hazardous”.**

Transportation of Dangerous Good, Manual of Test and Criteria

Alkalines



Hazards:

- **Electrolyte leak:** KOH can corrode aluminum, caustic electrolyte- could cause skin damage and permanent eye damage.
- **High temperatures:** produce temperatures as high as 250 °F

Failure Modes:

- **Overdischarge, inadvertant charge, short circuit, exposure to temperature extremes.**

Controls:

- **100 % acceptance test for leakage.**
- **Short circuits:** fuses, PTCs, temperature label
- **Inadvertant charge, overdischarge:** Redundant diodes on parallel strings to prevent charging, prevent overdischarge, Low voltage cutoff used in equipment. temperature control and presence of wicking material.
- **Leakage:** 100 % vacuum leak checks, presence of wicking material, Vented Battery compartments
- **High Temperature:** Temperature control installed in equipment.

NiMH and NiCd



Hazards:

- **Electrolyte Leakage:** Strong caustic electrolyte
- **Vent, Rupture and Explosion**

Failure Modes:

- **Short Circuit:** High rate capability cells can overheat due to short circuit or excessive rates and vent, rupture or explode.
- **Overcharge:** can create combustible mixture of H₂ and O₂
- **Overdischarge:** can cause generation of H₂ and O₂.

Controls:

- **Short Circuit:** Battery level fuses, PTCs, thermostats, thermistors
- **Electrolyte Leakage:** Vacuum leak checks or equivalent test for leakage, wicking material.
- **Overcharge:** charger fuses, high voltage controls and cutoff timers.
- **Overdischarge:** Device low-voltage cutoffs
- **Tolerance:** Cells more tolerance to abuse due to higher weight and thermal mass and non-flammable electrolyte with very low vapor pressure.

Li-ion Batteries



- **Hazards:**
- **Electrolyte leakage:** Flammable electrolyte, salt in electrolyte is a strong irritant- Tox 2
- **Venting, explosion and fire.**
- **Failure Modes:**
- **Short circuit:** High energy density cells – can cause high temperatures, high current spikes, venting with release of flammable electrolyte, rupture, explosion and fire. (Dell and Compaq laptop battery recalls involved potential short circuits with fire).
- **Overcharge:** high temperatures, high pressures, venting, rupture, explosion and fire.
- **Overdischarge:** heat generation, permanent cell damage.
- **High temperature:** exposure can cause thermal runaway, venting, rupture, explosion and fire.
- **Internal Short:** electrolyte leakage, venting and fire.

Li-ion Batteries



Controls:

Cell level:

- **PTC** – Positive Temperature coefficient-overcurrent and overtemperature – only present in cylindrical cells.
- **CID** – current interrupt device- activates when there is excessive internal pressure, activation is permanent – mostly present in cylindrical cells only.
- **shut-down separator** – becomes opaque to the flow of ions due to a melting of one of the layers in the separator.
- **Fusible lead/tab** - present in most prismatic cells, where the lead melts due to passage of high current.

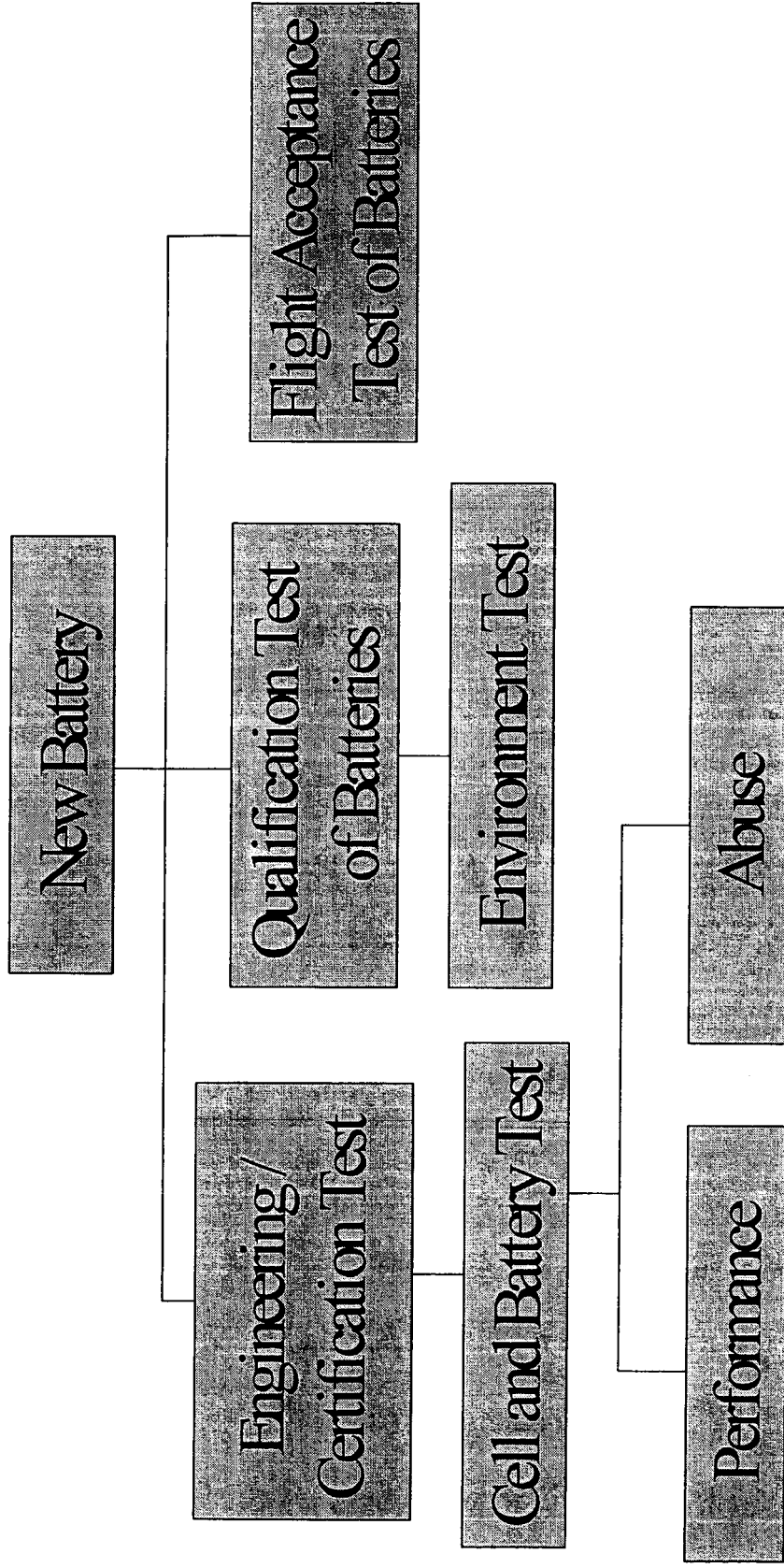
Battery level:

- **Protective circuitry**- overvoltage, undervoltage and overcurrent cutoffs with **MOSFETS**. High temperature cutoff in some cases, fuses – hard-blow and thermal
- **Equipment/device:** Low voltage cutoff, temperature cutoff.
- **Charger:** High voltage cutoff, fuses, thermostats.
- **Screening for Internal Shorts.**



Tests Performed at JSC

Battery Test Process



Performance Test – Battery Level



- **OCV – open circuit voltage measurement of ‘as obtained’ batteries.**
- **CCV – load equivalent to 1.5 C current for 100 ms.**
- **Functional performance of battery by performing *in-situ* testing or by simulating the usage.**
- **Vacuum Leak – to check for leakage and for tolerance to up to 6 hours of vacuum environment.**
- **Thermal Environment – performance of batteries at 20 deg F above and below flight operational environment.**
- **Vibration – Batteries are qualified for up to five times that required for locker stowed items.**

Abuse Tests



- **Overcharge**
- **Overdischarge**
- **External Short Circuit**
- **Internal Short Circuit (Crush)**
- **High temperature and Heat-to-Vent**
- **Vent and Burst Pressure**
- **DPA with electrolyte Analysis**

Test Details



Overcharge:

- Failures: Charger failure; protective circuit board failure.
- Cell Level: 3C rate fast charge, Overvoltage (to 5.0 V for Li-ion and 2.5 V for NiMH, NiCd, etc.), Overcharge to 12.0 V for 50 minutes (UL test)
- Battery level: Verify protective feature for overcharge/overvoltage

Overdischarge:

- Failures: Low-voltage cutoff in equipment failure; protective circuit board failure.
- Cell Level:
 - Fast discharge at 3 C rate; Discharge into reversal.
- Battery Level:
 - Characterize low cutoff switch setting; Verify logic in circuitry to determine if individual cell voltage or total battery voltage opens safety MOSFET switch.

Test Details



External Short:

- Failures: Inadvertant shorting across terminals, fuse failure in battery, protective “smart” circuit board failure, failure of thermal fuses, polyswitches.
- Cell Level and Battery Level: External hard short imposed on battery.

Internal Short:

- Presence of impurities (metal burrs, particles, dust) that can be dislodged due to vibration.
- Simulated internal short using a crush method. Crush is a non-credible failure but the test gives valuable information. e.g. Reaction of NiMH vs Li-ion

Heat-to-Vent:

- Temperature tolerance on cells and determination of thermal runaway temperatures.

Drop Test:

- Simulates problems encountered during ground handling and transportation – inadvertant drops.

Test Details



Vibration: Batteries and cells vibrated to determine vibration tolerance to launch and descent.

- Also used as a screen for workmanship standards.
- Used as a screen for internal shorts in some lithium primary and all lithium-ion cells/batteries.

Typical vibration spectrum for qualification of the li-ion batteries is the following:

<u>Frequency</u>	<u>Level</u>
20-80 Hz	+3 dB/octave
80-350 Hz	0.1 g ² /Hz
350-2000 Hz	-3dB/octave

15 minutes in each independent axis.

Acceptance test:

<u>Frequency</u>	<u>Level</u>
20-80 Hz	+3 dB/octave
80-350 Hz	0.067 g ² /Hz
350-2000 Hz	-3dB/octave

1 minute in each independent axis.

Test Details



Vent and Burst Pressure:

- Requirements for pressure systems/ pressurized containers.
- Vent/burst pressure ratio ≥ 2.5

DPA with Electrolyte Analysis:

- For toxicology assessment and report

Vacuum Leak Check:

- Leak check on 100 % of flight. Qualification/certification test is performed on engineering and qualification hardware.
- Method of test can vary depending on the test agency – helium leak, vacuum leak, overcharge method on NiMH to check for leaks.

Qualification Tests



These tests require quality coverage.

- **Physical and Electrochemical Characteristics:** Dimensions, weight, OCV, CCV, capacity checks.
- **Environment Test:**
Charge and Discharge at temperatures that are 20 degrees F above and below actual temperatures seen during operation. For example, batteries used for IVA (in-cabin) will be tested at 50 and 90 °F. This also depends on the storage location of the battery during flight.

Vibration: The fully charged battery packs shall be vibrated using the following spectrum for 15 minutes in each of the x, y and z axes. For NiMH and NiCds a load shall be placed on the battery during the vibration and the voltage recorded using a strip chart recorder.

<u>Frequency</u>	<u>Level</u>
20-80 Hz	+3 dB/octave
80-350 Hz	0.04 g ² /Hz
350-2000 Hz	-3 dB/octave

Functional checks are performed after the vibration.

Flight Acceptance Tests



Physical and Electrochemical Characterization with pass/fail criteria.

- **Vacuum Leak Check** – as described earlier with pass/fail criteria for post functional checkout and weight change.
- **Vibration Test:** The fully charged battery packs shall be vibrated using the following spectrum for one minute in each of the x, y and z axes. For NiMH and NiCds, a load shall be placed on the battery during the vibration and the voltage recorded using a strip chart recorder. For li-ion, only voltage monitoring is performed. OCV is checked between each axis of vibration.

<u>Frequency</u>	<u>Level</u>
20-80 Hz	+3 dB/octave
80-350 Hz	X g ² /Hz –(depends on chemistry and location during launch)
350-2000 Hz	-3 dB/octave

Functional checks are performed after the vibration.

Reported Hazards



HAZARD INCIDENT LIST

- CPSC Release #94-011 – NEC Technologies, Inc.; Recall on two laptop computer batteries (PC-17-01 & PC-17-02); can explode and catch fire; 13,000 computers sold; seven incidents of smoke and/or fire. (Li-Ion batteries, I think; replaced with Ni-MH.)
- CPSC Release # 98-019 – Nursery Monitor rechargeable batteries can rupture; 25,000 batteries sold; 76 reports of batteries rupturing.
- CPSC Release # 97-084 – Hitachi Koki rechargeable, 9.6 volt battery packs on 20,000 cordless drills could overheat and melt while being recharged.
- CPSC Release # 92-127 – Coleman 12 volt Powerstation, rechargeable battery pack units can short, potentially causing a fire. 9,000 units were sold; no specific incident reported except for Coleman employee experiencing an in-store short circuit.
- CPSC Release # 92-023 – Tyco recalled a battery-powered toothbrush using 4 AA cells with 330,000 sold. If one cell reversed in toothbrush, cell could leak or explode. Three incidents reported of leaking cells causing burns; one exploding cell caused eye injury. Incidents thought to be caused by defective cells or by improper installation.
- CPSC Release # 99-129 – Hasbro recalls Star Wars Lightsaber toys using 2 alkaline C cells, due to spring dislodging, causing the cells to overheat or rupture. 618,000 sold; 38 reports of overheating with 6 of those rupturing, 3 reports of minor burns and one of eye irritation.
- CPSC Document # 5088 – Estimates that 3,700 people a year are treated in hospital emergency rooms for battery-related chemical burns, due to recharging the wrong

Reported Hazards



battery, or using the wrong charger; mixing batteries (alkaline and carbon-zinc or old and new); or putting batteries in backwards.

- News report: Kodak recalled 120,000 AC adapters sold for use in Kodak digital cameras. The adapters, when improperly installed, can cause the batteries to overheat, leak electrolyte, and explode. 3 reports received with one person receiving minor injuries.
- Notice from NSWC: Lithium 9 volt batteries fabricated into a “big” pack, sitting at user site, still in shipping container when a violent “explosion” occurred. Believe caused by leakage of flammable electrolyte and subsequent ignition.
- CPSC Release # 86-37 – Mura cordless telephone batteries ruptured. 400,000 phones sold between 1982 and 1984, with >100 incidents reported, with no known serious injury or death resulting.
- CPSC Release # 99-012 – Fisher-Price Power Wheels recall of up to 10,000,000 ride-on cars & trucks. 700 reports received of overheating during riding, charging, parking, or storage. 150 fires reported. 9 children suffered burns. \$300,000 damage to 22 houses & garages. 71 vehicles reported not stopping with 6 minor injuries to children. Vehicles used 6 volt and 12 volt lead-acid batteries.
- CPSC Release # 99-172a - Sonca sold 5,500 toy flashlights with 2 AA alkaline cells; the battery compartment spring can dislodge, causing the cells to overheat or leak. Four incidents with property damage and eye irritation have been reported.
- CPSC Release # 87-087 – Hedstrom battery-powered riding toy was sold without fuse; 30,000 sold; 8 incidents reports with vehicle catching fire; one of these resulted in serious fire in mobile home. Fires can occur while being ridden or stored.

Battery Hazard



Houston Chronicle:

Nov. 14, 2003, 12:53AM

Nokia examines its batteries to prevent exploding phones

Bloomberg Business News

Nokia said Thursday it will cooperate with a researcher to make sure its handset batteries are safe as the number of reported cases of exploding Nokia phones approaches 40.

The world's largest mobile-phone maker will work with Belgian consumer group Test-Aankoop after an earlier study by the researcher that found Nokia batteries could explode was found to be "unreliable," said Jonas Geust, who is in charge of quality at Nokia.

Geust said there have been between 30 and 40 cases of exploding Nokia handsets, including one in August in Amsterdam in which a woman was injured when a Nokia phone ignited. Espoo, Finland-based Nokia repeated that all reported phone explosions were caused by nonoriginal Nokia batteries, half of them illegal counterfeit products.

"All original Nokia batteries are safe for the end user," Geust said. "It is difficult for a consumer to identify a counterfeit battery. We are doing everything we can to stop pirate products being sold."

The nonoriginal batteries exploded because of internal short circuits, Geust said. He said a Test-Aankoop study last week had suggested some original Nokia batteries could explode because they lacked proper safety measures against short circuits. The study was found to be "false" as some nonoriginal batteries were used in it, Geust said.

Test-Aankoop will conduct a new study, helped by Nokia, and publish the results "as soon as possible," Geust said.

Other phone makers have experienced similar problems. Kyocera Corp., a Japanese handset maker, last month halted shipments of some mobile phones to investigate a complaint of a battery overheating.

April 19-22, 2004

COTS Battery Testing / Judith A. Jeevarajan

Battery Hazard



NOVAK MANDATORY PRODUCT RECALL NOTICE

Date: February 28, 2003
Products: Novak #5000 SPY Lithium-Ion Battery Pack and
Novak #4405 SPY Charger and Lithium-Ion Battery Pack

Notice Updated: March 4, 2003

Novak Electronics, Inc. has become aware of a potential problem with the **Lithium-Ion battery pack** that is included in item **#5000 SPY Lithium-Ion Battery** and item **#4405 SPY Charger & Lithium-Ion Battery Pack**. There have been a few cases of the battery packs exploding, and Novak Electronics, Inc. is currently investigating the cause of the problem.

If you have purchased either of these items, **it is important that you discontinue the use of the Lithium-Ion battery pack immediately**, and that you return the product to Novak Electronics, Inc.

Even if you feel that the Lithium-Ion battery pack is in good working order, because there is a potential safety issue, **you must discontinue the use of the Lithium-Ion battery pack immediately** and return the product to Novak Electronics, Inc.

Complete the information on the Recall Form (download below) and return the form and your products to Novak Electronics, Inc. Customer options are listed on the form.

Click on the link below to download the **Recall Form** (pdf format):

SPY Li-Ion Recall Form (PC users right click and select "Save Target As...")



To open the Acrobat file you will need to have already installed the free **Adobe Acrobat Reader**. The **Adobe Acrobat Reader** is available for **UNIX, Microsoft Windows, and Apple Macintosh computer systems**.

For customers outside of the U.S. or Canada, please contact your hobby dealer or distributor for return procedures. Please **click here** for a list of International Distributors.

All of us here at Novak Electronics, Inc. understand the customers inconvenience and we would like to thank each customer for their help and cooperation.

Payload vs GFE Battery usage




- Payload may require just one or a small number of batteries.
- GFE (Government Furnished Equipment) battery requirement can vary between 50 to a few hundreds.

Conclusions and Recommendations



- High risk undertaken with the use of COTS batteries.
- Hazard control verification is required to allow the use of these batteries on manned space flights.
- Failures during use cannot be understood if different scenarios of failure are not tested on ground.
- Testing is performed on small sample numbers due to restrictions on cost and time. Recommend testing of larger sample size to gain more confidence in the operation of the hazard controls.



Payload Safety and Mission Success Conference 2004
April 19-22, 2004

Dear Dr. Jeevarajan:

Thank you for agreeing to provide a presentation for the Payload Safety and Mission Success Conference 2004. Included in this letter are ***deadlines and submittal requirements*** so that your presentation can be included in the conference binder, which will be published ***prior to the conference***. I will be the session moderator for your session.

For US presenters: You will be responsible for obtaining any necessary approvals for release of Scientific & Technical Information (STI) and for obtaining Export Control clearances (due to International participation) according to your company's policies and Government regulations. This can take weeks, so please look into your organization's processes for this. The conference planning team is not obtaining a global STI release for the conference binder.

Non-US presenters: You are responsible for obtaining any necessary approvals for us to release information (re-export of information).

- **Registration:** All presenters must register and obtain their own travel arrangements: (see the following web site for details) <http://www.westoverconferences.com/psms/>.
- **Provided for You at the Session:**
 - PC and/or laptop (CD/floppy drive with PowerPoint and Word)
 - Compatible data viewer
 - Podium for speaker
 - Table with chairs for potential panel discussion
 - **Upon request**, we can provide a VCR
 - Session support person who will be there to help with last-minute details.
- **Data Requirements**
 - Briefings: Power Point – Use template provided
 - White Papers (if used): Please use Times New Roman 12 pt font; margins should be 1" for top and bottom, 1.25" for left and right; .5" header and footer; left gutter position, with page numbers centered in the footer.
 - Copies: At registration, each attendee will receive the **Conference Binder** with all conference briefings/papers
- **Data submittal information:**
 - Deadline for electronic data submittal: **Friday, March 12, 2004**
 - Upload files to the Payload Safety Data Management System (DMS). If you do not currently have access to this system, contact Mindi Mudd, the system administrator, for details (281.483.9078).
 - **INCLUDE:** a statement covering release of STI and Export Control. For NASA employees this would include Forms 548/1676.
 - Submit session equipment set-up requirements and special equipment requests to Leanne Brasington, Logistics Chairman by **Friday, March 12, 2004**

Your session is integral to the success of the overall conference, so we will make every effort to assist you where we can. If you have questions, please contact Leanne Brasington (281.244.5997 or leanne.e.brasington1@jsc.nasa.gov).

Sincerely,
Vic Chang
Program Committee Member