AEROSPACE BATTERY ACTIVITIES
AT
NASA/GODDARD SPACE FLIGHT CENTER

Gopalakrishna M. Rao
Code 563
Power Systems Branch
Electrical Engineering Division
Applied Engineering and Technology Directorate
NASA Goddard Space Flight Center
Greenbelt, Maryland 20771
Content

- Prelude
- Battery Chemistry
- Nickel-Cadmium (NiCd) Chemistry
- Nickel-Hydrogen (NiH₂) Chemistry
- Lithium-Ion (Li-Ion) Chemistry
- NASA/Goddard Space Flight Center (GSFC) Spacecraft
- Summary
Prelude

- Identify the Maturity of a Rechargeable Secondary Battery Cell Chemistry for Aerospace Use
- Test and Validate the Matured Cell for Aerospace Application
- Design, Test, Qualify and Infuse the Advanced Battery into Spacecraft
- Manage on board Battery Operation for a Successful Mission
- GSFC "Pioneered" Rechargeable Secondary Battery for Aerospace Application since early 1960
Battery Chemistry

- Nickel-Cadmium (NiCd) Battery
- Nickel-Hydrogen (NiH₂) Battery
- Lithium-Ion (Li-Ion) Battery
NiCd Battery

- Conventional
  - Gates Aerospace Batteries
  - SaFT
  - ACME

- Super
  - Hughes Aerospace/Eagle Picher Technologies
NiCd Battery Conventional - cont’d.

- Gates Aerospace Batteries
  - 1 to 50 Ah
  - Design, Test, Infuse and Use
  - Low-Earth-Orbit (LEO), Geosynchronous-Earth-Orbit (GEO), Libration Point
  - Over 80 Spacecraft over 40 years
    - LANDSAT (22 plus years) and ERBS
    - (19 plus years) batteries have the longest onboard LEO life
NiCd Battery Conventional - cont'd.

- SaFT
  - 40 Ah
  - Design, Test, Infuse and Use
  - LEO and GEO
    - TDRS
    - POES
    - FUSE
NiCd Battery Conventional- cont’d.

- ACME
  - 6.5 Ah
  - First LEO Application
  - Design, Test, Infuse and Use
  - LEO
  - CHIPSAT
Super NiCd Battery

- Hughes/Eagle Picher Technologies
  - 9 to 50 Ah
  - Design, Test, Infuse and Use
  - LEO
    - SMEX (5)
    - XTE
    - TRMM
    - Image
    - TOMS
    - NEAR
    - Contour
Major Current NiCd Battery Flight Project

- **POLAR ORBITAL ENVIRONMENTAL SATELLITE (POES) : N’**
  - Additional spacecraft is in consideration
    - Possible delay in NPOES launch
  - Requirements
    - 3 SaFT batteries, 17 40Ah NiCd cells in series per battery
    - LEO/Polar
    - 2 years (Design), 3 years (Goal)
    - 0 to 21% Depth-of-Discharge (DoD), 5°C
  - Launch is scheduled for December 2007
NiH$_2$ Battery

- Individual Pressure Vessel (IPV)
- Common Pressure Vessel (CPV)
- Single Pressure Vessel (SPV)
- All from Eagle Picher technologies except as indicated
NiH$_2$ Battery - cont’d.

- IPV
  - 50 to 160 Ah
  - Design, Test, Infuse and Use
  - Advanced Catalytic Wall Wick Application
    - TERRA, LANDSAT, AQUA, AURA AND NPOES
  - Both LEO, GEO and Libration Point
    - First LEO Application (HST)
    - First In-Orbit Refurbishment (HST)
- TERRA
- LANDSAT
- AQUA
- TDRS (Boeing)
- GOES (Boeing)
- TIMED
- AURA
- SWIFT
- NPP
- NPOES
- GLAST
NiH$_2$ Battery - cont’d.

- CPV
  - 16 Ah to 40 Ah
  - Design, Test, Infuse and Use
  - GOES Project Funded the 16 Ah Development
  - MAP Developed 23 Ah with Bypass Circuitry
  - Both LEO, LEO and Libration Point
    - SSTI
    - MAP
    - ICESAT
    - MESSENGER
    - STEREO
NiH$_2$ Battery - cont’d.

- SPV
  - 12 Ah to 40 Ah
  - Design, Test, Infuse and Use
  - HQ Funded 20 Ah Development
  - LEO
    - Glory
Major Current NiH₂ Battery Flight Projects

- Geostationary Operational Environmental Satellite (GOES): N - Q
- Hubble Space Telescope (HST)
- Others
GOES

- GOES-N, O, P; GOES-N Launch 1/06
- Requirements
  - 1 Battery, 24 cells/Battery, 123 Ah, <75 % DoD nominal during maximum eclipse, safehold DoD <94%
  - Launch with ~65% State-of-Charge (SoC)
  - GEO for 10 years, -10 to 15°C
- Cell and Battery Status
  - IPV, Boeing (Hughes); Eagle Picher Technologies, Colorado Springs (N&O) and Torrance (P)
  - One battery per S/C with three packs in series; each pack consists of eight cells in series
  - GOES-N/O flight lot activation in 3/04; cells for GOES-O were placed in cold storage after activation and cell acceptance testing
  - GOES-P flight lot built (3/03) were placed in dry storage until needed
  - GOES-N, battery were installed on S/C in 9/04
- Issues/Concerns
  - Qualification of Torrance and Extended dry and wet storage of cells
  - Ground handling of charged batteries at launch site and Lack of cooling at launch site
  - Temperature differences between battery packs during ground operations, orbit raising, and on-orbit operations
  - Cell Imbalance and Cell Leak or Short
HST

- Tentative Battery Change-out for Servicing Mission 4
- Requirements
  - 6 Batteries (22 Cells/Battery, 80 Ah NiH₂) and 1 Spare Battery
  - LEO, 5 years design (32,000 cycles) w/ 10 years goal (64,000 cycles), <10% DoD, -5 to 5°C
- Cell and Battery Status
  - Rabbit-ear, Man-tech Design
  - 26 cells (13 each from lot 10 and lot 11) activated in 96. Nominal 2 years stress test performance, six 5-cell pack system test at MSFC completed 2000 successful cycles (apparent poor load sharing and cell voltage divergence due to cell heritage, cell lot and some questionable cells)
  - 13 cells (7 from lot 10 and 6 from lot 11) activated in 98. Nominal 8000 stress cycles and subsequent 3000 mission profile cycles
  - Activated remaining dry stored (in cold) flight cells in 8/00, stress test completed 9000 nominal cycles
  - 7 batteries built and finished battery level ATP at Joplin, completed in 4/02
  - Assembly, test, and delivery of 2 modules and spare battery to GSFC in 10/02
  - 2 flight battery modules and 1 spare battery in storage (0°C ± -5°C) at GSFC
- Issues/Concerns
  - Proper storing of the batteries at launch site and wet-life
Major Current NiH₂ - Others

- AIM (9/06)
- STEREO (8/06)
- GLAST (07)
- GLORY (07)
- NPP (08)
- NPOES (13)
- JWST (13)
Li-Ion Battery

- **Emerging Technology**
  - High specific energy
  - High energy density
  - Benign handling requirements compared to Nickel Chemistry

- **Concerns**
  - Overcharge
  - Cell Balancing
  - Cycle Life
  - Calendar Life and Solstice Storage

- **Mitigation**
  - Started Cell Test Program in late 02
  - Selected Vendors
    - Japanese Storage Batteries (JSB)
    - AEA Technology Battery Systems Ltd. (ABSL)
    - SaFT
    - Lithion
    - Quallion
Li-Ion Battery - Test Profile

- **Low-Earth-Orbit (LEO)**
  - Temperature: 20 ± 2°C
  - Depth of Discharge: about 30%
  - Discharge: Constant current for 36 minutes
  - Charge: Constant current to a battery voltage clamp with taper for 60 minutes

- **Low-Lunar-Orbit (LLO)**
  - Temperature: 20 ± 2°C
  - Depth of Discharge: about 30 or 40% (twice a year 80%)
  - Discharge: Constant current for 48 minutes (160 minutes for 80% DoD)
  - Charge: Constant current to a battery voltage clamp with taper for 65 minutes

- **Geosynchronous-Earth-Orbit (GEO)**
  - Temperature: 20 ± 10°C
  - Eclipse Period: 42 days, Discharge at 0.6 C for a maximum shadow period of 72 minutes, Charge at C/20 to a battery voltage clamp with taper for the remainder of duration
  - Solstice Period: 140 days, battery voltage maintained at a battery voltage clamp (~70% SoC)
  - Prior to each eclipse season, the battery is charged up to 100% SoC using C/20 charge rate to battery voltage clamp with taper
# Li-Ion Battery - LEO Test Data

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Battery Size (Ah)</th>
<th>Start Date</th>
<th>Clamp Voltage (V)</th>
<th>EoD Voltage (V)</th>
<th>Cycle #</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSL</td>
<td>60</td>
<td>2/03</td>
<td>33.6</td>
<td>29.2</td>
<td>6000*, b</td>
</tr>
<tr>
<td>JSB</td>
<td>100</td>
<td>5/03</td>
<td>31.6</td>
<td>28.6</td>
<td>14,500</td>
</tr>
<tr>
<td>SaFTc</td>
<td>80</td>
<td>11/03</td>
<td>31.2</td>
<td>27.7</td>
<td>10700**</td>
</tr>
<tr>
<td>Lithion</td>
<td>100</td>
<td>1/04</td>
<td>7.8***</td>
<td>7.14****</td>
<td>8750</td>
</tr>
</tbody>
</table>

* First 1800 cycles at 40% DoD  
** 12 cycles at 27 %, and 32 cycles at 13% DoD  
*** 31.2 V at battery level  
**** 28.56 V at battery level  
  
a End-of-Discharge (EoD)  
  
b The testing stopped due to gradual failure of strings (total six(6)) after 2250 cycles at 30% DoD - ABSL attributed this to the effect of the short that occurred after 30% DoD 900 cycles  
  
c Cell balancing circuit
# Li-Ion Battery - LLO Test Data

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Battery Size (Ah)</th>
<th>Start Date</th>
<th>Clamp Voltage (V)</th>
<th>EoD Voltage (V)</th>
<th>Cycle #</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSL(^a)</td>
<td>60</td>
<td>1/05</td>
<td>33.6</td>
<td>30.8</td>
<td>4000</td>
</tr>
<tr>
<td>JSB(^b)</td>
<td>50</td>
<td>2/05</td>
<td>31.6/32*</td>
<td>28.75</td>
<td>3200</td>
</tr>
<tr>
<td>saFT(^b)</td>
<td>40</td>
<td>2/05</td>
<td>31.2/32.8*</td>
<td>28.1</td>
<td>3400</td>
</tr>
<tr>
<td>Lithion(^b)</td>
<td>50</td>
<td>4/05</td>
<td>15.8/16.4*, **</td>
<td>14.1***</td>
<td>2600</td>
</tr>
<tr>
<td>Quallion(^b)</td>
<td>15</td>
<td>2/05</td>
<td>31.6/32.8*</td>
<td>28.2</td>
<td>3400</td>
</tr>
</tbody>
</table>

* 2\(^{nd}\) voltage clamp used prior to 80% discharge cycle, all batteries completed at least one 80% DoD cycle
** 31.6/32.8 V at battery level
*** 28.2 V at battery level
\(^a\) 30% DoD
\(^b\) 40% DoD
# Li-Ion Battery - GEO Test Data

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Battery Size (Ah)</th>
<th>Start Date</th>
<th>Clamp Voltage (V)</th>
<th>EoD Voltage at Maximum DoD (V)</th>
<th>Shadow Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSL</td>
<td>80</td>
<td>2/03</td>
<td>33.6</td>
<td>27.5</td>
<td>5</td>
</tr>
<tr>
<td>JSB</td>
<td>100</td>
<td>5/03</td>
<td>16.0*</td>
<td>14.8***</td>
<td>5</td>
</tr>
<tr>
<td>SaFT&lt;sup&gt;a&lt;/sup&gt;</td>
<td>80</td>
<td>11/03</td>
<td>32.8</td>
<td>28.0</td>
<td>4</td>
</tr>
<tr>
<td>Lithion</td>
<td>100</td>
<td>1/04</td>
<td>8.2**</td>
<td>7.1****</td>
<td>4</td>
</tr>
</tbody>
</table>

* 32.0 V at battery level  
** 32.8 V at battery level  
*** 29.6 at battery level  
**** 28.4 at battery level  
<sup>a</sup> Cell balancing circuit
Major Current Li-Ion Battery Flight Projects

- NEW MILLENNIUM PROGRAM (NMP)
  - Space Technology - 5 (ST-5)
- SOLAR DYNAMIC OBSERVATORY (SDO)
- LUNAR RECONNAISSANCE ORBITER (LRO)
- OTHERS
NMP : ST-5

- February 2006 Launch
- Requirements
  - 1 Battery, 7.5 Ah
  - Elliptical, sun synchronous orbit with some moon eclipses, 3 months duration, less than 400 cycles, up to 60% DoD, -10 to 40°C
- Cell and Battery Status
  - 1 Test Battery, 1 Qual. Battery, and 3 Flight Batteries
  - Awarded contract to ABSL in 01
  - 6 parallel-strings each containing 2 1.5 Ah SONY cells in series
  - Prototype battery delivered, testing completed
  - Battery successfully completed qualification testing and delivered in 5/02
  - I&T have been supporting spacecraft operations through environmental testing
  - Flight batteries (1 for each of 3 spacecraft) successfully completed acceptance testing; delivered to GSFC in 7/03
  - Discharged batteries stored in cold
- Issues/Concerns
  - Charging during short sunlight periods
SDO

• August 2007 Launch
• Requirements
  – 1 Battery, 800 cells (100 parallel strings of 8 cells in series)/Battery, 120 Ah
  – GEO, 5 years goal (approx 400 cycles), 60% max. DoD, 10 to 30°C
• Cell and Battery Status
  – 1 Test Battery, 1 Qual. Battery, and 2 Flight Batteries
  – ABSL selection and award announced in 8/05
  – Design discussions and test program Completed in 9/05
  – Design Conformance Review in 1/06
• Issues /Concerns
  – Overcharge
  – Range safety requirements
LRO

- October 2008 Launch
- Requirements
  - 1 Battery, 80 Ah
  - LLO, 14 months (about 6,000 cycles), nominal 30% DoD and a few 80% DoD, 10 to 30°C
    - Goal 5 years at reduced DoD
- Cell and Battery Status
  - Li-Ion Chemistry is base lined due to mass constraints
  - 1 Qual. Battery, 1 Test Battery, and 2 Flight Batteries
  - Released Request for Proposal in 12/05
  - Proposals are due in 1/06
- Issues and concerns
  - Schedule
  - Cell balancing methodology for parallel/series cell configuration
  - Overcharge
Major Current Li-Ion - Others

- Cream (05 on)
- Calipso (06)
- THEMIS (8/06)
- GPM (12))
- LISA (12)
- HST (12)?
- MMS (13)
- JWST (13)?
<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Launch Date</th>
<th>Battery/Cell Manufacturer</th>
<th>Battery Size</th>
<th>Cell Type</th>
<th>Orbit (km x km) and Inclination</th>
<th>Orbit (km x km) and Inclination</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOFTI-1</td>
<td>2/61</td>
<td>Sonotone</td>
<td>3.5 Ah. Cyl.</td>
<td>F Cell, **Cyl.</td>
<td>LEO, 106 m.</td>
<td>LEO, 106 m.</td>
</tr>
<tr>
<td>Explorer VI</td>
<td>8/59</td>
<td>F Cell, **Cyl.</td>
<td>14 Cell</td>
<td>F Cell, **Cyl.</td>
<td>1075X887, 79.0°</td>
<td>1075X887, 79.0°</td>
</tr>
<tr>
<td>Explorer XXII</td>
<td>10/10/64</td>
<td>Sonotone</td>
<td>23 Cell</td>
<td>2 - 10 Cell</td>
<td>LEO, 95.9 m.</td>
<td>770X361, 53.8°</td>
</tr>
<tr>
<td>Ariel I</td>
<td>4/26/62</td>
<td>Sonotone</td>
<td>5 Ah. Cyl.</td>
<td>1 - 19 Cell</td>
<td>LEO, 157.7 m.</td>
<td>5642X944, 44.8°</td>
</tr>
<tr>
<td>Telstar I</td>
<td>7/62</td>
<td>Sonotone</td>
<td>5 Ah. Cyl.</td>
<td>1 - 19 Cell</td>
<td>LEO, 157.7 m.</td>
<td>5642X944, 44.8°</td>
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<tr>
<td>Telstar II</td>
<td>5/7/63</td>
<td>Sonotone</td>
<td>5 Ah. Cyl.</td>
<td>1 - 19 Cell</td>
<td>LEO, 225 m.</td>
<td>LEO, 225 m.</td>
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<tr>
<td>Alouette I</td>
<td>9/29/62</td>
<td>Sonotone</td>
<td>5 Ah. Cyl.</td>
<td>6 - 12 Cell</td>
<td>LEO, 105 m.</td>
<td>10.800X971, 42.7°</td>
</tr>
<tr>
<td>Syncom II</td>
<td>2/14/63</td>
<td>Sonotone</td>
<td>5 Ah. Cyl.</td>
<td>6 - 12 Cell</td>
<td>LEO, 105 m.</td>
<td>10.800X971, 42.7°</td>
</tr>
<tr>
<td>Syncom II</td>
<td>7/26/63</td>
<td>Sonotone</td>
<td>6 Ah</td>
<td>2 - 10 Cell</td>
<td>LEO, 94.4 m.</td>
<td>602X357, 98.7°</td>
</tr>
<tr>
<td>Nimbus I</td>
<td>8/19/64</td>
<td>Sonotone</td>
<td>6 Ah</td>
<td>2 - 10 Cell</td>
<td>LEO, 108 m.</td>
<td>1182X1096, 100.4°</td>
</tr>
<tr>
<td>Nimbus II</td>
<td>5/15/66</td>
<td>Sonotone</td>
<td>6 Ah</td>
<td>2 - 10 Cell</td>
<td>LEO, 108 m.</td>
<td>1182X1096, 100.4°</td>
</tr>
</tbody>
</table>

(GSFC) Space Flight Center

NASA/Goddard Space Flight Center
### NASA/GSFC Spacecraft (cont’d)

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Launch Date(s)</th>
<th>Orbit (km X km) and Inclination</th>
<th>Cell Type</th>
<th>Battery Size</th>
<th>Battery/Cell Manufacturer</th>
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</thead>
<tbody>
<tr>
<td>OAO-A1</td>
<td>Apr 66, 12/7/68, 8/21/72</td>
<td>LEO, 100 m, 750x750, 35° (nominal)</td>
<td>20 Ah Prismatic</td>
<td>3 22 Cell</td>
<td>Grumman/Gulton</td>
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<tr>
<td>OAO-A2</td>
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<td></td>
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<td>OAO-3</td>
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<tr>
<td>OSO-1</td>
<td>3/7/62</td>
<td>Leo, 95.2 m 595x553, 32.8°</td>
<td>12 Ah</td>
<td>2</td>
<td>Ball Bros.</td>
</tr>
<tr>
<td>SAS-A</td>
<td>12/12/70, 11/16/72</td>
<td>LEO, 96 m, 3.0°  LEO, 95 m, 1.9° (550x550)</td>
<td>6 Ah</td>
<td>1 8 Cell</td>
<td>APL/Gulton</td>
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<tr>
<td>SAS-B</td>
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<td>APL/GE</td>
</tr>
<tr>
<td>ATS-F (6)</td>
<td>5/30/74</td>
<td>GEO, m, 1-6°</td>
<td>15 Ah</td>
<td>2 - 19 Cell</td>
<td>Fairchild/Gulton</td>
</tr>
<tr>
<td>TIROS -1</td>
<td>4/1/60, 11/60, 6/61, 2/62</td>
<td>LEO, 99 m, 738x689, 48.3°</td>
<td>F Cell ** Cyl.</td>
<td>3 21 Cell</td>
<td>GE-Astro/ Sonotone</td>
</tr>
<tr>
<td>TIROS -2</td>
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<tr>
<td>TIROS -3</td>
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<tr>
<td>TIROS -4</td>
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<tr>
<td>TIROS -5</td>
<td>6/62, 9/62, 6/63, 12/63</td>
<td>LEO, 955x591, 58.1°</td>
<td>F Cell ** Cyl.</td>
<td>3 21 Cell</td>
<td>GE-Astro/ Sonotone</td>
</tr>
<tr>
<td>TIROS -6</td>
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<tr>
<td>TIROS -7</td>
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<tr>
<td>TIROS -8</td>
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<tr>
<td>TIROS -9</td>
<td>1/65, 7/2/65</td>
<td>LEO, 2581x705, 96.3° LEO, 835x741, 98.6°</td>
<td>F Cell ** Cyl.</td>
<td>3 21 Cell</td>
<td>GE-Astro/ Sonotone</td>
</tr>
<tr>
<td>TIROS -10</td>
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<tr>
<td>Spacecraft</td>
<td>Launch Date(s)</td>
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<td>Battery Size</td>
<td>Orbit (km x km) and Inclination</td>
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<td>---------------------------------</td>
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</tr>
<tr>
<td>NOAA-1 (LSTOS-A)</td>
<td>12/11/70, 10/72, 11/73, 11/74, 7/76</td>
<td>2 Ah</td>
<td>LEO: 115 m x 1472 x 1492, 101.9°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOAA-6...11</td>
<td>6/79...9/88, 3/84, 7/82, 11/89, 5/17/74, 2/6/75</td>
<td>5 Ah</td>
<td>LEO: 115 m x 1472 x 1492, 101.9°, GEO: 21.8 h, 1.8°, GEO: 23.9 h, 0.1°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landsat -4</td>
<td>7/16/82</td>
<td>D</td>
<td>LEO: 98.6 m x 7070 x 683, 98°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMS -1 (A)</td>
<td>3/17/74</td>
<td>2 Ah</td>
<td>LEO: 900 x 900, Sun Synchronous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GOES -1, SMS -C</td>
<td>10/75</td>
<td>2 Ah</td>
<td>GEO: 24.05 h, 1.0°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GOES -C</td>
<td>6/77</td>
<td>3 Ah</td>
<td>GEO: 24.05 h, 1.0°</td>
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<td></td>
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<tr>
<td>Spacraft</td>
<td>Battery/Cell Size</td>
<td>Battery Type</td>
<td>Manufacturer</td>
<td>Orbit (km x km) and Inclination</td>
<td>Launch Date(s)</td>
</tr>
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<tr>
<td>IUE</td>
<td>6 Ah</td>
<td>2</td>
<td>GSFC/GE</td>
<td>HEO, 23.9, 45,464 x 25722, 28.6°</td>
<td>1/26/78</td>
</tr>
<tr>
<td>SMM</td>
<td>40 Ah</td>
<td>20 AH</td>
<td>GE</td>
<td>LEO, 66 x 558, 97.6°</td>
<td>Feb 80</td>
</tr>
<tr>
<td>TDRS-A-D (4)</td>
<td>9 Ah</td>
<td>1</td>
<td>Boeing/EPI</td>
<td>LEO, 66 x 558, 641 x 548, 54.9°</td>
<td>4/26/78</td>
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<tr>
<td>HCMM (AEM-A)</td>
<td>9 Ah</td>
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<td>Boeing/EPI</td>
<td>LEO, 66 x 558, 97.6°</td>
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<tr>
<td>SAGE</td>
<td>9 Ah</td>
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<td>LEO, 66 x 558, 97.6°</td>
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<tr>
<td>GRO</td>
<td>50 Ah</td>
<td>6 *- 22 Cell</td>
<td>MDESC/GAB</td>
<td>LEO, 66 x 558, 97.6°</td>
<td>4/5/91</td>
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<tr>
<td>UARS</td>
<td>50 Ah</td>
<td>6 *- 22 Cell</td>
<td>MDESC/GAB</td>
<td>LEO, 66 x 558, 97.6°</td>
<td>Sep 91</td>
</tr>
<tr>
<td>EUVE</td>
<td>50 Ah</td>
<td>6 *- 22 Cell</td>
<td>MDESC/GAB</td>
<td>LEO, 66 x 558, 97.6°</td>
<td>Aug 92</td>
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<tr>
<td>TOPEX</td>
<td>50 Ah</td>
<td>6 *- 22 Cell</td>
<td>MDESC/GAB</td>
<td>LEO, 66 x 558, 97.6°</td>
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<tr>
<td>Spacecraft</td>
<td>Launch Date (s)</td>
<td>Orbit (km X km) and Inclination</td>
<td>Cell Type</td>
<td>Battery Size</td>
<td>Battery/Cell Manufacturer</td>
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<tr>
<td>ERBS</td>
<td>Oct 84</td>
<td>LEO, 610X610, 57°</td>
<td>50 Ah</td>
<td>2 - 22 Cell</td>
<td>MDESC/GAB</td>
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<tr>
<td>SAMPEX</td>
<td>July 1992</td>
<td>LEO, 550 X 675, 82°</td>
<td>S, 9 Ah</td>
<td>1 - 22 Cells</td>
<td>Hughes/EPI</td>
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<tr>
<td>FAST</td>
<td>August 1996</td>
<td>350 X 4200, 8°</td>
<td>S, 9 Ah</td>
<td>1 - 22 Cells</td>
<td>Hughes/EPI</td>
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<tr>
<td>SWAS</td>
<td>Dec. 1998</td>
<td>LEO, 600 Km Circular, 70°</td>
<td>S, 21 Ah</td>
<td>1 - 22 Cells</td>
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<tr>
<td>WIRE</td>
<td>March 1999</td>
<td>LEO, 470 X 540, 97.4°</td>
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<td>Hughes/EPI</td>
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<tr>
<td>TRACE</td>
<td>April 1998</td>
<td>LEO, 600 X 650, Sun Synchronous</td>
<td>S, 9 Ah</td>
<td>1 - 22 Cells</td>
<td>Hughes/EPI</td>
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<tr>
<td>EO - 1</td>
<td>Nov. 2000</td>
<td>LEO, 705 km Circular, Sun Synchronous</td>
<td>S, 50 Ah</td>
<td>1 – 22 Cells</td>
<td>Hughes/EPI</td>
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<tr>
<td>RXTE</td>
<td>Dec. 1995</td>
<td>LEO, 600 Km Circular, 23°</td>
<td>S, 50 Ah</td>
<td>2 – 22 Cells</td>
<td>Hughes/EPI</td>
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<tr>
<td>TRMM</td>
<td>Nov. 1997</td>
<td>LEO, 405 Km Circular, 35°</td>
<td>S, 50 Ah</td>
<td>2 – 22 Cells</td>
<td>Hughes/EPI</td>
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<tr>
<td>TOMS</td>
<td>July 1996</td>
<td>LEO, 500 km Circular boosted to 740 km, Sun Synchronous</td>
<td>S, 9 Ah</td>
<td>1 – 22 Cell</td>
<td>Hughes/EPI</td>
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<tr>
<td>GGS - WIND</td>
<td>Nov. 1994</td>
<td>L2</td>
<td>26.5 Ah</td>
<td>3 – 16 Cells</td>
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<tr>
<td>GGS - POLAR</td>
<td>Feb. 1996</td>
<td>51,000 X 5,100, 86°</td>
<td>26.5 Ah</td>
<td>3 – 16 Cells</td>
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## NASA/GSFC Spacecraft (cont’d)

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Launch Date (s)</th>
<th>Orbit (km X km) and Inclination</th>
<th>Cell Type</th>
<th>Battery Size</th>
<th>Battery/Cell Manufacturer</th>
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<tbody>
<tr>
<td>MAP</td>
<td>June 2001</td>
<td>GEO, L2</td>
<td>23 Ah NiH2</td>
<td>1 - 22 Cells</td>
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<tr>
<td>AQUA</td>
<td>May 2002</td>
<td>705 Km, Circular, Sun Synchronous, 98°</td>
<td>160 Ah NiH2</td>
<td>1 - 24 Cells</td>
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<td>TERRA</td>
<td>Dec. 1999</td>
<td>705 Km, Circular, Sun Synchronous, 98°</td>
<td>50 Ah NiH2</td>
<td>2 - 54 Cells</td>
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<tr>
<td>LANDSAT 7</td>
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<td>705 Km, Circular, Sun Synchronous, 98°</td>
<td>50 Ah NiH2</td>
<td>2 - 17 Cells</td>
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<tr>
<td>HST</td>
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<td>600 Km, 28.47°</td>
<td>80 Ah NiH2</td>
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<tr>
<td>ACE</td>
<td>August 1997</td>
<td>Libration</td>
<td>12 Ah</td>
<td>1-18 Cells</td>
<td>GAB/SAFT</td>
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<td>FUSE</td>
<td>1999</td>
<td>LEO</td>
<td>40 Ah</td>
<td>1-22 Cells</td>
<td>SAFT</td>
</tr>
</tbody>
</table>

**Notes:**
* Consists of one or more Modular Power Systems (MPS). Each MPS contains three (3) 50 Ah, NiCd batteries.
** Sonotone’s cylindrical F cell was typically rated at 5 Ah.
S Super NiCd, no designation means conventional NiCd
Summary

- Goddard Space Flight Center has “Pioneered” Rechargeable Secondary Battery Design, Test, Infusion and In-orbit Battery Management among NASA Installations
- Nickel-Cadmium Batteries of various Designs and Sizes have been Infused for LEO, GEO and Libration Point Spacecraft
  - Over 18 years of mission life for LANDSAT (22 plus), ERBS (19 plus) and IUE batteries
  - Disabled and subsequently in-orbit stored ERBS battery was brought into service (adventure!!!) to gather important ozone data (the only satellite, at that time, that could gather this information)
  - Mr. Goldin, then NASA Administrator, credited GSFC for the Super NiCd battery development and for the infusion of the technology into the NASA missions
Summary - cont’d.

- Nickel-Hydrogen Batteries have Currently been Baseline for Majority of our Missions
  - HST is the first LEO application, and the onboard batteries have the longest (16 years) LEO cycle life
  - Advanced features were first implemented in onboard LANDSAT batteries
  - Designed and developed 16 Ah CPV battery
    - MARS missions benefited
  - MAP 23 Ah CPV battery design was adopted for missions like MESSENGER, STEREO etc.
  - 20 Ah SPV battery design is qualified for two year LEO missions
    - Glory spacecraft battery adapted the design
Summary - cont’d.

• Li-Ion Batteries from ABSL, JSB, SàFT and Lithion have been Designed and Tested for Aerospace Application
  – Emerging Technology for future NASA Missions
  – Completed two plus years of Real Time LEO and GEO cycles
  – ST - 5, a four-month mission, will be our first Li-Ion application and first application of ABSL batteries in America
  – Baselined for SDO (GEO) and LRO (LEO)
    • Life (Cycle and Calendar), solstice charge mode and cell balancing in a battery are the major issues flying the Li-Ion technology
  – ST-5, Calipso and THEMIS that are scheduled for launch in 06 would provide valuable in orbit battery performance experience and the lesson learned would be implemented in the future Cell/Battery Designs, Battery Ground Handling, and the onboard Battery Management