

Nickel Metal Hydride LEO Cycle Testing

Eric Lowery

NASA
George C. Marshall Space Flight Center

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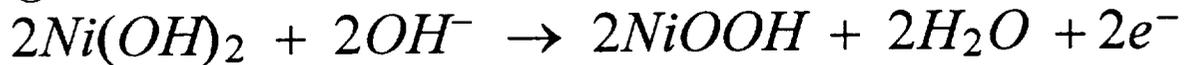
The George C. Marshall Space Flight Center is working to characterize aerospace AB5 Nickel Metal Hydride (NiMH) cells. The cells are being evaluated in terms of storage, low earth orbit (LEO) cycling and response to parametric testing (high rate charge and discharge, charge retention, pulse current ability, etc.). Cells manufactured by Eagle Picher are the subjects of the evaluation.

There is speculation that NiMH cells may become direct replacements for current Nickel Cadmium cells in the near future. Flight application of the subject NiMH cells is planned on a small university student satellite in 1997.

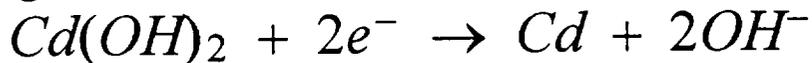
Electrode Reactions

NiCd Charge

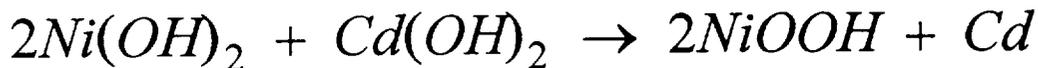
@Positive Electrode (Nickel):



@Negative Electrode (Cadmium):



Overall:

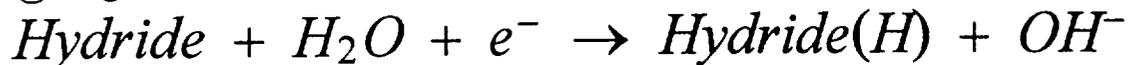


NiMH Charge

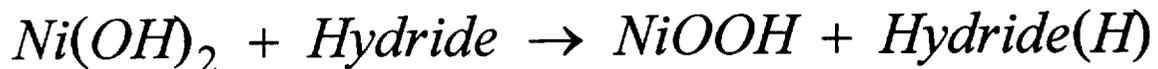
@Positive Electrode (Nickel):



@Negative Electrode (Metal Hydride):



Overall:



The energy density of the metal hydride cell is approximately 1.2 - 1.5 times the energy density of the NiCd cell. The actual ratio is dependent upon the packaging required. The Environmental Protection Agency has no objections to the disposal of spent NiMH cells. The mature NiMH cell is expected to be an order of magnitude less expensive than a comparable NiCd cell.

The operation of the NiMH cell is similar to the operation of the Nickel Cadmium (NiCd) cell. The reaction at the positive nickel electrode in the NiCd is the same as at the positive nickel electrode in the NiMH. Cadmium is oxidized and reduced at the negative electrode in the NiCd cell. In the NiMH cell, hydrogen is adsorbed and desorbed by the active hydride metal of the negative electrode.

Nickel Metal Hydride - Alloy

AB_2

Primarily Nickel Titanium (NiTi) or Iron Titanium (FeTi) with various mischmetal percentages of Zirconium (Zr), Nickel (Ni), Vanadium (V), Chromium (Cr) and transition metals generally referred to as X and Y components.

AB_5

Primarily Lanthanum Nickel₅ (LaNi₅) or Cerium Nickel₅ (CeNi₅), with various mischmetal percentages of Cobalt (Co), Silicon (Si) etc.

The two primary hydride classes that are used to manufacture NiMH cells are AB_2 and AB_5 . Most of the early work with NiMH was with the AB_2 alloy. This alloy is found most prominently in the cylindrical cells manufactured for the consumer market. The AB_5 alloy was developed later. The AB_5 alloy seems to have properties better suited to aerospace applications. The cycle life and mechanical integrity of the AB_5 alloy seems to be greater.

Aerospace NiMH vs. Commercial NiCd

	Metal Hydride Eagle-Picher AB5, Prismatic	Nickel Cadmium Gates, Cylindrical	Nickel Cadmium Saft, Cylindrical
Rated Capacity @ avg volt = 1.25	10 Ampere Hrs.	7 Ampere Hrs.	7 Ampere Hrs.
Length	2.591 cm	8.778 cm	8.852 cm
Width/Dia.	5.192 cm	3.226 cm	3.231 cm
Height	7.999 cm		
Mass	349.56 g	225.67 g	202.48 g
Energy Density	116.2 Wh/l	121.9 Wh/l	120.6 Wh/l
Specific Energy	35.7 Wh/kg	38.8 Wh/kg	43.21 Wh/kg

An effort is being made to utilize commercial technology wherever possible to reduce the cost of programs and bring them to fruition faster. This chart is a comparison of two commercial NiCd cells with an aerospace NiMH. The relatively low energy density of the NiMH is due to heavier packaging; however, if use of commercial technology is possible, a large cost and weight saving may be realized.

EPI RMH-10

10 Ampere Hour Nickel Metal Hydride Cell Produced by Eagle-Picher Ind, Joplin, MO.

10 Positive (Nickel) plates and 11 Negative (Hydride) plates.
Polypropylene Separators.

31% Potassium Hydroxide Electrolyte.

Orbit Profile

Highly Elliptical, 99 minute length.

69 Minutes Sun, 30 Minutes Eclipse.

Constant Power Load = 17.0 watts.

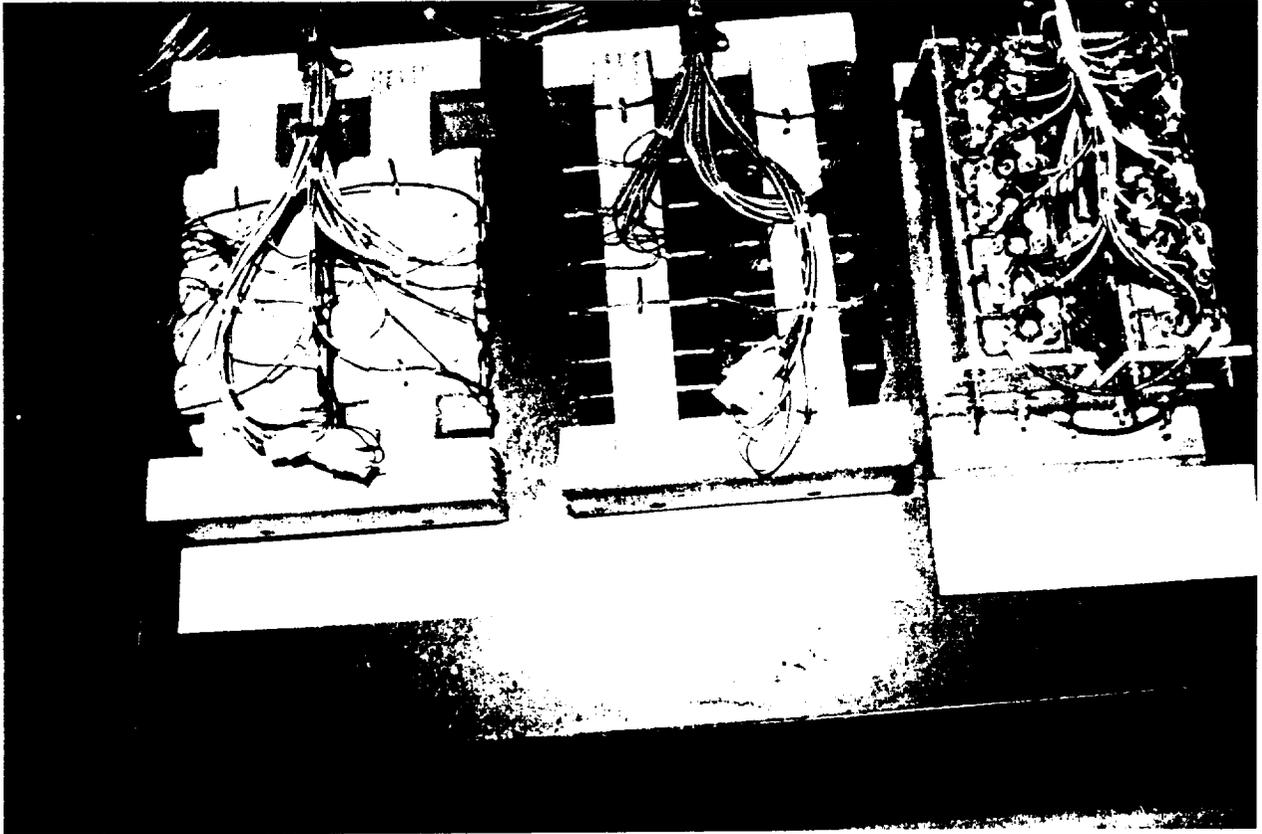
4% DOD (NiMH), 5.6% DOD (NiCd)

5300 LEO Orbits Annually.

The planned application of the NiMH batteries is on a small amateur radio satellite built by the Students for the Exploration and Development of Space (SEDS). The name of the satellite built by the group is the Students for the Exploration and Development of Space Satellite (SEDSAT). This small satellite is designated to be launched from the Space Shuttle in early 1997 as the effective endmass for a flight of NASA's Small Expendable Deployer System (also SEDS). The student SEDS group is composed of university students from around the world working cooperatively to further their understanding and interest in space. This small satellite is a practical application of all new technologies possible.

The power system baselines NiMH battery cells because of their energy density. The spacecraft power bus can operate between 16 and 40 volts because of voltage converters; however, the solar array capability can only charge 16 battery cells.

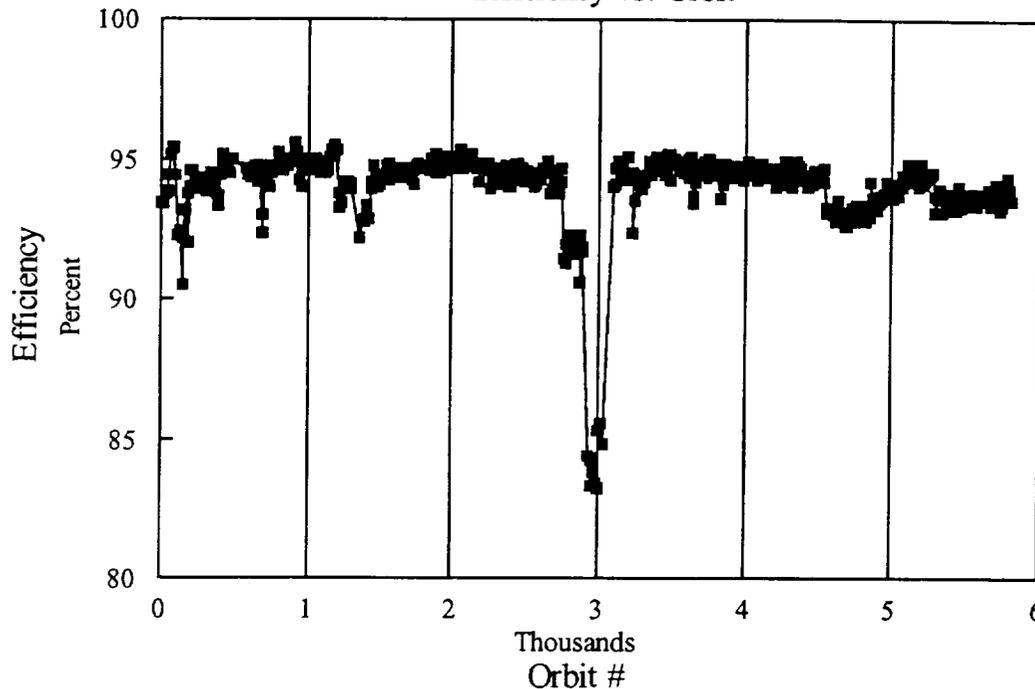
A 16 cell NiMH battery is being LEO cycled in a simulated power system in support of the anticipated launch. Two commercial NiCd batteries are also being cycled in the same manner for comparison and as possible alternative flight batteries.



THE PHOTOGRAPH ON THIS PAGE ILLUSTRATES THE TEST BATTERIES.

The battery on the left is composed of commercial 7 ampere hour cylindrical NiCd cells manufactured by Gates Energy. The middle battery is composed of commercial 7 ampere hour cylindrical NiCd cells manufactured by Saft. The battery on the right is composed of aerospace 10 ampere hour NiMH cells manufactured by Eagle-Picher. Instrumentation for the batteries includes battery voltage, cell voltage, battery current and temperature. The batteries have been cycled 5800 real time orbits.

CDDF/SEDSAT NiMH LEO Cycling Efficiency vs. Orbit

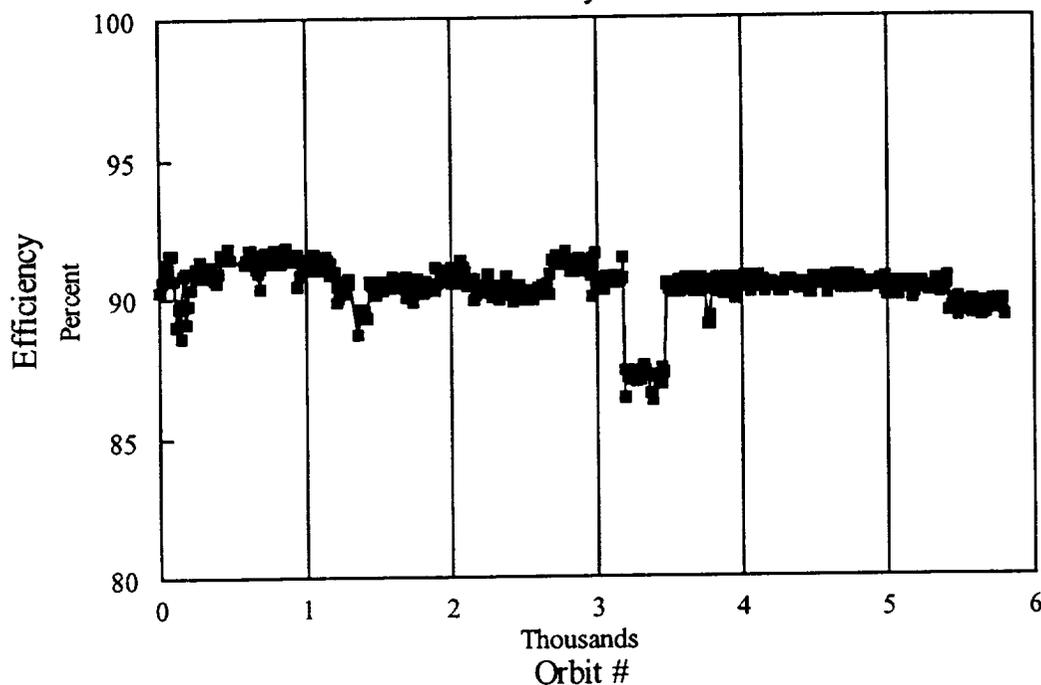


10 Ampere Hour Eagle-Picher (AB5)
Nov-94

The NiMH battery is very efficient. The average watt hour efficiency over the 5800 orbits has been 94%. The depth of discharge is very low (4%) and the load during discharge has not caused the voltage to decrease very much from the charge value. The battery efficiency on an ampere hour basis is 91%. The recharge ratio was adjusted to minimize overcharge and to maximize the efficiency.

The decrease in efficiency at 3000 cycles was caused by a loss of two of the cells. The first cell began to show degraded performance at 2950 cycles. The cell began to develop an impedance during charge and exhibited a severe loss of capacity during discharge. The poor performance of the cell is attributed to degradation of the separator. The cell was removed from the battery after 2990 cycles. A second cell began to exhibit the same type of behavior at 3030 cycles. This cell also began to develop an impedance during charge and exhibited a severe loss of capacity during discharge. The second cell was removed from the pack at 3070 cycles.

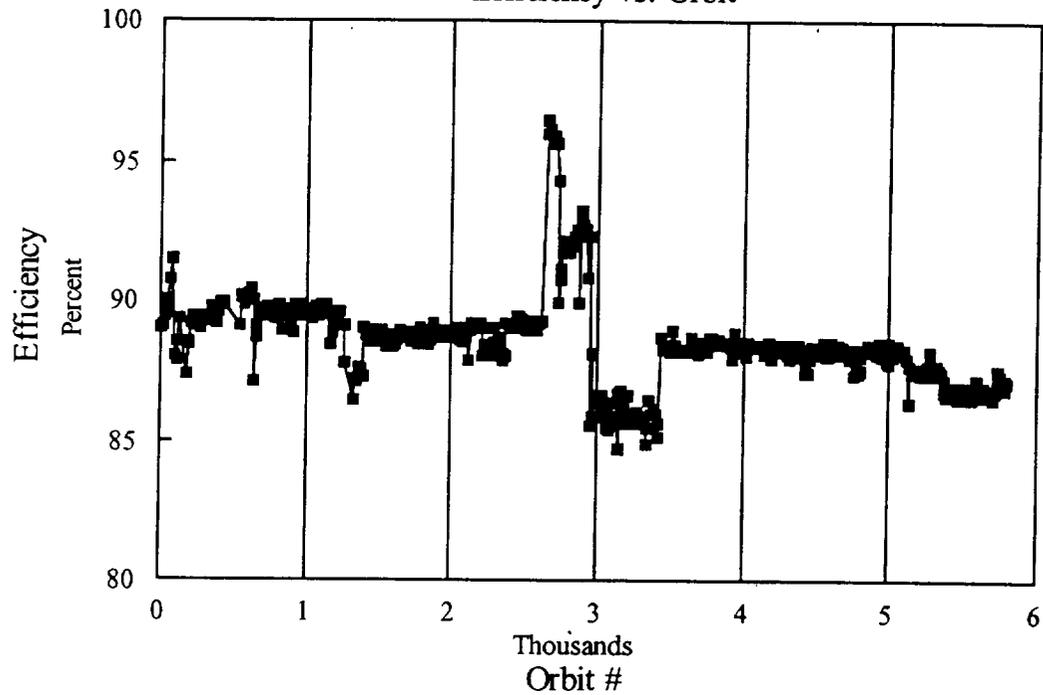
CDDF/SEDSAT NiCd LEO Cycling Efficiency vs. Orbit



7 Ampere Hour Gates
Nov-94

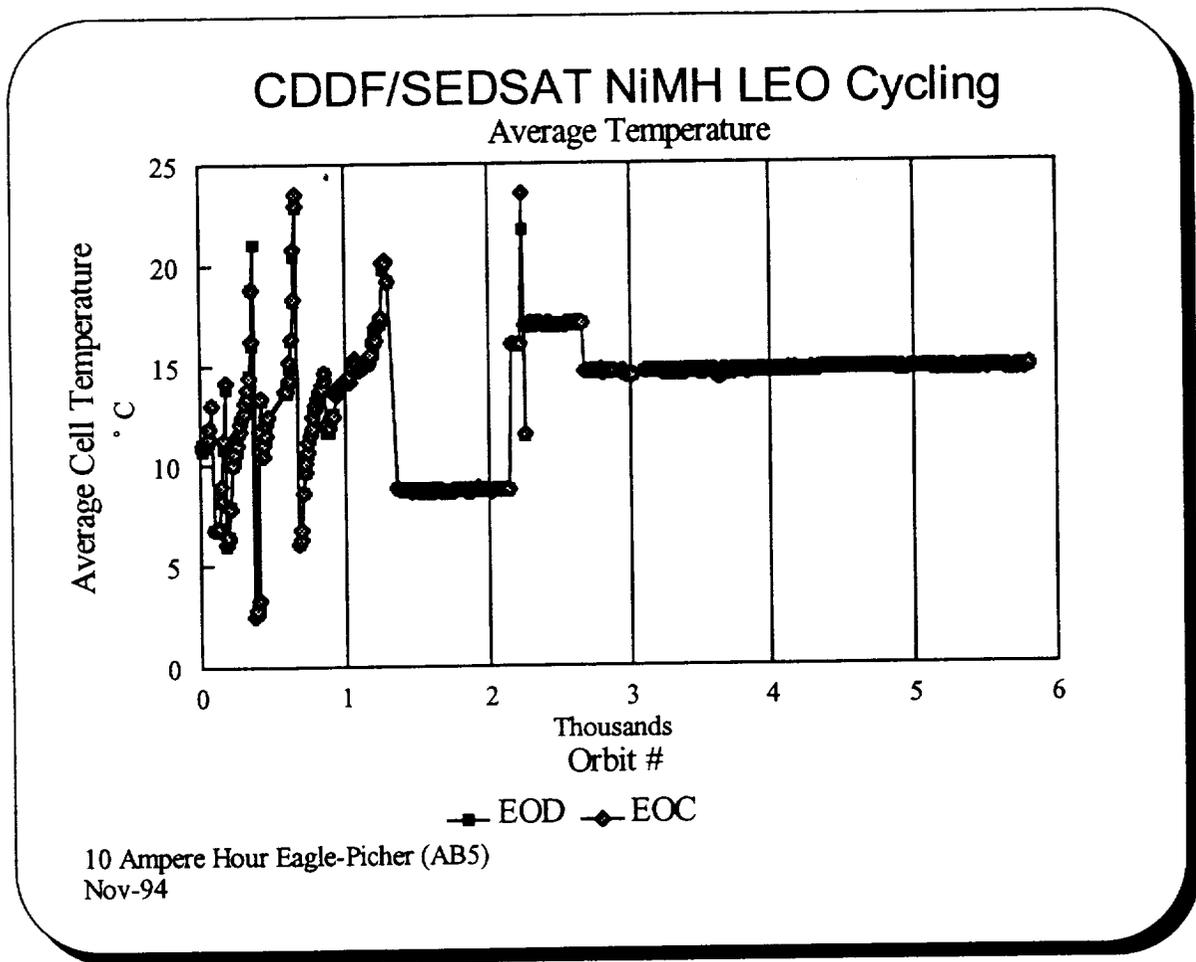
The commercial NiCd cells did not perform as well as expected. The light load and the minimal overcharge were hoped to produce a higher watt hour efficiency. The efficiency of the 7 ampere hour commercial NiCd cells manufactured by Gates averaged 91% over the first 5800 real time LEO cycles. The depth of discharge for the 7 ampere hour cells is 5.6%. The recharge ratio during the 5800 cycles was set at 1.04. The recharge ratio was adjusted based on the performance of the NiMH cells. The charge acceptance efficiency may have been a factor in the performance of the NiCd cells. All three of the batteries were charged to a recharge ratio of 1.04 at a moderate rate with less than five minutes of trickle charge. The NiMH cells charge acceptance efficiency is very high at moderate charge rates. The charge acceptance efficiency of the NiMH cell is also very high at high rates of charge. The charge acceptance efficiency of the NiCd cell is high at high charge rates but decreases substantially at lower rates of charge.

CDDF/SEDSAT NiCd LEO Cycling Efficiency vs. Orbit



7 Ampere Hour Saft
Nov-94

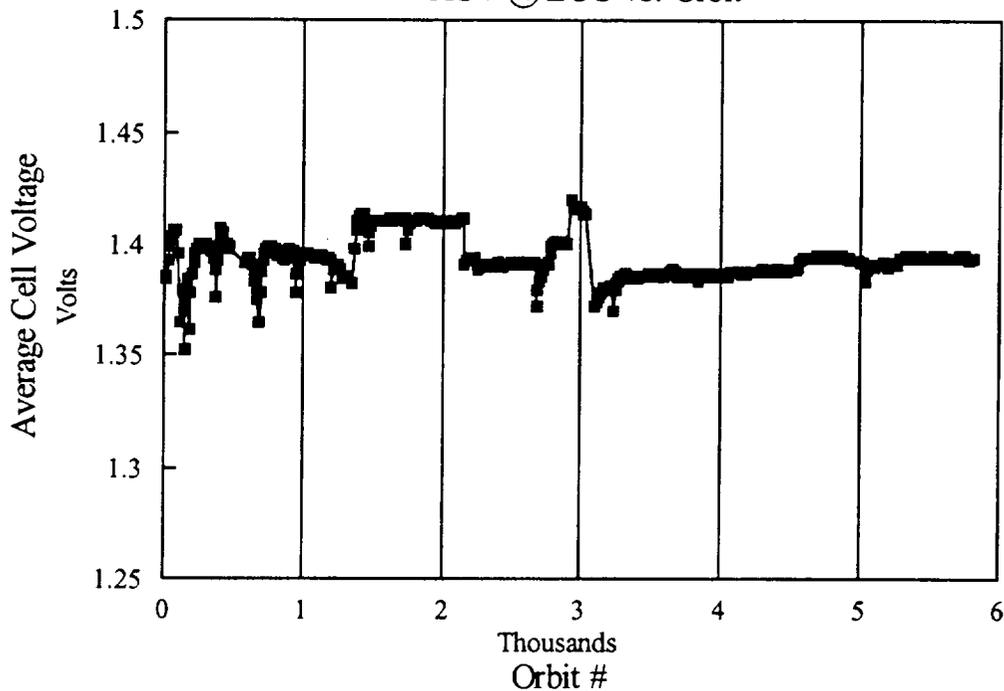
The watt hour efficiency of the commercial NiCd cells produced by Saft was not as high as the efficiency of the commercial cells produced by Gates. The average watt hour efficiency of the Saft cells over the 5800 orbits was 89%.



The temperature of the test batteries fluctuated greatly during the first 1000 cycles; however, the efficiency of the batteries was not affected. The efficiency of all three batteries was constant during the period of thermal variance. The early thermal variation was due to problems with the environmental chamber providing thermal control. Temperature did not appear to have a significant effect on performance of the NiMH or the NiCd batteries during the first 5800 LEO cycles.

CDDF/SEDSAT NiMH LEO Cycling

ACV @ EOC vs. Orbit

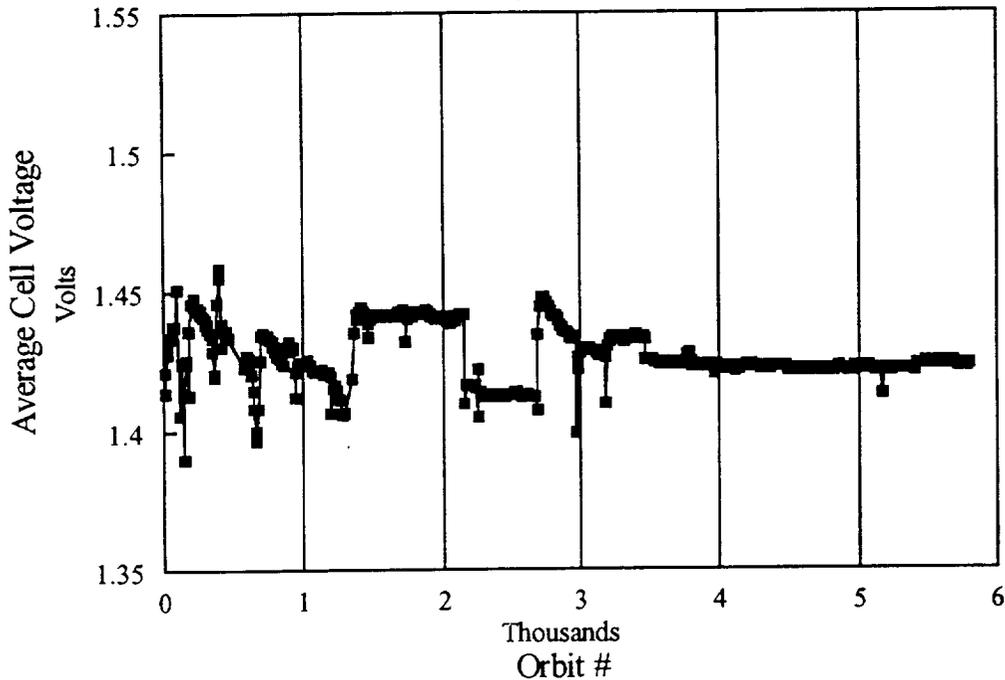


10 Ampere Hour Eagle-Picher (AB5)
Nov-94

This chart shows the average cell voltage at the end of the high rate charge period. The NiMH cell does not show a large variation from its initial value. This data indicates that the cells are not developing an internal impedance operating under the test conditions. The lack of variation in the end of charge voltage may indicate that the active hydride material has remained stable and that there has been little movement.

CDDF/SEDSAT NiCd LEO Cycling

ACV @ EOC vs. Orbit

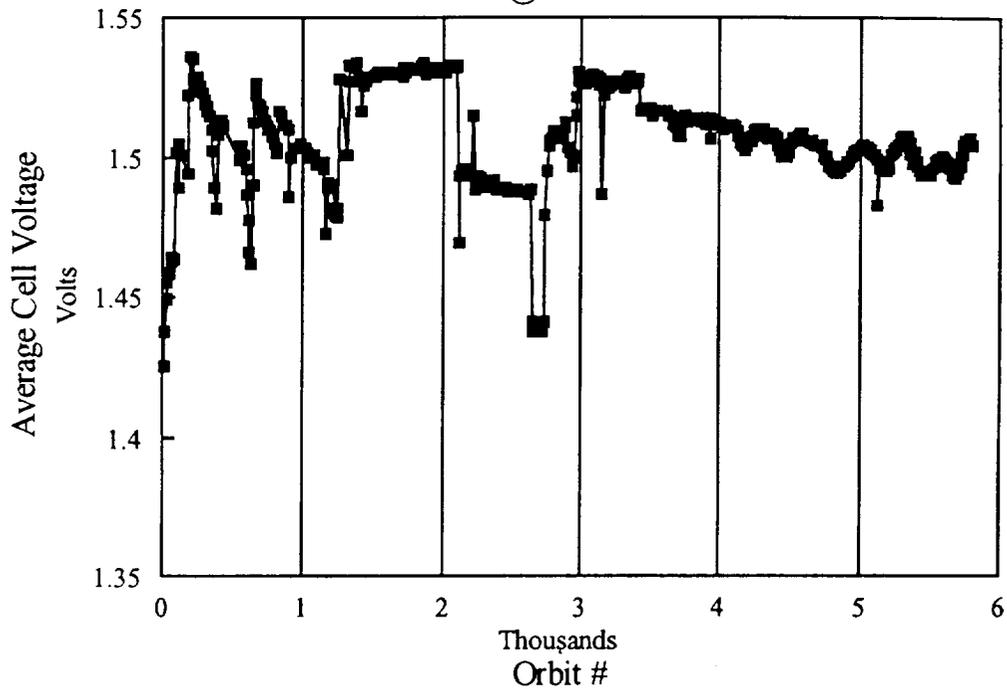


7 Ampere Hour Gates
Nov-94

The average cell voltage at the end of the high rate charge period for the NiCd cells manufactured by Gates was 1.43 volts. This voltage is three millivolts higher than the average voltage of the NiMH cells. This difference would be .5 volts at the battery level. This difference is partially responsible for the lower efficiency of the NiCd cells. Internal impedance is responsible for this voltage differential.

CDDF/SEDSAT NiCd LEO Cycling

ACV @ EOC vs. Orbit

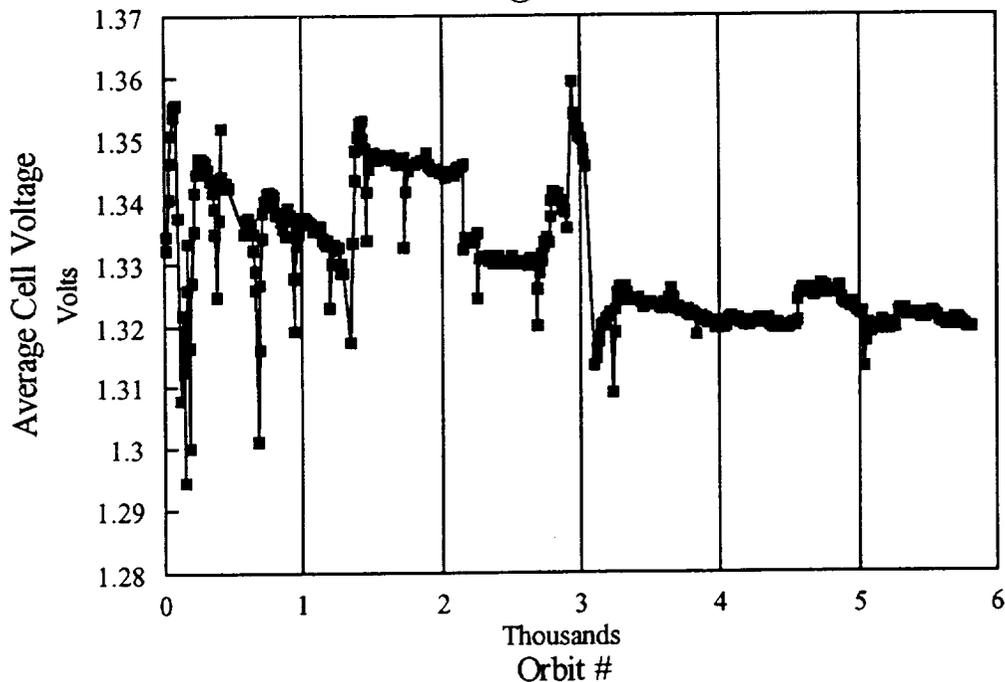


7 Ampere Hour Saft
Nov-94

The average cell voltage at the end of the high rate charge period for the NiCd cells manufactured by Saft was 1.52 volts. This difference from the comparable commercial NiCd cell is thought to be attributable to separator impedance.

CDDF/SEDSAT NiMH LEO Cycling

ACV @ EOD vs. Orbit



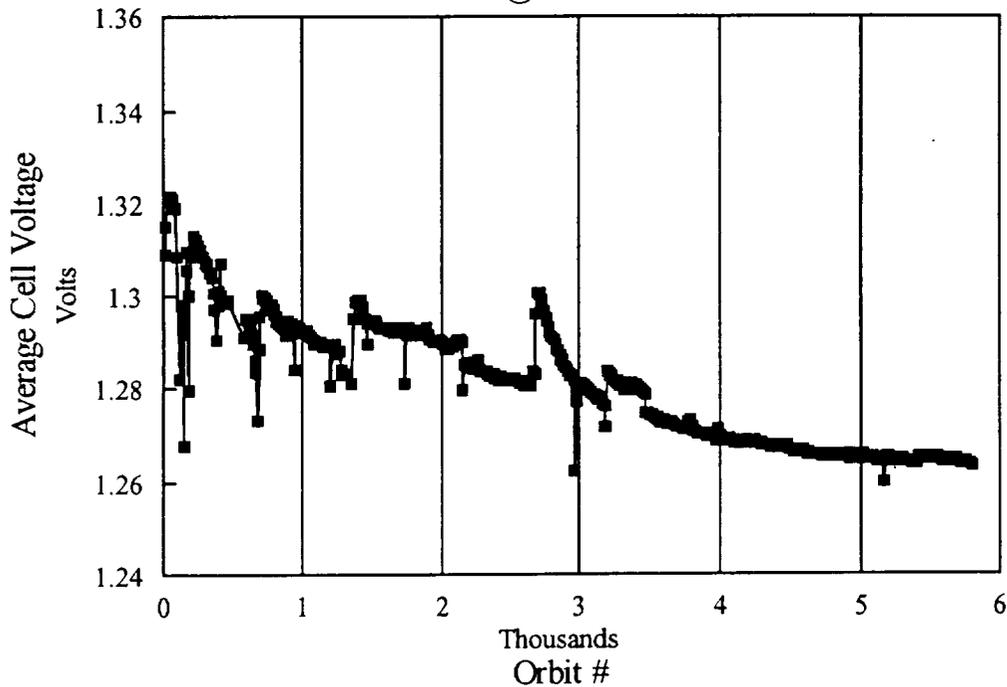
10 Ampere Hour Eagle-Picher (AB5)
Nov-94

The average cell voltage at the end of discharge is a good general indicator of the true health of a battery. A number of factors can affect the end of discharge voltage. To use the end of discharge voltage as specific indicator of health, the effects of variables such as recharge ratio, amount of overcharge, life history, system operation, anomalies, etc. must be quantified. Understanding the relationship of all of the variables related to the performance of the battery is very complex.

The end of discharge voltage has decreased an average of two millivolts over the 5800 cycles. This decrease is attributable to normal degradation.

CDDF/SEDSAT NiCd LEO Cycling

ACV @ EOD vs. Orbit

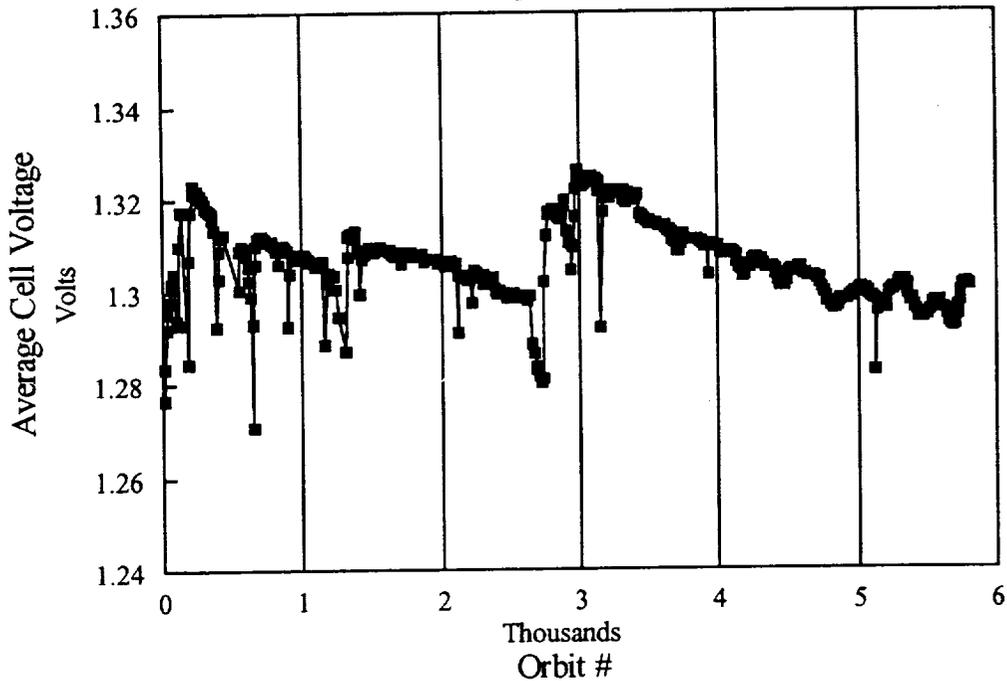


7 Ampere Hour Gates
Nov-94

The Gates NiCd end of discharge voltage has decreased an average of six millivolts over the 5800 cycles. This loss is normal and expected in commercial cells. The cells are exhibiting normal aging and wearout mechanisms.

CDDF/SEDSAT NiCd LEO Cycling

ACV @ EOD vs. Orbit

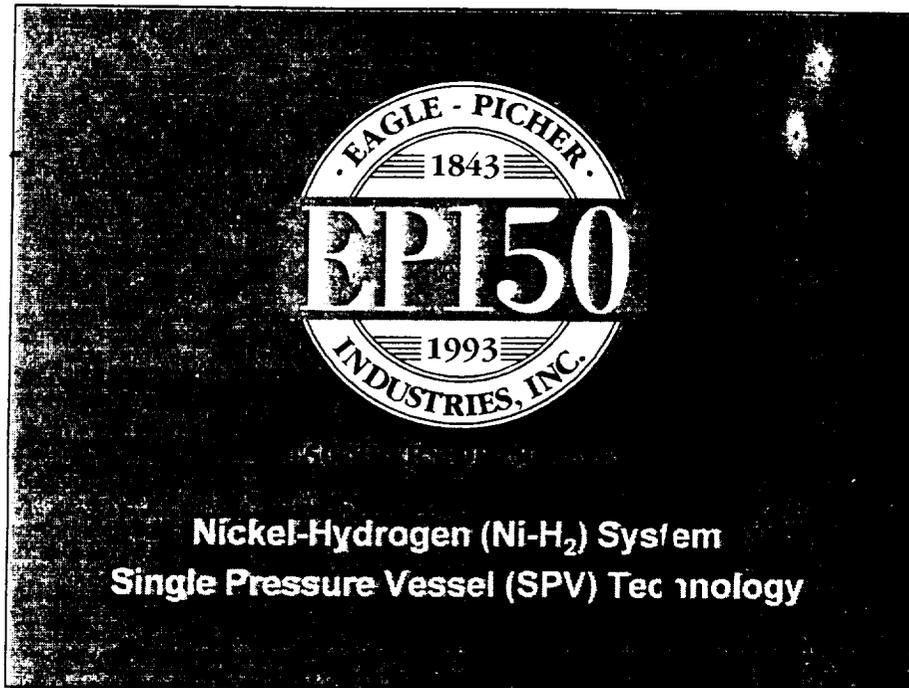


7 Ampere Hour Saft
Nov-94

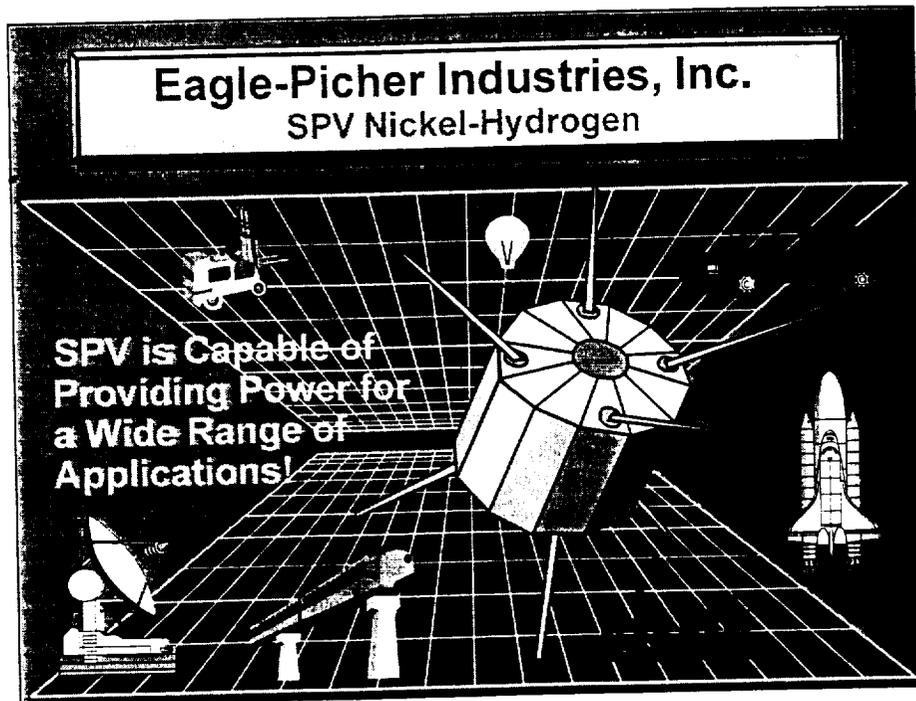
The Saft commercial NiCd cells have not exhibited the expected decrease in end of discharge voltage. This phenomena may be due to an excess of active material in the cell present since manufacturing.

The performance of the NiMH cells is very satisfactory at this point. The comparison between the NiCd and NiMH cells favors use of the NiMH cells. The present results indicate that NiMH cells are feasible direct replacements for NiCd cells in many applications.

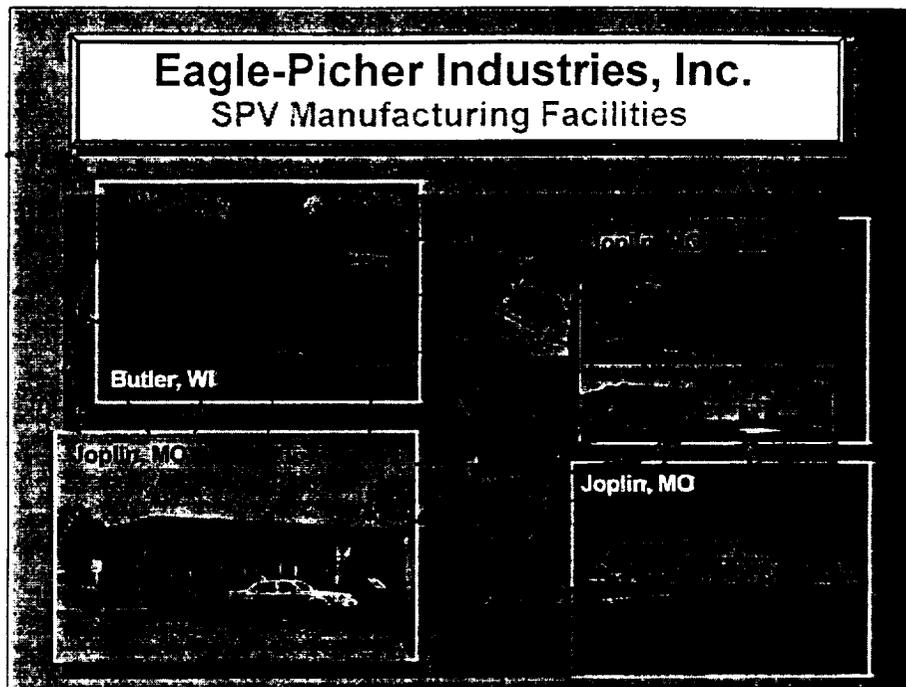
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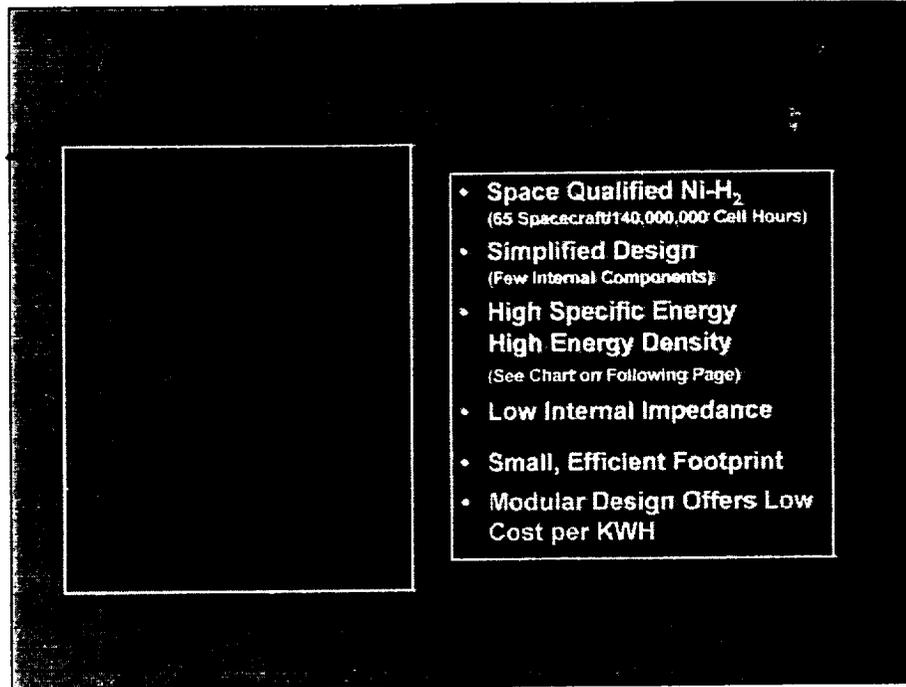
- Founded in 1843, Cincinnati, OH
- 1993 Revenues \$661.5 Million
- 15 Operating Divisions
- Approximately 6500 employment (1500 associated with battery manufacturing)
- 55 Manufacturing Facilities (11 Batteries)
- 50 Domestic - 5 International Locations



- Satellite Power
- Electric Vehicles (Cars, buses, trains, utility vehicles)
- Terrestrial Applications
 - Telecommunications Equipment
 - "Fiber-in-the-loop"
 - Remote repeater/antenna array backup power
 - Utility Load Leveling
 - Uninterruptible Power Systems (UPS)

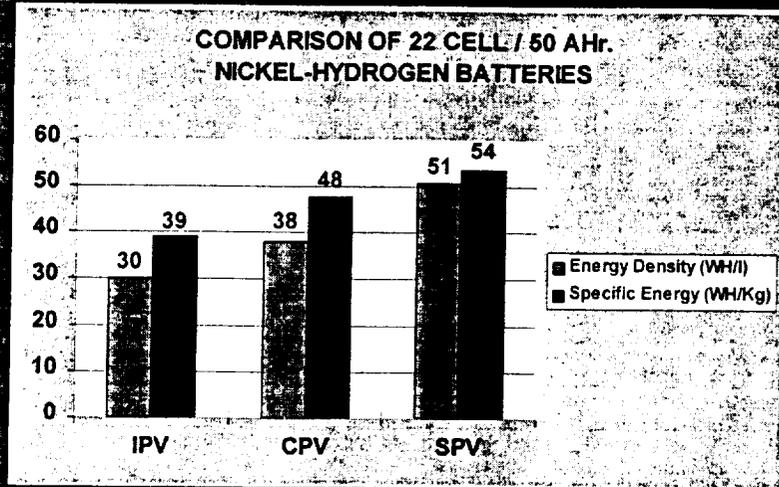


- Eagle-Picher Acquired Former Johnson Controls Ni-H2 Space Battery Assets in Butler, WI June 1, 1994.
- Merging of Respective SPV Technologies Has Produced a Superior Battery Design.
- Acquisition will produce a hybrid design SPV.
- Both technologies are COMSAT licensed. The Butler facility continued with flexible, thin film cell case design. EPI went another direction and developed a rigid cell case design.
- Two (2) lower cost, Commercial Aerospace, manufacturing plants (located in Joplin, Missouri and Butler, Wisconsin) have now been designated to support the industries requirements.



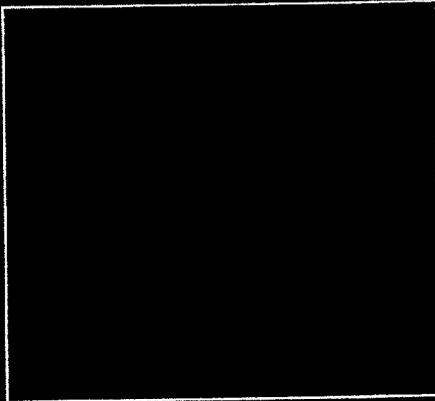
- Battery utilizes the same proven nickel-hydrogen electrode technology which has currently been demonstrated on over 65 satellite launches and has accumulated an excess of 140,000,000 successful cell hours in space
- When compared to IPV and CPV batteries, there are fewer components.
- Internal impedance is lower due to shortened conductor path within the battery. (SPV 20 mOhms/ IPV 30-35 mOhms)
- Higher specific energy when compared to Ni-Cd, IPV and CPV

Eagle-Picher Industries, Inc. Nickel-Hydrogen Systems Comparison



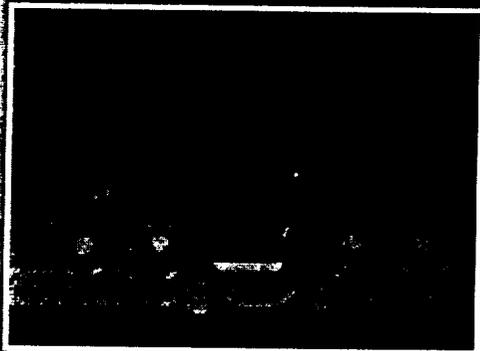
- For Ni-H₂ comparison, assumed equal power capability (conductor IR loss) plus same pressure vessel safety margin.
- Ni-Cd projection assumed current available cell technology and "frame" type battery design.

Eagle-Picher Industries, Inc.
SPV Nickel-Hydrogen



- Each Cell Enclosed Within an Individual Cell Container
- Radial Thermal Fin for Internal Cell Heat Transfer
- Cell Container is Vented Allowing for Common Hydrogen Access

Eagle-Picher Industries, Inc.
SPV Nickel-Hydrogen

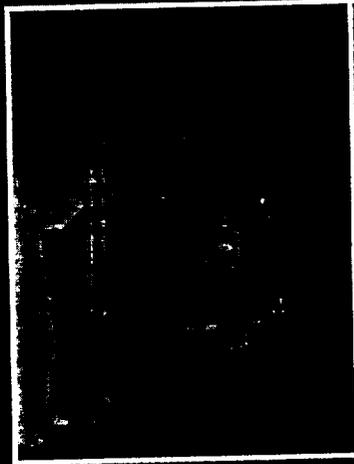


- **Ease of Manufacture Through Modular Assembly**
- **Basic Module Used As Battery Building Blocks Within a Single Pressure Vessel.**
- **Proven Ni-H₂ Cell Components**

Modular assembly allows:

- Various battery capacity sizes to share common components.
- Ease of assembly.
- Critical cell functional testing prior to battery assembly (Joplin).
- Butler battery is assembled as a stack before activation takes place. Testing is possible at this level before insertion into PV.

Eagle-Picher Industries, Inc.
SPV Flight Heritage

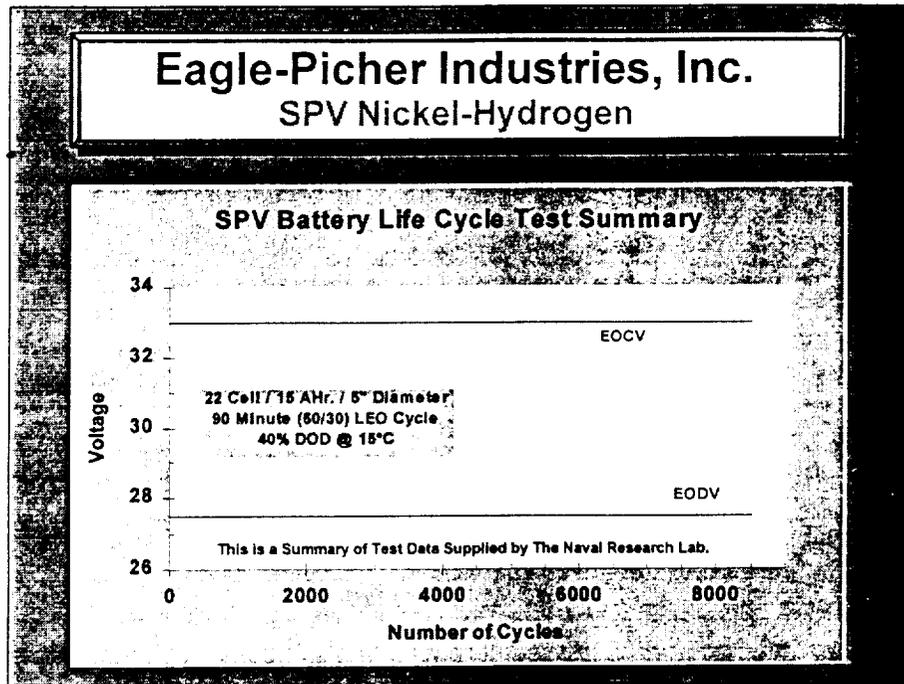


**Clementine
Spacecraft**

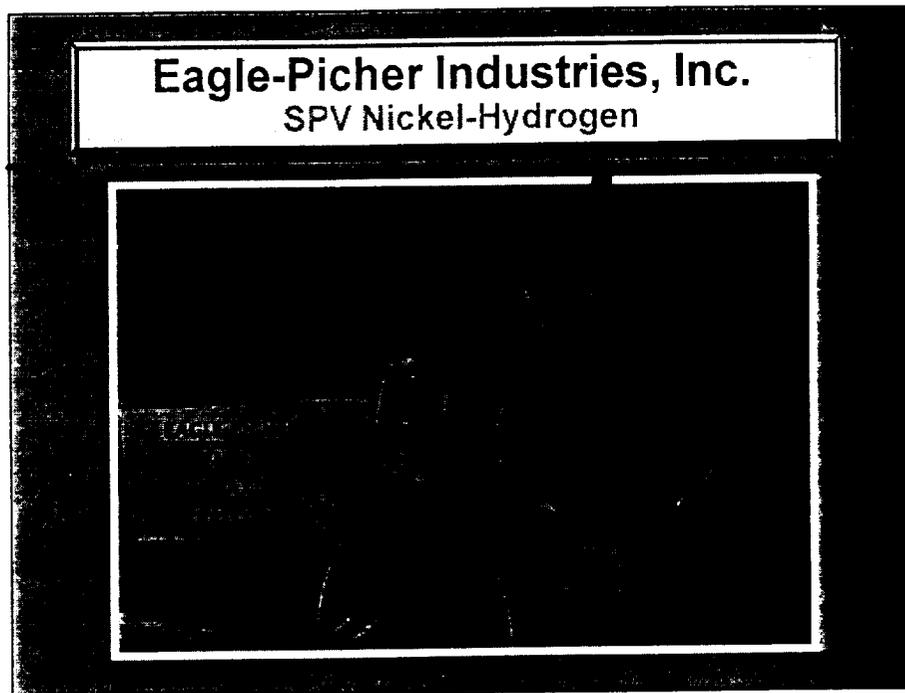


- SPV Technology has been space flight qualified.
- Clementine (NRL) 15 AHr. / 28 Volt
- IRIDIUM® (Iridium, Inc.) 50 AHr. / 28 Volt

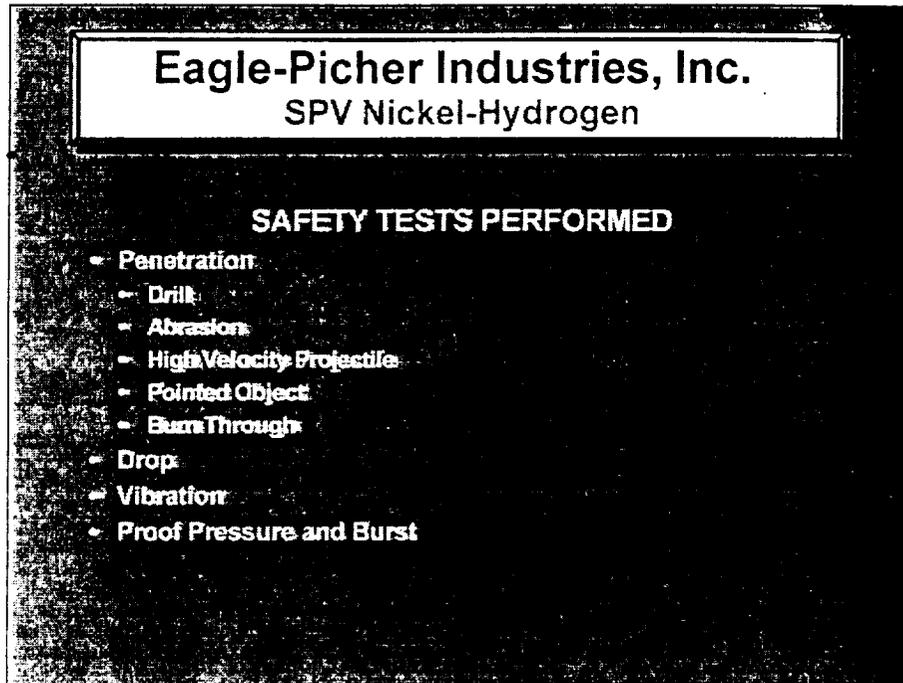
Eagle-Picher Industries, Inc. SPV Nickel-Hydrogen



- Test performed by the Naval Research Laboratory.
 - Depth of Discharge = 40%
 - Test Temperature = 15°C
 - Cycles Completed = 8,500
- Additional Life Cycling data is on file from COMSAT Labs:
 - 30,000 cycles on a 2 cell SPV



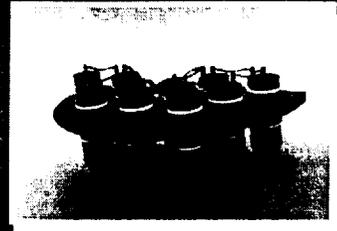
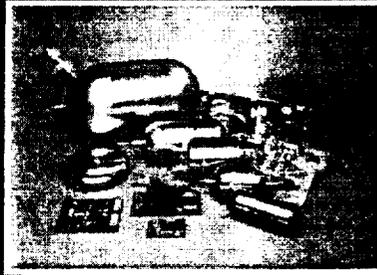
- Test performed on charged 10" diameter, 50 AHr. battery
- 5A discharge during vibration
- 19 GRMS in 2 axes (Y and Z)



Fatigue/Burst:

- $>2.0 \times$ Maximum Expected Operating Pressure (MEOP) burst pressure after 100,000 fatigue cycles per MIL-STD-1522A.

Eagle-Picher Industries, Inc.
SPV & Complementary Ni-H₂ Designs



- Currently the only domestic manufacturer of the SPV (and CPV) Technology.
- Licensed from COMSAT and Johnson Controls.
- Other Ni-H₂ designs manufactured:
 - IPV
 - CPV
 - DPV
 - Low Pressure Vessel (LPV) Under development
- Other Space Qualified Products Manufactured:
 - Intelligent Battery Charger
 - Charge/Discharge Controller Circuitry
 - Special Test Equipment
 - Heater Controllers
 - Temperature Monitoring Systems
 - Strain Gage assemblies
 - Strain Gage signal amplification circuitry

Eagle-Picher Industries, Inc.

Nickel-Hydrogen Advantages

- **Long Cycle Life**
- **Long Calendar Life With No Maintenance**
- **Pressure is an Indication of State-of-Charge**
- **Abuse Tolerance**
 - **Overcharge**
 - **Overdischarge**
 - **Operation at any State-of-Charge**
- **Low "Per Cycle" Cost**
- **Excellent Low Temperature Operation**
- **Environmentally Friendly**

- **Long Cycle Life**
 - 100K+ cycles demonstrated
- **Long Calendar Life With No Maintenance**
- **Pressure is an Indication of State-of-Charge**
 - Approximately 50 to 1200 psig
- **Abuse Tolerance**
 - Overcharge
 - Overdischarge
 - Operation at any State-of-Charge
- **Low "Per Cycle" Cost**
- **Excellent Low Temperature Operation**
 - -10°C preferred (excursions to -20°C are permissible)
OLYMPUS spacecraft was frozen and successfully recovered
- **Environmentally Friendly**
 - No Cadmium, Lead or Mercury in the system
 - Hermetically Sealed System

