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Nickel-Hydrogen Batteries—An Overview

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This article on nickel-hydrogen batteries is an overview of the various nickel-hydrogen battery design options, technical accomplishments, validation test results, and trends. There is more than one nickel-hydrogen battery design, each having its advantage for specific applications. The major battery designs are individual pressure vessel (IPV), common pressure vessel (CPV), bipolar, and low-pressure metal hydride. State-of-the-art nickel-hydrogen batteries are replacing nickel-cadmium batteries in almost all geosynchronous Earth orbit applications requiring power above 1 kW. However, for the more severe low-Earth orbit (LEO) applications (>30,000 cycles), the current cycle life of 4000-10,000 cycles at 60-80% DOD should be improved. A NASA Lewis Research Center innovative advanced design IPV nickel-hydrogen cell led to a breakthrough in cycle life enabling LEO applications at deep depths of discharge (DOD). A trend for some future satellites is to increase the power level to greater than 6 kW. Another trend is to decrease the power to less than 1 kW for small low-cost satellites. Hence, the challenge is to reduce battery mass, volume, and cost. A key is to develop a lightweight nickel electrode and alternate battery designs. A CPV nickel-hydrogen battery is emerging as a viable alternative to the IPV design. It has the advantage of reduced mass, volume, and manufacturing costs. A 10-A-h CPV battery has successfully provided power on the relatively short-lived Clementine spacecraft. A bipolar nickel-hydrogen battery design has been demonstrated (15,000 LEO cycles, 40% DOD). The advantage is also a significant reduction in volume, a modest reduction in mass, and like most bipolar designs, features a high-pulse power capability. A low-pressure aerospace nickel-metal-hydride battery cell has been developed and is on the market. It is a prismatic design that has the advantage of a significant reduction in volume and a reduction in manufacturing cost.

Introduction

THERE is more than one nickel–hydrogen battery cell design, each having its own advantages for specific applications. The major battery designs are individual pressure vessel (IPV),[1-20] common pressure vessel (CPV),[21-27] bipolar,[28-32] and low-pressure metal hydride.[33-36]

In this presentation, an overview of the various nickel–hydrogen battery design options will be discussed, technical accomplishments will be described, validation test results will be reported, and trends will be presented.

IPV Nickel-Hydrogen Battery Cells

State-of-the-Art Cells

Development of IPV nickel–hydrogen cells was initiated in 1970 by Comsat Laboratories together with Tyco Laboratories. The cell was a back-to-back design and was developed for geosynchronous orbit (GEO) applications where not many cycles are required over the life of the system, 1000 cycles over a 10-year life.

A concurrent effort was initiated by Hughes Aircraft Company. The cell was a recirculating design and was developed for the more severe low-Earth orbit (LEO) applications, which require 30,000 cycles over a 5-year life.

The state of development of these IPV nickel–hydrogen cells is such that they are acceptable for GEO applications. They are providing energy storage and delivery to over 60 GEO satellites. Nickel–hydrogen batteries are replacing nickel–cadmium batteries in almost all GEO applications requiring power above 1 kW. They are also acceptable for LEO applications at shallow depths of discharge of <40%. The Hubble Space Telescope is using nickel–hydrogen batteries at a very conservative shallow depth of discharge (DOD) of <10%. This is the first application of nickel–hydrogen batteries for a major LEO mission. However, state-of-the-art (SOA) technology at deep depths of discharge is 4000–10,000 cycles (60–80% DOD)[7]. Since this cycle life did not meet NASA's deep DOD LEO requirements of 30,000 cycles, a program was initiated in 1986 to improve cycle life and performance. Battery cycle life has a major impact on life cycle cost for LEO applications such as the International Space Station that has a design life of 30 years. The primary drivers are transportation to orbit and battery costs. The usable specific energy is directly proportional to DOD. If the DOD is doubled, the battery usable specific energy is doubled; hence, the battery mass is reduced by 50%. (For reference purposes the nickel–cadmium battery has a specific energy of 30–38 W-h/kg and the SOA nickel–hydrogen battery is ≥50 W-h/kg.)

Nickel–hydrogen technology was advanced by 1) using 26% potassium hydroxide (KOH) electrolyte to improve cycle life and performance; 2) modifying the SOA cell designs to eliminate identified failure modes and further improve cycle life; and 3) developing a lightweight nickel electrode to reduce battery mass, hence, launch cost and/or satellite payload.

The influence of KOH electrolyte concentration on cycle life was investigated at Hughes Aircraft Company. There was a dramatic effect. A breakthrough in cycle life was reported.[18,19] The results are summarized in Fig. 1. Boiler plate cells containing 26% KOH were cycled for about 40,000 accelerated LEO cycles at 80% DOD and at 23°C, compared to 3500 cycles for cells containing 31% KOH as used in SOA cells. These results were validated using 48-A-h flight cells and real-time LEO cycles at the U.S. Naval Surface Warfare Center, Crane, Indiana. Six 48-A-h Air Force/Hughes recirculating design

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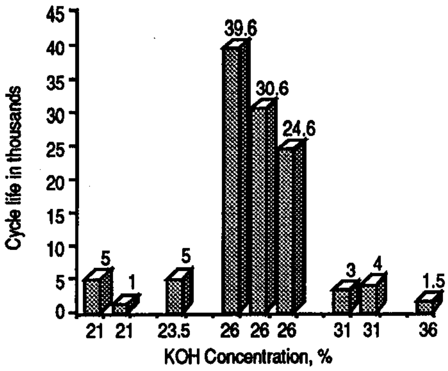

Fig. 1 Effect of KOH electrolyte concentration on LEO cycle life–80% DOD, 23°C.

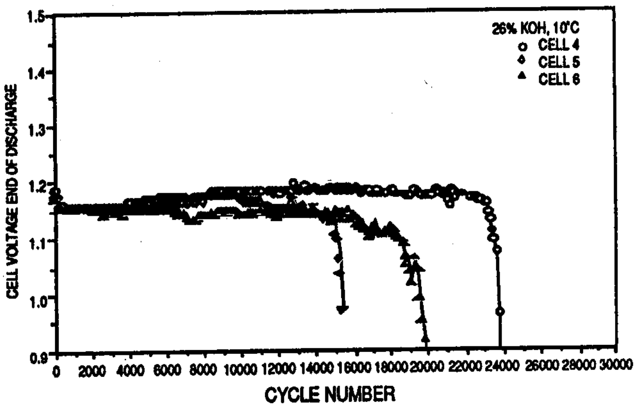

Fig. 2 Effect of LEO cycling at 80% DOD on 48-A-h IPV Hughes flight cells containing 26% KOH electrolyte, 10°C.

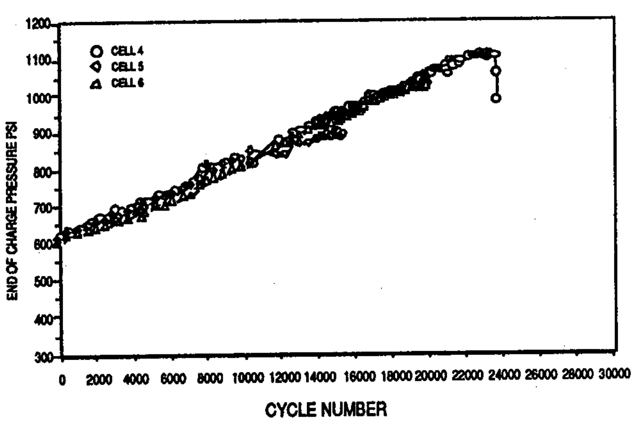

Fig. 3 Effect of LEO cycling at 80% DOD on 48-A-h IPV Hughes flight cells containing 26% KOH.

IPV nickel–hydrogen flight cells manufactured by Hughes underwent cycle life testing. Three of the cells contained 26% KOH electrolyte (test cells). The other three cells (control cells) were identical to the test cells except they contained 31% KOH. Both the test and control cells contained an equal number of components. Details of the cell design are in Ref. 14.

The influence of LEO cycling at 80% DOD on the end-of-discharge voltage for the 48-A-h IPV nickel–hydrogen flight cells containing 26% KOH is summarized in Fig. 2. The three cells containing 26% KOH failed on the average at cycle 19,500 (cycle 15,314, 19,518, and 23,659). The influence of cycling on the end of charge pressure for the 26% KOH cells is shown in Fig. 3. The pressure increase per 1000 cycles is 23.3 psi (160.7 kPa). The pressure increase could be indicative of nickel plaque corrosion that converts nickel to active material. The increase in pressure will result in a shift in the beginning of life state-of-charge vs pressure curve.

The influence of LEO cycling at 80% DOD on the end of discharge voltage for the cells containing 31% KOH is shown in Fig. 4. The three cells containing 31% KOH failed on the average at cycle 6400 (cycles 3729, 4165, and 11,355). The failure mode for each cell was characterized by degradation of discharge voltage to 1.0 V. No cell failed because of an electrical short. A comparison of the discharge curve at the beginning and end of life for cell 1, which failed at cycle 3729, is shown in Fig. 5. This information also shows a voltage degradation. The ampere–hour capacity decrease for cell 1 was about 33% (1.4 C or charge rate, 10°C); for cell 2, 33%; and for cell 3, 36%. The influence of cycling on the end of charge pressure for the 31% KOH cells is shown in Fig. 6. The pressure change can be correlated with the discharge voltage change caused by cycling. The pressure increase per 1000 cy-

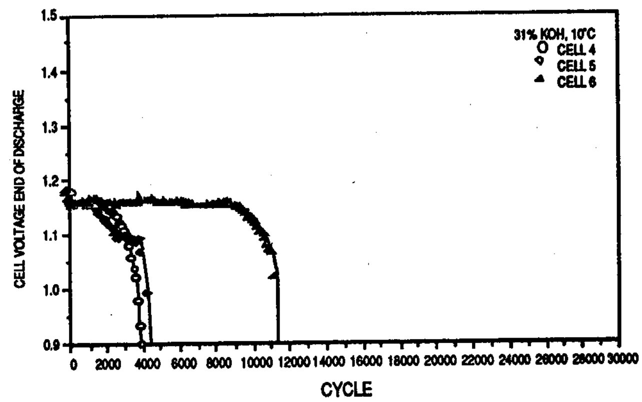

Fig. 4 Effect of LEO cycling at 80% DOD on Hughes flight cells containing 31% KOH electrolyte, 10°C.

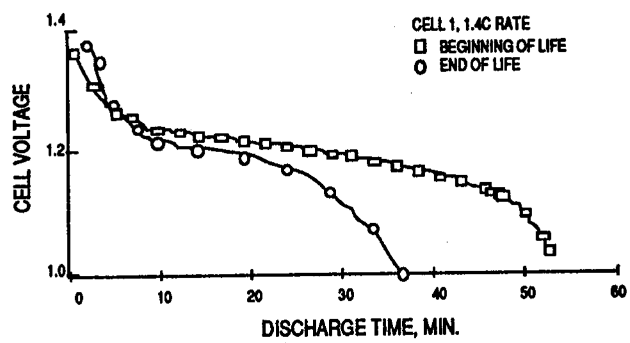

Fig. 5 Comparison of Hughes 48-A-h IPV Ni/H2 flight cells containing 31% KOH electrolyte.

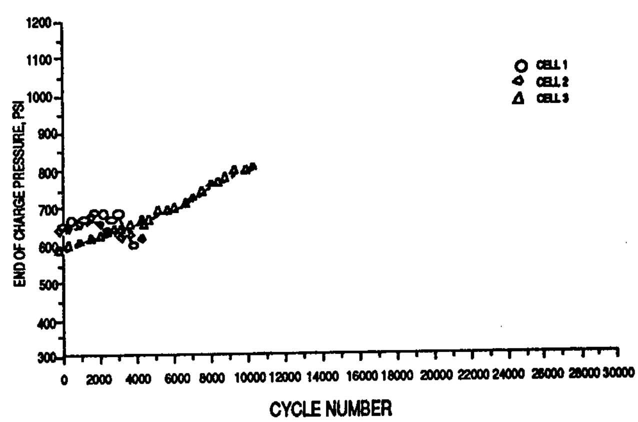

Fig. 6 Effect of LEO cycling at 80% DOD on Hughes flight cells containing 31% KOH.

cles is 23.3 psi (160.7 kPa). The pressure increase is the same as for the 26% KOH.

The cycle life of the cells containing 26% KOH was a factor of 3–4 better than those with 31% KOH. The superior performance of the 26% KOH cells is in agreement with boiler plate cell results previously reported.[17,18] It is attributed to the crystallographic change of active material.[11] γ NiOOH is converted to β NiOOH in 26% KOH. β NiOOH has a lower capacity, but a longer life.

Advanced Cells

To further improve cycle life, an innovative battery cell was conceived, designed, and patented at NASA Lewis Research Center. The design is referred to as the advanced cell and is illustrated in Fig. 7. The new features of this design, which are not incorporated in the SOA Air Force/Hughes or COMSAT/Intelsat Cells are 1) the use of a 26 rather than 31% KOH electrolyte, which improves cycle life; 2) the use of a catalyzed wall wick located on the inside surface of the pressure vessel wall that chemically recombines oxygen generated at the end of charge and on overcharge with hydrogen to form water. SOA nickel–hydrogen cells recombine the oxygen on the catalyzed hydrogen electrode surface in the stack. The catalyzed wall wick should improve oxygen and thermal management[12]; 3) the use of serrated-edge separators to facilitate gaseous oxygen and hydrogen flow within the cell, while still maintaining physical contact with the wall wick for electrolyte management; 4) the use of a floating rather than fixed stack (SOA) to accommodate nickel–electrode expansion caused by charge/discharge cycling. This is accomplished by the use of Belleville disc springs located at each end of the stack. The significant improvements resulting from these innovations are extended cycle life, enhanced oxygen, thermal and electrolyte management, and the accommodation of some of the nickel–electrode expansions. Six 125-A-h advanced-design IPV nickel–hydrogen flight cells fabricated by Eagle–Picher, Joplin, are presently undergoing cycle life testing. The nickel electrodes were fabricated at Eagle–Picher, Colorado Springs and were impregnated with active material by the alcoholic Pickett process.[20] Three of the cells (test cells) contain all of the advanced design features.[10] The other three cells (control cells) are the same as the test cells except they do not have a catalyst on the wall wick. The catalyzed wall wick is a key design feature. All six cells contain 26 rather than 31% KOH.

The influence of LEO cycling at 60% DOD on the end of discharge voltage for the 125-A-h catalyzed wall wick IPV nickel–hydrogen flight cells is summarized in Fig. 8. After 32,937 cycles, there has been no cell failure in the continuing test. The influence of cycling on the end of charge pressure for the catalyzed wall wick cells is shown in Fig. 9. No pressure for cell 2 is available because the cell had a bad strain gauge. For cells 1 and 3, the pressure increased relatively rapidly up to about cycle 1400, then decreased. The average pressure increase at cycle 1400 is about 11% higher than at the beginning of life.

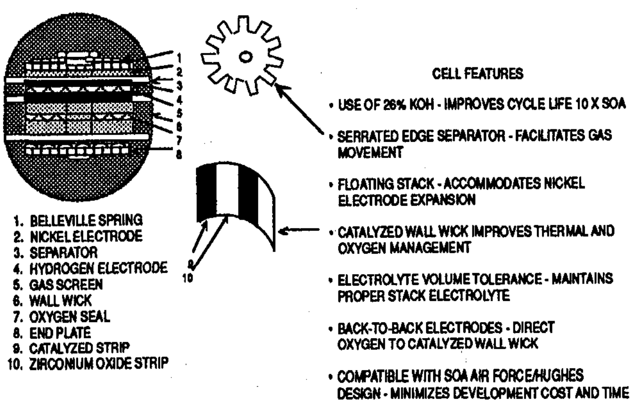

Fig. 7 NASA advanced design IPV nickel–hydrogen cell-catalyzed wall wick.

The influence of LEO cycling at 60% DOD on the end of discharge voltage for the 125-A-h noncatalyzed wall wick IPV nickel–hydrogen flight cells is shown in Fig. 10. All three of the noncatalyzed wall wick cells failed (cycles 9.588; 13,900; and 20,575). The failure was characterized by degradation of the end of discharge voltage to 1.0 V. The cells did not fail because of an electrical short. The influence of cycling on the end of charge pressure for the noncatalyzed wall wick cells is

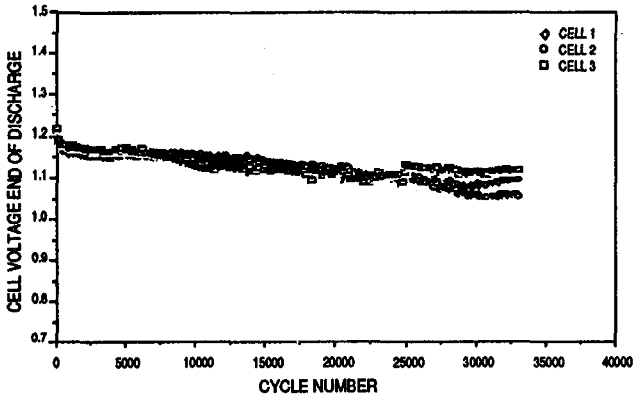

Fig. 8 Effect of LEO cycling on 125-A-h NASA Lewis advanced catalyzed wall wick IPV Ni/H_2 cells manufactured by Eagle–Picher–26% KOH, 60% DOD, 10°C.

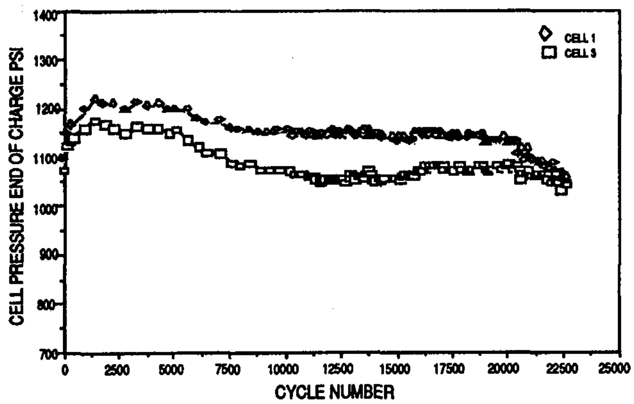

Fig. 9 Effect of LEO cycling on 125-A-h NASA Lewis advanced catalyzed wall wick IPV Ni/H_2 cells manufactured by Eagle–Picher, 26% KOH, 60% DOD, 10°C.

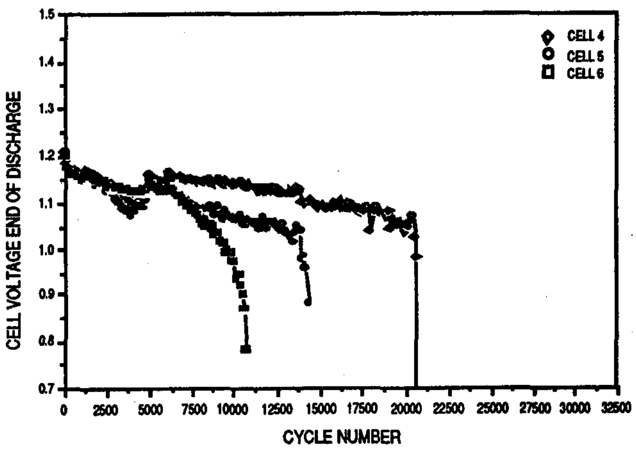

Fig. 10 Effect of LEO cycling on 125-A-h NASA Lewis advanced noncatalyzed wall wick IPV Ni/H_2 cells manufactured by Eagle–Picher, 26% KOH, 60% DOD, 10°C.

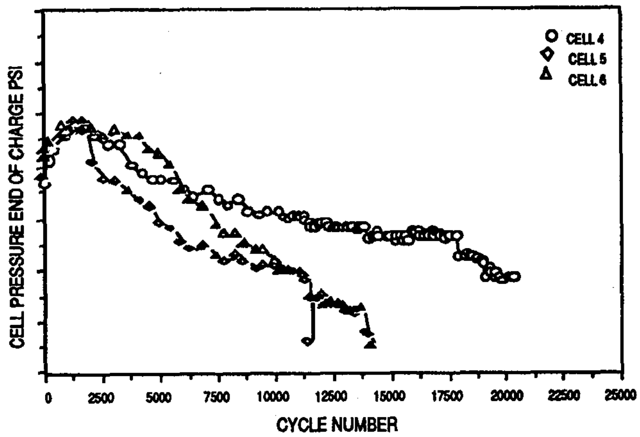

Fig. 11 Effect of LEO cycling on 125-A-h NASA Lewis advanced noncatalyzed wall wick IPV Ni/H_2 cells manufactured by Eagle–Picher, 26% KOH, 60% DOD, 10°C.

shown in Fig. 11. The pressure for the three cells increased up to about cycle 2000 then decreased. The average pressure increase at cycle 2000 is about 9% higher than at the beginning of life.

Lightweight Nickel Electrode

A trend for some future spacecraft is to increase the power level to >6 kW. Another trend is to decrease the power level to <1 kW for small low-cost spacecraft. The challenge is to reduce battery mass, volume, and cost. In support of a lightweight battery, NASA Lewis Research Center has an in-house and contract effort to develop a lightweight nickel electrode that is key to reducing the battery mass for any battery using nickel chemistry.

Several lightweight designs and thick porous fiber substrates are being evaluated as possible supports for the nickel–hydroxide active material. The electrodes are being evaluated in boiler plate cells described in Ref. 15. The nickel electrodes tested were made from an 80-mil-thick, 90% porous fiber substrate loaded with active material to 1.6 g/cm^3 void volume, the diameter of the nickel substrate fiber was 20 μm. The influence of LEO cycling at 40% DOD on utilization is shown in Fig. 12. The influence of cycling on the end of discharge voltage is shown in Fig. 13. An end of discharge voltage of about 1.175 V was observed from the first 1000 cycles. The end of discharge voltage dropped to about 1.060 V after 9000 cycles and remained constant until the end of the life test. The effect of electrode design on battery mass is shown in Fig. 14.

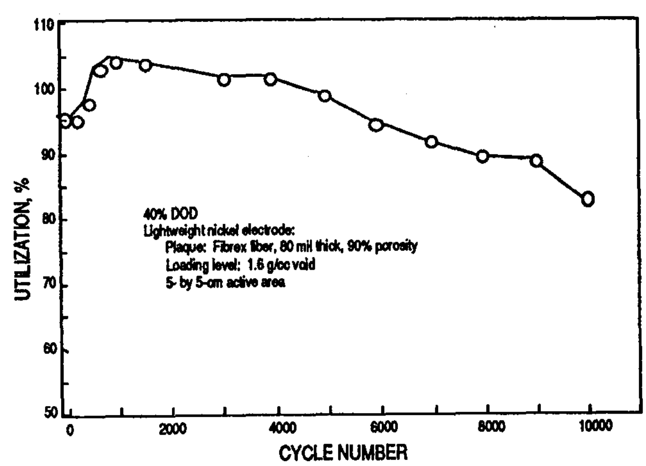

Fig. 12 Utilization vs cycle number of a nickel–hydrogen cell using a fibrex nickel electrode.

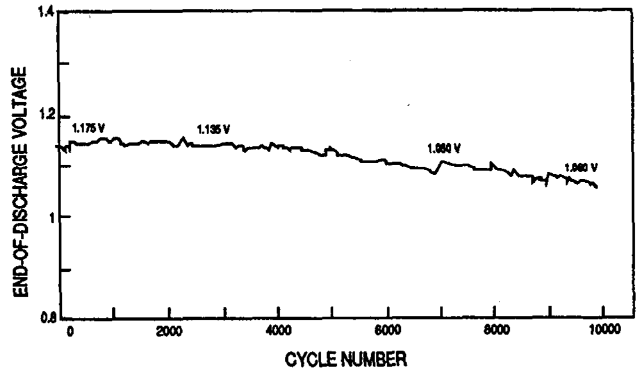

Fig. 13 End of discharge voltage vs number of cycles for a nickel–hydrogen cell using a fibrex nickel electrode.

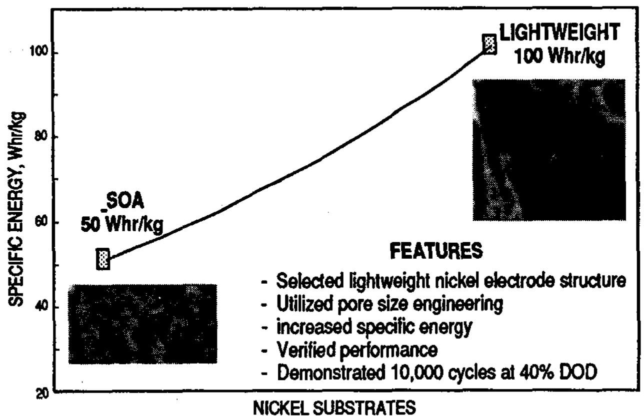

Fig. 14 Effect of nickel electrode design on IPV nickel–hydrogen cell specific energy.

Common Pressure Vessel Battery

A common pressure vessel (CPV) nickel–hydrogen battery consists of a number of individual cells connected electrically in series and contained in a single-pressure vessel. An IPV nickel–hydrogen battery consists of a number of IPV cells, each contained in their own pressure vessel that are connected electrically in series. The CPV battery has the advantage of reduced volume mass and manufacturing costs.

A feasibility study of the CPV nickel–hydrogen battery was initiated by Energy Impact Company (EIC) in 1979 under sponsorship of the WPAFB. A subsequent contract was awarded in 1982 to the Hughes Aircraft Company to develop the CPV battery. The contract was redirected in 1984 to develop an 11.4-cm- ($4\frac{1}{2}$-in.-) diam, 150-A-h, IPV nickel–hydrogen battery. The development of the CPV battery was discontinued under the contract because larger IPV cells were considered a nearer-term technology with fewer development risks and costs.[2,6]

An aerospace CPV battery development effort was also conducted jointly by Comsat and Johnson Controls Inc. in the mid-1980s. A 25.4-cm- (10-in.-) diam, 32 V, 24-A-h lightweight CPV battery was fabricated and tested to demonstrate the feasibility of the design in LEO applications. The battery underwent LEO cycle life testing at a 44% DOD. It failed at about cycle 6000 because of degradation in battery voltage.[24]

Rockwell International and Eagle–Picher in the mid-1980s jointly designed, produced, and tested a 40-A-h proof-of-concept dual cell module (i.e., two 40-A-h stacks in series) CPV battery. The battery was successfully tested for over 10,000 cycles.[21]

Even though a long-life database on CPV batteries is limited, the CPV battery is emerging as an alternative to SOA IPV nickel–hydrogen batteries. A 10-A-h CPV battery manufactured by Johnson Controls Inc. has successfully provided power on the relatively short-lived Clementine Spacecraft that was launched in 1994.[27] CPV batteries are scheduled to provide power on the Iridium satellite, a program designed to launch 66 satellites for communication applications. The Johnson Controls Inc. CPV nickel–hydrogen battery technology was recently purchased by Eagle–Picher.

Bipolar Nickel-Hydrogen Battery

A bipolar nickel–hydrogen battery is being developed.[28–33] A bipolar battery consists of a number of unit cells connected electrically in series by conducting plates and contained in a single-pressure vessel. The advantages of this battery compared to an IPV battery are significantly reduced volume, modest mass reduction, and high-pulse power capability. A 75-A-h boiler plate bipolar nickel–hydrogen battery was designed, fabricated, and tested. The test results are summarized in Fig. 15. The battery was cycled for over 15,000 LEO cycles at a 40% DOD, which demonstrates the design feasibility. The next step is to construct flight hardware.

Nickel-Metal-Hydride Battery Cells

Nickel–metal–hydride cells are low-pressure cells. Hydrogen generated on charge is stored as a hydride at the negative electrode rather than as hydrogen gas. Since the pressure is low, a pressure vessel package is not required as is the case for an IPV nickel–hydrogen cell. Aerospace nickel–metal–hydride cells are packaged in a prismatic case that results in an increase in energy density of 166% compared to IPV nickel–hydrogen cells.[37]

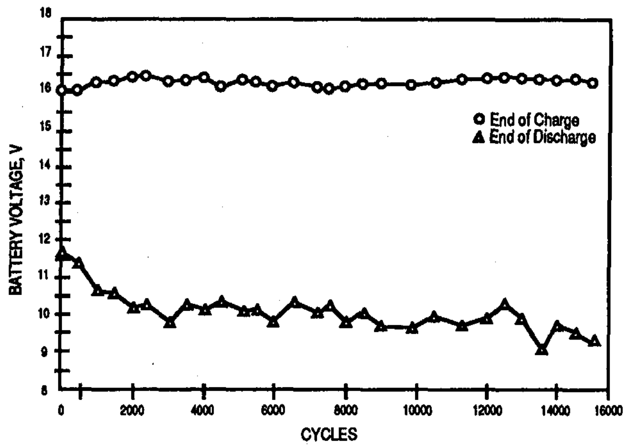

Fig. 15 Effect of LEO cycling on 75-A-h bipolar nickel-hydrogen battery 40% DOD, 10°C.

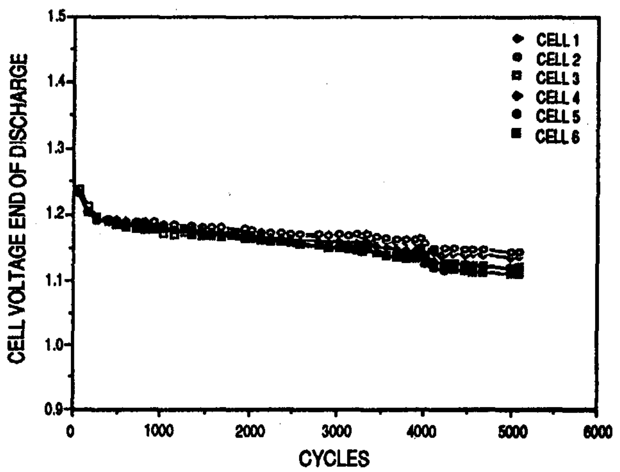

Fig. 16 Effect of LEO cycling on 10-A-h Eagle-Picher nickel metal-hydride cells, 40% DOD, 10°C.

Nickel–cadmium batteries are used to provide power to spacecraft requiring less than 1 kW. Nickel–metal–hydride cells have a specific energy that is 30% greater than nickel–cadmium cells and an energy density that is 29% greater than nickel–cadmium cells.[37] In addition, nickel–metal–hydride batteries are environmentally friendly since they do not contain toxic materials such as cadmium, mercury, or asbestos. Hence, they are challenging the nickel–cadmium battery applications and may soon replace them. The database on aerospace nickel–metal–hydride cells is limited. However, the available data have indicated a LEO cycle life of 1–3 years.[33]

NASA Lewis Research Center is presently evaluating SOA nickel–metal–hydride cells. Six, 10-A-h Eagle–Picher aerospace nickel–metal–hydride cells are undergoing cycle life testing at NSWC, Crane, Indiana. The test results are summarized in Fig. 16. The cells have been cycled for over 5000 LEO cycles at 40% DOD and 10°C. No cell failures have been experienced so far in this continuing test.

Concluding Remarks

SOA IPV nickel–hydrogen batteries are acceptable for GEO applications, where not many cycles are required over the life of the system, e.g., 1000 cycles over a 10-year life. They are providing energy storage to over 60 GEO satellites. Nickel–hydrogen batteries are replacing nickel–cadmium batteries in almost all GEO applications requiring power above 1 kW. They are also acceptable for shallow depths discharge of <40% in LEO applications. The Hubble Space Telescope is using nickel–hydrogen batteries at a very conservative shallow DOD of <10%. This is the first application of nickel–hydrogen batteries for a major LEO mission. However, at deep depths of discharge (60–80%), the SOA technology of 4000–10,000 cycles is not acceptable for most LEO missions. For a DOD greater than 40%, the NASA Lewis Research Center advanced design cell with a catalyzed wall wick is acceptable, or a SOA design using 26% KOH electrolyte. The nice thing about 26% KOH is that it is inexpensive, easy to use, and can be used with any cell design.

A trend for some future spacecraft is to increase the power level to greater than 6 kW. Another trend is to decrease the power to less than 1 kW for small low-cost satellites. Hence, the challenge is to reduce battery mass, volume, and cost. Two keys are to develop a lightweight nickel electrode and an alternative battery design. Even though a long-life database on CPV batteries is limited, the CPV nickel–hydrogen battery is emerging as a viable contender for small satellite applications. It has the advantage of reduced mass, volume, and manufacturing costs. A 10-A-h CPV battery manufactured by Johnson Controls, Inc. has successfully provided power to the relatively short-lived Clementine spacecraft that was launched in 1994.

A bipolar nickel–hydrogen battery design has been demonstrated (15,000 LEO cycles, 40% DOD). The advantage is also a significant reduction in volume, a modest reduction in mass, and a high-pulse power capability.

A low-pressure aerospace nickel–metal–hydride battery cell is on the market, and the limited database looks encouraging. It has a specific energy that is 30% greater than nickel–cadmium cells and an energy density that is 29% greater than nickel–cadmium cells. In addition, it is environmentally friendly, and is challenging the nickel–cadmium battery applications that it may soon replace.

Acknowledgments

The authors acknowledge the early sponsorship of nickel–hydrogen work by Intelsat and Wright-Patterson Air Force Base. The authors also acknowledge the support of NASA Lewis Research Center in the development of the advanced nickel–hydrogen battery.

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