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Nickel Hydrogen Batteries—An Overview

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NICKEL HYDROGEN BATTERIES - AN OVERVIEW

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Abstract

This paper 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 (SOA) nickel hydrogen batteries are replacing nickel cadmium batteries in almost all geosynchronous orbit (GEO) 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 to 10,000 cycles at 60 percent DOD should be improved.

A LeRC 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 light weight nickel electrode and alternate battery designs.

A common pressure vessel (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 Ah 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 percent 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 which 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 (33-37).

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 under the sponsorship of Intelsat. 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 under the sponsorship of the Wright Patterson Air force

Base (WPAFB). 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 five 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 percent. Hubble Space Telescope is using nickel hydrogen batteries at a very conservative shallow DOD of <10 percent. This is the first application of nickel hydrogen batteries for a major LEO mission. However, SOA technology at deep depths of discharge is 4,000 to 10,000 cycles (60 percent DOD). Since this cycle life did not meet NASA's deep depth of discharge LEO requirements of 30,000 cycles, a program was initiated at NASA Lewis Research Center 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 which 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 percent.

Nickel hydrogen technology was advanced by the NASA Lewis Research Center. Some of the advancements are as follows: (1) use 26 percent potassium hydroxide (KOH) electrolyte to improve cycle life and performance, (2) modify the state-of-the-art cell designs to eliminate identified failure modes and further improve cycle life and (3) develop 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 under a NASA Lewis contract. 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 percent KOH were cycled for about 40,000 accelerated LEO cycles at 80 percent DOD and at 23°C, compared to 3,500 cycles for cells containing 31 percent KOH as used in SOA cells. These results were validated using 48 Ah flight cells and real time LEO cycles under a NASA Lewis contract with the Naval Surface Warfare Center, Crane, Indiana. Six 48 Ah Air Force/Hughes recirculating design IPV nickel hydrogen flight cells manufactured by Hughes underwent cycle life testing. Three of the cells contained 26 percent KOH electrolyte (test cells). The other three cells (control cells) were identical to the test cells except they contained 31 percent KOH. Both the test and control cells contained an equal number of components. Details of the cell design are in reference 14.

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

The influence of LEO cycling at 80 percent DOD on the end of discharge voltage for the cells containing 31 percent KOH is shown in Fig. 4. The three cells containing 31 percent KOH failed on the average at cycle 6,400 (cycles 3,729, 4,165 and 11,355). The failure mode for each cell was characterized by degradation of discharge voltage to 1.0V. No cell failed due to an electrical short. A comparison of the discharge curve at the beginning and end of life for Cell 1, which failed at cycle 3,729, is shown in Fig. 5. This information also shows a voltage degradation. The ampere-hour capacity decrease for cell 1 was about 33 percent (1.4 C rate, 10°C), for cell 2, 33 percent, and for cell 3, 36 percent. The influence of cycling on the end of charge

pressure for the 31 percent KOH cells is shown in Fig. 6. The pressure change can be correlated with the discharge voltage change due to cycling. The pressure increase per 1000 cycles is 23.3 PSI. The pressure increase is the same as for the 26 percent KOH.

The cycle life of the cells containing 26 percent KOH was a factor of 3 to 4 better than those with 31 percent KOH. The superior performance of the 26 percent KOH cells compared to the 31 percent cells is in agreement with boiler plate cell results previously reported (17,18). It is attributed to crystallographic change of active material (11). Gamma NiOOH is converted to beta NiOOH in 26 percent KOH. Beta NiOOH has a lower capacity but longer life.

Advanced Cells

To further improve cycle life, an innovative battery cell was conceived, designed and patented at NASA Lewis. 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 state-of-the-art Air Force/Hughes or COMSAT/Intelsat Cells are: (1) use of 26 rather than 31 percent KOH electrolyte which improves cycle life and (2) use of catalyzed wall wick located on the inside surface of the pressure vessel wall which chemically recombines oxygen generated at the end of charge and on overcharge with hydrogen to form water. State-of-the-art 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) 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) use of a floating rather than fixed stack (SOA) to accommodate nickel electrode expansion due to charge/discharge cycling. This is accomplished by 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 accommodation of some of the nickel electrode expansions. Six 125 Ah advanced design IPV nickel-hydrogen

flight cells fabricated by Eagle-Picher, Joplin according to NASA Lewis specification 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 as described in (10). The other three cells (control cells) are the same as the test cells except they do not have catalyst on the wall wick. The catalyzed wall wick is a key design feature. All six cells contain 26 rather than 31 percent KOH.

The influence of LEO cycling at 60 percent DOD on the end of discharge voltage for the 125 Ah catalyzed wall wick IPV nickel-hydrogen flight cells is summarized in Fig. 8. After 30,180 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 percent higher than at the beginning of life.

The influence of LEO cycling at 60 percent DOD on the end of discharge voltage for the 125 Ah 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 end of discharge voltage to 1.0V. The cells did not fail due to an electrical short. The influence of cycling on the end of charge pressure for the noncatalyzed wall wick cells is 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 percent higher than at the beginning of life.

Light Weight Nickel Electrode

A trend for some future spacecraft is to increase power level to >6 kW. Another trend is to decrease power level to <1 kW for small low cost spacecraft. The challenge is to reduce

battery mass, volume, and cost. In support of a light weight battery, NASA Lewis has an in-house and contract effort to develop a light weight nickel electrode which is key to reducing battery mass for any battery using nickel chemistry.

Several light weight 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 reference 15. The nickel electrodes tested were made from an 80 mil thick, 90 percent porous fiber substrate loaded with active material to 1.6 gm/cm³ void volume the diameter of the nickel substrate fiber was 20 microns. The influence of LEO cycling at 40 percent DOD on utilization is shown in Fig. 12. The influence of cycling on end of discharge voltage is shown in Fig. 13. An end of discharge voltage of about 1.175V was observed from the first 1000 cycles. The end of discharge voltage dropped to about 1.060 volts 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.

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 IVP nickel hydrogen battery consists of a number of IVP cells, each contained in their own pressure vessel which 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 Hughes Aircraft company by WPAFB to develop the CPV battery. The contract was redirected in 1984 to develop a 4 1/2 inch diameter, 150 Ah, IVP nickel hydrogen battery. The development of the CPV battery was discontinued under the contract because larger IVP cells were considered a nearer term technology with fewer

development risk and costs (2, 6).

An aerospace CPV battery development effort was also conducted jointly by Comsat and Johnson Controls Inc. in the mid 1980's. A 10 inch diameter, 32V, 24 Ah 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 percent DOD. It failed at about cycle 6000 due to degradation in battery voltage (24).

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

Even though a long life data base on CPV batteries is limited, the CPV battery is emerging as an alternative to SOA IVP nickel hydrogen batteries. A 10 Ah CPV battery manufactured by Johnson Controls Inc. has successfully provided power on the relatively short lived Clementine Spacecraft which was launched on 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 at NASA Lewis and under a Lewis sponsored contract (28-33). A bipolar battery consists of a number of unit cells connected electrically in series by conducting plate and contained in a single pressure vessel. The advantages of this battery compared to an IVP battery are significantly reduced volume, modest mass reduction, and high pulse power capability. A 75 Ah 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 percent 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 which results in an increase in energy density of 166 percent compared to IPV nickel hydrogen cells.⁽³⁷⁾

Nickel cadmium batteries are used to provide power to spacecraft requiring less than 1 kW. Nickel metal hydride cells have a specific energy which is 30 percent greater than nickel cadmium cells and an energy density which is 29 percent 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 data base on aerospace nickel metal hydride cells is limited. However, the available data have indicated a LEO cycle life of one to three years ⁽³³⁾.

NASA Lewis is presently evaluating state-of-the-art nickel metal hydride cells. Six, 10 Ah 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 percent DOD, and 10°C. No cell failures have been experienced so far in this continuing test.

Concluding Remarks

State-of-the-art IPV nickel hydrogen batteries are acceptable for GEO applications, where not many cycles are required over the life of the system, 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 of discharge of <40 percent in LEO applications. Hubble Space Telescope is using nickel hydrogen batteries at a very conservative shallow DOD of <10 percent. This is the first application of nickel hydrogen batteries for a major LEO mission. However, at deep depths of discharge (60 to 80 percent), the SOA technology of 4000 to 10,000 cycles is not acceptable for most LEO missions. For a DOD greater than 40 percent, the NASA advanced design cell with a catalyzed wall wick is acceptable, or a state-of-the-art design using 26 percent KOH electrolyte. The nice thing about 26 percent KOH is that it is inexpensive, easy to use, can be used with any cell design.

A trend for some future spacecraft is to increase the power level 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 light weight nickel electrode and alternate battery design. Even though a long life data base 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 Ah CPV battery manufactured by Johnson Controls, Inc. has successfully provided power to the relatively short lived Clementine Spacecraft which was launched in 1994.

A bipolar nickel hydrogen battery design has been demonstrated (15,000 LEO cycles, 40 percent 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 data base looks encouraging. It has a specific energy which is 30 percent greater than nickel cadmium cells and an energy density which is 29 percent greater than nickel cadmium cells. In addition, it is environmentally friendly, and is challenging the nickel cadmium battery applications which it may soon replace.

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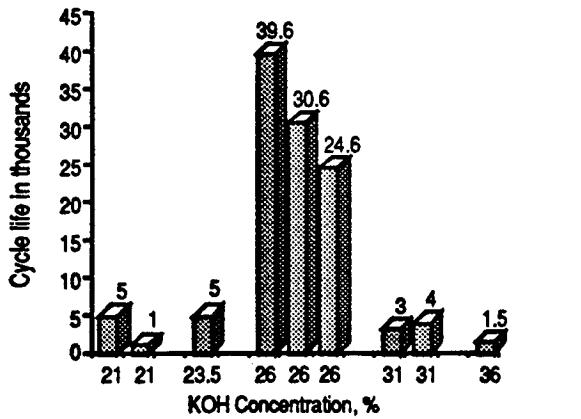


FIGURE 1 - EFFECT OF KOH ELECTROLYTE CONCENTRATION ON LEO CYCLE LIFE - 80 PERCENT DOD, 23°C.

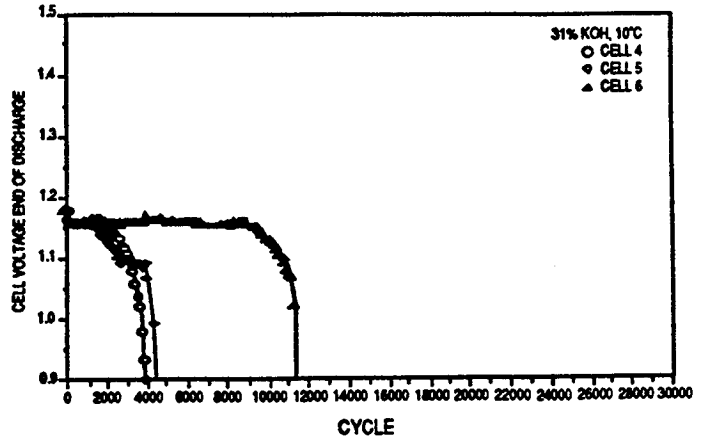


FIGURE 4 - EFFECT OF LEO CYCLING AT 80 PERCENT DOD ON HUGHES FLIGHT CELLS CONTAINING 31 PERCENT KOH ELECTROLYTE, 10°C.

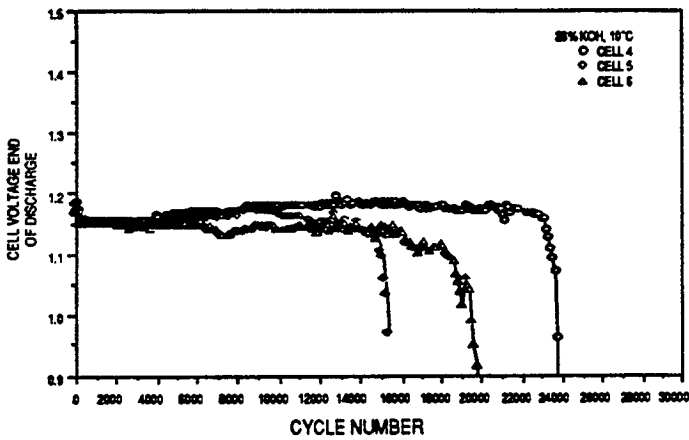


FIGURE 2 - EFFECT OF LEO CYCLING AT 80 PERCENT DOD ON 48 A-hr IPV HUGHES FLIGHT CELLS CONTAINING 26 PERCENT KOH ELECTROLYTE, 10°C.

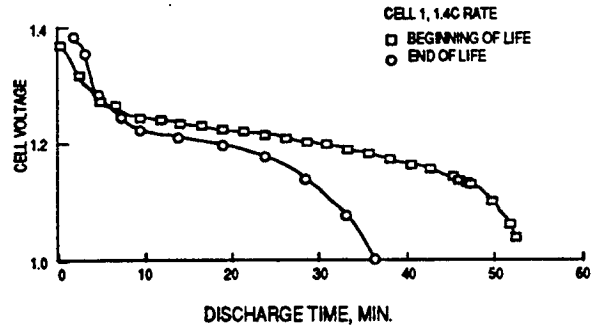


FIGURE 5 - COMPARISON OF HUGHES 48 A-hr IPV Ni/H₂ FLIGHT CELLS CONTAINING 31 PERCENT KOH ELECTROLYTE

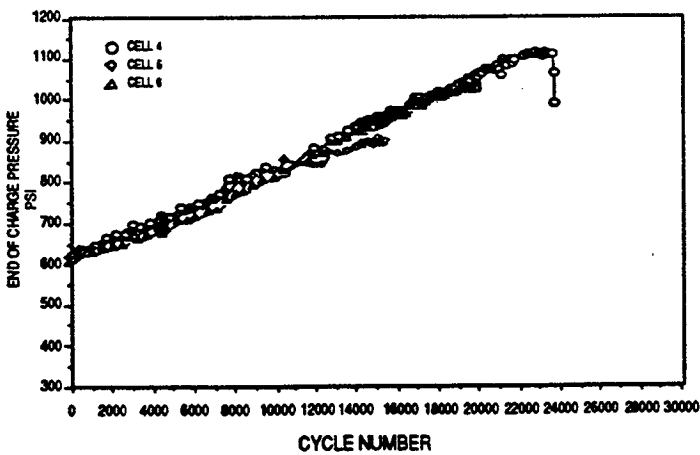


FIGURE 3 - EFFECT OF LEO CYCLING AT 80 PERCENT DOD ON 48 A-hr IPV HUGHES FLIGHT CELLS CONTAINING 26 PERCENT KOH.

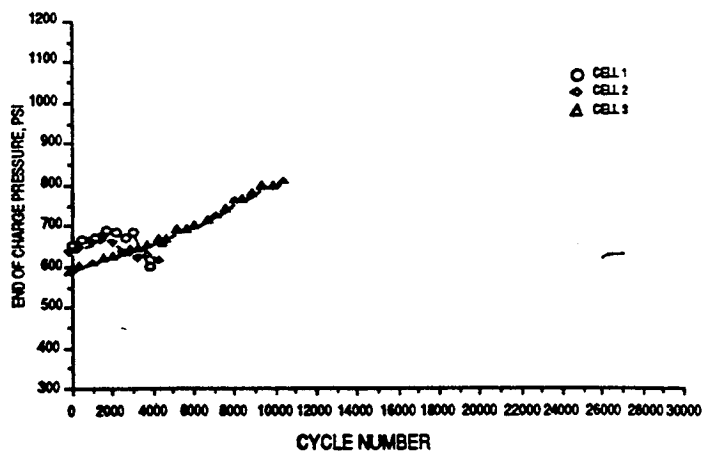


FIGURE 6 - EFFECT OF LEO CYCLING AT 80 PERCENT DOD ON HUGHES FLIGHT CELLS CONTAINING 31 PERCENT KOH.

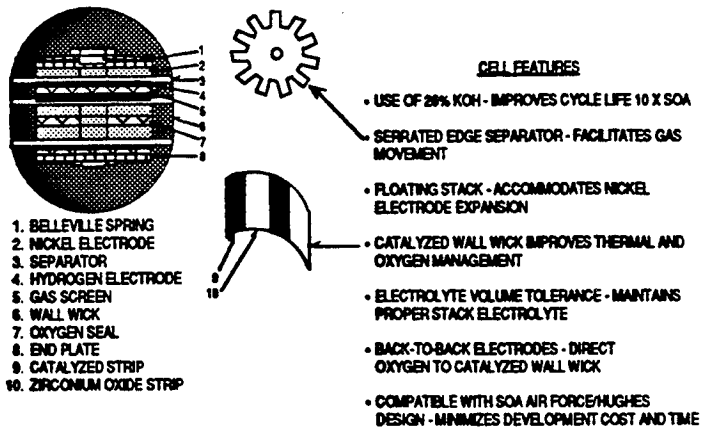


FIGURE 7 - NASA ADVANCED DESIGN IPV NICKEL HYDROGEN CELL - CATALYZED WALL WICK.

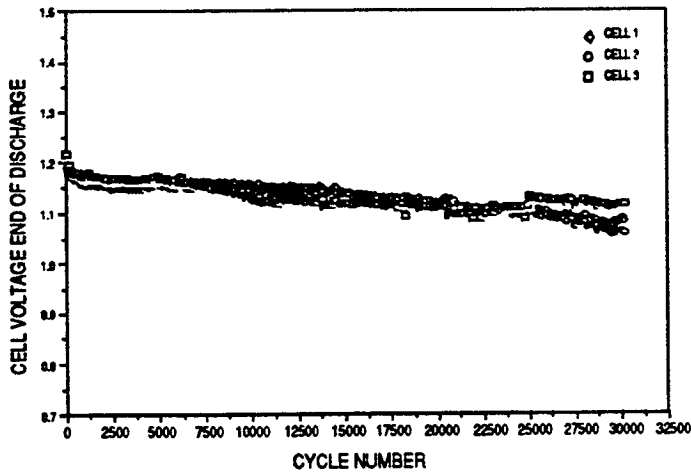


FIGURE 8 - EFFECT OF LEO CYCLING ON 125 Ah NASA LEWIS ADVANCED CATALYZED WALL WICK IPV Ni/H₂ CELLS MANUFACTURED BY EAGLE PICHER - 26% KOH, 60% DOD, 10°C.

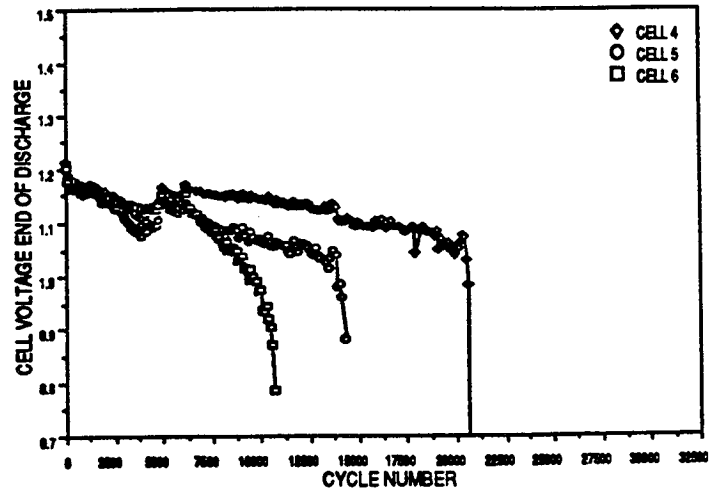


FIGURE 10 - EFFECT OF LEO CYCLING ON 125 A-hr NASA LEWIS ADVANCED NON-CATALYZED WALL WICK IPV Ni/H₂ CELLS MANUFACTURED BY EAGLE-PICHER, 26 PERCENT KOH, 60 PERCENT DOD, 10°C.

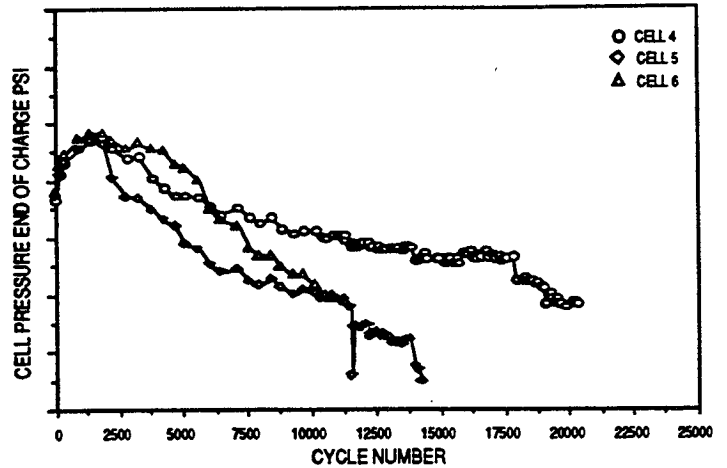


FIGURE 11 - EFFECT OF LEO CYCLING ON 125 A-hr NASA LEWIS ADVANCED NONCATALYZED WALL WICK IPV Ni/H₂ CELLS MANUFACTURED BY EAGLE-PICHER, 26 PERCENT KOH, 60 PERCENT DOD, 10°C.

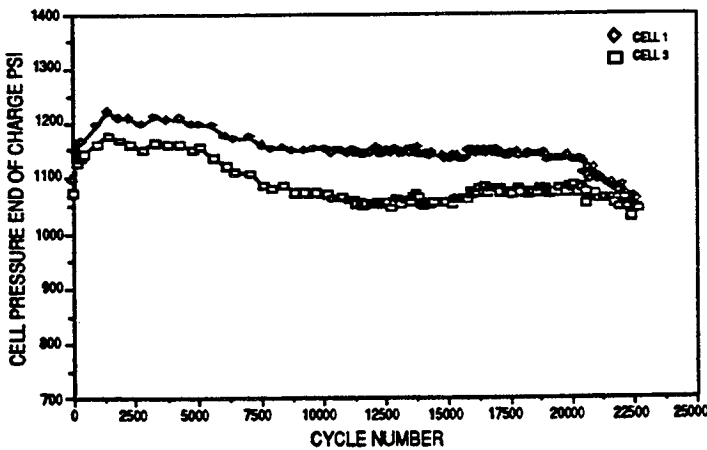


FIGURE 9 - EFFECT OF LEO CYCLING ON 125 A-hr NASA LEWIS ADVANCED CATALYZED WALL WICK IPV Ni/H₂ CELLS MANUFACTURED BY EAGLE-PICHER, 26 PERCENT KOH, 60 PERCENT DOD, 10°C.

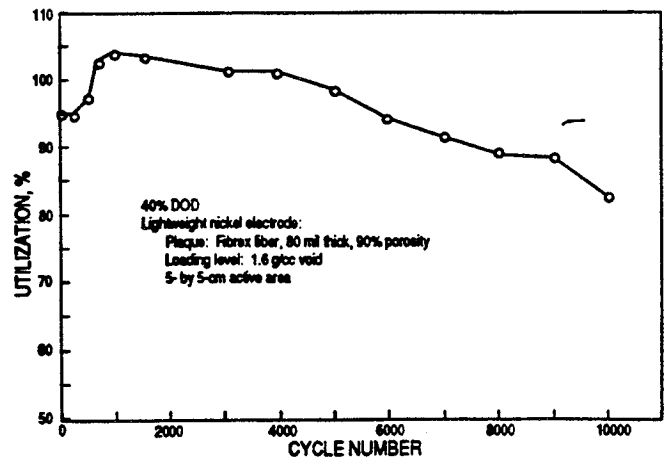


FIGURE 12 - UTILIZATION VERSUS CYCLE NUMBER OF A NICKEL-HYDROGEN CELL USING A FIBREX NICKEL ELECTRODE.

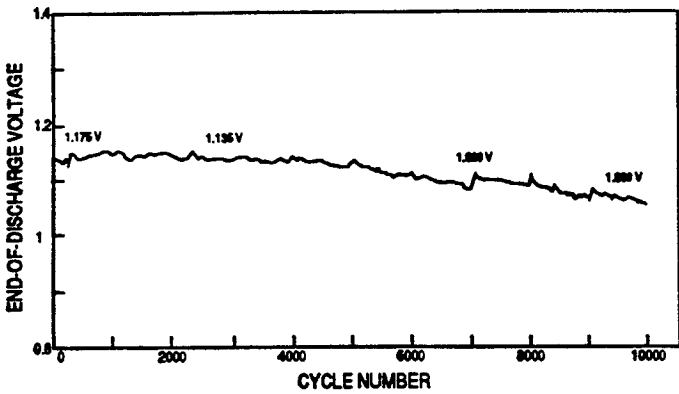


FIGURE 13 - END OF DISCHARGE VOLTAGE VERSUS NUMBER OF CYCLES FOR A NICKEL-HYDROGEN CELL USING A FIBREX NICKEL ELECTRODE.

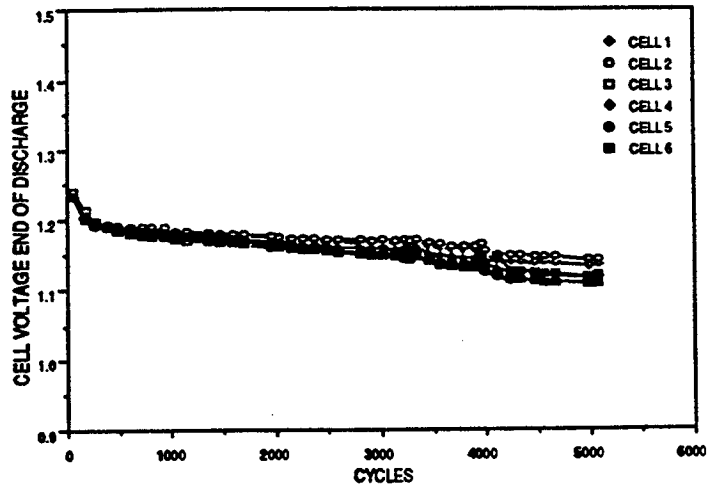


FIGURE 16 - EFFECT OF LEO CYCLING ON 10 Ah EAGLE PICHER NICKEL METAL HYDRIDE CELLS, 40% DOD, 10°C

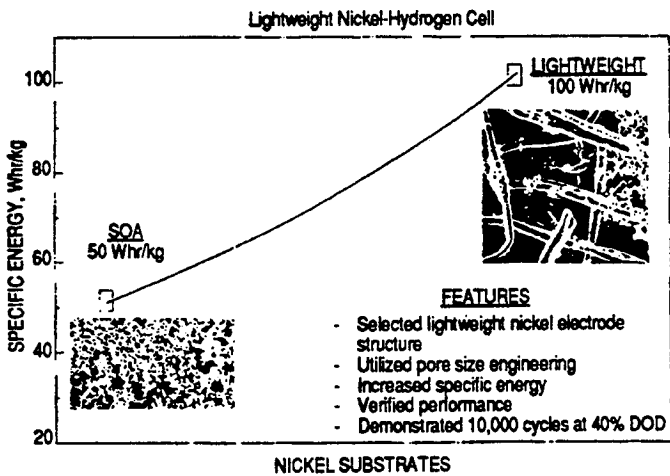


FIGURE 14 - EFFECT OF NICKEL ELECTRODE DESIGN ON IPV NICKEL HYDROGEN CELL SPECIFIC ENERGY

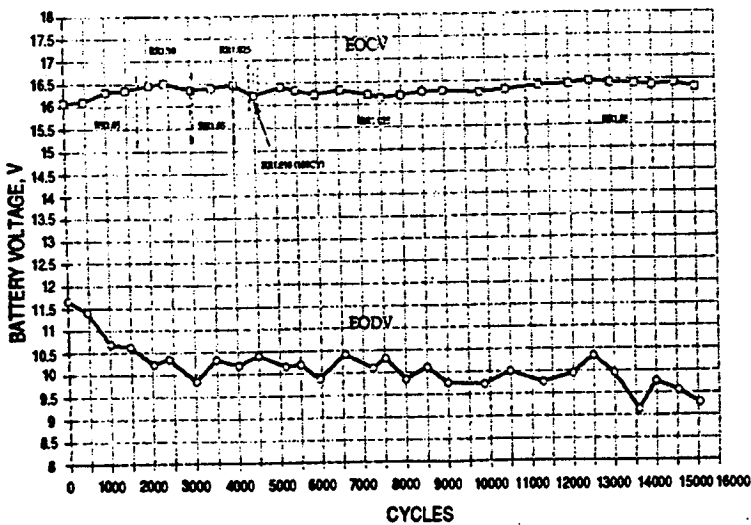


FIGURE 15 - EFFECT OF LEO CYCLING ON 75 Ah BIPOLAR NICKEL HYDROGEN BATTERY 40% DOD, 10°C

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13. ABSTRACT (Maximum 200 words) This paper 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 (SOA) nickel hydrogen batteries are replacing nickel cadmium batteries in almost all geosynchronous orbit (GEO) 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 to 10,000 cycles at 60 percent DOD should be improved. A LeRC 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 light weight nickel electrode and alternate battery designs. A common pressure vessel (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 Ah 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 percent 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 which has the advantage of a significant reduction in volume and a reduction in manufacturing cost.			
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