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Current Status of Nickel–Hydrogen Battery Technology Development

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Nickel–hydrogen (NiH_2) batteries are widely used in Earth-orbital satellites. Several advanced NiH_2 cell and battery designs are under development, including common pressure vessel (CPV), single pressure vessel (SPV), and dependent pressure vessel designs. Cells are being manufactured in sizes ranging from 64 to 250 mm in diameter. CPV NiH_2 batteries, utilizing low-cost 64-mm cell diameter technology, have been designed and built for several small satellite programs. An advanced 90-mm-diam NiH_2 cell design is being manufactured for the space station program. Production 250-mm-diam SPV batteries are currently under construction and initial testing has shown excellent results. Cell component level development is aimed at reducing battery cost while improving performance and maintaining reliability and cycle life. NiH_2 cycle life testing is being continued and cells have currently completed more than 95,000 accelerated low-Earth-orbit charge/discharge cycles and 30 eclipse seasons in accelerated geosynchronous-Earth-orbit testing. Nickel–metal hydride battery development is continuing for both aerospace and electric vehicle applications.

Introduction

NICKEL–HYDROGEN (NiH_2) batteries are the system of choice for both low-Earth-orbit (LEO) and geosynchronous-Earth-orbit (GEO) communications and surveillance satellites. The NiH_2 battery system offers unequaled performance and cycle life, as well as extreme abuse tolerance, simplified state-of-charge indication, and high reliability levels. The first NiH_2 batteries were launched in 1976 aboard the U.S. Navy NTS-2 satellite and a U.S. Air Force Flight Experiment satellite. There were several additional GEO satellites using Eagle-Picher NiH_2 batteries launched throughout the 1980s, including INTELSAT V, G-Star, AmericanSat, Spacenet, and SatCom K1 and K2. NiH_2 batteries are flying aboard more than 50 satellites, including several European spacecraft such as Olympus (British Aerospace), Eutelsat II (Aerospatiale), TVSat II (AEG), Telecom II, and HispaSat (Matra). NiH_2 batteries are also being used in demanding LEO applications such as the Hubble Space Telescope (HST). This flight database amounts to more than 110,000,000 operational cell-hours in space.

NiH_2 Life Testing

The NiH_2 battery system has an extensive flight history database. There is also an extensive ground testing database. A full summary of NiH_2 testing at Eagle-Picher has been previously published.[1] There are currently more than 150 flight-type NiH_2 cells on life test under several different cycle regimes and depths-of-discharge (DOD). A summary of some of the testing being done is indicated in Table 1. Cells have accumulated over 95,000 charge/discharge cycles under an accelerated LEO regime at 15% DOD. The cells charge for 23.5 min and discharge for 21.5 min for a total of 32 cycles/24-h day. Testing is done at 5°C. Several 76-A-h cells are being tested under the same regime and have accumulated more than 74,000 charge/discharge cycles. Intelsat V type RNH-30 cells have completed more than 55,000 real-time LEO cycles at 30% DOD. These cells are operating on a standard 55-min charge/35-min discharge LEO regime for a total of 16 cycles/day. This test has been in continuous operation for more than nine years. Typical end-of-charge (EOCV) and end-of-discharge voltages (EODV) as a function of the number of cycles are indicated in Fig. 1. No performance degradation has been observed to date.

Cells are also being tested under accelerated and real-time GEO test regimes as indicated in Table 1. This testing has completed up to 30 eclipse seasons as shown in Fig. 2. Each 42-day eclipse season is performed in real-time. Test acceleration is achieved by eliminating the trickle charge period between seasons. In this manner, approximately eight eclipse seasons can be performed per calendar year, rather than only two. The test is operating at 75% DOD maximum and the cells are reconditioned about every fifth season. Figure 2 shows the EODV for day 21 for each season. Day 21 is the day on which the maximum DOD occurs, and therefore, represents the minimum voltage experienced by the cell during the season. Extrapolation of these data indicates that cell failure, defined as an EODV on day 21 of less than 1.0 V, would not occur before approximately 42 seasons. Additional testing indicated in Table 1 shows 24,000 and 40,000 cycles in real-time test regimes and up to 8900 cycles in nickel–metal hydride cell testing [rechargeable metal hydride (RMH) designation].

Table 1 EPI life test summary

Cell	Regime[a]	% DOD	No. of cycles[b]
RNH-30-1	R/T LEO	30	55,000
RNH-50-15	ACC LEO	15	95,000
RNH-76-3	ACC LEO	15	74,000
RNH-76-3	R/T 1	—	24,000
RNH-76-3	R/T 2	—	40,000
RNH-76-3	R/T 3	—	39,000
RMH-4	R/T LEO	40	8,900
RMH-10	R/T LEO	15	6,700
RNH-65-1-3	ACC GEO	75 max	30[c]
SAR-10017	ACC GEO	75 max	16[c]
SAR-10017	R/T GEO	75 max	6[c]

[a]R/T, real-time; ACC, accelerated. [b]As of May 1994. [c]Eclipse seasons.

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Space Station Cell Testing

NiH_2 individual pressure vessel (IPV) batteries have been selected as the power supply for the space station program. The batteries will be used to supply power to the station during the eclipse portion of the orbit (LEO). In the fall of 1990, 130 NiH_2 cells were delivered for life-testing and development work. These cells were designed for service in LEO, and specifically for use in evaluating power system requirements for the space station program. The cells consisted of two basic designs: a standard design and an advanced design. The cells were built in two sizes, 65 and 81 A-h. Both standard and advanced cells were built in the 65-A-h size, but only the advanced cell was built in the 81-A-h size.

The cells were fully characterized prior to delivery to NASA. The cells deliver up to 56 W-h/kg with a very narrow capacity distribution over the production lots. Following delivery of the cells in the fall of 1990, most were placed on cycling tests at the U.S. Naval Surface Warfare Center-Crane, as part of the space station life test program. The standard design 65-A-h cells were built into six cell packs containing eight cells each. Three cell packs are operating at 35% DOD and the other three packs are being tested at 60% DOD. These cells have accumulated more than 5600 cycles. The advanced 65-A-h cells were split into four separate tests containing five cells each. The four tests have completed from 5000 to 10,000 charge/discharge cycles. The advanced 81-A-h cells are also split into four tests, with each test containing 10 cells. The 81-A-h cells have completed from 3000 to 8000 cycles. Testing is still underway and is planned to be continued. Three of the advanced 81-A-h cells were also provided to NASA Goddard Space Flight Center for evaluation as part of the Earth observing system (EOS) program.

Cell Component Level Development

Cell component level development work is aimed at improving cell level performance while reducing system cost. The nickel electrode is currently the limiting component in terms of cell performance and energy density. Work is directed at increasing the energy density of the electrode by increasing the ratio of active materials to inactive materials. Hydrogen electrodes and alternative separator materials are being identified and qualified in an effort to reduce system cost while maintaining current levels of performance and reliability.

Nickel Electrode

State-of-the-art aerospace nickel electrodes consist of a sintered carbonyl nickel powder substrate, impregnated with nickel–hydroxide active material by an electrochemical deposition method. The electrodes are manufactured with strict traceability requirements and quality assurance provisions. Extensive testing is required at each step of the manufacturing process as well as at the finished electrode. The electrodes are relatively expensive but yield correspondingly high levels of performance, cycle life, and reliability. The electrode weight specific energy is relatively low compared to commercial nickel electrodes, but the cycle life is much longer. Aerospace grade nickel electrodes are capable of more than 1000 full-depth (100% DOD) charge/discharge cycles operating at the 10 C charge rate and more than 100,000 charge/discharge cycles operating at 15% DOD. (When used to designate a charge or discharge rate, the symbol C stands for a current in amperes numerically equal to the cell capacity in ampere-hours.) This level of performance was developed for critical, high-reliability, long life geostationary satellite applications. There is a new market for small satellites that have reduced requirements for mission duration and require lower-cost power storage systems.

Nickel fiber-based electrode substrates are being developed to replace traditional sintered nickel powder. The fiber-based materials can provide adequate mechanical strength at a higher bulk porosity and increased active material loading level. This results in a net increase in electrode specific energy. Fiber nickel electrodes have been prepared, using existing manufacturing methods, which demonstrate a 50% increase in weight energy density compared to standard aerospace nickel electrode technology. A significant weight savings is achieved sim-

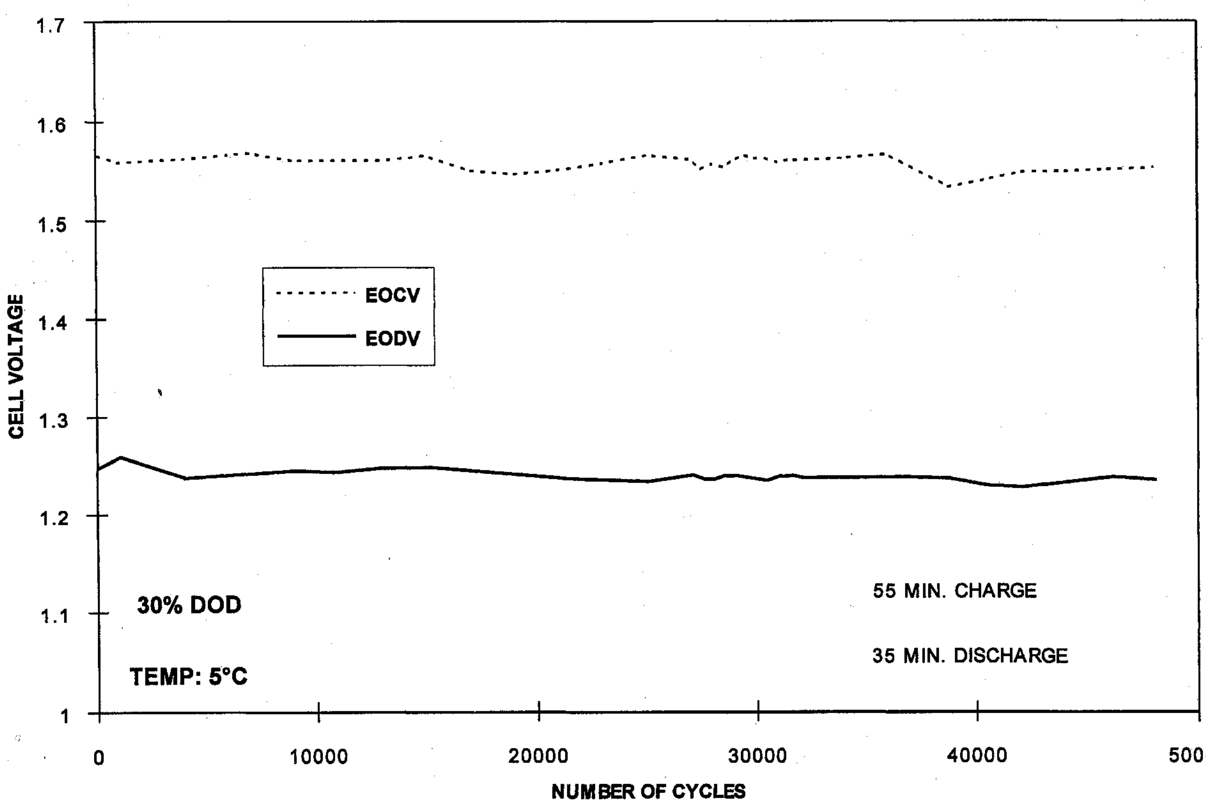

Fig. 1 Real-time LEO life test.

ply by eliminating the wire mesh substrate/current collector used in sintered powder electrodes. The fiber-based electrode substrates are mechanically stronger and more electrically conductive than sintered nickel powder and the wire mesh is not required. The higher porosity attainable with the fiber-based materials also allows higher active material loading to be achieved. This greatly increases the ratio of active mass to inactive mass in the electrode. Aerospace nickel electrodes are typically about 37% active mass with the rest of the electrode weight comprised of the wire mesh and nickel powder. Fiber-based nickel electrodes contain 58% active mass or higher. Increasing the ratio of active-to-inactive mass provides a significant increase in specific energy. Fiber technology may also yield some cost benefit because the fibers are made directly from ingot nickel with minimal processing.

Advanced Hydrogen Electrode Design

Low catalyst loading gas diffusion membrane electrodes have been developed for the aerospace NiH_2 battery system. This has been accomplished through the use of alternative catalytic materials, new electrode designs and innovative manufacturing methods. Some of the preliminary data has been published.[2] Current state-of-the-art NiH_2 spaceflight battery electrodes use fuel-cell-grade platinum black at relatively high catalyst loading levels to maintain derating and reliability requirements. At this usage level, platinum represents a major cost in the NiH_2 cell. Low-cost NiH_2 cell technology requires lower cost cell components. This is particularly applicable to the emerging smallsat market. New catalyst supports and alternative catalyst systems have been developed to decrease catalyst loading levels, and therefore reduce cost, without reducing performance or reliability. Electrodes can be produced with platinum loading as low as 10% of current levels, while maintaining adequate performance and retaining the existing aerospace heritage and database. Figure 3 shows representative EOCV and EODV values, as a function of cycling, for low-catalyst-loading electrodes that are built into a dual-stack common pressure vessel (CPV) cell design. These electrodes exhibit excellent performance and have completed more than 12,000 cycles under a 90-min LEO test regime operating at 40% DOD.

Alternative catalyst systems can further reduce platinum usage to less than 10% of current levels or completely eliminate the use of platinum with alternate catalyst materials. Materials such as palladium, iridium, and ruthenium have been tested at the electrode and cell levels. Novel catalyst support materials have also been evaluated as a method of reducing catalyst loading while maintaining the high surface area necessary for catalytic activity. This advanced electrode technology has currently accumulated more than 13,000 cycles in real-time LEO testing and has been incorporated into several NiH_2 spaceflight programs. Comparative data for several catalyst variables are shown in Fig. 4. The chart shows voltage vs time for a full 90-min LEO cycle, number 12,882. Performance has been excellent for several of the electrode variables with very little degradation being observed as a function of cycling. Pure palladium does not provide adequate performance but can be used as part of a mixed catalyst system with other catalyst materials. Testing is being continued. The hydrogen electrode technology developed has been incorporated into several flight programs including a low-cost NiH_2 CPV battery (64-mm cell diameter), which was built for the TUBSAT B spacecraft.

Alternative Separator Evaluation Testing

Zirconium–oxide cloth is currently used as the battery separator in most NiH_2 cell designs, particularly those that incorporate a zirconium–oxide wall wick on the inner surface of the pressure vessel. This material is relatively expensive and fragile to handle in a production operation. Alternative separator materials are being developed and qualified for advanced cell designs, particularly for lower-cost, small satellite power systems. A large number of candidate materials have been

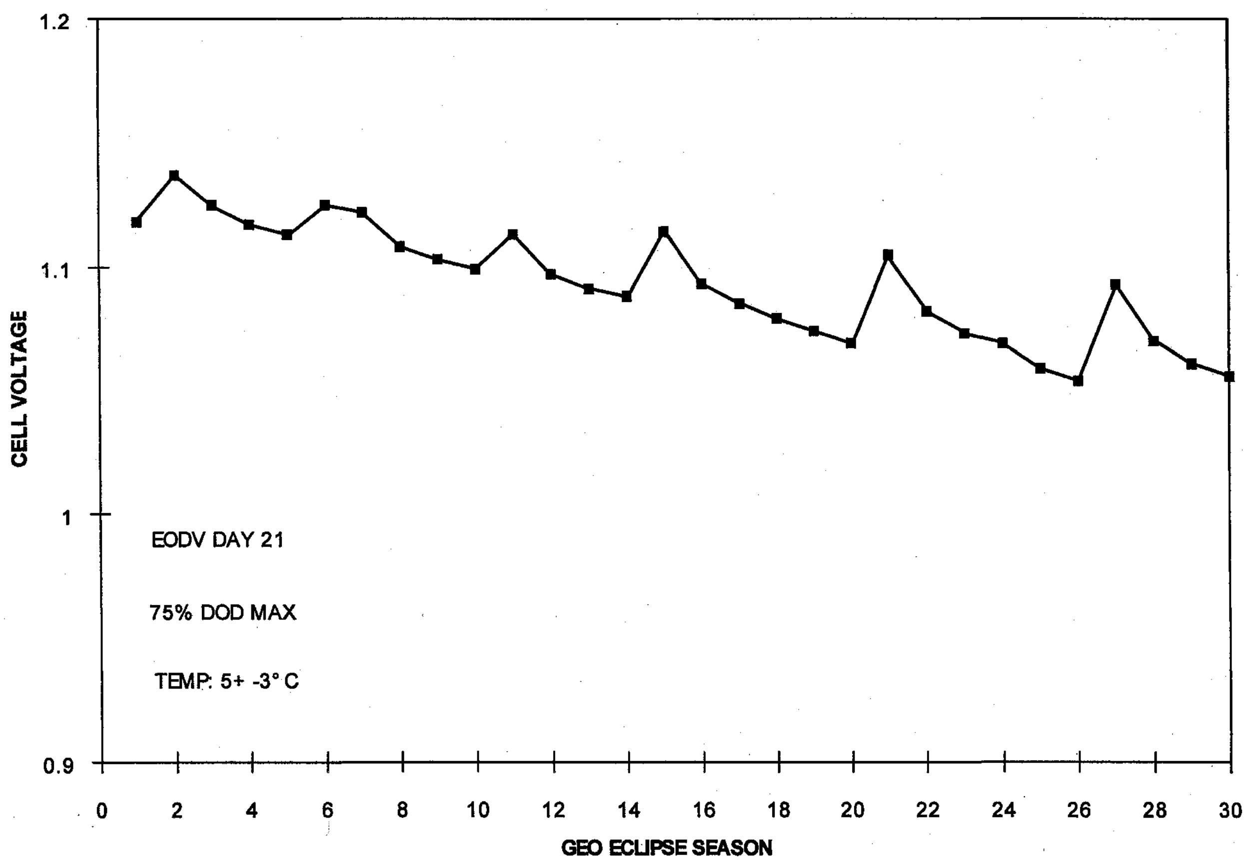

Fig. 2 Accelerated GEO life cycle test.

identified, procured, and undergone initial screening test procedures. Some of the initial parameters that are considered are material type, chemical compatibility, oxidation resistance, long-term stability, wicking ability, wettability, electrolyte retention, bubble pressure, thickness, availability, cost (near term and long term), and other factors. Initial separator evaluation testing is typically done at the boilerplate cell level, which provides a rapid, efficient means of generating comparative data. The most promising samples are built into flight-type NiH_2 cells for performance testing, characterization, and cycle-life evaluation.

Approximately 15 materials have been evaluated for potential application in the NiH_2 battery system. Additional materials have been evaluated in the nickel–metal hydride system. The materials range from inorganics to treated and untreated polymeric, organic materials. More than 60 flight-type NiH_2 cells have been built specifically for the purpose of separator materials evaluation. Most of the comparative cell testing is done using the same design variables to minimize any extraneous effects on the separator being tested. Some materials are being considered for optimization in specific cell designs. Several separator types have been selected for long-term cycle life testing based on superior performance characteristics in basic material and initial boilerplate cell level testing. This testing has been underway for several years and some materials have accumulated up to 35,000 charge/discharge cycles in accelerated LEO testing. Most of the cycle life testing is being done under accelerated cycle regimes to accumulate cycles in the shortest possible time. The effect of DOD and electrolyte concentration is also being considered. These and other factors may affect the ultimate cycle life obtained from a given material. Several versions of polyolefin materials are under test along with other types of organic separator materials. Results are promising to date. Materials continue to be developed in conjunction with separator manufacturers. Test results and data are being used to optimize materials for future application. This effort will continue to provide a database for these materials in support of future spaceflight programs.

Cell/Battery Design

Advanced cell level components are being developed in conjunction with new, lightweight cell and battery designs. Significant weight and cost savings can be achieved through more efficient cell and battery packaging. Several of the newly developed designs, such as the common pressure vessel technology, are already flying in Earth-orbital spacecraft. Work is continuing to develop, optimize, and flight qualify other cell and battery designs for specific spaceflight applications.

CPV Technology

Dual-stack NiH_2 CPV cells are currently being built in both 60 and 90 mm diam. The technology is also applicable to high-power 114-mm-diam cell designs as well. The 64-mm cells are specifically designed for small satellite applications. Cells have been produced for the APEX, SeaStar, and OrbComm programs with Orbital Sciences Corporation and are currently flying in the TUBSAT B spacecraft, built by the Technical University of Berlin, and the MSTI 2 spacecraft. Several 90-mm CPV cells have been built for the SALT program with Intraspace and cells were provided to the Naval Research Laboratory. A typical 60-mm CPV battery design is shown in Fig. 5. The dual-stack CPV design provides several important advantages over conventional IPV technology, including a 50% reduction in the mounting footprint of the battery, a 30% reduction in cell volume, and a 10% reduction in mass. There are also reduced IR conductor losses resulting from the shorter internal series connection as compared to wiring two cells together externally. The dual-stack approach provides a low technical risk because of minimal deviation from accepted spaceflight qualified designs. The dual-stack CPV cell is very similar to the dual-stack IPV cell, except that the two cell stacks are connected electrically in series instead of in parallel. There-

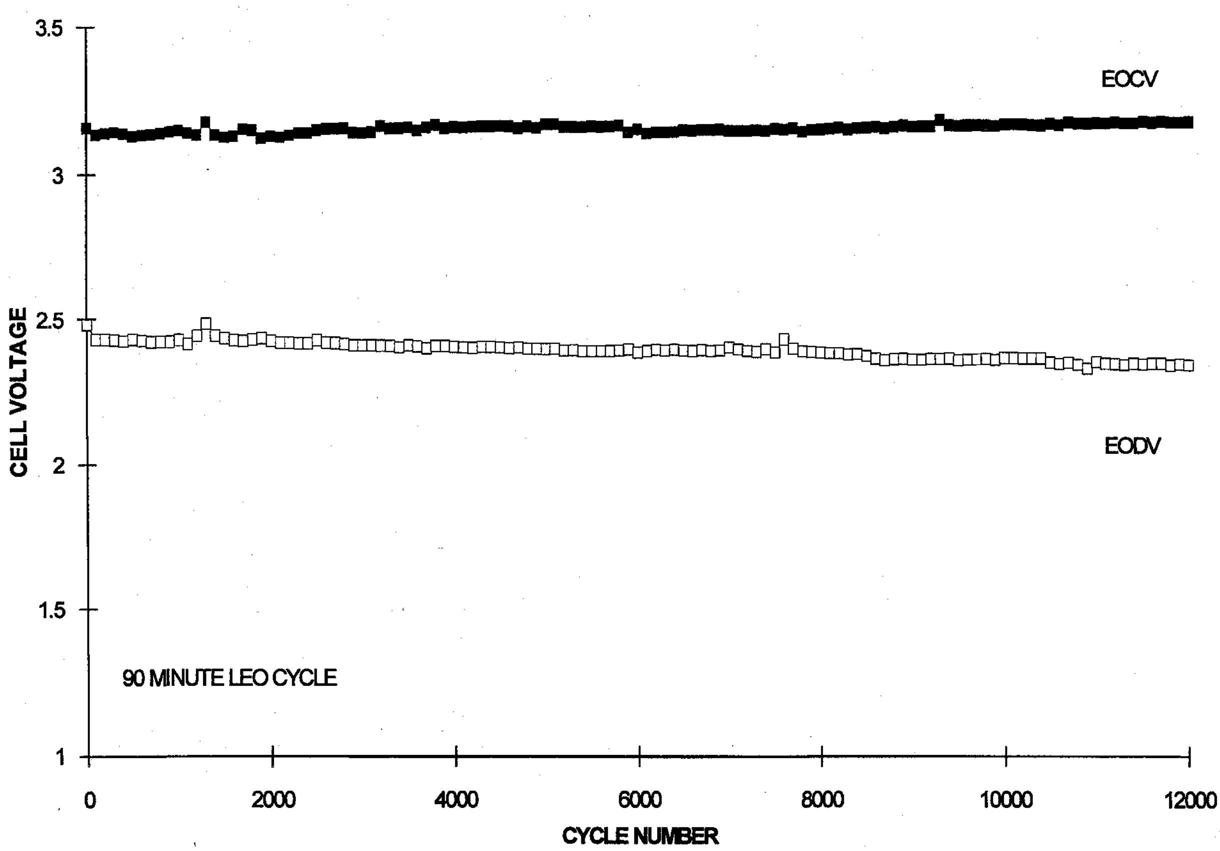

Fig. 3 Reduced catalyst loading in CPV.

fore, the CPV cell has an output voltage of 2.5 V, which is the sum of the two series-connected cell stacks. 40-A-h CPV cells (90 mm diam) have completed over 16,000 cycles at 50% DOD in a real-time LEO test regime. No performance degradation has occurred and testing is being continued.

SPV Technology

SPV technology differs from the previously discussed CPV technology by combining an entire multicell NiH_2 space battery in a single pressure vessel. SPV technology has been developed to simplify the NiH_2 system at the battery level and ultimately to reduce overall battery cost and increase system reliability. The battery mechanical design is shown in Fig. 6. The pressure vessel has an o.d. of 254 mm (10 in.). Internal construction is modular and allows any number of individual cells to be stacked together.

Each cell module is designed to deliver the rated capacity of the battery, with the resultant battery voltage being the sum of the series-connected cells. The length of the pressure vessel is determined by the number of cell modules and the desired operating pressure. The system is designed to operate at internal hydrogen pressures up to 6.9 MPa (1000 psi), but the pressure can be reduced by including additional free volume to accommodate the hydrogen gas. Each cell module is sealed to retain the potassium–hydroxide electrolyte. This prevents any potential electrolyte bridging between cells. A microporous plug allows the diffusion of hydrogen gas into and out of each cell module for normal cell operation. The plug is impermeable to the aqueous electrolyte.

Dependent Pressure Vessel Technology

Dependent pressure vessel (DPV) technology is also a modular approach to NiH_2 space battery design. DPV battery construction offers the potential for substantial improvements in battery specific-energy (weight) and energy-density (volume). The DPV battery offers potential savings in weight and volume of 25–30% compared to a conventional IPV battery design. This design was first reported in 1974[3] and new spacecraft applications have renewed interest in this design. The battery concept is illustrated in Fig. 7. As shown in the figure, the geometry of a DPV cell requires some support of the flat surfaces and the cell is partially dependent upon the battery package for gas pressure containment. A major design advantage is that the battery support structure is efficiently required to restrain only the force applied to a portion of the end cell only. As the DPV cells are stacked in series to achieve the desired system voltage, this increment of the total battery weight becomes small.

The advantage of the DPV cell design over the SPV design is that the problem of a single point failure in the event of a hydrogen leak is avoided. The DPV provides a lower risk approach to achieving substantial energy density improvement by offering less deviation from accepted flight qualified technology. The geometry of the DPV cell also promotes compact, minimum volume packaging and places all cell terminals in close proximity along the length of the battery. The resulting ability to reduce intercell current conductor size offers additional significant weight savings.

Typical internal cell construction is shown in Fig. 8. The electrode stack is rectangular within the pressure vessel. A second major advantage, the dramatic improvements in weight and volume, are achieved with minimal design risks. The cell's liquid electrolyte is hermetically sealed in a single vessel as are current flight technology cells. And, a maximum, direct electrode stack-to-vessel wall interface is achieved ensuring superior system thermal management.

DPV cells of a 50-A-h design have been built and tested, yielding more than 70 W-h/kg. This is the highest specific energy reported for space NiH_2 cells to date. More than 80 W-h/kg have been extrapolated for this design using some of the component level design improvements outlined earlier.

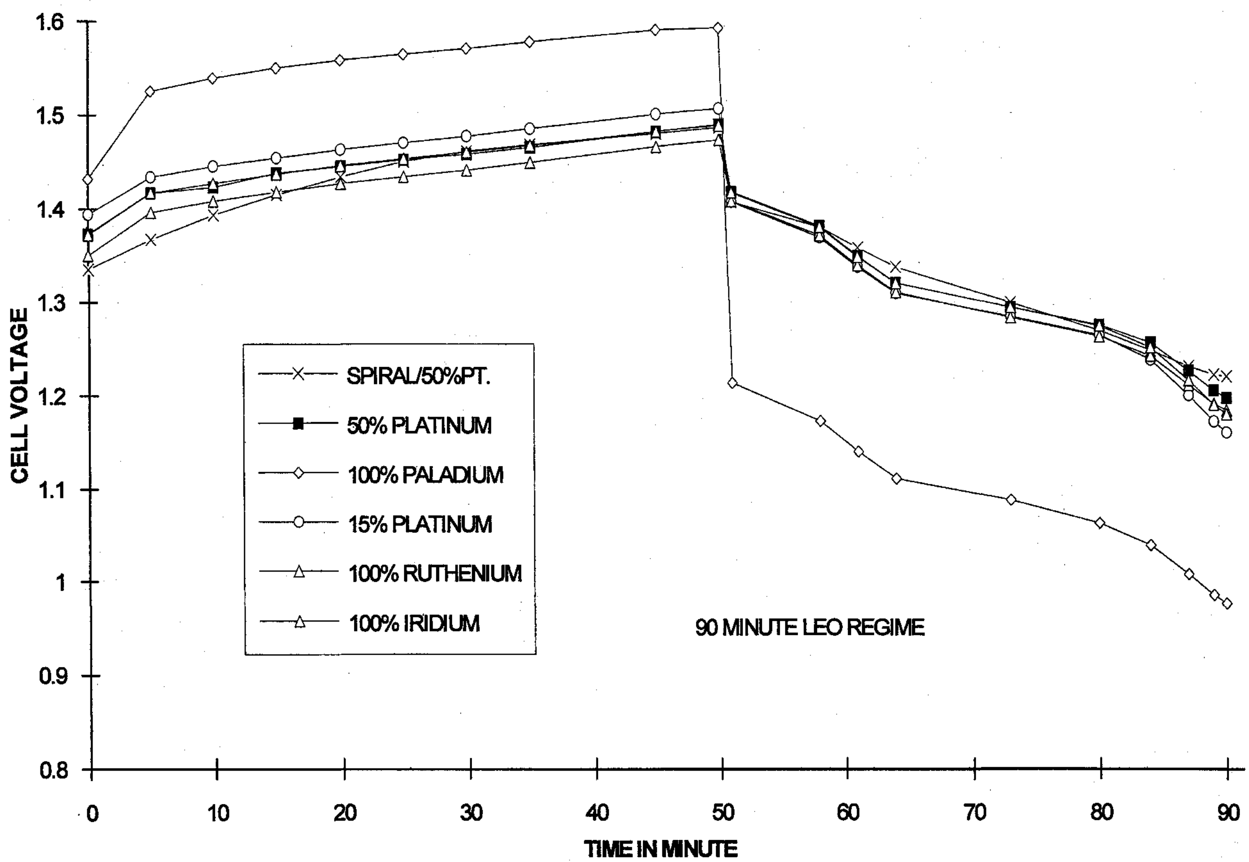

Fig. 4 Alternate catalyst test matrix.

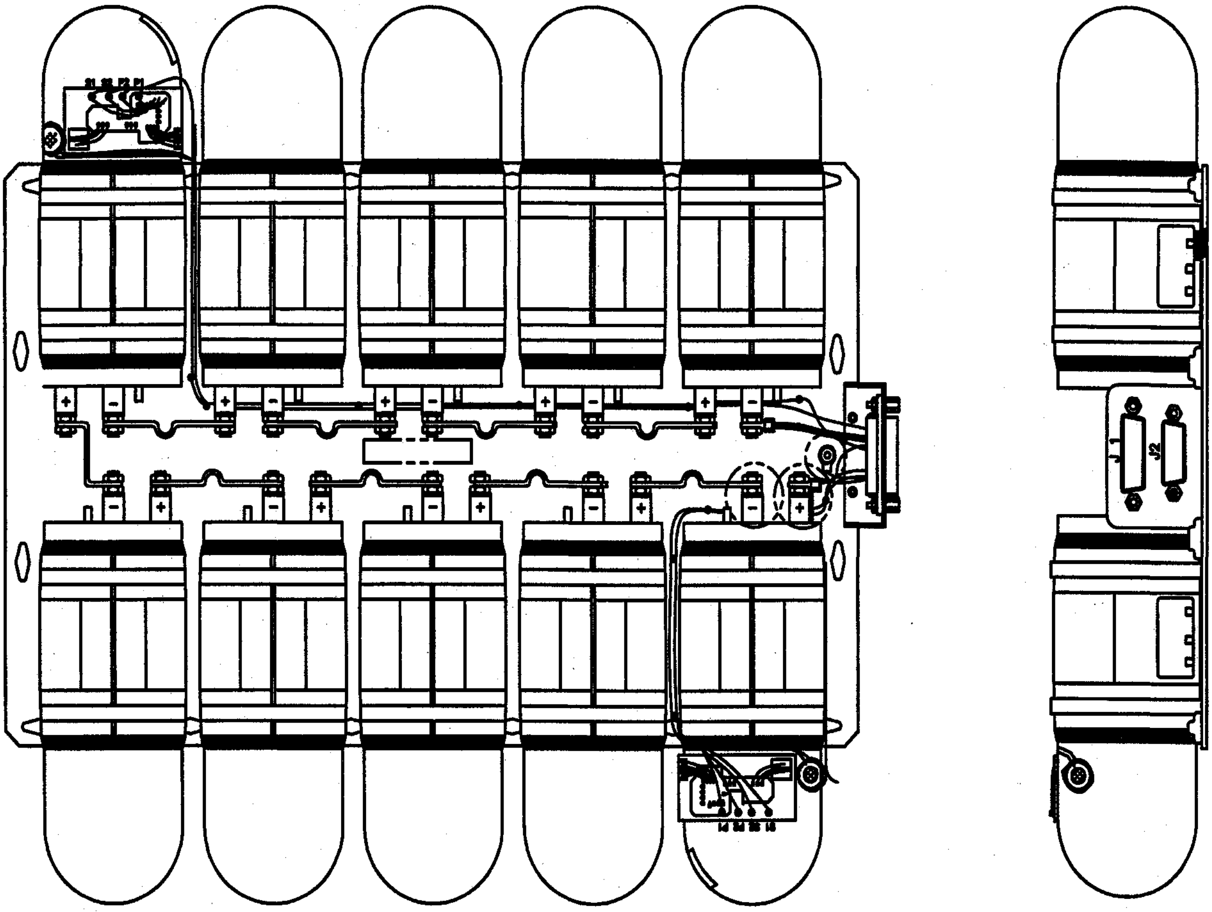

Fig. 5 SAR-10027 $Ni-H_2$ battery outline.

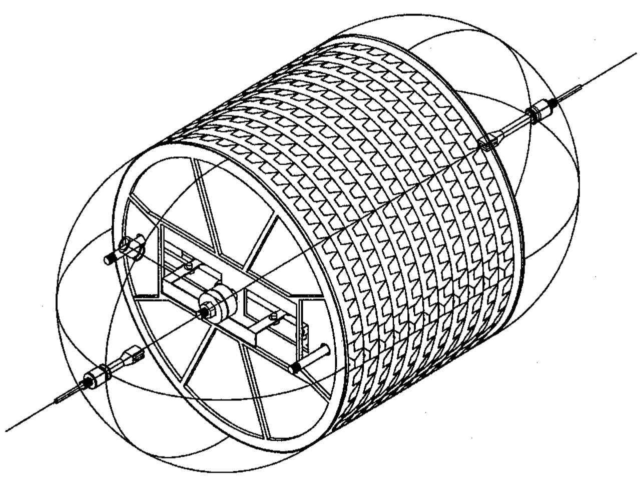

Fig. 6 Single pressure vessel battery.

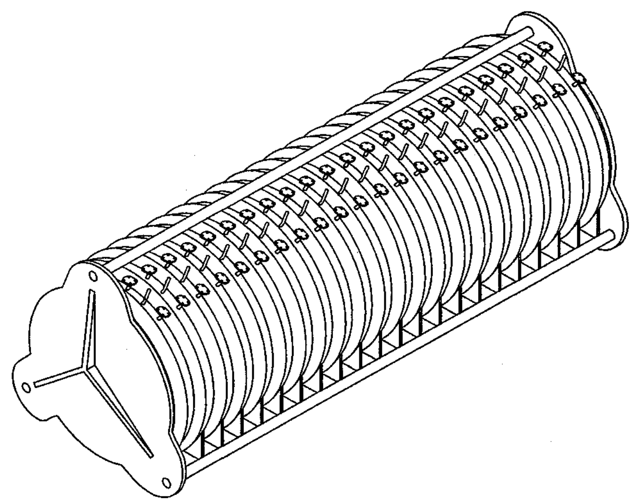

Fig. 7 $Ni-H_2$ DPV battery design.

Low-Pressure NiH_2 Technology

There has been a growing interest recently in several low-pressure NiH_2 (LPV) battery designs, including nickel–metal hydride (NiMH) batteries. The NiMH battery is electrochemically identical with the NiH_2 system, except that the hydrogen is stored as a solid metallic hydride rather than as a gas. Working with low-pressure NiH_2 battery systems began in the early 1970s in connection with space battery research and development programs.[4] The interest was to increase the volumetric efficiency (energy density) of the NiH_2 battery by lowering the maximum operating pressure. The idea was to store the hydrogen as a solid hydride instead of as a gas. This would eliminate the need for free volume inside the cell pressure vessel required to accommodate the hydrogen gas at manageable pressures. This would lead to a substantial increase in volumetric energy density and eliminate the need for a cylindrical pressure vessel. The disadvantage is that the linear pressure vs state-of-charge indication of the NiH_2 system is no longer valid. Also, an additional failure mechanism is introduced into the cell in that the hydride material could possibly degrade and fail before the normal cell wear-out mechanism is reached.

Recent advances in hydride materials technology have made possible the use of low-pressure NiH_2 batteries for aerospace applications.[5] The hydride material can either be used electrochemically as the discharge anode in the cell or can be used as ancillary chemical hydrogen storage for a normal pressure-

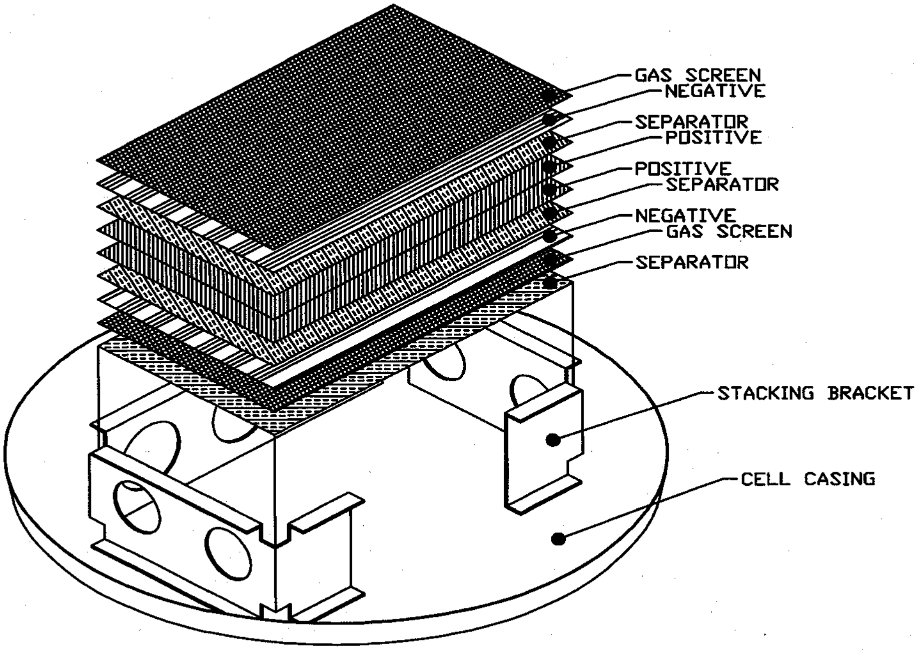

Fig. 8 Internal DPV cell stack construction.

type NiH_2 cell. In either case the entire system can be hermetically sealed, and therefore, maintenance-free. Chemical hydrogen storage offers the advantage of potentially much longer cycle life. The problems of hydride material pulverization, performance degradation, or oxygen/water/electrolyte poisoning are avoided. Low-pressure 200-A-h NiH_2 batteries have been built and tested with excellent results. Low-pressure NiH_2 technology offers significant advantages for volume critical applications compared to traditional IPV NiH_2 batteries. The technology is applicable to both aerospace and terrestrial commercial applications. A 300-V, 40-A-h nickel–metal hydride battery was recently supplied for a ground-up design electric vehicle. The vehicle placed first in the performance categories and third overall in the Ford Hybrid Electric Challenge in June 1993. This is the world's first nickel–metal hydride battery-powered vehicle.

Conclusions

Work is under way in a number of areas to improve and further develop the NiH_2 battery system. These include subcell level components, such as nickel and hydrogen electrodes, and cell and battery level design improvements. The technology being developed is applicable to both commercial and aerospace applications. A number of these advanced NiH_2 battery designs are currently in production and under development. The designs are applicable to many aerospace applications including Earth-orbital satellites. New designs such as CPV, SPV, and DPV will continue to develop and push forward the state of the art in aerospace battery technology. This evolution in battery design is necessary to keep pace with the rapid advances being made in other aspects of electronics and materials science. NiH_2 battery research and development will be continued in support of future flight programs as varied as the space station and low-cost, small satellite programs. Electrical, mechanical, and thermal aspects of battery design will continue to evolve. Battery performance, including useful life and charge/discharge cycle life, must be maximized while reducing battery cost. These power systems must provide the high degree of safety and reliability required by manned space programs and space-based orbital systems. Advanced NiH_2 batteries will continue to fulfill these demanding requirements well into the next century.

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