Advanced Nickel-Hydrogen Spacecraft Battery Development

Pg 5 10

D.K. Coates, C. L. Fox, D. J. Standlee and B. K. Grindstaff
Advanced Systems Operation
Eagle-Picher Industries, Inc.
Joplin, Missouri 64802

N94-28129

Abstract

Eagle-Picher currently has several advanced nickel-hydrogen (NiH_2) cell component and battery designs under development including common pressure vessel (CPV), single pressure vessel (SPV) and dependent pressure vessel (DPV) designs. A CPV NiH_2 battery, utilizing low-cost 64mm (2.5 in.) cell diameter technology, has been designed and built for multiple smallsat programs, including the TUBSAT B spacecraft which is currently scheduled (24 Nov 93) for launch aboard a Russian Proton rocket. An advanced 90 mm (3.5 in.) NiH_2 cell design is currently being manufactured for the Space Station Freedom program. Prototype 254mm (10 in.) diameter SPV batteries are currently under construction and initial boilerplate testing has shown excellent results. NiH_2 cycle life testing is being continued at Eagle-Picher and IPV cells have currently completed more than 89,000 accelerated LEO cycles at 15% DOD, 49,000 real-time LEO cycles at 30% DOD, 37,800 cycles under a real-time LEO profile, 30 eclipse seasons in accelerated GEO and 6 eclipse seasons in real-time GEO testing at 75% DOD maximum. Nickel-metal hydride battery development is continuing for both aerospace and electric vehicle applications. Eagle-Picher has also developed an extensive range of battery evaluation, test and analysis (BETA) measurement and control equipment and software, based on Hewlett-Packard computerized data acquisition/control hardware.

Introduction/Background

Eagle-Picher Industries, Inc. (EPI) has been supplying the defense and aerospace industry with high quality, high reliability batteries for more than forty years. More than 25 electrochemical systems are represented including nickel-hydrogen, nickel-cadmium, nickel-iron, nickel-metal hydride, nickel-zinc, silver-zinc, silver-metal hydride, sodium-sulfur, lead-acid and a wide variety of thermal and lithium battery systems. EPI batteries have been included in a large number of space and missile systems including the Hubble Space Telescope, Skylab, the Patriot and Cruise missiles, Standard Missile, Sidewinder, Copperhead, AMRAAM, TOW and many others. Eagle-Picher manufactures more than 80% of all batteries used in U. S. missile and weapons systems. Nearly every manned U. S. spaceflight has used EPI batteries including the Mercury, Gemini, Apollo and Space Shuttle missions. Eagle-Picher built the silver-zinc cells which powered the Lunar Rover on the surface of the moon. More than 50 earth-orbital communications and surveillance spacecraft which use EPI nickel-hydrogen batteries have been launched.

EPI batteries have also been used in a number of solar and electric race vehicles in such races as the GM Sunrayce, the Solar 300 and the Australian World Solar Challenge. Eagle-Picher has supplied batteries to more winning electric race vehicles than any other manufacturer. Michigan State University placed first in performance and third overall in a ground-up design vehicle with EPI nickel-metal hydride batteries in the Ford Hybrid Electric Challenge in June, 1993. The University of Michigan solar/electric race vehicle won the 1993 Sunrayce using EPI batteries. Eagle-Picher is currently operating the world's only advanced electric vehicle battery manufacturing plant. This facility is manufacturing nickel-iron batteries for the Chrysler TE electric minivan. In addition, EPI has set multiple land and water speed records for electric vehicles and electric boats and set the world's electric vehicle record for the longest distance driven on a single charge.

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. NiH_2 batteries have almost completely replaced sealed aerospace nickel-cadmium (NiCd) batteries for these applications. The NiH_2 battery system has been in production at EPI for more than fifteen years. 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 EPI NiH_2 batteries launched throughout the 1980's including INTELSAT V, G-Star, AmericanSat, Spacenet and SatCom K1 and K2. Eagle-Picher now has NiH_2 batteries flying aboard more than fifty satellites, including several European spacecraft such as Olympus (British Aerospace), Eutelsat II (Aerospatiale), TVSat II (AEG), Telecom II and HispaSat (Matra). EPI 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 97,000,000 operational cell-hours in space.

Nickel-Hydrogen Life Testing

There is also an extensive ground testing database. NiH_2 cells and batteries are being cycle life tested at EPI and other organizations, in both the U. S. and Europe. A full summary of NiH_2 testing at EPI has been recently published (1). EPI currently has more than 100 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 Figure 1. Cells have accumulated over 89,000 charge/discharge cycles under an accelerated LEO regime at 15% DOD. This test is an accelerated LEO regime in which the cells charge for 23.5 minutes and discharge for 21.5 minutes for a total of 32 cycles per 24 hour day. Testing is done at 5±3 °C. The cells are operating at 15% DOD under the accelerated regime which would be equivalent to 30% DOD under a real-time LEO regime, based on current density. Several 76 Ahr cells are being tested under the same regime and have accumulated more than 69,500 charge/discharge cycles.

Cell	Regime	%DOD	#Cycles*
RNH-30-1	R/T LEO	30	49,000
RNH-50-15	ACC LEO	15	89,000
RNH-76-3	ACC LEO	15	69,500
RNH-76-3	R/T 1	--	21,500
RNH-76-3	R/T 2	--	37,800
RNH-76-3	R/T3	--	37,000
RMH-4	R/T LEO	40	8900
RMH-10	R/T LEO	15	6,700
RNH-65-1-3	ACC GEO	75 MAX	30**
SAR-10017	ACC GEO	75 MAX	16**
SAR-10017	R/T GEO	75 MAX	6**
R/T=Real Time		ACC=Accelerated	
*As of November, 1993		**Eclipse Seasons	

Figure 1 — EPI Life Test Summary

Intelsat V type RNH-30 cells have completed more than 49,000 real-time LEO cycles at 30% DOD. These cells are operating on a standard 55/35 LEO regime for a total of 16 cycles per day. This test has been in continuous operation for more than 9 years. Typical end-of-charge (EOCV) and end-of-discharge voltages (EODV) as a function of the number of cycles are indicated in Figure 2. No performance degradation has been observed to date.

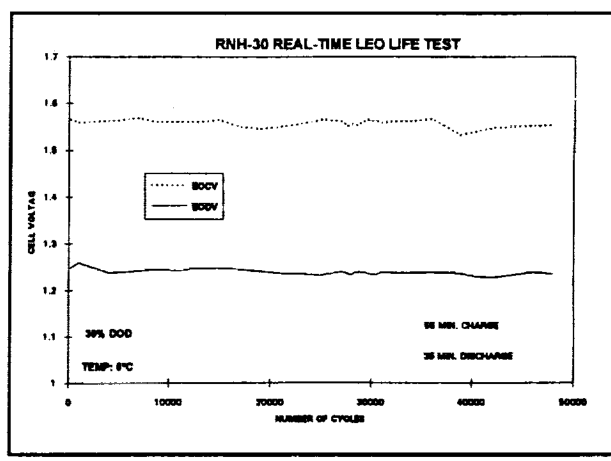

Figure 2 — Real Time LEO Life Test

Cells are also being tested under accelerated and real-time GEO test regimes as indicated in Figure 1. This testing has completed up to 30 eclipse seasons as shown in Figure 3. Each forty-two 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 every fifth season. Figure 3 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 this data indicates that cell failure, defined as an EODV on Day 21 of less than 1.0 volt, would not occur before approximately 42 seasons. Another accelerated GEO test has accumulated 16 seasons and the real-time GEO test is up to 6 seasons. This test includes trickle charging between eclipse seasons. Additional testing indicated in Figure 1 shows 21,500 cycles, 37,000 cycles and 37,800 cycles in three separate real-time test regimes and up to 8900 cycles in nickel-metal hydride cell testing (RMH designation).

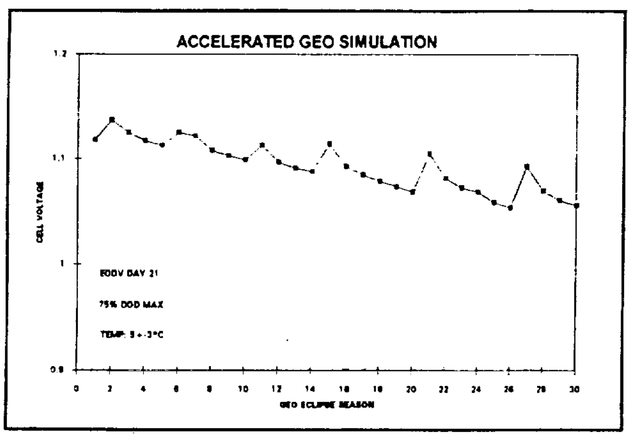

Figure 3 — Accelerated GEO Life Cycle Test

Space Station Freedom Cell Testing

Nickel-hydrogen IPV batteries have been selected as the power supply for the SSF program (2). The batteries will be used to supply power to the station during the eclipse portion of the orbit (LEO). In response to a NASA-Lewis Research Center contract in the fall of 1990, Eagle-Picher delivered 130 NiH_2 cells for life-testing and development work. These cells were designed for service in low-earth-orbit, and specifically for use in evaluating battery requirements for the SSF program. The cells consisted of two basic designs: a "standard" design and an "advanced" design. The standard cell was an Eagle-Picher "Mantech" design using pineapple-slice type electrodes in the back-to-back configuration. The cell uses a zirconium-oxide wall-wick and continuous electrode leads. Terminal seals were of the nylon compression type. All of the cells were nickel precharged (hydrogen limited) in the cell electrolyte activation procedure. The advanced design used a combination of asbestos and Zircar separators, lower cell stack compression, a double spring washer arrangement and a catalyzed wall-wick. The cells were built in two sizes, 65 Ahr and 81 Ahr. Both standard and advanced cells were built in the 65 Ahr size, but only the advanced cell was built in the 81 Ahr size. All cells were equipped with microstrain gages and aluminum thermal sleeves. The sleeve serves to remove heat from the area of the cell adjacent to the dual cell stacks and provides a means of mechanically mounting the cell for testing.

The cells were fully characterized at Eagle-Picher prior to delivery to NASA. Initial acceptance testing at EPI showed excellent electrical performance and uniformity. The cells deliver up to 56 Whr/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 Naval Surface Warfare Center-Crane, as part of the SSF life test program. The standard design 65 Ahr cells were built into 6 cell packs containing 8 cells each. Three cell packs are operating at 35% DOD and the other 3 packs are being tested at 60% DOD. The cells are operating at a charge-return ratio of 1.04 (the ampere-hour ratio of charge to discharge). As of March 1993, these cells had achieved 5200 to 5600 cycles. The advanced 65 Ahr cells were split into four separate tests containing 5 cells each. The four tests have currently completed from 5000 to 10,000 charge/discharge cycles. The advanced 81 Ahr cells are also split into four tests, with each test containing 10 cells. The 81 Ahr cells have completed from 3000 to 8000 cycles. Testing is still underway and is planned to be continued. Three of the advanced 81 Ahr cells were also provided to NASA Goddard Space Flight Center for evaluation as part of the EOS program.

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 novel catalytic materials, new electrode designs and innovative manufacturing methods. Some of the preliminary data has been published (3). Current state-of-the-art NiH_2 spaceflight battery electrodes use fuel cell grade platinum black at relatively high catalyst loading levels. 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. Novel 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 levels as low as 20% of previous levels, while maintaining current performance levels and retaining the existing aerospace heritage and database. Figure 4 shows representative EOCV and EODV values as a function of cycling for low catalyst loading electrodes which are built into a dual stack CPV cell design. These electrodes exhibit excellent performance and have completed more than 12,000 cycles under a 90-minute LEO test regime operating at 40% DOD.

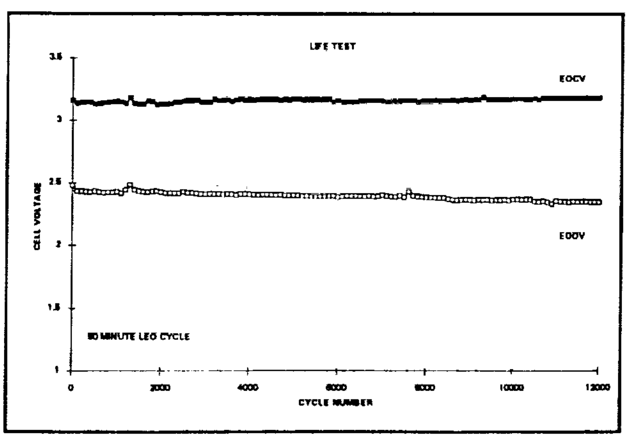

Figure 4 — Reduced Catalyst Loading In CPV

Alternative catalyst systems can further reduce platinum usage to less than 10% of previous 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 is shown in Figure 5. The chart shows voltage versus time for a full ninety minute 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. Palladium is shown in Figure 5 as an example of a material which does not perform well. Testing is being continued. The hydrogen electrode technology developed has been incorporated into several flight programs including a low-cost NiH_2 CPV battery (64mm cell diameter) which was built for the TUBSAT B spacecraft. This satellite, built by the Technical University of Berlin, is scheduled for launch this year aboard a Russian Proton rocket.

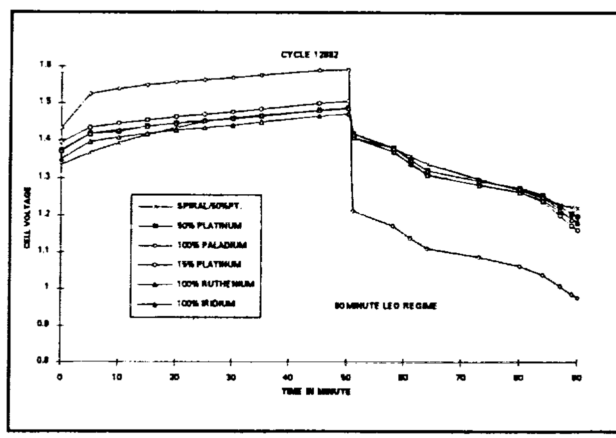

Figure 5 — Alternate Catalyst Test Matrix

Alternative Separator Evaluation Testing

Eagle-Picher currently has over 2,000 NiH_2 cells (equivalent to more than 50 batteries) currently operating in earth-orbital satellites. The vast majority of this flight database is with standard fuel-cell-grade asbestos separator. More recently, zirconium-oxide cloth has become integrated into several cell designs, particularly those which incorporate a wall-wick on the inner surface of the pressure vessel. Eagle-Picher has an ongoing program to procure, test and evaluate alternative separator materials. The purpose is to identify and qualify for flight, materials other than the two mentioned above. A large number of candidate materials have been identified from several different manufacturers. These materials are subjected to an initial screening procedure and materials which show promise are then evaluated in actual cell testing. 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 cell testing is typically done at the boilerplate cell level which provides a simple, rapid means of generating comparative data. The most promising samples are built into flight-type NiH_2 cells for performance testing and cycle life evaluation.

Approximately 15 materials have been evaluated for potential applications in the NiH_2 battery system. Additional materials have been evaluated in the NiMH system. The materials range from inorganics to treated polymeric materials. More than 60 flight-type NiH_2 cells have been built specifically for the purpose of separator materials evaluation. Most of the comparative testing is done using the same cell design variables in order to minimize any extraneous effects on the separator being tested. Several separator types have been selected for 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 cycles in accelerated LEO testing. Most of the life testing is being done under accelerated cycle regimes in order to accumulate cycles in the shortest possible time. The effect of DOD and electrolyte concentration on the separator is also being considered. These and other factors may affect the ultimate cycle life obtained. Several versions of polyolefin material are under test along with other types of organic separators. Results are promising to date. Materials continue to be developed in conjunction with separator vendors. Test results and data are fed back to vendors in order to optimize the most promising materials being tested. This cooperative effort will continue as new materials are selected for evaluation and new test results become available.

Common Pressure Vessel (CPV) Technology

Dual stack NiH_2 CPV cells are currently being built in both 64mm and 90mm diameters. The technology is applicable to high power 114mm (4.5 in.) diameter cell designs as well. The 64mm cells are specifically designed for small satellite applications. Cells have been produced for the "APEX", "SeaStar" and "ORBCOMM" programs with Orbital Sciences Corporation and will be flown in the TUBSAT B spacecraft built by the Technical University of Berlin. Several 90mm CPV cells have been built for the "SALT" program with Intraspace and cells were provided to the Naval Research Laboratory (NRL). A typical 64mm CPV battery design is shown in Figure 6.

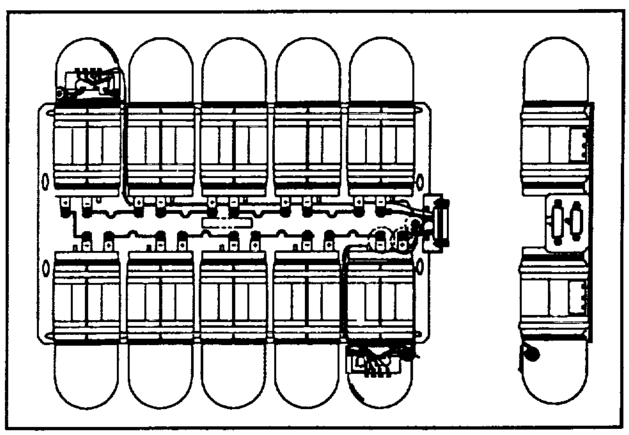

Figure 6 — SAR-10027 Ni-H_2 Battery Outline

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 due to the shorter internal series connection as compared to wiring two cells together externally. The dual stack approach provides a low technical risk due to 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. Therefore, the CPV cell has an output voltage of 2.5 volts, which is the sum of the two series-connected cell stacks. 40 Ahr CPV cells (90mm diameter) have completed over 16,000 cycles at 50% DOD in a real-time LEO test regime. No performance degradation has occurred and testing will be continued.

Single Pressure Vessel (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 Figure 7. The pressure vessel has an outside diameter of 254mm. 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 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. As the battery is charged, hydrogen gas generated inside each cell module diffuses into the free volume of the pressure vessel. The pressure inside the cell module remains equalized with the internal pressure of the battery. As the individual cell module does not contain any net pressure differential, it can be made of lightweight plastic materials. The SPV battery design is flexible and can be configured for both high voltage, low capacity systems and high capacity, low voltage systems. This design is particularly attractive for large arrays of batteries with multiple series/parallel arrangements for systems such as SSF or other future large space-based systems. The use of SPV batteries would allow increased overall power system flexibility as compared to traditional multicell IPV battery designs.

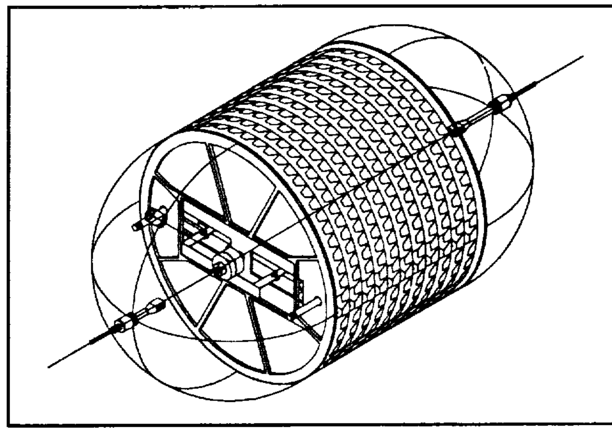

Fig. 7 Single Pressure Vessel Battery

Dependent Pressure Vessel (DPV) Technology

Dependent pressure vessel 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 to 30% compared to a conventional IPV battery design. This design was first reported by Eagle-Picher in 1974 (4) and new applications such as large communications satellites and the SSF program have renewed interest in this design. The battery concept is illustrated in Figure 8. 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.

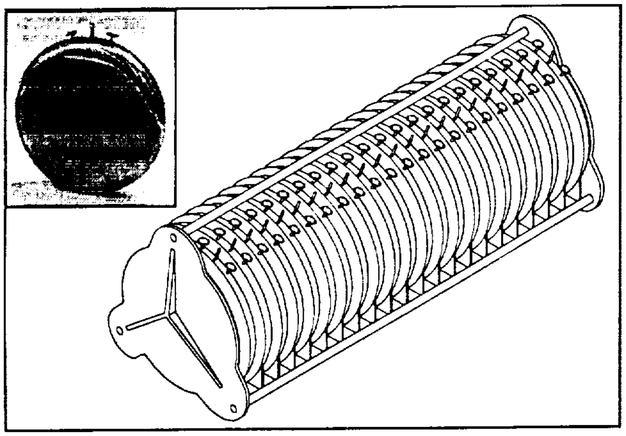

Figure 8 — Ni-H_2 DPV Battery Design

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 Figure 9. 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

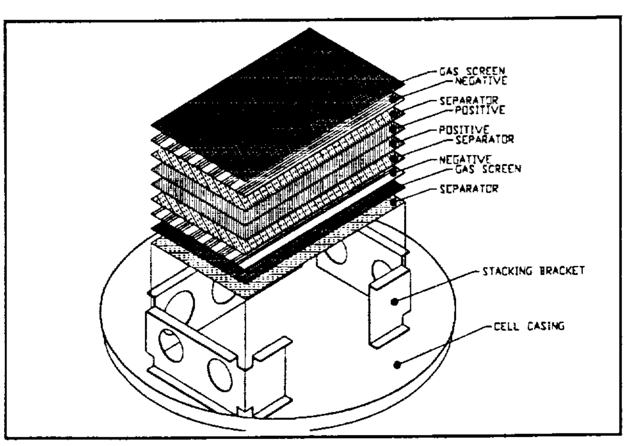

Figure 9 — Internal DPV Cell Stack Construction

thermal management. DPV cells of a 50 Ahr design have been built and tested yielding more than 70 Whr/kg. This is the highest specific energy reported for space NiH_2 cells to date.

Low-Pressure Nickel-Hydrogen Technology

There has been a growing interest recently in several low pressure NiH_2 battery designs, including nickel-metal hydride (NiMH) batteries. The NiMH battery is electrochemically identical with the nickel-hydrogen system except atomic hydrogen is stored as a solid metallic hydride rather than as a molecular gas. Eagle-Picher began working with low pressure NiH_2 battery systems in the early 1970's in connection with space battery R&D programs. Comsat Laboratories also investigated this technology (5). The interest was to increase the volumetric efficiency (energy density) of the NiH_2 battery by lowering the maximum operating pressure (MOP). 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 versus 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 (6). 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-type nickel-hydrogen 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. Metal hydride cells are being manufactured and tested in a variety of designs and capacity ranges. These include both nickel and silver cathode cells. Hermetically sealed 10 Ahr aerospace cells have completed more than 2,000 LEO cycles at 45% DOD and 4 Ahr aerospace design cells have completed more than 8,000 cycles at 47% DOD. Low pressure 200 Ahr 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 300V, 40 Ahr nickel-metal hydride battery was recently supplied to Michigan State University 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.

Cell and Battery Automated Test Equipment

The Electronics Systems Group, within the Advanced Systems Operation, has developed extensive hardware and software capabilities in the area of cell and battery level automated test equipment (ATE). This capability has been developed and continuously upgraded over a period of several years in tandem with the development of spaceflight qualified battery systems, such as the nickel-hydrogen battery. Current nickel-hydrogen test system capability at Eagle-Picher includes the capacity of simultaneously testing more than 1,000 individual nickel-hydrogen cells and 15 fully integrated spacecraft batteries. This capability is being significantly increased in the near future to keep pace with current and upcoming flight programs. The specialized requirements, extremely tight tolerances and strict system controls dictated by the space industry are not addressed by commercially available test systems. The absence of appropriate computer-based hardware systems and associated software forced Eagle-Picher to develop this capability in-house. As a result, this system level battery test expertise has developed into an independent commercial operation directed at the highly specialized aerospace battery market. Specialized battery test systems are currently being supplied on a custom basis to the industry. These Battery Evaluation, Test and Analysis (BETA) systems can be configured for a variety of specific test requirements.

The core BETA test system is based on Hewlett-Packard computer and data acquisition/control (DAC) hardware. A typical BETA test system is shown in Figure 10. The specific hardware configuration and supporting software is developed in-house to meet the specific requirements of the application. Eagle-Picher is a licensed "Channel Partner" of Hewlett-Packard through the formation of a value-added business partnership. This collaboration allows Eagle-Picher to provide highly specialized advanced battery testing capabilities for military, aerospace, industrial and premium commercial applications. Statistical Process Control (SPC) options can be incorporated into the BETA test system for additional battery test and analysis capabilities. Test systems can be configured for variable levels of operator independence. Some specialized aerospace battery testing requires intensive personnel monitoring for a variety of purposes. In this instance, the BETA system is configured primarily for data acquisition and can be programmed to provide appropriate operator prompts where required. The BETA system can not only prompt specific operator interaction but also monitor and verify that the proper interaction has occurred. Various alarm capability can be included, as well. This minimizes the potential operator-incurred test faults that can

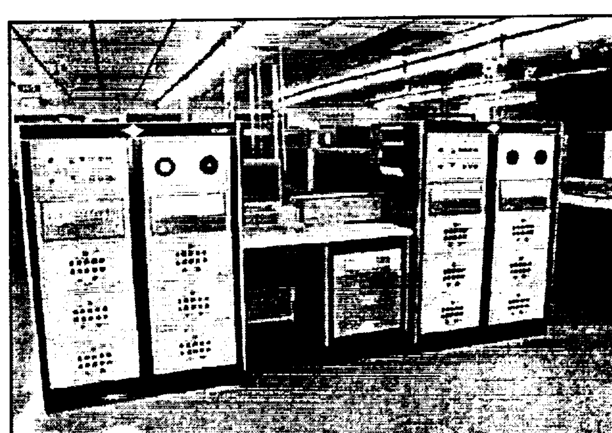

Figure 10 — Typical EPI BETA Test System

occur during 24-hour per day, 7-day per week operation and testing schedules, which are common in the aerospace industry.

Conclusions

Eagle-Picher is currently working in a number of areas to improve and further develop the nickel-hydrogen battery system. These include sub-cell 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 the Space Station Freedom (SSF). 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 R&D will be continued in support of future flight programs as varied as SSF and "smallsat" programs. Electrical, mechanical and thermal aspects of battery design will continue to evolve. Battery performance, including useful life and charge/discharge cycle life, must also be maximized. These power systems must provide the high degree of safety and reliability required by manned space programs and large space-based orbital systems. Advanced nickel-hydrogen batteries will continue to fulfill these demanding requirements well into the next century.

References

(1) Coates, D.; et.al. Proc. 35th Intl. Pow. Srcs. Symp. 1992 pp.164-167.

(2) Daman, M.: et.al. Proc. 27th IECEC 1992 pp.483-486.

(3) Grindstaff, B., Coates, D.; Proc. 28th IECEC 1993.

(4) Miller, L. Proc. 26th Intl. Pow. Srcs. Symp. 1974 pp.21-24.

(5) Earl, M., Dunlop, J., Proc. 26th Intl. Pow. Srcs. Symp. 1974 pp.24-27.

(6) Coates, D. Proc. 27th Intersoc. Ener. Con. Eng. Conf. (IECEC) 1992 pp.165-170.