NEW DEVELOPMENTS IN NICKEL-HYDROGEN DEPENDENT PRESSURE VESSEL (DPV) CELL AND BATTERY DESIGN

Dwight B. Caldwell, Chris L. Fox, and Lee E. Miller
Technologies Division, Eagle-Picher Industries, Inc.
P.O. Box 47
Joplin, MO 64802
(417) 623-8333

Abstract

The Dependent Pressure Vessel (DPV) Nickel-Hydrogen (NiH2) design is being developed by Eagle-Picher Industries, Inc. (EPI) as an advanced battery for military and commercial, aerospace and terrestrial applications. The DPV cell design offers high specific energy and energy density as well as reduced cost, while retaining the established Individual Pressure Vessel (IPV) technology flight heritage and database. This advanced DPV design also offers a more efficient mechanical, electrical and thermal cell and battery configuration and a reduced parts count. The DPV battery design promotes compact, minimum volume packaging and weight efficiency, and delivers cost and weight savings with minimal design risks.

INTRODUCTION

The NiH2 battery has a number of unique features and advantages which are superior to other battery systems. Hydrogen provides a very lightweight, efficient energy storage material. Due to the unique electrochemistry, the NiH2 system is an inherently fault-tolerant design with excellent overcharge, overdischarge and deep-cycle capabilities. The battery is hermetically sealed and truly maintenance-free. The internal hydrogen pressure is a direct linear function of battery state-of-charge (SOC) and thereby provides a simple and reliable method of determining the SOC of the battery. Also, the NiH2 battery contains no toxic materials such as lead, cadmium or mercury and can be readily recycled. Projected battery costs are directly comparable with other nickel battery systems and competitive with lead-based batteries on a life-cycle cost basis.

The NiH2 battery is also the most reliable aerospace battery system available. Batteries have completed more than 180,000,000 cell-hours in orbital spacecraft operation. NiH2 batteries offer the longest cycle life of any battery system. Batteries on test have completed more than 115,000 charge/discharge cycles. Batteries have operated in Geostationary-Earth-Orbit (GEO) for more than 15 years. NiH2 batteries have low internal impedance and excellent high rate and pulse discharge capability. The many advantages and features of the NiH2 battery are the reason the system has been heavily developed for advanced critical applications such as earth-orbital spacecraft. Many of these same features and advantages are also equally desirable in terrestrial applications.

Several distinct NiH2 cell and battery designs are currently in production and under development for a wide variety of applications. These include traditional aerospace applications such as earth-orbital communications satellites, as well as terrestrial uses such as telecommunications equipment, utility load leveling and remote location power systems. Traditional IPV NiH2 technology has been supplemented by newer Common Pressure Vessel (CPV) cell designs and other cell and battery designs such as the Single Pressure Vessel (SPV) and Low Pressure Vessel (LPV) battery. The DPV battery design is the next step in the continued development and evolution of the NiH2 battery system.

DPV CELL DESIGN

A unique feature of the DPV cell design is the prismatic (rectangular) electrode stack. This stacking arrangement is more efficient than the standard cylindrical electrode stack. Also, rectangular cell components produce less waste when cut to size from the stock material which is also rectangular. Die-punching circular electrode, separator and gas screen material leaves a significant amount of unusable scrap material which must be added to the cost of the cell. The electrode stack is the electrochemically active part of the cell. It contains nickel electrodes and hydrogen electrodes interspersed with an absorbent separator material. A back-to-back stacking arrangement is used as shown in Figure 1. This stacking arrangement provides that each nickel electrode is opposed by the catalyst side of a hydrogen electrode. This puts the hydrophobic sides of the two adjacent hydrogen electrodes facing towards each other. A gas spacer is inserted in order to facilitate hydrogen gas diffusion into and away from the hydrogen electrode during charge and discharge (Francisco 1995).

The pressure vessel geometry is another unique feature of the DPV cell. The cell case consists of two nearly identical, seamless halves. One of the halves is fitted with cell terminal bosses attached by a laser weld. The bosses are offset 15° from a central axis and elevated 30° from the plane of the girth weld as shown in the cell outline drawing in Figure 2. The DPV cell is termed "dependent" because the cell geometry requires the cell to be supported by adjacent cells or endplates in order to contain the hydrogen pressure developed inside the cell during charging. Since the pressure vessel is not required to support the full internal cell pressure, the pressure vessel can be made with a thinner wall thickness and a corresponding weight savings. The rounded edge of the pressure vessel has a relatively small radius, which is very efficient for pressure containment with minimum pressure vessel material (Coates 1995).

A metal stacking bracket holds the electrode stack in place within the cell pressure vessel. Insulation material electrically isolates the electrode stack from the pressure vessel and the stacking bracket. The electrical tabs from the electrodes emerge through a window in the stacking bracket. The lead bundles are stress relieved by introducing an "S" into the leads. This prevents mechanical stress, such as launch vibration, from being transmitted into the electrode/tab connection. Several options are available for the cell terminal/intercell connector. These are based on two types, either mechanical, such as a screw-type connection, or a solder connection between the cell terminal and intercell connector.

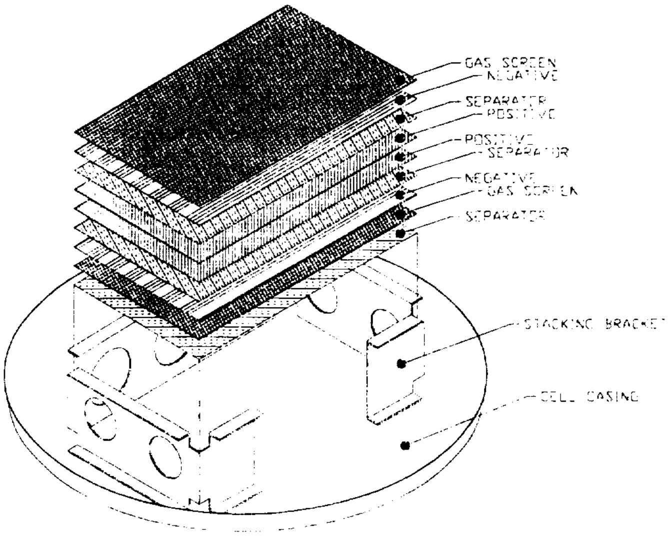

FIGURE 1. DPV Cell Stack.

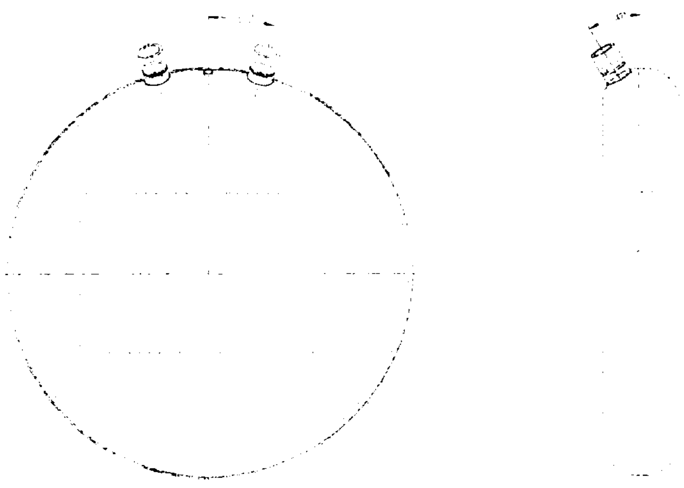

FIGURE 2. Cell Outline Drawing.

CELL DEVELOPMENT STATUS

EPI initial DPV cell development efforts began in 1973 and were first reported in the "26th Power Sources Symposium", 29-30 and 1-2 May, 1974. This effort resulted in the production of a 50 ampere-hour (Ah) rated cell lot. Although subsequent electrical testing was very successful, industry interest at that time continued to be focused in the IPV battery area and further development efforts were discontinued.

In our current development program, EPI has so far produced DPV cells of two sizes: 40 and 60 Ah cells. The first 40 Ah cells were activated in December of 1995. Figure 3 is a design summary of the 40 Ah cell. The stack contains eight positive and negative electrode pairs. Cell testing and cycling commenced in January, 1996, and the cells have consistently produced over 120% of rated capacity at 10°C. Three 40 Ah cells are currently in life-testing on a Low-Earth-Orbit (LEO) program and are doing well. Figure 4 shows charge/discharge data from that ongoing test.

Production of the 60 Ah cell was initiated in January using the same 7.75" diameter pressure vessel as the 40 Ah cell. Figure 5 is a design summary of the 60 Ah cell. Compared with the 40 Ah cell, the 60 Ah stack is longer, wider and thicker, and contains nine positive and negative electrode pairs. Similar to the 40 Ah cells during cell testing/cycling, the 60 Ah cells have consistently produced over 120% of rated capacity at 10°C. We have just commenced life-testing three 60 Ah cells in a LEO regime and will soon place three more in a GEO test profile.

FIGURE 3. 40 AH Cell Design Summary.

Cell Type	*RNHD 40-1*
Nominal Voltage	*1.25 Volts*
Rated Capacity	*40 .0 Ampere-hours*
Actual Capacity	*49.2 Ampere-hours*
No. of Positive Electrodes	*16*
Separator	*Zircar*
Weight	*1235 g.*
Specific Energy	*49.8 WHR/kg*
Diameter	*19.68 cm*
Height	*3.81 cm*
Vessel Wall Thickness	*0.038 cm*
MEOP	*500 psig*
Vessel Safety Factor	*> 2.0 X MEOP*

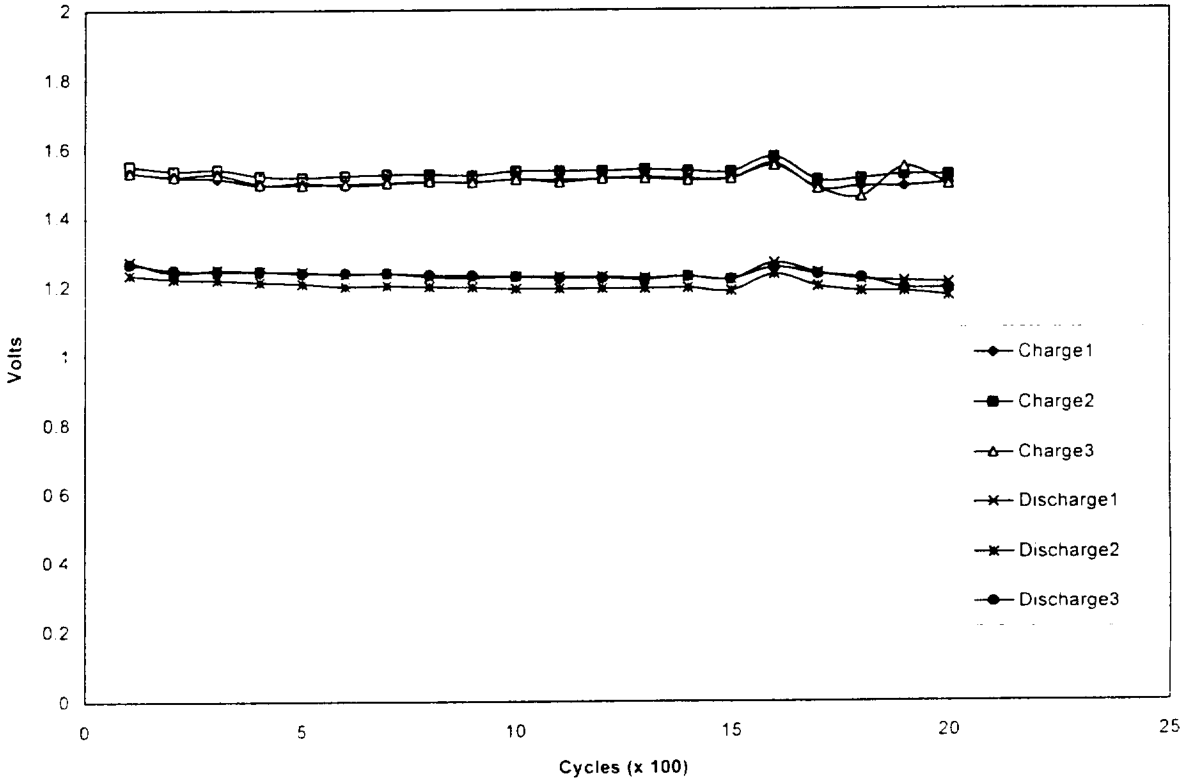

FIGURE 4. 40 AH Life Test Data Chart.

The success of this DPV development program has given EPI invaluable experience and provides a solid foundation to move ahead with further research into DPV applications examining both larger and smaller capacity cells and batteries for a variety of uses.

EPI is now under contract to produce 90 Ah DPV cells. Few changes are anticipated in the design approach for these cells as compared to the development cells described above. Briefly, these changes include: sizing the pressure vessel for a 700 psi maximum expected operating pressure (MEOP) and sizing the stack for the rated 90 Ah capacity. Figure 6 is the preliminary design summary of the 90 Ah cell.

DPV BATTERY DESIGN

The DPV cell is basically an IPV type design in that each pressure vessel contains one cell, and therefore delivers 1.25 VDC. Most applications require voltages which necessitate the connection of multiple cells in series. This is a simple, straightforward concept, however, it is a critical aspect of design for high reliability spacecraft applications. The cells must be packaged into batteries or battery modules which will meet the performance and reliability requirements of the spacecraft. This includes the mechanical, electrical and thermal design of the battery.

Mechanical Design

The mechanical design of the battery addresses primarily the physical aspects of packaging. The cells must be bound together into physically manageable units for handling and spacecraft integration. In fact, the mechanical design is primarily defined by how the battery must physically fit into the spacecraft. Standard practice for battery integration is to mount the battery to a baseplate which is not only the mechanical interface to the spacecraft but also the thermal interface as well. The dimensions of the baseplate are defined by the physical footprint of the battery, the space/volume available in the spacecraft structure and the thermal requirements of the battery/spacecraft interface. The spacecraft configuration must be considered in designing the battery and vice versa.

FIGURE 5. 60 AH Cell Design Summary.

Cell Type	*RNHD 60-1*
Nominal Voltage	*1.25 Volts*
Rated Capacity	*60 .0 Ampere-hours*
Actual Capacity	*73.0 Ampere-hours*
No. of Positive Electrodes	*18*
Separator	*Zircar*
Weight	*1510 g.*
Specific Energy	*60.43 WHR/kg*
Diameter	*19.68 cm*
Height	*3.81 cm*
Vessel Wall Thickness	*0.038 cm*
MEOP	*800 psig*
Vessel Safety Factor	*> 2.0 X MEOP*

FIGURE 6. 90 AH Cell Design Summary.

Cell Type	*RNHD 90-1*
Nominal Voltage	*1.25 Volts*
Rated Capacity	*90.0 Ampere-hours*
Predicted Capacity	*108 Ampere-hours*
No. of Positive Electrodes	*18*
Separator	*Zircar*
Weight	*2200 g. (Est.)*
Specific Energy	*61.4 WHR/kg*
Diameter	*24.41 cm*
Height	*3.81 cm*
Vessel Wall Thickness	*0.038 cm*
MEOP	*700 psig*
Vessel Safety Factor	*>2.0 X MEOP*

One of the advantages of the DPV cell design is that the mechanical battery assembly concept is much simpler than with standard cylindrical IPV cells. The DPV cells are designed to be sandwiched between two endplates, which defines the basic packaging concept for the battery design. It is simple, efficient, easily assembled and requires few parts. A multicell IPV NiH_2 battery requires additional parts, such as cell mounting sleeves, which mean additional weight and cost, and additional handling and assembly work. The DPV battery packaging concept has an established heritage in the aerospace industry. The endplate/connecting rod battery design has been used with nickel-cadmium (NiCd) and silver-zinc (AgZn) cells for spacecraft applications for many years. Several battery assembly possibilities exist, which make overall DPV battery design modular and flexible. This makes the DPV battery adaptable for a variety of spacecraft designs. There is a significant advantage of the endplate battery design because the percentage of the total battery weight contributed by the battery packaging components is smaller than with the standard IPV battery.The DPV battery minimizes battery level components (Coates 1995).

The preferred (with respect to optimizing specific energy/energy density) DPV battery assembly presents the cells in a single row sandwiched between two endplates as shown in Figure 7. The endplates are tied together with threaded connecting rods. Mechanical support of the cells is provided by the endplates to support the internal hydrogen pressure developed during charging. Another basic design is shown in Figure 8, where the cells are packaged into two rows. Wiring and connectors are omitted from the figure for clarity. The advantage of two rows of cells is that the overall battery is somewhat more compact. A typical 22 cell, 28 VDC, 60 Ah battery, for example, would be approximately 22 cm wide and approximately 90 cm long for a single row of cells. With two rows of cells, the same battery would be approximately 41 cm wide and 48 cm long. The battery with two rows of cells provides a more nearly square package. A disadvantage is that the larger endplates contribute slightly more weight to the overall battery package. Therefore the single row battery will have slightly higher energy density, but the double row battery will typically be easier to integrate into a spacecraft.

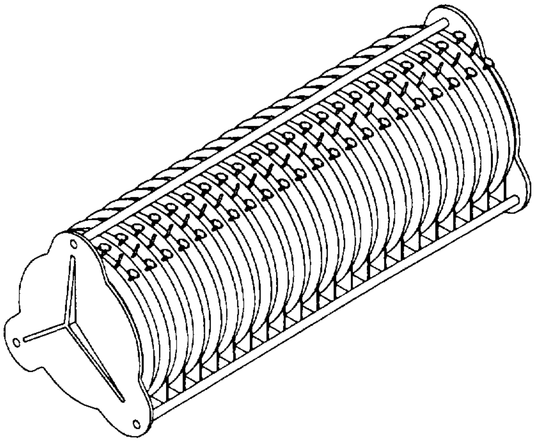

FIGURE 7. Single Row DPV Battery Design.

Electrical Design

The electrical design includes aspects and components such as intercell connection, conductor IR voltage losses, the battery electrical interface, connectors, battery monitoring, charge controllers and battery electronics such as strain gauges, strain gauge amplifiers, heaters, heater controllers, cell bypass diodes, cell voltage monitoring, current monitoring, temperature monitoring and others, depending on the specific battery design, spacecraft design and interface requirements. The battery electrical interface includes integration into the spacecraft and interface with additional batteries or battery modules on the spacecraft. Communications satellites typically carry two non-redundant batteries. Having two separate batteries, rather than a single larger one, aids in balancing the battery mass in the spacecraft and also eases the thermal interface requirements. In contrast, some small satellites may contain only a few cells wired in series with no battery electronics. The batteries have to be adaptable to a wide range of spacecraft designs, power levels and electrical requirements.

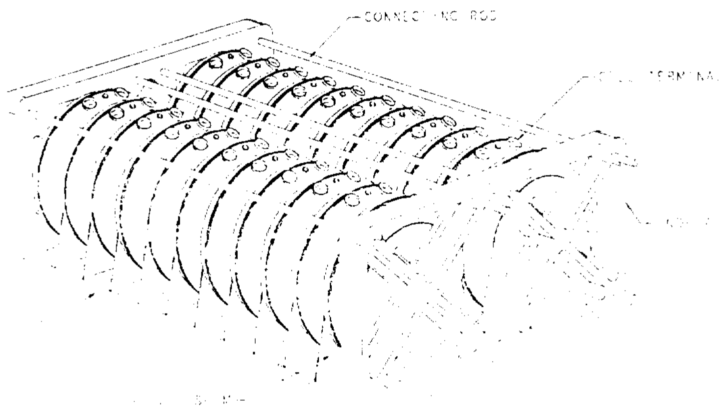

FIGURE 8. Double Row DPV Battery Design.

The battery cells are series-connected in the battery, observing cell polarity. The positive terminal of one cell is connected to the negative terminal of the next, and so on. One end of the cell string will have a remaining positive terminal open and the other end will have an unused negative cell terminal. These cell terminals are connected to the battery interface connector and provide the power connections to the spacecraft. Silver foil, nickel foil or spacecraft-rated wiring is used as the intercell connectors. It depends primarily on the length required between cell terminals and the allowable voltage losses. Batteries are generally designed to minimize the length of the intercell connection. This is done in IPV batteries by inverting every other cell such that the positive and negative cell terminals alternate at the top and bottom of the battery. This eliminates having to connect the top of one cell to the bottom of another. The DPV battery is even more efficient by aligning all of the cell terminals along a central axis running the length of the battery. Or, in the case of the dual cell, side by side battery design, two rows of cell terminals along the length of the battery (Klein 1993). Foil bus bar type intercell connectors are the most efficient method for very short connections such as in the DPV battery. Silver or nickel foil would be used, based primarily on cost considerations. The exposed portion of the intercell connector between cell terminals can be insulated with space-rated materials, though this is not typically required. The intercell connector is mechanically connected to the cell terminal. Wire, or redundant wires, are generally used for the slightly longer connection between the two cell terminals and the battery connectors. The wire is mechanically connected to the cell terminals and soldered into the battery connector.

Strain gauge circuitry is a critical item. This component measures the microflex of the pressure vessel produced by internal pressure changes. A four bridge, active circuit is used. Two gauges are active and two gauges are null indicators. The strain gauge must be calibrated after installation on the specific cell on which it will be operated. This is done after the cell closure girth weld, but before electrolyte activation, by pressurizing the cell case with helium gas. Since the strain gauge bridge is an active circuit, an excitation voltage must be provided through the battery electronics and interface. The output signal is small, so an amplification circuit is typically supplied on the battery to boost the signal to an adequate level for spacecraft telemetry. The strain gauge output signal provides a direct indication of the cell internal pressure, and therefore the cell state-of-charge. Strain gauges are typically included on three cells in the battery for comparison and redundancy purposes. Cell heaters are usually supplied in order to closely control the battery temperature during all phases of operation. Some batteries are supplied with on-board heater controller circuitry. Heat is removed by thermal fins which contact the battery baseplate/thermal radiator. Battery temperature is monitored using thermistors. Generally, three are mounted at different locations in the battery. This provides redundancy and a measure of temperature uniformity across the battery. Battery current sensing is provided by an on-board current sensing element, usually of the non-contact, inductive type. All battery monitoring information such as voltage, current, temperature and strain gauge output are supplied to the spacecraft telemetry system through the battery electrical interface connector.

Thermal Design

Temperature control is an important aspect of battery design and spacecraft integration. Cell heaters are typically supplied to help regulate cell temperature during orbital operation. The battery is also usually mounted to a baseplate to remove excess heat when required. This baseplate normally mounts directly to a bulkhead in the spacecraft and radiates excess battery heat into space. A considerable amount of thermal analysis, calorimetry testing and thermal modeling has been done with the NiH2 system. Basically, the cell is endothermic during the bulk of charging until near the end-of-charge. At this point, as the cell goes into overcharge, oxygen gas is evolved at the nickel electrode. This oxygen gas is being generated in the presence of large excess of hydrogen gas and in the presence of a good catalyst (the hydrogen electrode). Reactions now occuring, including the reaction of hydrogen and oxygen gas, are exothermic, so excess heat is generated by the cell which must be removed. The NiH2 cell is capable of accepting extreme amounts of overcharge if this heat is removed. Even so, the cell temperature begins to rise near full state-of-charge and provides an indication, along with the pressure, that full charge has been achieved.

In an IPV battery, each cell is mounted in a thermal sleeve which serves as a heat sink to conduct excess heat from the cell into the battery baseplate. This is fairly efficient thermally, but the sleeve adds weight and cost to the battery. The approach to thermal design in the DPV battery is more direct and cost and weight efficient. A thin aluminum thermal shim is inserted between each pair of adjacent cells so each cell has a shim contacting both flat sides of the pressure vessel. The shim is electrically insulated from, and thermally coupled to, the metal pressure vessel by a thin layer of electrically insulating but thermally conductive material. The material is space-rated and is currently used for the same purpose in IPV batteries. The shim provides a large cross-sectional area through which heat can be removed from the internal electrode stack. The electrode stack has a large thermal cross-section with respect to the pressure vessel because the stack directly contacts the flat pressure vessel wall. In the IPV cell the electrode stack is perpendicular to the cylindrical pressure vessel wall with no direct contact between the electrode stack and the pressure vessel. Heat can only be rejected by the electrode stack across a narrow hydrogen gap between the electrode stack and the pressure vessel wall. The DPV provides a more direct thermal path for heat rejection by the cell (Coates 1995).

CONCLUSIONS

The NiH2 electrochemical energy storage system provides the best reliability, performance and cycle life available in an aerospace qualified battery system. The DPV design offers an important advance in this critical aerospace battery technology and will provide a substantial improvement in the mass and volume performance of the NiH2 battery system. While DPV designs are in the preliminary stages and testing and qualification is still required prior to spaceflight applications, DPV development programs are moving forward rapidly, and the cell and battery designs show great promise for military, scientific and commercial, aerospace and terrestrial uses.

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