POWERING SMALL SATELLITES WITH ADVANCED NiH_2 DEPENDENT PRESSURE VESSEL (DPV) BATTERIES

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Abstract

The Dependent Pressure Vessel (DPV) nickel-hydrogen (NiH_2) design is being developed by Eagle-Picher Industries, Inc. (EPI), as a spacecraft battery for both large and small, military and commercial satellites. The DPV cell design offers high specific energy, energy density and reduced cost, while retaining the established IPV technology flight heritage and database. This advanced design also offers a more efficient mechanical, electrical and thermal cell and battery configuration and a reduced parts count. The geometry of the DPV cell promotes compact, minimum volume packaging and battery weight efficiency. The DPV battery design offers significant cost and weight savings potential while providing minimal design risks. In this presentation, we will discuss design features and present test data from existing development cells and address issues relevant to design and production of a DPV battery suitable for a small satellite application which would retain the energy increases and weight and cost reductions proposed. With the DPV, EPI has combined the unique features and significant advantages of NiH_2 electrochemistry with the simplicity and extensive design heritage of the NiCd battery system.

Introduction

The NiH_2 battery has a number of unique features and advantages which are superior to other battery systems. The battery has virtually unlimited overcharge and overdischarge capability if the resultant heat from the oxygen/hydrogen gas recombination reaction is adequately removed. Since hydrogen gas is one of the battery reactants, the internal pressure in the battery provides a reliable measurement of battery state-of-charge. The internal pressure can be readily monitored remotely by a pressure transducer or strain gauge. The NiH_2 battery is also the most reliable aerospace battery system available. Batteries have completed more than 150,000,000 cell-hours in orbital spacecraft operation. NiH_2 batteries offer the longest cycle life of any battery system. Batteries on test have completed more than 100,000 charge/discharge cycles. Batteries have operated in geostationary-earth-orbit for more than 15 years. NiH_2 batteries have low internal impedance and excellent high rate and pulse discharge capability. The many advantages and features of the NiH_2 battery are the reason the system has been heavily developed for critical applications such as earth-orbital spacecraft. Many of these same features and advantages are also equally desirable in terrestrial (e.g., commercial) battery applications.

Several distinct NiH_2 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 individual pressure vessel (IPV) NiH_2 technology has been supplemented with the common pressure vessel (CPV), the single pressure vessel (SPV) and the low pressure vessel (LPV) battery. The dependent pressure vessel (DPV) battery design is the next step in the continued development and evolution of the NiH_2 battery system.

DPV Cell Design

Literature on DPV cell and battery design is not plentiful, but there have been a few notable sources. References 1 and 2 discuss work done using advanced or alternative component materials, and reference 3 specifically discusses a SmallSat DPV application. A unique feature of the DPV cell design is the prismatic (rectangular) electrode stack. The DPV cell/electrode stacking concept is shown in Figure 1. This pressure vessel geometry is another unique feature of the DPV cell. The flat sides of the pressure vessel are intended to be supported by the battery endplates in the final assembly. The DPV cell is termed "dependent" because the cell geometry requires the cell to be externally supported in order to contain the hydrogen pressure developed inside the cell

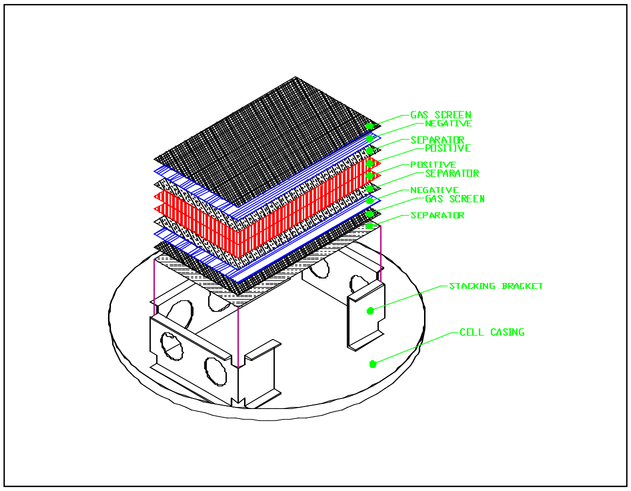

Fig. 1 DPV Cell Stack

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.

The pressure vessel consists of two nearly identical, seamless halves. One of the pressure vessel halves is fitted with cell terminal bosses which are attached to the pressure vessel by a laser weld. The bosses are offset 15° from a central axis and are elevated 30° from the plane of the girth weld as shown in the cell outline drawing in Figure 2.

The electrode stack contains the electrochemically active part of the cell. It consists of 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 arrangement provides that each

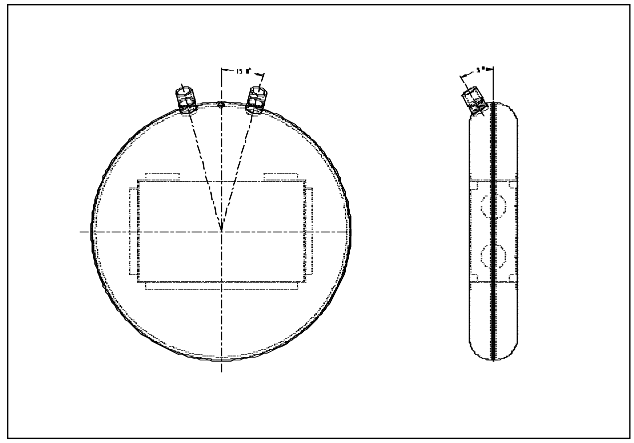

Fig. 2 Cell Outline Drawing

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.

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 within the electrode stack emerge through a window in the stacking bracket. The lead bundles are stress relieved by introducing an "S" loop 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.

Cell Development Status

Our initial development efforts began in 1973 and were first reported in the "26th Power Sources Symposium", 29-30 April and 1-2 May, 1974. This effort resulted in the production of a 50Ah 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 activities were discontinued.

In our current development program EPI has so far produced DPV cells of two sizes: 40 and 60Ah cells. The first 40Ah cells were activated in December of 1995. Figure 3 is a design summary of the 40Ah 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 40Ah cells are currently in life testing on a LEO program and are doing well. Figure 4 shows charge/discharge data from that test.

• Cell Type	RNHD40-1
• 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 W-Hr/kg
• Diameter	7.75"
• Height	15.0"
• Vessel Wall Thickness	0.015"
• MEOP	500 psig
• Vessel Safety Factor	>2.0 X MEOP

Fig. 3 40 AH Cell Design Summary

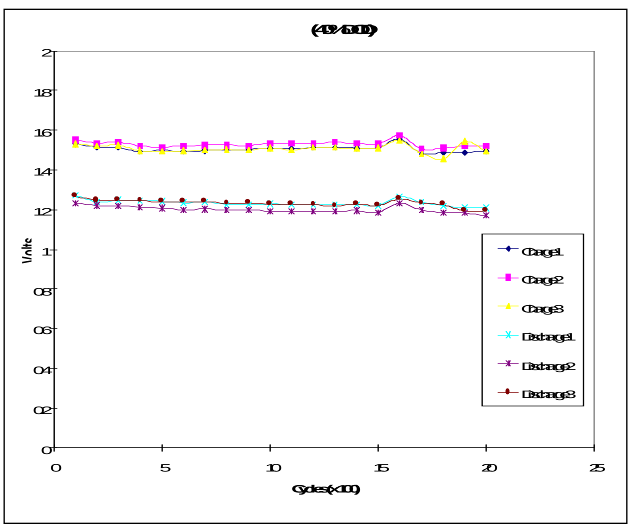

Fig. 4 40 AH Life Test Data

Production of the 60Ah cell was initiated in January using the same 7.75" diameter pressure vessel as the 40Ah cell. Figure 5 is a design summary of the 60Ah cell. Compared with the 40 Ah cell, the 60Ah stack is longer, wider and thicker,

• Cell Type	RNHD60-1
• 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 W-Hr/kg
• Diameter	7.75"
• Height	15.0"
• Vessel Wall Thickness	0.015"
• MEOP	800 psig
• Vessel Safety Factor	>2.0 X MEOP

Fig. 5 60 AH Cell Design Summary

and contains nine positive and negative electrode pairs. Like the 40Ah cells during cell testing/cycling, the 60Ah cells have consistently produced over 120% of rated capacity at 10°C. We have just commenced life testing three 60Ah cells in a LEO regime and will soon place three more in a GEO test profile.

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 all sizes of spacecraft.

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 40Ah and 60 Ah 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 90Ah capacity. Figure 6 is a preliminary design summary of the 90Ah cell.

SmallSat DPV Cell Design

Using the experience gathered thus far in DPV system design and production, EPI is now engaged in DPV applications directed toward the increasing number of small spacecraft (SmallSats). One of these cell designs has a rated capacity of 15Ah. The SmallSat 15Ah DPV cell design summary is presented in Figure 7. As shown, the diameter of the 15Ah cell is approximately 5.5" and the stack would contain seven

Cell Type	RNHD90-1
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	9.6"
Height	15.0"
Vessel Wall Thickness	0.015"
MEOP	700 psig
Vessel Safety Factor	>2.0 X MEOP

Fig. 6 90 AH Cell Design Summary

Cell Type	RNHD15-1
Nominal Voltage	1.25 Volts
Rated Capacity	15.0 Ampere-hours
Predicted Capacity	18.0 Ampere-hours (Est.)
No. of Positive Electrodes	14
Separator	Zircar
Weight	485 g (Est.)
Specific Energy	46.2 WHR/kg (Est.)
Diameter	5.5"
Height	11.2"
Vessel Wall Thickness	0.015"
MEOP	500 psig
Vessel Safety Factor	>2.0 X MEOP

Fig. 7 15 AH Cell Design Summary

positive and negative electrode pairs. Additional component level development technology is also being directed toward SmallSat applications.

Predicted SmallSat DPV cell design values shown are generated by a NiH_2 cell/battery prediction program which calculates the characteristics of the subject cell/battery. As with the previous DPV cells developed by EPI, the SmallSat DPV cell design would retain the extensive NiH_2 flight heritage and offer similar energy increases and weight and cost savings as proposed for higher capacity cells.

DPV Battery Design

The DPV cell is basically an IPV type design in that each pressure vessel contains only one cell, and therefore delivers only 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.

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, both large and small. 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.

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 8. 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 and prevent the flat sides of the cells from deforming. Another basic design is shown in Figure 9, where the cells are packaged into two rows, each containing an equal number of cells. 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.

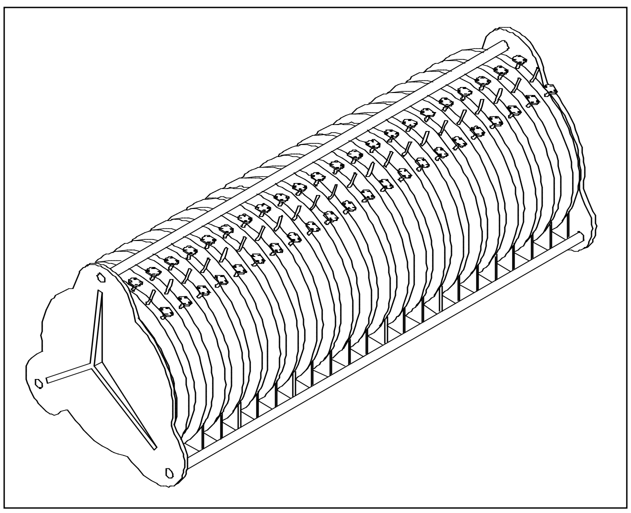

Fig. 8 Single Row DPV Battery Design

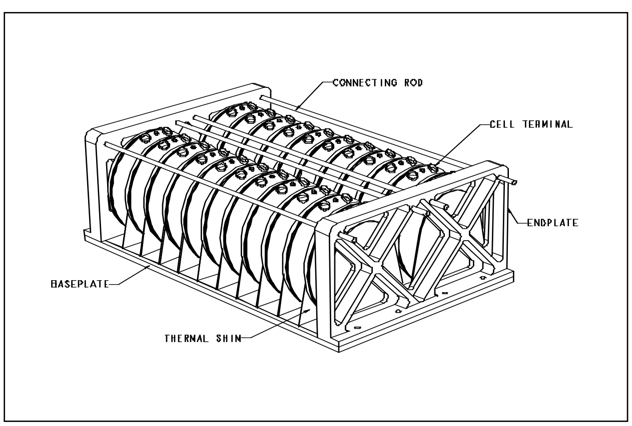

Fig. 9 Double Row DPV Battery Design

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.

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. Foil bus bar type intercell connectors are the most efficient method for very short connections such as in the DPV battery. Silver or nickel 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 pressure vessel 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 may also be mounted to a baseplate to remove excess heat when required. The battery baseplate usually 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 NiH_2 system. Basically, the cell is endothermic during the major, initial portion of a charge. Then after the thermal neutral voltage is exceeded, the remainder of the charge cycle is exothermic. 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). The reaction of hydrogen and oxygen gas is exothermic, so excess heat is generated by the cell which must be removed. The NiH_2 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 thermal shim is inserted between each pair of adjacent cells so that each cell has a thermal shim contacting both flat sides of the pressure vessel. The shim is made from aluminum, which is a very thermally conductive material. 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. Each shim has a flange which contacts the battery baseplate. This provides a direct thermal path from the cell pressure vessel to the baseplate, which acts as a heatsink. The baseplate would either contact a thermal radiator in the spacecraft or would act as a radiator itself. A thermal shim directly contacts the large flat surface of the pressure vessel on both sides of each cell. This 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 much more direct thermal path for heat rejection by the cell.

SmallSat Battery Design

As discussed above, the mechanical, electrical and thermal advantages of a NiH_2 DPV battery are numerous and the disadvantages few. The goal of the EPI DPV development effort is to place the DPV technology into a battery production program. One approach to this is the production of a SmallSat DPV battery suitable for one or more of the small spacecraft programs which are growing at an accelerated pace.

A preliminary version of the SmallSat 15Ah DPV cell was defined previously in this paper. The general requirements and considerations for design of a DPV battery were discussed above. A preliminary design for a SmallSat 15 Ah DPV battery can be outlined now. For example, a single row, 28 VDC, 15 Ah battery package consisting of 22 cells, as shown in Figure 8, would measure approximately 17 centimeters (cm) in height and 70 cm long. For the same battery with two rows of cells, as shown in Figure 9, these dimensions would be approximately 35 cm wide and 36cm 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.

Conclusions

The nickel-hydrogen electrochemical energy storage system provides the best reliability, performance and cycle life available in an aerospace qualified battery system. The DPV design provides 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 and commercial satellites, both large and small.

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Author's Biography

Mr. Caldwell was born and raised in Memphis, Tennessee. In 1962, he entered the United States Naval Academy in Annapolis, MD, graduating in 1966 with a BS in engineering. After graduation, Ensign Caldwell commenced Naval flight training. He was designated a Naval Aviator in 1968 and spent most of the next eight years serving as a carrier-based fighter/attack pilot. During this period he also attended graduate school in Monterey, CA, receiving his MS in meteorology. In 1976, Mr. Caldwell left active duty and began work with McDonnell-Douglas Corporation. He spent fifteen years with MDC in various capacities such as design, operations analysis, marketing and program management. Mr. Caldwell is currently with Eagle-Picher Industries, Inc. in Joplin, MO, working primarily on advanced DPV and SPV NiH_2 battery development programs.