BIPOLAR NICKEL-HYDROGEN BATTERIES FOR AEROSPACE APPLICATIONS

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INTRODUCTION

Space platforms and many other future spacecraft are expected to operate at electrical power levels of 20 to 125 kW and beyond. To reduce distribution losses, the electrical power systems are likely to operate at higher bus voltages (150-250V) than commonly used today. Space qualified energy storage systems compatible with these high-power and high-voltage requirements do not exist and must be developed. An additional desirable characteristic of such systems is that they should lend themselves to rather straightforward installation and integration in orbit.

One energy storage system which has been identified as an excellent candidate for these applications is the bipolar nickel-hydrogen battery. Studies aimed at identifying design approaches for this battery system have been conducted by several organizations. Ford Aerospace & Communications Corporation and Yardney Electric Corporation have designed a bipolar nickel-hydrogen battery which effectively addresses all key requirements, including long-term reliability and low mass. In 1984 Ford Aerospace and Yardney will start development of this battery under NASA Lewis sponsorship. This paper discusses this design in the context of system requirements and nickel-hydrogen ($Ni-H_2$) battery technology in general.

SYSTEM DESIGN OBJECTIVES

To achieve the ultimate goal of an aerospace application of a bipolar $Ni-H_2$ battery several objectives must be met in the design and development of the system. These objectives include:

o Maximization of reliability and life
o High specific energy and energy density
o Reasonable cost of manufacture, test, and integration
o Ease in scaling for growth in power requirements

These basic objectives translate into a number of specific design requirements, which are discussed below.

BIPOLAR BATTERY REQUIREMENTS

Electrolyte Management

A key requirement for a practical bipolar Ni-H$_2$ battery is effective electrolyte management. A significant electrolyte path between two cells in a bipolar stack essentially shorts out these cells and any in between, leading to substantial performance problems. The requirement for electrolyte isolation between cells is more stringent in a bipolar battery than in a multiple, conventional stack common pressure vessel (CPV) design. In a CPV the height of the electrode stack and the required intercell distance can be used to advantage to prevent an electrolyte path from developing from cell to cell. Conversely, because the cell compartment containing the two electrodes of a bipolar cell requires very little height, it is possible to have high voltages across very short stack distances.

One of the most effective methods of dealing with potential electrolyte paths is to utilize hydrophobic materials and to provide long and tortuous electrolyte paths if the individual cells cannot be completely sealed. This can be accomplished by designing necessary gas vent openings so that the cell provides a lengthy path constructed of a material such as polytetrafluoroethylene through which the gases must pass.

Finally, the method of sealing the perimeter of each cell in the areas other than a vent opening must be reliable. Because of the creep characteristics of the potassium hydroxide electrolyte, any slight sealing flaws will be vulnerable to leakage. Therefore, redundant or permanent sealing features must be considered wherever possible.

Material Balance

Material balance management is a particularly critical issue in a bipolar battery design. Gases (H$_2$ and O$_2$) must be reacted in the cells where they were stoichiometricaly evolved; otherwise the drying out of one cell and the flooding of another may occur. This requires careful control of the flow of oxygen from the nickel electrode on overcharge so that it is directed to the recombination sites. These must be designed so that all oxygen is scavenged before it can reach the common gas space. Because of the relatively large size of the electrodes, material utilization gradients across the surface must be considered and minimized. This can be achieved by maintaining good thermal control, providing good electrolyte wicking and reservoir materials, and properly filling the cells initially with electrolyte.

Thermal Management

The heat dissipated as a result of stack resistive losses is minimized by the bipolar electrode approach. However, heat evolved because

of charging/discharging inefficiencies (e.g., O_2 generation and electrode polarization) and the exothermic O_2-H_2 recombination reaction must still be removed from the stack. In fact, thermal control of a bipolar battery is more challenging than for a conventional stack individual pressure vessel (IPV) or CPV battery, because a single-electrode bipolar cell, of equivalent capacity, is substantial in size. Further, electrolyte isolation requires encasement of each cell, hindering heat transfer and eliminating electrode to pressure vessel wall proximity. Also, in a continuously operating bipolar battery, cell-to-cell temperature gradients must be eliminated to maintain long-term material balance.

Current state-of-the-art LEO or GEO cells, with an electrode size of approximately 3.5 inch diameter, can be adequately cooled by employing passive cooling. Because of the constraints imposed by a multiple, high capacity bipolar electrode stack configuration, the only viable approach to thermal control is an active cooling system.

Two possible physical arrangements for an active system are either to place cooling plates within the electrode stack, parallel to the electrodes, or to place cooling plates externally, in contact with the edges of the cell stack. Parallel cooling plates require heat transfer perpendicular to the stack components including the negative electrode and separator, which have a low coefficient of heat transfer. In addition, when the cooling plates are placed at intervals of several cells to minimize mass, a thermal gradient will exist from cell to cell. Furthermore, parallel cooling plates may require the battery current to flow through them. In this case extreme care must be taken so that the cooling loops do not electronically short out the bipolar stack via the conduits or ionically via the coolant. Lastly, the large number of fluid path connections raises serious concerns about the long term reliability.

Edge cooling, however, results in relatively even temperatures from cell to cell. Yet, the thermal gradient across each electrode could be greater than with parallel cooling plates. Therefore, in order to hold this gradient to a manageable level, the distance from any part of the electrode to the cooling plate must be reasonably small. Additionally an edge cooling system is electrically isolated from the cell stack.

A significant positive factor resulting from the need for active cooling is that it eliminates the requirement that the cell stack perimeter be adjacent to the pressure vessel wall. This allows the consideration of other than a circular cell configuration as is necessary with the multi-electrode IPV and CPV passive cooling systems.

BIPOLAR BATTERY DESIGN

Battery Configuration

The bipolar battery design which Ford Aerospace and Yardney will develop consists of 210 cells of 75 Ah capacity each. The battery will be a hermetically sealed pressure vessel containing the cell stack, an active edge cooling system, and support hardware. To minimize temperature gradients within each cell, the shape of the cell is rectangular, with an approximate electrode size of 12.7 x 96.0 cm (5 x 37.8 inches). The cell stack assembly is divided into three series-connected stacks of 70 cells each. Including the cell frames, the approximate size of the individual stacks will be 14.0 x 97.3 x 25.1 cm (5.5 x 38.3 x 9.9 inches) and with heat removal channels installed on each side 15.2 x 97.3 x 25.1 cm (6 x 38.3 x 9.9 inches). The three stacks, combined in a final stack assembly measuring 45.7 x 93.7 x 30.5 cm (18 x 38.3 x 12 inches), is installed in a cylindrical pressure vessel with the stack's long dimension parallel to the vessel longitudinal axis. Figure 1 illustrates the overall layout of the battery and bipolar cell stacks.

The decision to change electrode configuration from circular to a long, rectangular shape is initially difficult to accept because the natural shape which fits the pressure vessel is circular. However, extensive and intensive review of the implications of this change led Ford Aerospace and Yardney to the realization that it yields a number of significant benefits. One is essential to the successful long-term performance of bipolar $Ni-H_2$ batteries, namely the maintenance of the lowest cell-to-cell temperature gradients possible. Using an edge cooling system with long, narrow electrodes achieves the same level of thermal control within each electrode as in the case of the established IPV designs. Another advantage is that heat removal with a heat-pipe system becomes a practical option, which would control intra-electrode gradients even better.

A perceived disadvantage of rectangular electrodes is that they may not be as efficiently packaged in a pressure vessel. However, the required combined stack and gas volume will be independent of electrode configuration. With a practical maximum operating pressure of 41 to 48 atmospheres (600 to 700 psi), the volume impact is insignificant.

Stack Configuration

Each bipolar stack consists of 70 cells directly connected in series. These cells each consist of a group of active components and a bipolar conduction plate placed within a polymer frame in the following sequence:

        o   Bipolar conduction plate
        o   Metallic gas diffusion screen

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o Hydrogen electrode
o Asbestos separator
o Nickel electrode
o Oxygen recombination site/electrolyte reservoir

The reservoir is placed against the back of the nickel electrode, a similar approach to that used in some recirculating stack designs. The reservoir, by choice of material properties and pore size distribution will readily yield most of its electrolyte content to the nickel electrode. However, during overcharge it will absorb and retain electrolyte displaced from the nickel electrode due to oxygen gassing. The pore size structures of the asbestos separator and the reservoir are such that the asbestos forms a much more effective gas barrier. As a result, oxygen is forced into the reservoir. The total cell electrolyte inventory should be chosen such that the reservoir is only partially filled with electrolyte during overcharge, so that the oxygen will pass through relatively easily to the recombination layer. This structure could be a metal screen or perforated metal sheet with platinum dispersed on it. Alternatively, a platinum impregnated reservoir type material could be used. On the back of the recombination layer a porous teflon sheet is placed to provide for hydrogen access to the recombination sites.

The cell seal is obtained by joining the frames of two adjacent cells. The frames are molded with sealing and alignment provisions to enhance the seal quality. Depending on material selection, the seal may be accomplished by mechanical compression, heat sealing (ultrasonic bonding), or adhesives. Gas access holes in the walls of the frame provide for adequate hydrogen flow during both charge and discharge.

The second major element in accomplishing individual cell sealing is the bipolar conduction plate molded in place in each frame. This provides both an effective cell-to-cell electrolyte barrier and an effective electronic cell-to-cell bipolar contact.

The heat conduction path through the cell frame is improved by extending the bipolar plate into the frame. The thermal path can be further improved by increasing the foil thickness, but this does entail a mass penalty.

The estimated mass breakdown for the 75 Ah bipolar $Ni-H_2$ battery is shown in Table I.

DEVELOPMENT PLAN

NASA Lewis Research Center has selected Ford Aerospace and Yardney to develop the 75 Ah bipolar $Ni-H_2$ battery under a program titled "Advanced Nickel-Hydrogen Battery Development". The three year program

scheduled to start in January 1984, will consist of three overlapping phases: development, improvement, and optimization.

The Development Phase consists of the design, fabrication, and test activities associated with the development of an initial bipolar battery design. Two bipolar stacks of 10 cells will be fabricated and tested in boiler plate pressure vessels. Another design will be considered in parallel with the design described in the preceeding paragraphs. This design eliminates the bipolar plate and achieves the bipolar connection in a different manner. It has the advantage that it permits significant mass savings. The estimated specific energy for this configuration is 50.8 Wh/kg (23.1 Wh/lb) for a 75 Ah battery. Two stacks of 10 cells using this design will be assembled and tested. At the conclusion of the Development Phase of the program one of the two designs or a hybrid version will be selected to continue through the final two phases of the program.

The Improvement Phase has the objective to improve the initial design based on information generated in the Development Phase. Two more 10 cell stacks will be fabricated and evaluated based on the improved design.

Based on the experience with the initial and improved stacks, the Optimization Phase will result in a final design. Two optimized design cell stacks of 10 cells will be assembled and tested.

All cell stacks will undergo a characterization test followed by a LEO cycling test. Characterization testing will be performed at three charge rates (C, C/2, C/4) and four discharge rates (2C, C, C/2, C/4). The LEO regime consists of a one hour charge and a one-half hour discharge.

CONCLUSION

Ford Aerospace and Yardney have designed a bipolar $Ni-H_2$ battery capable of meeting the electrical power levels for spece platforms and other future spacecraft. The design achieves the system design objectives in a mass efficient way. Development of two designs will be sponsored by NASA Lewis Research Center beginning in early 1984. The design represents a significant improvement in bipolar $Ni-H_2$ technology. The development program provides the opportunity to achieve a space quality energy storage system for high power applications.

TABLE I

Mass Breakdown – 75 Ah Bipolar Ni-H$_2$ Battery

Component	Mass (Kg)	Mass (lbs)
Cell Stack:		
Bipolar Plate	78.6	173
Nickel Electrode	142.7	314
Separator	6.4	14
Hydrogen Electrode	9.5	21
Recombination Site/Reservoir	23.2	51
Electrolyte	46.8	103
Cell Frames	31.4	69
Miscellaneous Hardware	3.2	7
Total Cell Components	341.8	752
Battery:		
Cooling Channel Assembly	14.1	31
Coolant	14.5	32
Assembly Hardware	8.6	19
Stack Supports	4.1	9
Pressure Vessel	86.6	191
Miscellaneous	16.4	36
Total Battery	486.3	1070
Specific Energy (18,900 Wh)	38.9 Wh/kg	17.7 Wh/lb

STACK END PLATES

PRESSURE VESSEL

(COOLING MANIFOLDING AND ELECTRICAL BUSS BARS NOT SHOWN FOR CLARITY)

−NO SCALE−

BIPOLAR CELL STACK − 3 EACH

STACK COOLING PANELS − 4 EACH
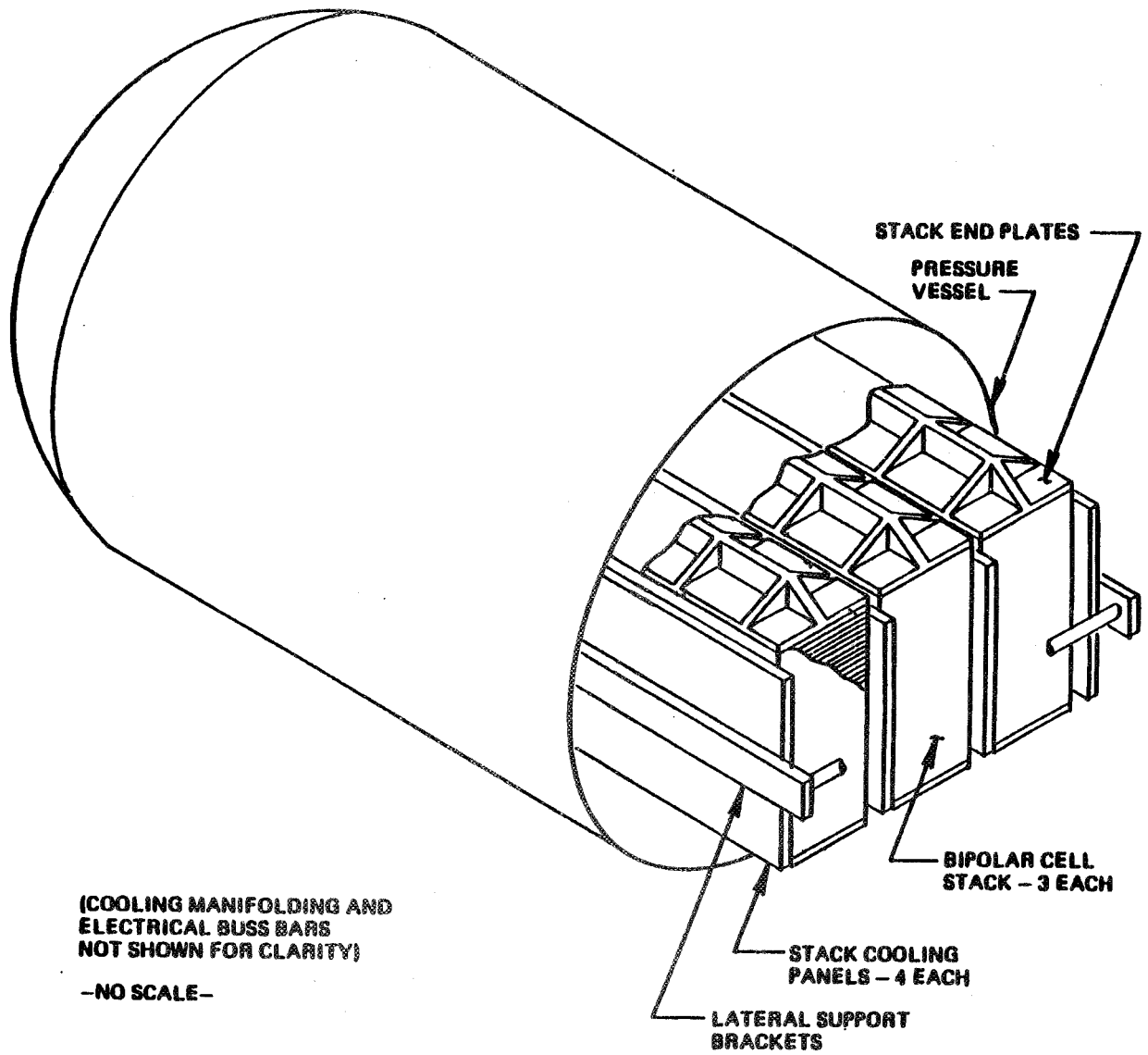
LATERAL SUPPORT BRACKETS

Figure 1. Ford Aerospace/Yardney Bipolar Battery.

Comment

Lackner, Defense Research Canada: You've got an awful lot of trouble when you are getting a specific energy at 17½ amp hours.

Koehler, Ford Aerospace Corporation: 17½ watt hours per pound.

Lackner, DND/DREO: There is a figure mentioned by Jim Dunlop something like 44 a little earlier and I'm wondering is all this trouble wroth what you are doing.

Koehler, Ford Aerospace Corporation: I'm not quite sure what assumptions Jim is using in his. Maybe I can hit on that again. The number was 389 watt hours per kilogram. I based that on a worst case end of life assumption of 1.2 volts per cell.

Q. Unidentified: What is the best you can get out of it?

A. Koehler, Ford Aerospace Corporation: I'm sorry.

Q. Unidentified: What is is the best potential you can get out of the system?

A. Koehler, Ford Aerospace Corporation: I think plateau voltages and discharge of at least 1.25 volts are conceivable.

Q. Ritterman, Comsat: Is your 38.4 based on 100% depth discharge or 80% depth discharge?

A. Koehler, Ford Aerospace Corporation: No that's all the way down. That's complete discharge.

Q. Unidentified: The potential you are talking about is voltage potential. I'm wondering about the energy density potential that you can possibly get out of it?

Q. Koehler, Ford Aerospace Corporation: The energy well it would be maybe you can help me Gert. The question is what would be the optimistic specific energy?

COMMENT

Unidentified: I think we have to look at bipolar batteries in a way
that really doesn't concentrate completely on specific energy, there's
a few other reasons why bipolar batteries are being pursued. I can
answer the question directly and state that with the bipolar plate
approach we can probably reach specific energies on the order of 21
hours per pound. If the other approach is successful that we are
going to take a look at the, might reach 23 or 24 watt hours per
pound. The lower specific energy system with the bipolar plate has
a number of advantages through that in terms of overall cost effect
of the system as it is applied they'll be very significant. One
thing is that it has a pretty high current capability because of the
very large cross section. That gives the system a very high pulse
rate capability which for many future applications is a very important
consideration. The other thing is that the cost effectiveness of
integrating the large battery we are talking multi kilowatt hours into
a work space station or other space systems. The cost of integrating
a large battery is likely to be much less than the cost of
integrating many individual cells. There are two of the reasons
beyond specific energy that this system is being pursued so vigorously.

Q. Lim, Hugh Research Lab: I understand you have the cooling panel
    vertical to the bipolar rate?

A. Koehler, Ford Aerospace: Yes that's right.

Q. Lim, Hughes Research Lab: And if you have that the heat collection
    should be through the frame of the cell and I'm wondering if you
    have an advantage of collecting that way versus the heat collection
    parallel to the bipolar plate or incorporated inside a bipolar
    plate.

A. Koehler, Ford Aerospace: One thing that we are going to try to
    incorporate in the design is that the conduction plate will be
    incased in the cell frame and the conduction plate will actually
    stick into the cell frame almost to the very outside edge. There
    will be a very small layer of the frame covering the edge of the
    bipolar plate but it will be very close.

Q. Sperber, GTE: Is your design a constant compressive force on the
    stack design?

A. Koehler, Ford Aerospace: Yes that would be required that the
    compressant force over the stack area has to be very uniformed and
    the stack compressant plates will have to be designed accordingly
    to provide that function.

Q. **Unidentified**: Do you have some sort of spring arrangement to provide that?

A. **Koehler, Ford Aerospace**: The specific details of the design have not been set. The developmental phase of the program is approximately a year to a year and half project in itself and no specific type details will be identified at that point.