NASA Technical Memorandum 82844

(NASA-TM-82844) DESIGN OF A 35-KILOWATT BIPOLAR NICKEL-HYDROGEN BATTERY FOR LOW EARTH ORBIT APPLICATION (NASA) 10 p
HC A02/MF A01
CSCL 10C
N82-24647
Unclas
G3/44 09901

Design of a 35-Kilowatt Bipolar Nickel-Hydrogen Battery for Low-Earth-Orbit Applications

Robert L. Cataldo and John J. Smithrick
Lewis Research Center
Cleveland, Ohio

Prepared for the
Seventeenth Intersociety Energy Conversion Engineering Conference
cosponsored by the IEEE, AIAA, ACS, AIChE, ANS, ASME, and SAE
Los Angeles, California, August 8-13, 1982

DESIGN OF A 35-KILOWATT BIPOLAR NICKEL-HYDROGEN BATTERY FOR LOW-EARTH-ORBIT APPLICATIONS

By Robert L. Cataldo and John J. Smithrick

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

E-1214

This preliminary design of a nickel-hydrogen battery utilizing bipolar construction in a common pressure vessel addresses the needs of multikilowatt storage for low-earth-orbit applications. The modular concept, with projected energy densities of 20-24 W-hr/lb and 700-900 W-hr/ft^3, has significant improvements over state-of-the-art capabilities. Other design features are; active cooling, a new scheme for H_2-O_2 recombination, and pore size engineering of all cell components.

INTRODUCTION

In the low-earth orbit multikilowatt mission studies being carried on at Lewis Research Center Space Power and Propulsion Division and elsewhere, a possible need has surfaced for electrochemical storage subsystems that will be quite different than those in current use. The general trend for the multikilowatt application is toward higher cell capacity and higher battery voltage. It is generally conceded that the nickel-hydrogen system would represent the best candidate for scale-up from its current size of from 30 to 50 AH to a size more compatible with the miltikilowatt missions.

In response to this challenge, Lewis Research Center Electrochemistry Technology Section has undertaken the effort of designing an advanced configuration for the nickel-hydrogen system that fulfills the requirements of future multikilowatt low-earth orbit missions. The output of the design effort was a complete battery system that incorporated active cooling for thermal control. The individual cells are constructed in a bipolar manner and are contained within a common pressure vessel. The cell stack resembles that of a fuel cell where only one electrode pair is housed in each cell compartment. Thus, the electrode/battery ampere-hour capacity is a function of the electrode dimensions. Active cooling is accomplished by either liquid coolant or gaseous hydrogen. The battery power output was designed to supply 35 kW for a 35-minute eclipse. This was accomplished with a 130-ampere hour, 275 volt battery supplying 130 amperes. The high voltage/low current combination minimizes distribution losses and weight of terminals, connectors and current carrying conductors; a major consideration for high power systems. The high voltage/low current system is ideal for a bipolar design since the total cell capacity is in a single electrode plate and current densities must be kept within reasonable limits for optimum performance.

There are some surprising and significant results of this design regarding energy densities and projected cost. The gravimetric energy density of this non-weight optimized design is about 20 WH per pound, a 40-50 percent increase over a battery comprised of state-of-the-art individual pressure vessel (IPV) nickel-hydrogen cells. Similarly, the volumetric energy density is about 1 kWH per cubic foot, a 3-4 fold improvement over an IPV battery.

The bipolar design is especially attractive when looking at cost and system integration. With the bipolar design there is only one stack and vessel, whereas about 450 state-of-the-art IPV cells are needed in series-parallel combination to match the 35 kW power requirement.

The bipolar and other advanced configuration designs warrant further investigation to promote advancement in technology for the future state-of-the-art nickel-hydrogen cells and batteries.

The design of the bipolar Ni-H_2 battery was an in-house team effort lasting 3 months. The team members are listed in alphabetical order: Dr. Kathleen Abbey, Doris Britton, Robert Cataldo, JoAnn Charleston, Olga Gonzalez-Sanabria, Mark Hoberecht, Arthur Lieberman, Michelle Manzo, John Smithrick, Daniel Soltis, Dale Stanaker, and Dr. Lawrence Thaller.

OVERALL DESIGN

The concept of bipolar power sources is not new to the field of electrochemistry. This concept has been used in fuel cells and redox systems with success. However, it is a new application with the nickel-hydrogen battery. This design could be viewed as a fuel cell with one gas electrode (H_2) and one solid electrode (Ni). The hydrogen gas need not flow through the battery for the reaction to occur. Instead, small vents link the hydrogen electrode gas screen through the cell frame to the hydrogen gas within the pressure vessel. Gas flows out these vents during charge to pressurize the vessel and is subsequently consumed during discharge.

Figure 1 shows what a bipolar nickel-hydrogen battery stack might look like. Each cell is housed in one frame and sealed to maintain material balance. Cooling plates can be added to the stack as dictated by mission requirements. The medium for cooling can be hydrogen gas or a liquid coolant, and since both methods have their advantages and disadvantages, the trade-offs should be considered.

Figure 2 shows a cross-section of one cell. Each cell unit contains a hydrogen electrode with an associated gas flow screen, separator, "floating" nickel electrode, electrolyte reservoir plate with catalyzed oxygen recombination wires and a bipolar cooling plate. The frame holding the cell components in place is made of polysulfone that is molded with the appropriate ports for cooling channels and hydrogen access. Each frame is fitted for "O" rings and gaskets that seal the cooling ports and frame edge, respectively. It is of utmost importance that electrolyte is maintained within each cell to eliminate shunt electrical paths and possible electrolyte migration between cells.

The recombination of evolved oxygen with hydrogen takes place behind the nickel electrode. The high bubble pressure separator forces the oxygen to come in contact with the recombination sites located within the electrolyte reservoir plate. Its proximity to the cooling plate facilitates the vapor's return to water which in turn is wicked back to the separator. This scheme also helps in electrolyte management.

Hydrogen Electrode

The negative electrode for the bipolar cell is somewhat different than that used in present nickel hydrogen cells. Two main reasons are: 1) current must be passed through the electrode and 2) it is not intended that oxygen be recombined on it. This design suggests a thin nickel substrate pressed with active material on one side. Active material consists of blending together high surface platinum based powder and TFE 30 teflon. A loading of 3-5 mg/cm^2 should be sufficient for a designed 30-35 ma/cm^2 current density. The electrode thickness can be about 5-15 mils; however, using the thin electrode may require an electrolyte reservoir plate to furnish added electrolyte storage volume.

A Gore-tex membrane cannot be used as a backing for the electrode to prevent flooding (present technology) since it would be an insulator to current flow. However, the probability of flooding the hydrogen electrode is greatly reduced because oxygen is recombined behind the nickel electrode within an electrolyte reservoir plate. Here, the platinum catalyst is situated within a teflon wrapper permitting gas and vapor exchange while physical and electronic isolation from the nickel electrode is maintained, thus preventing self-discharge.

Controlling the electrode pore size in relation to other cell components can also reduce the risk of flooding the H$_2$-electrode with electrolyte. The pore size relationship should be such that the H$_2$-electrode will give up excess electrolyte back to the separator. Cell performance is adversely affected when the H$_2$-electrode becomes flooded.

Nickel Electrode

The nickel electrode in the bipolar battery has a surface area of about 4 ft^2 and a 0.030 in. thickness with a theoretical capacity of 130 ampere-hours. The dimensions of the electrode are smaller than the inside frame dimensions to allow for electrode expansion resulting from cyclic operation. The proposed size of the electrode creates some manufacturing difficulties considering currently used procedures.

The present technologies for the manufacture of sintered nickel electrodes are varied. However, they possess the same basic steps: (1) preparation of a highly porous sintered plaque by loose sintering of nickel powder followed by (2) introduction of the active material by impregnation, usually, by chemical or electrochemical means. Generally, these electrodes are small and could not be made very large by this process. However, some new electrode processes show promise in making larger electrodes. One such process has been carried out at Battelle Research Center, Geneva, Switzerland (Ref. 1).

The process involves hot-pressing, sintering and impregnation of the electrode in one step. Reported advantages of this method are: more control over pore size, high mechanical integrity of the plaque, reproducibility and fabrication of large electrodes. In addition, it is reported that this process promises a significant improvement in cycle life. The advantage of controlled pore size is of particular interest.

The pore size relationship of the nickel electrode and separator should be such that they interchange electrolyte freely. This prevents the separator from drying out, which causes high resistance cells. However, as the nickel electrode is cycled, it is believed that the pore sizes decrease, holding more electrolyte and drying out the separator. As the cell cycles, the separator could dry out enough to cause high resistance and cell failure. If the electrode structure would remain unaltered during cycling, a separator could be selected with the proper pore size to maintain effective electrolyte management.

Thermal Management

The performance of the nickel electrode in regards to its discharge capacity, self discharge, and life, is a function of operating temperature. Many problems with today's nickel-hydrogen cells are related to the method of heat removal, which is limited by its configuration to passive rejection. However, the bipolar configuration is ideally suited for active heat removal. The cooling medium can be either circulating hydrogen gas or a dielectric liquid.

One positive feature of cooling with circulating hydrogen through a heat exchanger is that there is no possibility of contamination as with a liquid coolant. However, this advantage is offset by increased weight and power consumption compared to a liquid coolant system. Either hydrogen or liquid coolant is pumped through the plated magnesium cooling plates at a flow rate that maintains an inlet to outlet ΔT less than 3^{o} C.

The thermal gradient between cells should be maintained at an acceptable level, because cell performance is dependent on temperature. Large thermal gradients can cause cell to cell imbalance which would severely reduce the performance and shorten the life of the battery.

Active cooling can be integrated with the postulated spacecraft cooling systems. Battery waste heat can be removed via heat pipes, separate heat exchanger or directly into the existing cooling lines. In this design the maximum battery heat load is about 8 kW during the eclipse period and about 4 kW during charge. Battery weight and volume can be reduced by not cooling every cell. Preliminary test data on a scaled pre-prototype battery built to this design will furnish the necessary information to optimize thermal gradients and cooling system weight.

Oxygen Management

This design offers a unique approach to the task of recombining oxygen and hydrogen that differs significantly from state-of-the-art designs. Presently, the oxygen generated near the end of charge and on overcharge is allowed to flow through a zircar separator from the nickel to the hydrogen electrode. Then, on the catalyzed H_2 electrode surface, the O_2 and H_2 chemically react to form water. Two disadvantages of this method are: 1) localized hot spots can occur, resulting in burn holes in the H_2 electrode; 2) possible flooding of the H_2 electrode, particularly on overcharge when the rate of oxygen generation is greatest. By recombining in an area other than the H_2 electrode, these problems can be eliminated.

The approach taken in this design is for recombination to occur behind the Ni electrode. Figure 3 depicts the methodology used. A high bubble pressure asbestos separator forces the O_2 into a highly porous electrolyte reservoir plate. The recombination sites are catalized with platinum. They are encapsulated with a vapor permeable coating to allow passage of gases in and water vapor out, but remains hydrophobic to liquid. The coating must also isolate the catalyst electrically, otherwise it will react with the nickel electrode as a parasitic reaction. This method of oxygen management benefits the overall electrolyte management scheme.

The water formed within the electrolyte reservoir plate is returned to the separator by the wicking action of the portion of separator that is in contact with the electrolyte resevoir plate. This is analogous to the wall wick used in the Air Force flight cells that returns any free electrolyte on the vessel walls back to the electrode stack.

Electrolyte Management

Electrolyte management can have a significant effect on the cycle life of a nickel-hydrogen battery and should be a prime consideration of the overall battery design. The objective of electrolyte management is to prevent flooding of the hydrogen electrodes and prevent drying of the nickel electrodes and s rators. The approach taken to achieve this objective is to incorporate pore size distributions in the separator which appropriately overlap the distributions in the electrodes (Ref. 2).

The subject of electrolyte management can be more fully understood with the help of the following discussion. The overpotential of the hydrogen electrode on discharge as a function of electrolyte content is shown in figure 4(a). The curves indicate that the overpotential is very sensitive to electrolyte content and passes through a minimum. This is what one would expect, since the hydrogen electrode functions as a gas diffusion electrode during discharge. The overpotential of the hydrogen electrode as a function of electrolyte content during charge is shown in figure 4(b) and indicates that beyond a certain point the overpotential is relatively independent of electrolyte content. The nickel electrode overpotential on both charge and discharge exhibits a similar behavior as the hydrogen electrode on charge.

The proposed pore size distributions of the hydrogen electrode and separator are shown in figure 5. Both the hydrogen electrode and separator have a bimodal pore size distribution, which overlap. The water generated during discharge, at the hydrogen electrode, is removed by the capillary action of the smaller pores in the separator. In this way the optimum hydrogen electrode electrolyte content is maintained minimizing the cell overpotential. The small pores in the hydrogen electrode, insure adequate electrolyte to maintain the required electrochemical reactions. The smaller pores in the separator prevent dry-out, thus insuring a low separator resistance to ion transport.

The nickel electrode pore size distribution is similar to that of figure 4 except everything is shifted to the left because the pore size of the nickel electrode is smaller than that of the hydrogen electrode. A proposed pore size distribution for the hydrogen electrode, nickel electrode, and separator system is shown in figure 6. This indicates that each component has a bimodal pore size distribution. The separator has a broad pore size distribution which overlaps the pore size distribution of both the hydrogen and nickel electrode. What is new here is that the pore size distributions were designed, in light of the function of the entire electrode/separator system.

In general, a separator for the nickel-hydrogen battery would be one with pore size distributions overlaping those of the electrodes. As an example, the separator could be a composite, which consists of the NASA inorganic/organic (I/O) separator (K 168) and a layer of knit zircar.

Pressure Vessel

The nickel-hydrogen battery stack is packaged in a pressure vessel. The weight and volume for four different pressure vessels were calculated to evaluate their impact on the nickel-hydrogen battery gravimetric and volumetric energy density. The four possible pressure vessel designs considered were a cylindrical shell with torrispherical heads, ellipsoidal heads, hemispherical heads and a sphere. The weight, volume dimensions and maximum operating pressure for the four different pressure vessels are summarized in figure 7.

The weight of the spherical pressure vessel (lightest option) is about 34% less than the cylindrical pressure vessel with torrispherical heads. However, the volume of the spherical pressure vessel is about 52% greater than that of the torrispherical head vessel which has the least volume. The pressure vessels would be fabricated from inconel-718, which is resistant to hydrogen embrittlement. The tank design pressure is twice the maximum operating pressure. The precharge hydrogen pressure was taken as 100 psi. The final choice of pressure vessel will be dependent on the individual mission constraints.

Battery System Weight Breakdown

The battery system weight breakdown for the bipolar design is summarized in figure 8. The total system weight is about 1600 lbs. The most significant weight contributor is the nickel electrodes (33%). If a light weight electrode could be developed, it would have a significant impact on the stack weight and hence, battery energy density. Over 50% of the nickel electrode weight is due to the nickel plaque. He development effort for a light weight nickel electrode should be directed towards development of a light weight plaque.

Energy Density Comparison for Energy Storage Options

The gravimetric and volumetric energy density for two different nickel-hydrogen battery designs are shown in figure 9. One design is the bipolar battery, and the other is a battery composed of individual pressure vessel Air Force recirculating design cells. Selection of the bipolar design battery system results in about a 37% increase in gravimetric energy density. The volumetric energy density for the bipolar design is 1070 watt hrs/ft^3. The volumetric energy density for the individual pressure vessel battery is to be determined. However, for a single individual pressure vessel cell the value is 950 watt-hr/ft^3.

CONCLUSIONS

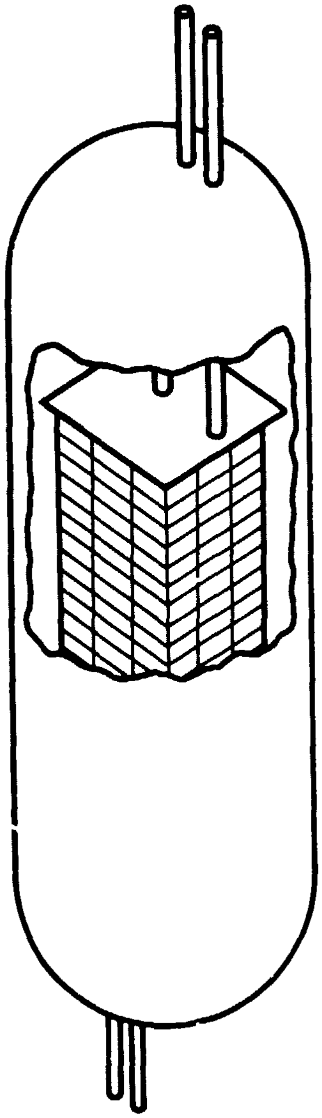
A preliminary design of a 35 kW nickel-hydrogen battery featuring bipolar construction, a common pressure vessel and active cooling was developed. The initiative for this project is NASA proposed missions like the Space Operating Center(SOC) or Space Platform that will require high power energy storage.

The outcome of the design effort indicates that the nickel-hydrogen system is capable of meeting those requirements in an effective manner. The inherent characteristics of the bipolar concept lends itself to a high voltage low current operation. Using a common pressure vessel for the entire battery offers significant improvement in both gravimetric and volumetric energy densities. In addition, spacecraft/battery integration is a simpler task when considering that this one 35 kW module (or a modified modular concept) would replace many state-of-the-art cells in series (parallel configuration).

REFERENCES

1. P. Jonville, J. M. Frèsnel, K. D. Beccu, and J. Bezaudum, "A New Technique for Manufacturing Electrodes by Hot Pressing," in Power Sources 4: Research and Development in Non-Mechanical Electrical Power Sources; Proceedings of the Eighth International Symposium, pp. 223-240, 1973.

2. K. M. Abbey, L. H. Thaller, "Pore Size Engineering as Applied to Starved Electrochemical Cells and Batteries," in the 17th Intersociety Energy Conversion Engineering Conference, 1982.



BATTERY SPECIFICATIONS

POWER	35 kW
LOAD VOLTAGE	275 V
CURRENT	127 A
DISCHARGE CAPACITY/ AT 0.6 hr ECLIPSE	76
DEPTH OF DISCHARGE	70%
THEORETICAL CAPACITY	128 A-hr
SERIES CELLS	229
PLATE AREA	625 in.^{2}
CELL THICKNESS	0.095 in.
STACK DIMENSIONS	27 x 27 x 28 in.
BATTERY WEIGHT	1583 lb
ENERGY DENSITY	19 W-hr/lb AT 100% DOD
VOLUMETRIC ENERGY DENSITY	780 W-hr/ft^3
VESSEL CONFIGURATION	TBD

Figure 1. - Conceptual drawing of a 35 kW bipolar constructed nickel hydrogen battery including specifications.

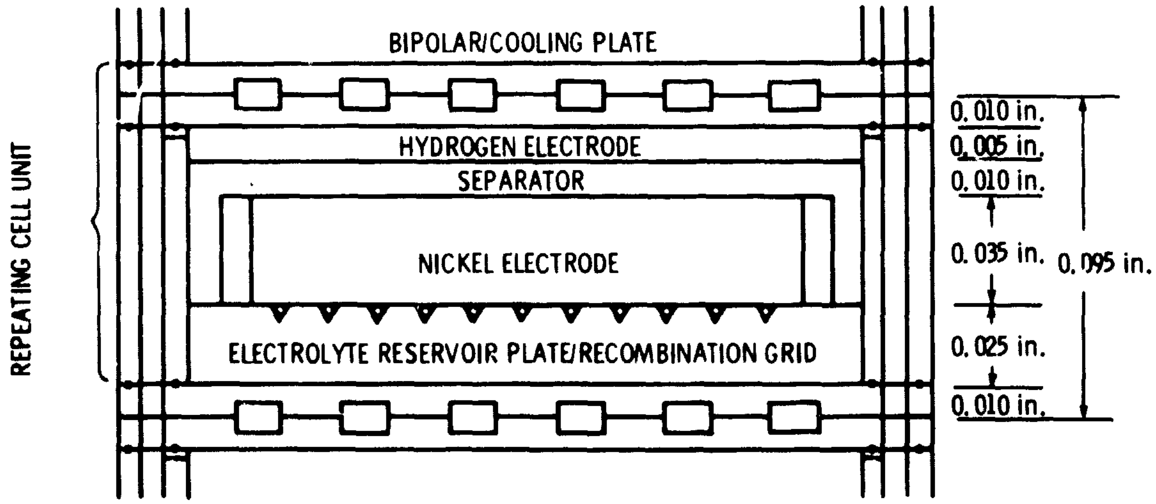


Figure 2. - Cross-sectional view of individual cell.

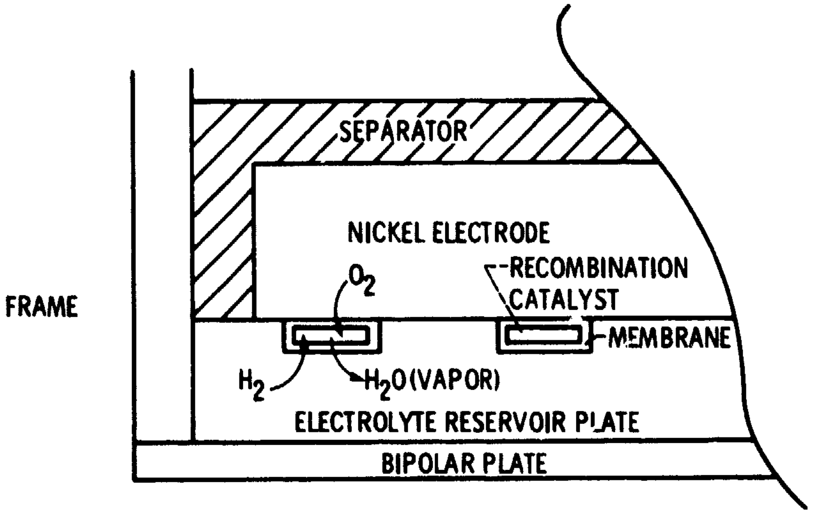
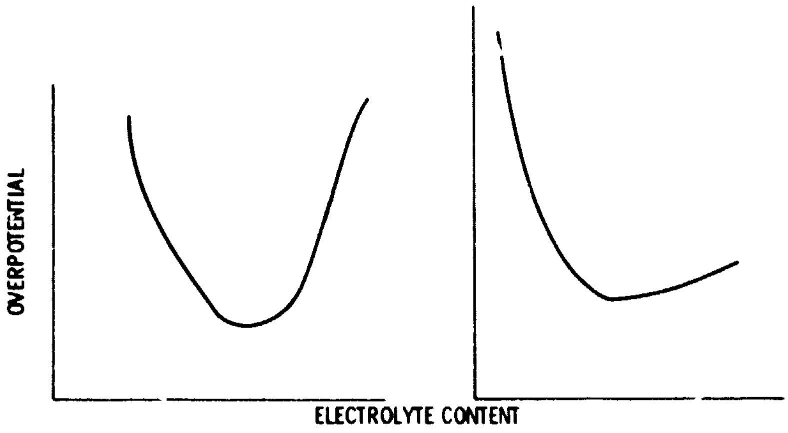


Figure 3. - Graphic representation of oxygen - hydrogen recombination.



(a) H_2 electrode on discharge.

(b) H_2 electrode on charge; Ni electrode on charge and discharge.

Figure 4. - Overpotential vs electrolyte content.

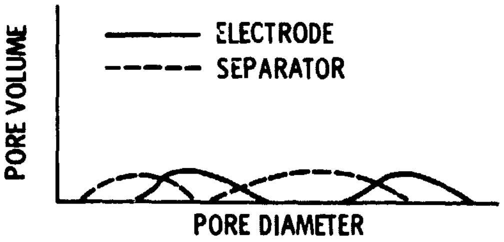


Figure 5. - Idealized pore size distribution for hydrogen electrode and separator.

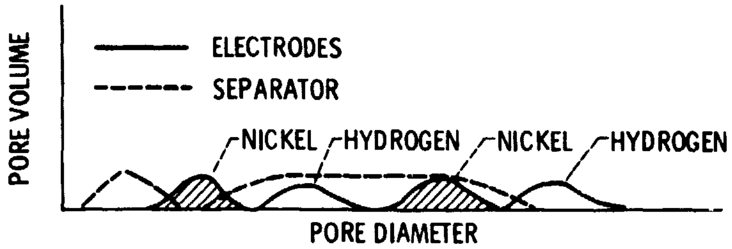


Figure 6. - Idealized pore size distribution for the nickel - hydrogen battery.

PRESSURE VESSEL TYPE^a	WEIGHT, lb.	EXTERNAL VOLUME, ft^3	OUTSIDE DIAM., in.	HEIGHT, in.	MAX. OPR. PRESSURE, psi^b
CYLINDRICAL SHELL W/TORISPHERICAL HEADS	213.7	31.5	42-7/8	44-1/2	442
CYLINDRICAL SHELL W/ELLIPSOIDAL HEADS	176.4	35.8	46-11/16	50-13/16	377
CYLINDRICAL SHELL W/HEMISPHERICAL HEADS	132.3	47.6	42-9/16	72	282
SPHERICAL TANK	114.1	47.9	54-1/16	54-1/16	281

[a] ALL PRESSURE VESSELS ARE BASED ON THE USE OF INCONEL 718

[b] TANK DESIGN PRESSURE IS TWICE MAXIMUM OPERATING PRESSURE

Figure 7. - Vessel specifications and options.

COMPONENT	TOTAL WEIGHT	% OF TOTAL
NICKEL ELECTRODES	508 lb	32.5%
HYDROGEN ELECTRODES	70	4.5
SEPARATORS	35	2.0
ELECTROLYTE RESERVOIR PLATES	185	12.0
RECOMBINATION GRIDS	15	1.0
COOLING PLATES	180	11.5
PRESSURE VESSEL	200	13.0
ELECTROLYTE	246	16.0
HARDWARE (TIE RODS, TERMINAL CABLES, COOLANT LINES, ETC.)	30	2.0
FOAM	10	.6
FRAMES	54	3.4
COOLANT	20	1.2
END PLATES	30	2.0
TOTAL WEIGHT	1583 lb	100.0%

Figure 8. - Battery components and weights.

BATTERY	GRAVIMETRIC ENERGY DENSITY[d], W-hr/lb	VOLUMETRIC ENERGY DENSITY[d], W-hr/ft^3
BIPOLAR[a] Ni/H_2	19-21	800-1000
IPV[b] Ni/H_2	12.0-15.0	TBD[c]

[a] PRESSURE VESSEL - CYLINDER WITH TORISPHERICAL HEADS

[b] IPV - AIR FORCE/HUGHES INDIVIDUAL PRESSURE VESSEL DESIGN BATTERY

[c] TO BE DETERMINED FOR BATTERY, HOWEVER FOR AN IPV CELL VALUE IS 950 W-hr/ft^3

[d] 100% DEPTH-OF-DISCHARGE, 1.2V AVERAGE CELL DISCHARGE VOLTAGE

Figure 9. - Energy density comparison for energy storage options.