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Overview of the Design, Development, and Application of Nickel-Hydrogen Batteries

Lawrence H. Thaller and Albert H. Zimmerman
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June 2003

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National Aeronautics and
Space Administration

Glenn Research Center

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Foreword

This report was prepared under contract between the NASA Glenn Research Center and The Aerospace Corporation of El Segundo, California, under NASA Contract number C-31010-G. Michelle Manzo served as the program manager and technical point of contact for this effort.

The preparation of this report was supported as a task under the NASA Aerospace Flight Battery Systems Program, a NASA-wide program aimed at ensuring the quality and reliability of aerospace batteries for NASA applications. The program deals with cell and battery technology as well as system-level issues. Publication of technology overview reports is consistent with the objectives of the program, which are to

- (1) Develop, maintain, and provide tools for the validation of aerospace battery technologies
- (2) Accelerate the readiness of technology advances and provide infusion paths for emerging technologies
- (3) Provide NASA projects with the database and guidelines for technology selection
- (4) Disseminate validation and assessment tools, quality assurance, and availability information to the NASA and aerospace battery communities

This report complements and updates some of the information presented in the “NASA Handbook for Nickel-Hydrogen Batteries” (NASA RP-1314), an earlier publication supported by the NASA Aerospace Flight Battery System Program. The original document was published in 1993. Since that time, nickel-hydrogen batteries have become widely accepted for aerospace energy storage requirements and much additional knowledge has been learned. The intent of this report is to document some of that knowledge.

The Aerospace Corporation was contracted to assemble this report, and Government and industry personnel, cell and battery manufacturers, technology providers, and technology users reviewed the draft versions. The final product provides an update on the status of the design development and application of nickel-hydrogen batteries. As the program manager and technical point of contact for this work, I would like to thank the authors and all the contributors to this report; their efforts and helpful comments have provided much value to the final product.

Michelle A. Manzo

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1.0 Summary

This document provides an overview of the design, development, and application of nickel-hydrogen (Ni-H₂) battery technology for aerospace applications. It complements and updates the information presented in NASA RP-1314, NASA Handbook for Nickel-Hydrogen Batteries, published in 1993. Since that time, nickel-hydrogen batteries have become widely accepted for aerospace energy storage requirements and much more has been learned. The intent of this document is to capture some of that additional knowledge. This document addresses various aspects of nickel-hydrogen technology including the electrochemical reactions, cell component design, and selection considerations; overall cell and battery design considerations; charge control considerations; and manufacturing issues that have surfaced over the years that nickel-hydrogen battery technology has been the major energy storage technology for geosynchronous and low-Earth-orbiting satellites.

2.0 Introduction

This report was prepared to assist individuals planning for the use of nickel-hydrogen cells and batteries. It addresses many different aspects of a well-established, but ever-changing, technology that offers many more choices and options than does the nickel-cadmium technology that it has largely displaced. Its primary purpose is to identify options, address the pros and cons of the available choices, and identify many of the pitfalls that have been experienced during the development and ongoing production phases. It is not intended to explain all the intricate chemical and electrochemical processes that occur within nickel-hydrogen cells. General background information is provided and ample references are cited that direct readers to technical papers covering many of these issues.

Cells and batteries generally go through a design phase, a manufacturing phase, and a qualification/acceptance phase. The earlier in this sequence that inappropriate cell and battery designs are identified and rejected, the better the outcome is in terms of both dollars and schedule. An inappropriate cell or battery design is identified by a disappointing cycle life or poor electrochemical performance. An appropriate cell or battery design is identified by acceptable cycle life and electrochemical performance. Prescribing an appropriate cell design requires an up-to-date understanding of the nickel-hydrogen system and a diligent review of the available cycle-life databases. Factors that affect the assessment process and focus on cell design are stressed. These include modeling efforts that address processes that are known to take place within cells over the course of cycling, as well as a review of available databases that can assist in evaluating the relationship between stress and cycle life.

Manufacturing problems have also been responsible for numerous quality and performance issues in completed cells and batteries, often affecting finances and schedules significantly. Over the years, specialized tests and analytical techniques have been developed to detect problems with cell components. These techniques are very technical in nature and, as such, they are described only in generalities to alert readers to some of the approaches that address some of the manufacturing issues that have arisen over the years. References are provided.

Component-level acceptance test procedures have been developed to screen out unacceptable product before it is assembled into a finished cell. Unfortunately, fully manufactured cell lots have occasionally been rejected by customers. Customers' oversight of the manufacture of nickel-hydrogen cells and batteries coupled with customers' in-house staffs of electrochemical and battery engineers have addressed many of the problems that have surfaced within the manufacturing community. Much of this report comes from customer experience with cell and

battery problems as well as the accumulated electro-analytical expertise that has resulted from successfully addressing many of these issues.

3.0 Overview of the Nickel-Hydrogen System

Nickel-hydrogen energy storage is a newer technology than nickel-cadmium storage. A solid nickel electrode, similar to that used in nickel-cadmium cells, and a negative platinum gas electrode, which contains catalyzed sites that permit the electrochemical reaction of the hydrogen gas, characterize a nickel-hydrogen cell. Because the negative active material is hydrogen gas, the entire cell is contained in a pressure vessel forming the cell case.

Following experimental flights in 1976 and 1977, nickel-hydrogen batteries began service in 1983 on Intelsat V-B geosynchronous-Earth-orbit (GEO) communication satellites. Since then, there has been a gradual shift away from nickel-cadmium to nickel-hydrogen energy storage by many flight programs. The switch to nickel-hydrogen batteries was necessitated by the demand for increased payload capability that required higher capacity and more energy dense energy-storage subsystems. Nickel-hydrogen systems generally provide a higher usable energy density at an equivalent life for certain missions. The launch of the Hubble Space Telescope in 1990 was the first major use of nickel-hydrogen batteries in a low-Earth-orbit (LEO) application. The "NASA Handbook for Nickel-Hydrogen Batteries" (ref. 1) provides an excellent historical review of this technology, and readers are referred to this reference for a more in-depth coverage of the history of this technology area.

Nickel-hydrogen technology was originally built up around individual pressure vessel (IPV) designs and 3.5-in.-diameter hardware. IPV refers to the design configuration where the components for an individual cell with a nominal operating voltage of 1.25 V are placed within a pressure vessel. The 3.5-in. dimension refers to the nominal diameter of the thin-walled Inconel 718 cylindrical section of the pressure vessel used to contain the high-pressure hydrogen gas associated with these cells. The energy density of IPV cells designed for LEO and GEO applications, in the range of capacities from 50 to 90 A-hr, varies from about 40 to 75 W-hr/kg at the cell level when discharged to 100-percent depth-of-discharge (DOD). IPV cells with diameters of 2.5, 4.5, and 5.5 in. also have been successfully built, tested, and flown.

In addition to the IPV cell configuration, configurations with 2 to 22 cells within a single pressure container are becoming increasingly available. These different design configurations are known as common pressure vessel (CPV) and single pressure vessel (SPV) designs. These configurations are addressed in later sections.

Many design variations and cell configurations within the nickel-hydrogen (Ni-H₂) family have been manufactured, tested, and flown. As a result of the large volume of cells manufactured and 20 years of experience with this technology, a number of manufacturing, storage, and use-related issues have been resolved, and many of the idiosyncrasies of these cells are now reasonably well understood.

Eagle Picher, Gates Aerospace Batteries, Boeing Satellite Systems (formerly Hughes Aircraft Co.), Yardney, and SAFT have all produced various nickel-hydrogen cell types. Yardney withdrew from nickel-hydrogen cell production; and in 1994, SAFT, the French battery manufacturer, purchased Gates Aerospace Batteries, and the entire manufacturing line was moved to France.

4.0 Relevant Chemical and Electrochemical Reactions

The equations on the next page present a simplistic view of reactions that take place within nickel-hydrogen cells during normal charge and discharge. The equations for overdischarge differ slightly depending on whether the cells have a positive or negative precharge. This depends on whether there is excess capacity associated with the positive nickel electrodes (positive precharge) or with the negative hydrogen material (negative precharge). The first nickel-hydrogen cells were built with negative precharge. In these situations, when a cell is fully discharged there is a residual pressure due to the undischarged hydrogen gas. There were several reasons for having hydrogen precharge. The performance of the hydrogen electrode is enhanced by a higher partial pressure of hydrogen present at the end of discharge; excess hydrogen serves as a reserve of usable material in the event of a gradual loss of hydrogen gas through the terminal seals; and the constant presence of hydrogen pressure during discharged storage would apply a compressive force to the seal, enabling it to remain leak tight. Later experience with negative precharge cells identified an undesirable capacity loss mechanism caused by the reaction of hydrogen with the cobalt additive of the active material in the positive electrodes (refs. 2 and 3). As a

Normal operation during discharge:		
At the nickel electrode,	$\text{NiOOH} + \text{H}_2\text{O} + \text{e}^- \Rightarrow \text{Ni}(\text{OH})_2 + \text{OH}^-$	(1)
At the hydrogen electrode,	$\frac{1}{2} \text{H}_2 + \text{OH}^- \Rightarrow \text{H}_2\text{O} + \text{e}^-$	(2)
Overall reaction within the cell,	$\text{NiOOH} + \frac{1}{2} \text{H}_2 \Rightarrow \text{Ni}(\text{OH})_2$	(3)
Overcharge reactions:		
At the nickel electrode,	$2 \text{OH}^- \Rightarrow 2 \text{e}^- + \frac{1}{2} \text{O}_2 + \text{H}_2\text{O}$	(4)
At the hydrogen electrode,	$2 \text{H}_2\text{O} + 2 \text{e}^- \Rightarrow 2 \text{OH}^- + \text{H}_2$	(5)
Reaction at catalyzed sites,	$\frac{1}{2} \text{O}_2 + \text{H}_2 \Rightarrow \text{H}_2\text{O} + \text{heat}$	(6)
Overdischarge (reversal) reactions:		
In cells with positive precharge,		
At the nickel electrode, (until precharge is consumed)	$\text{NiOOH} + \text{H}_2\text{O} + \text{e}^- \Rightarrow \text{Ni}(\text{OH})_2 + \text{OH}^-$	(1)
Then, at the nickel electrode,	$2 \text{H}_2\text{O} + 2 \text{e}^- \Rightarrow 2 \text{OH}^- + \text{H}_2$	(7)
At the hydrogen electrode,	$2 \text{OH}^- \Rightarrow \frac{1}{2} \text{O}_2 + \text{H}_2\text{O} + 2 \text{e}^-$	(4)
Reaction at the catalyzed sites,	$\frac{1}{2} \text{O}_2 + \text{H}_2 \Rightarrow \text{H}_2\text{O} + \text{heat}$	(6)
In cells with negative precharge,		
At the nickel electrode,	$2 \text{H}_2\text{O} + 2 \text{e}^- = 2 \text{OH}^- + \text{H}_2$	(5)
At the hydrogen electrode,	$\frac{1}{2} \text{H}_2 + \text{OH}^- = \text{e}^- + \text{H}_2\text{O}$	(2)
Net reactions within the cell,	No net reaction	

result, most newer cell designs specify positive precharge, that is, at full discharge, there is capacity remaining in the positive electrodes of the cell.

These equations do not fully consider that there are several different valence levels associated with the charged nickel active material and that in the higher oxidation state, water molecules and potassium hydroxide are incorporated into the lattice structure. This higher oxidation state material ($\text{Ni}^{+3.67}$) is referred to as the gamma phase, and the lower oxidation state ($\text{Ni}^{+3.0}$) of the charged active material is referred to as the beta phase. These reactions are written for the case where the beta phase is representative of the charged form of the active material. Reactions more representative of the actual cell chemistry can be used when a more accurate description of nickel electrode reactions is required. See the studies by Barnard and Randell (ref. 4) for descriptions of the stoichiometry and valence character of the beta and gamma forms of the active material.

5.0 Component Selection Considerations

A number of components make up a nickel-hydrogen cell. These include nickel electrodes (section 5.1), hydro-

gen electrodes (section 5.2), separators (section 5.3), electrolyte (section 5.4), and gas screens (section 5.5). These components are common to all nickel-hydrogen designs and configurations. Multiple component options exist for a modern nickel-hydrogen cell. These include choices of dry powder or slurry plaque substrate material for the positive electrodes, the impregnation technique, the loading level of active material within the electrode plates, the amount of cobalt additive, and the type of separator material. In the following sections, these topics are reviewed in light of the latest understanding of cell electrochemistry and the current status of life-cycle testing. Recommendations in regard to component selection are given assuming a GEO application. If significant differences exist between a LEO and GEO application, a dual recommendation is given. Note that variants that are not recommended might perform satisfactorily, but may not be regarded as optimum. Where concerns or cautions exist, they are mentioned along with the reasons for them.

5.1 Nickel Electrode

Nickel-hydrogen cell manufacturers offer a range of nickel electrode types based on different processes used to make the nickel substrate (called the plaque) and different processes used to impregnate the plaque with

active material (principally nickel hydroxide doped with small amounts of cobalt hydroxide).

5.1.1 Plaque type.—Most plaque material is manufactured from small nickel particles that are made by a process that decomposes nickel carbonyl (ref. 5). Slurry plaque has been used since the late 1930's following its development in Europe. The dry powder process is a more recent development and is used for aerospace applications by several manufacturers. The dry powder process is more labor intensive than the slurry process, but it has been reported that a more uniform distribution of pore sizes results (refs. 6 to 8). More uniform pore sizes in the plaque give a more uniformly loaded finished electrode and, thus, a higher utilization of the active material within the electrode. More recently, improvements in the slurry process at Eagle-Picher have reduced the differences in the uniformity of the plaque made by these two processes.

In general industrial practice, slurry sinter material is less porous (~80 versus ~84 vol%) but stronger than plaque made using the dry powder process. When the nickel screen material is included in the porosity calculations, these numbers drop to about 76 and 80 percent. Both of these processes sometimes experience quality control problems. The most important characteristic of material made by either process is the pore size distribution through the plaque thickness. Typical plaque specifications only control average pore size and bend strength; thus, special tests have been developed to augment manufacturing acceptance tests to verify quality control. These are outlined in more detail in section 10.0.

For a LEO application where tens of thousands of cycles are required, the strength of the plaque becomes an important consideration. High-quality slurry material, because of its high strength, has demonstrated lower rates of plate expansion in comparison to dry powder plaque. Furthermore, slurry plaque has experienced lower rates of corrosion compared with dry powder plaque. A passivation process has been developed and tested for dry powder plaque material that has reduced its rate of corrosion (ref. 9). Tests supported by the NASA Glenn Research Center have demonstrated a reduced rate of nickel substrate corrosion associated with passivated dry powder plaque material. Both dry powder and slurry plaque material have performed well under LEO cycling conditions, but the slurry process is recommended as being more robust and tolerant of abuse. However, in cases where energy density is of prime importance, the lighter weight dry powder plaque is recommended.

Lightweight nickel fiber and foam materials are being considered as possible alternate forms of plaque

material. Acme Electric of Tempe, Arizona, SORAPEC of France, Eagle-Picher Industries, Boeing Satellite Systems, and Glenn have all worked with nickel foams or felts as a possible alternative to the heavier materials made by sintering together nickel carbonyl powders. However, modeling studies carried out by Zimmerman (ref. 10) and experimental efforts reported by Sac-Epée et al. (ref. 11) suggest that because of the larger pore sizes of most noncarbonyl materials, utilization of active material will typically be lower than in traditional plaque materials at the current densities (discharge rates) of interest. Plate expansions well in excess of those experienced by dry sinter or slurry carbonyl plates, have been reported by several authors (refs. 12 and 13). Lightweight alternatives to sintered plaque are widely used in commercial applications where decreased performance and life are acceptable to reduce battery cost.

5.1.2 Impregnation method.—The active material used in these electrodes is introduced into the pore structure of plaque material by a process called impregnation. Two methods of electrochemical impregnation, the "aqueous" (ref. 14) and "alcoholic" (ref. 15) types, have found general acceptance for use in nickel-hydrogen cells. The impregnation solution used for the alcoholic process differs from the solution used in the aqueous process only by the addition of ethyl alcohol. A more in-depth discussion of these two electrochemical processes can be found in reference 1. Each manufacturer has its own favored method. For the applications under consideration here, a clear preference cannot be suggested on the basis of electrode performance data. The current density within the impregnation bath, the flow patterns, the solution pH, the bath temperature, the nickel-to-cobalt-ratio, and the nitrate level are all critical for the manufacture of quality plate material. Although advocates of the alcoholic impregnation process suggest that bath concentrations are easier to control (ref. 16), the authors' experience is that both the alcoholic and aqueous process are quite sensitive to the conditions of impregnation and sinter structure. Both processes can produce high-quality plate material if adequate process and quality controls are in place. As evidenced by the cycling results generated at the Navy cycling facility at Crane, Indiana, both the aqueous and alcoholic impregnation processes have produced plate material that, within properly designed cells, has fully demonstrated the cycle-life requirements for any application envisioned. The impregnation process in place will depend on the selected vendor.

The electrochemical impregnation method is highly sensitive to changes in process variables and plaque structures. Thus, any change in plaque thickness, porosity, or pore distribution is likely to require modifications to, and revalidation of, the impregnation process.

5.1.3 Loading level of active material.—The amount of active material contained in the nickel plaque determines the electrode's ampere-hour capacity. The capacity is defined in terms of loading level based on the grams of active material deposited into the void volume of an electrode plaque. Following some early Glenn-funded studies (ref. 17), cell manufacturers have commonly used a loading level between 1.6 and 1.7 g of active material per cm³ of plaque void volume. This results in a capacity per plate of about 1.3 to 1.5 A-hr for a single, 0.030-in.-thick, 3.5-in.-diameter electrode. The loading level is typically calculated by the weight pickup following impregnation. This often results in an error by the amount of plaque material that is corroded away during the impregnation process. This can vary up to 12 percent of the original plaque weight. Control of the pH of the bath, and of the electrode rinse rates after the plaque material is removed from the bath, is critical to control the corrosion. Screening tests have been developed (ref. 18) to measure corrosion from the impregnation process and to discover finished plate material that has the proper amount of loading by weight but has an unacceptable distribution of active material within the pores. When these screening tests are combined with the manufacturer's acceptance test data for nickel electrodes, uniform utilization and capacity is assured for different manufacturing lots.

Cobalt is commonly used as an additive to the nickel-hydroxide active material. The levels of cobalt or other additives used in the impregnation step are generally considered proprietary, and direct discussions with the vendor are suggested to review suggested attributes of the type and level of additive used. It has been suggested that higher amounts of cobalt (10 versus 5 wt%) result in a higher conductivity of the active material and, therefore, slightly better performance due to what is suggested to be their higher conductivity for protons (ref. 19). However, electrodes containing 10 wt% cobalt appear to be more sensitive to various storage-related capacity fading issues (ref. 20). Cells with lower levels of cobalt have performed satisfactorily for LEO applications.

Two very important features of a finished plate (electrode) are (1) the distribution of pore sizes across the plaque thickness and (2) the distribution of active material across the thickness of the porous sinter structure. A nonuniform distribution of pore sizes in the plaque can

result in nonuniform loading and utilization of the active material. This results in low or variable capacity, reduced cell performance, and shortened cycle life.

5.2 Hydrogen Electrode

The hydrogen electrodes used in nickel-hydrogen cells are based on designs developed for the gas electrodes used in alkaline fuel cells. A mixture of platinum particles, Teflon (DuPont) particles in the form of a liquid slurry, and Triton X100 (an emulsifying agent) are blended together, filtered to the desired size and thickness, transferred onto a nickel screen or an electroformed nickel substrate, pressed together, and finally placed into an oven to sinter the Teflon particles together. Giner and Hunter present a classical discussion of the gas diffusion electrode (ref. 21). Depending on the manufacturer, catalyst-loading levels may range from 1 to 10 mg of platinum per cm² of electrode. Generally, manufacturers do not offer options related to their hydrogen electrode. The structures are about 50-percent porous, and about half the pores are wetted by electrolyte. The other half of the electrode is hydrophobic so that gas can enter and diffuse through the thin layer of electrolyte to the catalyst particles.

Some problems related to hydrogen electrodes are associated with poor adherence of catalyst particles to the electrode structure, which can lead to short circuits to the adjacent cathode. The presence of traces of emulsifying agent used in preparing the catalyst/Teflon suspension can result in an overly wettable hydrogen electrode (flooded) such that it is very difficult for gas to diffuse to the catalyst particles. It is critical that contaminants, such as iron, which can poison the catalyst, be controlled to low levels (i.e., < 2.0 ppm).

Standard tests are available from fuel cell technology for evaluating the kinetic and diffusional properties of gas electrodes. These tests typically measure the electrode polarization at high charge and discharge rates when the hydrophilic side of the electrode is flooded with alkaline electrolyte and the hydrophobic side is exposed to 1.0 atm of hydrogen gas. Giner and Smith describe a well-respected test procedure (ref. 22).

5.3 Separator Material

The separator is placed between the nickel and hydrogen electrodes. It physically separates the electrodes so that there are no short circuits within the cell, and when filled with electrolyte, it forms an ionic path between the electrodes so that the electrochemical reactions can be

maintained. There are several requirements for materials used as separators:

(1) They should resist the oxidizing power of the nickel electrodes and the oxygen liberated at the nickel electrode during the latter portion of the recharge cycle.

(2) They should be dimensionally stable to help maintain proper compression on the full assembly of anodes, cathodes, separators, and gas screens.

(3) They should have electrolyte retention characteristics based on their pore size and wettability properties to provide good ionic conductivity between the electrodes as well as to act as a reservoir for supplying electrolyte to the positive electrode as it expands.

(4) They should manage the transport of oxygen from the surface of the nickel electrodes to control "popping" (see section 5.4.1).

(5) They should be chemically stable in concentrated KOH solutions.

Adequate performance and life in GEO and LEO applications have been obtained using properly prepared asbestos separator material, and very encouraging cycle-life experience has come from cells using asbestos separators (ref. 23). A group of three cells using asbestos separator cycled to 60-percent DOD accumulated between 45 000 and 55 000 cycles. However, the lack of assurance of a continuing supply of material with the proper fiber structure coupled with the environmental hazards associated with its processing and use are the main factors for discontinuing the use of asbestos separators. Furthermore, Zimmerman and Quinzio have reported that naturally occurring impurities within certain sources of asbestos have resulted in severe performance problems in some completed cells (ref. 24). The asbestos materials used successfully in the original cell types was of a variety that either had smaller amounts of detrimental impurities than is currently available or had undergone a "remanufacturing" process that removed these constituents. Cell designs utilizing a single layer of asbestos and minimal amounts of electrolyte have also been prone to increased impedances during cycling.

Asbestos has virtually been replaced with Zircar cloth (Zircar Zirconia, Inc., Florida, NY) as the separator of choice for nickel-hydrogen cells. Zircar cloth is a zirconium textile fabricated by the deposit of yttrium-stabilized zirconium oxide on an organic precursor textile. During the manufacturing process, the zirconium oxide adopts the textile weave of the precursor fabric. Zircar can hold more useable electrolyte than other commonly used separator materials. This property facilitates the maintenance of the proper electrolyte distribution for

good cell operation. Cells with two layers of 0.012-in.-thick Zircar typically have operating voltages that are about 20 mV higher and charge voltages that are lower than those of cells with asbestos separators.

SAFT has successfully used a polyamide separator material for many years (ref. 25). This results in a lighter weight cell because the nonwoven polyamide material is considerably lighter than either one or two layers of Zircar. However, the use of this lighter weight material is not recommended for several reasons. Polyamide materials are susceptible to melting in areas where "popping" occurs (see section 5.4.1), they are more compressible than ceramic structures such as Zircar, and they are susceptible to dryout problems (ref. 26). Studies reported by Lim et al. (ref. 27) and verified by others (ref. 28) outlined the degradation that takes place with this type of material as a result of oxidation by oxygen and hydrolysis by potassium hydroxide. These reactions are accelerated at elevated temperatures. The use of the more robust ceramic Zircar material guards against these problems. Furthermore, the ability of Zircar to hold more usable electrolyte than asbestos or polyamide materials facilitates maintenance of the proper electrolyte distribution that is needed for good cell operation.

Other materials are being evaluated in experimental cells as potentially lower cost, lighter weight alternatives to Zircar (ref. 29). Some flight-type cell designs have been built and successfully operated with only one layer of Zircar. However, the use of two layers of Zircar is recommended for LEO applications because it has an established test and flight history as well as a greater tolerance to the changes taking place during the cycle life of cells in actual applications because of its ability to hold more electrolyte. If battery weight is critical, as it is for many GEO missions, a single-layer Zircar separator can be fully adequate if this is coupled with a battery design that has good thermal control, adequate electrolyte fill, physically stable nickel electrodes, and controlled amounts of overdischarge.

5.4 Electrolyte

The electrolyte used in nickel-hydrogen cells is an aqueous solution of potassium hydroxide (KOH). The primary electrolyte function is to form ionically conductive paths for ionic current to freely flow through the separator between the two electrodes. If the electrolyte volume is too small or its conductivity is too low, performance difficulties will result. The volume and the concentration of the electrolyte are critical parameters that affect the performance and life of nickel-hydrogen cells.

5.4.1 Electrolyte quantity.—Nickel-hydrogen cells are typically run in what is referred to as the starved condition, that is the cell is filled with as much electrolyte as can be held within the wettable pore structure of the components. This includes the nickel electrode, the separator, about a quarter of the hydrogen electrode, and the wall wick. There is no free electrolyte in the cell. This usually results in cells that are not subject to excessive amounts of “popping” if the recharge ratio is limited to 1.03 to 1.04. Early failures were found to occur in cells that contained amounts of electrolyte that were in excess of the wettable pore structure of the components of the plate pack (ref. 30). These cells had free electrolyte and were placed on their sides for testing. This caused the excess electrolyte to form a puddle along the side of the cell. This, in turn, resulted in edges of the cell plates being submerged in excess electrolyte. Oxygen gas formed during recharge was not free to diffuse through the gas space between the plates where it could recombine in a slow, even manner. Instead, a bubble would build up at the nickel electrode until it was large enough to push away the excess electrolyte. Then the large bubble would recombine with a large “pop” at the hydrogen electrode. The force of these pops was strong enough to displace some of the catalyst particles until finally a small short circuit would develop within the cell. Most premature failures that are not attributed to manufacturing flaws have historically resulted from popping caused by excessive electrolyte amounts. Excess electrolyte is a problem for spinning spacecraft where the spinning motion can impart forces that would cause free electrolyte to be forced against the cell wall.

One of the known causes of cell failure is an inadequate amount of electrolyte within the cell components. This is usually referred to as a separator dryout problem. Proper electrolyte fill levels are critical to the life of nickel-hydrogen cells. As degradation processes that are outlined in section 6.0 gradually progress during cycling, there is a slow reduction in the amount of electrolyte remaining within the separator. The pore structure of an expanding nickel electrode is such that electrolyte is drawn out of the separator pore structure by capillary action. Reference 31 treats this situation in more detail. More recently, a volume tolerance study in a specially modified cell quantified the effect of changes in the electrolyte volume on the performance of a cell (ref. 32). Electrolyte amounts are often quoted in terms of grams per ampere-hour of rated capacity. These numbers have ranged from a low of about 2.5 g/A-hr in cells that

later proved to be underfilled, to a high of 4.5 g/A-hr for cells that displayed excessive amounts of destructive popping due to overfilling.

A more meaningful measure is the percentage of the wettable pores that are filled with electrolyte. Static and dynamic modeling studies suggest that the initial fill percent should not exceed 95-percent of the available wettable pore volume (ref. 33). Cell manufacturers who keep accurate records of plate porosity, separator porosity, wettable porosity of the hydrogen electrode, and other parameters can calculate the porous volume of the plate pack and the amounts of electrolyte that should be added to the cell. This technique has been used with cells in SPV batteries. One possible difficulty with this method of precalculating the proper amount of electrolyte stems from a typical activation procedure that is carried out where excess electrolyte is present. The active material following the impregnation process and washing to a neutral pH is not ready to cycle efficiently. Several cycles, as prescribed by the manufacturer's process sheet, are carried out with an excess amount of electrolyte (flooded condition) in the cell. Once the nickel hydroxide has been activated and, in some cases, the desired precharge has been set for the cell, excess electrolyte is drained from the cell and it is sealed off. Cells can be weighed to verify the presence of the correct amount of electrolyte. (Note: manufacturers follow different procedures to set the precharge in a cell.)

As cells cycle, the pore structure of the nickel electrodes changes and demands additional electrolyte, this results in an overall decline in the amount of electrolyte in the separator. Toward the end of life, as a value of 40-vol% overall fill of the wettable pore structure of the separator is approached, separator dryout becomes a problem since capillary forces of the cathode tend to gradually draw electrolyte out of the separator. There is a gradual increase in the internal resistance of the cell as the separator loses electrolyte to the nickel electrode. The internal resistance under this condition where the separator is 40-percent filled can be twice that of a new cell. At an overall fill of Zircar separators of about 30 percent, a condition known as a diffusional limiting current can exist. A significant reduction in cell performance would be expected under these conditions. It is recommended that the stack pore volume that is filled with electrolyte be tracked starting from the cell design to the individual cell lot level to assure reliable performance and long cycle life.

5.4.2 Electrolyte concentration.—Nickel-hydrogen cells are typically activated with 31 wt% KOH, which appears to have been a carryover from nickel-cadmium practice. An extensive study of the effect of 31 wt% electrolyte concentration on the cycle life of boilerplate cells demonstrated the desirability in some situations of using 26 wt% KOH as the electrolyte concentration instead. The use of 26 wt% KOH has significantly increased cycle life in flight-weight cells at the expense of a small decrease in energy density when the cells are fully discharged (ref. 34). A reduction in electrode swelling appears to be the main cause of this increased cycle life at deep DODs.

The lower electrolyte concentration favors the beta-beta nickel electrode reaction, whereas the higher concentration promotes the gamma-alpha electrode reaction, which has significantly larger changes in the lattice constants of the active material over the course of a complete cycle. The larger changes in the lattice spacing that occur when the active material is charged to the gamma phase are believed to increase the electrode expansion in those situations.

The changes in the structural characteristics of the active material in a nickel electrode can be better understood with the help of the Bode diagram shown in figure 1 (ref. 35). The diagram presents a useful summary of the morphological species involved in nickel electrodes as they are cycled. Figure 1 may be understood as

follows: The beta form of nickel hydroxide, labeled $\beta(\text{II})$, is the thermodynamically stable form of this material in a solution of KOH. Its structure is depicted as a series of evenly spaced platelets. When this material is charged, it is converted to a structurally similar form where the nickel valence has changed from +2 to +3. If the charging voltage is increased further, the beta form of the charged material, $\beta(\text{III})$, is converted to a higher valence form that has an average valence of 3.66. Some of the ions remain at the +3 valence, whereas others are oxidized to the +4 valence state. This material is labeled $\gamma(\text{III})$. In this crystallographic form, the nickel-to-nickel distance is the same as for the $\beta(\text{III})$ form, but the spacing between the platelets is increased significantly. Molecules of water and KOH are incorporated into the lattice structure. The expanded crystal lattice of gamma phase material can result in electrode expansion in weaker plaque structures. Factors that favor gamma phase formation include higher KOH concentrations, lower temperatures, and higher cobalt contents.

The maximum conductivity versus concentration relationship for KOH occurs at about 28 wt%. Conductivity is not the only consideration relative to selecting the concentration to be used in these cells. The modeling of mass transport processes within these cells as a function of electrolyte concentration suggests that diffusional processes can limit total cell current as the electrolyte concentration is lowered (ref. 36). Studies of the

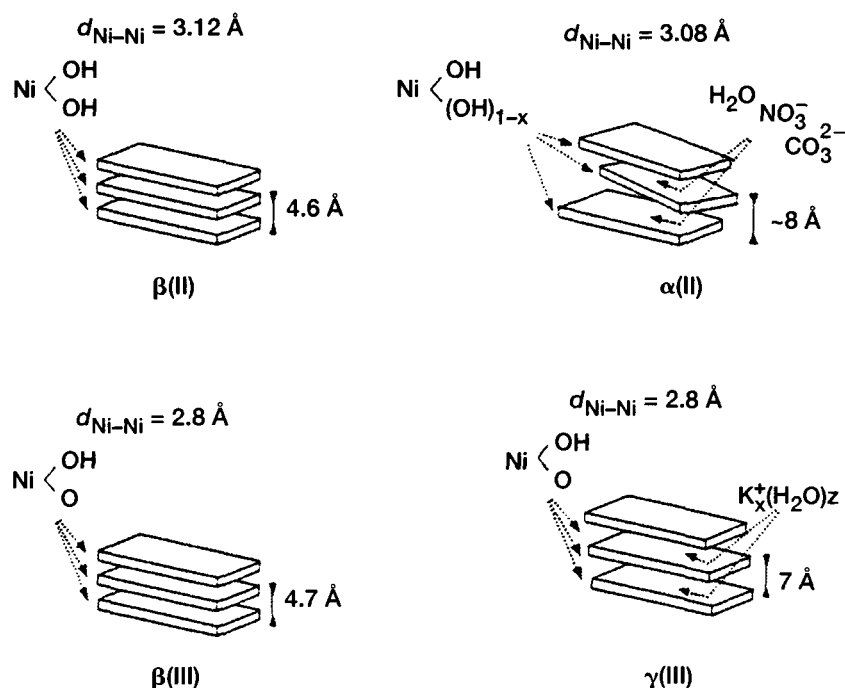


Figure 1.—Bode diagram of nickel electrode species (ref. 35); d , distance.

structural characteristics of the gamma form of the charged active material suggest that significant amounts of KOH can be incorporated into the lattice and thus removed from the electrolyte. Barnard and Randell (ref. 4) state that each mole of active material incorporates one-third of a mole of KOH within its lattice when fully converted to gamma phase. This will amplify any electrolyte issue related to low ionic conductivity. A further consideration of electrolyte concentration is related to the ease by which gamma phase material is formed during overcharge. Where cycle-life requirements for an application are moderately severe, the use of 26 wt% KOH is recommended, along with a sufficient amount of electrolyte (typically 3.5 g/A-hr) to accommodate changes caused by corrosion of the sinter material, phase changes in the active material, and electrode swelling over the cycle life of the cell.

Higher electrolyte concentrations (typically 36 to 38 wt%) have been used successfully in programs where most of the emphasis was on energy density and much less was on cycle life. These higher concentrations facilitate the formation of the gamma phase during the long periods of trickle charge associated with GEO applications. Pure gamma phase material has a higher average valence than the beta phase does (3.66 vs. 3.0), resulting in a higher capacity per unit of active material. In a study by Ritterman (ref. 37), the capacity of similar cells varied from 47 to 66 A-hr as the electrolyte concentration was increased from 25 to 38 wt%. A decade ago, it was typical to use these higher concentrations in cells for GEO applications, but more recently at least one manufacturer has adopted the use of 26 wt% for their GEO applications (ref. 38). Lower electrolyte concentrations are, however, more susceptible to water losses from the stack and onto the cell wall if the wall is below the dewpoint of the electrolyte. This is because the vapor pressure of a 26 wt% KOH solution is closer to that of pure water than that of a 31 wt% KOH solution. This phenomenon is addressed in detail in reference 39. As an example, at 10 °C the dewpoint of 31 wt% KOH is 10 °C below that (0 °C), but the dewpoint of 26 wt% KOH is 6 °C below the ambient temperature (4 °C).

For modern GEO applications where longer cycle lives and DODs are required, the higher concentrations of electrolyte (36 to 38 wt%) used earlier are not recommended. For these applications, 31 wt% KOH is recommended, but if the mission duration is not too long and energy density is critical, 36 wt% KOH can be used. A technique that has been adopted by Space Systems Loral allows them to charge GEO batteries at a low

temperature that encourages the formation of the higher capacity gamma phase while the batteries are warmed up and discharged under conditions where the internal resistance of the cell is lower (ref. 40). For LEO applications, the use of 26 wt% KOH should be considered because of promising life-cycle test results from different manufacturers for different cell designs (ref. 36).

5.5 Gas Screen

Hydrogen gains access to the backside of the hydrogen electrodes by way of gas screens that are placed immediately behind them. Woven polypropylene materials have been used for many years. Different weave patterns and thicknesses are available, and several different types are now in use. Thinner screen thicknesses and tighter weave patterns are associated with larger amounts of electrolyte retention in the open weave patterns of the screen following the activation sequence. Although the screen material is hydrophobic in nature, it is easier for electrolyte to be retained inside the more tightly woven material. This is undesirable since such material can hinder access to the entire surface area of the electrode. Tests at high current densities should be conducted to assure that sufficient amounts of radial hydrogen flow could take place as the end of discharge is approached. Thinner gas screens result in shorter stack lengths and are desired for that reason. Thicknesses in the range of 0.016 to 0.023 in. have been found to be acceptable.

6.0 Overall Design Considerations

The most important consideration in designing a cell is that it be tolerant to the changes that are known to, or are expected to, take place during its storage and use in the specific application for which it is intended. The fact that there is not a single standard design suggests that the factors to be considered are not all fully understood or that the applications are different. As are most cells and batteries used in aerospace applications, nickel-hydrogen cells are referred to as "starved." In some instances, cell designs have electrolyte quantities over and above the amount that can be held in the wettable capillaries of the different components. Care must be taken with these designs to preclude gas management problems that have been associated with free electrolyte in the cell especially during operation in weightless or induced gravitational fields. Cell designs must be tolerant to changes that occur over the cell's entire life span. These include the

changes that occur during storage prior to use, those that take place within the nickel electrode crystal structure during a complete charge-discharge cycle, those that occur over thousands or tens of thousands of charge-discharge cycles, and finally, any that occur as a result of the inadvertent abuse that cells or batteries can be subjected to during any one of these phases. The changes that take place tend to redistribute the electrolyte between the wettable components within the cell in a manner that results in a gradual separator dryout. As these tolerance issues are better understood and appreciated, battery engineers will be able to make more perceptive selections of the many different features within the diverse field of nickel-hydrogen cell designs. Some of these factors follow:

(1) Positive plate expansion: This phenomenon is a function of active material loading level, plaque bend strength, electrolyte concentration, and the amount of overcharge that is used during the recharging cycles of the completed cell or battery. Increases in electrode thickness, determined by disassembling cells following life-cycle testing, have ranged from a minimum of 5 percent to greater than 15 percent in cases of excessive plate expansion (ref. 41).

(2) Nickel sinter corrosion: This phenomenon is a function of the amount of overcharge, the cobalt levels in the active material, the type of process used in plaque manufacture, and whether or not the plaques were passivated prior to being impregnated. Corrosion has ranged from a low of 5 wt% to higher than 25 wt% of the original sinter material (ref. 41).

(3) The potassium hydroxide concentration used in cells: This phenomenon affects the amount of KOH that is incorporated into the nickel electrode active material as it is charged to the gamma phase. It is also a function of the amount of overcharge during the charging process and the cell operating temperature. Under certain circumstances, electrolyte concentration can be reduced to undesirably low levels as a result of potassium uptake by the nickel electrode. Barnard and Randell suggest that one molecule of KOH is incorporated into the gamma phase lattice for every three nickel ions (ref. 4).

(4) The amount of water that is condensed onto cold cell walls if they are at a temperature below the dewpoint of the electrolyte contained in the warmer plate pack: This phenomenon is a function of the electrolyte concentration, the temperature gradients within the cell, and the presence or absence of wettable wall wicks that are intended to return water back to the plate pack (ref. 39).

Minimizing the thermal gradient between the plate pack and the cell wall can reduce this phenomenon.

In the latter sections of this report, tradeoffs that are associated with some of the major configurations and components are addressed. Several modeling efforts (refs. 42 to 45) have incorporated these effects into both static and dynamic cell models and have shown the importance of the amount, distribution, and concentration of electrolyte in any cell design. A static cell model (ref. 42) was developed to help explore the long-term performance projections for nickel-hydrogen cells and batteries. The model calculates the distribution of electrolyte and its concentration in the three major wettable cell components and permits the estimation of any accompanying performance problems due to separator dryout. This model has been verified using a specially modified cell where the cell performance was monitored as the electrolyte volume was varied (ref. 31). The completed model suggests that one of the most important features of a cell design is the percentage of the separator's pores that remain filled with electrolyte over the course of cell cycling. Factors that reduce the amount of electrolyte contained in the separator adversely affect the mass transport processes within the cell. Cell models that can accurately predict changes in electrolyte distribution through the cell components seem to provide good correlations between design robustness and cycle-life data. The modeling carried out by Zimmerman (ref. 43) and Di Stefano et al. (ref. 45) focused on being able to predict a cell's operating voltage for a given set of assumed cell features.

Separate studies relating the effect of separator electrolyte content to performance difficulties are available in the literature (refs. 46 and 47). They suggest that strict limits exist for permissible loss of electrolyte from the separator due to cell charge and discharge operation as well as physical and chemical degradation processes occurring in the cell over its cycle life. For each cell design, these limits can be predicted on the basis of correlations between test data and model predictions.

6.1 Individual Pressure Vessel (IPV) Configurations and Component Selection

Nickel-hydrogen cells and batteries come in a large number of possible combinations of internal component types as well as a variety of internal configurations. The following sections briefly cover the major features of these cell and battery types. When considering design

options, it is important to be aware of and at least partially understand the processes that take place within a cell over the course of storage and cycling. In this way, designs can be selected that will tolerate these changes.

Nickel-hydrogen technology has been built up around what is called the 3.5-in.-diameter of hardware. Shown in figure 2 (ref. 1) is only one of a number of possible IPV configurations. Electrodes are stacked onto a centrally located core piece and connected in parallel. In this configuration, the plate pack of electrodes is fixed at one end to a weld ring. At the weld ring, the hydroformed cylinder and the shorter end cap are welded together. Within certain limits, set by the hydroforming process to deep draw the Inconel into a cylinder with a hemispherical-shaped end, capacity can be varied over a wide range. Once the capacity of a 3.5-in.-diameter cell reaches about 50 A-hr, the length limit of the hydroformed cylinder with end caps is reached. However, by position-

ing the weld ring at the center of two hydroformed pieces, capacity can then be increased to a limit of about 100 A-hr. From an energy density point of view, however, there are capacity boundaries that would suggest different diameters than the basic 3.5 in. Computer codes (refs. 48 and 49) have been used to suggest an optimum diameter to yield the highest energy density. The industry has adopted 3.5 and 4.5 in. for cells with capacities from 25 to 250 A-hr. The break point in using 4.5-in.-diameter vessels instead of 3.5 in. is about 100 A-hr. In addition, several manufacturers have developed 5.5-in.-diameter IPV cell designs, enabling cells with more than 250 A-hr to be built. Within the family of IPV cell types, designs that emphasize cycle life, pulsing power, or high energy density have been investigated on an experimental basis. A decrease in one of the other factors usually accompanies the emphasis on a specific one. The energy density at the cell level when discharged to a 1.0-V cutoff, at a rate

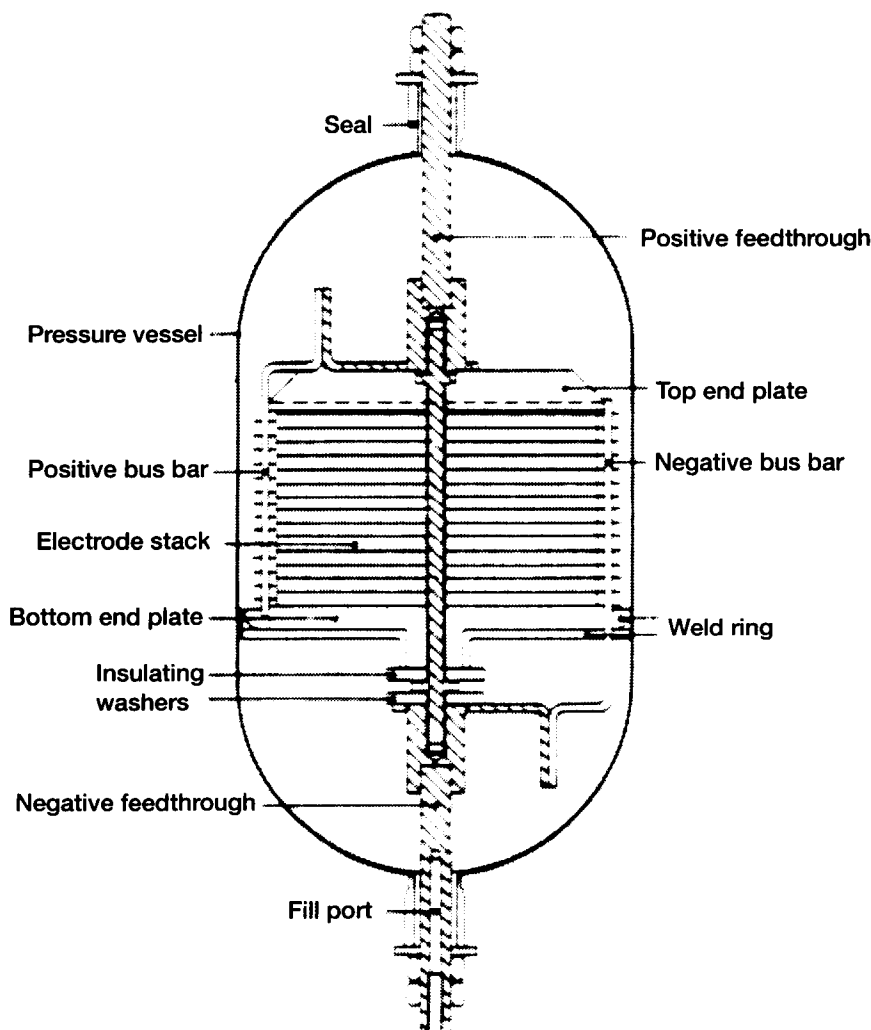


Figure 2.—Cross-sectional view of the COMSAT/EPI-NTS-2 cell (ref. 1).

that would result in the nameplate capacity being fully discharged in 2 hr, ranges from 40 to 70 W-hr/kg. This rate of discharge is called a C/2 discharge rate.

In this section, the many different configurations and options within an IPV type of cell are addressed. Potential advantages and disadvantages of many of these choices are mentioned. Designs that are intended for GEO applications can be quite different from designs that are intended for LEO applications. GEO applications only experience about 90 charge-discharge cycles per year. These occur during two eclipse seasons of 44 days, with varying lengths of discharge each day up to a maximum of 1.2 hr. The maximum discharge duration occurs on day 22 of each of two cycling seasons seen each year. GEO designs must be able to withstand only about 900 cycles over the course of a decade or longer, but the designs must also accommodate long periods of trickle charge during the sunlit periods between eclipse seasons. LEO missions, on the other hand, experience a full cycle every 90 to 100 min. LEO designs must withstand the stresses associated with tens of thousands of cycles, and accordingly, energy density is of secondary importance. These applications have very different requirements that will result in different design recommendations depending on the intended battery use.

6.1.1 Stacking arrangement.—Nickel-hydrogen cells contain nickel electrodes, hydrogen electrodes, separator sheets, and gas screens. These components are stacked in repeating units that are in turn connected in parallel to yield the desired ampere-hour cell capacity. Originally Comsat Corporation developed what came to be known as the Comsat design. Comsat design cells are “back-to-back” in terms of their stacking arrangement (fig. 3 and ref. 1) and have positive and negative buses located along opposite edges of the stack of plate pairs.

The Air Force configuration originally used a “recirculating” stacking arrangement of cell components having “pineapple slice” geometry. Thin nickel foil plate tabs are arranged as a bundle within a central cell core that is partially hollow to allow space for the tabs to be directed to the top and bottom of the cell. Both of these cell designs have performed satisfactorily.

Gradually, it was found that the back-to-back arrangement was better able to handle the oxygen that is generated during the latter portions of the recharge cycle. This is particularly true when low-bubble-pressure Zircar separators are used. Originally, higher bubble-pressure asbestos was used as the separator material of choice. In

cells with asbestos separators, oxygen generated within the nickel electrode during the latter stages of the charge cycle left the backside of the electrode and recombined around the outer edges of the hydrogen electrode. In cells with the lower bubble-pressure Zircar separators, oxygen is able to pass through the separator as small bubbles that recombine with hydrogen on the catalyzed surface of the hydrogen electrode. Under certain circumstances, a large bubble of oxygen can build up and combine all at once with hydrogen, creating a small explosion known as a pop. These pops can be heard unaided, and in some tests, have been counted with the help of proper audio equipment. The back-to-back stacking of electrodes is less susceptible to the destructive popping damage to cell components.

Popping can have several undesirable effects inside the cell. Evidence collected during posttest analysis of cells shows that the force of these small explosions can move catalyst particles from their positions on the hydrogen electrode to positions inside the separator or positive electrodes. The extent of this problem ranges from loss of hydrogen electrode performance to low-level short-circuit formation between the nickel and hydrogen electrodes. If these short circuits occur during the activation or acceptance steps, affected cells should be rejected for flight usage. This requires adequate acceptance-level screening. If this problem occurs while on orbit, consequences can be more serious. In addition, popping has also been responsible for holes in the hydrogen electrode. This not only reduces the effective electrode area, but results in a loss of the hydrophobic nature of the electrode in these spots. A less damaging result of popping is a loss of the surface area of the catalyst particles due to sintering caused by the heat associated with recombining hydrogen and oxygen.

The back-to-back stacking arrangement also results in a shorter, lighter weight stack of plate pairs. There are several other factors that developed in the field of IPV nickel-hydrogen technology that have led to the gradual industry-wide movement toward a modified cell design combining the back-to-back stacking arrangement of the Comsat design with the pineapple slice geometry and wall wick of the Air Force design. This design thus combines the higher energy density of the Comsat design with the improved gas, electrolyte, and thermal management properties of the Air Force design, and it incorporates the positive stack compression devices common to Air Force design cells.

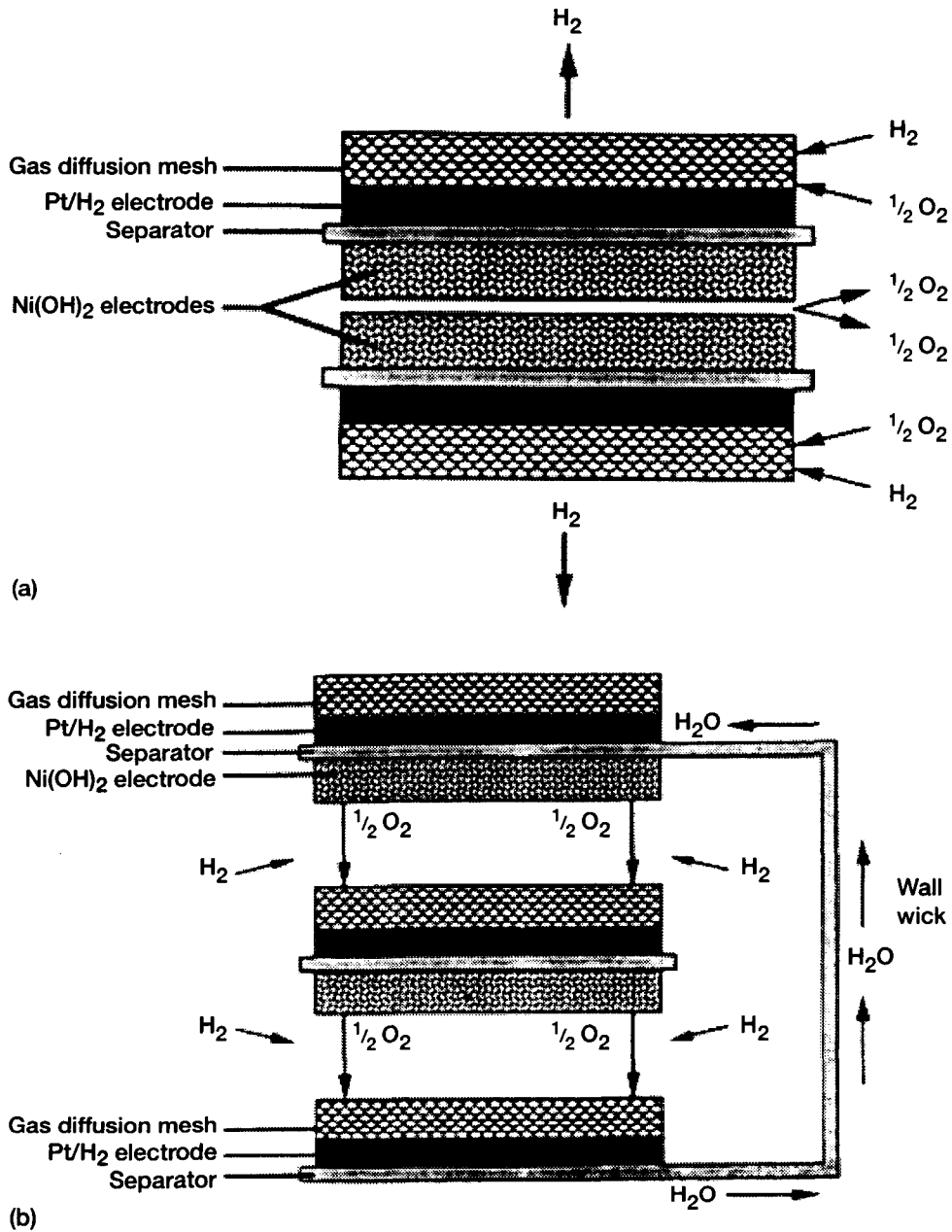


Figure 3.—Stacking arrangements for nickel-hydrogen cell components (ref. 1). (a) Back-to-back stacking. (b) Recirculating stacking.

6.1.2 Wall wick.—The Air Force and combined cell designs have a wettable wall wick to help redistribute electrolyte throughout the cell. The wall wick consists of a thin layer of wettable ceramic material that is flame-sprayed onto the interior surface of the cylindrical portion of the Inconel pressure vessel. Newer versions provide the option of adding catalytic material to the porous ceramic wall wick to encourage oxygen recombination on the wall where the heat can be more easily removed from the cell. Depending on the charge rate, amount of

overdischarge, and the thermal control system, the use of catalyzed wall wicks may not be necessary, but in limited life tests, cells with catalyzed wall wicks (ref. 50), have always outlasted equivalent cells without catalyzed wall wicks. For robust gas and thermal management, it is recommended that catalyzed wall wicks be used in applications where many cycles at deep DODs are required. These applications generally have quite high peak charge rates involving larger amounts of oxygen evolution during the charge cycles.

6.2 Cell Terminals

Aspects of cell terminals that should be considered include their diameter, the sealing method, and whether the cell has both terminals at one end or a terminal at each end.

6.2.1 Types of seals.—There are three types of terminal seals in common use. One type uses molded nylon to make the seal (Ziegler seal), another uses compressed Teflon, and a third uses ceramic bushings. All three have performed satisfactorily. However, each of these has occasionally been a source of difficulty.

Seal leaks have occurred occasionally with both the generic Teflon compression seal and the Ziegler seal designs commonly used. Ceramic seals can leak if the ceramic fractures. The most common cause for leaking in Teflon seal designs is dirt in the seal area. Such seals also can leak if the cell temperature increases rapidly because of the large differential expansion of seal materials. Cells, in general, should be warmed slowly upon coming out of storage to minimize such thermal effects. Nylon-based Ziegler seals, when made with adequate compressive margin on the sealing surfaces are quite robust. However, they do not respond well to high-temperature excursions on the cell terminals, since heat causes the seal compression to anneal over time and, in extreme cases, can cause nylon to soften and completely lose its ability to seal the cell.

Cells with Ziegler seals are subject to a fire hazard from hydrogen leaks if the seals exceed the melting point of nylon (above 260 °C). This most commonly happens if there is thermal runaway in the test chambers or a short circuit on a battery, which can produce enough resistive heating in the terminals to melt the seal and release hydrogen from the cell. It should be noted that each manufacturer has a preferred terminal type, and the terminal type is generally not an option available to the customer.

6.2.2 Terminal arrangement.—Cells can be built with both terminals at one end (rabbit-ear design) or with a terminal at each end (axial design). In the rabbit-ear design, lead resistance to different electrodes in the stack will vary because of their different lead lengths. This can result in the electrodes at the top of the cell (closest to the terminals) discharging first. This preferential discharge pattern can be countered by using thicker electrode leads for the electrodes that are farther away from the terminals. This is done in practice by using three or four different thicknesses of tab material or by configuring individual leads for electrodes at different positions in the cell

pack. Cells using the rabbit-ear configuration have a shorter overall length, and thus, batteries made from these cells require less headspace. In addition, having both terminals at one end reduces the amount of wiring required in the resultant battery. Cell designs with terminals at both ends (axial design) will discharge the plates more evenly. Potential users should discuss these design options with the manufacturer to determine whether significant advantages in wire weights would occur using the rabbit-ear configuration. These considerations involve not only the cell designers, but the battery and spacecraft designers as well.

Terminals that are 0.625 in. long are recommended for cells of 100 A-hr or greater or if high discharge rates are used in smaller cells. The voltage drop in the tabs and terminal can be significant, about a 30-mV drop can occur between the electrode and the cell terminal. This voltage drop can be reduced in some designs by specifying thicker metal leads between the electrodes and the cell terminal.

6.3 Pressure Vessel

Many cells have been built, tested, and flown with a 650-psi maximum operating pressure at the beginning of life. Cells on NASA's Hubbell Space Telescope were designed to operate to about 1200 psi. A safety factor of about three is designed into both of these cell designs. The thin Inconel pressure vessels are designed to leak before they burst. A small gain in energy density is seen in the higher pressure designs at the expense of a higher rate of self-discharge. The self-discharge rate has been found to be directly proportional to hydrogen pressure. But for typical temperatures of 0 to -5 °C, the self-discharge rates are quite low, even in cells at 1000 psi. A higher rate of self-discharge could necessitate a higher recharge ratio for operating temperatures above 10 °C, and therefore, more solar array power would be needed. Depending on the weight, cost, solar array tradeoffs, and other parameters, the lower or higher operating pressure may be better suited for a particular application.

The pressure vessel is a critical component in the performance of a battery. A leak will result in loss of hydrogen capacity and cell dryout, and can ultimately lead to an open-circuit battery failure. For this reason, systems requiring high reliability should either have extra capacity so that operation could continue with one less battery, or have switching circuits to either replace or bypass an open cell. Pressure vessel leaks can arise from loss of electrical isolation between the plate pack and

ground followed by electrolytic corrosion. Leaks can also arise from a seal leak or a flawed pressure vessel. All three of these problems have been experienced, albeit infrequently, in actual practice and, therefore, should be considered as potential conditions during cell and battery procurement. All pressure vessels used for nickel-hydrogen cells should be screened for flaws with special dye-penetrant inspection and should be tested for helium leaks. Defective Inconel pressure vessels usually occur in production lots, with all vessels in a lot being either "good," or infrequently, many containing flaws. If more than 20 percent of a lot is found to be flawed by leak check or dye penetrant inspection, the entire lot of pressure vessels should be considered suspect.

Inconel pressure vessels for nickel-hydrogen cells have ranged in wall thickness from 12 to 50 mils. Wall thicknesses under 30 mils typically require more demanding levels of inspection to assure that no critical flaws exist. Thicknesses below 20 mils are typically produced using chemical milling procedures, thus allowing welds to be done on the thicker parent material. Thicknesses above 40 mils have been used in situations where safety margins above 4.0 have been required.

6.4 Precharge Considerations

As with other cell chemistries, nickel-hydrogen cells are built with a certain amount of what is referred to as precharge. This term is used to describe the amount of any source of capacity that is remaining when a cell is fully discharged. It is based on the balance between the amount of active material in the nickel electrodes and the supply of hydrogen. In the case of a hydrogen precharged cell (also referred to as negative precharge since the hydrogen electrode is the negative electrode), the amount of precharge is measured as residual hydrogen pressure after the cell has been completely discharged. Since there is hydrogen already present as the cell begins the recharge step, the cell is referred to as a cell with hydrogen precharge. An analogous statement can be made for cells that begin the recharge with the nickel electrodes already containing some of the active material in the charged state. In the case of a nickel precharged cell, there is remaining capacity in the nickel electrodes following a complete discharge of the cell. This condition is also referred to as positive precharge since the nickel electrode is the positive electrode in these cells. The following paragraphs discuss the historical trends related to the pros and cons of these two types of precharge settings.

6.4.1 Type and amount of precharge.—Nickel-hydrogen cells built in the late 1970s through the mid-to-late 1980s were designed to have an excess of hydrogen gas in them when fully discharged. The practice of having a residual hydrogen pressure came about because designers felt that at higher hydrogen pressures, the cell would work better and in case there was a low level leak, it would take a longer length of time for the cell to become inoperative. The presence of a residual gas pressure can also help keep the terminal seal gas tight. Cells appeared to work fine until extended periods of storage at low cell voltages were experienced. Early nickel-hydrogen storage techniques calling for cells being discharged and shorted during storage were a carry-over from practices used with nickel-cadmium cells and batteries. Two significant studies confirmed that, at low nickel electrode potentials, hydrogen gas could react with the discharged nickel hydroxide to produce byproducts that resulted in the permanent loss of usable capacity (refs. 2 and 51). These entities have not been unequivocally identified but are known to consist of an insoluble form of cobalt and oxygen. It was found that by having excess positive material relative to the amount of hydrogen, this situation could be avoided.

The use of positive precharge in cells is not without concerns either. When cells are fully discharged and the terminal voltage approaches zero, the potentials of both the electrodes are the same. If the cell has residual amounts of hydrogen, then the nickel electrode is forced to the reducing conditions of the hydrogen electrode, which causes some of the cobalt additive of the nickel electrode to reduce. If the residual capacity is present in the form of positive precharge, then the hydrogen electrode is brought to the oxidizing potential of the nickel electrode. Studies (ref. 52) have shown that, consequently, some of the platinum catalyst oxidizes. Platinum oxides are soluble in KOH solutions and will be plated back onto the hydrogen electrode as soon as the cell is recharged, but in a lower surface area form of catalyst. This is typically not an issue since the relatively high platinum loading level (considering the low current used in these cells in comparison to the 100 to 200 mA/cm² used in fuel cell applications of similar electrode structures) in the negative electrode gives a wide margin of electrode performance. With consideration of both sides of this issue, it is strongly recommended that cells be designed to have at least 10 percent of the nickel electrode in the form of positive precharge. With proper storage and handling procedures, 10- to 15-percent positive precharge

can reliably enable 2 to 3 years of passive cell or battery storage. The issues associated with storage are addressed in a later section.

6.4.2 Methods for setting the level of precharge.— Before cells are sealed shut, the precharge type and level are set by one of several methods. Up until this time, cells have been fitted with valves and pressure gauges. The precharge level is set during the latter stages of the in-cell activation procedure, which uses the manufacturers' proprietary process. This level can be verified during a destructive physical analysis (DPA), but it is usually sufficient to determine the amount at the beginning of life by carefully carrying out the procedure for setting the level of precharge.

Section 5.4.1 explains advantages of setting a level of positive precharge in cells prior to final pinchoff or closure. Because modern cells are set almost exclusively with positive precharge, only this technique is described in detail. In cases where negative precharge is used, cells are simply fully discharged and, typically, 15 psi of hydrogen pressure is added to each cell before it is sealed off. In the process of sealing off a cell, the fill tube is first cold-welded-closed by a compression tool; then the tip is TIG welded¹ to make sure the closure is secure.

Cells designed to have positive precharge do not necessarily sacrifice any of their usable ampere-hour capacity if the precharge is set appropriately. This can be understood as follows. Cells are typically assigned a usable capacity by charging them at the C/10 rate for 16 hr and then discharging them at the C/2 rate to a 1.0-V low-voltage cutoff. All this is carried out at or about 10 °C. Other values may be used depending on the preferences of the buyer. At this point, further discharge at a lower rate and to a lower cutoff voltage would yield more capacity. This lower rate capacity available from the electrochemically active material is usually referred to as "residual capacity." The residual capacity in typical nickel electrodes ranges from 10 to 15 percent of the capacity measured at the C/2 rate to the 1.0-V cutoff. This residual capacity can be used as positive precharge without the loss of usable capacity.

Two general methods can be used to set the desired precharge amount. In the first method, a cell is given a number of charge-discharge cycles to stabilize its capacity. The cell is then discharged at the C/2 rate to a predetermined end-of-discharge condition (for example, 1.0 V at the C/2 rate), and then the remaining hydrogen is vented from the cell via the valve. This would result in

the residual capacity less the 1 atm of residual hydrogen (about 15 percent of the electrochemically active material) being used as positive precharge. As long as the end-of-discharge condition used to set the precharge succeeds in discharging all the usable capacity of the cell, there will be no reduction in cell capacity.

An alternative method that more precisely sets the ampere-hour level of precharge starts with a fully let-down cell (i.e., C/2 discharge to 1.0 V, followed by a C/10 discharge to 0.01 V, followed by a resistive discharge to 0.005 V). At this point, the cell is charged for the number of ampere-hours of precharge that are desired, and then the cell is vented. After the cell is resealed, the subsequent charging current will result in additional and equal amounts of nickel and hydrogen capacities. The temperatures, cutoff voltages, and charge or discharge currents may vary according to the manufacturers' specific procedures.

7.0 Design Considerations for Low-Earth-Orbit and Geosynchronous-Earth-Orbit Applications

As nickel-hydrogen technology matures and experience is gained from life-cycle testing and on-orbit performance, designs that are specific to LEO and GEO applications are emerging. GEO applications that require only a limited number of cycles over their 10- or 15-yr mission life can be made lighter in weight than a LEO design of the same capacity. Since most GEO applications are commercial telecommunication spacecraft, weight and profit considerations are paramount. With these drivers, factors that enhance the usable specific energy and energy density are emphasized. These include charging to high states of charge and discharging to deep depths of discharge. Larger amounts of waste heat are associated with this type of cycling. Conditions favoring the gamma phase of the charged active material are also employed. These include the use of higher concentrations of KOH and lower recharge temperatures. These conditions must be traded off against the added expansion by the nickel electrode that accompanies these conditions. Another possible tradeoff is the use of higher loading levels in conjunction with lower concentrations of KOH. Cell designers have a number of options and tradeoffs relative to designing for GEO applications.

LEO applications, on the other hand, must be designed to accommodate the degradation processes that take

¹Gas tungsten arc welded.

place during the many cycles that accompany long-term missions in this orbit. Results now available from life-cycle testing of many types of nickel-hydrogen cells under a wide spectrum of conditions have been helpful in quantifying the rates of the different naturally occurring degradation mechanisms within these cells and permitting designs to be selected and cycling conditions to be used that would minimize these problems within the performance requirements of the mission. A recent publication (ref. 36) reviewed the status of these mechanisms on the basis of the results of several ongoing life-cycle data-basing programs. Specific suggestions for these applications are outlined in subsequent sections. It is interesting to note that on a daily basis, the amount of overcharge that occurs in a GEO battery is about the same as occurs in a LEO battery with a recharge ratio of 1.04.

8.0 Alternative Cell Configurations

Several variations of nickel-hydrogen cell and battery configurations have been developed in recent years. They represent significant departures from the original IPV configuration that first appeared in the early 1970s. However, these configurational variants possess unique qualities that merit closer examination for certain missions. These alternative configurations are based on the same component database and the same established manufacturing capability as the more traditional IPV configuration. As a result, these newer concepts may experience an easier acceptance into the user community. Advantages brought forth by these newer configurations appear to be best manifested in smaller spacecraft with power requirements below 1.0 kW. Some of them offer a significant decrease in the "footprint" (the area taken up by the completed battery), whereas others offer an increase in the battery's energy density. In the following paragraphs, each of these variants is addressed: their strong and weak points are noted, their advocates identified, and the state of their technology briefly described. Since the databases for these design variants are not nearly as extensive as those for the IPV cell designs, they are not treated in the same depth as the IPV family of designs.

8.1 Two-Cell Common Pressure Vessel (CPV)

During the development of larger IPV designs, pressure vessel fabrication constraints required higher capacity cells to have their girth weld in the middle of the cell

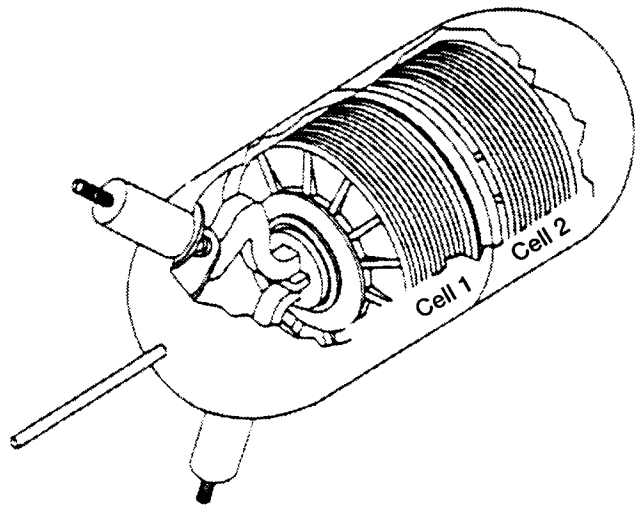


Figure 4.—Two-cell common pressure vessel battery (ref. 1).

and the cell stack itself to be split between the upper and lower halves of the cell (ref. 53). It was an easy step to connect the two stack portions in series rather than parallel (fig. 4 and ref. 1).

This results in a battery unit that has a voltage twice that of the IPV version with half the ampere-hour capacity. A reduction in the footprint can result from this configuration. That is, for a nominal 28-V battery, only 11 series-connected devices are required using the two-cell version compared with 22 cells of the more traditional IPV concept. For applications where lower capacity cells are required, batteries built with CPV devices have certain advantages.

There has been some encouraging life-cycle testing on 3.5-in.-diameter pressure vessel batteries of this type. About 26 000 LEO cycles at 40-percent depth of discharge were accumulated prior to discontinuing the test because of lack of support. Life-cycle testing of 2.5-in. cells using stainless steel cases has also shown encouraging results. These two-cell devices with stainless steel cases are a less expensive alternative to the lightweight, but more expensive, devices with Inconel case material. This design variant has been discontinued in favor of the more traditional thin-wall Inconel aerospace designs. The energy density for a single two-cell battery with the heavyweight case is about 35 W-hr/kg, and the energy density of the same device inside a lightweight case is about 54 W-hr/kg.

The main concern associated with the CPV configuration is the possibility of electrolyte bridging from one section of the two-cell battery to the other. This would

ultimately result in transfer of electrolyte from one cell to the other. Eventually, there would be a loss of performance of one of the cells as it dried out. Cell designs typically include provisions to prevent the formation of an electrolyte bridge between the upper and lower cell segments. Designs have been produced with and without wall wicks.

8.2 Single Pressure Vessel (SPV)

Twenty-two-cell, SPV batteries were developed by both Johnson Controls and Eagle Picher-Joplin (fig. 5). These designs, as the name implies, require only one pressure vessel (ref. 53). Individual cells within an SPV battery are placed in bags or rigid containers to preclude electrolyte communication between cells. This configuration possesses certain energy density and footprint advantages. Both these developments stemmed from agreements with Comsat Laboratories; currently all manufacturing efforts are taking place within Eagle-Picher Industries. SPV designs also have certain advantages regarding volumetric energy density and internal impedance. This concept has received a large amount of attention from commercial satellite manufacturers.

A key issue related to this technology is concerned with maintaining a constant vapor pressure of water throughout the battery by minimizing the transport of water vapor by condensation from warmer portions of the battery to cooler portions. In addition, oxygen generated in one cell during recharge can move to another cell, where it can recombine with hydrogen to form water. Both of these processes disperse the electrolyte volume and concentration among the battery cells. Adequate heat transfer is also a concern since the surface area for heat rejection per unit of battery capacity is much lower for this type of battery than for IPV designs.

Another issue is related to the electrolyte filling or activation procedure. Typically, a prescribed amount of electrolyte is added to each cell as part of the assembly process. Cell-to-cell preferences for electrolyte quantities, if they exist, cannot be accommodated using this method. Typically, IPV cells are initially flooded, and then all excess electrolyte is drained out. It has not been fully established that a proper electrolyte amount can be calculated beforehand—some cells can be left too wet and others too dry.

As in the two-cell concept, electrolyte communication between the cells in an SPV battery must be prevented. Advanced design concepts have been generated within this configuration using methods that prevent the escape

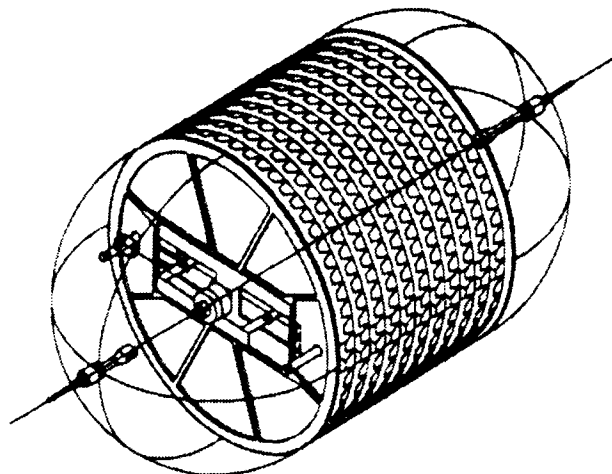


Figure 5.—Single pressure vessel battery design (ref. 1).

of electrolyte and oxygen from individual cells. Recombination devices have been introduced to prevent passage of oxygen gas from one cell into another where it may recombine with hydrogen to form water, changing the electrolyte concentration of the cells. Temperatures within SPV devices must be kept above 0 °C to prevent the formation of ice, which can block the free passage of hydrogen through the recombination device. Modifications to the encasement material used for each cell have reduced electrolyte communication between cells. Footprint and energy density advantages are available with this design, particularly in smaller battery sizes. Thermal management issues are more complicated with these battery types. The Naval Research Laboratory tested this concept in space with a pioneering launch that demonstrated the feasibility of this technology (ref. 54). SPV batteries were selected for use in the Iridium fleet of satellites. There have been no reported failures or difficulties with this configuration. Energy density numbers reported by the manufacturer for a 50 A-hr, 22-cell battery have ranged from 50 to 55 W-hr/kg.

8.3 Dependent Pressure Vessel (DPV)

In the dependent pressure vessel configuration (fig. 6) the components for one cell are placed within a flat-sided container that is gas tight, but that cannot withstand the internal pressure of the cell without assistance (ref. 55). The DPV concept employs rigid end plates and tie bolts to strengthen the battery so that it can withstand the high operating pressures of nickel-hydrogen cells (500 to 1000 psi). A few cells of different sizes have been built and are currently undergoing life-cycle testing. This

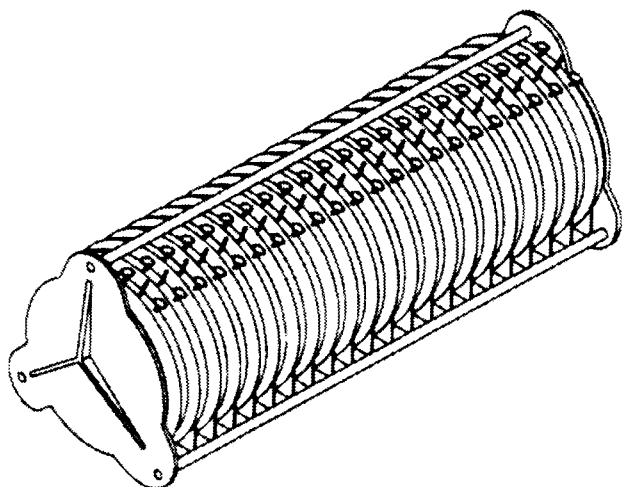


Figure 6.—Dependent pressure vessel battery design (ref. 1).

configuration has significant advantages related to reduced footprint and simplicity of construction in comparison to batteries based on IPV designs. Furthermore, cells do not suffer from the potential problems associated with CPV and SPV designs—electrolyte bridging and water vapor and oxygen transport—which are driven by thermal gradients within the overall battery. Conductive plates placed between cells and affixed to a cold plate provide heat rejection from the battery. A potential issue with this type of battery would arise if one of the cells lost pressure relative to the others. A cell with a low internal pressure relative to the others could disrupt the pack tightness unless internal cell supports were provided. Cycle life information was reported as of 1999 (ref. 56).

9.0 Nickel-Hydrogen Cycle-Life and Charge-Control Considerations

The authors have conducted an ongoing review of the results of life-cycle tests carried out at the Navy facility in Crane, Indiana, under NASA and Air Force sponsorship. Several of these reports have appeared in the open literature (refs. 36, 57, and 58). The authors performed a study to determine which factors most impact cycle life in nickel-hydrogen cells. The results of that study suggest that cell temperature, the depth-of discharge, and the recharge ratio are the most significant factors. The recharge ratio is the ratio of the number of ampere-hours returned to a cell during the charge portions of the cycle divided by the number of ampere-hours discharged dur-

ing the discharge portion of the cycle. It was further noted that some cell designs performed better than other cell designs.

9.1 Status of Nickel-Hydrogen Technology and Life-Cycle Testing

So that researchers could gain confidence in the use of nickel-hydrogen cells for particular applications, extensive life-cycle testing programs were initiated starting in the 1980s. The majority of these testing programs used IPV cells from different manufacturers, and the cells were cycled under different conditions of temperature, DOD, and recharge ratio. Cells were tested either individually or in multicell packs. Cycling was conducted to some predetermined failure criteria—usually a low end-of-discharge voltage limit. NASA, the U.S. Air Force, and other Government organizations have sponsored extensive testing programs. Cell manufacturers and spacecraft prime contractors have also carried out selected testing programs. A large percentage of the testing being done for different NASA and Air Force sponsors was conducted at the Navy facility in Crane, Indiana; other tests were carried out at NASA Glenn, the NASA Marshall Space Flight Center, Lockheed Martin in Denver, Colorado, Space Systems Loral in Palo Alto, California, and Eagle-Picher Industries in Joplin, Missouri. Readers are also referred to the proceedings of the NASA Aerospace Battery Workshop and the Intersociety Energy Conversion Engineering Conference (IECEC) for many references to the results of life-cycle testing, DPA analyses, and theories regarding degradation mechanisms for nickel-hydrogen cells. Several of these are referenced in this report.

In these testing programs, cycling conditions have often been varied in an attempt to introduce different amounts of stress to the cell or cells being tested. Researchers felt that testing cells to failure at different temperatures, DODs, and recharge protocols would produce data showing a relationship between the cycle life and the amount of stress placed on the cell by the selected test conditions. Results of these programs have shown that nickel-hydrogen cells usually cycle longer than nickel-cadmium cells when cycled to the same DOD or have significantly higher usable energy densities when cycled under conditions that resulted in the same cycle life. Only limited analysis of these cycling data and details of posttest DPA analyses are available. Published reports from tests conducted at Crane consist of trend plots of end-of-charge and end-of-discharge voltage,

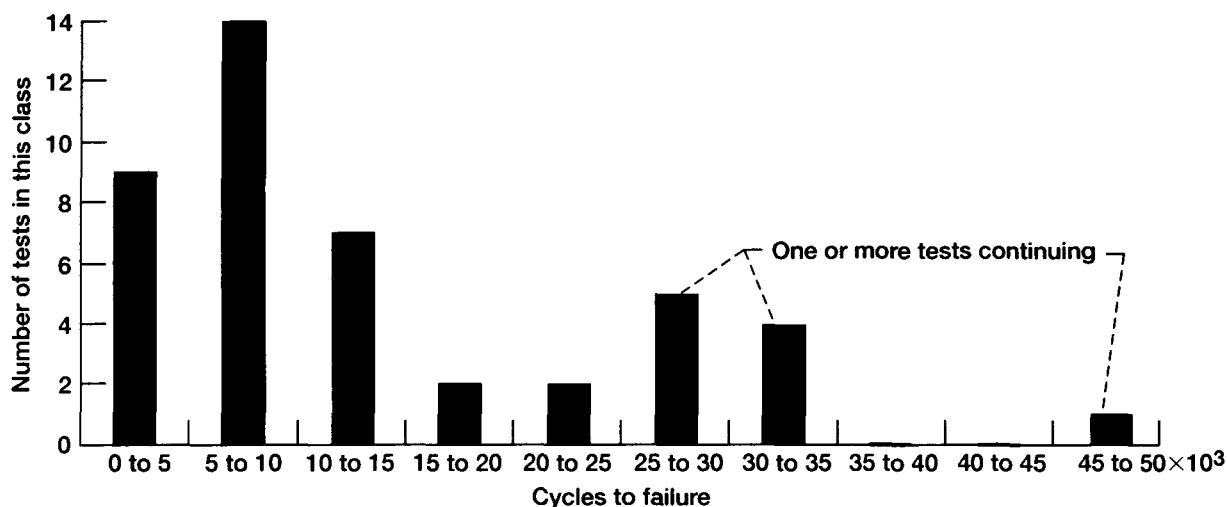


Figure 7.—Span of life-cycle tests conducted at 60-percent depth of discharge. (The number of cells in a cell pack can range from 1 to 10 depending on the design of the test.)

end-of-charge and end-of-discharge pressure, and recharge ratio. From these trend plots, only degradation in cell voltage and estimates of the amount of plaque corrosion can be made. The effect of factors such as the cell design details, the component quality, and the heat-rejection scheme used for the test will be necessary for a clear interpretation of these test results. Large amounts of test data have been collected and stored in databanks that are accessible with permission of the test sponsors.

Certain trends are becoming clear as attempts are made to categorize the different relative amounts of stress when cells that are similar in design are compared directly. It has been shown from these cycling studies that (1) cells using 26 wt% KOH as electrolyte cycle longer than comparable cells filled with 31 wt% or higher concentrations of KOH, (2) cells with electrodes configured in a back-to-back arrangement usually outperform, in terms of cycle life, cells configured in the recirculating arrangement, (3) cells with catalyzed wall wicks outperform comparable cells that do not have catalyzed wall wicks, and (4) cells cycled to 60-percent DOD at 10 °C tend to last longer than cells cycled to 60-percent DOD and tested at -5 °C. When cycled to 40-percent DOD, cycling at both these temperatures has resulted in cycle lives well beyond 40 000 cycles.

Available data on the amount of electrolyte in a cell were studied. Cells containing less than 2.8 g/A-hr of their nameplate electrolyte capacity are prone to separator dryout problems during extended cycling, whereas cells with more than 4.8 g/A-hr tend to be overly wet and susceptible to popping damage during the charge portion of the cycle. The actual ampere-hour capacities of

most of these cell designs are not known. The manufacturer is at liberty to assign a nameplate capacity designation to his cells. A cell's actual capacity depends on the temperature and recharge conditions at which the cell's capacity is measured. A paper by Wheeler (ref. 59) suggested a standardized method of assigning a nameplate capacity to IPV cells as manufactured by Eagle-Picher Industries. However, the ratio of the actual capacity to the nameplate capacity is not a fixed number.

The trends and results just listed are a reflection of the robustness of the cell design, the quality of the positive plates, the electrolyte fill amount, the thermal environment of the test, the charging protocol, and/or the recharge ratio. With this wide range of variables and large span in the most recent life-cycle testing results, it is difficult to precisely quantify a general relationship between cycle life and DOD for nickel-hydrogen cells and batteries.

Figure 7 is a histogram showing the results as of 1999 of life-cycle testing from several test programs cycling cells to 60-percent DOD. (Data are from Air Force, Lockheed Martin Associates, Glenn, and NASA International Space Station databases). The histogram was generated by reviewing cycling data at 60-percent DOD and noting the first test failure associated with cells in that group. Most tests were made up of 5 or 10 cells, but others had only between one and three cells. The cycle at which the first cells failed were placed in 5000 cycle bins and then plotted in the form of a histogram. The actual data span ranges from less than 1000 cycles to failure to over 50 000 cycles and still cycling. The extremely wide span in results was likely caused by

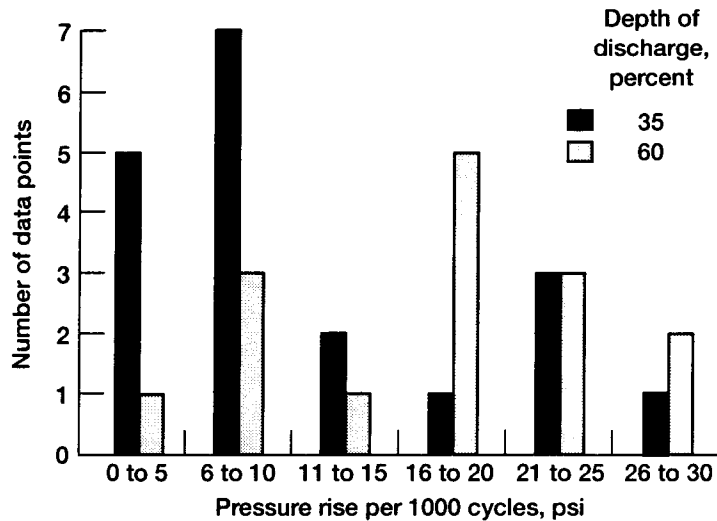


Figure 8.—Span of estimated corrosion rates at different depths of discharge. (Data from Air Force, Martin Marietta, Glenn, and NASA International Space Station databases.)

testing cells under cycling conditions that were inappropriate for that particular cell design. Under other cycling conditions of temperature and recharge ratio, these cells may have cycled for longer periods of time. Figure 7 alerts the reader to the effect of uncontrolled or unknown factors that impact the cycle ability of IPV nickel-hydrogen cells.

Figure 8 is another example of the effect of uncontrolled or unknown factors. In this figure, the rate of corrosion of the nickel electrode sinter is related to the pressure increase measured by the surface-mounted strain gauge at the end-of-charge for tests that were run at 35- and 60-percent DOD. Figure 8 was generated by measuring the average slope of the end-of-charge pressure over the duration of the cycling test. The slope is expressed in pounds per square inch per 1000 cycles. Cells were divided into groups depending on the rate at which the pressure increased during the course of cycling. As in figure 7, a wide dispersion is seen within both DOD data sets. As expected, there is a higher average pressure increase at 60-percent compared with 35-percent DOD, but the degree of overlap is considerable. As did the cycle-life data, this plaque corrosion data suggests that there are variables involved that are either not under control or not understood. One such variable may involve gradual shifts in state-of-charge that influence the pressure readings.

Extensive DPA studies of cycled cells have been carried out at several laboratories (refs. 36, 60, and 61). These studies have revealed that the cycle-life capability

of any particular cell depends on what has taken place during each of the four phases a cell passes through (1) design, (2) manufacture, (3) storage, and (4) cycling. A recent multiyear study carried out in the laboratories of The Aerospace Corporation, which incorporated cycling results generated at the Navy facility in Crane, Indiana, with selective DPA studies of cell components from these same cells, has resulted in significant advances in understanding the relationships between cycling stress and cycle life (ref. 41). Degradation in performance during the cycling phase was shown to result from contributions related to (1) separator dryout, (2) plate expansion, (3) plaque corrosion, and (4) formation of an electrochemically inactive form of nickel hydroxide.

To maximize the cycle ability of any particular cell design for any specific application, careful consideration must be given to all four phases that a cell passes through. Factors resulting in abbreviated cycling can result from difficulties during any one of these four phases in the life of a cell or battery. Within each of these four phases, there are one or more factors responsible for performance degradation that must be fully understood. The following sections of this report discuss and refer to the different factors that affect the overall cycling capability of nickel-hydrogen cells. Unfortunately, not all the factors are fully understood. The recommendations presented or discussed in the references were intended to take advantage of the knowledge base that has been accumulated from the many life-cycle tests and

DPA studies that have been completed or are still in progress.

9.2 Nickel-Hydrogen Charge-Control Considerations

The use of appropriate charge-control methods during the operation of nickel-hydrogen batteries is critical for realizing the extremely long cycle life and high DOD capabilities of these batteries. For this reason, cell designs must be coordinated with spacecraft designers to be sure that the charge-control approach is compatible with the cell design and the thermal rejection subsystem. An inappropriate charge-control method that uses an excessive amount of overcharge or allows the cell to experience an excessively high end-of-charge voltage will shorten the mission life of an otherwise good cell and battery design. Although most nickel-hydrogen cell designs can tolerate significant amounts of overcharge for a few cycles without catastrophic damage, overcharge has historically been one of the major causes for the accumulation of damage in cells leading to premature failure. Thus, the major charge-control issue is returning sufficient recharge to maintain all cells in a battery at an acceptable state of charge, while limiting overcharge stresses to the minimum possible level.

Overcharge stress in nickel-hydrogen cells generally arises from two effects. The first of these is the elevation of temperature within the cells in response to added amounts of oxygen recombination during overcharge. An increase in cell temperature increases the rate of self-discharge as well as the rates of all the gradual degradation processes occurring over the battery's life. In addition, an increase in overcharge typically increases the thermal gradients across the individual cells, both in the radial and vertical directions. Thermal gradients can increase the stress on cells by enabling water vapor movement and condensation, by concentrating oxygen evolution in localized regions of the cell stacks, and by localizing the charge-discharge cycling in the cell stacks. If average cell temperatures are kept below 10 °C, particularly when the state of charge is high, self-discharge losses near the end of charge are usually not a significant issue. Under these conditions, trickle-charge rates no greater than C/100 are required to maintain a good state of charge. In addition, thermal gradients between the hottest and coldest parts of each cell in a battery should be kept below 10 °C to minimize water transfer from the stack, or between multiple stacks in larger cells. Remaining within a 10 °C

thermal gradient will also keep typical stresses from localized current concentrations at acceptable levels.

The second cause of overcharge-related stress in nickel-hydrogen cells arises from recombining oxygen produced at the nickel electrode on the platinum catalyst. Such recombination, or popping in more extreme cases, results when the partial pressure of oxygen gas at the platinum surface exceeds about 2 percent of the hydrogen pressure. The ability of cell designs to manage high rates of oxygen evolution without damage to the cell stacks can vary significantly. Cell designs should not have free electrolyte. In addition, the evolution of oxygen during cell operation should be carefully controlled. Cell designs using catalyzed wall wicks have demonstrated significantly longer cycle lives in comparison to similar cells that did not have catalyzed wall wicks (ref. 62). Recharge protocols can be adjusted to reduce the rate of oxygen evolution and the associated degradation to the cell components. This is most effectively done by placing a limit on the battery recharge voltage and by assuring that the state-of-charge of all cells in the battery remain well matched. The rate of oxygen evolution is exponentially dependent on cell voltage. For this reason, a temperature-compensated voltage limit (V/T) type charge-control should always be imposed for LEO cycling conditions to limit the charge current at high states of charge, either for primary or backup charge-control purposes. The primary charge control should effectively recharge the battery by returning an appropriate recharge ratio to compensate for self-discharge losses. Cell pressure (compensated for temperature) provides an excellent indication of whether adequate recharge is being applied, and may be used either directly by the charge-control system or simply as supporting data for battery management. If the charge-control system uses pressure to control recharge, a number of pressure set points should be provided to accommodate pressure drift and redundant pressure indicators should be provided. For GEO cycling conditions, charging to a fixed recharge ratio or to a pressure limit is recommended.

10.0 Manufacturing Issues

The identification and resolution of issues relating to the manufacture of nickel-hydrogen cells has resulted in a significant database, permitting a variety of quality and performance problems to be addressed so that they can be avoided in the future. Several of these issues are covered in this section.

10.1 Manufacturing Issues Prior to Assembly

There are processes that occur prior to cell assembly that should be monitored to ensure quality components. In addition, screening tests that verify that components have the proper properties can be used to characterize components and identify quality and manufacturing issues prior to assembly in a cell.

Nickel plaque material is typically specified according to a desired degree of porosity. This averages about 82 percent, but it is usually lower for plaque made by the slurry process and somewhat higher for plaque made by the powder process. However, specification of plaque porosity is not sufficient to ensure good quality material. Plaque material can be made improperly and still have the proper value of overall porosity. Desirable plaque material has a particular pore size distribution that coincidentally has an associated value for its porosity. However, the reverse is not true. Material that has been sintered improperly (too high a temperature or too low a belt speed in the sintering furnace, for instance) can result in product that has a surface layer consisting of very fine pore sizes and an interior that is more porous than desirable such that, on an overall basis, the material has the specified porosity. If plaque material possesses an undesirable pore size character, impregnation or performance problems can result. A screening test has been developed to address this issue (ref. 63). It has been utilized to detect and measure this and other anomalous sinter conditions. The technique is referred to as scanning porosimetry. The equipment for this technique consists of piezoelectric xyz positioners developed for use in scanning tunneling microscopy. For this evaluation, a sample of electrode is mounted such that its width is placed under a fine tungsten whisker that can detect either a conductive portion of the sinter material or a nonconductive area of a pore within the plaque. A computer program uses the piezoelectric positioners to lift the whisker, move it a few micrometers, and then lower it onto the mounted sample of plaque. After sampling the mounted piece of plaque many tens of thousands of times, a statistical analysis identifies the patterns of conductive and nonconductive areas of the sample, and generates pore size distributions in different locations across the width of the sample.

Impregnated plaque material is usually called plate. Individual electrodes are cut from a large piece of impregnated plate. The amount of active material electrochemically deposited into the plaque can be specified in terms of the grams per cubic centimeter of the void

volume of the sinter or in terms of the grams per square centimeter of the frontal area of the plate. It is typically measured according to the weight pickup of plaque material. Here again, it is generally assumed that the active material has been deposited evenly throughout the plate interior. The finished plate is tested for usable capacity per unit area as a way of measuring the suitability of the plate for inclusion into the cell assembly process. Problems arise when active material has been disproportionately deposited near the surface of the plate. This type of plate will have very low porosity near the surfaces and thus poor mass transport characteristics. It will also have poor capacity per unit of frontal area. A technique using ion microprobe analysis has been developed to characterize the distribution of active material across the thickness of an electrode (ref. 18). Ion microprobe analysis has been used to relate substandard electrochemical performance to a misdistribution of active material. Scanning electron microscope photos of this same electrode qualitatively confirmed the presence of a higher loading level at the front and back surface of the plate samples.

Quality problems can also arise if the degree of acidity (pH), temperature, or solution mixing in the impregnation bath is not properly controlled and excessive sinter corrosion takes place. Loss of sinter material introduces errors in interpretation of weight pickup numbers and results in a finished electrode that would be less resistant to expansion during cycling.

Electrochemically deposited active material forms as a dense layer tightly bound to the nickel substrate material. As such, nickel electrodes are not ready to cycle efficiently immediately following the impregnation process and washing to a neutral pH. Nickel electrodes typically undergo a formation procedure designed to exercise the active material. This activation sequence involves a series of charge and discharge cycles that reduce the density of the material and allow freer access of the electrolyte. It is recommended that this activation process be carried out prior to the electrodes being built into a completed cell. When the electrodes are formed outside of the cell, they may be *mêlangé* in a manner that will result in cell packs that are more closely matched than if they had been assembled in a random manner.

Once the electrodes have passed through their formation process, representative samples are subjected to a stress test before the entire production lot is accepted for use in cells. A typical stress test consists of 200 charge-discharge cycles at the 10C discharge rate in flooded test fixtures. For a single 3.5-in.-diameter electrode, this

would be about 12 A. The amount of swelling or number of blisters (indicative of poor adherence of the sinter material to the screen substrate) is measured, and the plate lot is either accepted or rejected on the basis of predetermined criteria.

It is recommended that manufacturers not only be required to meet the specified overall porosity specifications for the plaque material, but also initiate the use of semiautomated microscopic techniques using appropriate software analyses of pore size distribution on representative samples of plaque material. Currently, a poor-quality surface character of plaque material is only discovered through difficulties in the impregnation process or poor cell capacity. High surface loading levels, low capacities per plate, and poor stress test results are indicative of poor quality plaque material. Plaque material with the proper pore size character typically loads evenly and passes the stress test much more easily.

10.2 Cell Assembly and Acceptance Problems

At this point, the qualified cell components are assembled onto the plastic core piece. The plate pack of cathodes, anodes, separators, and gas screens is usually compressed between end plates and one or more Belleville washers. The nickel leads are then welded to their respective terminals, and the plate pack is slid into the Inconel pressure vessel. The two portions of the pressure vessel are then welded together using a TIG, an electron beam, or a laser welder. The cells are first flooded with electrolyte and drained to varying degrees; then, the active material is overcharged to the point where ample amounts of oxygen are evolved. Following assembly into cells and electrolyte addition, a burn-in procedure that is particular to the manufacturer is carried out. The burn-in step distributes the electrolyte throughout the cell components and stabilizes cell capacity. After a number of charge-discharge cycles, excess electrolyte is drained from the cell. Proper activation should leave a cell with no free electrolyte, the gas screens free of liquid, and a well-controlled amount of electrolyte having the desired concentration. This concentration can be determined by a DPA.

Just before the cells are finally sealed, the level of precharge is set. This topic is covered in detail in section 6.4.2. Following burn-in, cells typically undergo preacceptance cycling to stabilize performance, after which they are acceptance tested. As part of the acceptance testing, newly built cells are evaluated for low-level short circuits using, for example, a 72-hr capacity reten-

tion test. The rate of capacity loss during open-circuit stand as a function of temperature and hydrogen pressure is reasonably well known for cells that do not have low-level internal short circuits. Thus, the capacity remaining after the 72-hr open-circuit stand test can be evaluated against the known rate of self-discharge in the absence of any short circuits. Manufacturers tend to suggest very low values for the acceptable amount of remaining capacity. Unfortunately, this test was not sensitive enough to exclude cells that had potentially significant short circuits. A more sensitive test has been developed (ref. 64) to give an accurate measurement of low-level short circuits that might otherwise have gone undetected using the typical capacity retention requirements of the open-circuit capacity retention test. Special statistical analysis of the manufacturer's charge retention test data has been used to indicate when the more sensitive test would be appropriate.

The loss of electrical isolation between the cell case and the internal stack of electrodes will typically result in pressure vessel corrosion followed by cell failure. Such an open-circuit failure must be avoided. A test based on polarization of the case (internal surface of the pressure vessel) due to its contact with the plate pack has been developed (ref. 18) and successfully used to verify that the cell case is isolated following cell activation. Manufacturers often use one or more x-ray techniques to detect contact between the tab bundle and the inner wall of the cell case. The combination of this test with existing manufacturing checks for gross short-circuiting problems is a key technique for assuring cell reliability and manufacturing quality control. Since several recent satellites have reported what appear to be open failures, it appears that this is not a trivial problem.

10.3 Cell Acceptance Test Procedures

Table I shows an example matrix of acceptance tests for cells to be used with a flight program. This matrix calls for a cell-level vibration test, which is typically only required of a new cell design. The exact matrix of tests and detailed descriptions of procedures, pass/fail criteria, rework limitations, and other parameters, must be incorporated into the contract between the customer and the manufacturer. Individual programs have different requirements with respect to minimum and maximum cell capacity, charge retention following open-circuit stand, spread in the ampere-hour capacity among cells, and other factors.

TABLE I.—TYPICAL CELL ACCEPTANCE TEST MATRIX

Test	Performance measurement												
	Weight and dimensions	Workmanship	Identification and product marking	Internal impedance	Leakage	Capacity	Overcharge voltage	Charge retention	Strain gauge bridge design	Random vibration	Discharge voltage	Hermeticity	Foreign particles
Evaluation of product	√	√	√										
Internal impedance				√									
Electrolyte leakage					√								
20 °C capacity						√	√				√		
10 °C capacity						√	√				√		
0 °C capacity						√	√				√		
Hermeticity												√	
Charge retention								√					
Strain gauge bridge characterization									√				
Vibration test										√			
Radiographic examination													√

11.0 Battery Design Considerations

This section addresses a number of key battery design considerations, including thermal control of the cells, bypass circuitry, pressure monitoring, and storage. In addition to these items, cell surfaces and battery terminals should be protected from electrical contact, surface finishes should be controlled for proper emissivity, and all battery connectors should be protected.

11.1 Attachment to Cold Plate

Heat transfer considerations are more important in nickel-hydrogen batteries than in nickel-cadmium batteries. This is due to a greater susceptibility to water vapor transport from warmer to cooler portions of the cell as well as lower charge efficiency at high temperatures. Water transport has been known to cause performance problems due to reductions in the amount of electrolyte remaining in the cell pack (ref. 39). Since the plate pack in nickel-cadmium cells typically has better thermal contact with the cell walls than in nickel-hydrogen cells, the driving force for water vapor movement from one

portion of the cell to another in nickel-hydrogen cells is much greater. Nickel-hydrogen cells can be assembled into batteries using thermal skirts that conduct the heat to a baseplate located beneath the cells. Many battery designs have used this approach.

A second configuration uses a thermal flange located at the midpoint of the cell. This second design was used for many batteries that were produced by Hughes (now Boeing) and for some manufactured by Eagle-Picher. Figure 9 shows the difference between these two methods. Both designs require the cells to be electrically isolated from the thermal sleeve portion of the battery. In the case of the thermal skirt design, care must be taken to not have an excessive amount of the radiative heat loss from the bottom of the cell to the cold plate. This can cause water vapor originating from the electrolyte to condense onto the cold portions of the cell case (ref. 39). The centrally located option with its thermal flange has a larger footprint since the cells have a greater spacing between each other. Locating the flange at the midpoint of the cell instead of using the thermal skirt configuration results in about one half of the thermal gradient along the length of the cell. For applications where close thermal

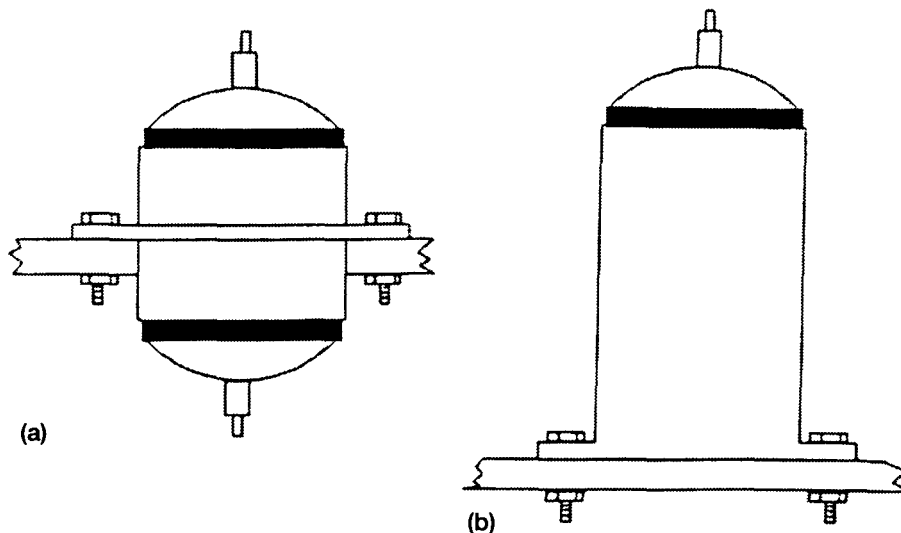


Figure 9.—Attachment options used with nickel-hydrogen cells (ref. 1). (a) Centrally located flange. (b) Thermal skirt.

control is required, centrally located thermal flanges are recommended. The thermal skirt design, if used, must preclude the condensation of water vapor at the lower cell dome that is in radiative view of the cold plate. Waste heat is removed from the cold plate via heat pipes or is radiated directly to space. It is recommended that, for either overall system thermal design, temperature gradients measured from the hottest to the coldest portion of the cells be kept below 5 °C. This limitation reduces the tendency to develop undesirable concentration gradients and transpiration of water to the colder walls.

11.2 Cell Operating Temperature

Nickel-hydrogen cells have a higher rate of self-discharge than nickel-cadmium cells, and this rate increases rapidly with temperature. It is important to design the battery to operate at a low temperature in keeping with the ability to reject large amounts of waste heat associated with a large spacecraft. It is suggested that the mean temperature at the cell's midpoint be about 5 °C. Mean-temperature design points above 10 °C or below -5 °C are not recommended. Above 10 °C, the charge efficiency decreases and the self-discharge increases, making reliable thermal control and charge maintenance more difficult. Below -5 °C, the resistivity of the electrolyte and the active material in the nickel electrode increase. In a recent Aerospace Corporation publication, life-cycling data that were accumulated as part of NASA- and Air-Force-sponsored test programs were reviewed extensively and compiled with extensive DPA studies

on selected cell components. This publication suggests certain advantages of operating at -5 °C (ref. 41). The highest heat loads will occur during the latter portions of discharge when the discharge current is high, and at the transition from charge to discharge where the oxygen recombination is the greatest. These heat loads can be accurately modeled from documented thermal design studies (ref. 43) and should be validated for each battery usage in a power system thermal vacuum test.

11.3 Use of Strain Gauges and Thermistors

It is strongly recommended that strain gauges and thermistors be used. There has been a gradual acceptance of the reliability of these devices to where they have been incorporated into the charge-control function of several spacecraft. Onboard ampere-hour integration may be the primary form of charge control, with pressure as a backup. Pressure monitoring is an excellent way of monitoring the overall state-of-charge of the battery as well as any drift that may occur in either the end-of-charge pressure or the end-of-discharge pressure. The use of as many as four strain gauges and four thermistors per battery is recommended. Reference 41 details the changes that have been found to take place in cell pressure because of corrosion of the nickel sinter material. That same reference presents evidence of an upward drift in the reading of strain gauges. On the basis of a few results where the internal pressure was compared with the reading of the strain gauge, it appears that the rate of upward drift in the strain gauge reading is higher when cells are

cycled at 10 °C than when cells are cycled at -5 °C. Charging protocols and operating temperature have been found to significantly affect the rate at which the end-of-charge pressure increases as the cell is cycled. The use of multiple sensors permits majority voting between at least three of the operational sensors. Thermistors should be located as close as possible to the warmest portion of the warmest cell, which can be predicted with thermal models.

Pressure or onboard ampere-hour integration is recommended as the primary form of charge control for GEO applications. For LEO applications, where the charging voltage must be more closely controlled, temperature-compensated voltage is recommended as a hardwired backup charge-control mode if the batteries are charged to a pressure limit or are charged to a recharge ratio. Over-temperature protection should always be provided to prevent catastrophic overcharge or thermal runaway.

11.4 Bypass Diodes and Mechanical Switches

The use of bypass diodes (ref. 65) is not universally accepted as a way to bypass a cell that has failed "open." The spacecraft's architecture and redundancy provisions determine whether or not bypass diodes are the most weight-effective way of dealing with a power system problem. Typically, bypass diodes or mechanical switches are required where a cell-level redundancy is selected, and they are not used when a battery-level redundancy is selected. In addition to adding weight to the battery system, diodes affect the thermal control of the overall spacecraft. A review of possible types of mechanical switches appeared in the 1998 ESA Power Systems Workshop (ref. 66).

12.0 Battery Acceptance

The acceptance of batteries should be based on a range of tests and analyses that are sufficient to verify an adequate performance level over life in each application. Tests typically required at the battery level must verify the workmanship of all battery hardware, including thermal and electrical interfaces within the battery structure. Some tests required as part of the Space Station Program are listed in table II. Shock and thermal vacuum cycling tests are typically run in addition to the tests in table II.

The following tests are recommended:

(1) Continuity checks should be done for all electrical paths from the battery connector pins, and isolation tests should be done for all isolated components. The isolation between the cell cases and battery structure in particular is critical and must be guaranteed. Double electrical isolation is often used to provide this guarantee. As a minimum, these tests must be done both at the start and at the end of battery acceptance testing.

(2) Capacity and performance measurements should be made on the group of cells manufactured for a battery, and those that appear to be most closely matched in terms of capacity and performance should be selected for the battery. Standard capacity tests should be performed to verify proper operation of all cells and the battery over the expected operating temperature range. Battery capacity requirements should be only slightly less than cell requirements, since there is normally a range of cell thermal environments present in an operating battery. Significant changes in the performance of individual cells after being put into a battery usually indicates a problem either with the cell or with its thermal or electrical interfaces within the battery.

(3) A nonoperating battery should be exposed to a thermal cycling test to verify the integrity of the thermal interfaces required for cell performance. This test should be followed by a standard capacity test to verify that the thermal cycling did not induce any performance changes.

(4) The charged battery should be exposed to acceptance-level vibration, with levels dictated by anticipated exposure limits. Battery voltage and isolation from battery terminals to the structure should be monitored for transients induced during vibration. This test should be followed by a standard capacity test to verify that no performance changes were induced by vibration.

(5) Battery impedance should be measured, either by a standard milliohmmeter or by measuring the battery voltage change in response to a large change in discharge current. The measured impedance should be within the range calculated from the sum of the individual cell impedances and the expected (or actual) interconnect and connector resistances.

(6) A battery should be let down to low voltages either through a separate connector or by other means such that the lowest capacity cells are not reversed. Although reversal at low rates does not damage nickel-hydrogen cells, it can create performance disparities between the supposedly well-matched cells in the battery and, therefore, should be avoided.

TABLE II.—ACCEPTANCE TEST MATRIX FOR THE BATTERY SUBASSEMBLY ORBITAL REPLACEMENT UNIT FOR THE SPACE STATION

Performance measurement	Test sequence													
	Isolation	Electrical bonding	Chassis ground resistance	Burn-in	Charge retention	Electrical performance	Vibration	Postvibration orbital rate capacity	Thermal vacuum	Residual capacity	Charge retention	Reference capacity	Final orbital rate capacity	Electrical bonding
Reference capacity												√		
Residual capacity										√				
Charge retention					√						√			
Charge						√								
Discharge						√								
Voltage requirements						√								
State of charge						√								
Capacity						√			√					
Contingency and postcontingency cycling						√								
Contingency discharge						√								
Postcontingency charge						√								
Contingency and postcontingency cycling voltage						√								
Isolation	(a)													
Temperature range									√					
Heater power									√					
Heater voltage									√					
Hermiticity									√					
Normal operating temperature range									√					
Normal mounting on vibration fixture							√							
Electrical bonding		(b)												√
External metal parts			√											
Orbital rate capacity ^c				√				√					√	

^aPerformed in orbital replacement unit fabrication process.

^bMay not be required, see paragraph 1.4.

^cFor information purposes only.

13.0 Storage Considerations

Nickel-hydrogen cells have higher rates of self-discharge than nickel-cadmium cells have. In addition, the active material of the nickel electrode in nickel-hydrogen cells is sensitive to poor storage conditions that can reduce the usable capacity of cells and batteries.

Three types of storage are considered here: (1) dry storage of cells prior to being filled with electrolyte, (2) wet storage under conditions where temperature can be monitored and controlled to avoid harming the cells or batteries, and (3) active storage where the potential at the nickel electrode must be monitored and controlled using electrical circuitry.

13.1 Dry Storage

Contractual considerations may dictate that an entire production run of cells be manufactured at one time. Because of limitations that are imposed on the duration that cells are allowed to be activated with electrolyte prior to launch, it may be necessary to store fully manufactured cells in a dormant manner for activation with electrolyte later. Activation with electrolyte may take place following several years of inactivated (dry) storage. There is evidence that in the dry state, nickel electrodes can lose some of their capacity. Very little information is available from the open literature on this subject. The best method for dry storing cells is not fully understood at this time, but the following recommendations should be followed. The cells should be filled with a relatively dense inert gas, such as argon, to a small positive pressure (~15 psi), and the temperature should be kept at -20 to 0 °C to minimize any recrystallization of the active material. Nitrogen, although inert, is not recommended since it can be mistaken for the intrusion of air. Stored cells should be sealed in a plastic protective wrapping. Leakage during storage is detected by loss of the inert gas pressure.

13.2 Activated (Wet) Storage

A number of procedures are used to store nickel-hydrogen cells between the time they are activated and the time the batteries are installed on a spacecraft. This section addresses the period between the time cells are activated with electrolyte and when they are assembled into a battery. The ease of implementation and the cost of storage often dictate the appropriateness of these procedures rather than what is best for the battery cells. In many cases, the state of precharge in the cell is important in defining acceptable storage conditions. It is generally accepted today that cells or batteries that have hydrogen precharge must be stored using a method that maintains typical operational voltages (1.2 V) on each cell. The objective of these storage techniques is to prevent the nickel electrode from falling below a potential at which the cobalt additive material can be reduced to either cobalt hydroxide or metallic cobalt. This potential is estimated to be a difference of 1.05 V from the hydrogen electrode, but to be on the safe side, a potential of 1.2 V is recommended as a minimum for active storage procedures. The following paragraphs outline the different methods now in use.

Generally, the active or pseudoactive storage modes, such as trickle or top-charge storage, are carried out at 10 to 15 °C, whereas passive storage modes are at 0 °C whenever possible. During some test operations, room-temperature passive storage may be necessary for limited periods. The term "active" nickel precharge is defined as chemical precharge in the nickel electrode that is also electrochemically active. Therefore, active precharge can hold the nickel electrode at its characteristic electrochemical potential. For cells that have active nickel precharge, discharged and open-circuited storage conditions can be used. In this situation, the nickel precharge holds the desired storage potential on all nickel electrodes. This is the least expensive and simplest storage mode. However, slow reactions occur in the nickel-hydrogen cell that, over time, can convert the nickel precharge to a less active form. Thus, after an extended period (several years) in discharged storage, a cell will lose its "active" nickel precharge. Any cell operation after this storage period will result in residual hydrogen precharge. At this point, the cell is regarded as having hydrogen precharge and should be periodically recharged or performance fading will follow. The rate of precharge degradation can be controlled with proper storage conditions at reduced temperatures.

Trickle-charge storage can be used to maintain a voltage (and significant charge) in all cells during storage. This is a safe storage mode that is independent of the type or quantity of precharge. One drawback of this technique is that the internal pressure can slowly climb because of corrosion of the nickel electrode sinter structure. Typically, the rate of this corrosion process is slow (and somewhat variable between different production lots and cell designs), requiring many years to become a performance issue. Another drawback is the waste heat that must be dissipated during trickle charge.

Top-charge storage can also be used to maintain a voltage on each cell and also is acceptable for all precharge situations. Typically, a cell or battery is charged to a near full state of charge, and then allowed to stand open circuited for 1 to 2 weeks, or a time short enough to guarantee that no cell will be fully self-discharged. The cells or batteries are then charged up again at the C/10 rate to an ampere-hour return value based on the stand time or a temperature rise of several degrees Celsius. This sequence is repeated throughout the storage period. This storage mode has been associated with some increase in internal cell pressure during storage, but it is widely used because the heat dissipated by the battery can be

considerably less than in the trickle-charge storage mode, where more significant cooling is usually needed. With this storage mode, the cell capacities may need to be rebalanced periodically. This is done by discharging the battery at a low rate until the first cell reaches a low voltage limit of about 1.0 V. The battery is then charged with some degree of overcharge to bring the lower capacity cells up to near full charge. This is repeated two or three times to bring the cells back into electrochemical balance. No references are available for this technique.

A controlled voltage at about 1.2 V on discharged cells is recommended as the best approach to maintaining cell or battery performance when active storage becomes necessary. This approach does not depend on the type and amount of precharge in the cell, and it prevents platinum corrosion in the hydrogen electrode of nickel-precharged cells during storage. It also minimizes the rate of nickel sinter corrosion while maintaining a safe voltage level on the nickel electrode. This storage method can be easily implemented at the battery or cell level by placing diodes with the desired forward bias across each cell, then applying a trickle-charge rate to the string of cells that is high enough to hold all cells at the forward bias of the diodes. Individual leads are required to measure cell voltages. Although this active storage method will always work, positive precharge (which is a much easier storage condition to control) allows passive storage for about 3 years.

13.3 Preparation for Storage

There are a number of operational and test issues that are related to storage. These issues require that nickel-hydrogen cells and batteries be prepared for storage in a controlled manner. The first issue is to avoid having cells in charged open-circuit stand just before placing them into storage, since this can temporarily isolate a significant amount of active nickel precharge. In this situation, capacity has been lost because of residual hydrogen remaining in the cells following a full discharge. Such temporary isolation can be eliminated if the cells are prepared for storage by doing a full charge and then an immediate and full discharge and letdown at room temperature.

The second issue involves repeatedly taking cells or batteries in and out of storage. This should be minimized, particularly with the passive storage regimes, since each time that the cells or batteries are removed from storage and charged and discharged, they can lose active nickel precharge and be left with residual hydrogen gas. Cells

or batteries that are put into storage with active nickel precharge can be stored indefinitely as long as they are not removed from storage and exercised. This is possible since there is no hydrogen in these cells to initiate the problems associated with its presence at low nickel electrode potentials. Finally, if batteries have remained in active storage for any period of time, they should not be returned to, or placed into passive storage without verifying precharge levels in all cells. It is possible, and in some situations, desirable to go from passive to active storage, but going from active to passive storage is generally not recommended.

13.4 Battery Storage

Considerations related to the storage of completed batteries are similar to those already mentioned related to the storage of cells. Depending on the circuitry available on a battery, modifications to the cell storage techniques must be made. Since batteries do not usually permit control at the cell level, overall battery voltages are monitored rather than individual cell voltages. Storage of batteries containing cells that are known to possess active nickel precharge is best accomplished by cold (less than 5 °C) storage in the open-circuited, discharged state. This allows the nickel precharge to hold the cell electrodes at desirable storage potentials. For storage periods less than about 90 days, trickle charge is considered a better storage option because the stresses on the precharge in the cell that result from entering and leaving storage can be significant.

Batteries that contain any cells with hydrogen precharge (a situation that is likely to develop with extended testing, storage, or use) should be stored in a trickle-charged state (or be top charged periodically), with the trickle-charge rate sufficient to keep all cells above 1.2 V. It should be noted that CPV and SPV devices, because of the commonality of their gases, will retain a nickel precharge as long as any one cell contains active nickel precharge. The temperature should be kept below 20 °C during trickle-charge storage to minimize all parasitic reactions. If colder temperatures are used, care must be taken that water does not condense onto the cell walls.

Batteries should be prepared for storage by making sure that all cells are properly discharged, as discussed in section 13.3. Before batteries are fully discharged in preparation for storage, they should be fully charged. This sequence guards against having an apparently fully discharged battery that contains active charge that is isolated within the electrodes. This situation can

convert a cell originally configured to have positive precharge to a situation where residual hydrogen is present. The presence of residual hydrogen in fully discharged cells or batteries can result in unrecoverable capacity loss due to hydrogen sickness (ref. 2). Storage and testing should always be done with the batteries protected from moisture or moist air that could condense on the battery surfaces.

13.5 Charged Stand Prior to Launch

Charged stand conditions prior to launch are very important since nickel-hydrogen cells have a higher rate of self-discharge (an exothermic process) than nickel-cadmium cells have (refs. 66 and 67). The heat generated during the initial portions of an open-circuit stand period can heat the cells, resulting in an increase in the rate of self-discharge and further heat generation. Figure 10 plots the percentage of capacity remaining following extended periods of storage at different ambient temperatures. This plot is based on a generic cell that is charged to its nameplate capacity (850-psi hydrogen pressure) prior to being placed on open circuit at three different assumed temperatures. Simulation tools have been used and validated at The Aerospace Corporation to model this process under different conditions of ambient temperature and thermal coupling of the battery to the environment (ref. 43). These tools were used to generate figure 10. Actual cell data can also be used to generate this type of plot. The results shown in figure 10 agree very closely with the data from actual cells, as presented in figure 11, which represents data from an earlier general-purpose nickel-hydrogen handbook (ref. 1).

Under conditions of open-circuit stand, the cell pressure (as measured by a strain gauge) may no longer be an

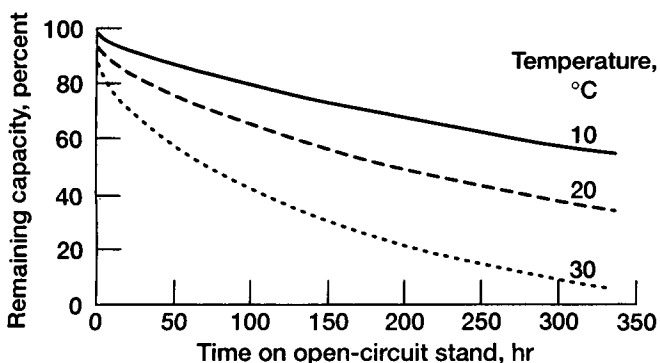


Figure 10.—Capacity retention following different lengths of open-circuit stand.

accurate measure of the usable electrochemical capacity of a cell that has been allowed to self-discharge. For this reason, modeling or actual cell data are needed to estimate the remaining usable capacity following open-circuit stand periods. During these times, three concurrent self-discharge reactions take place. At high states of charge, the active material decomposes, releasing oxygen. In addition, hydrogen gas reacts chemically and electrochemically with the active material at lower rates. As these reactions take place, regions of charged active material that are not electrochemically dischargeable are formed. This “isolated” material is recovered by charging the cell back to a fully charged condition.

Efforts are made to keep batteries as fully charged as possible prior to disconnecting the ground support services just before launch. However, the charge efficiency characteristics of nickel-hydrogen cells drop very rapidly as cells or batteries approach full charge. This results in significantly higher heat loads at higher states of charge in addition to heat from the self-discharge reactions. At some launch sites, batteries are cooled by circulating cold air provided by the launch facility, rather than by a fully functioning thermal control system consisting of circulating coolant, heat pipes, or radiators. In other cases, cooling is provided up to shortly before launch by quick-disconnect fittings for the circulating coolant. If active cooling is required prior to launch, this feature must be designed into the satellite and into the ground support services. The space shuttles do not provide active cooling to payloads located in the bay. Other launch vehicles provide chilled air at a temperature that depends on the launch site and the launch vehicle.

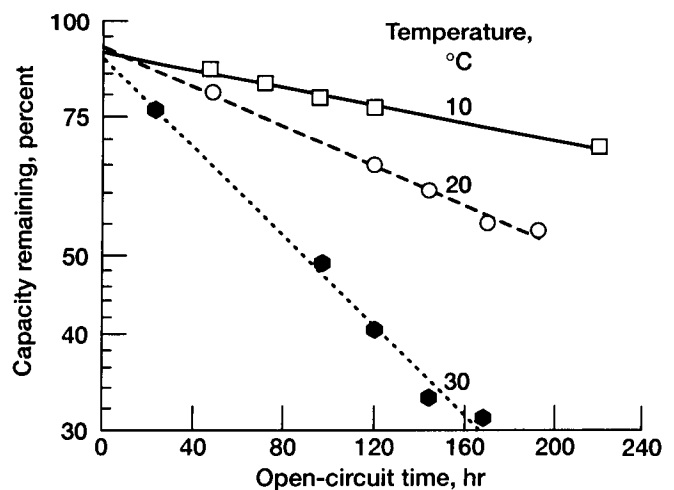


Figure 11.—Capacity retention data from actual cells (ref. 1).

The factors that affect the rate of usable capacity loss prior to launch follow:

- (1) The battery temperature, which is determined by the temperature of the cooling air (or circulating coolant) and the thermal coupling of the battery to this heat-rejection path
- (2) The hydrogen pressure within the cells
- (3) The length of time the cell has been on open-circuit stand
- (4) The amount of nickel precharge contained in the cell

It is imperative that the available capacity at the time of launch meet the needs of the mission (with margin) until the solar array is deployed and in position to recharge the battery. Several possible approaches can be taken to maximize the charged stand time allowed prior to launch, depending on the situation, as described in the following paragraph.

Knowing the capacity loss rate will determine the allowable time on the pad before the battery must be recharged. If calorimeter-based modeling capabilities are not available, the following procedures are recommended. First, the required capacity plus any desired margin at the time of launch must be established by the requirements of the mission under consideration. The thermal environment in terms of temperature and thermal coupling within the launch vehicle must be established. By using a form of figure 11 for the cell and launch vehicle under consideration and different amounts of stand time and thermal environment prior to launch, one can determine when the capacity of the battery will fall below the minimum capacity level. If data to generate the capacity retention curve for the application being considered are not available, they must be generated or modeled. Modeling techniques, once validated, have the necessary accuracy to make this estimate. For generating the relationship from actual cell data, the following procedure is recommended. The cell should be fully charged at 10 °C, as would be done on the ground at the launch site prior to installation on the spacecraft. The usable capacity should be measured following 5, 10, 20, 40, 80, 160, and 320 hr of open-circuit stand time at the expected temperature just prior to launch. At the point where the remaining usable capacity falls below the required value, top-off charging, trickle charging, or removal from the spacecraft must begin.

The charge rate of these top-off charges must be set to avoid any thermal runaway situation where the tempera-

ture rise within the cell increases the hydrogen recombination rate. If the cell ambient temperature is above 25 °C, and active cooling is not available, charging on the spacecraft is not recommended. If refrigerated circulating air is available, charging can be done at a low rate (C/20) until the cell temperature increases several degrees. Following a rest period during which the cell cools back down, charging may begin again. This process is then repeated when the usable battery capacity again drops below the preset critical value.

14.0 Suggested Elements of a Manufacturer's Proposal

The following is a basic list of items that a manufacturer should provide. It is assumed that the cell manufacturer is also providing the battery. If the battery is being built from cells by a third party, the items related to the battery assembly should shift to that third party.

- (1) A manufacturing control document (This may consist of a process and assembly flow plan that references the appropriate procedures and drawings utilized by the manufacturer. The important quality control procedures and inspection points should also be included.)
- (2) An interface control plan that identifies the thermal control and electrical interfaces that the system must provide to the battery to have it function properly (for example, the interface with the system must be able to handle the heat produced by the battery without allowing temperatures to go too high or low, and the system must provide an appropriate charge-control system)
- (3) A thermal analysis of the cell and battery to demonstrate that the cells will stay within acceptable operational temperature limits
- (4) A qualification test plan for the cell and battery that demonstrates acceptable operation over the electrical and environmental ranges supplied by the customer
- (5) Cell and battery acceptance test procedures
- (6) Detailed cell activation procedures and storage procedures
- (7) A mechanical analysis of the battery structure, demonstrating acceptable margins of safety

15.0 Concluding Remarks

Over the past three decades, nickel-hydrogen batteries have advanced from the early stages of development to serving as the primary energy storage system for geosynchronous and low-Earth-orbiting satellites. Nickel-hydrogen batteries will continue to serve this role for many future NASA, military, and commercial missions. This document will aid in the implementation and understanding of nickel-hydrogen technology.

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John H. Glenn Research Center at Lewis Field
Cleveland, Ohio, 44135 August 19, 2002

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13. ABSTRACT (Maximum 200 words) This document provides an overview of the design, development, and application of nickel-hydrogen (Ni-H ₂) battery technology for aerospace applications. It complements and updates the information presented in NASA RP-1314, "NASA Handbook for Nickel-Hydrogen Batteries," published in 1993. Since that time, nickel-hydrogen batteries have become widely accepted for aerospace energy storage requirements and much more has been learned. The intent of this document is to capture some of that additional knowledge. This document addresses various aspects of nickel-hydrogen technology including the electrochemical reactions, cell component design, and selection considerations; overall cell and battery design considerations; charge control considerations; and manufacturing issues that have surfaced over the years that nickel-hydrogen battery technology has been the major energy storage technology for geosynchronous and low-Earth-orbiting satellites.			
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