Nickel-Hydrogen Batteries: Principles and Practice

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1 Overview of Nickel-Hydrogen Cell Technology

The nickel-hydrogen battery cell is a rechargeable electrochemical cell that has found wide use in high-reliability space applications that require extended service life. These applications include satellites operating for 15 or more years in geosynchronous orbits, as well as orbital spacecraft (in low Earth orbits) that require many tens of thousands of charge and discharge cycles from the batteries. In these applications, the nickel-hydrogen battery system has largely replaced the sealed nickel-cadmium technology that was widely and successfully used to power space systems from the early days of spaceflight.

Nickel-hydrogen technology was developed for space use beginning in the early 1970s as a spin-off of the hydrogen-oxygen regenerative fuel cell and is a technology capable of long life and high reliability without the periodic refueling and servicing needs typical of fuel cells. The nickel-hydrogen battery cell performs essentially as a quasireversible hydrogen-oxygen electrochemical cell, with the oxygen being stored in the positive electrode as a metastable nickel oxyhydroxide and the hydrogen being stored as high-pressure gas in a pressure vessel. The positive electrode was selected to be the highly reliable and robust nickel electrode that had been used for years in the nickel-cadmium cell. The energy storage reaction at the positive electrode can be represented by the simplified reaction in Eq. (1.1).

$$Ni(OH)_2 + OH^- \overset{\text{Charge}}{\Rightarrow} NiOOH + H_2O + e^- \quad (1.1)$$

The negative electrode is a catalyst-based gas electrode that has been largely developed and utilized in the fuel cell industry. This electrode electrochemically stores energy by the reaction in Eq. (1.2) in the form of hydrogen gas, which is contained in the cell container at high pressures.

$$2H_2O + 2e^- \underset{\text{Pt catalyst}}{\overset{\text{Charge}}{\Rightarrow}} H_2 + 2OH^- \quad (1.2)$$

The combination of these two electrodes began the development of a nickel-hydrogen battery technology that today is unmatched for providing highly reliable performance combined with a service life that can easily support decades of continuous operation in the most demanding applications.

After more than 30 years of development and maturation, nickel-hydrogen technology has reached a point of key historical significance. While the technology is now the dominant rechargeable energy-storage system used in the space and satellite industry, support for further nickel-hydrogen cell development, system optimization, and technology maintenance is decreasing each year. Without a critical level of technology development or maintenance support, it frequently has been the case that even the most established battery technology can be compromised by erosion of production infrastructure and manufacturing expertise. This pattern was a real factor in the replacement of nickel-cadmium technology with nickel-hydrogen in the 1980s. One of the principal goals of this work is to point out key areas where the existing nickel-hydrogen technology requires continued attention if it is to meet the future needs of space power.

This book is divided into three parts. Part I provides an introduction to nickel-hydrogen technology, Part II covers the fundamental principles of the technology, and Part III discusses the practical and applied aspects of the technology. In Part I the existing experience with nickel-hydrogen technology will be introduced, from both a historical viewpoint and a performance-capability viewpoint. A brief historical monograph will provide an understanding of how today's nickel-hydrogen cells evolved from the earliest concepts. This historical perspective will cover the development of all variations of nickel-hydrogen cell design that have been used or are available for use today. The typical electrical and thermal performance characteristics of the nickel-hydrogen cell will also be described in Part I.

Part II will deal with the fundamental principles of the nickel-hydrogen cell and its components. This discussion will start with the basic designs and key processes in the cell components: the nickel electrode, the hydrogen electrode, and the separator. Many of the key performance characteristics of the nickel-hydrogen cell are related to the dynamics of how all its components function together in the operating cell or battery. For the nickel-hydrogen cell this is probably more true than it is for most other types of battery cells, for the simple reason that gas, liquid, and solid species must all interact and function as designed for proper performance to be maintained. A detailed discussion of cell dynamics will describe the most important interactions that can affect the performance of the cell components and how the components function together to dictate cell and battery behavior.

During the past 10 to 15 years, significant effort has centered on modeling nickel-hydrogen cell performance, either from using an empirical model or from a first-principles approach. Various approaches for such modeling will be discussed in Part II, along with the validation, utility, and successes of each approach. Examples of such modeling efforts will be provided to suggest that very-high-fidelity performance modeling is made possible by including all chemical, physical, and electrochemical processes in a realistic microscopic and macroscopic model of the cell. High-fidelity models that are well validated will become an essential part of designing nickel-hydrogen cells and characterizing cell behavior in a climate where the time and funding are not always available to support testing.

Part III will discuss the important factors involved in the application of nickel-hydrogen cells and batteries, and the practices involved in properly maintaining and using them. Charge management, as for all types of battery cells, is an essential factor in realizing high reliability and long cycle life. Similarly, appropriate thermal management is critical in nickel-hydrogen cells, largely because their performance is highly sensitive to the thermal environment. Testing of cells and batteries will also be discussed, including typical acceptance, qualification, and life cycle testing. Typical life test experience for the various cell designs that have been tested will be presented and discussed.

Life test results invariably point to degradation modes, failures, and weak points in any battery cell design. Part III will include a discussion of nickel-hydrogen cell and battery degradation and failure modes in the context of test experience. This section will provide detailed information on how nickel-hydrogen cell and battery technology and the management of batteries can be improved or optimized to get the best performance possible from a given battery system. A detailed discussion of destructive physical analysis and diagnostic techniques will also be provided to list the observed performance signatures associated with the chemical and physical root causes for cell and battery degradation. Finally, expert systems that have recently been developed to link observed performance signatures to their underlying root causes will be reviewed.

1.1 Position of Nickel-Hydrogen Technology in Space Power

The development of nickel-hydrogen technology for space power use began in the early 1970s, largely to obtain a longer battery lifetime capability than could be reliably provided by nickel-cadmium batteries. Nickel-cadmium batteries were reliably providing three years in low Earth orbit applications and seven to ten years in geosynchronous satellite applications. Very early in the process of developing nickel-hydrogen technology, it became very clear that this technology was capable of exceedingly long life. In fact, early testing of nickel-hydrogen cells found it very difficult to induce failures, in some cases creating performance expectations that were not always borne out by more comprehensive and realistic testing and modeling. The cells often appeared capable of handling the stresses of inadvertent reversal or excessive overcharge with little evidence of the damage or performance degradation that had been the rule for nickel-cadmium cells.

Chapter 2 provides details on the history of nickel-hydrogen technology development. Because of the technology's robustness and excellent performance, nickel-hydrogen batteries quickly found their way into two flight tests within 10 years of the start of its development. These flight tests were the NTS-2 flight and the Air Force Flight Experiment, both of which were launched in 1977, performing well for 1.5 and 4 years respectively. As a result of these successful flight tests, along with the life test programs initiated by the United States Air Force, the National Aeronautics and Space Administration (NASA), Martin Marietta, and battery manufacturers, nickel-hydrogen battery technology became a viable space power option that began to be baselined for new space missions. However, because of the 5–10 year (or longer) period involved in the planning, design, acquisition, and launching of these missions, it was not until the early 1990s that nickel-hydrogen batteries had replaced nickel-cadmium batteries as the dominant system on newly launched spacecraft.

Figure 1.1 shows the decline of spacecraft launched with nickel-cadmium batteries along with the rise of those with nickel-hydrogen batteries for noncommercial launches in the United States from 1980 to 2000, a period when nickel-hydrogen batteries essentially replaced nickel-cadmium batteries in satellites. There is another plot similar to Fig. 1.1 reflecting the increase in commercial satellite use of nickel-hydrogen batteries at the expense of nickel-cadmium batteries; however, commercial usage has entailed large spikes in the number of launches arising from the launch of large satellite constellations such as Iridium, as well as periodic fluctuations in the commercial space market.

Today there are essentially no new spacecraft launched with nickel-cadmium batteries, with the smaller and shorter-lived missions having transitioned to lithium-ion batteries. The satellite missions that previously utilized nickel-cadmium batteries are the most likely candidates for transitioning to the emerging lithium-ion battery technology. During the past few years, another battery usage plot similar to Fig. 1.1 has been developing, showing the growth of lithium-ion battery use in space missions at the expense of nickel-hydrogen batteries.

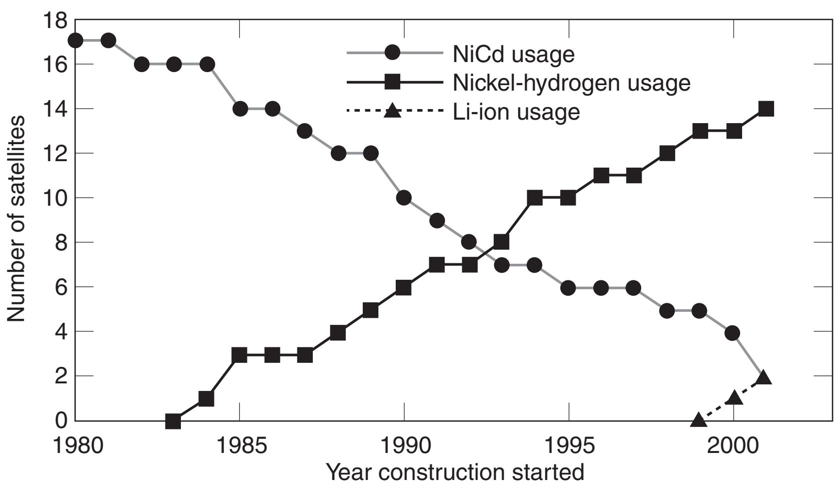

Figure 1.1. Noncommercial usage of nickel-cadmium and nickel-hydrogen batteries in satellites during the period when nickel-hydrogen largely replaced nickel-cadmium.

The issues and factors that drive the transition from one established space battery technology to another emerging one are numerous. Clearly, a successful ground and flight test history for the emerging technology is important, as was the case for nickel-hydrogen. In addition, the safety record of the emerging technology has become a very significant factor with the advent of crewed launch systems such as the space shuttle. It should be noted that with today's safety standards, if nickel-cadmium batteries were an emerging technology, it would probably be regarded as unsafe, because sealed nickel-cadmium batteries do not tolerate high-rate overcharge or reversal safely. Nickel-hydrogen batteries, on the other hand, have been repeatedly demonstrated to be safe under such conditions of abuse. Table 1.1 lists several of the most important drivers that have historically influenced new battery technologies to be either successful or unsuccessful in transitioning into space power systems.

The last factor in Table 1.1, mission requirements, is one of the most elusive. Spacecraft design practices are extremely conservative. A new battery technology may be lighter, smaller, and less costly than the technology presently in common usage, but unless these advantages actually enable a mission at the time it is being planned, the new technology will often be viewed as involving unnecessary risk. Nickel-hydrogen battery technology has been fortunate in this area. Longer-lived missions that were being planned in the late 1970s and the 1980s were actually enabled by nickel-hydrogen technology. Geosynchronous satellite missions of 15 years or longer could be considered, and low Earth orbiting satellites lasting 5 to 10 years could be designed. A good example of the advantages of nickel-hydrogen is provided by the Hubble Space Telescope, which has operated for more than 15 years on nickel-hydrogen batteries with limited battery degradation. These capabilities, when coupled with growing manufacturing and performance problems with spacecraft nickel-cadmium batteries in the mid-1980s, clearly pushed nickel-hydrogen batteries into space use.

Table 1.1. Factors Driving Space Battery Technology

Factor	Importance for Nickel-Hydrogen
Weight	Moderate
Life	High
Reliability	High
Cost	Low
Safety	Moderate
Ease of handling	Low
Size or volume	Low
Mission requirements	High

Nickel-hydrogen batteries do, however, have a number of strengths and weaknesses that have influenced and will continue to influence their use in space power systems relative to other battery technologies. Weight has historically been a significant factor in the development of technologies for use in space systems, and the technology of batteries is not an exception. The cost of launching each kilogram into low Earth orbit is high, and weight is very costly indeed to lift into geosynchronous orbit. The horizontal axis of the graph in Fig. 1.2 shows how nickel-hydrogen cell energy density compares to other rechargeable battery technologies that can be considered for space power use. Clearly, nickel-hydrogen technology would not be the obvious choice for space power systems based on weight alone. Nickel-metal-hydride technology has a slight advantage, and lithium-ion technology a significant advantage, in terms of weight. Indeed, this weight advantage may eventually enable lithium-ion battery technology to replace nickel-hydrogen in many space missions.

The vertical axis of the graph in Fig. 1.2 shows the expected life capability of rechargeable battery systems, in terms of the watt-hour throughput over typical high-reliability lifetimes. Clearly, nickel-hydrogen is one of the best technologies available based on life expectancy. The wide range that is indicated in Fig. 1.2 for lithium-ion battery cycle-life is a result of the present lack of completed life test databases for this emerging technology. The range indicated in Fig. 1.2 for lithium-ion batteries extends from demonstrated performance levels in flight-type cells at the low end, to the optimistic extrapolations of the test data at the high end. Clearly, such extrapolations do not rule out lithium-ion life as being competitive with nickel-hydrogen. Increased life capability can typically be translated into increased reliability by simply increasing the required performance margins.

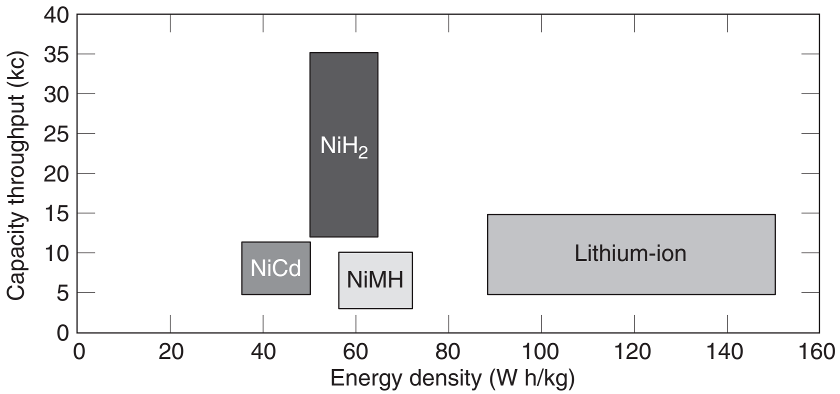

Figure 1.2. Relative life and energy density characteristics of common rechargeable battery types used in satellite applications.

It is generally possible to increase reliability at the expense of life and weight. One example of this trade is the classic choice of a depth of discharge that is consistent with the required lifetime and reliability.

While the cost of batteries is a significant driver in selecting technology for terrestrial applications, it is usually a secondary factor in selecting batteries for spacecraft systems, because of the high "paper" costs associated with testing, verification, and traceability. Nickel-hydrogen batteries are significantly more costly than any of the other technologies shown in Fig. 1.2 in terms of manufacturing costs. However, this difference is significantly reduced if similar extra costs of extensive testing and documentation are included for all the technologies, although nickel-hydrogen remains the most costly by a factor of about 50–100%. The higher cost of nickel-hydrogen has not been a major technology driver, because of the significantly enhanced life and reliability possible with it.

Nickel-hydrogen cells and batteries have historically displayed a robust safety record relative to nickel-cadmium and lithium-based batteries. They are tolerant of high rate overcharge, reversal, and short circuits, often responding to these events with no change in performance. The safety issues for nickel-hydrogen batteries are discussed in detail in chapter 3. The principal issues are associated with the possibility of hydrogen gas leaking and its flammability.

The handling and storage of nickel-hydrogen cells and batteries has historically been an area fraught with pitfalls, although to some extent this has been true of most batteries used in space power systems. Handling and storage will probably remain an area of difficulty in the future. As will be discussed in more detail in chapters 3 and 4, nickel-hydrogen cells and nickel electrodes in these cells are sensitive to precharge, have a high self-discharge rate, are very sensitive to temperature, may require active storage, and can display highly history-dependent performance. While these factors have not been major issues in selecting nickel-hydrogen over nickel-cadmium batteries in most cases, they have clearly been an inconvenience that has increased the costs associated with managing nickel-hydrogen batteries on the ground.

Nickel-hydrogen batteries are not generally chosen for an application based on their volume. The pressure vessels that contain the hydrogen gas in the cell typically occupy a large volume even in high-pressure cells that operate at 1000 psi or more. The packing density of these pressure vessels in a battery structure also generally adds more volume. It is this characteristic that makes nickel-hydrogen batteries particularly unattractive for powering small satellites that have little extra volume. It is in the microsatellites, nanosatellites, and picosatellites that lithium-ion batteries will likely be required to enable small-satellite missions, simply because there is insufficient volume for other battery types.

The combination of factors discussed above and listed in Table 1.1 has resulted in nickel-hydrogen technology largely replacing nickel-cadmium during the past 25 years in rechargeable space power applications. The principal driver in this transition has been the cycle life capability of nickel-hydrogen. As part of this transition, space power systems, their manufacturers, and their users have had to learn how to best deal with the performance, charge control, storage and handling, testing, modeling, degradation modes, and diagnostics related to nickel-hydrogen usage. This book will discuss the details of how to best deal with nickel-hydrogen batteries in all these areas.