

Chapter 9

Battery

9.1 Introduction

The energy storage is required to meet the spacecraft load demand not only during eclipse, but also when the demand exceeds the power generation at any time. The most widely used energy storage technology is the battery, which stores energy in an electrochemical form. There are two basic types:

Primary battery, in which the electrochemical reaction is irreversible. It cannot be reused after full discharge, so it is discarded. It finds applications in very short duration missions as the primary source of power. It has a specific energy that is an order of magnitude higher compared to the secondary battery.

Secondary or rechargeable battery, in which the electrochemical reaction is reversible. After a discharge, it can be recharged with direct current from an external source. It finds applications in long duration missions where another independent power source is available for recharging the battery periodically. Most satellites use the secondary battery.

9.2 Electrochemical Cell

The battery is made of numerous electrochemical cells assembled in a series-parallel circuit combination to obtain the required voltage and current. The internal construction of a typical electrochemical cell is shown in Figure 9.1. It has positive and negative electrode plates with insulating separator and a chemical electrolyte in-between. The two electrode plates are connected to two external terminals mounted on the casing. The cell stores electrochemical energy at a low electrical potential. The cell voltage depends solely on the electrochemistry, and not on the physical size. Commonly used electrochemistries produce 1.5–3.5 V when fully charged. The cell capacity, denoted by C , depends on the physical size. It is defined as the ampere-hours (Ah) charge the cell can deliver at room temperature until it reaches a cut-off voltage of about $2/3^{\text{rd}}$ of the fully charged voltage. The battery can deliver C amperes for 1 h or C/n amperes for n hours. The capacity measures the Ah output at the terminals, not the input or that

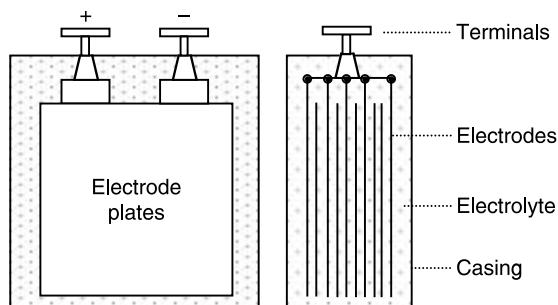


FIGURE 9.1 Typical electrochemical cell construction.

stored between the plates. A 1.5-V cell discharged to 1.0V delivers practically full capacity of the cell. The Ah capacity to 0.1 V discharge is only a few percent greater than that at 1.0 V discharge.

The battery voltage rating is stated in terms of the average voltage during discharge. The higher the battery voltage, the higher the number of cells required in series. The product of the voltage and the Ah rating makes the energy rating in watt-hours (Wh) the battery can deliver to a load from the fully charged state.

The battery charge and discharge rates are stated in fraction of the capacity. For example, charging a 100-Ah battery at 10-A rate is said to be charging at $C/10$ rate. Discharging this battery at $C/2$ rate means drawing 50 A. At this rate the battery will be fully discharged in 2 h. The state of charge (SOC) of the battery at any instant is defined as

$$\text{SOC} = \frac{\text{Ah capacity remaining in the battery}}{\text{rated Ah capacity}} \quad (9.1)$$

The state of charge affects the cell voltage, specific gravity, and freezing point of the electrolyte. The electrolyte in a fully charged battery has high specific gravity and freezes at a much lower temperature. On the other hand, a fully discharged battery freezes at a higher temperature. This shows the importance of keeping the battery fully charged when exposed to low temperatures.

The battery depth of discharge (DOD) is defined as

$$\text{DOD} = \frac{\text{Ah capacity drained from fully charged battery}}{\text{rated Ah capacity}} \quad (9.2)$$

Obviously,

$$\text{DOD} = 1 - \text{SOC} \quad (9.3)$$

Major secondary batteries used in the spacecraft industry at present are nickel cadmium (NiCd), nickel hydrogen (NiH₂), and lithium-ion (Li-ion). New electrochemistry is being continuously researched by NASA for space applications,¹ and by the United States Advance Battery Consortium for a variety of ground based applications — consumer electronics, electric vehicles, utility load leveling, and renewable power systems. Lithium-polymer (Li-poly) and nickel metal hydride (NiMH) are two such examples in the commercial world.

The selection of electrochemistry for a given application is a matter of performance and cost optimization. The following figures of merit are often used in comparing relative performance of various electrochemistries:

Specific energy, defined as the gravimetric energy density, which is the energy stored per unit mass, Wh/kg.

Energy density, defined as the volumetric energy density, which is the energy stored per unit volume, Wh/l.

Specific power and power density, defined as the power the battery can practically deliver per kilogram of mass and liter of volume, respectively. It is sometimes necessary to think in terms of the power parameters also, since the internal resistances of the battery may limit the rate at which the energy can be discharged within practical design limits.

Cycle life, defined as the number of charge/discharge (C/D) cycles the battery can deliver while maintaining the cut-off voltage.

9.3 Types of Battery

The NiCd battery had been the workhorse of the spacecraft industry since the earliest missions, and is still used in some missions. However, since the mid-1980s, it has been replaced with the NiH₂ battery for general use. The NiH₂ provides deeper DOD for comparable cycle life, thus requiring lower Ah capacity, which translates into lighter weight. Today, the industry appears to be moving towards the lithium based batteries for potentially 2 to 5 times the specific energy compared to the NiH₂ chemistry. No single electrochemistry available on the market can meet the wide range of space mission requirements. All chemistries will perhaps continue in use where they fit the best for a minimum mass and cost design. However, the more commonly used electrochemistries and their unique construction and performance features are presented in this chapter.

9.3.1 Nickel Cadmium

The NiCd is a matured electrochemistry that powered almost all satellites until mid-1980s. It comes in a sealed vented prismatic cell with positive and negative electrode plates made of a sintered nickel structure. The positive plate is impregnated with nickel hydroxide active material and the negative plate with cadmium hydroxide active material. The plates are die-cut with corner radii and coined edges to prevent shorting. The negative plate design includes a thin TeflonTM impregnation on the surface. This feature extends the operational life by enhancing oxygen recombination and retarding cadmium migration. The positive and negative plates are separated by nonwoven nylon or asbestos, which has been replaced with Pellon 2536TM. The electrolyte is potassium hydroxide and the casing is made of stainless steel.

The NiCd electrochemistry offers relatively lower specific energy, is temperature sensitive, and has shorter cycle life. Moreover, the cadmium has been placed under environmental regulatory scrutiny. For these reasons, NiH₂ has replaced the NiCd for most space applications.

9.3.1.1 Memory effect

A major disadvantage of the NiCd battery comes from its peculiar characteristic known as the *memory effect*. The NiCd battery remembers its DOD in most frequent use in the recent past, does not work well beyond that, and partially loses its unused capacity for subsequent use. For example, if a NiCd battery is repeatedly charged and discharged 25% of its capacity to point M in Figure 9.2, it *remembers* point M. If the battery is discharged beyond point M in a subsequent use, the cell voltage will drop much below its original normal value as shown by dotted line in the figure.

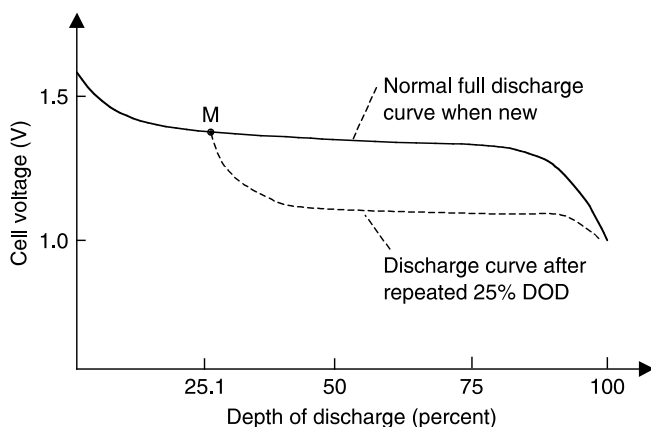


FIGURE 9.2 Memory effect in NiCd cell.

The end result is a partial loss of capacity after repeated shallow discharge cycles. The phenomenon is like losing a muscle in the human body due to lack of use over a long time.

9.3.1.2 Reconditioning

A remedy to counter the memory effect for restoring the battery to full capacity is *reconditioning*, in which the battery is fully discharged to almost zero voltage and then fully charged to about 1.55 V per cell. In the spacecraft power system, this is done twice a year at a convenient time in the orbit. In GEO, it is done outside the two eclipse seasons. In LEO, however, the spacecraft must carry an extra battery just for reconditioning purposes, adding significant mass and cost. Other types of batteries have negligible memory effect, offering a significant advantage over the NiCd battery.

A battery letdown unit is used to recondition the battery in orbit operation. It is capable of discharging the battery completely at more than one discharge rate through dedicated resistors, either at the cell level or at the battery level. In the latter case, each battery has its own battery letdown resistor. Generally the battery reconditioning starts at high rate around $C/50$. Upon the first cell reaching 0.5 V, the battery letdown unit is commanded to disconnect one of the discharge paths, and continue the battery discharge at $C/100$ rate. Upon any battery cell reaching 0.1 V, the remaining discharge path is disconnected to terminate the discharge. After the full discharge, the battery is then brought back to full charge in a normal manner. The battery cell voltage monitor provides information on each cell voltage during reconditioning and also during flight. The cell voltage data during flight is not directly useful, as little can be done if anomalies are found in flight. However, the data can be useful to the customer in the following ways:

- Predict the remaining life
- Plan replacement in serviceable spacecraft
- Reduce the load if necessary and possible
- Redesign the battery for future spacecraft

9.3.1.3 Advanced NiCd

The NiCd electrochemistry has been relatively fixed for several decades with some incremental improvements in performance in terms of life and specific energy. For example, reduction in electrode loading levels has been used in recent years to limit internal stresses that cause cell degradation. Despite a series of improvements, NiCd does not match other electrochemistries at present.

A major improvement program was undertaken under Department of Defense funding. Under this program, optimized electro-deposited nickel

and cadmium electrodes, advanced separator system, and special charge control methods were developed to achieve longer life at higher DOD, and eliminate the memory effect. Such space-qualified cells are available from a few sources, one under the trade name SuperNiCdTM. These cells compete well with NiH₂ at a power level of 1 to 2 kW, and can reduce the battery weight by a factor of 2 or more. Such an advanced NiCd battery gives about twice the life at a given DOD, or twice the DOD for a given life. The final result is the same — a significantly lighter battery. In the tests simulating LEO service, Sanyo's advanced NiCd battery of 35-Ah capacity survived more than 35,000 cycles at 20°C and 40% DOD.

The advanced NiCd competes with NiH₂ for some niche low power spacecraft, particularly in defense applications. It has negligible memory effect. Its cycle life for a given DOD is several-fold higher than the conventional NiCd and a few-fold higher than NiH₂.² It had been used in over 50 missions by the year 2000 in capacities ranging from 5 Ah to 50 Ah, typically in small satellites in LEO for NASA, the U.S. Navy, and the U.S. Air Force.³ These batteries are not being reconditioned. The typical design DOD has been around 75% in 5- to 12-year GEO missions, and 10 to 20% for 1- to 8-year LEO missions. Advanced NiCd gives better performance than the old NiCd only below 50-Ah capacities, and matches with NiH₂ in higher capacities. The primary limitation for this capacity restriction is the heat removal difficulty across the plates. Although the charging is endothermic during initial charge, it becomes exothermic beyond 75 to 80% SOC.

9.3.2 Nickel Hydrogen

The NiH₂ has been the most widely used cell in space during the last 20 years, both in LEO and GEO satellites. Over 100 satellites carrying more than 10,000 cells have been flown. They have accumulated almost one billion cell-hours of highly reliable operation. The NiH₂ battery takes the best from two electrochemistries, the nickel oxide electrode from the NiCd and the hydrogen catalyst electrode from the fuel cell. The NiH₂ cells can withstand some abuse in over-charge and over-discharge. On the other hand, NiH₂ has the following disadvantages:

- Low energy density in Wh/l
- Pressure vessel rupture, handling, and safety concerns
- High self-discharge rate around 0.5%
- High loss of capacity on storage

In the most widely used configuration of NiH₂, each elementary cell developing 1.25 V is packed in an individual pressure vessel (IPV). Figure 9.3 depicts a simplified view of the IPV cell components. The positive electrode is made of aqueous impregnated slurry of sintered nickel. The

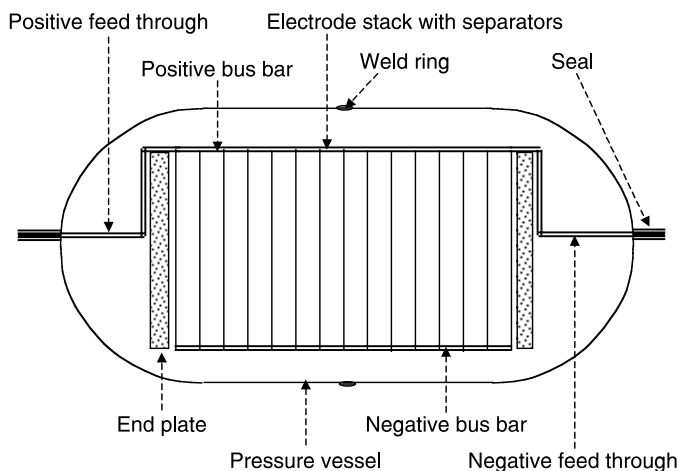


FIGURE 9.3 NiH₂ cell components — simplified view.

negative electrode is made of platinum. The electrodes are stacked in pairs with the leads extending through the center core. A separator is placed on each side of the positive electrode. The electrolyte is 26 or 31% potassium hydroxide (KOH). Other factors include ceramic to metal seals with integral terminals, double stack supports (no cantilever) for shock resistance, and zirconium separators that yield longer life. Life tests approaching 42,000 cycles have been demonstrated at 60% DOD.⁴

A plastic diffusion screen is placed on the back side of each negative electrode to diffuse gas to the back side. A number of such electrode pairs with separators are placed in one pressure vessel to obtain the required Ah capacity. The internal gas pressure rises to about 1000 psig when the cell is fully charged. To sustain such high pressure, the vessel is made of age hardened Inconel-718 with burst pressure of at least 2.5 times the maximum operating pressure at full SOC. It must comply with MIL-STD-1522 pressure vessel requirements. The vessel is made in two parts, each with an end-dome and one half of the cylindrical center body. The assembled vessel has the ring of electron beam weld in the center. Because of the high-pressure design requirement, the vessel contributes significant portion (about 40%) of the total cell mass.

Two types of positive electrode plates have been used. Both are based on a sintered nickel substrate, with one impregnated using aqueous procedure and the other using an alcohol procedure. Both behave almost similarly in all aspects. Two commonly used electrodes thicknesses are 30 mils for GEO and 35 mils for LEO applications. The 35-mil electrode gives longer wear life and slightly higher discharge voltage. However, it uses heavier electrodes and double separators, hence longer cell length and higher weight. Some manufacturers process the electrodes in aqueous solution, whereas some in alcoholic solution, although both are purged later on. The

alcoholic solution gives a little better performance, but is believed to result in a capacity fading in wet storage in discharged condition. That is, when revived, the battery does not restore to the same capacity for hundreds of cycles. Hence, it needs some trickle charging in wet storage. The cell processed in aqueous solution does not pose such a problem. It comes to full life on the first recharge after wet storage for up to 3 years.

Battery technology is rapidly changing. Some of the recent improvements for increasing the specific energy in NiH_2 chemistry are described by Britton.⁵ A few examples are the catalyzed wall-wicks incorporated in the KOH solution, and the replacement of traditional sintered substrate used in nickel electrodes with lightweight porous nickel felt. A positive plate is the key to all improvements in cycle life, voltage stability, and extended storage. The positive plate is typically 0.75 to 1 mm thick with active material loading of around 1.5 g/cm^3 .

The cell capacity is a function of the loading level of the positive active material, KOH concentration, and temperature. The earlier NiH_2 construction used 21% KOH and a double layer zirconium separator, which was replaced by a single layer for mass reduction in GEO satellites. However, the cell for LEO applications still uses the double layer zirconium with thicker electrodes to meet the longer cycle life requirement.

The 3.5-inch diameter cell had been standard for a long time, but is inefficient for larger than 100 Ah capacity due to increased length. The 4.5-inch diameter cell is a direct scale-up of the widely used 3.5-inch diameter cell, while maintaining the stack length. The 3.5 and 4.5-inch diameter cells in 35- to 150-Ah capacity range is currently flying in many satellites. To extend the Ah range on both sides, 2.5- and 5.5-inch diameter cells have also been fully developed and are flying in a number of satellites. As seen in Figure 9.4, the specific energy varies with the ampere-hour rating and also

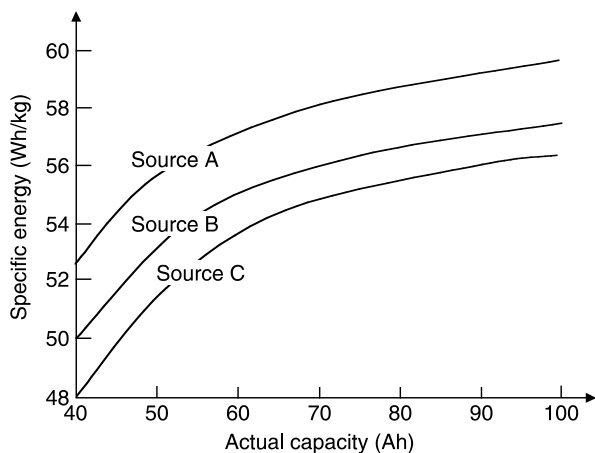


FIGURE 9.4 Specific energy of NiH_2 cells — industry range.

with design variations in the separator, electrolyte concentration, and gas management provisions such as a catalyzed wall-wick.

For the International Space Station (ISS), the NiH_2 was selected after evaluating many other options, including the regenerating fuel cell. The ISS NiH_2 cell is made of dry sintered Ni electrode, sintered Teflon-bonded platinum black H_2 electrode with Teflon backing and photo etched nickel grid, 31% KOH concentration electrolyte, and zirconium oxide clothe (ZircarTM) separators. The positive electrode is electrochemically impregnated using an alcohol–water process. The cell contains two back-to-back stacks of many pairs of electrodes, placed in two halves of the cylindrical stainless steel case welded at the longitudinal center.

Compared to NiCd, the NiH_2 chemistry has superior charge/discharge cycle life and low internal resistances. Another attractive feature of the NiH_2 cell is the linear dependence of the SOC with the internal pressure that can be measured by strain gages mounted on the outside wall. Temperature compensated strain gages are accurately matched in bridge circuits, and processed by signal conditioning amplifiers. A two-stage regulator provides stable power for the circuit. Adhesive and conformal coating materials are used for mounting the gages and the flexible circuit board is made of space-qualified, low out-gassing materials. The strain gages are calibrated individually on each cell.

Although the NiH_2 cell does not exhibit a noticeable memory effect, a number of battery design engineers believe that reconditioning is required in both NiCd and NiH_2 ; in fact, in all batteries with a positive nickel electrode. As a result, reconditioning has been done in the past as a practice inherited from the NiCd experience. Cumulative flight data to date suggests no need of reconditioning. Most customers do not require it anymore, and most power system designs have eliminated this function. However, the battery letdown unit is often installed on NiH_2 battery to discharge before shipping, on the launch pad to measure the capacity, or before placing in storage. If the letdown unit is not made part of the battery assembly, a separate unit is needed for any one of these reasons.

The mass distribution in the cell is shown in Figure 9.5. It is dominated by the pressure vessel, which requires a thick wall to limit the hoop stress under high pressure. Moreover, the cylindrical shape makes packaging of a large battery in a 15 to 20 kW satellite difficult due to the large volume. Figure 9.6 depicts a NiH_2 battery assembly with cells mounted vertically.

Over the past decade, cell manufacturers have introduced the following design improvements to reduce the battery mass and volume.

9.3.2.1 Common and single pressure vessels

The vessel portion of the individual pressure vessel mass can be reduced by packing two cells in a common pressure vessel (CPV), or by packing all cells

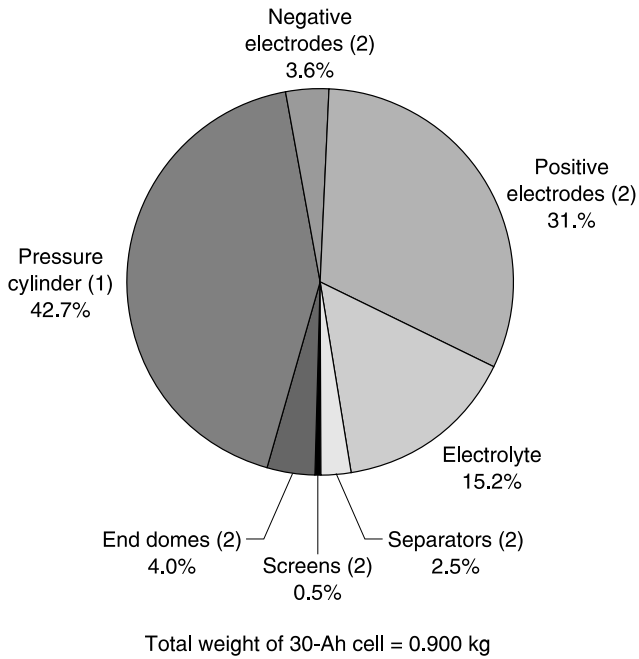


FIGURE 9.5 Mass composition of NiH_2 cell.

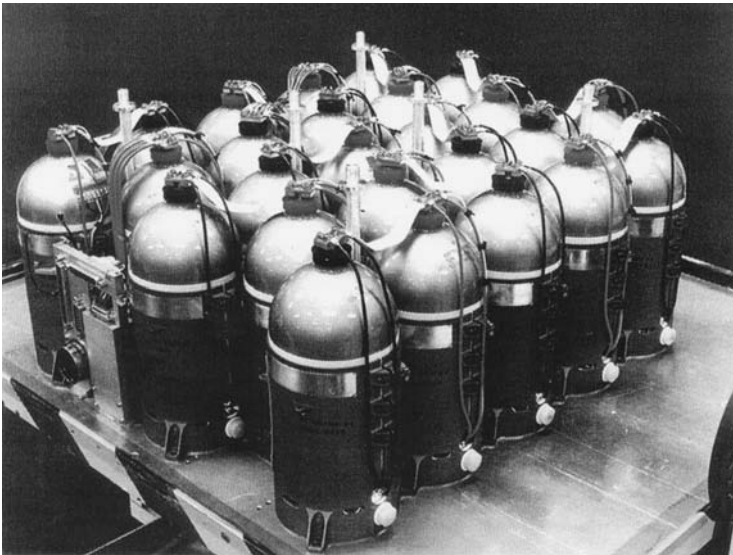


FIGURE 9.6 50-Ah 22-cell battery assembly using cylindrical NiH_2 cells mounted vertically. (Source: Dornier Satellitensysteme GmbH, Daimler-Benz Aerospace. With permission.)

in a single pressure vessel (SPV). The CPV looks just like the IPV, except for the internal connections (Figure 9.7). Two cells internally connected in series in CPV doubles the terminal voltage to 2.5 V. The battery is then assembled as usual, using one half as many CPV cells. Handling and testing fewer cells save in the manufacturing cost. The CPV cells have been used extensively on NASA/JPL programs. However, venting one vessel results in the loss of two cells, partially offsetting the gain in mass and volume, or compromising the reliability.

The SPV design places all cells in a single vessel. About 100 SPVs have successfully flown in various NASA/JPL/Navy/Air Force programs. Iridium satellites are flying with 50-Ah SPV batteries. The single pressure vessel requires a thicker wall to limit the hoop stress, partially compensating the mass savings. Overall, the SPV does save mass and volume, but the reduced reliability is a significant concern. A pressure leak or an internal arcing would result in a total loss of the battery. Moreover, it does not have the means of monitoring the individual cell voltages. The failed-cell bypass circuit generally used in the IPV battery design cannot be used in this case.

The following are commonly available NiH_2 cells from various vendors:

- | | |
|--|---------------|
| • 2.5 inch diameter IPV for small satellites | 2 to 20 Ah |
| • 3.5 inch diameter IPV | 20 to 100 Ah |
| • 4.5 inch diameter IPV | 100 to 330 Ah |
| • 5.5 inch diameter IPV for large satellites | 200 to 400 Ah |
| • 4.5 inch diameter CPV 2.5 V | 60 to 100 Ah |

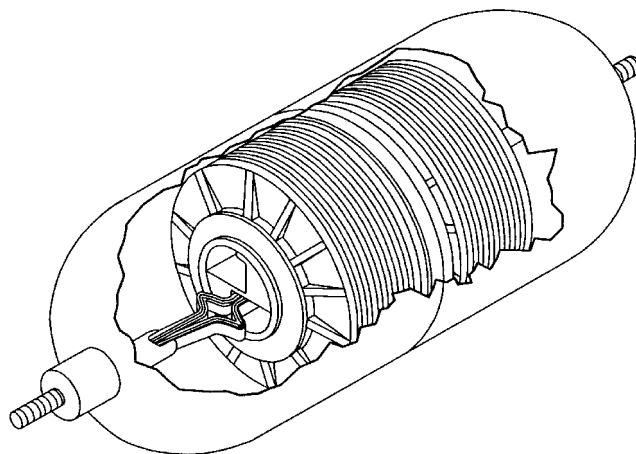


FIGURE 9.7 Common pressure vessel NiH_2 cell.

(From D.K. Coates et al. *Proc. IECEC*, ASME, p. AP-90, 1995. With permission.)

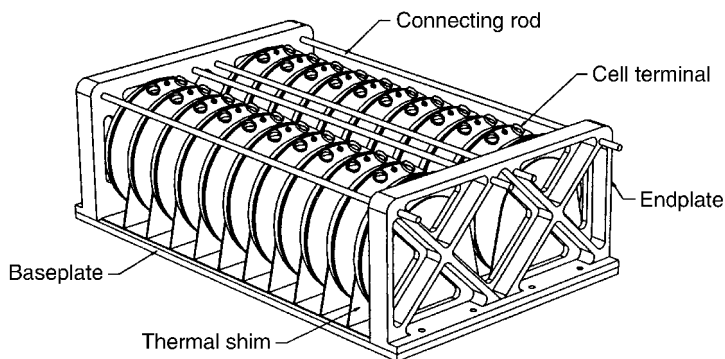


FIGURE 9.8 Dependent pressure vessel NiH_2 battery.

(From D.K. Coates et al. *Proc. IECEC*, ASME, p. AP-90, 1995. With permission.)

- A pressure leak in one cell may potentially crush all cells in a zipper mode. This concern is addressed by the cell designed with an internal bracket to support the failed cell and prevent crushing under the pressure of adjacent cells (Figure 9.9).
- Complex thermal control due to concentrated heat dissipation
- Must buy the whole battery from the vendor, which is uncommon at most satellite builders.

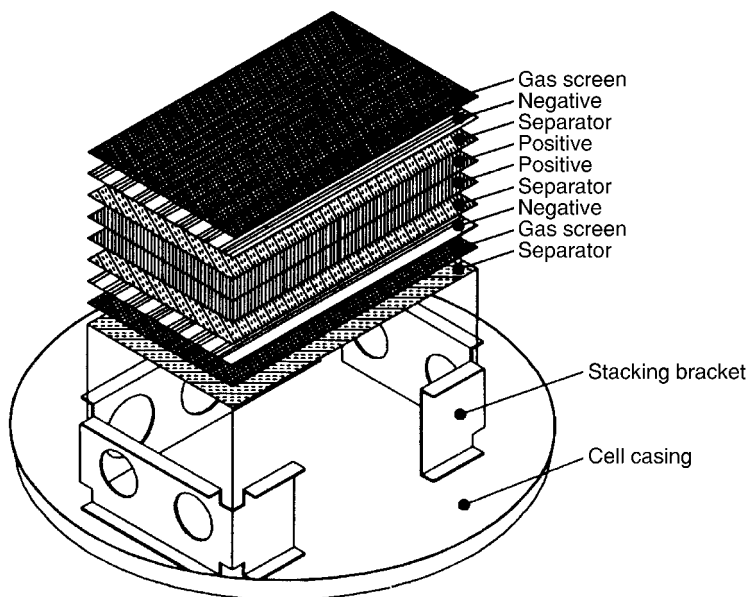


FIGURE 9.9 Dependent pressure vessel internal support bracket.

(From D.K. Coates et al. *Proc. IECEC*, ASME, p. AP-90, 1995. With permission.)

- Calibrating the strain gage reading with pressure on a hockey-puck cell is difficult. Without a reliable pressure data, the DPV has no advantage over the NiCd for interpreting the battery SOC.

For these reasons, the DPV does not offer significant advantage over the IPV cell, and is unlikely to find applications in space in the foreseeable future.

9.3.3 Nickel Metal Hydride

Concerns in working with cadmium in the NiCd battery and disposing of it helped to spark interest in using the NiMH battery for a variety of applications. In general, NiMH electrochemistry presents few health and safety risks, primarily because the electrode materials are nontoxic. Its anode is made of a metal hydride, which eliminates the environmental concerns of cadmium. The NiMH offers an improvement in specific energy over that in NiCd. Another performance improvement is that it has negligible memory effect. The NiMH, however, is less capable of delivering high peak power, has high self-discharge rate, is adversely sensitive to high temperature, and therefore is susceptible to damage due to over-charging. Compared to NiCd, NiMH is expensive at present, although the future price is expected to drop significantly. This expectation is based on current development programs targeted for its large-scale application in electric vehicles. For space applications, it has been flown on a few Japanese, European, and American flights.

Electrochemically, the NiMH is similar to the NiH_2 , except that the working hydrogen is stored as solid metallic hydride rather than gas. Having no internal pressure to withstand, these cells are made prismatic. This significantly improves the energy density and safety. Having less volume to pack, the battery requires less support structure, hence improves the specific energy as well. The disadvantage is that the linear pressure versus SOC relation of the NiH_2 is no longer available. Hermetically sealed aerospace cells have been successfully tested for several thousand C/D cycles at 50% DOD. Sanyo's 37-Ah NiMH battery survived 15,243 cycles at 40% DOD. Their loss in capacity when operating at 0°C is much greater than that in a NiCd battery.

The NiMH is prismatic and has the same operating voltage as the NiCd. Therefore, the two are easily interchangeable. The NiMH, however, produces heat during charging as opposed to the endothermic charging of NiCd.

The key features of NiMH, as compared to NiH_2 cells, are as follows:

- It offers some (10 to 20%) improvement in Wh/kg
- It offers significant (~100%) improvement in Wh/l

- It is less sensitive to temperature, hence it has lower thermal control cost
- It has a much lower operating pressure, hence is much safer

The cell rupture due to internal gas build-up is one possible hazard. The cell design with vent to release the gas pressure is therefore needed. The risk of venting hydrogen is minimized by limiting its amount during over-charging. As a health risk, nickel and its compounds may be carcinogenic, as in other cells.

9.3.4 Lithium-Ion

Lithium-ion (Li-ion) technology is a new development that offers significantly higher specific energy and energy density over that of NiH_2 . The prismatic shape (Figure 9.10) results in higher energy density. The large improvement in specific energy comes from lithium's low atomic weight of 6.9.

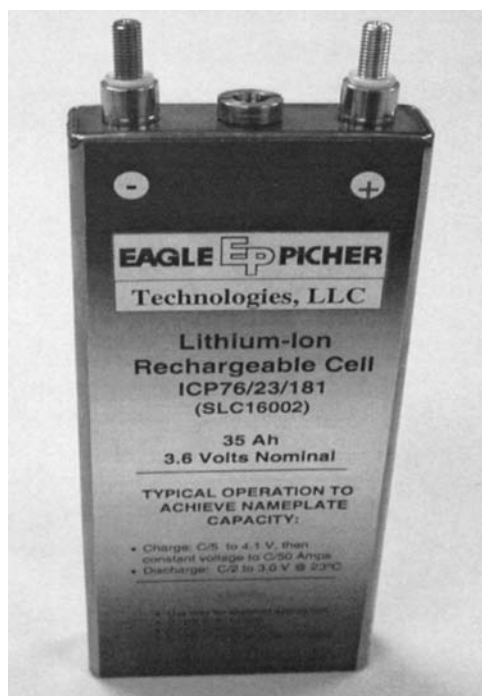


FIGURE 9.10 Lithium-ion cell of 35-Ah, 3.6-V ratings in prismatic casing.
(From J.A. DeGruson, *Proc. 36th IECEC*, ASME, p. AT-57, 2001. With permission.)

Lithium-ion batteries are widely used in laptop computers, digital cameras, and other commercial applications. The positive electrode is LiNiCoO_2 , the negative electrode is a mixture of two graphites with a non-PVDF binder, and the electrolyte is LiPF_6 salt. The cell construction uses a stainless steel prismatic case with a safety vent between the two terminals. The terminals are insulated from the case by polymeric seals as in the NiH_2 cell. Small cells are cylindrical and large cells are rectangular prismatic in shape. The prismatic shape gives high tolerance to shock and vibrations environments.

Since the Li-ion is non-aqueous chemistry, it is free from electrodes corrosion. On the negative side, lithium is highly reactive metal and must be stabilized by encapsulating the molecules in carbon using an expensive form of graphite. The lithium electrode reacts with the liquid electrolyte, creating a sort of passivation film. Each time the cell is discharged and then charged, the lithium is stripped away, a free metal surface is exposed to the electrolyte and a new film is formed. The cell uses thick electrodes to compensate for this. Otherwise the life would be short.

The Li-ion has the end of discharge cut-off voltage of 2.7V, average discharge voltages of 3.5V and end-of-charge voltage of 4.2V. The average discharge voltage of 3.5 versus 1.25 for NiCd and NiH_2 requires about one third the number of cells in series for a given battery voltage, thus reducing the assembly and test costs.

In operation, lithium-ion electrochemistry has a high charge efficiency. The coulombic efficiency is 100% all the way to 100% charging. Other desired characteristics of a space-qualified Li-ion cell are high-rate capability and potentially long cycle life at high DOD. Its low temperature sensitivity supports operation over a wide temperature range. It has low internal impedance, less than 1 m Ω in a 50-Ah cell, which supports high charge and discharge rates. It can deliver high short time peak power without an adverse effect on life.

The Li-ion cell has a potential of achieving 150 Wh/kg and 400 Wh/l, along with abuse tolerance. However, it costs more at present, but can be cost competitive with NiH_2 in the same volume production. It is vulnerable to damage under over-charging or other shortcomings in the battery management. Therefore, it requires more elaborate charging circuitry with adequate protection against over-charging. Batteries need to be trickle charged, which requires extreme care in Li-ion. Each cell may need charge control, which requires additional electronics.

Several roadblocks for space applications that have been recently addressed are:

- Relatively short life demonstrated so far
- Sensitive to over-charge and over-discharge
- High internal resistance at low temperature

The long calendar life for GEO and long cycle life for LEO are two issues in Li-ion technology that still need to be proven with a sufficiently long flight history. To date, 6000 cycles of charge/discharge at 25% DOD has been demonstrated on 35-Ah cells with stable performance. A Li-ion battery requires trickle charge at a rate of $C/50$ to $C/100$. The self-discharge rate is a few percent of that in the NiH_2 , but increases at high temperature. The internal impedance is low but increases at low temperature. The two must be traded in the design.

The present development funded by NASA and the U.S. Air Force has the following goals at the cell level:

- Cell capacity of 20 to 200 Ah
- Life of 30,000 cycle at 50% DOD
- Life of 40,000 cycles at 40% DOD
- Temperature range -40°C to $+80^\circ\text{C}$
- Charge rate $C/5$ to C
- Discharge rate $C/2$ to $2C$

The 2001 test results on *Mars Lander* batteries showed specific energy of about 150 Wh/kg.⁷ Nominally 5-Ah cells were tested for capacity when discharged at a 1-A rate at various temperatures. The cells were cycled from 2.4 V to 4.1 V. The tests showed significant degradation at low temperature, with only 60% capacity at -30°C . In internal heat generation tests on 25-Ah cells at 10°C during charge and discharge at 5-A rate, the heat generation spiked at the end of discharge due to increased polarization as the cell reached full discharge. The heat generation reduction at the end of charge was due to charge current tapered down to zero.

The tests on 10-Ah cells charged and discharged at the same temperature have shown⁸ that 600 cycles at 100% DOD at -20°C resulted in 6% capacity loss. Fellner⁹ reports test data on Li-ion cells cycled as follows for GEO and LEO applications:

- For LEO: 20-Ah cells, 40% DOD, charged to 4.1 V at $0.5C$ rate for 1 h, discharged at $0.8C$ rate for 30 min
- For GEO, 20-Ah cells, 100% DOD, charged at C rate to 4.1 V in 3 h, discharged at $C/5$ rate to 2.5 V.

The initial test data for a discharged cell show that the internal resistance grows exponentially with decreasing temperature for a given state-of-charge.

The Li-ion batteries can release lithium gas and flames when over-charged. This danger needs effective control of the over-charge. For this reason, the maximum charge voltage and minimum discharge voltage must

be maintained for successful incorporation of Li-ion cells into the space power system design. In this respect, Li-ion chemistry is very different to that of the NiH_2 in that the Li-ion does not tolerate over-charge or over-discharge. As a battery of many cells in series and parallel is cycled, it often becomes unbalanced due to small cell-to-cell differences in the rate of capacity fade, rate of impedance increase, or rate of self-discharge that are accumulated over many cycles. For charge balancing, various techniques such as switched capacitor and resistance or inductor equalization have been explored.

Li-ion has a better low temperature performance in the -20°C to $+40^\circ\text{C}$ range. It can operate even at -40°C with some capacity loss. Poor cell performance at lower temperature is attributed to the electrolyte becoming viscous or solid, and poor lithium diffusivity in the electrodes. An 8-cell 25-Ah battery was space qualified in 2001 for 2000 cycles at 100% DOD for the *Mars Lander* mission requiring such a low temperature range. The battery was designed for a 3.0 to 4.1-V operation, 2.5-V cut-off voltage, and C/5 and C/10 charge rates. Tests reported by Bruce and Marcoux¹⁰ at various temperatures cover design and fabrication features of large capacity cells up to 100 Ah. In cells for aircraft applications, the main concern is irreversible capacity loss at elevated temperature. The loss in capacity at high temperature comes primarily from the positive electrode degradation. In cells for space use, however, the shelf life and cycle life are critical.

9.3.5 Lithium Polymer

The electrochemical basis of the Li-ion solid polymer electrolyte (Li-poly) battery is similar to that of Li-ion, except that the electrolyte of the Li-ion is replaced by a solid polymer that encapsulates the electrodes. The cell is constructed with a film of metallic lithium bonded to a thin layer of solid polymer electrolyte. The solid polymer enhances the specific energy by acting as both the electrolyte and the separator. This construction also offers an improvement in safety compared to Li-ion by reducing flammability. Moreover, the metal in solid electrolyte reacts less than it does with liquid electrolyte. There are various types of Li-polymer cell, with markedly different characteristics. An advanced battery is under development by NASA with an industry team for aerospace and consumer applications. The goals of these programs are listed in Table 9.2. The 35,000 cycles life at 25% DOD addresses the LEO satellites requirements, while the 2000 cycles life at 100% DOD would meet the GEO satellite requirements.

On the safety side, the Li-ion system is relatively less reactive and more reliable than the present lithium metal systems, and may have performance advantage over some solid polymer electrolyte systems. However, the possibility of electrolyte spill is a disadvantage over a solid electrolyte. Some materials used in the Li-ion cells may be toxic and carcinogenic, such

Table 9.2 NASA goals for Li-ion research programs at cell level

Performance parameter	Li-poly (goals)	Present Li-ion	Present NiH ₂
Specific energy, Wh/kg	200–250	125–150	50–65
Energy density Wh/l	350–400	300	–
Life at 100% DOD, cycles	2000	1000	–
Life at 25% DOD, cycles	35,000	–	–

as lithium, nickel and arsenic compounds, and possibly cobalt, copper and polypropylene.

9.3.6 Silver Zinc

The silver zinc (AgO-Zn) secondary battery has high specific energy but shorter cycle life. It is suitable in missions requiring a low number of *C/D* cycles. It is used in military aircraft and spacecraft, launch vehicles, and undersea applications. The specific energy ranges from 125 to 250 Wh/kg and energy density 200 to 600 Wh/l. Prismatic cells are available in a wide range of ampere-hours in low-rate (LR) and high-rate (HR) types. Because resistance of the silver monoxide electrodes vary little with the state of charge, a stable operating voltage is provided until nearly all the capacity is drawn.

The AgO-Zn cell comes in two varieties: dry charged and dry unformed. In the dry-charged cell, the positive and negative electrodes are charged at factory, but the electrolyte is added at the launch site. The dry unformed cell is charged and the electrolyte is added at the launch site. In both cases, the cell comes to a full charge voltage of 1.86 V open circuit after the soak time. In subsequent *C/D* cycles, the full cell charging is terminated at 2.05 V, and the open circuit voltage drops to 1.86 V. Full charge level is indicated by the voltage as well as the electrolyte level on a visible scale.

9.4 Electrical Circuit Model

The battery works as a voltage source with small internal resistance. Its electrical circuit model is shown in Figure 9.11, where E_i is the internal electrochemical voltage and R_i is the internal resistance. The E_i decreases and R_i increases linearly with the ampere-hour discharge. That is, the internal voltage is lower and the internal resistance is higher in a partially discharge battery as compared to their values — designated as E_o and R_o , respectively — in the fully charged state. Quantitatively,

$$\begin{aligned} E_i &= E_o - K_1 \cdot \text{DOD} \\ R_i &= R_o + K_2 \cdot \text{DOD} \end{aligned} \quad (9.4)$$

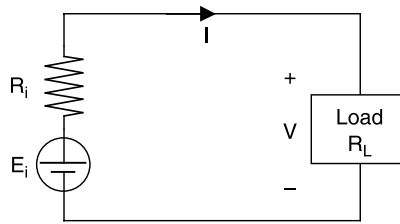


FIGURE 9.11 Equivalent electrical circuit of battery showing internal voltage and resistance.

where K_1 and K_2 are constants of the electrochemistry to be found by curve fitting the test data. Under load, the terminal voltage drops with increasing load, and the operating point P is the intersection of the battery line and the load line as shown in Figure 9.12.

9.5 Properties and Performance

The electrical performance of the battery depends on the electrochemistry and on many other parameters in a highly nonlinear manner. This makes the battery design one of the most difficult tasks for the power system engineer. Major performance characteristics of the battery in general are discussed in this section, mostly for NiH_2 , the widely used electrochemistry at present.

9.5.1 Charge/Discharge

The cell voltage varies during a typical charge/discharge (C/D) cycle as was shown earlier in Figure 4.3. The charge/discharge characteristic also depends on the charge rate, discharged rate, temperature, and age of the cell. Figure 9.13 shows such variations for a LEO satellite.

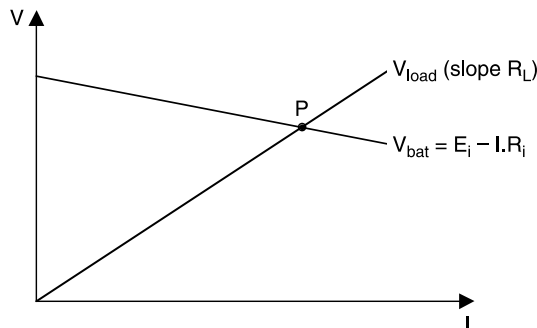


FIGURE 9.12 Battery line and load line intersecting at operating point.

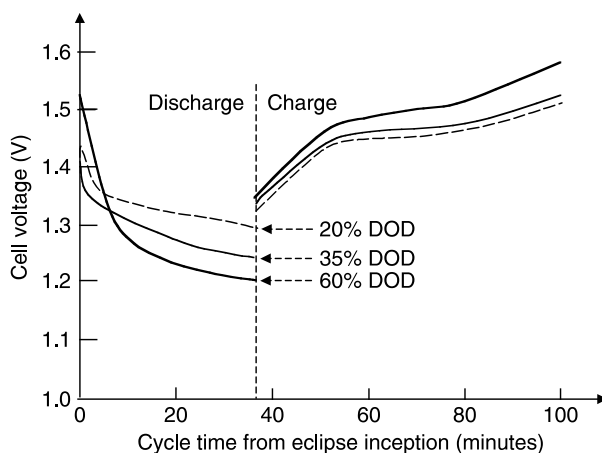


FIGURE 9.13 NiH₂ charge/discharge cycle at different rates in LEO.

Typical average NiH₂ and NiCd battery cell voltages are as follows:

- 1.55 V when fully charged
- 1.45 V average during charge
- 1.25 V average during discharge
- 1.10 V at 80% DOD
- 1.00 V when fully discharged

After discharging certain ampere-hours, the battery requires more ampere-hours of charge to restore the full state of charge. The charge/discharge ratio is defined as the ampere-hours input over the ampere-hours output for full state of charge. This ratio depends on the charge and discharge rates and also on temperature as shown in Figure 9.14. For example, a C/D ratio of 1.1 means the battery requires 10% more ampere-hours for restoring to fully charged state than what was discharged. Charging in LEO is usually at a much faster rate, which is more efficient than the slow charging rate typical in GEO. Therefore, a low C/D ratio of 1.05 to 1.1 is needed in LEO missions, while a higher ratio of 1.1 to 1.2 is needed in GEO missions. A high C/D ratio causes excessive corrosion of the nickel electrodes, and large amount of oxygen leading to heating and popping during recombination on the hydrogen electrode. On the other hand, low C/D ratio causes reduced usable capacity, low discharge voltage, and capacity degradation.

A new cell stores over 20% higher capacity when charged at -20°C compared to that at $+20^{\circ}\text{C}$ (Figure 9.15), but only about 10% higher after about 100 cycles of charge/discharge cycles (1 year in GEO). The maximum charge voltage also varies with temperature (Figure 9.16). The end of charge

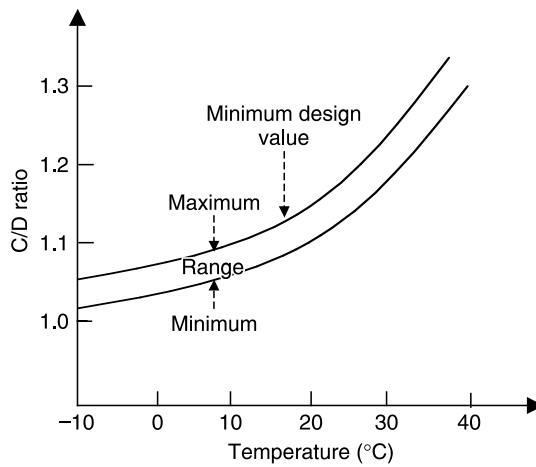


FIGURE 9.14 NiH₂ charge/discharge ratio versus temperature.

and end of discharge voltages in NiH₂ remain fairly flat with the number of C/D cycles even for several years in LEO missions, but not in NiCd.

The battery performs better under slow charge and discharge rates. A fast discharge rate results in fast voltage degradation and low ampere-hour capacity to the load. For these reasons, high charge and discharge rate applications require different design considerations than the low-rate applications.

After the battery is fully charged, the charge efficiency drops to zero. Any additional charge will be converted into heat. If over-charged at higher rate than the self-discharge rate for long time, the battery would overheat posing

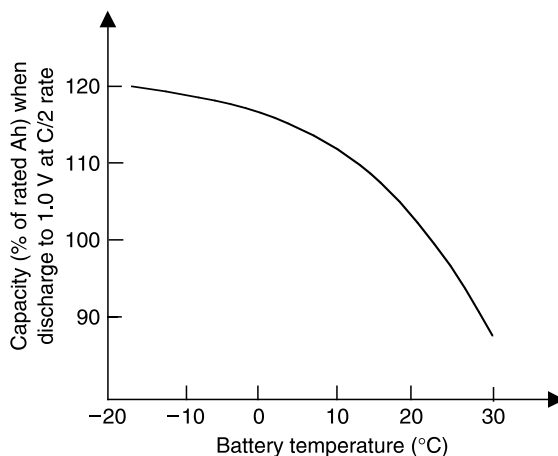


FIGURE 9.15 Cell Ah capacity versus temperature.

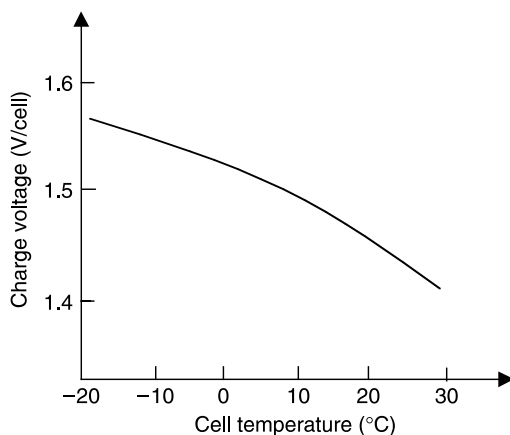


FIGURE 9.16 Full charge voltage at $C/10$ for 16 h.

a potential explosion hazard. Any excessive over-charging produces excessive gassing, which scrubs the electrode plates. Continuous scrubbing at high rate produces excessive heat, wears out electrodes, and shortens the life. For this reason, the battery charge circuit requires a regulator to cut back to the trickle charge rate once the battery is fully charged. The trickle charging produces a controlled amount of internal gassing. It causes mixing action of the battery electrolyte, keeping it ready to deliver full charge.

9.5.2 Internal Impedance

The internal impedance of the cell is made of the resistance, inductance, and capacitance. The resistance comes primarily from the electrodes and electrolyte, the inductance from the leads in and out of the cell, and the capacitance from the two electrode plates. The internal power loss during discharge or charge can be seen as having an internal resistance R_i . The value of R_i depends on the battery capacity, operating temperature, and the state of charge. The higher the cell capacity, the larger the electrodes and lower the internal resistance. The R_i varies with the state of charge as per Equation 9.4. It also varies with temperature as shown in Figure 9.17. The internal resistance and inductance of 50-Ah and 100-Ah NiH_2 cells at 10°C are given in Table 9.3.

9.5.3 Charge Efficiency

The charge efficiency, also known as coulombic efficiency, is defined as the ratio of the ampere-hours being deposited internally between the plates over that injected from the external terminals during charging. It is different from the energy efficiency. The coulombic efficiency varies as a function of

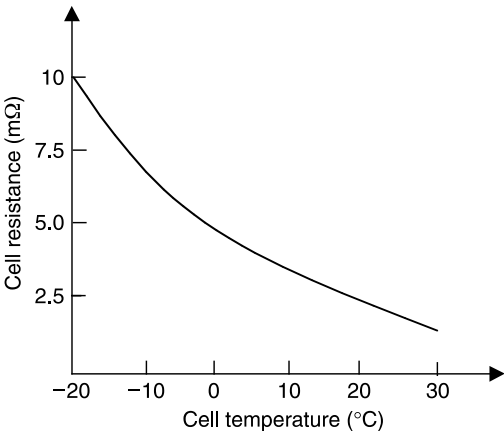


FIGURE 9.17 Internal resistance of 50-Ah NiH₂ cell at 100% SOC.

the SOC, charge rate, and the operating temperature, and is generally higher than 97%. The charge efficiency is almost 100% when the cell is empty of charge; the condition in which all charge received is deposited between the plates. As the SOC approaches 1, the charge efficiency tapers down to zero. The knee point where the charge efficiency starts tapering off depends on the charge rate and temperature (Figure 9.18). For example, at $C/2$ charge rate, the charge efficiency is almost 100% up to about 75% SOC. At a fast charge rate of $C/40$, on the other hand, the charge efficiency at 70% SOC is only about 50%.

9.5.4 Energy Efficiency

In both the charge and the discharge modes, a small fraction of energy is converted into heat. The energy efficiency over a round trip of full charge and discharge cycle is defined as the ratio of the energy output over the energy input at the electrical terminals of the battery. For a typical battery of capacity C at room temperature with an average discharge voltage of 1.25 V,

Table 9.3 Approximate impedance for IPV NiH₂ cells

Parameter	50-Ah cell	100-Ah cell
Cell resistances	4.5 mΩ at 1 kHz	2.25 mΩ at 1 kHz
	20 mΩ at 10 kHz	10 mΩ at 10 kHz
Cell inductance	0.70 μH at 1 kHz	0.60 μH at 1 kHz
	0.35 μH at 10 kHz	0.30 μH at 10 kHz

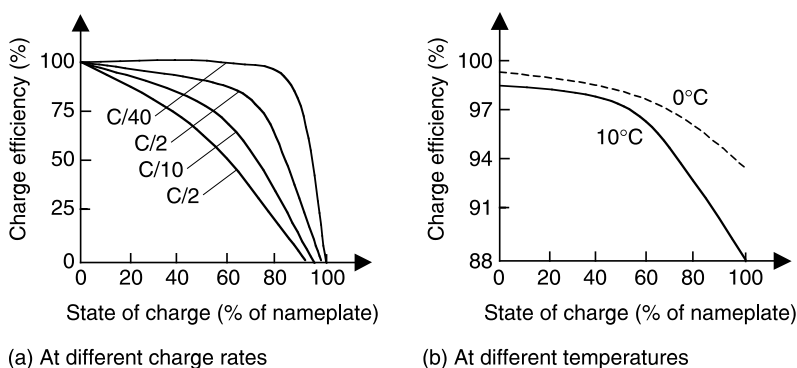


FIGURE 9.18 Charge efficiency versus state of charge for NiH₂ cell.

average charge voltage of 1.45 V, and the charge/discharge ratio of 1.10, the efficiency is calculated as follows:

- The energy output over the full discharge = $1.25 \times C$
- The energy input required to restore full charge = $1.45 \times 1.10C$
- Therefore, the round trip energy efficiency is

$$\eta_{\text{energy}} = \frac{1.25 \times C}{1.45 \times 1.10C} = 0.78 \text{ or } 78\% \quad (9.5)$$

These calculations indicate that about 22% energy is lost per charge/discharge cycle, which is converted into heat. Most of this energy loss occurs during discharge. The round trip energy efficiency varies with various factors, but is typically 75 to 80% for NiH₂ and 80 to 85% for NiCd.

9.5.5 V-T Characteristics

For most electrochemistries, the full charge voltage is a function of temperature and age of the battery as shown in Figure 9.19, where the limit numbers represent equally divided periods of the mission life. A similar relation for the C/D ratio is shown in Figure 9.20. Such voltage versus temperature (V-T) curves are used for on-orbit energy management as discussed in Chapter 13. With a NiH₂ battery, an alternative is to use the pressure-temperature (P-T) curves, which exhibit similar relations with age. The energy management software shifts the operation on-board as the battery ages in service.

9.5.6 Self-Discharge

The battery slowly self-discharges even with no load under open circuit. It must be continuously trickle charged to counter the self-discharge rate in

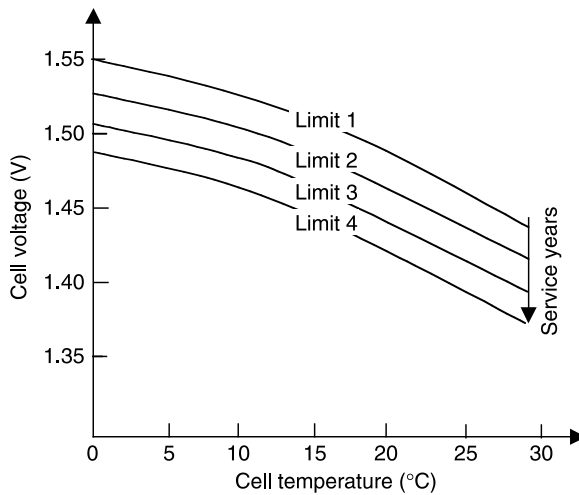


FIGURE 9.19 Temperature compensated V - T levels for NiH_2 cell.

order to maintain the full state of charge. This rate is usually less than 1% per day for most electrochemistry in normal working conditions. In NiH_2 cells, the self-discharge rate shows as a proportionate loss in pressure as seen in Figure 9.21. After the battery is fully charged, the charge efficiency drops to zero. Any additional charge will be converted into heat. If over-charged at higher rate then the self-discharge rate for long time, the battery would overheat posing a potential explosion hazard.

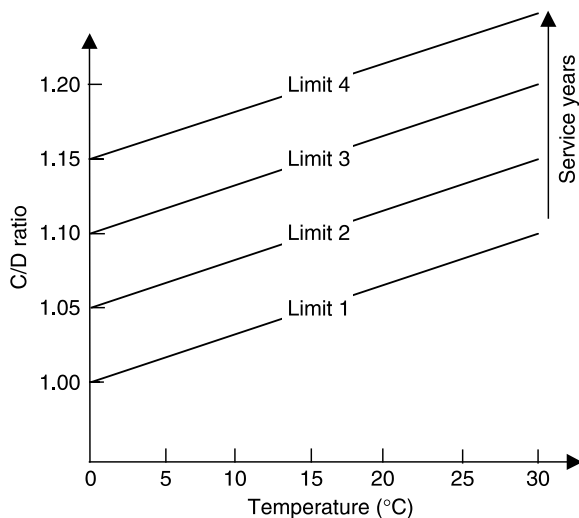


FIGURE 9.20 Temperature compensated charge/discharge ratios for NiH_2 cell.

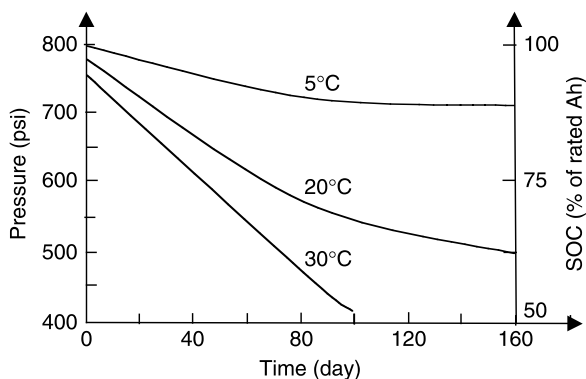


FIGURE 9.21 Self-discharge rates versus time in NiH₂ cell under open circuit.

9.5.7 Self-Heating

When the battery is initially put to charge, the internal heat generation rate is negative for a while, meaning that the electrochemical reaction during the initial charging period is endothermic (absorbing heat). The reaction changes to exothermic and generates heat as the battery approaches full charge. The temperature rise during this phase depends on the cooling method used to dissipate the heat by conduction, convection, and radiation.

The internal power loss (in watts) causes self-heating in the battery. It has a major impact on the battery temperature. During charge, it is equal to the sum of heat generated by charging of active materials (am) and the heat generated by over-charge reaction (or). That is,

$$H_c = H_{c,am} + H_{c,or} = -I_c \eta_c \{1.45 - E_c\} + I_c (1 - \eta_c) E_c \quad (9.6)$$

where I_c = charge current, η_c = instantaneous charge efficiency, E_c = charge voltage, and 1.45 is the ratio of the enthalpy in joules equivalent to the Faraday's constant for NiCd and NiH₂. The above equation simplifies to

$$H_c = -I_c \{1.45 \eta_c - E_c\} \quad (9.7)$$

At the beginning of the charging process when η_c is near unity and E_c is low, $1.45 \eta_c > E_c$ and H_c is negative, meaning the battery absorbs heat and self-cools. Near the end of charging, as η_c approaches zero and E_c rises, the battery generates heat and self-heats.

The heat generation rate (in watts) during discharge is given by

$$H_d = I_d \{1.50 - E_d\} \quad (9.8)$$

where I_d = discharge current and E_d = discharge voltage.

As seen in the above two equations, the required information for determining the internal heat generation rate is the current, voltage, and the instantaneous charge efficiency. During discharge, approximately 15% of the total energy released is heat, 5% is pressure-volume work and side reactions, and 80% is useful electricity. In this exothermic mode, it releases heat in addition to electrical power. Therefore, the battery temperature rises. During charge, on the other hand, the battery temperature falls as the chemical reaction requires heat. This is true until the full state of charge is attained as indicated by the battery voltage of 1.55 V or so. Beyond this point, the chemical reaction stops, and all energy supplied are turned into heat. The battery may over-heat quickly and may explode.

During over-charge and trickle charge, the heat generated is equal to the electrical power input. Thus, the efficiency depends upon the achievable trickle charge rate, which in turn depends upon the charge rate, temperature, charge regulator operation, etc. Typically, the battery is recharged before the eclipse starts with ample margin in time. Then it is placed into taper charge and over-charge if the V - T limit charge approach is used. During this period, the entire over-charge will convert into heat inside the battery. The thermal control is designed to maintain the battery within its desired operating temperature limits.

Figure 9.22 shows the power loss in a 40-Ah 22-cell NiH_2 battery delivering a 1200-W load during eclipse in GEO with 65% DOD and C/D ratio of 1.2. Figure 9.23 depicts the power loss in the NiH_2 battery on a 3000-W LEO platform with a maximum DOD of 35% and C/D ratio of 1.1 (EOS-AM batteries, each 54-cells 50-Ah capacity, 1500-W average load, 80-V battery voltage). For a lower C/D ratio, the power loss between 90 and 98 minutes would be lower. Note that the heat generation increases as the

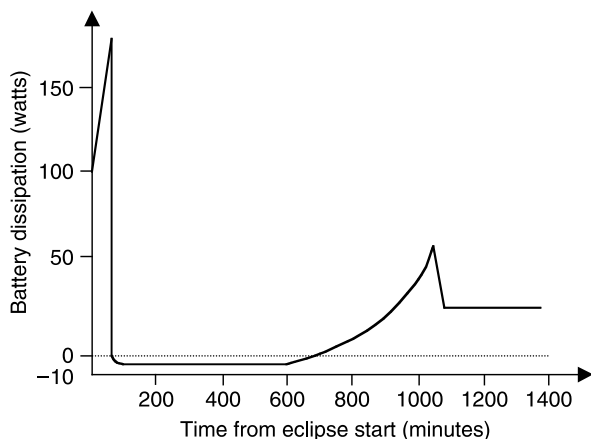


FIGURE 9.22 Battery power loss versus time starting with eclipse for 1200-W load and 1.2 C/D ratio in GEO orbit.

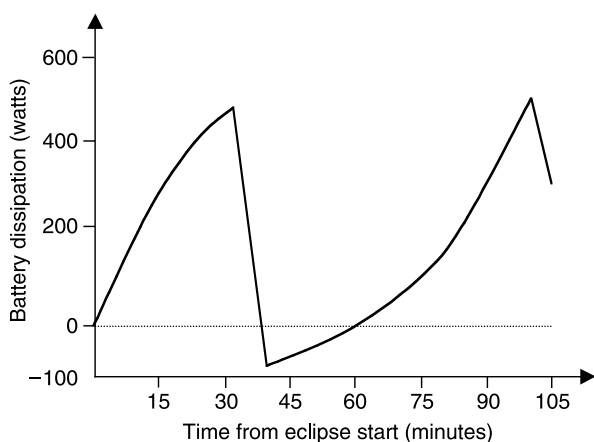


FIGURE 9.23 Battery power loss versus time starting with eclipse for 3000-W load and 1.1 C/D ratio in LEO orbit.

depth of discharge increases because of the increased internal resistance. In order to overcome possible cell voltage divergence, the C/D ratio can be increased. However, that would increase the orbit average dissipation. For NiH_2 cells, increasing the C/D ratio from 1.05 to 1.1 can increase the orbit average dissipation in LEO by 10% at 35% DOD and 15% at 70% DOD.

Different electrochemistry, however, generates internal heat at different rates. The heat generation between various batteries can be meaningfully compared in terms of the adiabatic temperature rise during discharge, which is given by the following relation:

$$\Delta T = \frac{WH_d}{M \cdot C_p} \left[1 - \eta_v + \frac{E_d}{E_o} \right] \quad (9.9)$$

where

ΔT = adiabatic temperature rise of the battery, in degrees centigrade

WH_d = watt-hour energy discharged

M = mass of the battery

C_p = battery specific heat, Wh/kg $^\circ\text{C}$

η_v = voltage efficiency factor on discharge

E_d = average cell entropy energy per coulomb during discharge,
i.e., average power loss per ampere of discharge, W/A

E_o = average cell open circuit voltage, volts

For full discharge, the WH_d/M ratio in the above expression becomes the specific energy. This indicates that higher specific energy cells would also

tend to have higher temperature rise during discharge, requiring enhanced cooling design. Figure 9.24 depicts the adiabatic temperature rise ΔT for various electrochemistries after a full discharge in short burst.

The thermal properties of the cell, such as the heat generation rate, thermal conductivity, and specific heat are useful for the thermal analysis and design. The specific heat of the NiCd cell is about 1000 J/kg°C, which is about that of pure aluminum. For the NiH₂ cell, it is about 1200 J/kg°C. In terms of the ampere-hour capacity, the following equation gives a reasonable first order approximation to the specific heat (in Ah·J/°C) of the cell:

$$C_p = 200 + 25 \quad (9.10)$$

The battery temperature generally means the wall temperature. A temperature gradient across the hydrogen gap between the wall and the internal stack in NiH₂ cell is typically 2 to 3°C.

9.6 Cycle Life

The battery fails when at least one cell fails. The cell failure is theoretically defined as the condition in which the cell voltage drops below certain low value before discharging the rated capacity at room temperature. The low value is generally taken as 1.0 V in cells with nominal voltage of 1.25 V. The remaining ampere-hours the cell can deliver from 1 V to 0 V is only a few percent. However, this is a conservative definition of battery failure. The battery does not fail like a light bulb, but gradually degrades in performance. In a degraded state with one cell dropping below 1.0 V, the rest of the cells providing voltage above 1.0 V may make up for the failed cell, and the battery as a whole may still provide the minimum required voltage. If the battery voltage falls below its required level at full load, it can

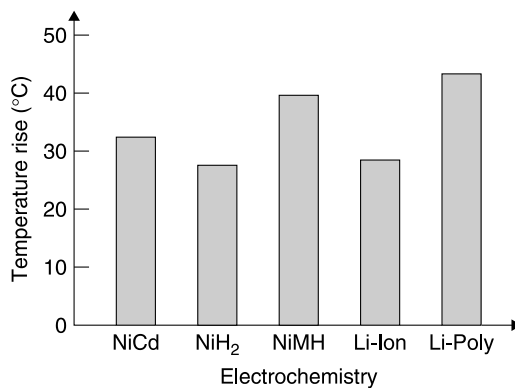


FIGURE 9.24 Adiabatic temperature rise under full discharge of capacity in various electrochemistries.

still deliver the required voltage for a short time if the load can be shed to lower the DOD.

Battery end of life is defined as one or more cell voltages dropping below 1.0 V at any point during the C/D cycle, usually at the end of discharge. The cell can fail either randomly or due to wear. It can fail open, short, or somewhere between (a soft short). A short that starts soft eventually develops into a hard short. In a low voltage battery, any attempt to charge with a shorted cell may result in physical damage to the battery and/or the charge regulator. On the other hand, the shorted cell in a high voltage battery with numerous series connected cells may work for a long time. However, it loses the voltage and ampere-hour capacity, and hence would work as a load on the healthy cells. An open cell, on the other hand, disables the entire string of series connected cells.

A spacecraft battery rarely fails randomly. Its primary failure mode is associated with electrode wear due to repeated charge/discharge cycles. The battery life is measured as the number of times it can be discharged and recharged before the electrodes wear out. The life depends strongly on the electrochemistry, the depth of discharge, and the temperature. Figure 9.25 shows the cycle life characteristic of NiCd and NiH₂ batteries. The life also depends to a lesser degree on electrolyte concentration, electrode porosity, and charge and discharge rates. The electrolyte concentration makes a significant difference to the cycle life of the NiH₂ cell. The cell with 26% concentration gives a greater cycle life compared to one with 31% concentration. The first set of factors is application related, whereas the others are construction related.

The number of charge/discharge cycles in a satellite equals the number of eclipses during the mission life. It is at least an order of magnitude greater in LEO satellites than in GEO. Such a long cycle life requirement in LEO can be achieved only by limiting the battery design to a low depth of discharge, typically 30% compared to 80% in GEO satellites. Obviously, such a design requires a proportionately much larger battery. A long cycle life at a given DOD and operating temperature reduces the battery mass in direct proportion.

It is noteworthy from Figure 9.25 that the life at a given temperature is an inverse function of the depth of discharge. If the life is 100 units at 50% DOD, then it would be about 200 units at 25% DOD. This makes the product of the cycles to failure and the DOD roughly constant in the first approximation. The cycle life multiplied by the DOD product decreases with increasing temperature. Such is true for most electrochemistries. This means that the battery at a given temperature can deliver the same number of equivalent full charges regardless of the depth of discharge. Phrased differently, the total watt-hour energy the battery can deliver over its life is roughly constant in the first approximation. The battery lasts proportionately longer if less energy is used per cycle. Such an observation is useful

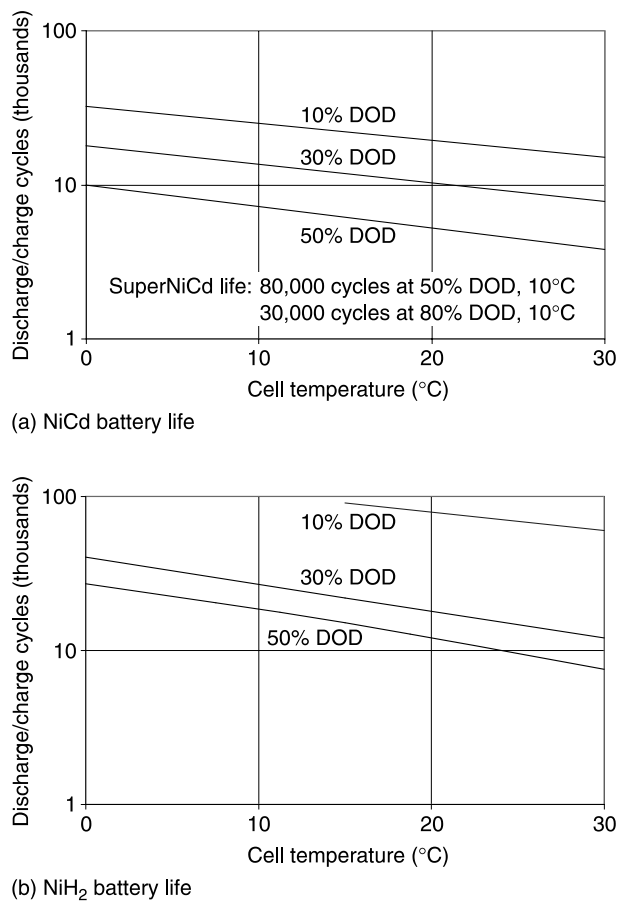


FIGURE 9.25 Cycle life versus temperature and DOD for NiCd and NiH₂ cells.

in comparing the costs of various batteries for a given application at the conceptual design stage.

The battery does not work fully well all the way until it dies. Its capacity remains fairly constant until it rapidly fades at the end as shown in Figure 9.26.

Since the battery cycle life is influenced primarily by the end of discharge DOD and temperature, the cell life prediction model is generally developed by fitting exponential curves to the test data on cycles to failure versus DOD at temperatures the battery would be subjected in orbit. The factors such as the charge and discharge rate and the electrolyte concentration are not included in such a model, but are factored into the cell life data by actual test or from previous experience. A reliability model then incorporates the predicated cell wear-out life and the random failure rates to estimate the mean time before battery failure by taking into account the number of cells

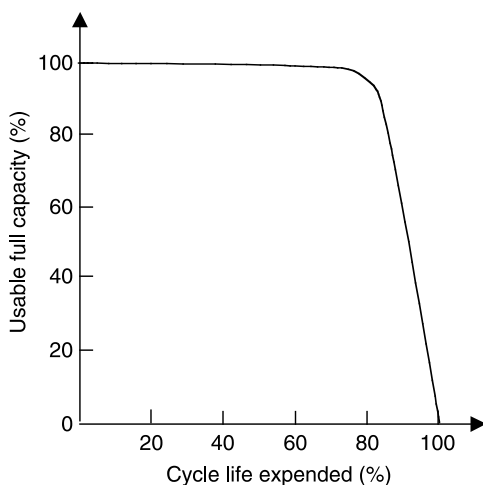


FIGURE 9.26 Capacity fade versus cycle life expended.

in series, the bypass diodes, and other components in the battery as a whole.

The battery life testing is generally done under accelerated cycling. For example, the GEO cycle is 24 h, but the battery testing is done in 8-h cycles. Smith and Brill¹¹ report such test data in NiH₂ cells. Many spacecraft design engineers believe that some electrochemical differences in actual cycling and accelerated cycling are still not fully acceptable.

9.7 Burst Power Capability

In fast discharge applications, such as for meeting a pulse power demand, the battery may be required to deliver the maximum possible power for a very short time. The peak power it can deliver can be derived using the maximum power transfer theorem in electrical circuits. It states that the maximum power can be transferred from the source to the load when the internal impedance of the source equals the conjugate of the load impedance. The battery can deliver maximum power to a d.c. load when $R_L = R_i$. This gives

$$P_{\max} = \frac{E_i^2}{4R_i} \quad (9.11)$$

Since E_i and R_i vary with the state of charge, the P_{\max} also varies accordingly. The internal loss is $I^2 R_i$, which is also equal to P_{\max} delivered to the load. The power transfer efficiency while delivering theoretical possible peak power is therefore only 50%. Such poor efficiency may not matter for a short-duration peak load. Both NiCd and NiH₂ batteries are

capable of following pulse discharge and charge lasting a few milliseconds. The battery voltage follows the load variations as expected even under pulse loading. The power peaks shorter than a few milliseconds durations primarily comes from the capacitance between the electrodes plates.

9.8 Performance Comparison

Figure 9.27 compares the specific energy and energy density of various electrochemical cells. The voltage varies with DOD. For 60% DOD, it varies from 1.22 to 1.26 V at moderate discharge rate. The average charge and discharge voltages are listed in Table 9.4. Other performance characteristics and properties of different types of cell are summarized and compared in Table 9.5 and Table 9.6. With NiCd and NiH₂ cells, the battery mass taking into considerations all design factors and the packaging hardware is given in Figure 9.28 for various load levels, service life, and DOD; and their qualitative differences are listed in Table 9.7. The battery mass required to meet typical power system performance with various cells is shown in Figure 9.29 in percentage of the NiCd battery mass. The life and cost are compared in Table 9.8.

9.9 Battery Design

The battery design starts with selecting the electrochemistry and the number of batteries based on the mission requirement and the heritage database. The following factors have strong influence the chemistry selection:

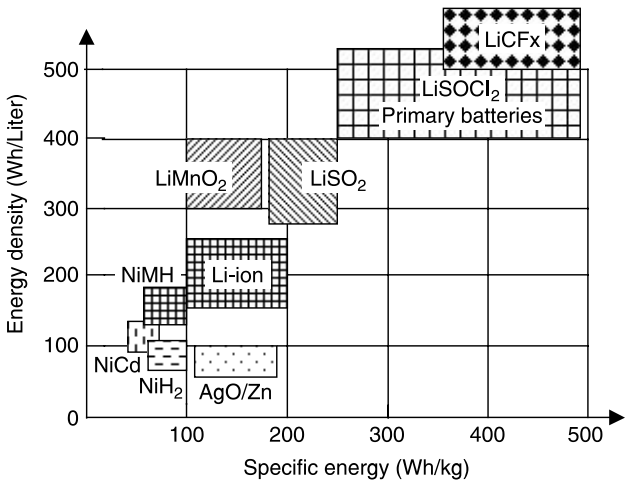


FIGURE 9.27 Specific energy and energy density of various electrochemistries.

Table 9.4 Voltage characteristics of various batteries for space applications

Electro-chemistry	Cut-off voltage	Discharge voltage	Charge terminate voltage	Remarks
NiCd	1.0	1.25	1.55	Exhibits memory effect
NiH ₂	1.0	1.25	1.55	No memory effect
NiMH	1.0	1.25	1.55	Temperature sensitive
Li-ion	2.7	3.50	4.20	Safe, contains no metallic lithium
Lithium-polymer	2.7	3.50	4.20	Contains metallic lithium
Silver-zinc	1.3	1.50	2.05	Needs good air management to limit self-discharge rate

Table 9.5 Energy and power densities of various cells

Electro-chemistry	Specific energy (Wh/kg)	Energy density (Wh/l)	Specific power (W/kg)	Power density (W/l)
NiCd	40–5	50–100	150–200	300–500
NiH ₂	45–65	35–50	150–200	200–300
NiMH	50–70	140–180	150–200	300–500
Li-ion	90–150	150–250	200–220	400–500
Lithium-polymer	100–200	150–300	>200	>400

Table 9.6 Battery characteristics affecting thermal design

Electro-chemistry	Operating range (°C)	Over-charge tolerance	Heat capacity (Wh/kg.K)	Mass density (kg/l)	Entropic heating on discharge W/A-cell
NiCd	–20 to 50	Medium	0.30	1.7	0.12
NiH ₂	–10 to 50	High	0.35	1.0	0.10
NiMH	–10 to 50	Low	0.35	2.3	0.07
Li-ion	10 to 45	Very low	0.38	1.35	0
Lithium-polymer	50 to 70	Very low	0.40	1.3	0

- Specific energy and energy density
- Cycle life, stability of capacity and voltage
- Round trip energy efficiency
- Mass and volume constrains
- Temperature effects on the performance
- Ampere-hour capacity ratings available

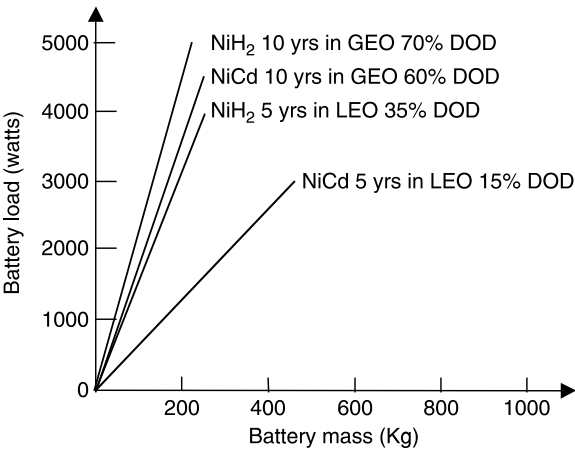


FIGURE 9.28 NiCd and NiH₂ battery mass versus load and missions duration.

Table 9.7 Qualitative differences in NiCd and NiH₂ batteries

Battery	Advantages	Disadvantages
NiCd	Prismatic cell requires less supporting Low operating temperature, hence simpler thermal management	Cell performance not easily scalable to high Ah ratings. Sensitive to over-charge at high temperature Must be maintained within narrow temperature range of -5 to 10°C . Memory effect requires periodic reconditioning, making the fully autonomous operation difficult.
NiH ₂	Less sensitive to over-charge Longer life	Cylindrical cells results in low energy density, heavy supporting structure, and poor cooling. High self-discharge rate

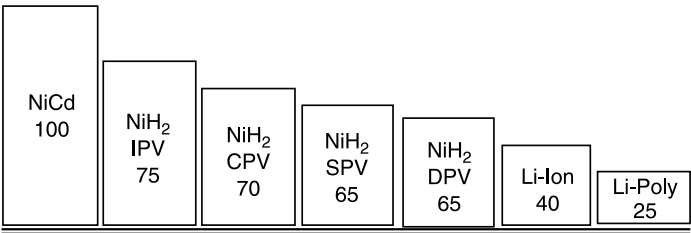


FIGURE 9.29 Battery mass with various electrochemistries relative to NiCd cell.

- Ease and speed of recharging
- Self-discharge rate
- Safety issues

Table 9.8 Life and cost comparison of various batteries

Electro-chemistry	Cycle life in full discharge cycles at 25° C	Calendar life, in years	Self-discharge (percent/month at 25° C)	Relative cost (\$/kWh)
NiCd	1000–2000	10–15	20–30	1500
NiH ₂	2000–4000	10–15	20–30	1500
NiMH	1000–2000	8–10	20–30	2000
Li-ion	500–1000 ^a	a	5–10	3000
Lithium-polymer	500–1000 ^a	a	1–2	>3000

^aUnder development.

Although NiH₂ offers higher energy storage capability per kilogram, both NiCd and NiH₂ continue to find applications. One can be more advantageous over the other depending on the mission-specific details. For example, NiCd is a more likely candidate for low power missions, because it is available in a wide range of capacity starting from a fraction of 1 Ah. The NiH₂ is generally better suited for high power satellites, and is not mass and cost effective below 25-Ah capacity.

Regarding the number of batteries, all GEO satellites have traditionally used two batteries, each with one half of the total Ampere-hours capacity needed to meet the energy demand during the worst case eclipse. For small LEO satellites, such as *Iridium*, one battery can be advantageous. The mass and cost of one large battery is always less than two small batteries of one half the capacity. On the business side, the customer generally has a strong preference, sometimes for documented or undocumented reasons, which is taken into account.

Once the chemistry and the number of batteries are settled, the battery design depends on the following system parameters:

- Bus voltage and load current
- Charge and discharge rates and duration
- Operating temperature during charge and discharge
- Life in number of charge and discharge cycles

The life consideration is the dominant design driver in setting the battery Ampere-hour ratings. Even when the load may be met with a smaller capacity, the battery is oversized to meet the cycle life requirement. For example, with the same watt-hour load, the battery that must deliver twice as many C/D cycles needs approximately double the capacity.

The battery design proceeds in the following steps:

- Determine the number of series cells required to meet the voltage requirement.
- Determine the ampere-hour discharge required to meet the load current demand.
- For the required number of charge/discharge cycles, determine the maximum allowable depth of discharge.
- The total ampere-hour capacity of the battery is then determined by dividing the ampere-hour discharge required by the allowable depth of discharge.
- Determine the number of battery packs required in parallel for the total ampere-hour capacity from packaging and other considerations.
- Determine the temperature rise and the thermal control requirement.
- Determine the required charge and discharge rate controls.

The actual ampere-hour capacity of each battery at operating temperature is given by the following expression:

$$Ah_b = \frac{P_e \cdot T_e}{N_b \cdot \eta_{dis} \cdot \{ (N_c - 1) V_{cdis} - V_d - V_{hdis} \} \cdot DOD} \quad (9.12)$$

where

Ah_b = capacity of each battery

P_e = load power demand during eclipse

T_e = eclipse duration, in hours

N_b = number of batteries in parallel

η_{dis} = discharge converter efficiency

N_c = number of series cells per battery

V_d = voltage drop in bypass diode in case a cell failed

V_{cdis} = voltage per cell, average during discharge

V_{hdis} = voltage drop in harness from battery to PRU

DOD = maximum allowable DOD in the worst case eclipse

Equation 9.12 allows one cell failure in each battery for single fault tolerant design. The failed cell is bypassed using diodes as shown in Figure 9.30. There is generally one bypass diode in the charge path and three diodes in the discharge path to limit the leakage current. Without such bypass diodes, if one battery in a two-battery system fails, the power available to the payload is significantly reduced, plus one arcjet would not work. The satellite must carry more fuel to compensate for this. Some

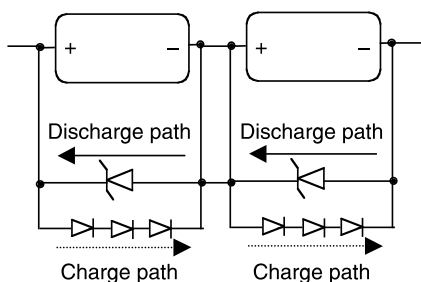


FIGURE 9.30 Cell bypass diodes in charge and discharge paths for reliability.

customers may prefer relay switches to the bypass diodes to minimize the power loss.

The battery round trip energy efficiency under the worst case with one cell failed is determined using the following expression:

$$\eta_b = \left[\frac{(N_c - 1)V_{cdis} - V_d - V_{hdis}}{(N_c - 1)V_{chg} + 3V_d + V_{hchg}} \right] \cdot \left[\frac{AH_{dis}}{AH_{chg}} \right] \quad (9.13)$$

where

N_c = number of series cell, V_d = voltage drop in one diode

V_{cdis} and V_{chg} = cell voltage during discharge and charge, respectively

V_{hdis} and V_{hchg} = voltage drop in harness during discharge and charge

AH_{dis} and AH_{chg} = ampere-hour discharged and charged, respectively.

There is a trade in selecting the cell ampere-hour rating in fully regulated DET bus. It is between using more small capacity cells giving closer to the bus voltage, versus fewer large capacity cells giving lower than bus voltage. The latter option requires greater buck and boost ratios in the battery regulators, but saves in mass and cost. Fewer larger cells have lower mass and volume and higher reliability. The battery voltage in any case is regulated by the duty ratio, and the regulator mass and efficiency do not change much with the battery voltage. A general guideline is to place cells in series to make the nominal battery voltage during discharge equal to about 80%, and during charge about 93% of the bus voltage. Even fewer cells may yield more savings as long as the buck and boost converter design is not adversely impacted.

Other factors also enter the battery design, such as the end of charge and end of discharge voltages. They remain fairly constant in NiH_2 , but degrade in $NiCd$ over the service life.⁴ The ampere-hour rating thus determined must be adjusted upwards if the battery voltage does not meet the bus

voltage requirement, cannot be fully recharged after the deepest DOD, or the nominal eclipse starts from a partially drained battery in some orbits.

All series cells must have equal Ampere-hour ratings within a few percent to avoid a cell voltage reversal leading to a total battery failure. For this reason, the cell selection is a critical acceptance test conducted at the vendor site. The cells are discharged to 1.0 V and the ampere-hour output measured at room temperature to match the nameplate capacity. All cells within ± 3 to 5% capacity variations around the average are selected for assembly in the flight battery. Since the actual battery capacity is the capacity of the weakest link, it is taken as the average cell capacity less 3 to 5%. Battery cells are selected also by the cell voltage variance. One may consider the magnetic signature method to gage the internal details. Only the stabilized cells are included in the selection. The full SOC pressure in NiH₂ cells is significantly low when new, but stabilizes after a number of C/D cycles.

Typical specifications of the battery for 5- to 10-kW 100-V GEO communication satellite include the following:

- For 800 psi full SOC pressure, the battery should withstand 1350 psi without permanent deformation, 5000 cycles of pressure test cycles from fully charge to fully discharge state, and 2400 psi proof test without rupture.
- d.c. isolation resistance of 50 M Ω at 1000 V d.c.
- Reliability of 0.985 over 10 years of life based on 30 FITS per cell
- The radiation dose of 5×10^5 rads over a 10-year mission life
- Ability to withstand the required dynamic environment of the launch

9.10 Launch and Ascent Power

Generally, the battery is designed to meet the on-orbit load and energy balance. The same battery is also used for the spacecraft power needs during launch and ascent phases. Several possibilities that may arise during this time are dealt in the following manner.

Case A: The battery fully charged at the time of launch is sufficient for the launch/ascent energy requirement. This is usually the case in most satellites, and does not require any extra step for the power system engineer.

Case B: The battery fully charged at the time of launch is slightly short of the launch/ascent energy need. In this case, a widely practiced solution is to pre-cool the battery by cold air or nitrogen before the

launch to increase the battery capacity by several percent or more as needed.

Case C: The launch/ascent power demand exceeds the battery capacity beyond the case B remedy. Increasing the on-board battery capacity, even in such a rare case, is almost never done, because it is very expensive. Instead, a primary battery having high specific energy is used to meet the shortage. This battery is jettisoned after the ascent. A primary battery that is widely used in space vehicles is lithium carbon monofluoride (LiCFx) having a specific energy of 350 to 500 Wh/kg, an order of magnitude higher than the commonly used secondary batteries.

9.11 Thermal Design

The battery is sometimes mounted on the exterior of the spacecraft body on a honeycomb panel on the anti-sun side. It is conductively isolated from the spacecraft honeycomb panel by G-10 fiberglass standoffs, radiatively isolated by multi-layer insulation blankets, and enclosed in an aluminum honeycomb micrometeoroid shield. A part of the shield front serves as the radiator, which is coated with silver Teflon. The remainder of the shield is insulated with multi-layer thermal blankets. The battery radiates heat to the radiator, which, in turn, radiates to space. Adequate thermal control for the battery, for both cooling and heating, is extremely important. A high temperature in a battery can lead to failure caused by electrolyte evaporation and decreased efficiency. A high cell-to-cell thermal gradient can cause uneven current sharing. The operating temperature significantly influences many performance parameters in the following ways:

- The capacity drops at a temperature above or below a certain range, and drops sharply as the temperature approaches the freezing point. The capacity significantly increases when charged at -20°C . Additional capacity obtained at low temperature is more stable than that obtained at 10°C when cycled.
- The battery voltage and charge efficiency decrease with increasing temperature.
- The self-discharge rate increase with temperature.
- The internal resistance increases as temperature decreases.

Table 9.9 shows the temperature sensitivity of NiCd cell. The process of determining the optimum operating temperature is illustrated in Table 9.10. It indicates that different attributes have different desirable operating temperature ranges shown by the vertical lines. With all attributes jointly considered, the most optimum operating temperature is the intersection of

Table 9.9 NiCd temperature sensitivity

Temperature	Charge efficiency (%)	Discharge efficiency (%)	Self-discharge rate, percent of C/day
−40°C	0	72	0.1
10°C	94	100	0.2
60°C	75	100	8.0

all the desirable ranges. For example, if we wish to limit the self-discharge rate below 1.0% and the charge efficiency above 90%, the optimum working temperature range is between −10°C and 25°C as shown by thin line in the first column. The actual temperature is then maintained between −5°C and +10°C shown by the heavy vertical line in order to allow some design and operating margins.

It is necessary to perform detailed thermal analyses for every mission, because it is mission unique. Controlling the battery temperature is a critical requirement of the thermal control system. This often requires dedicated radiators, conduction paths, heaters, blankets, temperature sensors, and

Table 9.10 Determination of optimum working temperature for a nickel cadmium battery

Operating temperature °C	Charge efficiency(%)	Discharge efficiency(%)	Self-discharge rate, percent capacity/day
−40	0	72	0.1
−35	0	80	0.1
−30	15	85	0.1
−25	40	90	0.2
−20	75	95	0.2
−15	85	97	0.2
−10	90	100	0.2
−5	92	100	0.2
0	93	100	0.2
5	94	100	0.2
10	94	100	0.2
15	94	100	0.3
20	93	100	0.4
25	92	100	0.6
30	91	100	1.0
35	90	100	1.4
40	88	100	2.0
45	85	100	2.7
50	82	100	3.6
55	79	100	5.1
60	75	100	8.0
65	70	100	12
70	60	100	20

control electronics. Multilayer insulating blankets are used to keep the heat or cold away as required for maintaining the orbit-average battery temperature. If the battery is running cold, blanketing a part of the external radiator surface can reduce the heater power requirement. The battery electrochemistry selection has a significant impact on the thermal system mass and cost. The chemistry that costs more but is less sensitive to the operating temperature can pay back at the satellite level.

Each cell in the battery pack is electrically insulated from each other and from the ground. The electrical insulation must be good conductor of heat to maintain low temperature gradient between the cells and also to the ground. The maximum temperature must remain below a set value to avoid damage to the battery or shortening the life. The minimum temperature must not be too low to reduce the battery efficiency in the operating mode. In the survival mode, the temperature must remain above the freezing point of the electrolyte to avoid the battery from being inoperable.

The cylindrical shape of IPV and CPV NiH_2 cells makes the thermal cooling difficult. Moreover, it increases the volume significantly and makes the heat conduction from the cell to the radiator plate inefficient compared to the battery with prismatic cells. Figure 9.31 shows a battery pack with prismatic NiCd or Li-ion cells. The cylindrical NiH_2 cells are packed in one of the following three configurations.

9.11.1 Flat Pack

The cells are laid flat on the radiator plate, offering the maximum cooling surface. Such design has been flown in communication satellites in several

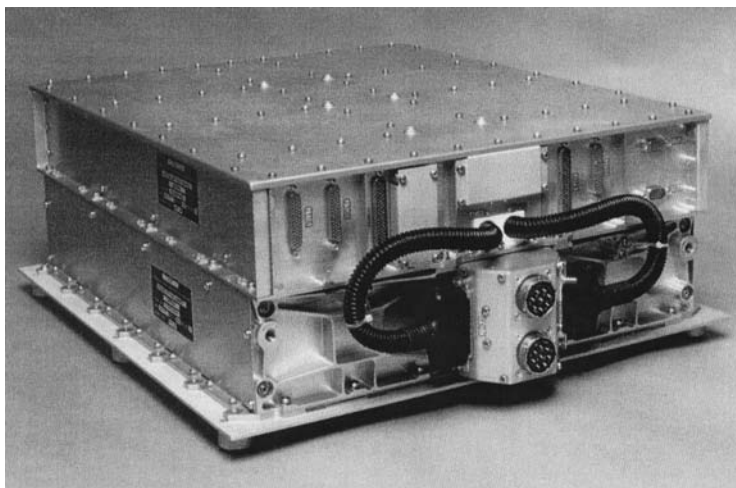


FIGURE 9.31 Battery assembly using prismatic NiCd cells.

(Source: Dornier Satellitensysteme GmbH, Daimler-Benz Aerospace. With permission.)

kilowatts power range. However, it requires much greater footprint and is vulnerable to shocks and vibration during launch.

9.11.2 Vertical Stack

This is the most common packaging method for NiH_2 cells at present, which was seen in Figure 9.6. The cells standing up and making contact with the radiator plate only at the dome point results in poor heat conduction. The conduction area is increased by providing conduction shims shown in Figure 9.32. The wedge shape minimizes the mass for the required heat transfer. The shims can be aluminum or graphite fiber composite for even lower mass.

9.11.3 Wine Rack

The cylindrical IPV's are sometimes packaged in a wine-rack configuration. In such design, the cell temperature can reach 15°C and maximum cell-to-cell gradient can reach 7°C in the worst case EOL. The cell-to-cell and cell-to-battery frame temperature can be improved by using metallic fiber, which could reduce the cell-to-cell temperature gradient to below 2°C , and maximum cell temperature to about 8°C .

The three NiH_2 cell stacking configuration options are compared in Table 9.11. The typical temperature requirements for large communication satellite battery design are listed in Table 9.12.

9.12 Safety Considerations

The battery design and operation require certain safety considerations. The most important is not to over-charge the battery. Any over-charge above the trickle charge rate is converted into heat, which can cause the battery to explode if allowed to build up beyond limit. This is particularly critical when the battery is charged directly from a dedicated photovoltaic module without a charge regulator in small science missions with short or infrequent eclipses. In such cases, the array is sized below certain safe

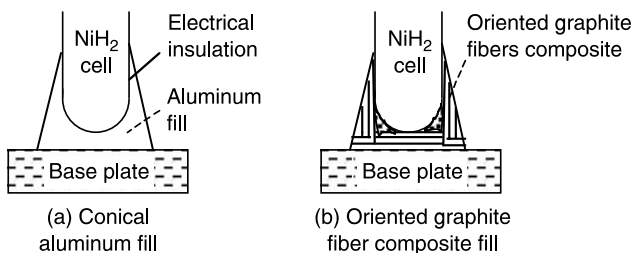


FIGURE 9.32 Mass-efficient conduction shims for vertical mounting of NiH_2 cell.

Table 9.11 NiH₂ cell stacking options and their relative performance

Configuration	Wine-rack	Flat pack	Vertical mount
Advantages	Low footprint, volume, and weight.	Lowest weight Largest foot print Better cooling	Best cooling Moderate footprint and volume
Disadvantages	Poor cooling	Large foot print	Heavy with metal cooling sleeve

limit. As a rule of thumb, such photovoltaic array rating is kept below the continuous trickle charge current that can be tolerated by the battery.

The battery design must consider a single failure mode of the battery without creating any safety hazard of contamination, corrosion, explosion, fire, injury or illness. This is required during all mission phases and ground operations. Major failure modes are listed below. Any one or more combinations could possibly cause venting of toxic, corrosive, and/or flammable materials with associated fire or explosion risk:

- Over-temperature from battery self-heat or ambient heat
- Short circuit, internal or external to the battery
- Reverse current due to inadvertent charging
- Cell voltage reversal due to over discharge
- Leakage of electrolyte or gases

Table 9.12 Typical thermal design requirement for NiH₂ battery in large communication satellite

Maximum gradient or any cell temperature	
Gradient along cell stack as measured at cell wall	5°C
Gradient between any two points of a cell wall	7°C
Gradient between any two cell stacks within a battery during charge	7°C
Gradient between average of the cell stacks between any two batteries or packs during charge	8°C
In transfer orbit during charge	30°C
During recharge following eclipse	15°C
During trickle charge	30°C
During EHT or arcjet firing	35°C
During reconditioning letdown	30°C
During reconditioning recharge	15°C
Minimum temperature in all scenarios	−10°C
Life average temperature of cell stack in a battery	15°C
Acceptance testing (excluding EHT/arcjet firing)	−10/+30°C
Qualification testing (including EHT/arcjet firing)	−15/+45°C

- Over-pressure due to over-charging or over-temperature

The design approach should preclude any of the above occurrences. If failure does occur, venting should be prevented. If that is not possible in the case of a major failure, it must be demonstrated that venting will occur in a manner that is not hazardous to the mission. Safe shipping requirements depend primarily on whether the battery is activated or not. If activated, the applicable shipping regulations depend on the chemical reactivity of the materials and the state of charge, both can be controlled by the battery manufacturer to meet the shipping regulations.

Govar and Squires¹² report safety tests on commercial off-the-shelf 9-V lithium-ion battery for navy applications. Battery packs consisting of two 9-V batteries in parallel were found relatively safe and experienced no violent behavior. On the other hand, packs with thirty 9-V batteries experienced venting, smoke, and flames under certain circumstances.

9.13 Charge Regulation

For safety reasons, it is extremely important that excessive charging of the battery is avoided at all times. Over-charging causes internal gassing, which causes loss of electrolyte in vented cell and premature aging. The charge regulator allows the maximum rate of charging until the gassing starts. Then the charge current is tapered off to trickle charge rate so that the full charge is approached gently.

During battery charging, the energy management software monitors the state of charge, the overall health and the safe termination criteria. The operating voltage, the current, and the temperature are monitored. The charging timer is started after all initial checks are successfully completed. Charging may be suspended (but not reset) if the software detects violation of critical safety criteria. The timer stops charging if the defect persists beyond a certain time limit.

The normal charging has the following three phases:

- Bulk (fast) charge, which deposits 80 to 90% of the drained capacity
- Taper (cut-back) charge in which the charge rate is gradually cut back to top off the remaining capacity
- Trickle (float) charge to counter the self-discharge rate after the battery is fully charged

The bulk charge and the taper charge termination criteria are pre-loaded in the battery management software to match with the battery electrochemistry and the system design parameters. For example, the NiCd and NiMH batteries are generally charged at constant current until about 95% SOC in 75 to 85% of the available sun time. Then onward, the charge current

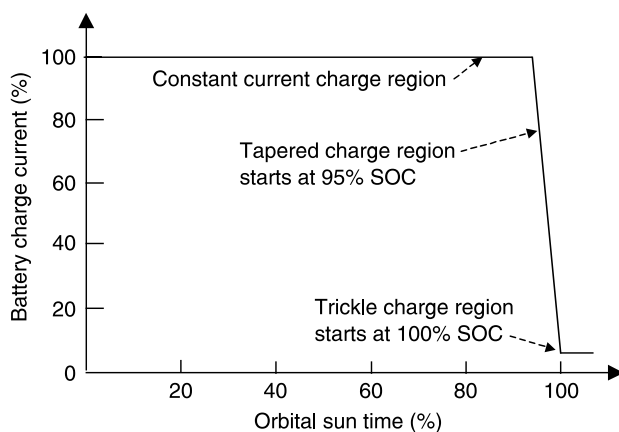


FIGURE 9.33 Battery charge profile versus orbital sun time.

is tapered off — gradually or in a few steps — to the trickle rate as shown in Figure 9.33. The decision is made to terminate the main charging and switch to the trickle charge when the continuously monitored ΔV is detected negative. On the other hand, Li-ion batteries, being sensitive to over-charging, can be charged at constant voltage, and then tapering off the charge current as needed.

Both NiCd and NiH₂ batteries show voltage roll-off and sudden temperature rise, i.e., negative dV/dt and positive dT/dt , soon after the full charge (Figure 9.34). Both of these characteristics are used in detecting the end of charge. In NiCd and NiH₂, the voltage roll-off is 20 to 30 mV per cell. In NiMH, on the other hand, the ΔV is much smaller (3 to 5 mV per cell) and the temperature rises steadily to the final value, making the

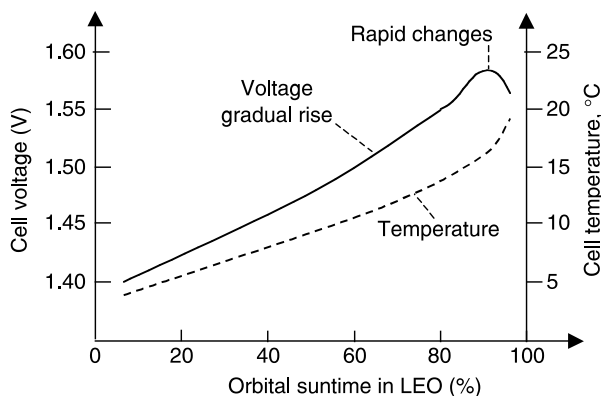


FIGURE 9.34 Battery voltage and temperature during charge showing rapid changes at the end of charge.

end of charge detection difficult. The rollover is attributed to the voltage decrease subsequent to temperature increase that results from the oxygen reaction with hydrogen. In some electrochemistries, the voltage rollover is distinct; in some it is rather flat. When the cells are over-charged at -20°C , the voltage rollover shows waviness with a smaller hump followed by a larger hump.

Rapid reaction of oxygen with hydrogen during over-charge is an undesirable feature, which causes an audible popping noise in certain cases. Popping results in melting of the gas screen pinholes in the negative plates, and heat stains in the core and the positive plate. In extreme cases, popping blows away the separator, resulting in shorts. Cells with significant positive plate swelling are prone to popping, which results in damage to the components. Swelling also causes extrusion of active material and reduction in the gap between the two positive plates. The final result is a decrease in the end of discharge voltage. Positive plates that show excessive swelling absorb more electrolytes. This is accompanied by a reduced absorption of electrolyte by the separator.

The batteries are charged in one of the following three ways using the voltage-limited tapered-current method or the constant-current ampere-hour return method.

9.13.1 Multiple Charge Rates

This is the best method, in which the battery is charged gently in multiple steps. First the battery is charged at full charge rate until 80 to 90% of the capacity is achieved. The charge current is then cut back, in steps, until the battery is fully charged. At this time, the charge current is further reduced to trickle-charge rate, keeping it fully charged until the next load demand comes on the battery. This method therefore needs at least three charge rates in the charge regulator design.

9.13.2 Single Charge Rate

This method uses simple low cost regulator, which is either on or off. The regulator is designed for only one charge rate. When the battery is fully charged, as measured by its terminal voltage, the charger is turned off by a relay. When the battery voltage drops below a preset value, the charger is again connected in full force. Since the charging is not gentle in this method, full charge is difficult to achieve and maintain. An alternate version of this charging method is the multiple pulse charging. Full current charges the battery up to the high preset voltage just below the gassing threshold. At this time, the charger is shut off for a short time to allow the battery chemicals to mix and voltage to fall. When the voltage falls below the low preset threshold, the charger is reconnected, again passing full current to the battery.

9.13.3 Unregulated Charging

This is the least cost method which uses no charge regulator. The battery is charged directly from a solar array module dedicated just for charging. The charging module is properly designed for safe operation for the given number of cells in the battery. When the battery is fully charged, the array is fully shunted to ground by a shorting switch (transistor). At this time, the battery voltage must still be slightly lower than the available solar array voltage so that the trickle charge can continue, but not much lower to avoid over charging. The shunt transistor switch is open when the battery voltage drops below certain value. An isolation diode would block the battery powering the array or the shunt at night.

If one cell in one of the two batteries working in parallel fails short, the two batteries would have different terminal characteristics. Charging or discharging such batteries in parallel can result in highly uneven current sharing, subsequently overheating one of the batteries. This can be avoided in two ways. One is to charge and discharge both batteries with individual current controls such that they both draw their rated share of the load. The other is to replace the failed cell immediately, which is not possible in space. In general, the individual charge/discharge control for each battery is the best strategy. It may also allow replacement of any one battery with different electrochemistry or different age, which would have different load sharing characteristics. The ISS batteries are designed for replacements several times during the life of the station.

The Li-ion battery requires additional circuitry for balancing individual cells to obtain maximum performance from the battery. The balancing method can vary from design to design. One method is to use d.c.-d.c. converters with multi-tap transformer to provide energy equilibrium in each cell. Another method is to use capacitor-switching technique called flying capacitor that shifts small packets of energy from higher voltage cells to lower voltage cells. The Saft Corporation has often used a resistive dissipation method that lowers the SOC of the highest cells down to match with the lowest common denominator cell. Sack, Croydon and Reynolds¹³ report yet another method using segmented charger. In this concept, the battery charger is broken up into separate cell chargers. The concept was tested on a 26-V 45-Ah Li-ion battery under U.S. Army funding.

9.14 Battery Management

Battery management electronics include the battery monitor and controller. The main function is to monitor the battery status and optimize its performance by adjusting the charging process. Electronic circuits monitor the battery voltage, current, state of charge, and temperature. If not managed properly, the battery performance could suffer and the life shortened. The following are some potential performance problems:

- Low charge efficiency resulting in low state of charge
- Loss of capacity to hold the rated ampere-hour charge
- Premature failure leading to loss of load availability
- Excessive gassing and heating, leading to short life
- Positive plate corrosion shortening the life
- Stratification and sulfation degrading the performance

The following features incorporated in the battery management can avoid the above problems:

- Temperature compensated charging, in that the charge termination occurs earlier if the battery temperature is higher than the reference temperature
- Individual charge control if two or more batteries are charged in parallel
- Accurate set points to start and to stop the charge and discharge modes

The batteries in modern power systems are managed by dedicated computer software, which monitors and controls the following performance parameters:

- Voltage and current
- Temperature and pressure
- Ampere-hour in and out of the battery
- State of charge and discharge
- Rate of charge and discharge
- Depth of discharge
- Number of charge and discharge cycles

The above parameters are determined by a number of measurements and limits, which include the following:

- Minimum charging current threshold
- Terminal voltage threshold
- Absolute temperature cut-off
- Rate of temperature change $\Delta T / \Delta t$
- Drop of the cell voltage after the peak ΔV
- Rate of voltage change $(\Delta V / \Delta t)$, including the peak and the inflection
- Actual charging time

The ampere-hour integrating meter is commercially available, which keeps track of the ampere-hours in and out of the battery and send required signals to the mode controller.

With age, NiCd and NiH₂ batteries experience walk-downs in capacity, voltage, and end-of-charge pressure. These are accounted by shifting the software on board. The cell voltage divergence is another concern, more so after reconditioning. One method of avoiding it is to over-charge, so that all cells saturate to full voltage, provided the thermal system can handle the associated heating.

The temperature compensation on the maximum battery voltage and the state of charge can improve the battery management, particularly when cold. It can allow additional charging during cold periods when the battery can accept more charge. The low voltage alert is a good feature, as excessive discharging below the threshold low voltage can cause cell voltage reversal, leading to battery failure. The alert can be used to shed noncritical loads from the battery to avoid battery damage. The battery cell voltage monitor allows a comprehensive health check of the total battery. This is important just before launching, when a problem can be fixed. A 22-cell voltage monitor adds less than 200 to 300 g, but adds much more in numerous telemetry wires.

9.15 Dynamic Model

The term impedance refers to the ratio of the cell voltage change to corresponding change in the alternating current through the cell. It is given by

$$Z = \sqrt{R^2 + X^2} \quad (9.14)$$

where R and X are the battery resistance and reactance, respectively. The dynamic impedance characteristics discussed in this section are applicable to all electrochemistries. They apply at a given SOC, i.e., when net d.c. current flow or energy conversion is not involved. The internal impedance determines the battery response to ripple, noise, and transients during charging and discharging. It varies inversely with the capacity, as large capacity cells have large plate area. The impedance versus frequency of a 50-Ah NiH₂ cell is shown in Figure 9.35. It has a relatively constant value up to 10 Hz, but rises rapidly at higher frequency indicating a strong inductive component. The battery R and X are obtained by multiplying the cell values with number of series cells in the battery. A simple dynamic model of the battery for stability analysis with the dynamic impedance $Z(s)$ in the Laplace domain is shown in Figure 9.36.

Complex battery models developed by electrochemists are not expressed in terms of the electromotive force, resistance, inductance, and capacitance.

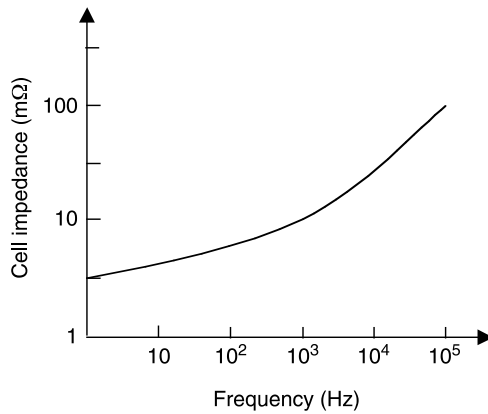


FIGURE 9.35 50-Ah NiH₂ cell impedance versus frequency.

Therefore, they are unsuitable for everyday use by the electrical engineer, who needs a model that represents the electrochemistry in the electrical network terms. Ceraola¹⁴ has developed a model to represent the battery's nonlinear behavior using two electrical branches shown in Figure 9.37. The main branch is designated with subscript m and the parasitic branch with subscript p. The E_m and Z_m are the internal electromotive force and the internal impedance, respectively. Both are functions of the Laplace parameters, the electrolyte temperature, θ , and the SOC. The parasitic branch models the nonreversible reactions that draw some current, but does not contribute to the main reversible reaction. The energy that is absorbed by E_p ceases to be electrical and is converted into other forms, such as gas or water electrolysis that occurs at the end of the charge process. The power dissipated in the real part of Z_m and Z_p is converted into heat that contributes to the self-heating of the battery. The R_o is common to both branches and represents resistance from the battery terminals to the plates.

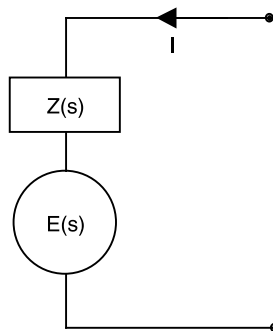


FIGURE 9.36 Simple dynamic electrical circuit model of the battery.

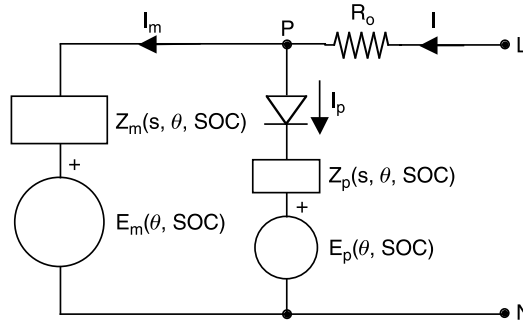


FIGURE 9.37 Dynamic circuit model of battery with main and parasitic reaction branches.

To make such a model useful, one need to determine the functional dependence of E and Z on s , θ , and SOC, and the battery thermal model from which the electrolyte temperature can be determined. The dependence on s can be stated by expressing each Z in terms of the equivalent R , L , and C values. The model can be simplified for a specific operating condition, if known. For example, the parasitic branch can be ignored in the initial charging phase when the charge efficiency is near unity. At the end of charge, however, it takes almost all power entering the battery terminals. Since the inductance is small and can be ignored, the battery model that is valid during both the charge and discharge is shown in Figure 9.38.

The battery capacity is maximum at certain optimum temperature and falls off on both sides of the optimum temperature. If the battery is maintained on the cooler side of the optimum temperature, the capacity at a constant discharge current and a constant electrolyte temperature is higher with higher temperature and lower discharge current. At a fixed discharge current, I , and temperature, θ , the capacity can be expressed as¹⁴

$$Ah(I, \theta) = Ah_o(I) \left\{ 1 - \frac{\theta}{\theta_f} \right\}^\alpha \quad (9.15)$$

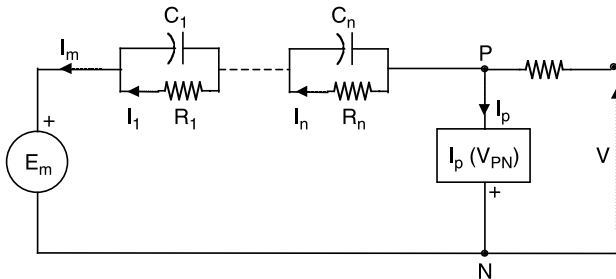


FIGURE 9.38 Dynamic circuit model of the battery during charge and discharge.

where Ah_o = battery capacity at 0°C at discharge current I , α = empirical constant, and $\theta > \theta_f$, the freezing temperature of the electrolyte (such as -40°C). Equation (9.15) gives the expected value of $Ah = 0$ at freezing temperature when the battery becomes inoperative. It is possible that $Ah_o(I)$ can be expressed in terms of its value at a reference temperature I_r and empirical constants K and β as follows:

$$Ah(I, \theta) = \frac{KAh_o(I_r) \left\{ 1 - \frac{\theta}{\theta_f} \right\}^\alpha}{1 + (K - 1) \left\{ \frac{I}{I_r} \right\}^\beta} \quad (9.16)$$

Equation (9.16) suggests that numerical values of the elements of the circuit model have to be established for each value of electrolyte temperature and SOC. In practice they can be established only for a few discrete values of these two quantities, and the values in-between can be obtained by interpolation. Determination of such parameters for the first time would take extensive analysis and test efforts. However, having made that investment, the model for a new battery can be established by using previous data on similar battery suitably modified for the new battery.

9.16 Cycle Life Model

As previously stated, the battery cycle life is related primarily to the DOD and the operating temperature. The life relationship can be expressed in terms of C/D cycles as the dependent variable, with the DOD and temperature as the independent variables. In developing a statistical model for the battery life, we must first select a mathematical expression that defines the relationship adequately, and then select a statistical distribution that best fit the test data. The selections can be guided by consideration of the physical behavior of the battery. For example, the number of cycles to failure decreases with increasing DOD and temperature. Various types of relationships commonly used for analyzing life test data can be considered to express such relationships. Among the alternatives, such as exponential, inverse power, and Arrhenius, more than one can give a reasonably good fit to the test data. However, the relationship that generally gives the best fit in similar life test data is the Arrhenius equation, which accounts for the chemical degradation limiting the life.^{15,16} That is

$$L = C_1 T^{-C_2} \cdot e^{-C_3 D} \quad (9.17)$$

where L = mean number of cycles to the first failure, T = temperature in degrees centigrade, D = DOD in each cycle, and C_1 , C_2 , and C_3 are the relationship constants to be determined by multiple regression curve fitting techniques.

Based on the physical considerations of the wear-out mode of failure being studied, the statistical distribution selected to represent the spread of life around the mean value derived from Equation (9.17) at a given temperature and DOD should have a continuously increasing hazard function. The hazard function is a conditional failure rate, which expresses the rate of failure for the surviving population at a given number of cycles L . Also, the distribution should have a good shape flexibility to fit the data. Two distributions, which can satisfy these requirements, are lognormal and Weibull. The Weibull distribution is the most commonly used for presentation of such life test data. It is given by

$$F(L) = 1 - e^{-(\frac{L}{\alpha})^\beta} \quad (9.18)$$

where $F(L)$ is the fraction of the population failing by L cycles, and positive parameters α and β are scale and shape parameters, respectively. The parameter β can be assumed to be constant, while α is a function of temperature and DOD. The values of both α and β are derived from test data. The curve fitting can be a simple procedure using least squares regression techniques if the failure times of all samples are known. However, in typical situations, the battery test data includes samples: (a) which are known to have failed during an interval, rather than at a specific time, and (b) many samples not yet failed at the end of the test period. Such censored data can only be analyzed by statistical techniques developed for dealing with incomplete life test data.^{17,18} They use the method of maximum likelihood, which involves selecting as an estimate for each unknown parameter the value that appears to be most probable on the basis of the given test data. The computations are based on the sample log likelihood which is a function of the unknown model coefficients (C_1 , C_2 , C_3). The estimates of the coefficients are obtained numerically by iterative methods on a computer, and the variances of these estimates are used to obtain approximate confidence intervals.

When the indicated analysis is performed on a set of test data, the expected life relationships is derived with its coefficients C_1 , C_2 , and C_3 established. Estimating the life from such considerations can be relatively less complex if the battery were used in an identical manner in each cycle over the mission life. It becomes more complex when it is used in one way sometimes and another way at other times, with significant variation in the usage patterns. In such cases, the life may be estimates using the *Milner's cumulative damage theory*^{19,20} often used in fracture mechanics and fatigue studies on metals and other material. The theory utilizes the cycle ratio as

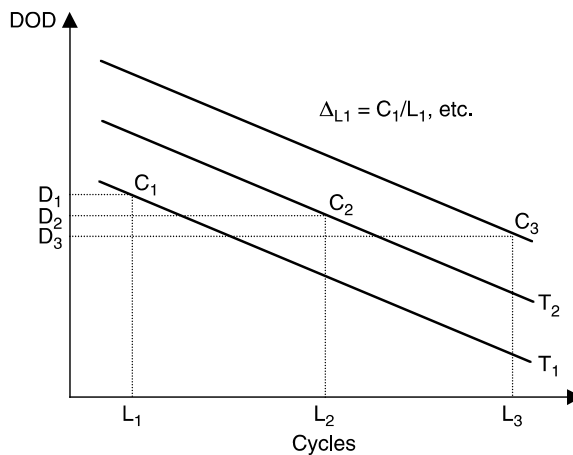
its basic measure of damage. For the battery life with two independent variables as shown in Figure 9.39, it can be modified as follows. If a battery temperature is T_i at depth of discharge D_i for C_i number of cycles, and if the life relationship estimates L_i cycles as its life at T_i and D_i , then the proportional damage, PD_i , caused during that time is

$$PD_i = \left\{ \frac{C_i(T_i, D_i)}{L_i(T_i, D_i)} \right\}^\alpha \quad (9.19)$$

where α is a positive constant to be evaluated from correlating available life data and experience. The battery can be expected to fail when the cumulative damage equals unity (i.e., when $\sum PD_i = 1.0$). The evaluation of the exponent α requires extensive data from batteries, which are much closer in scale factor to actual battery to be modeled.

The theory keeps incremental account of the fraction of life depleted during each segment of time depending on the life degradation factors prevailing over that duration of use. It can be used to estimate the remaining life, i.e.,

$$\text{remaining life} = 1 - \sum PD_i \quad (9.20)$$



L_1 = Cycles to failure when cycles at same temperature T_1 and some DOD D_1 every cycle

C_1 = Number of operational cycles at temperature T_1 and DOD D_1 , etc

FIGURE 9.39 Life model for cycles to failure versus DOD and temperature.

Milner's cumulative damage theory suggests the following for use with some judgment and experience:

- The battery life ends when sum total of the accumulated proportional damage reaches its limiting value of 1.0.
- A short time at high wear depletes the same fraction of life as a long time at low wear.

Although the life model presented in this section could not justify direct use of the life relationships in this fashion at present, it can be regarded as a potential future application. It is hoped that the theoretical consideration proposed here may serve as a guide to define, plan and analyze future research in this field.

9.17 Primary Battery

Among primary batteries, lithium/polycarbon monofluoride (LiCFx) has the highest specific energy. It has been in used in manned space vehicles, missiles, terrestrial and marine applications since the early 1970s, and has accumulated a safe and reliable database. LiCFx cells are produced in many ratings, but only a few are space qualified for NASA and Air Force applications. Hundreds of LiCFx batteries have flown on space shuttle flights and in many spacecraft. The reliability estimated as per the MIL-HDBK-217 range from 1.6 to 10×10^{-6} FIT. They are insensitive to shock, vibration, forced charging, and forced reversal. Many such cells can survive external hard short circuit without opening the cell vent. A high-rate battery with low heat rejection rate could potentially vent following a sudden internal short circuit. However, sudden shorts are estimated to be highly improbable, yielding the reliability of the cell better than 0.9999 with 90% confidence. The space-qualified battery design using 40 Ah LiCFx cells increases the assembly mass by 60 to 70% over that of the cells.

9.18 Advances in Battery Technologies

Incremental advances in the cell designs continue. The heavy sintered nickel powder plaque has been the substrate of choice for many years to support the electrochemically active material in all nickel-based batteries. The nickel electrode is the most critical and the heaviest component in any nickel-based battery, such as NiH₂, NiCd, and NiMH. The nickel powder plaque amounts to about one half of the electrode weight. Highly porous light weight nickel fiber plaques are being considered to reduce the electrode weight by 50% and the same time increase the capacity of the active material by increasing the surface area available for deposition of the active material. This may lead to higher specific energy for the battery.

Table 9.13 Replacement candidates for NiH₂ cell (50 Wh/kg)

Candidate	Li-ion	Li-Poly	Fly-wheel	Super NiCd	NiMH	Sodium-sulfur	H ₂ /O ₂ RFC
Wh/kg	130	150	a	50	65	120	75
Wh/l	200	300	a	115	200	250	50
Cycle life	> 10 k	> 10 k	High	> 45 k	>10 k	> 3 k	> 2 k
Used in space since	Since 2000	Not yet used	Not yet used	Since 1990	Qualified in 1992	Experimental flights	Not yet used
Dev. Stage	Active	Active	Planned to fly on ISS	Used in 30+ spacecraft	Used in 2 spacecraft	Inactive	Was proposed for ISS

^aUnder development.

Another approach that may result in higher specific energy is a thicker nickel electrode. Fewer thick electrodes reduce the number of other components, such as hydrogen electrodes and separators, thus reducing the weight of the cell.

Entirely new or derivatives of time proven electrochemistry are continuously evaluated in search of a better battery. The following figures of merit ultimately determine the battery mass and cost, and should be of interest to the power system design engineer:

- Specific energy and energy density
- Round trip energy efficiency
- Cycle life at the operating temperature and DOD
- Wider operating temperature range
- Better packaging

In recent years, Li-ion has emerged as the battery of choice for high performance commercial applications — cell phones, laptop computers, etc. It offers significant advantages over alkaline-based NiCd and NiMH batteries. The space applications often require the battery to operate over a wide temperature range (-40°C to $+65^{\circ}\text{C}$), long cycle life ($> 30,000$ cycles in LEO), and long calendar life (>10 years in GEO). NASA has qualified commercial off-the-shelf Li-ion technology to power electronic peripherals on the space shuttle and the ISS. The *Spirit* and *Opportunity* rovers that landed on Mars in 2004 were powered during eclipse by Li-ion batteries capable of 200 cycles at -20°C .

At present, Li-ion appears to be a candidate that may eventually replace the NiH_2 for general use in space.²¹ There are other candidates as well, such as the regenerative fuel cell and the flywheel. The flywheel is under significant research funding with a schedule to fly to the ISS in 2006. The NiH_2 replacement candidates as seen at present are compared in Table 9.13.

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