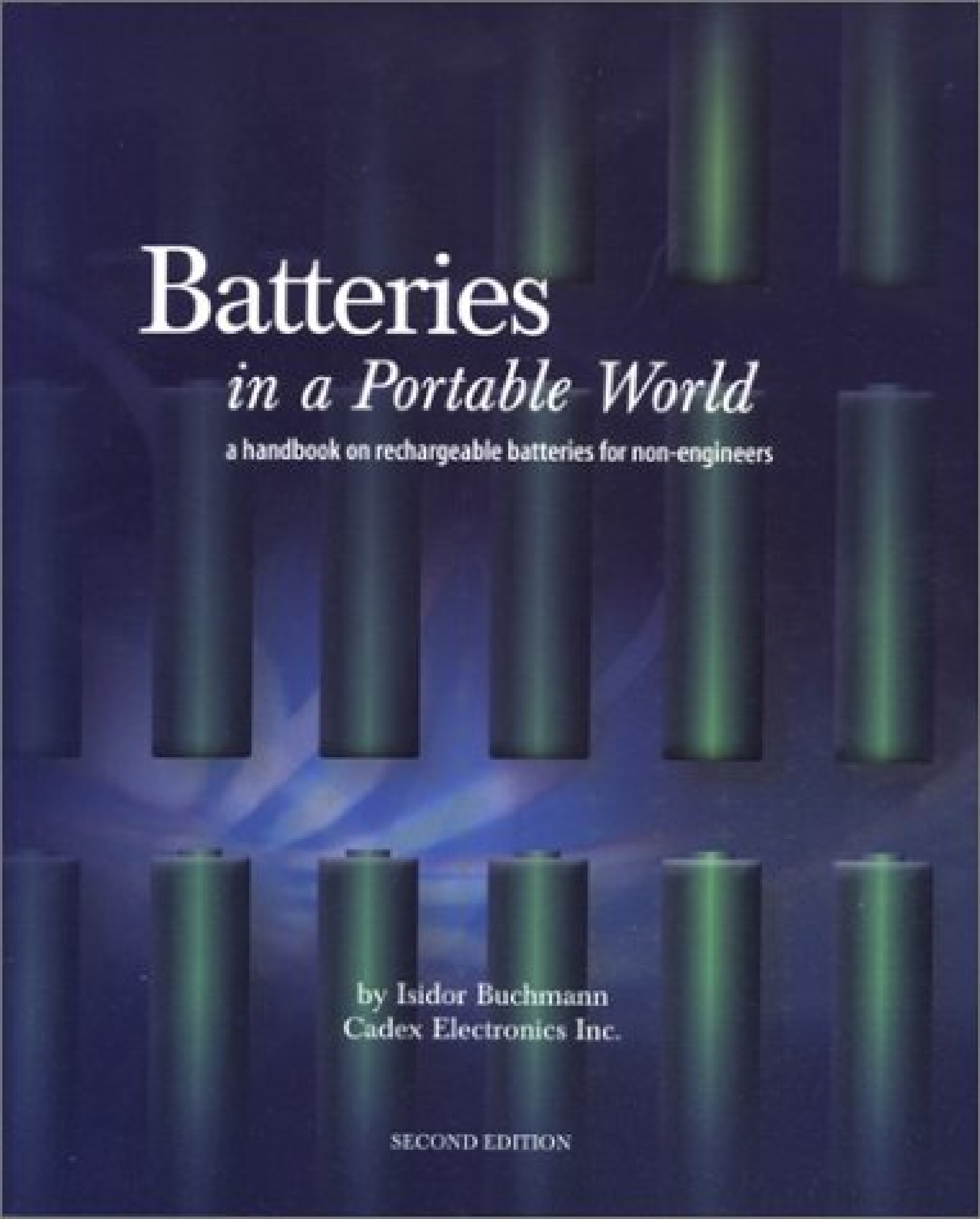


Batteries
in a Portable World

a handbook on rechargeable batteries for non-engineers

by Isidor Buchmann
Cadex Electronics Inc.

SECOND EDITION

Part One

Battery Basics Everyone Should Know

Author's Note

Battery user groups have asked me to write an edited version of *Batteries in a Portable World*. The first edition was published in 1997. Much has changed since then.

My very first publication in book form was entitled *Strengthening the Weakest Link*. It was, in part, a collection of battery articles which I had written. These articles had been published in various trade magazines and gained the interest of many readers. This goes back to the late 1980s and the material covered topics such as the memory effect of NiCd batteries and how to restore them.

In the early 1990s, attention moved to the nickel-metal hydride (NiMH) and the articles compared the classic nickel cadmium (NiCd) with the NiMH, the new kid on the block. In terms of longevity and ruggedness, the NiMH did not perform so well when placed against the NiCd and I was rather blunt about it. Over the years, however, the NiMH improved and today this chemistry performs well for mobile phones and other applications.

Then came the lithium-ion (Li-ion), followed by the lithium-ion polymer (Li-ion polymer). Each of these new systems, as introduced, claimed better performance, freedom from the memory effect and longer runtimes than the dated NiCd. In many cases, the statements made by the manufacturers about improvements were true, but not all users were convinced.

The second edition of *Batteries in a Portable World* has grown to more than three times the size of the previous version. It describes the battery in a broader scope and includes the latest technologies, such as battery quick test.

Some new articles have also been woven in and some redundancies cannot be fully avoided. Much of this fresh material has been published in trade magazines, both in North America and abroad.

In the battery field, there is no black and white, but many shades of gray. In fact, the battery behaves much like a human being. It is mystical, unexplainable and can never be fully understood. For some users, the battery causes no problems at all, for others it is nothing but a problem. Perhaps a comparison can be made with the aspirin. For some, it works to remedy a headache, for others the headache gets worse. And no one knows exactly why.

Batteries in a Portable World is written for the non-engineer. It addresses the use of the battery in the hands of the general public, far removed from the protected test lab environment of the manufacturer. Some information contained in this book was obtained through tests performed in Cadex laboratories; other knowledge was gathered by simply talking to diverse groups of battery users. Not all views and opinions expressed in the book are based on scientific facts. Rather, they follow opinions of the general public, who use batteries. Some difference of opinion with the reader cannot be avoided. I will accept the blame for any discrepancies, if justified.

Readers of the previous edition have commented that I favor the NiCd over the NiMH. Perhaps this observation is valid and I have taken note. Having been active in the mobile radio industry for many years, much emphasis was placed on the longevity of a battery, a quality that is true of the NiCd. Today’s battery has almost become a disposable item. This is especially true in the vast mobile phone market where small size and high energy density take precedence over longevity.

Manufacturers are very much in tune with customers' demands and deliver on maximum runtime and small size. These attributes are truly visible at the sales counter and catch the eye of the vigilant buyer. What is less evident is the shorter service life. However, with rapidly changing technology, portable equipment is often obsolete by the time the battery is worn out. No longer do we need to pamper a battery like a Stradivarius violin that is being handed down from generation to generation. With mobile phones, for example, upgrading to a new handset may be cheaper than purchasing a replacement battery. Small size and reasonable runtime are key issues that drive the consumer market today. Longevity often comes second or third.

In the industrial market such as public safety, biomedical, aviation and defense, requirements are different. Longevity is given preference over small size. To suit particular applications, battery manufacturers are able to adjust the amount of chemicals and active materials that go into a cell. This fine-tuning is done on nickel-based as well as lead and lithium-based batteries.

In a nutshell, the user is given the choice of long runtime, small size or high cycle count. No one single battery can possess all these attributes. Battery technology is truly a compromise.

Introduction

During the last few decades, rechargeable batteries have made only moderate improvements in terms of higher capacity and smaller size. Compared with the vast advancements in areas such as microelectronics, the lack of progress in battery technology is apparent. Consider a computer memory core of the sixties and compare it with a modern microchip of the same byte count. What once measured a cubic foot now sits in a tiny chip. A comparable size reduction would literally shrink a heavy-duty car battery to the size of a coin. Since batteries are still based on an electrochemical process, a car battery the size of a coin may not be possible using our current techniques.

Research has brought about a variety of battery chemistries, each offering distinct advantages but none providing a fully satisfactory solution. With today's increased selection, however, better choices can be applied to suit a specific user application.

The consumer market, for example, demands high energy densities and small sizes. This is done to maintain adequate runtime on portable devices that are becoming increasingly more powerful and power hungry. Relentless downsizing of portable equipment has pressured manufacturers to invent smaller batteries. This, however, must be done without sacrificing runtimes. By packing more energy into a pack, other qualities are often compromised. One of these is longevity.

Long service life and predictable low internal resistance are found in the NiCd family. However, this chemistry is being replaced, where applicable, with systems that provide longer runtimes. In addition, negative publicity about the memory phenomenon and concerns of toxicity in disposal are causing equipment manufacturers to seek alternatives.

Once hailed as a superior battery system, the NiMH has also failed to provide the universal battery solution for the twenty-first century. Shorter than expected service life remains a major complaint.

The lithium-based battery may be the best choice, especially for the fast-moving commercial market. Maintenance-free and dependable, Li-ion is the preferred choice for many because it offers small size and long runtime. But this battery system is not without problems. A relatively rapid aging process, even if the battery is not in use, limits the life to between two and three years. In addition, a current-limiting safety circuit limits the discharge current, rendering the Li-ion unsuitable for applications requiring a heavy load. The Li-ion polymer exhibits similar characteristics to the Li-ion. No major breakthrough has been achieved with this system. It does offer a very slim form factor but this quality is attained in exchange for slightly less energy density.

With rapid developments in technology occurring today, battery systems that use neither nickel, lead nor lithium may soon become viable. Fuel cells, which enable uninterrupted operation by drawing on a continuous supply of fuel, may solve the portable energy needs in the future. Instead of a charger, the user carries a bottle of liquid energy. Such a battery would truly change the way we live and work.

This book addresses the most commonly used consumer and industrial batteries, which are NiCd, NiMH, Lead Acid, and Li-ion/polymer. It also includes the reusable alkaline for comparison. The absence of other rechargeable battery systems is done for reasons of clarity. Some weird and wonderful new battery inventions may only live in experimental labs. Others may be used for specialty applications, such as military and aerospace. Since this book addresses the non-engineer, it is the author’s wish to keep the matter as simple as possible.

Chapter 1: When was the battery invented?

One of the most remarkable and novel discoveries in the last 400 years has been electricity. One may ask, “Has electricity been around that long?” The answer is yes, and perhaps much longer. But the practical use of electricity has only been at our disposal since the mid-to late 1800s, and in a limited way at first. At the world exposition in Paris in 1900, for example, one of the main attractions was an electrically lit bridge over the river Seine.

The earliest method of generating electricity occurred by creating a static charge. In 1660, Otto von Guericke constructed the first electrical machine that consisted of a large sulphur globe which, when rubbed and turned, attracted feathers and small pieces of paper. Guericke was able to prove that the sparks generated were truly electrical.

The first suggested use of static electricity was the so-called “electric pistol”. Invented by Alessandro Volta (1745-1827), an electrical wire was placed in a jar filled with methane gas. By sending an electrical spark through the wire, the jar would explode.

Volta then thought of using this invention to provide long distance communications, albeit only addressing one Boolean bit. An iron wire supported by wooden poles was to be strung from Como to Milan, Italy. At the receiving end, the wire would terminate in a jar filled with methane gas. On command, an electrical spark is sent by wire that would detonate the electric pistol to signal a coded event. This communications link was never built.

Figure 1-1: Alessandro Volta, inventor of the electric battery.
Volta’s discovery of the decomposition of water by an electrical current laid the foundation of electrochemistry.
©Cadex Electronics Inc.

In 1791, while working at Bologna University, Luigi Galvani discovered that the muscle of a frog contracted when touched by a metallic object. This phenomenon became known as animal electricity — a misnomer, as the theory was later disproven. Prompted by these experiments, Volta initiated a series of experiments using zinc, lead, tin or iron as positive plates. Copper, silver, gold or graphite were used as negative plates.

Volta discovered in 1800 that a continuous flow of electrical force was generated when using certain fluids as conductors to promote a chemical reaction between the metals or electrodes. This led to the invention of the first voltaic cell, better know as the battery. Volta discovered further that the voltage would increase when voltaic cells were stacked on top of each other.

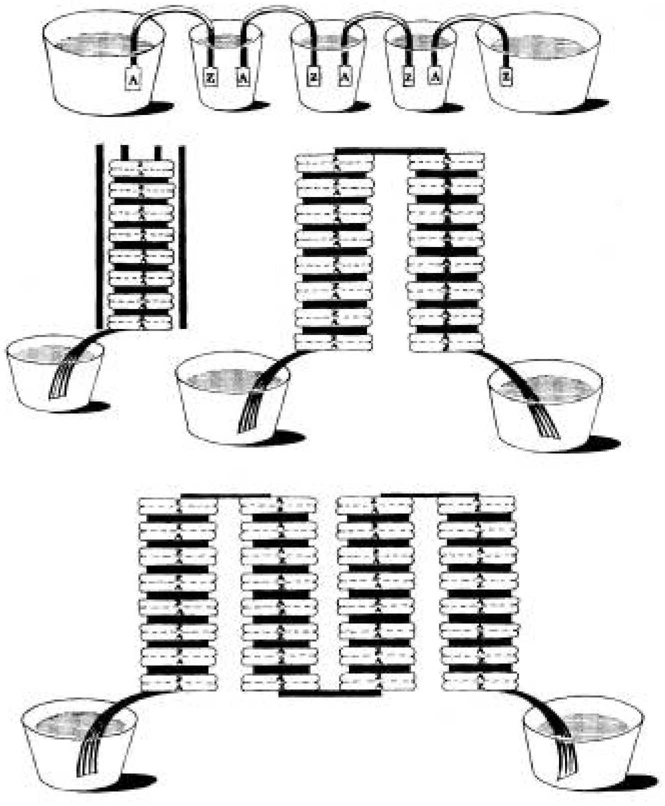


Figure 1-2: Four variations of Volta's electric battery.
Silver and zinc disks are separated with moist paper. ©Cadex Electronics Inc.

In the same year, Volta released his discovery of a continuous source of electricity to the Royal Society of London. No longer were experiments limited to a brief display of sparks that lasted a fraction of a second. A seemingly endless stream of electric current was now available.

France was one of the first nations to officially recognize Volta's discoveries. At the time, France was approaching the height of scientific advancements and new ideas were welcomed with open arms to support the political agenda. By invitation, Volta addressed the Institute of France in a series of lectures at which Napoleon Bonaparte was present as a member of the Institute.

Figure 1-3: Volta's experimentations at the French National Institute.
Volta's discoveries so impressed the world that in November 1800, he was invited by the French National Institute to lectures in which Napoleon Bonaparte participated. Later, Napoleon himself helped with the experiments, drawing sparks from the battery, melting a steel wire, discharging an electric pistol and decomposing water into its elements. ©Cadex Electronics Inc.

New discoveries were made when Sir Humphry Davy, inventor of the miner's safety lamp, installed the largest and most powerful electric battery in the vaults of the Royal Institution of London. He connected the battery to charcoal electrodes and produced the first electric light. As reported by witnesses, his voltaic arc lamp produced "the most brilliant ascending arch of light ever seen."

Davy's most important investigations were devoted to electrochemistry. Following Galvani's experiments and the discovery of the voltaic cell, interest in galvanic electricity had become widespread. Davy began to test the chemical effects of electricity in 1800. He soon found that by passing electrical current through some substances, these substances decomposed, a process later called electrolysis. The generated voltage was directly related to the reactivity of the electrolyte with the metal. Evidently, Davy understood that the actions of electrolysis and the voltaic cell were the same.

In 1802, Dr. William Cruickshank designed the first electric battery capable of mass production. Cruickshank had arranged square sheets of copper, which he soldered at their ends, together with sheets of zinc of equal size. These sheets were placed into a long rectangular wooden box that was sealed with cement. Grooves in the box held the metal plates in position. The box was then filled with an electrolyte of brine, or watered down acid.

The third method of generating electricity was discovered relatively late — electricity through magnetism. In 1820, André-Marie Ampère (1775-1836) had noticed that wires carrying an electric current were at times attracted to one another while at other times they were repelled.

In 1831, Michael Faraday (1791-1867) demonstrated how a copper disc was able to provide a constant flow of electricity when revolved in a strong magnetic field. Faraday, assisting Davy and his research team, succeeded in generating an endless electrical force as long as the movement between a coil and magnet continued. The electric generator was invented. This process was then reversed and the electric motor was discovered. Shortly thereafter, transformers were developed that could convert electricity to a desired voltage. In 1833, Faraday established the foundation of electrochemistry with Faraday's Law, which describes the amount of reduction that occurs in an electrolytic cell.

In 1836, John F. Daniell, an English chemist, developed an improved battery which produced a steadier current than Volta's device. Until then, all batteries had been composed of primary cells, meaning that they could not be recharged. In 1859, the French physicist Gaston Planté invented the first rechargeable battery. This secondary battery was based on lead acid chemistry, a system that is still used today.

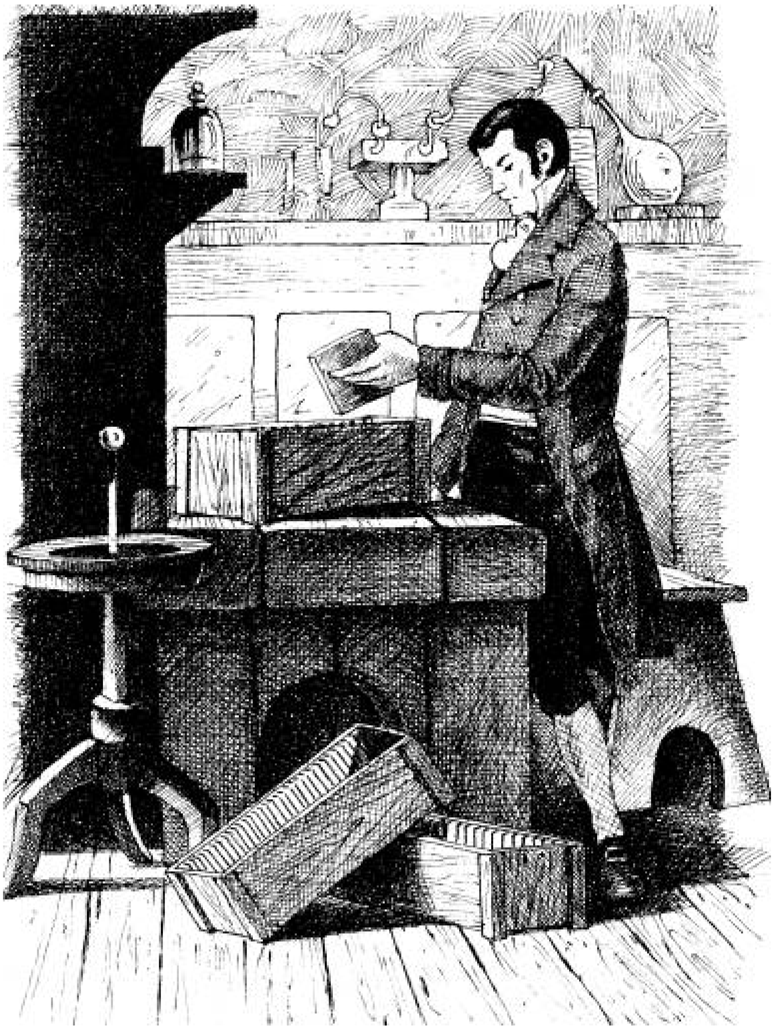


Figure 1-4: Cruickshank and the first flooded battery.
William Cruickshank, an English chemist, built a battery of electric cells by joining zinc and copper plates in a wooden box filled with electrolyte. This flooded design had the advantage of not drying out with use and provided more energy than Volta's disc arrangement. ©Cadex Electronics Inc.

Toward the end of the 1800s, giant generators and transformers were built. Transmission lines were installed and electricity was made available to humanity to produce light, heat and movement. In the early twentieth century, the use of electricity was further refined. The invention of the vacuum tube enabled generating controlled signals, amplifications and sound. Soon thereafter, radio was invented, which made wireless communication possible.

In 1899, Waldmar Jungner from Sweden invented the nickel-cadmium battery, which used nickel for the positive electrode and cadmium for the negative. Two years later, Edison produced an alternative design by replacing cadmium with iron. Due to high material costs compared to dry cells or lead acid storage batteries, the practical applications of the nickel-cadmium and nickel-iron batteries were limited.

It was not until Shlecht and Ackermann invented the sintered pole plate in 1932 that large improvements were achieved. These advancements were reflected in higher load currents and improved longevity. The sealed nickel-cadmium battery, as we know it toady, became only available when Neumann succeeded in completely sealing the cell in 1947.

From the early days on, humanity became dependent on electricity, a product without which our technological advancements would not have been possible. With the increased need for mobility, people moved to portable power storage — first for wheeled applications, then for portable and finally wearable use. As awkward and unreliable as the early batteries may have been, our descendants may one day look at today’s technology in a similar way to how we view our predecessors’ clumsy experiments of 100 years ago.

History of Battery Development

1600	Gilbert (England)	Establishment electrochemistry study
1791	Galvani (Italy)	Discovery of ‘animal electricity’
1800	Volta (Italy)	Invention of the voltaic cell
1802	Cruickshank (England)	First electric battery capable of mass production
1820	Ampère (France)	Electricity through magnetism
1833	Faraday (England)	Announcement of Faraday’s Law
1836	Daniell (England)	Invention of the Daniell cell
1859	Planté (France)	Invention of the lead acid battery
1868	Leclanché (France)	Invention of the Leclanché cell
1888	Gassner (USA)	Completion of the dry cell
1899	Jungner (Sweden)	Invention of the nickel-cadmium battery
1901	Edison (USA)	Invention of the nickel-iron battery
1932	Shlecht & Ackermann (Germany)	Invention of the sintered pole plate
1947	Neumann (France)	Successfully sealing the nickel-cadmium battery
Mid 1960	Union Carbide (USA)	Development of primary alkaline battery
Mid 1970		Development of valve regulated lead acid battery
1990		Commercialization nickel-metal hydride battery
1992	Kordesch (Canada)	Commercialization reusable alkaline battery
1999		Commercialization lithium-ion polymer
2001		Anticipated volume production of proton exchange membrane fuel cell

Figure 1-5: History of battery development.
The battery may be much older. It is believed that the Parthians who ruled Baghdad (ca. 250 bc) used batteries to electroplate silver. The Egyptians are said to have electroplated antimony onto copper over 4300 years ago.

Chapter 2: Battery Chemistries

Battery novices often argue that advanced battery systems are now available that offer very high energy densities, deliver 1000 charge/discharge cycles and are paper thin. These attributes are indeed achievable — unfortunately not in the same battery pack. A given battery may be designed for small size and long runtime, but this pack would have a limited cycle life. Another battery may be built for durability, but it would be big and bulky. A third pack may have high energy density and long durability, but would be too expensive for the commercial consumer.

Battery manufacturers are well aware of customer needs and have responded by offering battery packs that best suit the specific application. The mobile phone industry is an example of this clever adaptation. For this market, the emphasis is placed on small size and high energy density. Longevity comes in second.

The mention of NiMH on a battery pack does not automatically guarantee high energy density. A prismatic NiMH battery for a mobile phone, for example, is made for slim geometry and may only have an energy density of 60Wh/kg. The cycle count for this battery would be limited to around 300. In comparison, a cylindrical NiMH offers energy densities of 80Wh/kg and higher. Still, the cycle count of this battery will be moderate to low. High durability NiMH batteries, which are intended for industrial use and the electric vehicle enduring 1000 discharges to 80 percent depth-of discharge, are packaged in large cylindrical cells. The energy density on these cells is a modest 70Wh/kg.

Similarly, Li-ion batteries for defense applications are being produced that far exceed the energy density of the commercial equivalent. Unfortunately, these super-high capacity Li-ion batteries are deemed unsafe in the hands of the public. Neither would the general public be able to afford to buy them.

When energy densities and cycle life are mentioned, this book refers to a middle-of-the-road commercial battery that offers a reasonable compromise in size, energy density, cycle life and price. The book excludes miracle batteries that only live in controlled environments.

Chemistry Comparison

Let's examine the advantages and limitations of today’s popular battery systems. Batteries are scrutinized not only in terms of energy density but service life, load characteristics, maintenance requirements, self-discharge and operational costs. Since NiCd remains a standard against which other batteries are compared, let’s evaluate alternative chemistries against this classic battery type.

Nickel Cadmium (NiCd) — mature and well understood but relatively low in energy density. The NiCd is used where long life, high discharge rate and economical price are important. Main applications are two-way radios, biomedical equipment, professional video cameras and power tools. The NiCd contains toxic metals and is not environmentally friendly.

Nickel-Metal Hydride (NiMH) — has a higher energy density compared to the NiCd at the expense of reduced cycle life. NiMH contains no toxic metals. Applications include mobile phones and laptop computers.

Lead Acid — most economical for larger power applications where weight is of little concern. The lead acid battery is the preferred choice for hospital equipment, wheelchairs, emergency lighting and UPS systems.

Lithium Ion (Li-ion) — fastest growing battery system. Li-ion is used where high-energy density and light weight is of prime importance. The Li-ion is more expensive than other systems and must follow strict guidelines to assure safety. Applications include notebook computers and cellular phones.

Lithium Ion Polymer (Li-ion polymer) — a potentially lower cost version of the Li-ion. This chemistry is similar to the Li-ion in terms of energy density. It enables very slim geometry and allows simplified packaging. Main applications are mobile phones.

Reusable Alkaline — replaces disposable household batteries; suitable for low-power applications. Its limited cycle life is compensated by low self-discharge, making this battery ideal for portable entertainment devices and flashlights.

Figure 2-1 compares the characteristics of the six most commonly used rechargeable battery systems in terms of energy density, cycle life, exercise requirements and cost. The figures are based on average ratings of commercially available batteries at the time of publication. Exotic batteries with above average ratings are not included.

	NiCd	**NiMH**	**Lead Acid**	**Li-ion**	**Li-ion polymer**	**Reusable Alkaline**
Gravimetric Energy Density (Wh/kg)	45-80	60-120	30-50	110-160	100-130	80 (initial)
Internal Resistance (includes peripheral circuits) in mW	100 to 200[1] 6V pack	200 to 300[1] 6V pack	<100[1] 12V pack	150 to 250[1] 7.2V pack	200 to 300[1] 7.2V pack	200 to 2000[1] 6V pack
Cycle Life (to 80% of initial capacity)	1500[2]	300 to 500[2,3]	200 to 300[2]	500 to 1000[3]	300 to 500	50[3] (to 50%)
Fast Charge Time	1h typical	2-4h	8-16h	2-4h	2-4h	2-3h
Overcharge Tolerance	moderate	low	high	very low	low	moderate
Self-discharge / Month (room temperature)	20%[4]	30%[4]	5%	10%[5]	~10%[5]	0.3%
Cell Voltage (nominal)	1.25V[6]	1.25V[6]	2V	3.6V	3.6V	1.5V
Load Current - peak - best result	20C 1C	5C 0.5C or lower	5C[7] 0.2C	>2C 1C or lower	>2C 1C or lower	0.5C 0.2C or lower
Operating Temperature (discharge only)	-40 to 60°C	-20 to 60°C	-20 to 60°C	-20 to 60°C	0 to 60°C	0 to 65°C
Maintenance Requirement	30 to 60 days	60 to 90 days	3 to 6 months[9]	not req.	not req.	not req.
Typical Battery Cost (US$, reference only)	$50 (7.2V)	$60 (7.2V)	$25 (6V)	$100 (7.2V)	$100 (7.2V)	$5 (9V)
Cost per Cycle (US$)[11]	$0.04	$0.12	$0.10	$0.14	$0.29	$0.10-0.50
Commercial use since	1950	1990	1970	1991	1999	1992

Figure 2-1: Characteristics of commonly used rechargeable batteries.
The figures are based on average ratings of batteries available commercially at the time of publication; experimental batteries with above average ratings are not included.

1. Internal resistance of a battery pack varies with cell rating, type of protection circuit and number of cells. Protection circuit of Li-ion and Li-polymer adds about 100mW.
2. Cycle life is based on battery receiving regular maintenance. Failing to apply periodic full discharge cycles may reduce the cycle life by a factor of three.

3. Cycle life is based on the depth of discharge. Shallow discharges provide more cycles than deep discharges.
4. The discharge is highest immediately after charge, then tapers off. The NiCd capacity decreases 10% in the first 24h, then declines to about 10% every 30 days thereafter. Self-discharge increases with higher temperature.
5. Internal protection circuits typically consume 3% of the stored energy per month.
6. 1.25V is the open cell voltage. 1.2V is the commonly used value. There is no difference between the cells; it is simply a method of rating.
7. Capable of high current pulses.
8. Applies to discharge only; charge temperature range is more confined.
9. Maintenance may be in the form of ‘equalizing’ or ‘topping’ charge.
10. Cost of battery for commercially available portable devices.
11. Derived from the battery price divided by cycle life. Does not include the cost of electricity and chargers.

Observation: It is interesting to note that NiCd has the shortest charge time, delivers the highest load current and offers the lowest overall cost-per-cycle, but has the most demanding maintenance requirements.

The Nickel Cadmium (NiCd) Battery

Alkaline nickel battery technology originated in 1899, when Waldmar Jungner invented the NiCd battery. The materials were expensive compared to other battery types available at the time and its use was limited to special applications. In 1932, the active materials were deposited inside a porous nickel-plated electrode and in 1947, research began on a sealed NiCd battery, which recombined the internal gases generated during charge rather than venting them. These advances led to the modern sealed NiCd battery, which is in use today.

The NiCd prefers fast charge to slow charge and pulse charge to DC charge. All other chemistries prefer a shallow discharge and moderate load currents. The NiCd is a strong and silent worker; hard labor poses no problem. In fact, the NiCd is the only battery type that performs best under rigorous working conditions. It does not like to be pampered by sitting in chargers for days and being used only occasionally for brief periods. A periodic full discharge is so important that, if omitted, large crystals will form on the cell plates (also referred to as 'memory') and the NiCd will gradually lose its performance.

Among rechargeable batteries, NiCd remains a popular choice for applications such as two-way radios, emergency medical equipment, professional video cameras and power tools. Over 50 percent of all rechargeable batteries for portable equipment are NiCd. However, the introduction of batteries with higher energy densities and less toxic metals is causing a diversion from NiCd to newer technologies.

Advantages and Limitations of NiCd Batteries	
Advantages	Fast and simple charge — even after prolonged storage.
	High number of charge/discharge cycles — if properly maintained, the NiCd provides over 1000 charge/discharge cycles.
	Good load performance — the NiCd allows recharging at low temperatures.
	Long shelf life – in any state-of-charge.
	Simple storage and transportation — most airfreight companies accept the NiCd without special conditions.
	Good low temperature performance.
	Forgiving if abused — the NiCd is one of the most rugged rechargeable batteries.
	Economically priced — the NiCd is the lowest cost battery in terms of cost per cycle.
	Available in a wide range of sizes and performance options — most NiCd cells are cylindrical.
Limitations	Relatively low energy density — compared with newer systems.
	Memory effect — the NiCd must periodically be exercised to prevent memory.
	Environmentally unfriendly — the NiCd contains toxic metals. Some countries are limiting the use of the NiCd battery.
	Has relatively high self-discharge — needs recharging after storage.

Figure 2-2: Advantages and limitations of NiCd batteries.

The Nickel-Metal Hydride (NiMH) Battery

Research of the NiMH system started in the 1970s as a means of discovering how to store hydrogen for the nickel hydrogen battery. Today, nickel hydrogen batteries are mainly used for satellite applications. They are bulky, contain high-pressure steel canisters and cost thousands of dollars each.

In the early experimental days of the NiMH battery, the metal hydride alloys were unstable in the cell environment and the desired performance characteristics could not be achieved. As a result, the development of the NiMH slowed down. New hydride alloys were developed in the 1980s that were stable enough for use in a cell. Since the late 1980s, NiMH has steadily improved, mainly in terms of energy density.

The success of the NiMH has been driven by its high energy density and the use of environmentally friendly metals. The modern NiMH offers up to 40 percent higher energy density compared to NiCd. There is potential for yet higher capacities, but not without some negative side effects.

Both NiMH and NiCd are affected by high self-discharge. The NiCd loses about 10 percent of its capacity within the first 24 hours, after which the self-discharge settles to about 10 percent per month. The self-discharge of the NiMH is about one-and-a-half to two times greater compared to NiCd. Selection of hydride materials that improve hydrogen bonding and reduce corrosion of the alloy constituents reduces the rate of self-discharge, but at the cost of lower energy density.

The NiMH has been replacing the NiCd in markets such as wireless communications and mobile computing. In many parts of the world, the buyer is encouraged to use NiMH rather than NiCd batteries. This is due to environmental concerns about careless disposal of the spent battery.

The question is often asked, “Has NiMH improved over the last few years?” Experts agree that considerable improvements have been achieved, but the limitations remain. Most of the shortcomings are native to the nickel-based technology and are shared with the NiCd battery. It is widely accepted that NiMH is an interim step to lithium battery technology.

Initially more expensive than the NiCd, the price of the NiMH has dropped and is now almost at par value. This was made possible with high volume production. With a lower demand for NiCd, there will be a tendency for the price to increase.

Advantages and Limitations of NiMH Batteries	
Advantages	30 – 40 percent higher capacity over a standard NiCd. The NiMH has potential for yet higher energy densities.
	Less prone to memory than the NiCd. Periodic exercise cycles are required less often.
	Simple storage and transportation — transportation conditions are not subject to regulatory control.
	Environmentally friendly — contains only mild toxins; profitable for recycling.
Limitations	Limited service life — if repeatedly deep cycled, especially at high load currents, the performance starts to deteriorate after 200 to 300 cycles. Shallow rather than deep discharge cycles are preferred.
	Limited discharge current — although a NiMH battery is capable of delivering high discharge currents, repeated discharges with high load currents reduces the battery’s cycle life. Best results are achieved with load currents of 0.2C to 0.5C (one-fifth to one-half of the rated capacity).
	More complex charge algorithm needed — the NiMH generates more heat during charge and requires a longer charge time than the NiCd. The trickle charge is critical and must be controlled carefully.
	High self-discharge — the NiMH has about 50 percent higher self-discharge compared to the NiCd. New chemical additives improve the self-discharge but at the expense of lower energy density.
	Performance degrades if stored at elevated temperatures — the NiMH should be stored in a cool place and at a state-of-charge of about 40 percent.
	High maintenance — battery requires regular full discharge to prevent crystalline formation.
	About 20 percent more expensive than NiCd — NiMH batteries designed for high current draw are more expensive than the regular version.

Figure 2-3: Advantages and limitations of NiMH batteries

The Lead Acid Battery

Invented by the French physician Gaston Planté in 1859, lead acid was the first rechargeable battery for commercial use. Today, the flooded lead acid battery is used in automobiles, forklifts and large uninterruptible power supply (UPS) systems.

The SLA must
always be stored in
a charged state.

During the mid 1970s, researchers developed a maintenance-free lead acid battery, which could operate in any position. The liquid electrolyte was transformed into moistened separators and the enclosure was sealed. Safety valves were added to allow venting of gas during charge and discharge.

Driven by diverse applications, two designations of batteries emerged. They are the sealed lead acid (SLA), also known under the brand name of Gelcell, and the valve regulated lead acid (VRLA). Technically, both batteries are the same. No scientific definition exists as to when an SLA becomes a VRLA. (Engineers may argue that the word ‘sealed lead acid’ is a misnomer because no lead acid battery can be totally sealed. In essence, all are valve regulated.)

The SLA has a typical capacity range of 0.2Ah to 30Ah and powers portable and wheeled applications. Typical uses are personal UPS units for PC backup, small emergency lighting units, ventilators for health care patients and wheelchairs. Because of low cost, dependable service and minimal maintenance requirements, the SLA battery is the preferred choice for biomedical and health care instruments in hospitals and retirement homes.

The VRLA battery is generally used for stationary applications. Their capacities range from 30Ah to several thousand Ah and are found in larger UPS systems for power backup. Typical uses are mobile phone repeaters, cable distribution centers, Internet hubs and utilities, as well as power backup for banks, hospitals, airports and military installations.

Unlike the flooded lead acid battery, both the SLA and VRLA are designed with a low over-voltage potential to prohibit the battery from reaching its gas-generating potential during charge. Excess charging would cause gassing and water depletion. Consequently, the SLA and VRLA can never be charged to their full potential.

Among modern rechargeable batteries, the lead acid battery family has the lowest energy density. For the purpose of analysis, we use the term ‘sealed lead acid’ to describe the lead acid batteries for portable use and ‘valve regulated lead acid’ for stationary applications. Because of our focus on portable batteries, we focus mainly on the SLA.

The SLA is not subject to memory. Leaving the battery on float charge for a prolonged time does not cause damage. The battery’s charge retention is best among rechargeable batteries. Whereas the NiCd self-discharges approximately 40 percent of its stored energy in three months, the SLA self-discharges the same amount in one year. The SLA is relatively inexpensive to purchase but the operational costs can be more expensive than the NiCd if full cycles are required on a repetitive basis.

The SLA does not lend itself to fast charging — typical charge times are 8 to 16 hours. The SLA must always be stored in a charged state. Leaving the battery in a discharged condition causes sulfation, a condition that makes the battery difficult, if not impossible, to recharge.

Unlike the NiCd, the SLA does not like deep cycling. A full discharge causes extra strain and each discharge/charge cycle robs the battery of a small amount of capacity. This loss is very small while the battery is in good operating condition, but becomes more acute once the performance drops below 80 percent of its nominal capacity. This wear-down characteristic also applies to other battery chemistries in varying degrees. To prevent the battery from being stressed through repetitive deep discharge, a larger SLA battery is recommended.

Depending on the depth of discharge and operating temperature, the SLA provides 200 to 300 discharge/charge cycles. The primary reason for its relatively short cycle life is grid corrosion of the positive electrode, depletion of the active material and expansion of the positive plates. These changes are most prevalent at higher operating temperatures. Applying charge/discharge cycles does not prevent or reverse the trend.

There are some methods that improve the performance and prolong the life of the SLA. The optimum operating temperature for a VRLA battery is 25°C (77°F). As a rule of thumb, every 8°C (15°F) rise in temperature will cut the battery life in half. VRLA that would last for 10 years at 25°C would only be good for 5 years if operated at 33°C (95°F). The same battery would endure a little more than one year at a temperature of 42°C (107°F).

Advantages and Limitations of Lead Acid Batteries	
Advantages	Inexpensive and simple to manufacture — in terms of cost per watt hours, the SLA is the least expensive. Mature, reliable and well-understood technology — when used correctly, the SLA is durable and provides dependable service. Low self-discharge —the self-discharge rate is among the lowest in rechargeable batterysystems. Low maintenance requirements — no memory; no electrolyte to fill. Capable of high discharge rates.
Limitations	Cannot be stored in a discharged condition. Low energy density — poor weight-to-energy density limits use to stationary and wheeled applications. Allows only a limited number of full discharge cycles — well suited for standby applications that require only occasional deep discharges. Environmentally unfriendly — the electrolyte and the lead content can cause environmental damage. Transportation restrictions on flooded lead acid — there are environmental concerns regarding spillage in case of an accident. Thermal runaway can occur with improper charging.

Figure 2-4: Advantages and limitations of lead acid batteries.

The SLA has a relatively low energy density compared with other rechargeable batteries, making it unsuitable for handheld devices that demand compact size. In addition, performance at low temperatures is greatly reduced.

The SLA is rated at a 5-hour discharge or 0.2C. Some batteries are even rated at a slow 20 hour discharge. Longer discharge times produce higher capacity readings. The SLA performs well on high pulse currents. During these pulses, discharge rates well in excess of 1C can be drawn.

In terms of disposal, the SLA is less harmful than the NiCd battery but the high lead content makes the SLA environmentally unfriendly. Ninety percent of lead acid-based batteries are being recycled.

The Lithium Ion Battery

Pioneer work with the lithium battery began in 1912 under G.N. Lewis but it was not until the early 1970s that the first non-rechargeable lithium batteries became commercially available. Attempts to develop rechargeable lithium batteries followed in the 1980s, but failed due to safety problems.

Lithium is the lightest of all metals, has the greatest electrochemical potential and provides the largest energy density per weight. Rechargeable batteries using lithium metal anodes (negative electrodes) are capable of providing both high voltage and excellent capacity, resulting in an extraordinary high energy density.

After much research on rechargeable lithium batteries during the 1980s, it was found that cycling causes changes on the lithium electrode. These transformations, which are part of normal wear and tear, reduce the thermal stability, causing potential thermal runaway conditions. When this occurs, the cell temperature quickly approaches the melting point of lithium, resulting in a violent reaction called ‘venting with flame’. A large quantity of rechargeable lithium batteries sent to Japan had to be recalled in 1991 after a battery in a mobile phone released flaming gases and inflicted burns to a person’s face.

Because of the inherent instability of lithium metal, especially during charging, research shifted to a non-metallic lithium battery using lithium ions. Although slightly lower in energy density than lithium metal, the Li-ion is safe, provided certain precautions are met when charging and discharging. In 1991, the Sony Corporation commercialized the first Li-ion battery. Other manufacturers followed suit. Today, the Li-ion is the fastest growing and most promising battery chemistry.

The energy density of the Li-ion is typically twice that of the standard NiCd. Improvements in electrode active materials have the potential of increasing the energy density close to three times that of the NiCd. In addition to high capacity, the load characteristics are reasonably good and behave similarly to the NiCd in terms of discharge characteristics (similar shape of discharge profile, but different voltage). The flat discharge curve offers effective utilization of the stored power in a desirable voltage spectrum.

The Li-ion is a low maintenance battery, an advantage that most other chemistries cannot claim. There is no memory and no scheduled cycling is required to prolong the battery’s life. In addition, the self-discharge is less than half compared to NiCd and NiMH, making the Li-ion well suited for modern fuel gauge applications.

The high cell voltage of Li-ion allows the manufacture of battery packs consisting of only one cell. Many of today’s mobile phones run on a single cell, an advantage that simplifies battery design. Supply voltages of electronic applications have been heading lower, which in turn requires fewer cells per battery pack. To maintain the same power, however, higher currents are needed. This emphasizes the importance of very low cell resistance to allow unrestricted flow of current.

Chemistry variations — During recent years, several types of Li-ion batteries have emerged with only one thing in common — the catchword 'lithium'. Although strikingly similar on the outside, lithium-based batteries can vary widely. This book addresses the lithium-based batteries that are predominantly used in commercial products.

Sony’s original version of the Li-ion used coke, a product of coal, as the negative electrode. Since 1997, most Li-ions (including Sony’s) have shifted to graphite. This electrode provides a flatter discharge voltage curve than coke and offers a sharp knee bend at the end of discharge (see Figure 2-5). As a result, the graphite system delivers the stored energy by only having to discharge to 3.0V/cell, whereas the coke version must be discharged to 2.5V to get similar runtime. In addition, the graphite version is capable of delivering a higher discharge current and remains cooler during charge and discharge than the coke version.

For the positive electrode, two distinct chemistries have emerged. They are cobalt and spinel (also known as *manganese*). Whereas cobalt has been in use longer, spinel is inherently safer and more forgiving if abused. Small prismatic spinel packs for mobile phones may only include a thermal fuse and temperature sensor. In addition to cost savings on a simplified protection circuit, the raw material cost for spinel is lower than that of cobalt.

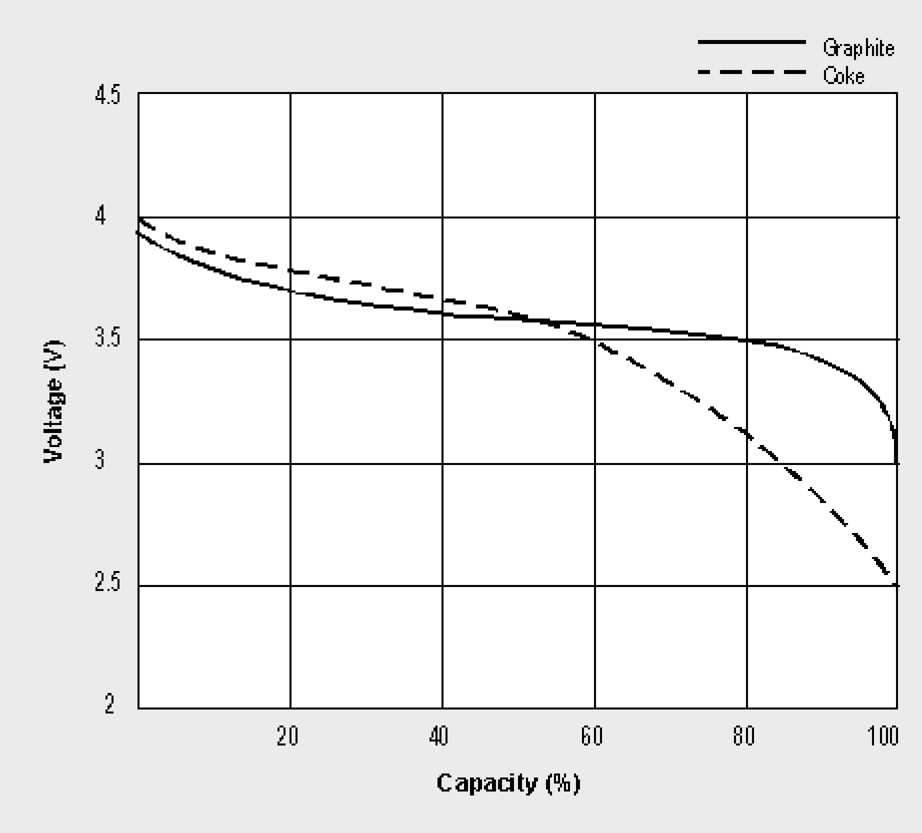


Figure 2-5: **Li-ion discharge characteristics.**
The graphite Li-ion only needs to discharge to 3.0V/cell, whereas the coke version must be discharged to 2.5V/cell to achieve similar performance.

As a trade-off, spinel offers a slightly lower energy density, suffers capacity loss at temperatures above 40°C and ages quicker than cobalt. Figure 2-6 compares the advantages and disadvantages of the two chemistries.

	Cobalt	**Manganese (Spinel)**
Energy density (Wh/kg)	140 [1]	120 [1]
Safety	On overcharge, the cobalt electrode provides extra lithium, which can form into metallic lithium, causing a potential safety risk if not protected by a safety circuit.	On overcharge, the manganese electrode runs out of lithium causing the cell only to get warm. Safety circuits can be eliminated for small 1 and 2 cell packs.
Temperature	Wide temperature range. Best suited for operation at elevated temperature.	Capacity loss above +40°C. Not as durable at higher temperatures.
Aging	Short-term storage possible. Impedance increases with age. Newer versions offer longer storage.	Slightly less than cobalt. Impedance changes little over the life of the cell. Due to continuous improvements, storage time is difficult to predict.
Life Expectancy	300 cycles, 50% capacity at 500 cycles.	May be shorter than cobalt.
Cost	Raw material relatively high; protection circuit adds to costs.	Raw material 30% lower than cobalt. Cost advantage on simplified protection circuit.

Figure 2-6: Comparison of cobalt and manganese as positive electrodes.
Manganese is inherently safer and more forgiving if abused but offers a slightly lower energy density. Manganese suffers capacity loss at temperature above 40°C and ages quicker than cobalt.

Based on present generation 18650 cells. The energy density tends to be lower for prismatic cells.

The choice of metals, chemicals and additives help balance the critical trade-off between high energy density, long storage time, extended cycle life and safety. High energy densities can be achieved with relative ease. For example, adding more nickel in lieu of cobalt increases the ampere/hours rating and lowers the manufacturing cost but makes the cell less safe. While a start-up company may focus on high energy density to gain quick market acceptance, safety, cycle life and storage capabilities may be compromised. Reputable manufacturers, such as Sony, Panasonic, Sanyo, Moli Energy and Polystor place high importance on safety. Regulatory authorities assure that only safe batteries are sold to the public.

Li-ion cells cause less harm when disposed of than lead or cadmium-based batteries. Among the Li-ion family, the spinel is the friendliest in terms of disposal.

Despite its overall advantages, Li-ion also has its drawbacks. It is fragile and requires a protection circuit to maintain safe operation. Built into each pack, the protection circuit limits the peak voltage of each cell during charge and prevents the cell voltage from dropping too low on discharge. In addition, the maximum charge and discharge current is limited and the cell temperature is monitored to prevent temperature extremes. With these precautions in place, the possibility of metallic lithium plating occurring due to overcharge is virtually eliminated.

Aging is a concern with most Li-ion batteries. For unknown reasons, battery manufacturers are silent about this issue. Some capacity deterioration is noticeable after one year, whether the battery is in use or not. Over two or perhaps three years, the battery frequently fails. It should be mentioned that other chemistries also have age-related degenerative effects. This is especially true for the NiMH if exposed to high ambient temperatures.

Storing the battery in a cool place slows down the aging process of the Li-ion (and other chemistries). Manufacturers recommend storage temperatures of 15°C (59°F). In addition, the battery should only be partially charged when in storage.

Extended storage is not recommended for Li-ion batteries. Instead, packs should be rotated. The buyer should be aware of the manufacturing date when purchasing a replacement Li-ion battery. Unfortunately, this information is often encoded in an encrypted serial number and is only available to the manufacturer.

Manufacturers are constantly improving the chemistry of the Li-ion battery. Every six months, a new and enhanced chemical combination is tried. With such rapid progress, it becomes difficult to assess how well the revised battery ages and how it performs after long-term storage.

Cost analysis — The most economical lithium-based battery in terms of cost-to-energy ratio is a pack using the cylindrical 18650 cell. This battery is somewhat bulky but suitable for portable applications such as mobile computing. If a slimmer pack is required (thinner than 18 mm), the prismatic Li-ion cell is the best choice. There is little or no gain in energy density per weight and size over the 18650, however the cost is more than double.

If an ultra-slim geometry is needed (less than 4 mm), the best choice is Li-ion polymer. This is the most expensive option in terms of energy cost. The Li-ion polymer does not offer appreciable energy gains over conventional Li-ion systems, nor does it match the durability of the 18560 cell.

Advantages and Limitations of Li-ion Batteries	
Advantages	High energy density — potential for yet higher capacities.
	Relatively low self-discharge — self-discharge is less than half that of NiCd and NiMH.
	Low Maintenance — no periodic discharge is needed; no memory.
Limitations	Requires protection circuit — protection circuit limits voltage and current. Battery is safe if not provoked.
	Subject to aging, even if not in use — storing the battery in a cool place and at 40 percent state-of-charge reduces the aging effect.
	Moderate discharge current.
	Subject to transportation regulations — shipment of larger quantities of Li-ion batteries may be subject to regulatory control. This restriction does not apply to personal carry-on batteries.
	Expensive to manufacture — about 40 percent higher in cost than NiCd. Better manufacturing techniques and replacement of rare metals with lower cost alternatives will likely reduce the price.
	Not fully mature — changes in metal and chemical combinations affect battery test results, especially with some quick test methods.

Figure 2-7: Advantages and limitations of Li-ion batteries.

Caution: Li-ion batteries have a high energy density. Exercise precaution when handling and testing. Do not short circuit, overcharge, crush, drop, mutilate, penetrate, apply reverse polarity, expose to high temperature or disassemble. Only use the Li-ion battery with the designated protection circuit. High case temperature resulting from abuse of the cell could cause physical injury. The electrolyte is highly flammable. Rupture may cause venting with flame.

The Lithium Polymer Battery

The Li-polymer differentiates itself from other battery systems in the type of electrolyte used. The original design, dating back to the 1970s, uses a dry solid polymer electrolyte only. This electrolyte resembles a plastic-like film that does not conduct electricity but allows an exchange of ions (electrically charged atoms or groups of atoms). The polymer electrolyte replaces the traditional porous separator, which is soaked with electrolyte.

The dry polymer design offers simplifications with respect to fabrication, ruggedness, safety and thin-profile geometry. There is no danger of flammability because no liquid or gelled electrolyte is used.

With a cell thickness measuring as little as one millimeter (0.039 inches), equipment designers are left to their own imagination in terms of form, shape and size. It is possible to create designs which form part of a protective housing, are in the shape of a mat that can be rolled up, or are even embedded into a carrying case or piece of clothing. Such innovative batteries are still a few years away, especially for the commercial market.

Unfortunately, the dry Li-polymer suffers from poor conductivity. Internal resistance is too high and cannot deliver the current bursts needed for modern communication devices and spinning up the hard drives of mobile computing equipment. Although heating the cell to 60°C (140°F) and higher increases the conductivity to acceptable levels, this requirement is unsuitable in commercial applications.

Research is continuing to develop a dry solid Li-polymer battery that performs at room temperature. A dry solid Li-polymer version is expected to be commercially available by 2005. It is expected to be very stable; would run 1000 full cycles and would have higher energy densities than today’s Li-ion battery.

In the meantime, some Li-polymers are used as standby batteries in hot climates. One manufacturer has added heating elements that keeps the battery in the conductive temperature range at all times. Such a battery performs well for the application intended because high ambient temperatures do not affect the service life of this battery in the same way it does the VRLA, for example.

To make a small Li-polymer battery conductive, some gelled electrolyte has been added. Most of the commercial Li-polymer batteries used today for mobile phones are a hybrid and contain gelled electrolyte. The correct term for this system is ‘Lithium Ion Polymer’. For promotional reasons, most battery manufacturers mark the battery simply as Li-polymer. Since the hybrid lithium polymer is the only functioning polymer battery for portable use today, we will focus on this chemistry.

With gelled electrolyte added, what then is the difference between Li-ion and Li-ion polymer? Although the characteristics and performance of the two systems are very similar, the Li-ion polymer is unique in that it uses a solid electrolyte, replacing the porous separator. The gelled electrolyte is simply added to enhance ion conductivity.

Technical difficulties and delays in volume manufacturing have deferred the introduction of the Li-ion polymer battery. This postponement, as some critics argue, is due to ‘cashing in’ on the Li-ion battery. Manufacturers have invested heavily in research, development and equipment to mass-produce the Li-ion. Now businesses and shareholders want to see a return on their investment.

In addition, the promised superiority of the Li-ion polymer has not yet been realized. No improvements in capacity gains have been achieved — in fact, the capacity is slightly less than that of the standard Li-ion battery. For the present, there is no cost advantage in using the Li-ion polymer battery. The thin profile has, however, compelled mobile phone manufacturers to use this promising technology for their new generation handsets.

One of the advantages of the Li-ion polymer, however, is simpler packaging because the electrodes can easily be stacked. Foil packaging, similar to that used in the food industry, is being used. No defined norm in cell size has been established by the industry.

Advantages and Limitations of Li-ion Polymer Batteries	
Advantages	Very low profile — batteries that resemble the profile of a credit card are feasible. Flexible form factor — manufacturers are not bound by standard cell formats. With high volume, any reasonable size can be produced economically. Light weight – gelled rather than liquid electrolytes enable simplified packaging, in some cases eliminating the metal shell. Improved safety — more resistant to overcharge; less chance for electrolyte leakage.
Limitations	Lower energy density and decreased cycle count compared to Li-ion — potential for improvements exist. Expensive to manufacture — once mass-produced, the Li-ion polymer has the potential for lower cost. Reduced control circuit offsets higher manufacturing costs.

Figure 2-8: Advantages and limitations of Li-ion polymer batteries.

Reusable Alkaline Batteries

The idea of recharging alkaline batteries is not new. Although not endorsed by manufacturers, ordinary alkaline batteries have been recharged in households for many years. Recharging these batteries is only effective, however, if the cells have been discharged to less than 50 percent of their total capacity. The number of recharges depends solely on the depth of discharge and is limited to a few at best. With each recharge, less capacity can be reclaimed. There is a cautionary advisory, however: charging ordinary alkaline batteries may generate hydrogen gas, which can lead to explosion. It is therefore not prudent to charge ordinary alkaline unsupervised.

In comparison, the reusable alkaline is designed for repeated recharge. It too loses charge acceptance with each recharge. The longevity of the reusable alkaline is a direct function of the depth of discharge; the deeper the discharge, the fewer cycles the battery can endure.

Tests performed by Cadex on ‘AA’ reusable alkaline cells showed a very high capacity reading on the first discharge. In fact, the energy density was similar to that of a NiMH battery. When the battery was discharged, then later recharged using the manufacturer’s charger, the reusable alkaline settled at 60 percent, a capacity slightly below that of a NiCd. Repeat cycling in the same manner resulted in a fractional capacity loss with each cycle. In our tests, the discharge current was adjusted to 200mA (0.2 C-rate, or one fifth of the rated capacity); the end-of-discharge threshold was set to 1V/cell.

An additional limitation of the reusable alkaline system is its low load current capability of 400mA (lower than 400mA provides better results). Although adequate for portable AM/FM radios, CD players, tape players and flashlights, 400mA is insufficient to power most mobile phones and video cameras.

The reusable alkaline is inexpensive but the cost per cycle is high when compared to the nickel-based rechargeables. Whereas the NiCd checks in at $0.04 per cycle based on 1500 cycles, the reusable alkaline costs $0.50 based on 10 full discharge cycles. For many applications, this seemingly high cost is still economical when compared to the non-reusable alkaline that has a one-time use. If the reusable alkaline battery is only partially discharged before recharge, an improved cycle life is possible. At 50 percent depth of discharge, 50 cycles can be expected.

To compare the operating cost between the standard and reusable alkaline, a study was done on flashlight batteries for hospital use. The low-intensity care unit using the flashlights only occasionally achieved measurable savings by employing the reusable alkaline. The high-intensity unit that used the flashlights constantly, on the other hand, did not attain the same result. Deeper discharge and more frequent recharge reduced their service life and offset any cost advantage over the standard alkaline battery.

In summary, the standard alkaline offers maximum energy density whereas the reusable alkaline provides the benefit of allowing some recharging. The compromise of the reusable alkaline is loss of charge acceptance after the first recharge.

Advantages and Limitations of Reusable Alkaline Batteries	
Advantages	Inexpensive and readily available — can be used as a direct replacement of non-rechargeable (primary) cells. More economical than non-rechargeable – allows several recharges. Low self-discharge — can be stored as a standby battery for up to 10 years. Environmentally friendly — no toxic metals used, fewer batteries are discarded, reduces landfill. Maintenance free — no need for cycling; no memory.
Limitations	Limited current handling — suited for light-duty applications like portable home entertainment, flashlights. Limited cycle life — for best results, recharge before the battery gets too low.

Figure 2-9: Advantages and limitations of reusable alkaline batteries.

The Supercapacitor

The supercapacitor resembles a regular capacitor with the exception that it offers very high capacitance in a small size. Energy storage is by means of static charge. Applying a voltage differential on the positive and negative plates charges the supercapacitor. This concept is similar to an electrical charge that builds up when walking on a carpet. Touching an object at ground potential releases the energy. The supercapacitor concept has been around for a number of years and has found many niche applications.

Whereas a regular capacitor consists of conductive foils and a dry separator, the supercapacitor is a cross between a capacitor and an electro-chemical battery. It uses special electrodes and some electrolyte. There are three kinds of electrode materials suitable for the supercapacitor, namely: high surface area activated carbons, metal oxide and conducting polymers. The one using high surface area activated carbons is the most economical to manufacture. This system is also called Double Layer Capacitor (DLC) because the energy is stored in the double layer formed near the carbon electrode surface.

The electrolyte may be aqueous or organic. The aqueous electrolyte offers low internal resistance but limits the voltage to one volt. In contrast, the organic electrolyte allows two and three volts of charge, but the internal resistance is higher.

To make the supercapacitor practical for use in electronic circuits, higher voltages are needed. Connecting the cells in series accomplishes this task. If more than three or four capacitors are connected in series, voltage balancing must be used to prevent any cell from reaching over-voltage.
The amount of energy a capacitor can hold is measured in microfarads or µF. (1µF = 0.000,001 farad). Small capacitors are measured in nanofarads (1000 times smaller than 1µF) and picofarads (1 million times smaller than 1µF). Supercapacitors are rated in units of 1 farad and higher. The gravimetric energy density is 1 to 10Wh/kg. This energy density is high in comparison to the electrolytic capacitor but lower than batteries. A relatively low internal resistance offers good conductivity.

The supercapacitor provides the energy of approximately one tenth that of the NiMH battery. Whereas the electro-chemical battery delivers a fairly steady voltage in the usable energy spectrum, the voltage of the supercapacitor is linear and drops from full voltage to zero volts without the customary flat voltage curve characterized by most chemical batteries. Because of this linear discharge, the supercapacitor is unable to deliver the full charge. The percentage of charge that is available depends on the voltage requirements of the application.

If, for example, a 6V battery is allowed to discharge to 4.5V before the equipment cuts off, the supercapacitor reaches that threshold within the first quarter of the discharge time. The remaining energy slips into an unusable voltage range. A DC-to-DC converter can be used to increase the voltage range but this option adds costs and introduces inefficiencies of 10 to 15 percent.

The most common supercapacitor applications are memory backup and standby power. In some special applications, the supercapacitor can be used as a direct replacement of the electrochemical battery. Additional uses are filtering and smoothing of pulsed load currents.
A supercapacitor can, for example, improve the current handling of a battery. During low load current, the battery charges the supercapacitor. The stored energy then kicks in when a high load current is requested. This enhances the battery's performance, prolongs the runtime and even extends the longevity of the battery. The supercapacitor will find a ready market for portable fuel cells to compensate for the sluggish performance of some systems and enhance peak performance.

If used as a battery enhancer, the supercapacitor can be placed inside the portable equipment or across the positive and negative terminals in the battery pack. If put into the equipment, provision must be made to limit the high influx of current when the equipment is turned on.

Low impedance supercapacitors can be charged in seconds. The charge characteristics are similar to those of an electro-chemical battery. The initial charge is fairly rapid; the topping charge takes some extra time. In terms of charging method, the supercapacitor resembles the lead acid cell. Full charge takes place when a set voltage limit is reached. Unlike the electro-chemical battery, the supercapacitor does not require a full-charge detection circuit. Supercapacitors can also be trickle charged.

Limitations Unable to use the full energy spectrum - depending on the application, not all energy is available. Low energy density - typically holds one-fifth to one-tenth the energy of an electrochemical battery. Cells have low voltages - serial connections are needed to obtain higher voltages. Voltage balancing is required if more than three capacitors are connected in series. High self-discharge - the self-discharge is considerably higher than that of an electrochemical battery.

Advantages and Limitations of Supercapacitors	
Advantages	Virtually unlimited cycle life - not subject to the wear and aging experienced by the electrochemical battery. Low impedance - enhances pulse current handling by paralleling with an electrochemical battery. Rapid charging - low-impedance supercapacitors charge in seconds. Simple charge methods - voltage-limiting circuit compensates for self-discharge; no full-charge detection circuit needed. Cost-effective energy storage - lower energy density is compensated by a very high cycle count.
Limitations	Unable to use the full energy spectrum - depending on the application, not all energy is available. Low energy density - typically holds one-fifth to one-tenth the energy of an electrochemical battery. Cells have low voltages - serial connections are needed to obtain higher voltages. Voltage balancing is required if more than three capacitors are connected in series. High self-discharge - the self-discharge is considerably higher than that of an electrochemical battery.

Figure 2-10: Advantages and limitations of supercapacitors.

By nature, the voltage limiting circuit compensates for the self-discharge. The supercapacitor can be recharged and discharged virtually an unlimited number of times. Unlike the electrochemical battery, there is very little wear and tear induced by cycling.

The self-discharge of the supercapacitor is substantially higher than that of the electrochemical battery. Typically, the voltage of the supercapacitor with an organic electrolyte drops from full charge to the 30 percent level in as little as 10 hours.

Other supercapacitors can retain the charged energy longer. With these designs, the capacity drops from full charge to 85 percent in 10 days. In 30 days, the voltage drops to roughly 65 percent and to 40 percent after 60 days.

Chapter 3: The Battery Pack

In the 1700 and 1800s, cells were encased in glass jars. Later, larger batteries were developed that used wooden containers. The inside was treated with a sealant to prevent electrolyte leakage. With the need for portability, the cylindrical cell appeared. After World War II, these cells became the standard format for smaller, rechargeable batteries.

Downsizing required smaller and more compact cell design. The button cell, which gained popularity in the 1980s, was a first attempt to achieve a reasonably flat geometry, or obtain higher voltages in a compact profile by stacking. The early 1990s brought the prismatic cell, which was followed by the modern pouch cell.

This chapter addresses the cell designs, pack configurations and intrinsic safety devices. In keeping with portability, this book addresses only the smaller cells used for portable batteries.

The Cylindrical Cell

The cylindrical cell continues to be the most widely used packaging style. The advantages are ease of manufacture and good mechanical stability. The cylinder has the ability to withstand high internal pressures. While charging, the cell pressure of a NiCd can reach 1379 kilopascals (kPa) or 200 pounds per square inch (psi). A venting system is added on one end of the cylinder. Venting occurs if the cell pressure reaches between 150 and 200 psi. Figure 3-1 illustrates the conventional cell of a NiCd battery.

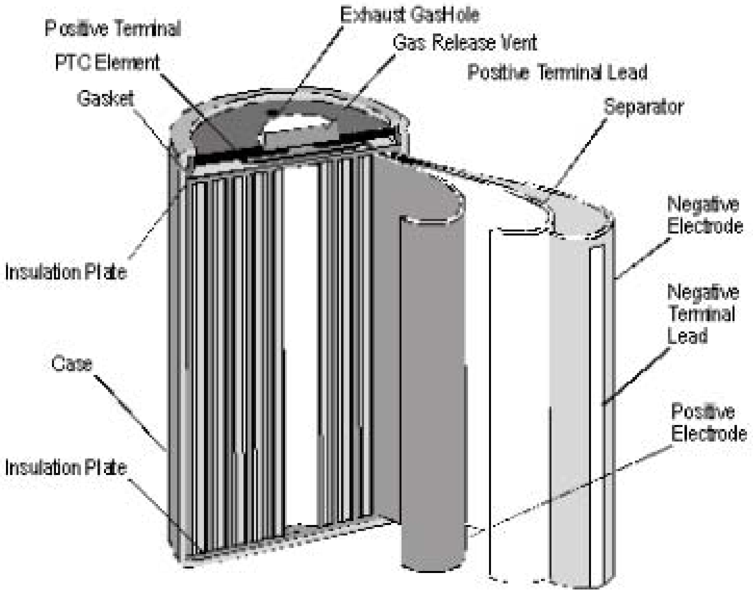


Figure 3-1: Cross-section of a classic NiCd cell.
The negative and positive plates are rolled together in a metal cylinder. The positive plate is sintered and filled with nickel hydroxide. The negative plate is coated with cadmium active material. A separator moistened with electrolyte isolates the two plates. Design courtesy of Panasonic OEM Battery Sales Group, March 2001.

The cylindrical cell is moderately priced and offers high energy density. Typical applications are wireless communication, mobile computing, biomedical instruments, power tools and other uses that do not demand ultra-small size.

NiCd offers the largest selection of cylindrical cells. A good variety is also available in the NiMH family, especially in the smaller cell formats. In addition to cylindrical formats, NiMH also comes in the prismatic cell packaging.

The Li-ion batteries are only available in limited cells sizes, the most popular being the 18650. ‘Eighteen’ denotes the diameter in millimeters and ‘650’ describes the length in millimeters. The 18650 cell has a capacity of 1800 to 2000mAh. The larger 26650 cell has a diameter of 26 mm and delivers 3200mAh. Because of the flat geometry of the Li-ion polymer, this battery chemistry is not available in a cylindrical format.

Most SLA batteries are built in a prismatic format, thus creating a rectangle box that is commonly made of plastic materials. There are SLA batteries, however, that take advantage of the cylindrical design by using a winding technique that is similar to the conventional cell. The cylindrical Hawker Cyclone SLA is said to offer improved cell stability, provide higher discharge currents and have better temperature stability than the conventional prismatic design.

The drawback of the cylindrical cell is less than maximum use of space. When stacking the cells, air cavities are formed. Because of fixed cell size, the pack must be designed around the available cell size.

Almost all cylindrical cells are equipped with a venting mechanism to expel excess gases in an orderly manner. Whereas nickel-based batteries feature a resealable vent, many cylindrical Li-ion contain a membrane seal that ruptures if the pressure exceeds 3448 kPa (500 psi). There is usually some serious swelling of the cell before the seal breaks. Venting only occurs under extreme conditions.

The Button Cell

The button cell was developed to miniaturize battery packs and solve stacking problems. Today, this architecture is limited to a small niche market. Non-rechargeable versions of the button cell continue to be popular and can be found in watches, hearing aids and memory backup.

The main applications of the rechargeable button cell are (or were) older cordless telephones, biomedical devices and industrial instruments. Although small in design and inexpensive to manufacture, the main drawback is swelling if charged too rapidly. Button cells have no safety vent and can only be charged at a 10 to 16 hour charge rate. New designs claim rapid charge capability.

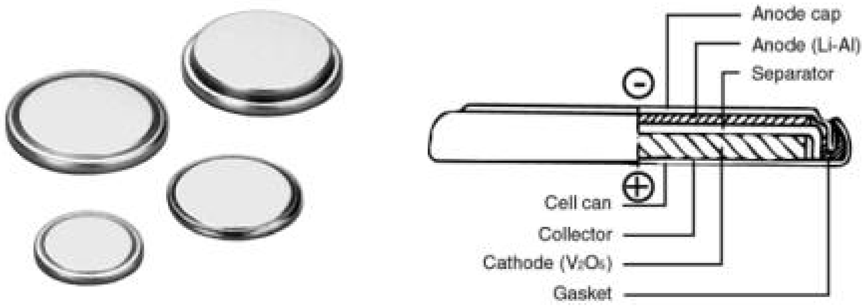


Figure 3-2: The button cell.
The button cell offers small size and ease of stacking but does not allow fast charging. Coin cells, which are similar in appearance, are normally lithium-based and are non-rechargeable. Photograph courtesy of Sanyo Corporation; design courtesy of Panasonic OEM Battery Sales Group, March 2001.

The Prismatic Cell

The prismatic cell was developed in response to consumer demand for thinner pack sizes. Introduced in the early 1990's, the prismatic cell makes almost maximum use of space when stacking. Narrow and elegant battery styles are possible that suit today's slim-style geometry. Prismatic cells are used predominantly for mobile phone applications. Figure 3-3 shows the prismatic cell.

Prismatic cells are most common in the lithium battery family. The Li-ion polymer is exclusively prismatic. No universally accepted cell size exists for Li-ion polymer batteries. One leading manufacturer may bring out one or more sizes that fit a certain portable device, such as a mobile phone. While these cells are produced at high volume, other cell manufacturers follow suit and offer an identical cell at a competitive price. Prismatic cells that have gained acceptance are the 340648 and the 340848. Measured in millimeters, '34' denotes the width, '06' or '08' the thickness and '48' the length of the cell.

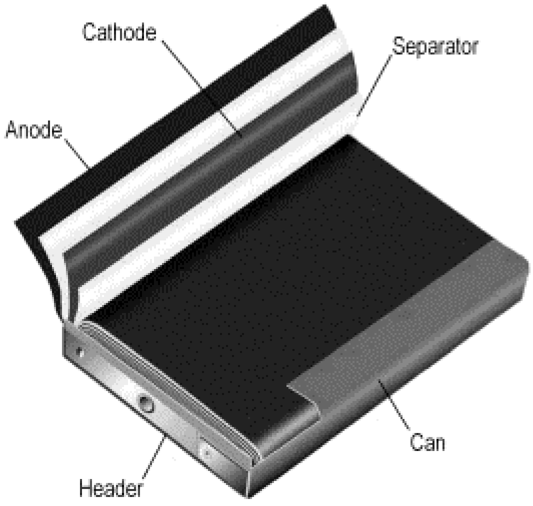


Figure 3-3: Cross-section of a prismatic cell.
The prismatic cell improves space utilization and allows more flexibility in pack design. This cell construction is less cost effective than the cylindrical equivalent and provides a slightly lower energy density. Design courtesy of Polystor Corporation, March 2001.

Some prismatic cells are similar in size but are off by just a small fraction. Such is the case with the Panasonic cell that measures 34 mm by 50 mm and is 6.5 mm thick. If a few cubic millimeters can be added for a given application, the manufacturer will do so for the sake of higher capacities.

The disadvantage of the prismatic cell is slightly lower energy densities compared to the cylindrical equivalent. In addition, the prismatic cell is more expensive to manufacture and does not provide the same mechanical stability enjoyed by the cylindrical cell. To prevent bulging when pressure builds up, heavier gauge metal is used for the container. The manufacturer allows some degree of bulging when designing the battery pack.

The prismatic cell is offered in limited sizes and chemistries and runs from about 400mAh to 2000mAh and higher. Because of the very large quantities required for mobile phones, special prismatic cells are built to fit certain models. Most prismatic cells do not have a venting system. In case of pressure build-up, the cell starts to bulge. When correctly used and properly charged, no swelling should occur.

The Pouch Cell

Cell design made a profound advance in 1995 when the pouch cell concept was developed. Rather than using an expensive metallic cylinder and glass-to-metal electrical feed-through to insulate the opposite polarity, the positive and negative plates are enclosed in flexible, heat-sealable foils. The electrical contacts consist of conductive foil tabs that are welded to the electrode and sealed to the pouch material. Figure 3-4 illustrates the pouch cell.

The pouch cell concept allows tailoring to exact cell dimensions. It makes the most efficient use of available space and achieves a packaging efficiency of 90 to 95 percent, the highest among battery packs. Because of the absence of a metal can, the pouch pack has a lower weight. The main applications are mobile phones and military devices. No standardized pouch cells exist, but rather, each manufacturer builds to a special application.

The pouch cell is exclusively used for Li-ion and Li-ion polymer chemistries. At the present time, it costs more to produce this cell architecture and its reliability has not been fully proven. In addition, the energy density and load current are slightly lower than that of conventional cell designs. The cycle life in everyday applications is not well documented but is, at present, less than that of the Li-ion system with conventional cell design.

A critical issue with the pouch cell is the swelling that occurs when gas is generated during charging or discharging. Battery manufacturers insist that Li-ion or Polymer cells do not generate gas if properly formatted, are charged at the correct current and are kept within allotted voltage levels. When designing the protective housing for a pouch cell, some provision for swelling must be made. To alleviate the swelling issue when using multiple cells, it is best not to stack pouch cells, but lay them side by side.

Similar to a chain, the more links that are used, the greater the odds of one breaking.

Figure 3-4: The pouch cell.
The pouch cell offers a simple, flexible and lightweight solution to battery design. This new concept has not yet fully matured and the manufacturing costs are still high.
© Cadex Electronics Inc.

The pouch cell is highly sensitive to twisting. Point pressure must also be avoided. The protective housing must be designed to protect the cell from mechanical stress.

Series and Parallel Configurations

In most cases, a single cell does not provide a high enough voltage and a serial connection of several cells is needed. The metallic skin of the cell is insulated to prevent the ‘hot’ metal cylinders from creating an electrical short circuit against the neighboring cell.

Nickel-based cells provide a nominal cell voltage of 1.25V. A lead acid cell delivers 2V and most Li-ion cells are rated at 3.6V. The spinel (manganese) and Li-ion polymer systems sometimes use 3.7V as the designated cell voltage. This is the reason for the often unfamiliar voltages, such as 11.1V for a three cell pack of spinel chemistry.

Nickel-based cells are often marked 1.2V. There is no difference between a 1.2 and 1.25V cell; it is simply the preference of the manufacturer in marking. Whereas commercial batteries tend to be identified with 1.2V/cell, industrial, aviation and military batteries are still marked with the original designation of 1.25V/cell.

A five-cell nickel-based battery delivers 6V (6.25V with 1.25V/cell marking) and a six-cell pack has 7.2V (7.5V with 1.25V/cell marking). The portable lead acid comes in 3 cell (6V) and 6 cell (12V) formats. The Li-ion family has either 3.6V for a single cell pack, 7.2V for a two-cell pack or 10.8V for a three-cell pack. The 3.6V and 7.2V batteries are commonly used for mobile phones; laptops use the larger 10.8V packs.

There has been a trend towards lower voltage batteries for light portable devices, such as mobile phones. This was made possible through advancements in microelectronics. To achieve the same energy with lower voltages, higher currents are needed. With higher currents, a low internal battery resistance is critical. This presents a challenge if protection devices are used. Some losses through the solid-state switches of protection devices cannot be avoided.

Packs with fewer cells in series generally perform better than those with 12 cells or more. Similar to a chain, the more links that are used, the greater the odds of one breaking. On higher voltage batteries, precise cell matching becomes important, especially if high load currents are drawn or if the pack is operated in cold temperatures.

Parallel connections are used to obtain higher ampere-hour (Ah) ratings. When possible, pack designers prefer using larger cells. This may not always be practical because new battery chemistries come in limited sizes. Often, a parallel connection is the only option to increase the battery rating. Paralleling is also necessary if pack dimensions restrict the use of larger cells. Among the battery chemistries, Li-ion lends itself best to parallel connection.

Protection Circuits

Most battery packs include some type of protection to safeguard battery and equipment, should a malfunction occur. The most basic protection is a fuse that opens if excessively high current is drawn. Some fuses open permanently and render the battery useless once the filament is broken; other fuses are based on a Polyswitch™, which resembles a resettable fuse. On excess current, the Polyswitch™ creates a high resistance, inhibiting the current flow. When the condition normalizes, the resistance of the switch reverts to the low ON position, allowing normal operation to resume. Solid-state switches are also used to disrupt the current. Both solid-state switches and the Polyswitch™ have a residual resistance to the ON position during normal operation, causing a slight increase in internal battery resistance.

A more complex protection circuit is found in intrinsically safe batteries. These batteries are mandated for two-way radios, gas detectors and other electronic instruments that operate in a hazardous area such as oil refineries and grain elevators. Intrinsically safe batteries prevent explosion, should the electronic devices malfunction while operating in areas that contain explosive gases or high dust concentration. The protection circuit prevents excessive current, which could lead to high heat and electric spark.

There are several levels of intrinsic safety, each serving a specific hazard level. The requirement for intrinsic safety varies from country to country. The purchase cost of an intrinsically safe battery is two or three times that of a regular battery.

Commercial Li-ion packs contain one of the most exact protection circuits in the battery industry. These circuits assure safety under all circumstances when in the hands of the public. Typically, a Field Effect Transistor (FET) opens if the charge voltage of any cell reaches 4.30V and a fuse activates if the cell temperature approaches 90°C (194°F). In addition, a disconnect switch in each cell permanently interrupts the charge current if a safe pressure threshold of 1034 kPa (150 psi) is exceeded. To prevent the battery from over-discharging, the control circuit cuts off the current path at low voltage, which is typically 2.50V/cell.

The Li-ion is typically discharged to 3V/cell. The lowest ‘low-voltage’ power cut-off is 2.5V/cell. During prolonged storage, however, a discharge below that cut-off level is possible. Manufacturers recommend a ‘trickle’ charge to raise such a battery gradually back up into the acceptable voltage window.

Not all chargers are designed to apply a charge once a Li-ion battery has dipped below 2.5V/cell. A ‘wake-up’ boost will be needed to first engage the electronic circuit, after which a gentle charge is applied to re-energize the battery. Caution must be applied not to boost lithium-based batteries back to life, which have dwelled at a very low voltage for a prolonged time.

Each parallel string of cells of a Li-ion pack needs independent voltage monitoring. The more cells that are connected in series, the more complex the protection circuit becomes. Four cells in series is the practical limit for commercial applications.

The internal protection circuit of a mobile phone while in the ON position has a resistance of 50 to 100 mW. The circuit normally consists of two switches connected in series. One is responsible for high cut-off, the other for low cut-off. The combined resistance of these two devices virtually doubles the internal resistance of a battery pack, especially if only one cell is used. Battery packs powering mobile phones, for example, must be capable of delivering high current bursts. The internal protection does, in a certain way, interfere with the current delivery.

Some small Li-ion packs with spinel chemistry containing one or two cells may not include an electronic protection circuit. Instead, they use a single component fuse device. These cells are deemed safe because of small size and low capacity. In addition, spinel is more tolerant than other systems if abused. The absence of a protection circuit saves money, but a new problem arises. Here is what can happen:

Mobile phone users have access to chargers that may not be approved by the battery manufacturer. Available at low cost for car and travel, these chargers may rely on the battery’s protection circuit to terminate at full charge. Without the protection circuit, the battery cell voltage rises too high and overcharges the battery. Apparently still safe, irreversible battery damage often occurs. Heat buildup and bulging is common under these circumstances. Such situations must be avoided at all times. The manufacturers are often at a loss when it comes to replacing these batteries under warranty.

Li-ion batteries with cobalt electrodes, for example, require full safety protection. A major concern arises if static electricity or a faulty charger has destroyed the battery’s protection circuit. Such damage often causes the solid-state switches to fuse in a permanent ON position without the user’s knowledge. A battery with a faulty protection circuit may function normally but does not provide the required safety. If charged beyond safe voltage limits with a poorly designed accessory charger, the battery may heat up, then bulge and in some cases vent with flame. Shorting such a battery can also be hazardous.

Manufacturers of Li-ion batteries refrain from mentioning explosion. ‘Venting with flame’ is the accepted terminology. Although slower in reaction than an explosion, venting with flame can be very violent and inflicts injury to those in close proximity. It can also damage the equipment to which the battery is connected.

Most manufacturers do not sell the Li-ion cells by themselves but make them available in a battery pack, complete with protection circuit. This precaution is understandable when considering the danger of explosion and fire if the battery is charged and discharged beyond its safe limits. Most battery assembling houses must certify the pack assembly and protection circuit intended to be used with the manufacturer before these items are approved for sale.

Battery chargers are commonly given low priority.

High temperature during charge and standby kills batteries.

Chapter 4: Proper Charge Methods

To a large extent, the performance and longevity of rechargeable batteries depends on the quality of the chargers. Battery chargers are commonly given low priority, especially on consumer products. Choosing a quality charger makes sense. This is especially true when considering the high cost of battery replacements and the frustration that poorly performing batteries create. In most cases, the extra money invested is returned because the batteries last longer and perform more efficiently.

All About Chargers

There are two distinct varieties of chargers: the personal chargers and the industrial chargers. The personal charger is sold in attractive packaging and is offered with such products as mobile phones, laptops and video cameras. These chargers are economically priced and perform well when used for the application intended. The personal charger offers moderate charge times.

In comparison, the industrial charger is designed for employee use and accommodates fleet batteries. These chargers are built for repetitive use. Available for single or multi-bay configurations, the industrial chargers are offered from the original equipment manufacturer (OEM). In many instances, the chargers can also be obtained from third party manufacturers. While the OEM chargers meet basic requirements, third party manufacturers often include special features, such as negative pulse charging, discharge function for battery conditioning, and state-of-charge (SoC) and state-of-health (SoH) indications. Many third party manufacturers are prepared to build low quantities of custom chargers. Other benefits third party suppliers can offer include creative pricing and superior performance.

Not all third party charger manufacturers meet the quality standards that the industry demands, The buyer should be aware of possible quality and performance compromises when purchasing these chargers at discount prices. Some units may not be rugged enough to withstand repetitive use; others may develop maintenance problems such as burned or broken battery contacts.

Uncontrolled over-charge is another problem of some chargers, especially those used to charge nickel-based batteries. High temperature during charge and standby kills batteries. Over-charging occurs when the charger keeps the battery at a temperature that is warm to touch (body temperature) while in ready condition.

Some temperature rise cannot be avoided when charging nickel-based batteries. A temperature peak is reached when the battery approaches full charge. The temperature must moderate when the ready light appears and the battery has switched to trickle charge. The battery should eventually cool to room temperature.

If the temperature does not drop and remains above room temperature, the charger is performing incorrectly. In such a case, the battery should be removed as soon as possible after the ready light appears. Any prolonged trickle charging will damage the battery. This caution applies especially to the NiMH because it cannot absorb overcharge well. In fact, a NiMH with high trickle charge could be cold to the touch and still be in a damaging overcharge condition. Such a battery would have a short service life.

A lithium-based battery should never get warm in a charger. If this happens, the battery is faulty or the charger is not functioning properly. Discontinue using this battery and/or charger.

It is best to store batteries on a shelf and apply a topping-charge before use rather than leaving the pack in the charger for days. Even at a seemingly correct trickle charge, nickel-based batteries produce a crystalline formation (also referred to as ‘memory’) when left in the charger. Because of relatively high self-discharge, a topping charge is needed before use. Most Li-ion chargers permit a battery to remain engaged without inflicting damage.

There are three types of chargers for nickel-based batteries. They are:

Slow Charger — Also known as ‘overnight charger’ or ‘normal charger’, the slow-charger applies a fixed charge rate of about 0.1C (one tenth of the rated capacity) for as long as the battery is connected. Typical charge time is 14 to 16 hours. In most cases, no full-charge detection occurs to switch the battery to a lower charge rate at the end of the charge cycle. The slow-charger is inexpensive and can be used for NiCd batteries only. With the need to service both NiCd and NiMH, these chargers are being replaced with more advanced units.

If the charge current is set correctly, a battery in a slow-charger remains lukewarm to the touch when fully charged. In this case, the battery does not need to be removed immediately when ready but should not stay in the charger for more than a day. The sooner the battery can be removed after being fully charged, the better it is.

A problem arises if a smaller battery (lower mAh) is charged with a charger designed to service larger packs. Although the charger will perform well in the initial charge phase, the battery starts to heat up past the 70 percent charge level. Because there is no provision to lower the charge current or to terminate the charge, heat-damaging over-charge will occur in the second phase of the charge cycle. If an alternative charger is not available, the user is advised to observe the temperature of the battery being charged and disconnect the battery when it is warm to the touch.

The opposite may also occur when a larger battery is charged on a charger designed for a smaller battery. In such a case, a full charge will never be reached. The battery remains cold during charge and will not perform as expected. A nickel-based battery that is continuously undercharged will eventually loose its ability to accept a full charge due to memory.

Quick Charger — The so-called quick-charger, or rapid charger, is one of the most popular. It is positioned between the slow-charger and the fast-charger, both in terms of charging time and price. Charging takes 3 to 6 hours and the charge rate is around 0.3C. Charge control is required to terminate the charge when the battery is ready. The well designed quick-charger provides better service to nickel-based batteries than the slow-charger. Batteries last longer if charged with higher currents, provided they remain cool and are not overcharged. The quick-chargers are made to accommodate either nickel-based or lithium-based batteries. These two chemistries can normally not be interchanged in the same charger.

Fast Charger — The fast-charger offers several advantages over the other chargers; the obvious one is shorter charge times. Because of the larger power supply and the more expensive control circuits needed, the fast-charger costs more than slower chargers, but the investment is returned in providing good performing batteries that live longer.

The charge time is based on the charge rate, the battery’s SoC, its rating and the chemistry. At a 1C charge rate, an empty NiCd typically charges in a little more than an hour. When a battery is fully charged, some chargers switch to a topping charge mode governed by a timer that completes the charge cycle at a reduced charge current. Once fully charged, the charger switches to trickle charge. This maintenance charge compensates for the self-discharge of the battery.

Modern fast-chargers commonly accommodate both NiCd and NiMH batteries. Because of the fast-charger’s higher charge current and the need to monitor the battery during charge, it is important to charge only batteries specified by the manufacturer. Some battery manufacturers encode the batteries electrically to identify their chemistry and rating. The charger then sets the correct charge current and algorithm for the battery intended. Lead Acid and Li-ion chemistries are charged with different algorithms and are not compatible with the charge methods used for nickel-based batteries.

It is best to fast charge nickel-based batteries. A slow charge is known to build up a crystalline formation on nickel-based batteries, a phenomenon that lowers battery performance and shortens service life. The battery temperature during charge should be moderate and the temperature peak kept as short as possible.

It is not recommended to leave a nickel-based battery in the charger for more than a few days, even with a correctly set trickle charge current. If a battery must remain in a charger for operational readiness, an exercise cycle should be applied once every month.

Simple Guidelines

A charger designed to service NiMH batteries can also accommodate NiCd's, but not the other way around. A charger only made for the NiCd batteries could overcharge the NiMH battery.

While many charge methods exist for nickel-based batteries, chargers for lithium-based batteries are more defined in terms of charge method and charge time. This is, in part, due to the tight charge regime and voltage requirements demanded by these batteries. There is only one way to charge Li-ion/Polymer batteries and the so-called 'miracle chargers', which claim to restore and prolong battery life, do not exist for these chemistries. Neither does a super-fast charging solution apply.

The pulse charge method for Li-ion has no major advantages and the voltage peaks wreak havoc with the voltage limiting circuits. While charge times can be reduced, some manufacturers suggest that pulse charging may shorten the cycle life of Li-ion batteries.

Fast charge methods do not significantly decrease the charge time. A charge rate over 1C should be avoided because such high current can induce lithium plating. With most packs, a charge above 1C is not possible. The protection circuit limits the amount of current the battery can accept. The lithium-based battery has a slow metabolism and must take its time to absorb the energy.

Lead acid chargers serve industrial markets such as hospitals and health care units. Charge times are very long and cannot be shortened. Most lead acid chargers charge the battery in 14 hours. Because of its low energy density, this battery type is not used for small portable devices.

In the following sections various charging needs and charging methods are studied. The charging techniques of different chargers are examined to determine why some perform better than others. Since fast charging rather than slow charging is the norm today, we look at well-designed, closed loop systems, which communicate with the battery and terminate the fast charge when certain responses from the battery are received.

Charging the Nickel Cadmium Battery

Battery manufacturers recommend that new batteries be slow-charged for 24 hours before use. A slow charge helps to bring the cells within a battery pack to an equal charge level because each cell self-discharges to different capacity levels. During long storage, the electrolyte tends to gravitate to the bottom of the cell. The initial trickle charge helps redistribute the electrolyte to remedy dry spots on the separator that may have developed.

> ***Commercial fast-chargers are often not designed in the best interests of the battery.***

Some battery manufacturers do not fully form their batteries before shipment. These batteries reach their full potential only after the customer has primed them through several charge/discharge cycles, either with a battery analyzer or through normal use. In many cases, 50 to 100 discharge/charge cycles are needed to fully form a nickel-based battery. Quality cells, such as those made by Sanyo and Panasonic, are known to perform to full specification after as few as 5 to 7 discharge/charge cycles. Early readings may be inconsistent, but the capacity levels become very steady once fully primed. A slight capacity peak is observed between 100 and 300 cycles.

Most rechargeable cells are equipped with a safety vent to release excess pressure if incorrectly charged. The safety vent on a NiCd cell opens at 1034 to 1379 kPa (150 to 200 psi). In comparison, the pressure of a car tire is typically 240 kPa (35 psi). With a resealable vent, no damage occurs on venting but some electrolyte is lost and the seal may leak afterwards. When this happens, a white powder will accumulate over time at the vent opening.

Commercial fast-chargers are often not designed in the best interests of the battery. This is especially true of NiCd chargers that measure the battery’s charge state solely through temperature sensing. Although simple and inexpensive in design, charge termination by temperature sensing is not accurate. The thermistors used commonly exhibit broad tolerances; their positioning with respect to the cells are not consistent. Ambient temperatures and exposure to the sun while charging also affect the accuracy of full-charge detection. To prevent the risk of premature cut-off and assure full charge under most conditions, charger manufacturers use 50°C (122°F) as the recommended temperature cut-off. Although a prolonged temperature above 45°C (113°F) is harmful to the battery, a brief temperature peak above that level is often unavoidable.

More advanced NiCd chargers sense the rate of temperature increase, defined as dT/dt, or the change in temperature over charge time, rather than responding to an absolute temperature (dT/dt is defined as delta Temperature / delta time). This type of charger is kinder to the batteries than a fixed temperature cut-off, but the cells still need to generate heat to trigger detection. To terminate the charge, a temperature increase of 1°C (1.8°F) per minute with an absolute temperature cut-off of 60°C (140°F) works well. Because of the relatively large mass of a cell and the sluggish propagation of heat, the delta temperature, as this method is called, will also enter a brief overcharge condition before the full-charge is detected. The dT/dt method only works with fast chargers.

Harmful overcharge occurs if a fully charged battery is repeatedly inserted for topping charge. Vehicular or base station chargers that require the removal of two-way radios with each use are especially hard on the batteries because each reconnection initiates a fast-charge cycle. This also applies to laptops that are momentarily disconnected and reconnected to perform a service. Likewise, a technician may briefly plug the laptop into the power source to check a repeater station or service other installations. Problems with laptop batteries have also been reported in car manufacturing plants where the workers move the laptops from car to car, checking their functions, while momentarily plugging into the external power source. Repetitive connection to power affects mostly ‘dumb’ nickel-based batteries. A ‘dumb’ battery contains no electronic circuitry to communicate with the charger. Li-ion chargers detect the SoC by voltage only and multiple reconnections will not confuse the charging regime.

More precise full charge detection of nickel-based batteries can be achieved with the use of a micro controller that monitors the battery voltage and terminates the charge when a certain voltage signature occurs. A drop in voltage signifies that the battery has reached full charge. This is known as Negative Delta V (NDV).

NDV is the recommended full-charge detection method for ‘open-lead’ NiCd chargers because it offers a quick response time. The NDV charge detection also works well with a partially or fully charged battery. If a fully charged battery is inserted, the terminal voltage raises quickly, then drops sharply, triggering the ready state. Such a charge lasts only a few minutes and the cells remain cool. NiCd chargers based on the NDV full charge detection typically respond to a voltage drop of 10 to 30mV per cell. Chargers that respond to a very small voltage decrease are preferred over those that require a larger drop.

To obtain a sufficient voltage drop, the charge rate must be 0.5C and higher. Lower than 0.5C charge rates produce a very shallow voltage decrease that is often difficult to measure, especially if the cells are slightly mismatched. In a battery pack that has mismatched cells, each cell reaches the full charge at a different time and the curve gets distorted. Failing to achieve a sufficient negative slope allows the fast-charge to continue, causing excessive heat buildup due to overcharge. Chargers using the NDV must include other charge-termination methods to provide safe charging under all conditions. Most chargers also observe the battery temperature.

The charge efficiency factor of a standard NiCd is better on fast charge than slow charge. At a 1C charge rate, the typical charge efficiency is 1.1 or 91 percent. On an overnight slow charge (0.1C), the efficiency drops to 1.4 or 71 percent.

At a rate of 1C, the charge time of a NiCd is slightly longer than 60 minutes (66 minutes at an assumed charge efficiency of 1.1). The charge time on a battery that is partially discharged or cannot hold full capacity due to memory or other degradation is shorter accordingly. At a 0.1C charge rate, the charge time of an empty NiCd is about 14 hours, which relates to the charge efficiency of 1.4.

During the first 70 percent of the charge cycle, the charge efficiency of a NiCd battery is close to 100 percent. Almost all of the energy is absorbed and the battery remains cool. Currents of several times the C-rating can be applied to a NiCd battery designed for fast charging without causing heat build-up. Ultra-fast chargers use this unique phenomenon and charge a battery to the 70 percent charge level within a few minutes. The charge continues at a lower rate until the battery is fully charged.

Once the 70 percent charge threshold is passed, the battery gradually loses ability to accept charge. The cells start to generate gases, the pressure rises and the temperature increases. The charge acceptance drops further as the battery reaches 80 and 90 percent SoC. Once full charge is reached, the battery goes into overcharge. In an attempt to gain a few extra capacity points, some chargers allow a measured amount of overcharge. Figure 4-1 illustrates the relationship of cell voltage, pressure and temperature while a NiCd is being charged.

Ultra-high capacity NiCd batteries tend to heat up more than the standard NiCd if charged at 1C and higher. This is partly due to the higher internal resistance of the ultra-high capacity battery. Optimum charge performance can be achieved by applying higher current at the initial charge stage, then tapering it to a lower rate as the charge acceptance decreases. This avoids excess temperature rise and yet assures fully charged batteries.

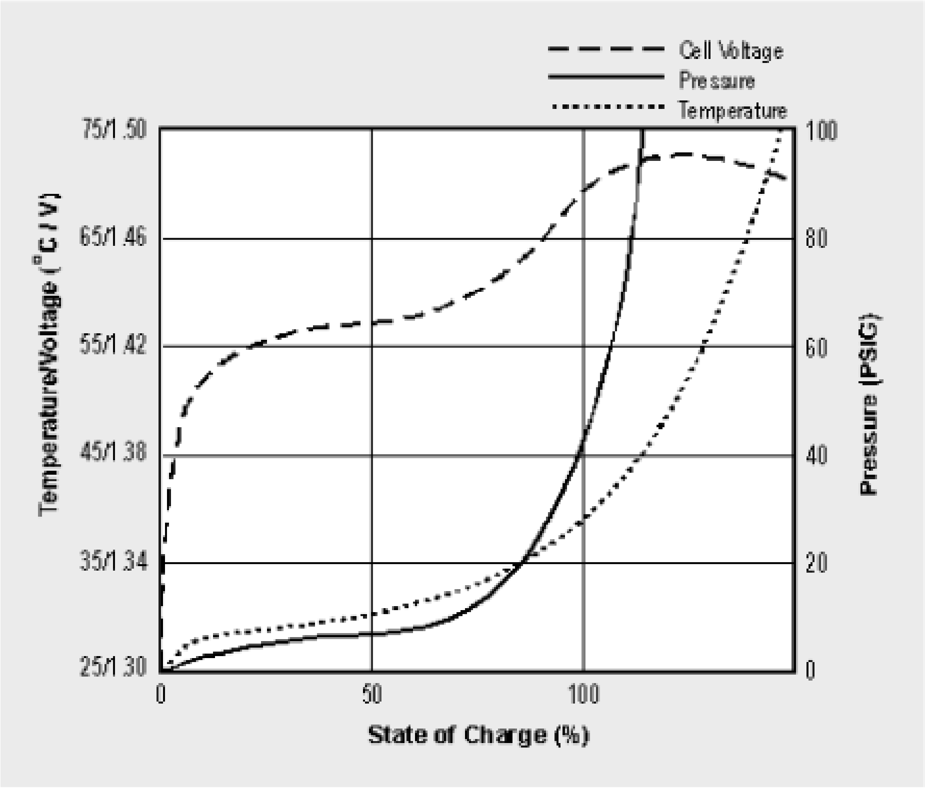


Figure 4-1: Charge characteristics of a NiCd cell.
These cell voltage, pressure and temperature characteristics are similar in a NiMH cell.

Interspersing discharge pulses between charge pulses improves the charge acceptance of nickel-based batteries. Commonly referred to as 'burp' or 'reverse load' charge, this charge method promotes high surface area on the electrodes, resulting in enhanced performance and increased service life. Reverse load also improves fast charging because it helps to recombine the gases generated during charge. The result is a cooler and more effective charge than with conventional DC chargers.

Charging with the reverse load method minimizes crystalline formation. The US Army Electronics Command in Fort Monmouth, NJ, USA, had done extensive research in this field and has published the results. (See Figure 10-1, Crystalline formation on NiCd cell). Research conducted in Germany has shown that the reverse load method adds 15 percent to the life of the NiCd battery.

After full charge, the NiCd battery is maintained with a trickle charge to compensate for the self-discharge. The trickle charge for a NiCd battery ranges between 0.05C and 0.1C. In an effort to reduce the memory phenomenon, there is a trend towards lower trickle charge currents.

Charging the Nickel-Metal Hydride Battery

Chargers for NiMH batteries are very similar to those of the NiCd system but the electronics is generally more complex. To begin with, the NiMH produces a very small voltage drop at full charge. This NDV is almost non-existent at charge rates below 0.5C and elevated temperatures. Aging and cell mismatch works further against the already minute voltage delta. The cell mismatch gets worse with age and increased cycle count, which makes the use of the NDV increasingly more difficult.

The NDV of a NiMH charger must respond to a voltage drop of 16mV or less. Increasing the sensitivity of the charger to respond to the small voltage drop often terminates the fast charge by error halfway through the charge cycle. Voltage fluctuations and noise induced by the battery and charger can fool the NDV detection circuit if set too precisely.

The popularity of the NiMH battery has introduced many innovative charging techniques. Most of today's NiMH fast chargers use a combination of NDV, voltage plateau, rate-of-temperature-increase (dT/dt), temperature threshold and timeout timers. The charger utilizes whatever comes first to terminate the fast-charge.

NiMH batteries which use the NDV method or the thermal cut-off control tend to deliver higher capacities than those charged by less aggressive methods. The gain is approximately 6 percent on a good battery. This capacity increase is due to the brief overcharge to which the battery is exposed. The negative aspect is a shorter cycle life. Rather than expecting 350 to 400 service cycles, this pack may be exhausted with 300 cycles.

Similar to NiCd charge methods, most NiMH fast-chargers work on the rate-of-temperature-increase (dT/dt). A temperature raise of 1°C (1.8°F) per minute is commonly used to terminate the charge. The absolute temperature cut-off is 60°C (140°F). A topping charge of 0.1C is added for about 30 minutes to maximize the charge. The continuous trickle charge that follows keeps the battery in full charge state.

Applying an initial fast charge of 1C works well. Cooling periods of a few minutes are added when certain voltage peaks are reached. The charge then continues at a lower current. When reaching the next charge threshold, the current steps down further. This process is repeated until the battery is fully charged.

Known as 'step-differential charge', this charge method works well with NiMH and NiCd batteries. The charge current adjusts to the SoC, allowing high current at the beginning and more moderate current towards the end of charge. This avoids excessive temperature build-up towards the end of the charge cycle when the battery is less capable of accepting charge.

NiMH batteries should be rapid charged rather than slow charged. The amount of trickle charge applied to maintain full charge is especially critical. Because NiMH does not absorb overcharge well, the trickle charge must be set lower than that of the NiCd. The recommended trickle charge for the NiMH battery is a low 0.05C. This is why the original NiCd charger cannot be used to charge NiMH batteries. The lower trickle charge rate is acceptable for the NiCd.

It is difficult, if not impossible, to slow-charge a NiMH battery. At a C-rate of 0.1C and 0.3C, the voltage and temperature profiles fail to exhibit defined characteristics to measure the full charge state accurately and the charger must depend on a timer. Harmful overcharge can occur if a partially or fully charged battery is charged on a charger with a fixed timer. The same occurs if the battery has lost charge acceptance due to age and can only hold 50 percent of charge. A fixed timer that delivers a 100 percent charge each time without regard to the battery condition would ultimately apply too much charge. Overcharge could occur even though the NiMH battery feels cool to the touch.

Some lower-priced chargers may not apply a fully saturated charge. On these economy chargers, the full-charge detection may occur immediately after a given voltage peak is reached or a temperature threshold is detected. These chargers are commonly promoted on the merit of short charge time and moderate price.

Figure 4-2 summarizes the characteristics of the slow charger, quick charger and fast charger. A higher charge current allows better full-charge detection.

	Charge C-rate	Typical charge time	Maximum permissible charge temperatures	Charge termination method
Slow Charger	0.1C	14h	0°C to 45°C (32°F to 113°F)	Fixed timer. Subject to overcharge. Remove battery when charged.
Quick Charger	0.3-0.5C	4h	10°C to 45°C (50°F to 113°F)	NDV set to 10mV/cell, uses voltage plateau, absolute temperature and time-out-timer. (At 0.3C, dT/dt fails to raise the temperature sufficiently to terminate the charge.)
Fast Charger	1C	1h+	10°C to 45°C (50°F to 113°F)	NDV responds to higher settings; uses dT/dt, voltage plateau absolute temperature and time-out-timer

Figure 4-2: Characteristics of various charger types.
These values also apply to NiMH and NiCd cells.

Charging the Lead Acid Battery

The charge algorithm for lead acid batteries differs from nickel-based chemistry in that voltage limiting rather than current limiting is used. Charge time of a sealed lead acid (SLA) is 12 to 16 hours. With higher charge currents and multi-stage charge methods, charge time can be reduced to 10 hours or less. SLAs cannot be fully charged as quickly as nickel-based systems.

A multi-stage charger applies constant-current charge, topping charge and float charge (see Figure 4-3). During the constant current charge, the battery charges to 70 percent in about five hours; the remaining 30 percent is completed by the slow topping charge. The topping charge lasts another five hours and is essential for the well-being of the battery. This can be compared to a little rest after a good meal before resuming work. If the battery is not completely saturated, the SLA will eventually lose its ability to accept a full charge and the performance of the battery is reduced. The third stage is the float charge, which compensates for the self-discharge after the battery has been fully charged.

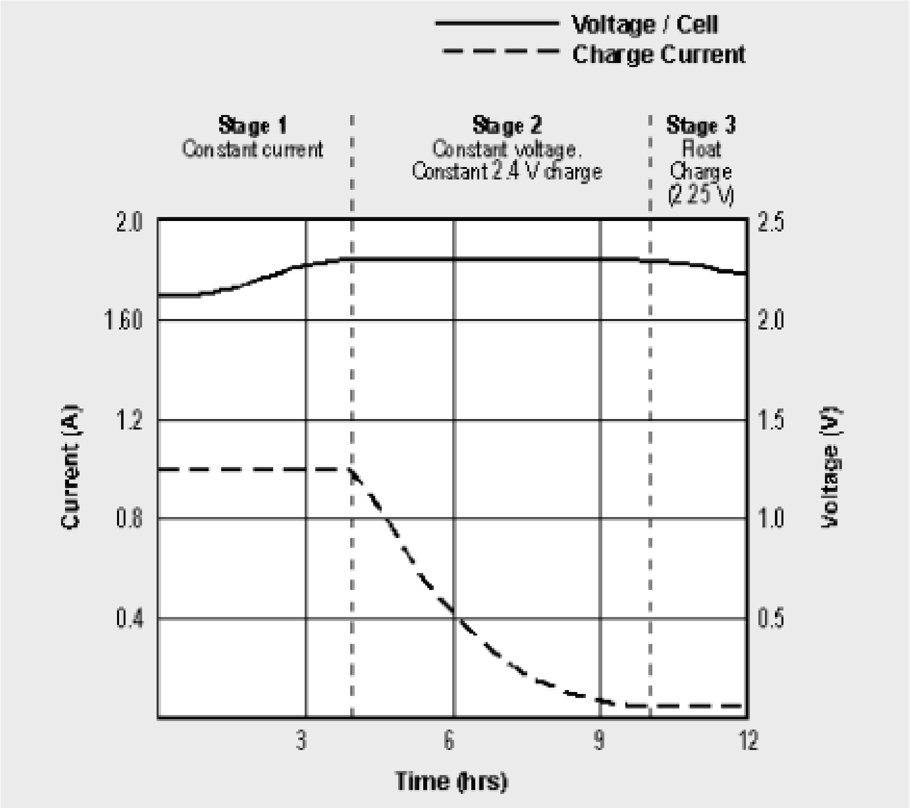


Figure 4-3: Charge stages of a lead acid battery.
A multi-stage charger applies constant-current charge, topping charge and float charge.

Correctly setting the cell-voltage limit is critical. A typical voltage limit is from 2.30V to 2.45V. If a slow charge is acceptable, or the room temperature may exceed 30°C (86°F), the recommended voltage limit is 2.35V/cell. If a faster charge is required, and the room temperature will remain below 30°C, 2.40 to 2.45V/cell may be used. Figure 4-4 compares the advantages and disadvantages of the different voltage settings.

	2.30V to 2.35V/cell	**2.40V to 2.45V/cell**
Advantage	Maximum service life; battery remains cool during charge; ambient charge temperature may exceed 30°C (86°F).	Faster charge times; higher and more consistent capacity readings; less subject to damage due to under-charge condition.
Disadvantage	Slow charge time; capacity readings may be low and inconsistent. If no periodic topping charge is applied, under-charge conditions (sulfation) may occur, which can lead to unrecoverable capacity loss.	Battery life may be reduced due to elevated battery temperature while charging. A hot battery may fail to reach the cell voltage limit, causing harmful over charge.

Figure 4-4: Effects of charge voltage on a plastic SLA battery.
Large VRLA and the cylindrical Hawker cell may have different requirements.

The charge voltage limit indicated in Figure 4-4 is a momentary voltage peak and the battery cannot dwell on that level. This voltage crest is only used when applying a full charge cycle to a battery that has been discharged. Once fully charged and at operational readiness, a float charge is applied, which is held constant at a lower voltage level. The recommended float charge voltage of most low-pressure lead acid batteries is between 2.25 to 2.30V/cell. A good compromise is 2.27V.

The optimal float charge voltage shifts with temperature. A higher temperature demands slightly lower voltages and a lower temperature demands higher voltages. Chargers that are exposed to large temperature fluctuations are equipped with temperature sensors to optimize the float voltage.

Regardless of how well the float voltage may be compensated, there is always a compromise. The author of a paper in a battery seminar explained that charging a sealed lead acid battery using the traditional float charge techniques is like 'dancing on the head of a pin'. The battery wants to be fully charged to avoid sulfation on the negative plate, but does not want to be over-saturated which causes grid corrosion on the positive plate. In addition to grid corrosion, too high a float charge contributes to loss of electrolyte.

Differences in the aging of the cells create another challenge in finding the optimum float charge voltage. With the development of air pockets within the cells over time, some batteries exhibit hydrogen evolution from overcharging. Others undergo oxygen recombination in an almost starved state. Since the cells are connected in series, controlling the individual cell voltages during charge is virtually impossible. If the applied cell voltage is too high or too low for a given cell, the weaker cell deteriorates further and its condition becomes more pronounced with time. Companies have developed cell-balancing devices that correct some of these problems but these devices can only be applied if access to individual cells is possible.

A ripple voltage imposed on the charge voltage also causes problems for lead acid batteries, especially the larger VRLA. The peak of the ripple voltage constitutes an overcharge, causing hydrogen evolution; the valleys induce a brief discharge causing a starved state. Electrolyte depletion may be the result.

Much has been said about pulse charging lead acid batteries. Although there are obvious benefits of reduced cell corrosion, manufacturers and service technicians are not in agreement regarding the benefit of such a charge method. Some advantages are apparent if pulse charging is applied correctly, but the results are non-conclusive.

Whereas the voltage settings in Figure 4-4 apply to low-pressure lead acid batteries with a pressure relief valve setting of about 34 kPa (5 psi), the cylindrical SLA by Hawker requires higher voltage settings. These voltage limits should be set according to the manufacturer’s specifications. Failing to apply the recommended voltage threshold for these batteries causes a gradual decrease in capacity due to sulfation. Typically, the Hawker cell has a pressure relief setting of 345 kPa (50 psi). This allows some recombination of the gases during charge.

An SLA must be stored in a charged state. A topping charge should be applied every six months to avoid the voltage from dropping below 2.10V/cell. The topping charge requirements may differ with cell manufacturers. Always follow the time intervals recommended by the manufacturer.

By measuring the open cell voltage while in storage, an approximate charge-level indication can be obtained. A voltage of 2.11V, if measured at room temperature, reveals that the cell has a charge of 50 percent and higher. If the voltage is at or above this threshold, the battery is in good condition and only needs a full charge cycle prior to use. If the voltage drops below 2.10V, several discharge/charge cycles may be required to bring the battery to full performance. When measuring the terminal voltage of any cell, the storage temperature should be observed. A cool battery raises the voltage slightly and a warm one lowers it.

Plastic SLA batteries arriving from vendors with less than 2.10V per cell are rejected by some buyers who inspect the battery during quality control. Low voltage suggests that the battery may have a soft short, a defect that cannot be corrected with cycling. Although cycling may increase the capacity of these batteries, the extra cycles compromise the service life of the battery. Furthermore, the time and equipment required to make the battery fully functional adds to operational costs.

The Hawker cell can be stored at voltages as low as 1.81V. However, when reactivating the cells, a higher than normal charge voltage may be required to convert the large sulfite crystals back to good active material.

Caution: When charging a lead acid battery with over-voltage, current limiting must be applied once the battery starts to draw full current. Always set the current limit to the lowest practical setting and observe the battery voltage and temperature during the procedure. If the battery does not accept a normal charge after 24 hours under elevated voltage, a return to normal condition is unlikely.

The price of the Hawker cell is slightly higher than that of the plastic equivalent, but lower than the NiCd. Also known as the ‘Cyclone’, this cell is wound similar to a cylindrical NiCd. This construction improves the cell’s stability and provides higher discharge currents when compared to the flat plate SLA. Because of its relatively low self-discharge, Hawker cells are well suited for defibrillators that are used on standby mode.

Lead acid batteries are preferred for UPS systems. During prolonged float charge, a periodic topping charge, also known as an ‘equalizing charge’, is recommended to fully charge the plates and prevent sulfation. An equalizing charge raises the battery voltage for several hours to a voltage level above that specified by the manufacturer. Loss of electrolyte through elevated temperature may occur if the equalizing charge is not administered correctly. Because no liquid can be added to the SLA and VRLA systems, a reduction of the electrolyte will cause irreversible damage. Manufacturers and service personnel are often divided on the benefit of the equalizing charge.

Some exercise, or brief periodic discharge, is believed to prolong battery life of lead acid systems. If applied once a month as part of an exercising program, the depth of discharge should only be about 10 percent of its total capacity. A full discharge as part of regular maintenance is not recommended because each deep discharge cycle robs service life from the battery.

More experiments are needed to verify the benefit of exercising lead acid batteries. Again, manufacturers and service technicians express different views on how preventive maintenance should be carried out. Some experts prefer a topping charge while others recommend scheduled discharges. No scientific data is available on the benefit of frequent shallow discharges as opposed to fewer deep discharges or discharge pulses.

Disconnecting the float charge while the VRLA is on standby is another method of prolonging battery life. From time-to-time, a topping charge is applied to replenish the energy lost through self-discharge. This is said to lower cell corrosion and prolong battery life. In essence, the battery is kept as if it was in storage. This only works for applications that do not draw a load current during standby. In many applications, the battery acts as an energy buffer and needs to be under continuous charge.

Important: In case of rupture, leaking electrolyte or any other cause of exposure to the electrolyte, flush with water immediately. If eye exposure occurs, flush with water for 15 minutes and consult a physician immediately.

Charging the Lithium Ion Battery

The Li-ion charger is a voltage-limiting device similar to the lead acid battery charger. The difference lies in a higher voltage per cell, tighter voltage tolerance and the absence of trickle or float charge when full charge is reached.

While the lead acid battery offers some flexibility in terms of voltage cut-off, manufacturers of Li-ion cells are very strict on setting the correct voltage. When the Li- ion was first introduced, the graphite system demanded a charge voltage limit of 4.10V/cell. Although higher voltages deliver increased energy densities, cell oxidation severely limited the service life in the early graphite cells that were charged above the 4.10V/cell threshold. This effect has been solved with chemical additives. Most commercial Li-ion cells can now be charged to 4.20V. The tolerance on all Li-ion batteries is a tight +/-0.05V/cell.

Industrial and military Li-ion batteries designed for maximum cycle life use an end-of-charge voltage threshold of about 3.90V/cell. These batteries are rated lower on the watt-hour-per-kilogram scale, but longevity takes precedence over high energy density and small size.

The charge time of all Li-ion batteries, when charged at a 1C initial current, is about 3 hours. The battery remains cool during charge. Full charge is attained after the voltage has reached the upper voltage threshold and the current has dropped and leveled off at about 3 percent of the nominal charge current.

Increasing the charge current on a Li-ion charger does not shorten the charge time by much. Although the voltage peak is reached quicker with higher current, the topping charge will take longer. Figure 4-5 shows the voltage and current signature of a charger as the Li-ion cell passes through stage one and two.

Some chargers claim to fast-charge a Li-ion battery in one hour or less. Such a charger eliminates stage 2 and goes directly to ‘ready’ once the voltage threshold is reached at the end of stage 1. The charge level at this point is about 70 percent. The topping charge typically takes twice as long as the initial charge.

No trickle charge is applied because the Li-ion is unable to absorb overcharge. Trickle charge could cause plating of metallic lithium, a condition that renders the cell unstable. Instead, a brief topping charge is applied to compensate for the small amount of self-discharge the battery and its protective circuit consume.

Depending on the charger and the self-discharge of the battery, a topping charge may be implemented once every 500 hours or 20 days. Typically, the charge kicks in when the open terminal voltage drops to 4.05V/cell and turns off when it reaches 4.20V/cell again.

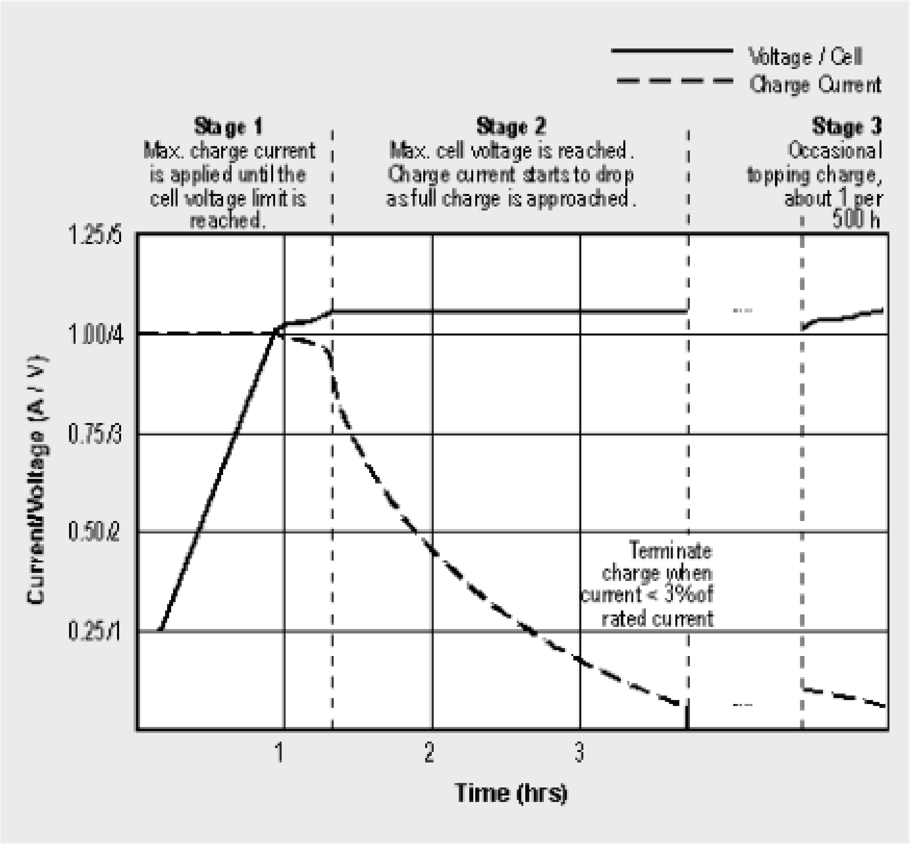


Figure 4-5: Charge stages of a Li-ion battery.
Increasing the charge current on a Li-ion charger does not shorten the charge time by much. Although the voltage peak is reached quicker with higher current, the topping charge will take longer.

What if a battery is inadvertently overcharged? Li-ion batteries are designed to operate safely within their normal operating voltage but become increasingly unstable if charged to higher voltages. On a charge voltage above 4.30V, the cell causes lithium metal plating on the anode. In addition, the cathode material becomes an oxidizing agent, loses stability and releases oxygen. Overcharging causes the cell to heat up.

Much attention has been placed on the safety of the Li-ion battery. Commercial Li-ion battery packs contain a protection circuit that prevents the cell voltage from going too high while charging. The typical safety threshold is set to 4.30V/cell. In addition, temperature sensing disconnects the charge if the internal temperature approaches 90°C (194°F). Most cells feature a mechanical pressure switch that permanently interrupts the current path if a safe pressure threshold is exceeded. Internal voltage control circuits cut off the battery at low and high voltage points.

Exceptions are made on some spinel (manganese) packs containing one or two small cells. On overcharge, this chemistry produces minimal lithium plating on the anode because most metallic lithium has been removed from the cathode during normal charging. The cathode material remains stable and does not generate oxygen unless the cell gets extremely hot.

Important: In case of rupture, leaking electrolyte or any other cause of exposure to the electrolyte, flush with water immediately. If eye exposure occurs, flush with water for 15 minutes and consult a physician immediately.

Charging the Lithium Polymer Battery

The charge process of a Li-Polymer is similar to that of the Li-ion. Li-Polymer uses dry electrolyte and takes 3 to 5 hours to charge. Li-ion polymer with gelled electrolyte, on the other hand, is almost identical to that of Li-ion. In fact, the same charge algorithm can be applied. With most chargers, the user does not need to know whether the battery being charged is Li-ion or Li-ion polymer.

Almost all commercial batteries sold under the so-called 'Polymer' category are a variety of the Li-ion polymer using some sort of gelled electrolyte. A low-cost dry polymer battery operating at ambient temperatures is still some years away.

Charging at High and Low Temperatures

Rechargeable batteries can be used under a reasonably wide temperature range. This, however, does not automatically mean that the batteries can also be charged at these temperature conditions. While the use of batteries under hot or cold conditions cannot always be avoided, recharging time is controlled by the user. Efforts should be made to charge the batteries only at room temperatures.

In general, older battery technologies such as the NiCd are more tolerant to charging at low and high temperatures than the more advanced systems. *Figure 4-6* indicates the permissible slow and fast charge temperatures of the NiCd, NiMH, SLA and Li-ion.

	Slow Charge (0.1)	**Fast Charge (0.5-1C)**
Nickel Cadmium	0°C to 45°C (32°F to 113°F)	5°C to 45°C (41°F to 113°F)
Nickel-Metal Hydride	0°C to 45°C (32°F to 113°F)	10C° to 45°C (50°F to 113°F)
Lead Acid	0°C to 45°C (32°F to 113°F)	5C° to 45°C (41°F to 113°F)
Lithium Ion	0°C to 45°C (32°F to 113°F)	5C° to 45°C (41°F to 113°F)

Figure 4-6: Permissible temperature limits for various batteries.
Older battery technologies are more tolerant to charging at extreme temperatures than newer, more advanced systems.

NiCd batteries can be fast-charged in an hour or so, however, such a fast charge can only be applied within temperatures of 5°C and 45°C (41°F and 113°F). More moderate temperatures of 10°C to 30°C (50°F to 86°F) produce better results. When charging a NiCd below 5°C (41°F), the ability to recombine oxygen and hydrogen is greatly reduced and pressure build up occurs as a result. In some cases, the cells vent, releasing oxygen and hydrogen. Not only do the escaping gases deplete the electrolyte, hydrogen is highly flammable!

Chargers featuring NDV to terminate full-charge provide some level of protection when fast-charging at low temperatures. Because of the battery's poor charge acceptance at low temperatures, the charge energy is turned into oxygen and to a lesser amount hydrogen. This reaction causes cell voltage drop, terminating the charge through NDV detection. When this occurs, the battery may not be fully charged, but venting is avoided or minimized.

To compensate for the slower reaction at temperatures below 5°C, a low charge rate of 0.1C must be applied. Special charge methods are available for charging at cold temperatures. Industrial batteries that need to be fast-charged at low temperatures include a thermal blanket that heats the battery to an acceptable temperature. Among commercial batteries, the NiCd is the only battery that can accept charge at extremely low temperatures.

Charging at high temperatures reduces the oxygen generation. This reduces the NDV effect and accurate full-charge detection using this method becomes difficult. To avoid overcharge, charge termination by temperature measurement becomes more practical.

The charge acceptance of a NiCd at higher temperatures is drastically reduced. A battery that provides a capacity of 100 percent if charged at moderate room temperature can only accept 70 percent if charged at 45°C (113°F), and 45 percent if charged at 60°C (140°F) (see Figure 4-7). Similar conditions apply to the NiMH battery. This demonstrates the typically poor summer performance of vehicular mounted chargers using nickel-based batteries.

Another reason for poor battery performance, especially if charged at high ambient temperatures, is premature charge cutoff. This is common with chargers that use absolute temperature to terminate the fast charge. These chargers read the SoC on battery temperature alone and are fooled when the room temperature is high. The battery may not be fully charged, but a timely charge cut-off protects the battery from damage due to excess heat.

The NiMH is less forgiving than the NiCd if charged under high and low temperatures. The NiMH cannot be fast charged below 10°C (45°F), neither can it be slow charged below 0°C (32°F). Some industrial chargers adjust the charge rate to prevailing temperatures. Price sensitivity on consumer chargers does not permit elaborate temperature control features.

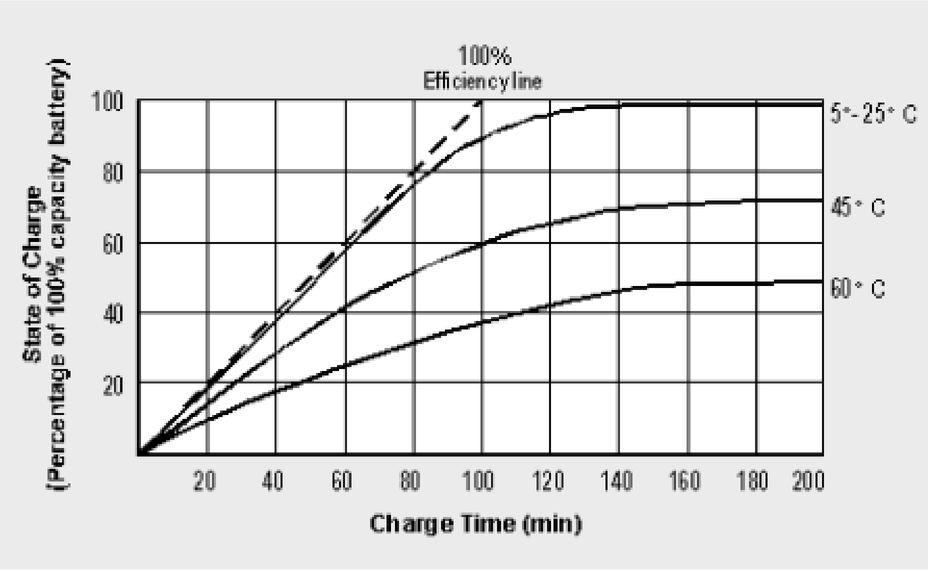


Figure 4-7: Effects of temperature on NiCd charge acceptance.
Charge acceptance is much reduced at higher temperatures. NiMH cells follow a similar pattern.

The lead acid battery is reasonably forgiving when it comes to temperature extremes, as in the case of car batteries. Part of this tolerance is credited to the sluggishness of the lead acid battery. A full charge under ten hours is difficult, if not impossible. The recommended charge rate at low temperature is 0.3C.

Figure 4-8 indicates the optimal peak voltage at various temperatures when recharging and float charging an SLA battery. Implementing temperature compensation on the charger to adjust to temperature extremes prolongs the battery life by up to 15 percent. This is especially true when operating at higher temperatures.

An SLA battery should never be allowed to freeze. If this were to occur, the battery would be permanently damaged and would only provide a few cycles when it returned to normal temperature.

	0°C (32°F)	25°C (77°F)	40°C (104°F)
Voltage limit on recharge	2.55V/cell	2.45V/cell	2.35V/cell
Continuous float voltage	2.35V/cell or lower	2.30V/cell or lower	2.25V/cell or lower

Figure 4-8: Recommended voltage limits on recharge and float charge of SLAs.
These voltage limits should be applied when operating at temperature extremes.

To improve charge acceptance of SLA batteries in colder temperatures, and avoid thermal runaway in warmer temperatures, the voltage limit of a charger should be compensated by approximately 3mV per cell per degree Celsius. The voltage adjustment has a negative coefficient, meaning that the voltage threshold drops as the temperature increases. For example, if the voltage limit is set to 2.40V/cell at 20°C, the setting should be lowered to 2.37V/cell at 30°C and raised to 2.43V/cell at 10°C. This represents a 30mV correction per cell per 10 degrees Celsius.

The Li-ion batteries offer good cold and hot temperature charging performance. Some cells allow charging at 1C from 0°C to 45°C (32°F to 113°F). Most Li-ion cells prefer a lower charge current when the temperature gets down to 5°C (41°F) or colder. Charging below freezing must be avoided because plating of lithium metal could occur.

Ultra-fast Chargers

Some charger manufacturers claim amazingly short charge times of 30 minutes or less. With well-balanced cells and operating at moderate room temperatures, NiCd batteries designed for fast charging can indeed be charged in a very short time. This is done by simply dumping in a high charge current during the first 70 percent of the charge cycle. Some NiCd batteries can take as much a 10C, or ten times the rated current. Precise SoC detection and temperature monitoring are essential.

The high charge current must be reduced to lower levels in the second phase of the charge cycle because the efficiency to absorb charge is progressively reduced as the battery moves to a higher SoC. If the charge current remains too high in the later part of the charge cycle, the excess energy turns into heat and pressure. Eventually venting occurs, releasing hydrogen gas. Not only do the escaping gases deplete the electrolyte, they are also highly flammable!

Several manufacturers offer chargers that claim to fully charge NiCd batteries in half the time of conventional chargers. Based on pulse charge technology, these chargers intersperse one or several brief discharge pulses between each charge pulse. This promotes the recombination of oxygen and hydrogen gases, resulting in reduced pressure buildup and a lower cell temperature. Ultra-fast-chargers based on this principle can charge a nickel-based battery in a shorter time than regular chargers, but only to about a 90 percent SoC. A trickle charge is needed to top the charge to 100 percent.

Pulse chargers are known to reduce the crystalline formation (memory) of nickel-based batteries. By using these chargers, some improvement in battery performance can be realized, especially if the battery is affected by memory. The pulse charge method does not replace a periodic full discharge. For more severe crystalline formation on nickel-based batteries, a full discharge or recondition cycle is recommended to restore the battery.

Ultra-fast charging can only be applied to healthy batteries and those designed for fast charging. Some cells are simply not built to carry high current and the conductive path heats up. The battery contacts also take a beating if the current handling of the spring-loaded plunger contacts is underrated. Pressing against a flat metal surface, these contacts may work well at first, and then wear out prematurely. Often, a fine and almost invisible crater appears on the tip of the contact, which causes a high resistive path or forms an isolator. The heat generated by a bad contact can melt the plastic.

Another problem with ultra-fast charging is servicing aged batteries that commonly have high internal resistance. Poor conductivity turns into heat, which further deteriorates the cells. Battery packs with mismatched cells pose another challenge. The weak cells holding less capacity are charged before those with higher capacity and start to heat up. This process makes them vulnerable to further damage.

Many of today’s fast chargers are designed for the ideal battery. Charging less than perfect specimens can create such a heat buildup that the plastic housing starts to distort. Provisions must be made to accept special needs batteries, albeit at lower charging speeds. Temperature sensing is a prerequisite.

The ideal ultra-fast charger first checks the battery type, measures its SoH and then applies a tolerable charge current. Ultra-high capacity batteries and those that have aged are identified, and the charge time is prolonged because of higher internal resistance. Such a charger would provide due respect to those batteries that still perform satisfactorily but are no longer ‘spring chickens’.

The charger must prevent excessive temperature build-up. Sluggish heat detection, especially when charging takes place at a very rapid pace, makes it easy to overcharge a battery before the charge is terminated. This is especially true for chargers that control fast charge using temperature sensing alone. If the temperature rise is measured right on the skin of the cell, reasonably accurate SoC detection is possible. If done on the outside surface of the battery pack, further delays occur. Any prolonged exposure to a temperature of 45°C (113°F) harms the battery.

New charger concepts are being studied which regulate the charge current according to the battery's charge acceptance. On the initial charge of an empty battery when the charge acceptance is high and little gas is generated, a very high charge current can be applied. Towards the end of a charge, the current is tapered down.

Charge IC Chips

Newer battery systems demand more complex chargers than batteries with older chemistries. With today’s charge IC chips, designing a charger has been simplified. These chips apply proven charge algorithms and are capable of servicing all major battery chemistries. As the price of these chips decreases, design engineers make more use of this product. With the charge IC chip, an engineer can focus entirely on the portable equipment rather than devoting time to developing a charging circuit.

The charge IC chips have some limitations, however. The charge algorithm is fixed and does not allow fine-tuning. If a trickle charge is needed to raise a Li-ion that has dropped below 2.5V/cell to its normal operating voltage, the charge IC may not be able to perform this function. Similarly, if an ultra-fast charge is needed for nickel-based batteries, the charge IC applies a fixed charge current and does not take into account the SoH of the battery. Furthermore, a temperature compensated charge would be difficult to administer if the IC chips do not provide this feature.

Using a small micro controller is an alternative to selecting an off-the-shelf charge IC. The hardware cost is about the same. When opting for the micro controller, custom firmware will be needed. Some extra features can be added with little extra cost. They are fast charging based on the SoH of the battery. Ambient temperatures can also be taken into account.

Whether an IC chip or micro controller is used, peripheral components are required consisting of solid-state switches and a power supply.

Chapter 5: Discharge Methods

The purpose of a battery is to store energy and release it at the appropriate time in a controlled manner. Being capable of storing a large amount of energy is one thing; the ability to satisfy the load demands is another. The third criterion is being able to deliver all available energy without leaving precious energy behind when the equipment cuts off.

In this chapter, we examine how different discharge methods can affect the deliverance of power. Further, we look at the load requirements of various portable devices and evaluate the performance of each battery chemistry in terms of discharge.

C-rate

The charge and discharge current of a battery is measured in C-rate. Most portable batteries, with the exception of the lead acid, are rated at 1C. A discharge of 1C draws a current equal to the rated capacity. For example, a battery rated at 1000mAh provides 1000mA for one hour if discharged at 1C rate. The same battery discharged at 0.5C provides 500mA for two hours. At 2C, the same battery delivers 2000mA for 30 minutes. 1C is often referred to as a one-hour discharge; a 0.5C would be a two-hour, and a 0.1C a 10 hour discharge.

The capacity of a battery is commonly measured with a battery analyzer. If the analyzer's capacity readout is displayed in percentage of the nominal rating, 100 percent is shown if 1000mA can be drawn for one hour from a battery that is rated at 1000mAh. If the battery only lasts for 30 minutes before cut-off, 50 percent is indicated. A new battery sometimes provides more than 100 percent capacity. In such a case, the battery is conservatively rated and can endure a longer discharge time than specified by the manufacturer.

When discharging a battery with a battery analyzer that allows setting different discharge C-rates, a higher capacity reading is observed if the battery is discharged at a lower C-rate and vice versa. By discharging the 1000mAh battery at 2C, or 2000mA, the analyzer is scaled to derive the full capacity in 30 minutes. Theoretically, the capacity reading should be the same as a slower discharge, since the identical amount of energy is dispensed, only over a shorter time. Due to energy loss that occurs inside the battery and a drop in voltage that causes the battery to reach the low-end voltage cut-off sooner, the capacity reading is lower and may be 97 percent. Discharging the same battery at 0.5C, or 500mA over two hours would increase the capacity reading to about 103 percent.

The discrepancy in capacity readings with different C-rates largely depends on the internal resistance of the battery. On a new battery with a good load current characteristic or low internal resistance, the difference in the readings is only a few percentage points. On a battery exhibiting high internal resistance, the difference in capacity readings could swing plus/minus 10 percent or more.

One battery that does not perform well at a 1C discharge rate is the SLA. To obtain a practical capacity reading, manufacturers commonly rate these batteries at 0.05C or 20 hour discharge. Even at this slow discharge rate, it is often difficult to attain 100 percent capacity. By discharging the SLA at a more practical 5h discharge (0.2C), the capacity readings are correspondingly lower. To compensate for the different readings at various discharge currents, manufacturers offer a capacity offset.

Applying the capacity offset does not improve battery performance; it merely adjusts the capacity calculation if discharged at a higher or lower C-rate than specified. The battery manufacturer determines the amount of capacity offset recommended for a given battery type.

Li-ion/polymer batteries are electronically protected against high discharge currents. Depending on battery type, the discharge current is limited somewhere between 1C and 2C.

This protection makes the Li-ion unsuitable for biomedical equipment, power tools and high-wattage transceivers. These applications are commonly reserved for the NiCd battery.

Depth of Discharge

The typical end-of-discharge voltage for nickel-based batteries is 1V/cell. At that voltage level, about 99 percent of the energy is spent and the voltage starts to drop rapidly if the discharge continues. Discharging beyond the cut-off voltage must be avoided, especially under heavy load.

Since the cells in a battery pack cannot be perfectly matched, a negative voltage potential (cell reversal) across a weaker cell occurs if the discharge is allowed to continue beyond the cut-off point. The larger the number of cells connected in series, the greater the likelihood of this occurring.

A NiCd battery can tolerate a limited amount of cell reversal, which is typically about 0.2V. During that time, the polarity of the positive electrode is reversed. Such a condition can only be sustained for a brief moment because hydrogen evolution occurs on the positive electrode. This leads to pressure build-up and cell venting.

If the cell is pushed further into voltage reversal, the polarity of both electrodes is being reversed, resulting in an electrical short. Such a fault cannot be corrected and the pack will need to be replaced.

On battery analyzers that apply a secondary discharge (recondition), the current is controlled to assure that the maximum allowable current, while in sub-discharge range, does not exceed a safe limit. Should a cell reversal develop, the current would be low enough as not to cause damage. A cell breakdown through recondition is possible on a weak or aged pack.

If the battery is discharged at a rate higher than 1C, the more common end-of-discharge point of a nickel-based battery is 0.9V/cell. This is done to compensate for the voltage drop induced by the internal resistance of the cell, the wiring, protection devices and contacts of the pack. A lower cut-off point also delivers better battery performance at cold temperatures.

The recommended end-of-discharge voltage for the SLA is 1.75V/cell. Unlike the preferred flat discharge curve of the NiCd, the SLA has a gradual voltage drop with a rapid drop towards the end of discharge (see Figure 5-1). Although this steady decrease in voltage is a disadvantage, it has a benefit because the voltage level can be utilized to display the state-of-charge (SoC) of a battery. However, the voltage readings fluctuate with load and the SoC readings are inaccurate.

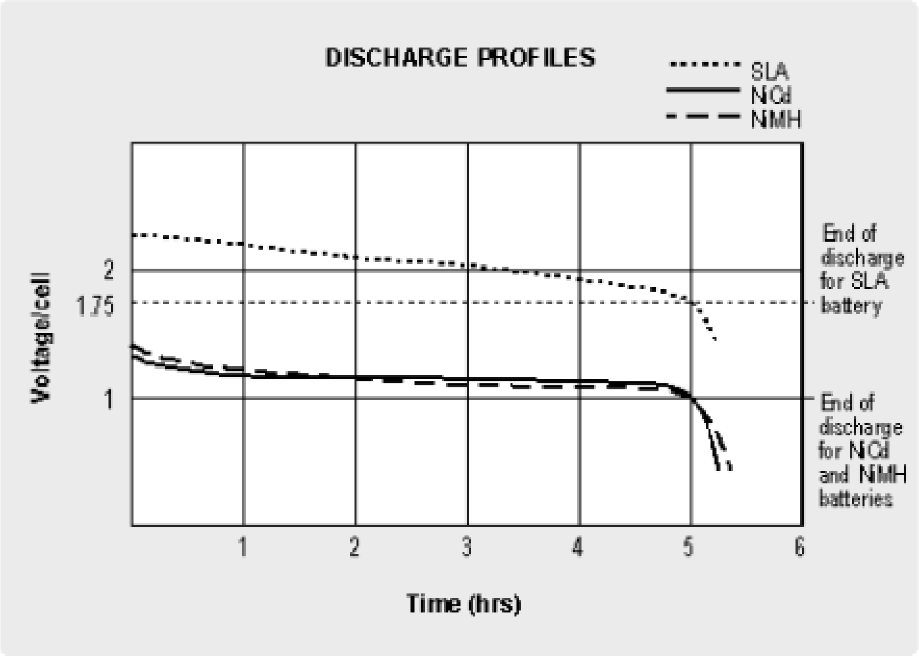


Figure 5-1: Discharge characteristics of NiCd, NiMH and SLA batteries.
While voltage readings to measure the SoC are not practical on nickel-based batteries, the SLA enables some level of indication as to the SoC.

°C (77°F) with respect to the depth of discharge is:

- 150 – 200 cycles with 100 percent depth of discharge (full discharge)
- 400 – 500 cycles with 50 percent depth of discharge (partial discharge)
- 1000 and more cycles with 30 percent depth of discharge (shallow discharge)

The SLA should not be discharged beyond 1.75V per cell, nor can it be stored in a discharged state. The cells of a discharged SLA sulfate, a condition that renders the battery useless if left in that state for a few days.

The Li-ion typically discharges to 3.0V/cell. The spinel and coke versions can be discharged to 2.5V/cell. The lower end-of-discharge voltage gains a few extra percentage points. Since the equipment manufacturers cannot specify which battery type may be used, most equipment is designed for a three-volt cut-off.

Caution should be exercised not to discharge a lithium-based battery too low. Discharging a lithium-based battery below 2.5V may cut off the battery's protection circuit. Not all chargers accommodate a recharge on batteries that have gone to sleep because of low voltage.

Some Li-ion batteries feature an ultra-low voltage cut-off that permanently disconnects the pack if a cell dips below 1.5V. This precaution prohibits recharge if a battery has dwelled in an illegal voltage state. A very deep discharge may cause the formation of copper shunt, which can lead to a partial or total electrical short. The same occurs if the cell is driven into negative polarity and is kept in that state for a while. A fully discharged battery should be charged at 0.1C. Charging a battery with a copper shunt at the 1C rate would cause excessive heat. Such a battery should be removed from service.

Discharging a battery too deeply is one problem; equipment that cuts off before the energy is consumed is another. Some portable devices are not properly tuned to harvest the optimal energy stored in a battery. Valuable energy may be left behind if the voltage cut-off-point is set too high.

Digital devices are especially demanding on a battery. Momentary pulsed loads cause a brief voltage drop, which may push the voltage into the cut-off region. Batteries with high internal resistance are particularly vulnerable to premature cut-off. If such a battery is removed from the equipment and discharged to the appropriate cut-off point with a battery analyzer on DC load, a high level of residual capacity can still be obtained.

Most rechargeable batteries prefer a partial rather than a full discharge. Repeated full discharge robs the battery of its capacity. The battery chemistry which is most affected by repeat deep discharge is lead acid. Additives to the deep-cycle version of the lead acid battery compensate for some of the cycling strain.

Similar to the lead acid battery, the Li-ion battery prefers shallow over repetitive deep discharge cycles. Up to 1000 cycles can be achieved if the battery is only partially discharged. Besides cycling, the performance of the Li-ion is also affected by aging. Capacity loss through aging is independent of use. However, in daily use, there is a combination of both.

The NiCd battery is least affected by repeated full discharge cycles. Several thousand charge/discharge cycles can be obtained with this battery system. This is the reason why the NiCd performs well on power tools and two-way radios that are in constant use. The NiMH is more delicate with respect to repeated deep cycling.

Pulse Discharge

Battery chemistries react differently to specific loading requirements. Discharge loads range from a low and steady current used in a flashlight, to intermittent high current bursts in a power tool, to sharp current pulses required for digital communications equipment, to a prolonged high current load for an electric vehicle traveling at highway speed. Because batteries are chemical devices that must convert higher-level active materials into an alternate state during discharge, the speed of such transaction determines the load characteristics of a battery. Also referred to as concentration polarization, the nickel and lithium-based batteries are superior to lead-based batteries in reaction speed. This reflects in good load characteristics.

The lead acid battery performs best at a slow 20-hour discharge. A pulse discharge also works well because the rest periods between the pulses help to disperse the depleted acid concentrations back into the electrode plate. In terms of capacity, these two discharge methods provide the highest efficiency for this battery chemistry.

A discharge at the rated capacity of 1C yields the poorest efficiency for the lead acid battery. The lower level of conversion, or increased polarization, manifests itself in a momentary higher internal resistance due to the depletion of active material in the reaction.

Different discharge methods, notably pulse discharging, also affect the longevity of some battery chemistries. While NiCd and Li-ion are robust and show minimal deterioration when pulse discharged, the NiMH exhibits a reduced cycle life when powering a digital load.

In a recent study, the longevity of NiMH was observed by discharging these batteries with analog and digital loads. In both tests, the battery discharged to 1.04V/cell. The analog discharge current was 500mA; the digital mode simulated the load requirements of the Global System for Mobile Communications (GSM) protocol and applied 1.65-ampere peak current for 12 ms every 100 ms. The current in between the peaks was 270mA. (Note that the GSM pulse for voice is about 550 ms every 4.5 ms).

With the analog discharge, the NiMH wore out gradually, providing an above average service life. At 700 cycles, the battery still provided 80 percent capacity. By contrast, the cells faded more rapidly with a digital discharge. The 80 percent capacity threshold was reached after only 300 cycles. This phenomenon indicates that the kinetic characteristics for the NiMH deteriorate more rapidly with a digital rather than an analog load.

Discharging at High and Low Temperature

Batteries function best at room temperature. Operating batteries at an elevated temperature dramatically shortens their life. Although a lead acid battery may deliver the highest capacity at temperatures above 30°C (86°F), prolonged use under such conditions decreases the life of the battery.

Similarly, a Li-ion performs better at high temperatures. Elevated temperatures temporarily counteracts the battery’s internal resistance, which is a result of aging. The energy gain is short-lived because elevated temperature promotes aging by further increasing the internal resistance.

There is one exception to running a battery at high temperature — it is the lithium polymer with dry solid polymer electrolyte, the true ‘plastic battery’. While the commercial Li-ion polymer uses some moist electrolyte to enhance conductivity, the dry solid polymer version depends on heat to enable ion flow. This requires that the battery core be kept at an operation temperature of 60°C to 100°C.

The dry solid polymer battery has found a niche market as backup power in warm climates. The battery is kept at the operating temperature with built-in heating elements. During normal operation, the core is kept warm with power derived from the utility grid. Only on a power outage would the battery need to provide power to maintain its own heat. To minimize heat loss, the battery is insulated.

The Li-ion polymer as standby battery is said to outperform VRLA batteries in terms of size and longevity, especially in shelters in which the temperature cannot be controlled. The high price of the Li-ion polymer battery remains an obstacle.

The NiMH chemistry degrades rapidly if cycled at higher ambient temperatures. Optimum battery life and cycle count are achieved at 20°C (68°F). Repeated charging and discharging at higher temperatures will cause irreversible capacity loss. For example, if operated at 30°C (86°F), the cycle life is reduced by 20 percent. At 40°C (104°F), the loss jumps to a whopping 40 percent. If charged and discharged at 45°C (113°F), the cycle life is only half of what can be expected if used at moderate room temperature. The NiCd is also affected by high temperature operation, but to a lesser degree.

At low temperatures, the performance of all battery chemistries drops drastically. While -20°C (-4°F) is threshold at which the NiMH, SLA and Li-ion battery stop functioning, the NiCd can go down to -40°C (-40°F). At that frigid temperature, the NiCd is limited to a discharge rate of 0.2C (5 hour rate). There are new types of Li-ion batteries that are said to operate down to -40°C.

It is important to remember that although a battery may be capable of operating at cold temperatures, this does not automatically mean it can also be charged under those conditions. The charge acceptance for most batteries at very low temperatures is extremely confined. Most batteries need to be brought up to temperatures above the freezing point for charging. The NiCd can be recharged at below freezing provided the charge rate is reduced to 0.1C.

Part Two

You and the Battery

Chapter 6: The Secrets of Battery Runtime

Is the runtime of a portable device directly related to the size of the battery and the energy it can hold? In most cases, the answer is yes. But with digital equipment, the length of time a battery can operate is not necessarily linear to the amount of energy stored in the battery.

In this chapter we examine why the specified runtime of a portable device cannot always be achieved, especially after the battery has aged. We address the four renegades that are affecting the performance of the battery. They are: declining capacity, increasing internal resistance, elevated self-discharge, and premature voltage cut-off on discharge.

Declining Capacity

The amount of charge a battery can hold gradually decreases due to usage, aging and, with some chemistries, lack of maintenance. Specified to deliver about 100 percent capacity when new, the battery eventually requires replacement when the capacity drops to the 70 or 60 percent level. The warranty threshold is typically 80 percent.

The energy storage of a battery can be divided into three imaginary sections consisting of available energy, the empty zone that can be refilled and the rock content that has become unusable. Figure 6-1 illustrates these three sections of a battery.

In nickel-based batteries, the rock content may be in the form of crystalline formation, also known as memory. Deep cycling can often restore the capacity to full service. Also known as ‘exercise’, a typical cycle consists of one or several discharges to 1V/cell with subsequent discharges.

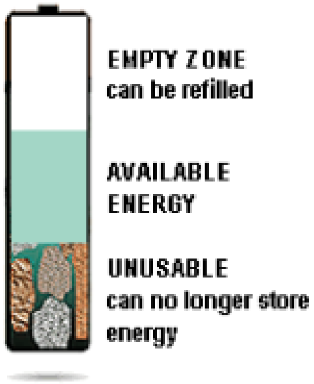


Figure 6-1: Battery charge capacity.
Three imaginary sections of a battery consisting of available energy, empty zone and rock content.

With usage and age, the rock content grows. Without regular maintenance, the user may end up carrying rocks instead of batteries.

The loss of charge acceptance of the Li-ion/polymer batteries is due to cell oxidation, which occurs naturally during use and as part of aging. Li-ion batteries cannot be restored with cycling or any other external means. The capacity loss is permanent because the metals used in the cells are designated to run for a specific time only and are being consumed during their service life.

Performance degradation of the lead acid battery is often caused by sulfation, a thin layer that forms on the negative cell plates, which inhibits current flow. In addition, there is grid corrosion that sets in on the positive plate. With sealed lead acid batteries, the issue of water permeation, or loss of electrolyte, also comes into play. Sulfation can be reversed to a certain point with cycling and/or topping charge but corrosion and permeation are permanent. Adding water to a sealed lead acid battery may help to restore operation but the long-term results are unpredictable.

Increasing Internal Resistance

To a large extent, the internal resistance, also known as impedance, determines the performance and runtime of a battery. If measured with an AC signal, the internal resistance of a battery is also referred to as impedance. High internal resistance curtails the flow of energy from the battery to the equipment.

A battery with simulated low and high internal resistance is illustrated below. While a battery with low internal resistance can deliver high current on demand, a battery with high resistance collapses with heavy current. Although the battery may hold sufficient capacity, the voltage drops to the cut-off line and the 'low battery' indicator is triggered. The equipment stops functioning and the remaining energy is undelivered.

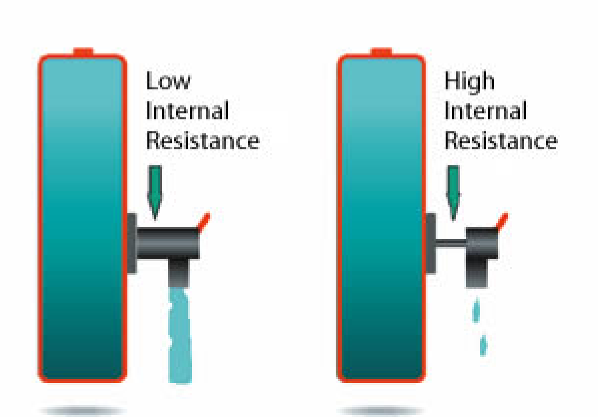


Figure 6-2: Effects of impedance on battery load.
A battery with low impedance provides unrestricted current flow and delivers all available energy. A battery with high impedance cannot deliver high-energy bursts due to a restricted path, and equipment may cut off prematurely.

NiCd has the lowest internal resistance of all commercial battery systems, even after delivering 1000 cycles. In comparison, NiMH starts with a slightly higher resistance and the readings increase rapidly after 300 to 400 cycles.

Maintaining a battery at low internal resistance is important, especially with digital devices that require high surge current. Lack of maintenance on nickel-based batteries can increase the internal resistance. Readings of more than twice the normal resistance have been observed on neglected NiCd batteries. After applying a recondition cycle with the Cadex *7000 Series* battery analyzer, the readings on the batteries returned to normal. Reconditioning clears the cell plates of unwanted crystalline formations, which restores proper current flow.

Li-ion offers internal resistance characteristics that are between those of NiMH and NiCd. Usage does not contribute much to the increase in resistance, but aging does. The typical life span of a Li-ion battery is two to three years, whether it is used or not. Cool storage and keeping the battery in a partially charged state when not in use retard the aging process.

The internal resistance of the Li-ion batteries cannot be improved with cycling. The cell oxidation, which causes high resistance, is non-reversible. The ultimate cause of failure is high internal resistance. Energy may still be present in the battery, but it can no longer be delivered due to poor conductivity.

With effort and patience, lead acid batteries can sometimes be improved by cycling or applying a topping and/or equalizing charge. This reduces the current-inhibiting sulfation layer but does not reverse grid corrosion.

Figure 6-3 compares the voltage signature and corresponding runtime of a battery with low, medium and high internal resistance when connected to a digital load. Similar to a soft ball that easily deforms when squeezed, the voltage of a battery with high internal resistance modulates the supply voltage and leaves the imprint of the load. The current pulses push the voltage towards the end-of-discharge line, resulting in a premature cut-off.

When measuring the battery with a voltmeter after the equipment has cut off and the load is removed, the terminal voltage commonly recovers and the voltage reading appears normal. This is especially true of nickel-based batteries. Measuring the open terminal voltage is an unreliable method to establish the state-of-charge (SoC) of the battery.

A battery with high impedance may perform well if loaded with a low DC current such as a flashlight, portable CD player or wall clock. With such a gentle load, virtually all of the stored energy can be retrieved and the deficiency of high impedance is masked.

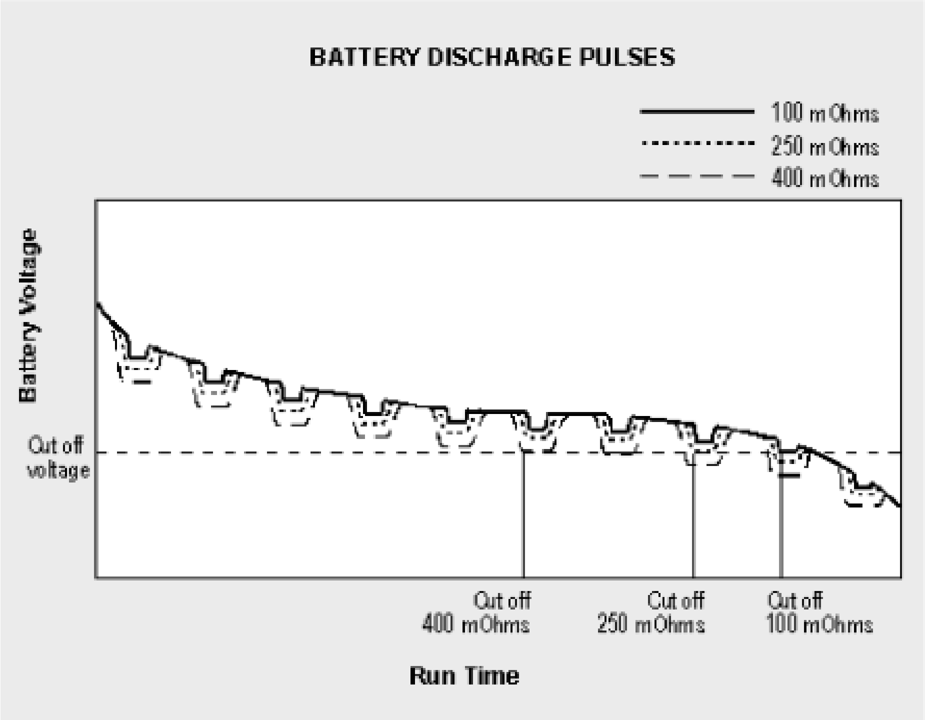


Figure 6-3: Discharge curve.
This chart compares the runtime of batteries with similar capacities under low, medium and high impedance when connected to a pulsed load.

The internal resistance of a battery can be measured with dedicated impedance meters. Several methods are available, of which the most common are applying DC loads and AC signals. The AC method may be done with different frequencies. Depending on the level of capacity loss, each technique provides slightly different readings. On a good battery, the measurements are reasonably close; on a weak battery, the readings between the methods may disperse more drastically.

Modern battery analyzers offer internal resistance measurements as a battery quick-test. Such tests can identify batteries that would fail due to high internal resistance, even though the capacity may still be acceptable. Internal battery resistance measurements are available in the Cadex *7000 Series* battery analyzers. (See Chapter 9: Internal Battery Resistance.)

Elevated Self-Discharge

All batteries exhibit a certain amount of self-discharge; the highest is visible on nickel-based batteries. As a rule, a nickel-based battery discharges 10 to 15 percent of its capacity in the first 24 hours after charge, followed by 10 to 15 percent every month thereafter.

The self-discharge on the Li-ion battery is lower compared to the nickel-based systems. The Li-ion self-discharges about five percent in the first 24 hours and one to two percent thereafter. Adding the protection circuit increases the self-discharge to ten percent per month.

One of the best batteries in terms of self-discharge is the lead acid system; it only self-discharges five percent per month. It should be noted, however, that the lead acid family has also the lowest energy density among current battery systems. This makes the system unsuitable for most hand-held applications.

At higher temperatures, the self-discharge on all battery chemistries increases. Typically, the rate doubles with every 10°C (18°F). Large energy losses occur through self-discharge if a battery is left in a hot vehicle. On some older batteries, stored energy may get lost during the course of the day through self-discharge rather than actual use.

The self-discharge of a battery increases with age and usage. For example, a NiMH battery is good for 300 to 400 cycles, whereas a NiCd adequately performs over 1000 cycles before high self-discharge affects the performance of the battery. Once a battery exhibits high self-discharge, no remedy is available to reverse the effect. Factors that accelerate self-discharge on nickel-based batteries are damaged separators (induced by excess crystalline formation, allowing the packs to cook while charging), and high cycle count, which promotes swelling in the cell.

Figure 6-4: Effects of high load impedance.
A battery may gradually self-discharge as a result of high temperature, high cycle count and age. In older batteries, stored energy may be lost during the course of the day through self-discharge rather than actual use.

At present, no simple quick-test is available to measure the self-discharge of a battery. A battery analyzer can be used by first reading the initial capacity after full charge, then measuring the capacity again after a rest period of 12 hours. The Cadex *7000 Series* performs this task automatically. In the future, quick test methods may be available that are able to measure the self-discharge of a battery within a few seconds.

Premature Voltage Cut-off

Some portable equipment does not fully utilize the low-end voltage spectrum of a battery. The equipment cuts off before the designated end-of-discharge voltage is reached and some precious battery power remains unused.

A high cut-off voltage problem is more widespread than is commonly assumed. For example, a certain brand of mobile phone that is powered with a single-cell Li-ion battery cuts off at

3.3V. The Li-ion can be designed to be used to 3V and lower. With a discharge to 3.3V, only about 70 percent of the expected 100 percent capacity is utilized. Another mobile phone using NiMH and NiCd batteries cuts off at 5.7V. The four-cell nickel-based batteries are designed to discharge to 5V.

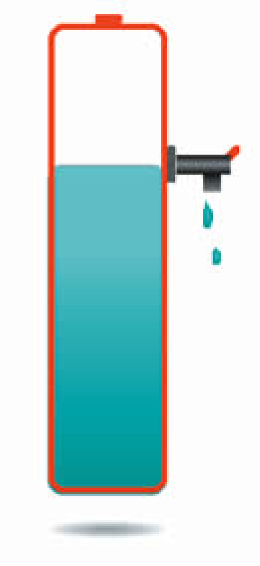
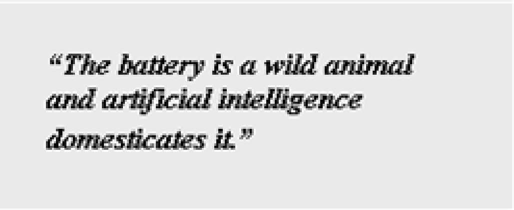


Figure 6-5: Illustration of equipment with high cut-off voltage.
Some portable devices do not utilize all available battery power and leave precious energy behind.

When discharging these batteries to their respective end-of-discharge threshold with a battery analyzer after the equipment has cut off, up to 60 percent residual capacity readings can be retrieved. High residual capacity is prevalent with batteries that have elevated internal resistance and are operated at warm ambient temperatures. Digital devices that load the battery with current bursts are more receptive to premature voltage cut-off than analog equipment.

A ’high cut-off voltage’ is mostly equipment related. In some cases the problem of premature cut-off is induced by a battery with low voltage. A low table voltage is often caused by a battery pack that contains a cell with an electrical short. Memory also causes a decrease in voltage; however, this is only present in nickel-based systems. In addition, elevated temperature lowers the voltage level on all battery systems. Voltage reduction due to high temperatures is temporary and normalizes once the battery cools down.



“The battery is a wild animal and artificial intelligence domesticates it.”

Chapter 7: The ‘Smart’ Battery

Aspeaker at a battery seminar remarked that, “The battery is a wild animal and artificial intelligence domesticates it.” An ordinary or ‘dumb’ battery has the inherit problem of not being able to display the amount of reserve energy it holds. Neither weight, color, nor size provides any indication of the battery’s state-of-charge (SoC) and state-of-health (SoH). The user is at the mercy of the battery when pulling a freshly charged battery from the charger.

Help is at hand. An increasing number of today’s rechargeable batteries are made ‘smart’. Equipped with a microchip, these batteries are able to communicate with the charger and user alike to provide statistical information. Typical applications for ‘smart’ batteries are notebook computers and video cameras. Increasingly, these batteries are also used in advanced biomedical devices and defense applications.

There are several types of ‘smart’ batteries, each offering different complexities, performance and cost. The most basic ‘smart’ battery may only contain a chip to identify its chemistry and tell the charger which charge algorithm to apply. Other batteries claim to be smart simply because they provide protection from overcharging, under-discharging and short-circuiting. In the eyes of the Smart Battery System (SBS) forum, these batteries cannot be called ‘smart’.

What then makes a battery ‘smart’? Definitions still vary among organizations and manufacturers. The SBS forum states that a ‘smart’ battery must be able to provide SoC indications. Benchmarq was the first company to commercialize the concept of the battery fuel gauge technology. Early IC chips date back to 1990. Several manufacturers followed suit and produced ‘smart’ chips for batteries.

During the early nineties, numerous ‘smart’ battery architectures with a SoC read-out have emerged. They range from the single wire system, the two-wire system and the system management bus (SMBus). Most two-wire systems are based on the SMBus protocol. This book will address the single wire system and the SMBus.

The Single Wire Bus

The single wire system is the simpler of the two and does all the data communications through one wire. A battery equipped with the single wire system uses only three wires, the positive and negative battery terminals and the data terminal. For safety reasons, most battery manufacturers run a separate wire for temperature sensing. Figure 7-1 shows the layout of a single wire system.

The modern single wire system stores battery-specific data and tracks battery parameters, including temperature, voltage, current and remaining charge. Because of simplicity and relatively low hardware cost, the single wire enjoys a broad market acceptance for high-end mobile phones, two-way radios and camcorders.

Most single wire systems do not have a common form factor; neither do they lend themselves to standardized SoH measurements. This produces problems for a universal charger concept. The Benchmarq single wire solution, for example, cannot measure current directly; it must be extracted from a change in capacity over time.

In addition, the single wire bus allows battery SoH measurement only when the host is ‘married’ to a designated battery pack. Such a fixed host-battery relationship is feasible with notebook computers, mobile phones or video cameras, provided the appropriate OEM battery is used. Any discrepancy in the battery type from the original will make the system unreliable or will provide false readings.

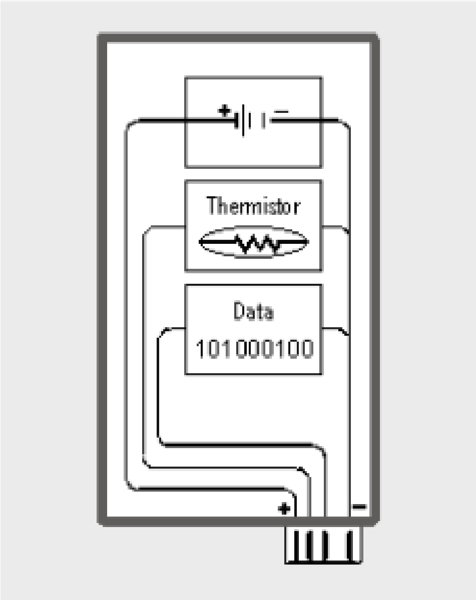


Figure 7-1: Single wire system of a ‘smart’ battery.
Only one wire is needed for data communications. Rather than supplying the clock signal from the outside, the battery includes an embedded clock generator. For safety reasons, most battery manufacturers run a separate wire for temperature sensing.

The SMBus

The SMBus is the most complete of all systems. It represents a large effort from the portable electronic industry to standardize to one communications protocol and one set of data. The SMBus is a two-wire interface system through which simple power-related chips can communicate with the rest of the system. One wire handles the data; the second is the clock. It uses I^2C as its backbone. Defined by Philips, the I^2C is a synchronous multi-drop bi-directional communications system, which operates at a speed of up to 100 kilohertz (kHz).

The Duracell/Intel SBS, in use today, was standardized in 1993. In previous years, computer manufacturers had developed their own proprietary ‘smart’ batteries. With the new SBS specification, a broader interface standard was made possible. This reduces the hurdles of interfering with patents and intellectual properties.

In spite of an agreed standard, many large computer manufacturers, such as IBM, Compaq and Toshiba, have retained their proprietary batteries. The reason for going their own way is partly due to safety, performance and form factor. Manufacturers claim that they cannot guarantee safe and enduring performance if a non-brand battery is used. To make the equipment as compact as possible, the manufacturers explain that the common form factor battery does not optimally fit their available space. Perhaps the leading motive for using their proprietary batteries is pricing. In the absence of competition, these batteries can be sold for a premium price.

The early SMBus batteries had problems of poor accuracy. Electronic circuits did not provide the necessary resolution; neither was real time reporting of current, voltage and temperature adequate. On some batteries, the specified accuracy could only be achieved if the battery was new, operated at room temperature and was discharged at a steady rate of 1C. Operating in adverse temperatures or discharging at uneven loads reduced the accuracy dramatically. Most loads for portable equipment are uneven and fluctuate with power demand. There are power surges on a laptop at start up and refresh, high inrush currents on biomedical equipment during certain procedures and sharp pulse bursts on digital communications devices on transmit.

In the absence of a reliable reporting system on the older generation of ‘smart’ batteries, capacity estimation was inaccurate. This resulted in powering down the equipment before the battery was fully depleted, leaving precious energy behind. Most batteries introduced in the late 1990s have resolved some or all of these deficiencies. Further improvements will be necessary.

Design— The design philosophy behind the SMBus battery is to remove the charge control from the charger and assign it to the battery. With a true SMBus system, the battery becomes the master and the charger serves as a slave that must follow the dictates of the battery. This is done out of concerns over charger quality, compatibility with new and old battery chemistries, administration of the correct amount of charge currents and accurate full-charge detection. Simplifying the charging for the user is an issue that is important when considering that some battery packs share the same footprint but contain radically different chemistries.

The SMBus system allows new battery chemistries to be introduced without the charger becoming obsolete. Because the battery controls the charger, the battery manages the voltage and current levels, as well as cut-off thresholds. The user does not need to know which battery chemistry is being used.

The analogy of charging a ‘smart’ and ‘dumb’ battery can be made with the eating habits of an adult and a baby. Charging a ‘smart’ battery resembles the eating choices of a responsible adult who knows best what food to select how much to take. The baby, in on the other hand, has limited communications skills in expressing the type and amount of food desired. Putting this analogy in parallel with charging batteries, the charger servicing ‘dumb’ batteries can only observe the approximate SoC level and avoid overcharge conditions.

Architecture — An SMBus battery contains permanent and temporary data. The permanent data is programmed into the battery at the time of manufacturing and include battery ID number, battery type, serial number, manufacturer’s name and date of manufacture. The temporary data is acquired during use and consists of cycle count, user pattern and maintenance requirements. Some of the temporary data is being replaced and renewed during the life of the battery.

The SMBus is divided into Level 1, 2 and 3. Level 1 has been eliminated because it does not provide chemistry independent charging. Level 2 is designed for in-circuit charging. A laptop that charges its battery within the unit is a typical example of Level 2. Another application of Level 2 is a battery that contains the charging circuit within the pack. Level 3 is reserved for full-featured external chargers.

Most external SMBus chargers are based on Level 3. Unfortunately, this level is complex and the chargers are costly to manufacture. Some lower cost chargers have emerged that accommodate SMBus batteries but are not fully SBS compliant. Manufacturers of SMBus batteries do not readily endorse this shortcut. Safety is always a concern, but customers buy these economy chargers because of the lower price.

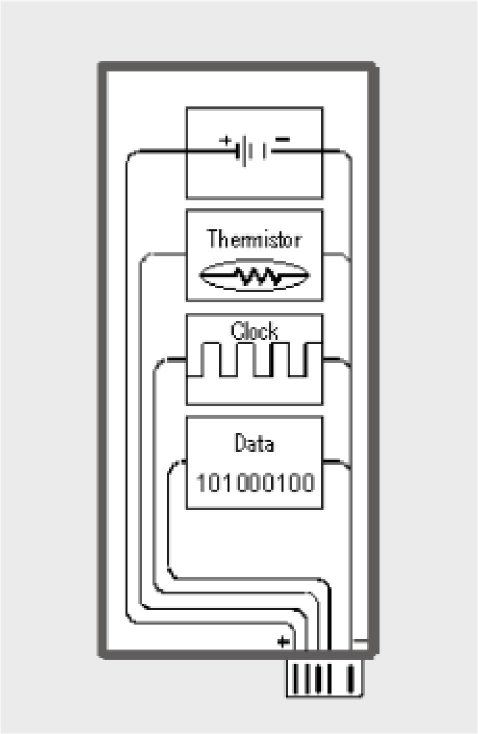


Figure 7-2: Two-wire SMBus system.
The SMBus is based on a two-wire system using a standardized communications protocol. This system lends itself to standardized state-of-charge and state-of-health measurements.

Serious industrial battery users operating biomedical instruments, data collection devices and survey equipment use Level 3 chargers with full-fledged charge protocol. No shortcuts are applied. To assure compatibility, the charger and battery are matched and only approved packs are used. The need to test and approve the marriage between specific battery and charger types is unfortunate given that the ‘smart’ battery is intended to be universal.

Among the most popular SMBus batteries for portable computers are the 35 and 202 form-factors. Manufactured by Sony, Hitachi, GP Batteries, Moltech (formerly Energizer), Moli Energy and many others, this battery works (should work) in all portable equipment designed for this system.

Figure 7-3 illustrates the 35 and 202 series ‘smart' batteries. Although the ‘35’ has a smaller footprint compared to the ‘202’, most chargers are designed to accommodate all sizes, provided the common five-prong knife connector is used.

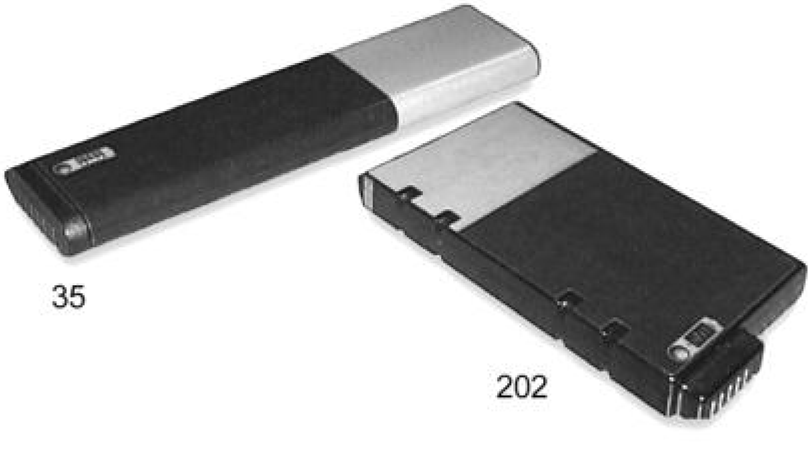


Figure 7-3: 35 and 202 series ‘smart’ batteries featuring SMBus.
Available in NiCd, NiMH and Li-ion chemistries, these batteries are used for mobile computing, biomedical

instruments and high-end survey equipment. The same form factor also accommodates NiCd and NiMH chemistries but without SMBus (‘dumb’).

Negatives of the SMBus — Like any good invention, the SMBus battery has some serious downsides that must be addressed. For starters, the ‘smart’ battery costs about 25 percent more than the ‘dumb’ equivalent. In addition, the ‘smart’ battery was intended to simplify the charger, but a full-fledged Level 3 charger costs substantially more than a regular dumb model.

A more serious issue is maintenance requirements, better known as capacity re-learning. This procedure is needed on a regular basis to calibrate the battery. The Engineering Manager of Moli Energy, a large Li-ion cell manufacturer commented, “With the Li-ion battery we have eliminated the memory effect, but are we introducing digital memory with the SMBus battery?”

Why is calibration needed? The answer is in correcting the tracking errors that occur between the battery and the digital sensing circuit during use. The most ideal battery use, as far as fuel-gauge accuracy is concerned, is a full charge followed by a full discharge at a constant 1C rate. This ensures that the tracking error is less than one percent per cycle. However, a battery may be discharged for only a few minutes at a time and commonly at a lower C-rate than 1C. Worst of all, the load may be uneven and vary drastically. Eventually, the true capacity of the battery no longer synchronizes with the fuel gauge and a full charge and discharge are needed to ‘re-learn’ or calibrate the battery.

How often is calibration needed? The answer lies in the type of battery application. For practical purposes, a calibration is recommended once every three months or after every 40 short cycles. Long storage also contributes to errors because the circuit cannot accurately compensate for self-discharge. After extensive storage, a calibration cycle is recommended prior to use.

Many applications apply a full discharge as part of regular use. If this occurs regularly, no additional calibration is needed. If a full discharge has not occurred for a few months and the user notices the fuel gauge losing accuracy, a deliberate full discharge on the equipment is recommended. Some intelligent equipment advises the user when a calibrating discharge is needed. This is done by measuring the tracking error and estimating the discrepancy between the fuel gauge reading and that of the chemical battery.

What happens if the battery is not calibrated regularly? Can such a battery be used in confidence? Most ‘smart’ battery chargers obey the dictates of the cells rather than the electronic circuit. In this case, the battery will be fully charged regardless of the fuel gauge setting. Such a battery is able to function normally, but the digital readout will be inaccurate. If not corrected, the fuel gauge information simply becomes a nuisance.

The level of non-compliance is another problem with the SMBus. Unlike other tightly regulated standards, such as the long play record introduced in the late 1950s, the audiocassette in the 1960s, the VCR in the 1970s, ISDN and GSM in the 1980s and the USB in the 1990s, some variations are permitted in the SMBus protocol. These are: adding a check bid to halt the service if the circuit crashes, counting the number of discharges to advise on calibration and disallowing a charge if a certain fault condition has occurred. Unfortunately, these variations cause problems with some existing chargers. As a result, a given SMBus battery should be checked for compatibility with the designated charger before use to assure reliable service. Ironically, the more features that are added to the SMBus charger and battery, the higher the likelihood of incompatibilities.

‘Smart’ battery technology has not received the widespread acceptance that battery manufacturers had hoped. Some engineers go so far as to suggest that the SMBus battery is a ‘misguided principal’. Design engineers may not have fully understood the complexity of charging batteries in the incubation period of the ‘smart’ battery. Manufacturers of SMBus chargers are left to clean up the mess.

The forecast in consumer acceptance of the ‘smart’ battery has been too optimistic. In the early 1990s when the SMBus battery was conceived, price many not have been as critical an issue as it is now. Then, the design engineer would include many wonderful options. Today, we look for scaled down products that are economically priced and perform the function intended. When looking at the wireless communications market, adding high-level intelligence to the battery is simply too expensive for most consumers. In the competitive mobile phone market, for example, the features offered by the SMBus would be considered overkill.

SMBus battery technology is mainly used by higher-level industrial applications and battery manufacturers are constantly searching for avenues to achieve a wider utilization of the ‘smart’ battery. According to a survey in Japan, about 30 percent of all mobile computing devices are equipped with a ‘smart’ battery.

Improvements in the ‘smart’ battery system, such as better compatibilities, improved error-checking functions and higher accuracies will likely increase the appeal of the ‘smart’ battery. Endorsement by large software manufacturers such as Microsoft will entice PC manufacturers to make full use of these powerful features.

The State-of-Charge Indicator

Most SMBus batteries are equipped with a charge level indicator. When pressing a SoC button on a battery that is fully charged, all signal lights illuminate. On a partially discharged battery, half the lights illuminate, and on an empty battery, all lights remain dark. Figure 7-4 shows such a fuel gauge.

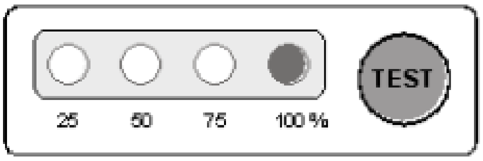


Figure 7-4: State-of-charge readout of a ‘smart’ battery.
Although the state-of-charge is displayed, the state-of-health and its predicted runtime are unknown.

While SoC information displayed on a battery or computer screen is helpful, the fuel gauge resets to 100 percent each time the battery is recharged, regardless of the battery’s SoH. A serious miscount occurs if an aged battery shows 100 percent after a full-charge, when in fact the charge acceptance has dropped to 50 percent or less. The question remains: “100 percent of what?” A user unfamiliar with this battery has little information about the runtime of the pack.

The Tri-State Fuel Gauge

The SoC information alone is incomplete without knowing the battery’s SoH. To fully evaluate the present state of a battery, three levels of information are needed. They are: SoC, SoH and the empty portion of the battery that can be replenished with a charge. (The empty portion is derived by deducting the SoC from the SoH.)

How can the three levels of a battery be measured and made visible to the user? While the SoC is relatively simple to produce, as discussed above, measuring the SoH is more complex. Here is how it works:

At time of manufacture, each SMBus battery is given its specified SoH status, which is 100 percent by default. This information is permanently programmed into the pack and does not change. With each charge, the battery resets to the full-charge status. During discharge, the energy units (coulombs) are counted and compared against the 100 percent setting. A perfect battery would indicate 100 percent on a calibrated fuel gauge. As the battery ages and the charge acceptance drops, the SoH begins to indicate lower readings. The discrepancy between the factory set 100 percent and the actual delivered coulombs is used to calculate the SoH.

Knowing the SoC and SoH, a simple linear display can be made. The SoC is indicated with green LED's; the empty part remains dark; and the unusable part is shown with red LED's. Figure 7-5 shows such a tri-state fuel gauge. As an alternative, the colored bar display may be replaced with a numeric display indicating SoH and SoC.

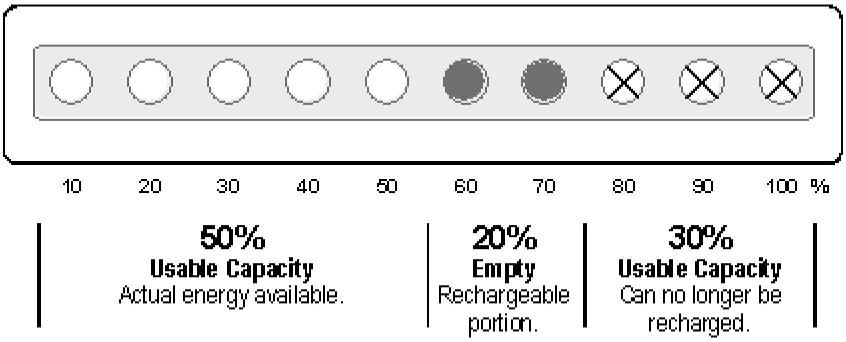


Figure 7-5: Tri-state fuel gauge.
The Battery Health Gauge reads the 'learned' battery information available on the SMBus and displays it on a multi-colored LED bar. This illustration shows a partially discharged battery of 50% SoC with a 20% empty portion and an unusable portion of 30%.

The most practical setting to place the tri-state-fuel gauge is on a charger. Only one display would be needed for a multi-bay charging unit. To view the readings of a battery, the user would simply press a button. The SoC and SoH information would be displayed within five seconds after inserting the battery into the charger bay. During charge, the gauge would reveal the charge level of each battery. This information would be handy when a functional battery is needed in a hurry. Cadex offers a series of SMBus chargers that feature the tri-state fuel gauge as an option.

The Target Capacity Selector

For users that simply need a go/no go answer and do not want to bother about other battery information, chargers are available that feature a target capacity selector. Adjustable to 60, 70 or 80 percent, the target capacity selector acts as a performance check and flags batteries that do not meet set requirements.

If a battery falls below target, the charger triggers the condition light. The user is prompted to press the condition button to cycle the battery. Condition consists of charge/discharge/charge and performs calibration and conditioning functions. If the battery does not recover after the conditioning service, the fail light illuminates, indicating that the battery should be replaced. A green ready light at the completion of the program assures that the battery meets the required performance level.

An SMBus charger with the above described features acts as charger, conditioner and quality control system. Figure 7-6 illustrates a two-bay Cadex charger featuring the target capacity selector and discharge circuit. This unit is based on Level 3 and services both SMBus and 'dumb' batteries.

Some SMBus chargers can be fully automated to apply a conditioning cycle whenever the battery falls below the target setting. An override button cancels the discharge if a fast-charge is needed instead. Such a system maximizes the life of fleet batteries and assures that deadwood is identified and removed.

Figure 7-6:The Cadex *SM2*+ charger
This Level 3 charger serves as charger, conditioner and quality control system. It reads the battery's true state-of-health and flags those that fall below the set target capacity. Each bay operates independently and charges NiCd, NiMH and Li-ion chemistries in approximately three hours. 'Dumb' batteries can also be charged.

By allowing the user to set the desired battery performance level, the question is raised as to what level to select. The answer is governed by the applications, reliability standards and cost policies.

It should be noted that the batteries are always charged to 100 percent, regardless of the target setting. The target capacity simply refers to the amount of charge the battery has delivered on the last discharge.

A practical target capacity setting for most applications is 80 percent. Decreasing the threshold to 70 percent will lower the performance standard but pass more batteries. A direct cost saving will result. The 60 percent level may suit those users who run a low budget operation, have ready access to replacement batteries and can live with shorter, less predictable runtimes.

Battery SoH readings are only available with Level 3 SMBus chargers servicing valid SMBus batteries. 'Dumb' batteries cannot provide SoH readings, even if they share the identical footprint of the 'smart' battery and can use the same charger.

Fuel Gauges for Large Batteries

Most 'smart' battery applications today are limited to portable electronic equipment, and the electronic circuit is built right into the battery pack. In applications where larger 'smart' batteries are needed, such as electric wheelchairs, scooters, robots and forklifts, the electronic circuit may be placed in a box external to the battery.

The main benefit of adding intelligence to the battery is to enable the measurement of SoH and reserve energy. Most measuring devices used are based on voltage, which is known to be highly inaccurate.

Cadex is extending the 'smart' battery technology to wheeled applications. Called the Cadex *Fuelcheck*™, the device is based on the tri-state fuel gauge described earlier in this section. The system consists of a controller, current measuring device and a display unit. The Cadex *Fuelcheck*™ device can be added to new equipment when it is manufactured and can be installed in existing equipment as a retrofit. The installation is permanent and each wheeled appliance requires one system.

A tri-state linear bar graph consisting of colored LED's would be the preferred display for a personal user, such as a wheelchair operator. By replacing the light display with a digital readout, additional information can be shown. For example, a display could indicate the remaining runtime based on the average power consumption logged. Corrections would be applied if the load factor changes during the course of the day. Figure 7-7 illustrates a digital fuel gauge using the LCD panel.

To initialize the Cadex *Fuelcheck*™ system, a one-time setup procedure is required. A PC will prompt the technician to enter information such as battery chemistry, desired end-of-discharge voltage, Ah rating of the battery, and designated service flags. The system is then calibrated by applying a full charge, followed by a full discharge. The initial discharge assesses the battery, or learns the performance. The SoH readings will be known after the first full discharge.

7-7: Cadex *Fuelcheck*™ digital fuel gauge.
The display indicates SoC, SoH, remaining power in hours, the voltage and current draw.

The simplest way to discharge the battery as part of calibration is to run it down through normal use in the equipment. The most accurate readings are obtained by using a load bank. Such a device may not be always available.

With a data logging option built into the system, the PC allows downloading service data that have been collected during use. Such information would benefit large equipment fleets and rental places that need to check the performance of the batteries on demand.

Similar to other 'smart' battery systems, calibration will be needed once every 6 to 12 months. More frequent calibrations may be required if the equipment is used for short durations between each recharge. The most practical way to calibrate the system is by occasionally allowing the battery to run down through continued use. Information relating to the date of the last calibration, or an early call for calibration if certain conditions occur, can be calculated and displayed.

Knowing the SoH of a battery at any time and scheduling timely service or replacement is a major benefit for industrial battery users. Such a system would be especially helpful for organizations in which different individuals use the equipment and no one is given maintenance responsibilities. Equipment rental places fall into this category.

Chapter 8: Choosing the Right Battery

What causes a battery to wear down — is it mechanical or chemical? The answer is ‘both’. A battery is a perishable product that starts deteriorating from the time it leaves the factory. Similar to a spring under tension, a battery seeks to revert to its lowest denominator. The rate of aging is subject to depth of discharge, environmental conditions, charge methods and maintenance procedures (or lack thereof). Each battery chemistry behaves differently in terms of aging and wear through normal use.

> ***Similar to a spring under tension, a battery seeks to revert to its lowest denominator.***

> ***The NiMH and NiCd are considered high maintenance batteries.***

What’s the best battery for mobile phones?

When buying a replacement battery, the buyer often has the choice of different battery chemistries. Li-ion and Li-ion polymer batteries are used on newer phones, whereas the NiMH and NiCd are found in older models. If the buyer has a choice, the sales person may advise a customer to go for the highest capacity rating and to stay away from the NiCd because of the memory effect. The customer may settle for the slim-line NiMH because it offers relatively high capacity in a small package and is reasonably priced.

Seemingly a wise choice, an analysis in this chapter reveals that other chemistries may have served better. The NiMH offers good value for the price but falls short in expected cycle life. Although excellent when new, the performance trails off quickly after about 300 cycles due to decreased capacity and rising internal resistance. In comparison, the Li-ion can be used for about 500 cycles. The best cycle count is achieved with NiCd. Properly maintained, the NiCd delivers over 1000 cycles and the internal resistance remains low. However, the NiCd offers about 30 percent less capacity compared to the NiMH. In addition, the NiCd is being removed from the mobile phone market because of environmental concerns.

Switching to environmentally friendlier batteries is fitting, especially in the mobile phone market where the NiMH performs reasonably well and can be economical. The battery disposal issue is difficult to control, particularly in the hands of a diverse user group.

The NiMH and NiCd are considered high maintenance batteries, which require regular discharge cycles to prevent what is referred to as ‘memory’. Although the NiMH was originally advertised as memory-free, both NiCd and NiMH are affected by the phenomenon. The capacity loss is caused by crystalline formation that is generated by the positive nickel plate, a metal shared by both systems.

Nickel-based batteries, especially NiCd’s, should be fully discharged once per month. If such maintenance is omitted for four months or more, the capacity drops by as much as one third. A full restoration becomes more difficult the longer service is withheld.

It is not recommended to discharge a battery before each charge because this wears down the battery unnecessarily and shortens the life. Neither is it advisable to leave a battery in the charger for a long period of time. When not in use, the battery should be put on a shelf and charged before use. Always store the battery in a cool place.

Is the Li-ion a better choice? Yes, for many applications. The Li-ion is a low maintenance battery which offers high energy, is lightweight and does not require periodic full discharge. No trickle charge is applied once the battery reaches full charge. The Li-ion battery can stay in most chargers until used. The charging process of a Li-ion is, in many ways, simpler and cleaner than that of nickel-based systems, but requires tighter tolerances. Repeated insertion into the charger or cradle does not affect the battery by inducing overcharge.

On the negative side, the Li-ion gradually loses charge acceptance as part of aging, even if not used. For this reason, Li-ion batteries should not be stored for long periods of time but be rotated like perishable food. The buyer should be aware of the manufacturing date when purchasing a replacement battery.

The Li-ion is most economical for those who use a mobile phone daily. Up to 1000 charge/discharge cycles can be expected if used within the expected service life of about two to three years. Because of the aging effect, the Li-ion does not provide an economical solution for the occasional user. If the Li-ion is the only battery choice and the equipment is seldom used, the battery should be removed from the equipment and stored in a cool place, preferably only partially charged.

So far, little is known about the life expectancy of the Li-ion polymer. Because of the similarities with the Li-ion, the long-term performance of both systems is expected to be similar. Much effort is being made to prolong the service life of lithium-based systems. New chemical additives have been effective in retarding the aging process.

What’s the best battery for two-way radios?

The two-way radio market uses mostly NiCd batteries. In the last few years, environmental agencies have been attempting to discourage the use of NiCd, especially in Europe. NiMH have been tried and tested in two-way radios for a number of years but the results are mixed. Shorter cycle life compared to NiCd is the major drawback.

The reasons for the relatively short life of NiMH are multi-fold. NiMH is less robust than NiCd and has a cycle life expectancy that is half or one third that of the standard NiCd. In addition, NiMH prefers a moderate discharge current of 0.5C or less. A two-way radio, on the other hand, draws a discharge current of about 1.5A when transmitting at 4W of power. High discharge loads shorten the life of the NiMH battery considerably.

NiCd has the advantage of maintaining a low and steady internal resistance throughout most of its service life. Although low when new, NiMH increases the resistance with advanced cycle count. A battery with high internal resistance causes the voltage to drop when a load is applied. Even though energy may still be present, the battery cannot deliver the high current flow required during transmit mode. This results in a drop in voltage, which triggers the ‘low battery’ condition and the radio cuts off. This happens mostly during transmission.

The Li-ion has been tested for use with two-way radios but has not been able to provide the ultimate answer. Higher replacement costs, restrictions posed by the safety circuit and aging pose limitations on this battery system.

What’s the best battery for laptops?

Batteries for laptops have a unique challenge because they must be small and lightweight. In fact, the laptop battery should be invisible to the user and deliver enough power to last for a five-hour flight from Toronto to Vancouver. In reality, a typical laptop battery provides only about 90 minutes of service.

> *For better or worse, we have learned to accept the short runtime of a laptop.*

Computer manufacturers are hesitant to add a larger battery because of increased size and weight. A recent survey indicated that, given the option of larger size and more weight to obtain longer runtimes, most users would settle for what is being offered today. For better or worse, we have learned to accept the short runtime of a laptop.

During the last few years, batteries have improved in terms of energy density. Any benefit in better battery performance, however, is being eaten up by the higher power requirements of the laptops. It is predicted that the even more power-hungry PC’s of the future will counteract any improvements in battery technology, as marginal as they might be. The net effect will result in the same runtimes but faster and more powerful computers.

The length of time the battery can be used will get shorter as the battery ages. A battery residing in a laptop ages more quickly than when used in other applications. After a warm-up, the official operating temperature inside a laptop computer is 45°C (113°F). Such a high ambient temperature drastically lowers the battery’s life expectation. At a temperature of 45°C, for example, the life expectancy of a NiMH battery is less than 50 percent as compared to running it at the ideal operating temperature of 20°C (68°F).

The Li-ion does not fare much better. At this high ambient temperature, the wear-down effect of the battery is primarily governed by temperature as opposed to cycle count. The situation is worsened by the fact that the battery resides in a high SoC most of the time. The combination of heat and high SoC promotes cell oxidation, a condition that cannot be reversed once afflicted.

A fully charged Li-ion battery that is stored at 45°C suffers a capacity loss from 100 percent to about 70 percent in as little as six months. If this condition persists, the capacity degrades further to 50 percent in twelve months. In reality, the battery in a laptop is exposed to elevated temperatures just during use and the battery is in a full charge state only part of the time. But leaving the laptop in a parked car under the hot sun will aggravate the situation.

Some Japanese computer manufacturers have introduced a number of sub-notebooks in which the battery is mounted externally, forming part of the hinge. This design improves battery life because the battery is kept at room temperature. Some models carry several size batteries to accommodate different user patterns.

What then is the best battery for a laptop? The choices are limited. The NiCd has virtually disappeared from the mobile computer scene and the NiMH is loosing steam, paving the way for the Li-ion. Eventually, very slim geometry will also demand thin batteries, and this is possible with the prismatic Li-ion polymer.

Besides providing reliable performance for general portable use, the Li-ion battery also offers superior service for laptop users who must continually switch from fixed power to battery use, as is the case for many sales people. Many biomedical and industrial applications follow this pattern also. Here is the reason why such use can be hard on some batteries:

On a nickel-based charging system, unless smart, the charger applies a full charge each time the portable device is connected to fixed power. In many cases, the battery is already fully charged and the cells go almost immediately into overcharge. The battery heats up, only to be detected by a sluggish thermal charge control, which finally terminates the fast charge. Permanent capacity loss caused by overcharge and elevated temperature is the result.

Among the nickel-based batteries, NiMH is least capable of tolerating a recharge on top of a charge. Adding elevated ambient temperatures to the charging irregularities, a NiMH battery can be made inoperable in as little as six months. In severe cases, the NiMH is known to last only 2 to 3 months.

For mixed battery and utility power use, the Li-ion system is a better choice. If a fully charged Li-ion is placed on charge, no charge current is applied. The battery only receives a recharge once the terminal voltage has dropped to a set threshold. Neither is there a concern if the device is connected to fixed power for long periods of time. No overcharge can occur and there is no memory to worry about.

NiMH is the preferred choice for a user who runs the laptop mostly on fixed power and removes the battery when not needed. This way, the battery is only engaged if the device is used in portable mode. The NiMH battery can thus be kept fresh while sitting on the shelf. NiMH ages well if kept cool and only partially charged.

Selecting a Lasting Battery

As part of an ongoing research program to find the optimum battery system for selected applications, Cadex has performed life cycle tests on NiCd, NiMH and Li-ion batteries. All tests were carried out on the Cadex *7000 Series* battery analyzers in the test labs of Cadex, Vancouver, Canada. The batteries tested received an initial full-charge, and then underwent a regime of continued discharge/charge cycles. The internal resistance was measured with Cadex's *Ohmtest*™ method, and the self-discharge was obtained from time-to-time by reading the capacity loss incurred during a 48-hour rest period. The test program involved 53 commercial telecommunications batteries of different models and chemistries. One battery of each chemistry displaying typical behavior was chosen for the charts below.

When conducting battery tests in a laboratory, it should be noted that the performance in a protected environment is commonly superior to those in field use. Elements of stress and inconsistency that are present in everyday use cannot always be simulated accurately in the lab.

The NiCd Battery — In terms of life cycling, the standard NiCd is the most enduring battery. In Figure 8-1 we examine the capacity, internal resistance and self-discharge of a 7.2V, 900mA NiCd battery with standard cells. Due to time constraints, the test was terminated after 2300 cycles. During this period, the capacity remains steady, the internal resistance stays flat at 75mW and the self-discharge is stable. This battery receives a grade 'A' for almost perfect performance.

The readings on an ultra-high capacity NiCd are less favorable but still better than other chemistries in terms of endurance. Although up to 60 percent higher in energy density compared to the standard NiCd version, Figure 8-2 shows the ultra-high NiCd gradually losing capacity during the 2000 cycles delivered. At the same time, the internal resistance rises slightly. A more serious degradation is the increase of self-discharge after 1000 cycles. This deficiency manifests itself in shorter runtimes because the battery consumes some energy itself, even if not in use.

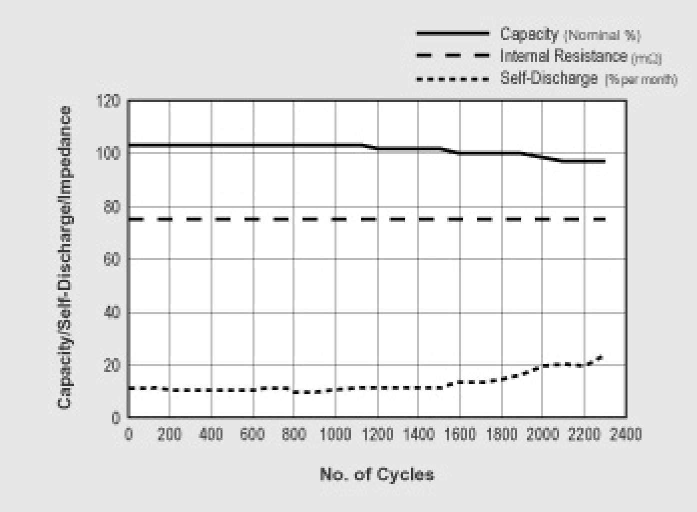


Figure 8-1: Characteristics of a standard cell NiCd battery.
This battery deserves an ‘A’ for almost perfect performance in terms of stable capacity, internal resistance and self-discharge over many cycles. This illustration shows results for a 7.2V, 900mA NiCd.

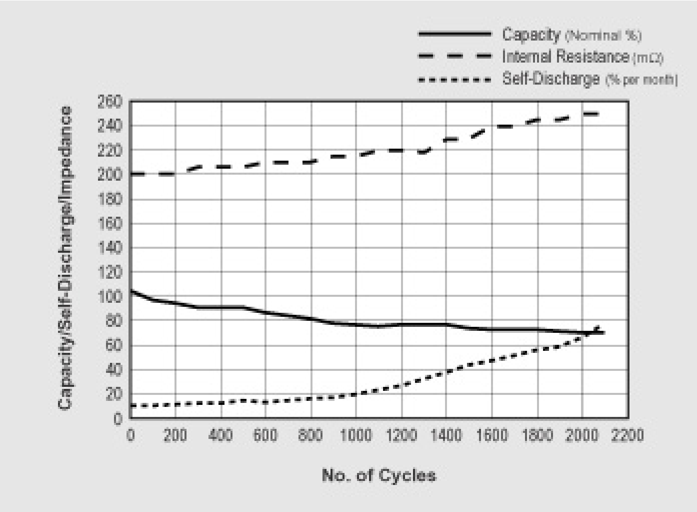


Figure 8-2: Characteristics of a NiCd battery with ultra-high capacity cells.
This battery is not as favorable as the standard NiCd but offers higher energy densities and performs better than other chemistries in terms of endurance. This illustrations shows results for a 6V, 700mA NiCd.

The NiMH Battery — Figure 8-3 examines the NiMH, a battery that offers high energy density at reasonably low cost. We observe good performance at first but past the 300-cycle mark, the performance starts to drift downwards rapidly. One can detect a swift increase in internal resistance and self-discharge after cycle count 700.

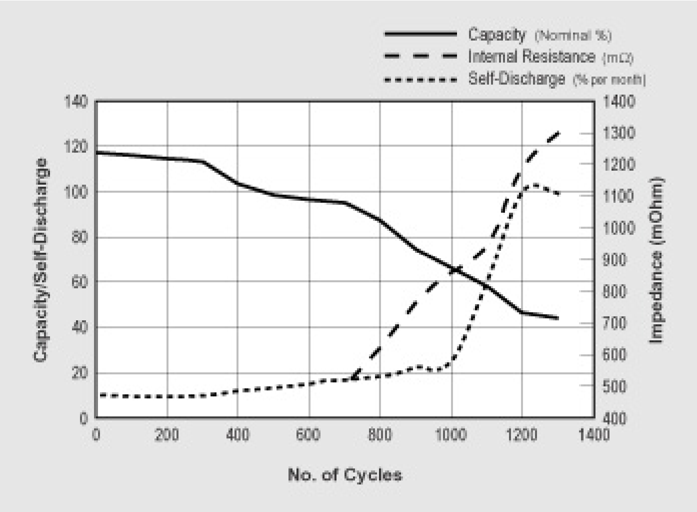


Figure 8-3: Characteristics of a NiMH battery.
This battery offers good performance at first but past the 300-cycle mark, the capacity, internal resistance and self-discharge start to deteriorate rapidly. This illustrations shows results for a 6V, 950mA NiMH.

The Li-ion Battery — The Li-ion battery offers advantages that neither the NiCd nor NiMH can match. In Figure 8-4 we examine the capacity and internal resistance of a typical Li-ion. A gentle capacity drop is observed over 1000 cycles and the internal resistance increases only slightly. Because of low readings, self-discharge was omitted for this test.

The better than expected performance of this test battery may be due to the fact that the test did not include aging. The lab test was completed in about 200 days. A busy user may charge the battery once every 24 hours. With such a user pattern, 500 cycles would represent close to two years of normal use and the effects of aging would become apparent.

Manufacturers of commercial Li-ion batteries specify a cycle count of 500. At that stage, the battery capacity would drop from 100 to 80 percent. If operated at 40°C (104°F) rather than at room temperature, the same battery would only deliver about 300 cycles.

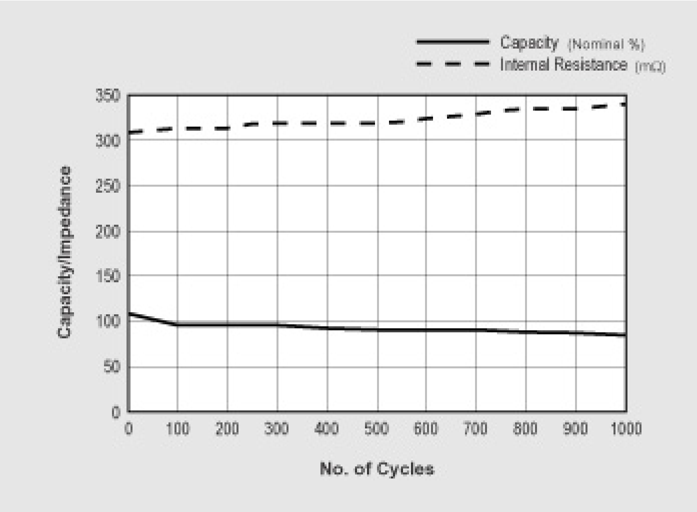


Figure 8-4: Characteristics of a Li-ion battery.
The above-average performance of this battery may be due to the fact that the test did not include aging. This illustration shows results for a 3.6V, 500mA Li-ion battery.

Chapter 9: Internal Battery Resistance

With the move from analog to digital devices, new demands are being placed on the battery. Unlike analog equipment that draws a steady current, the digital mobile phone, for example, loads the battery with short, high current bursts.

> *The internal resistance is the gatekeeper that, to a large extent, determines the runtime.*

Increasingly, mobile communication devices are moving from voice only to multimedia which allows sending and receiving data, still pictures and even video. Such transmissions add to the bandwidth, which require several times the battery power compared to voice only.

One of the urgent requirements of a battery for digital applications is low internal resistance. Measured in milliohms (mΩ), the internal resistance is the gatekeeper that, to a large extent, determines the runtime. The lower the resistance, the less restriction the battery encounters in delivering the needed power bursts. A high mΩ reading can trigger an early ‘low battery’ indication on a seemingly good battery because the available energy cannot be delivered in an appropriate manner.

Figure 9-1 examines the major global mobile phone systems and compares peak power and peak current requirements. The systems are the AMP, GSM, TDMA and CDMA.

	AMP	**GSM**	**TDMA**[1]	**CDMA**
Type	Analog	Digital	Digital	Digital
Used in	USA, Canada	Globally	USA, Canada	USA, Canada
Peak Power	0.6W	1-2W	0.6-1W	0.2W
Peak current[2]	0.3A DC	1-2.5A	0.8-1.5A	0.7A
In service since	1985	1986	1992	1995

Figure 9-1: Peak power requirements of popular global mobile phone systems.
Moving from voice to multi-media requires several times the battery power.

1. Some TDMA handsets feature dual mode (analog 800mA DC load; digital 1500mA pulsed load).
2. Current varies with battery voltage; a 3.6V battery requires higher current than a 7.2V battery.

Why do seemingly good batteries fail on digital equipment?

Service technicians have been puzzled by the seemingly unpredictable battery behavior when powering digital equipment. With the switch from analog to digital wireless communications devices, particularly mobile phones, a battery that performs well on an analog device may show irrational behavior when used on a digital device. Testing these batteries with a battery analyzer produces normal capacity readings. Why then do some batteries fail prematurely on digital devices but not on analog?

The overall energy requirement of a digital mobile phone is less than that of the analog equivalent, however, the battery must be capable of delivering high current pulses that are often several times that of the battery’s rating. Let’s look at the battery rating as expressed in C-rates.

A 1C discharge of a battery rated at 500mAh is 500mA. In comparison, a 2C discharge of the same battery is 1000mA. A GSM phone powered by a 500mA battery that draws 1.5A pulses loads the battery with a whopping 3C discharge.

A 3C rate discharge is fine for a battery with very low internal resistance. However, aging batteries, especially Li-ion and NiMH chemistries, pose a challenge because the mΩ readings of these batteries increase with use.

Improved performance can be achieved by using a larger battery, also known as an extended pack. Somewhat bulkier and heavier, an extended pack offers a typical rating of about 1000mAh or roughly double that of the slim-line. In terms of C-rate, the 3C discharge is reduced to 1.5C when using a 1000mAh instead of a 500mAh battery.

As part of ongoing research to find the best battery system for wireless devices, Cadex has performed life cycle tests on various battery systems. In Figure 9-2, Figure 9-3, and Figure 9-4, we examine NiCd, NiMH and Li-ion batteries, each of which generates a good capacity reading when tested with a battery analyzer but produce stunning differences on a pulsed discharge of 1C, 2C and 3C. These pulses simulate a GSM phone.

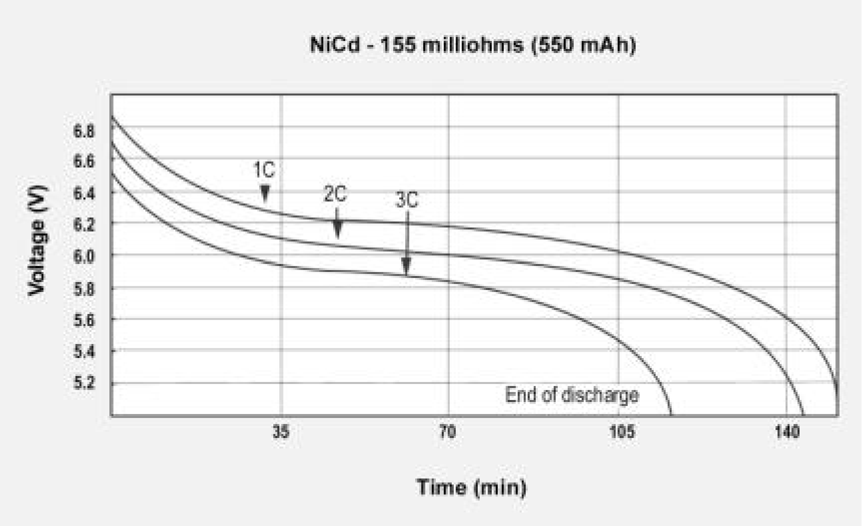


Figure 9-2: Talk-time of a NiCd battery under the GSM load schedule.
This battery has 113% capacity and 155mΩ internal resistance.

A closer look reveals vast discrepancies in the mΩ measurements of the test batteries. In fact, these readings are typical of batteries that have been in use for a while. The NiCd shows 155mΩ, the NiMH 778mΩ and the Li-ion 320mΩ, although the capacities checked in at 113, 107 and 94 percent respectively when tested with the DC load of a battery analyzer. It should be noted that the internal resistance was low when the batteries were new.

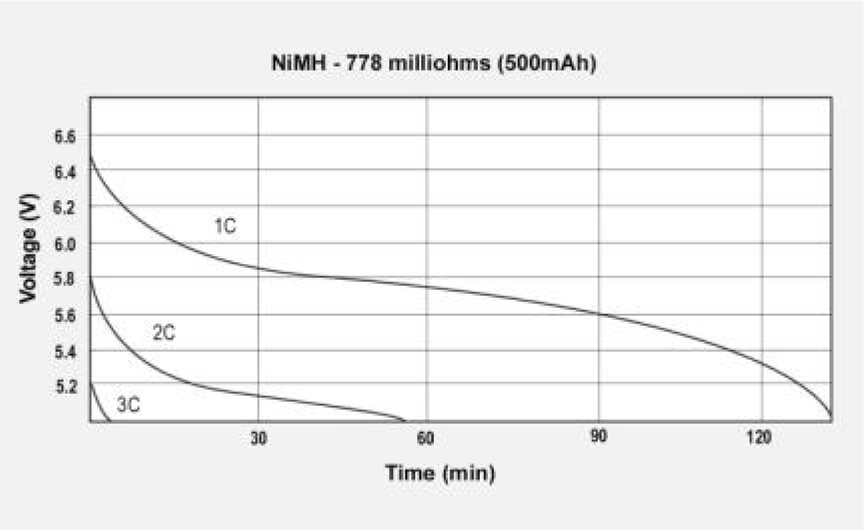


Figure 9-3: Talk-time of a NiMH battery under the GSM load schedule.
This battery has 107% capacity and 778mΩ internal resistance.

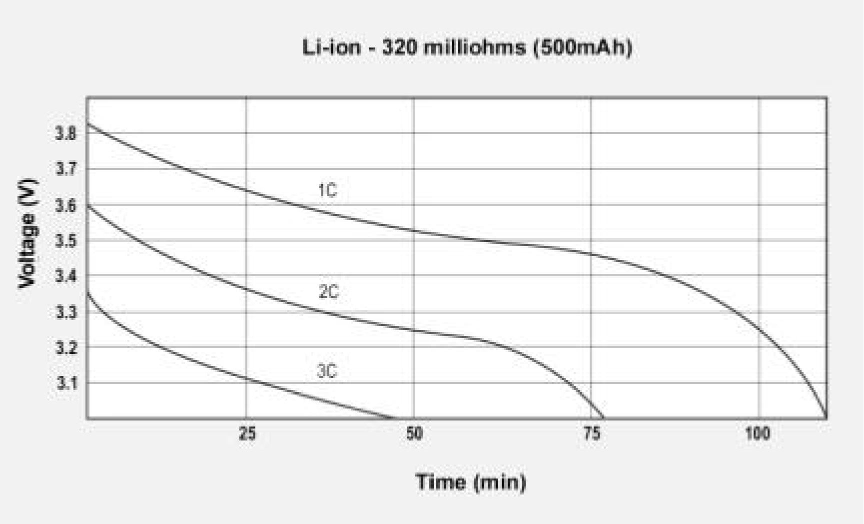


Figure 9-4: Talk-time of a Li-ion battery under the GSM load schedule.
This battery has 94% capacity and 320mΩ internal resistance.

From these charts we can see that the talk-time is in direct relationship with the battery's internal resistance. The NiCd performs best and produces a talk time of 140 minutes at 1C and a long 120 minutes at 3C. In comparison, the NiMH is good for 140 minutes at 1C but fails at 3C. The Li-ion provides 105 minutes at 1C and 50 minutes at 3C discharge.

How is the internal battery resistance measured?

A number of techniques are used to measure internal battery resistance. One common method is the DC load test, which applies a discharge current to the battery while measuring the voltage drop. Voltage over current provides the internal resistance (see Figure 9-5).

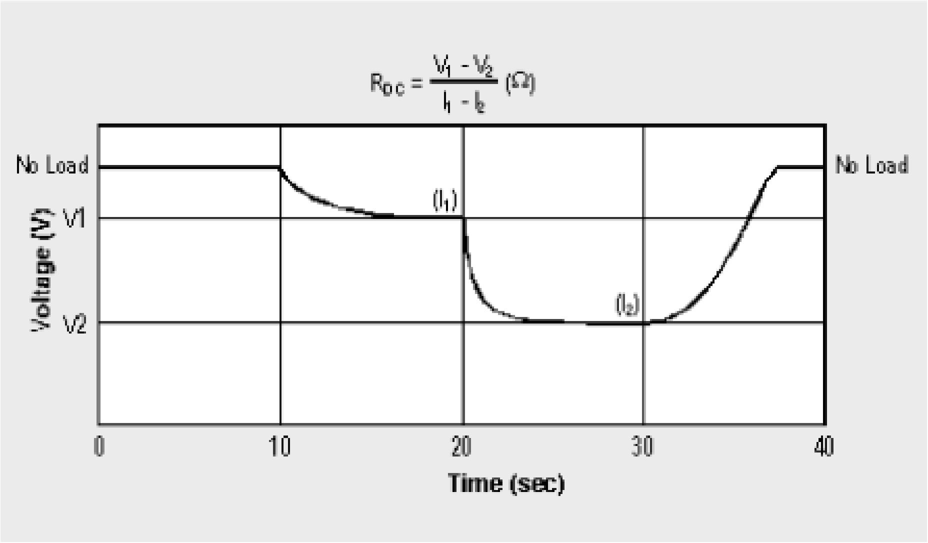


Figure 9-5: DC load test.
The DC load test measures the battery's internal resistance by reading the voltage drop. A large drop indicates high resistance.

The AC method, also known as the conductivity test, measures the electrochemical characteristics of a battery. This technique applies an alternating current to the battery terminals. Depending on manufacturer and battery type, the frequency ranges from 10 to 1000Hz. The impedance level affects the phase shift between voltage and current, which reveals the condition of the battery. The AC method works best on single cells. Figure 9-6 demonstrates a typical phase shift between voltage and current when testing a battery.

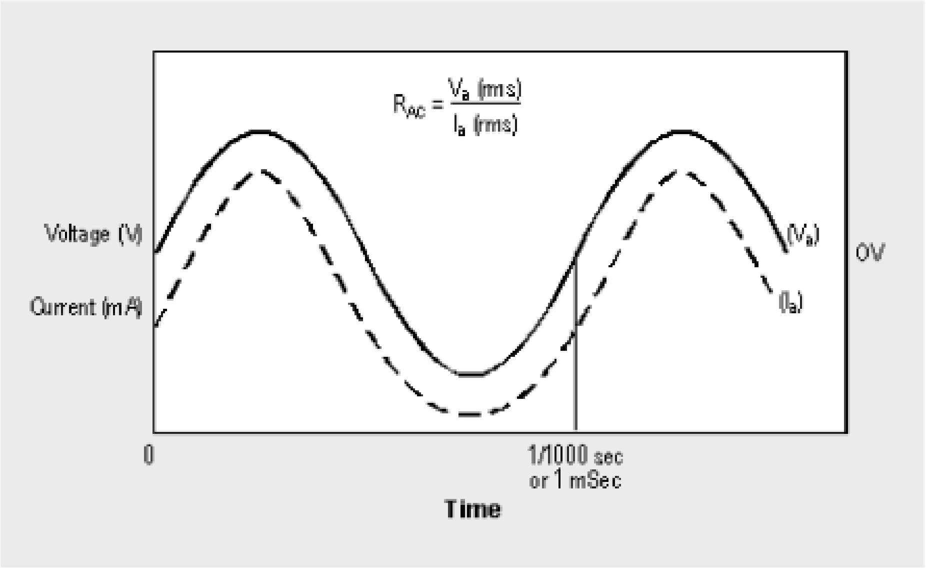


Figure 9-6: AC load test.
The AC method measures the phase shift between voltage and current. The battery's reactance is used to calculate the impedance.

Some AC resistance meters evaluate only the load factor and disregard the phase shift information. This technique is similar to the DC method. The AC voltage that is superimposed on the battery's DC voltage acts as brief charge and discharge pulses. The amplitude of the ripple is utilized to calculate the internal battery resistance.

Cadex uses the discreet DC method to measure internal battery resistance. Added to the Cadex *7000 Series* battery analyzers, a number of charge and discharge pulses are applied, which are scaled to the mAh rating of the battery tested. Based on the voltage deflections, the battery’s internal resistance is calculated. Known as *Ohmtest*™, the mΩ reading is obtained in five seconds. Figure 9-7 shows the technique used.

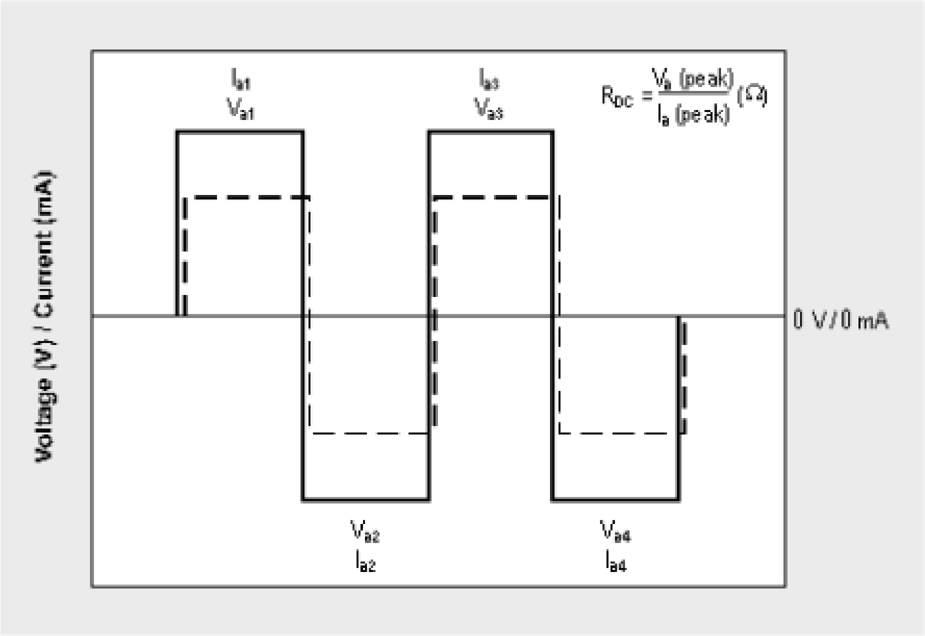


Figure 9-7: Cadex *Ohmtest*™.
Cadex’s pulse method measures the voltage deflections by applying charge and discharge pulses. Higher deflections indicate higher internal resistance.

Figure 9-8 compares the three methods of measuring the internal resistance of a battery and observe the accuracy. In a good battery, the discrepancies between methods are minimal. The test results deviate to a larger degree on packs with poor SoH.

Impedance measurement alone does not provide a definite conclusion as to the battery performance. The mΩ readings may vary widely and are dependent on battery chemistry, cell size (mAh rating), type of cell, number of cells connected in series, wiring and contact type.

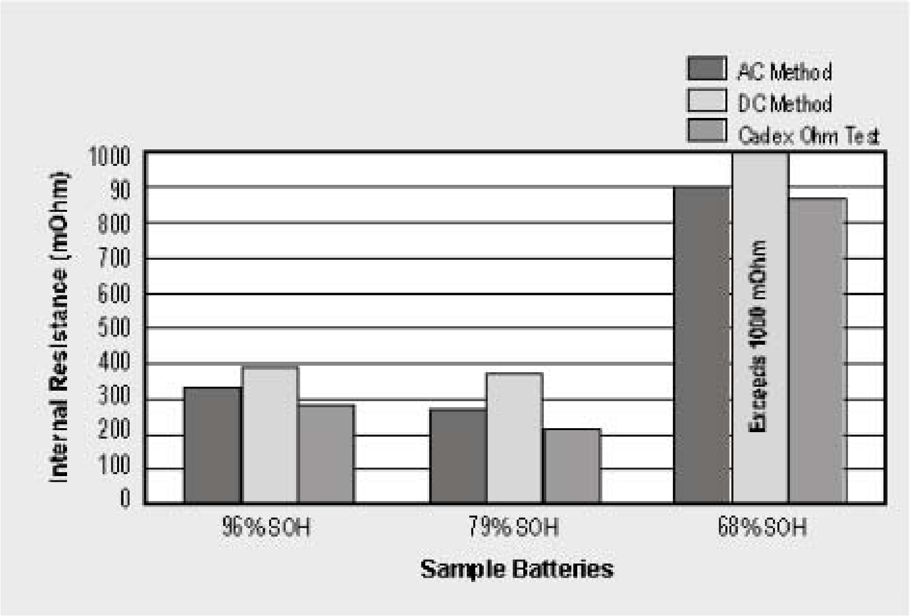


Figure 9-8: Comparison of the AC, DC and Cadex *Ohmtest*™ methods.
State-of-health readings were obtained using the Cadex *7000 Series* battery analyzer by applying a full charge/discharge/charge cycle. The DC method on the 68% SoH battery exceeded 1000mΩ.

When using the impedance method, a battery with a known performance should be measured and its readings used as a reference. For best results, a reference reading should be on hand for each battery type. Figure 9-9kl; provides a guideline for digital mobile phone batteries based on impedance readings.

The milliohm readings are related to the battery voltage. Higher voltage batteries allow higher internal resistance because less current is required to deliver the same power. The ratio between voltage and milliohm is not totally linear. There are certain housekeeping components that are always present whether the battery has one or several cells. These are wiring, contacts and protection circuits.

Temperature also affects the internal resistance of a battery. The internal resistance of a naked Li-ion cell, for example, measures 50mΩ at 25°C (77°F). If the temperature increases, the internal resistance decreases. At 40°C (104°F), the internal resistance drops to about 43mΩ and at 60°C (140°F) to 40mΩ. While the battery performs better when exposed to heat, prolonged exposure to elevated temperatures is harmful. Most batteries deliver a momentary performance boost when heated.

Milli-Ohm	Battery Voltage	Ranking
75-150mOhm	3.6V	Excellent
150-250mOhm	3.6V	Good
250-350mOhm	3.6V	Marginal
350-500mOhm	3.6V	Poor
Above 500mOhm	3.6V	Fail

Figure 9-9: Battery state-of-health based on internal resistance.
The milliohm readings relate to the battery voltage; higher voltage allows higher milliohm readings.

Cold temperatures have a drastic effect on all batteries. At 0°C (32°F), the internal resistance of the same Li-ion cell drops to 70mΩ. The resistance increases to 80mΩ at -10°C (50°F) and 100mΩ at -20°C (-4°F).

The impedance readings work best with Li-ion batteries because the performance degradation follows a linear pattern with cell oxidation. The performance of NiMH batteries can also be measured with the impedance method but the readings are less dependable. There are instances when a poorly performing NiMH battery can also exhibit a low mΩ reading.

Testing a NiCd on resistance alone is unpredictable. A low resistance reading does not automatically constitute a good battery. Elevated impedance readings are often caused by memory, a phenomenon that is reversible. Internal resistance values have been reduced by a factor of two and three after servicing the affected batteries with the recondition cycle of a Cadex *7000 Series* battery analyzer. Of cause, high internal resistance can have sources other than memory alone.

What's the difference between internal resistance and impedance?

The terms 'internal resistance' and 'impedance' are often intermixed when addressing the electrical conductivity of a battery. The differences are as follows: The internal resistance views the conductor from a purely resistive value, or ohmic resistance. A comparison can be made with a heating element that produces warmth by the friction of electric current passing through.

Most electrical loads are not purely resistive, rather, they have an element of reactance. If an alternating current (AC) is sent through a coil, for example, an inductance (magnetic field) is created, which opposes current flow. This AC impedance is always higher than the ohmic resistance of the copper wire. The higher the frequency, the higher the inductive resistance becomes. In comparison, sending a direct current (DC) through a coil constitutes an electrical short because there is only a very small ohmic resistance.

Similarly, a capacitor does not allow the flow of DC, but passes AC. In fact, a capacitor is an insulator for DC. The resistance that is present when sending an AC current flowing through a capacitor is called capacitance. The higher the frequency, the lower the capacitive resistance.

A battery as a power source combines ohmic, inductive and capacitive resistance. Figure 9-10 represents these resistive values on a schematic diagram. Each battery type exhibits slightly different resistive values.

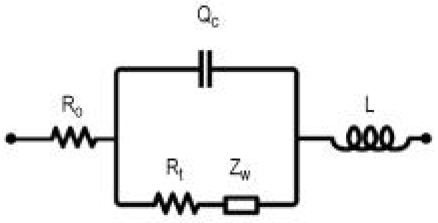


Figure 9-10: Ohmic, inductive and capacitive resistance in batteries.

- R_o = ohmic resistance
- Q_c = constant phase loop (type of capacitance)
- L = inductor
- Z_w = Warburg impedance (particle movement within the electrolyte)
- R_t = transfer resistance

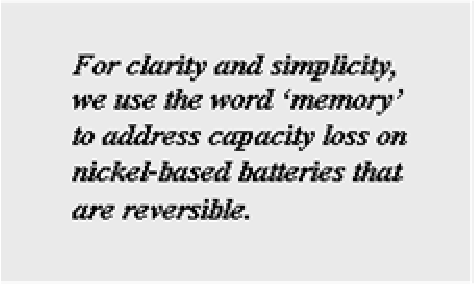
Chapter 10: Getting the Most from your Batteries

A common difficulty with portable equipment is the gradual decline in battery performance after the first year of service. Although fully charged, the battery eventually regresses to a point where the available energy is less than half of its original capacity, resulting in unexpected downtime.

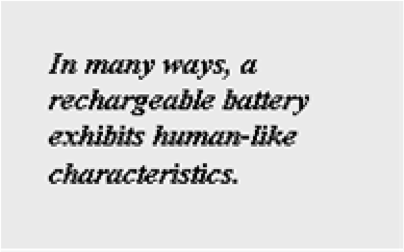
Downtime almost always occurs at critical moments. This is especially true in the public safety sector where portable equipment runs as part of a fleet operation and the battery is charged in a pool setting, often with minimal care and attention. Under normal conditions, the battery will hold enough power to last the day. During heavy activities and longer than expected duties, a marginal battery cannot provide the extra power needed and the equipment fails.

Rechargeable batteries are known to cause more concern, grief and frustration than any other part of a portable device. Given its relatively short life span, the battery is the most expensive and least reliable component of a portable device.

In many ways, a rechargeable battery exhibits human-like characteristics: it needs good nutrition, it prefers moderate room temperature and, in the case of the nickel-based system, requires regular exercise to prevent the phenomenon called ‘memory’. Each battery seems to develop a unique personality of its own.



For clarity and simplicity, we use the word ‘memory’ to address capacity loss on nickel-based batteries that are reversible.



In many ways, a rechargeable battery exhibits human-like characteristics.

Memory: myth or fact?

The word ‘memory’ was originally derived from ‘cyclic memory’, meaning that a NiCd battery can remember how much discharge was required on previous discharges. Improvements in battery technology have virtually eliminated this phenomenon. Tests performed at a Black & Decker lab, for example, showed that the effects of cyclic memory on the modern NiCd were so small that they could only be detected with sensitive instruments. After the same battery was discharged for different lengths of time, the cyclic memory phenomenon could no longer be noticed.

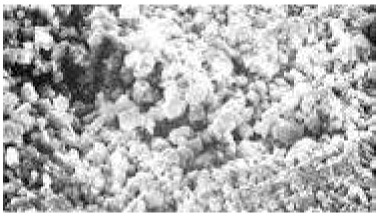
The problem with the nickel-based battery is not the cyclic memory but the effects of crystalline formation. There are other factors involved that cause degeneration of a battery. For clarity and simplicity, we use the word ‘memory’ to address capacity loss on nickel-based batteries that are reversible.

The active cadmium material of a NiCd battery is present in finely divided crystals. In a good cell, these crystals remain small, obtaining maximum surface area. When the memory phenomenon occurs, the crystals grow and drastically reduce the surface area. The result is a voltage depression, which leads to a loss of capacity. In advanced stages, the sharp edges of the crystals may grow through the separator, causing high self-discharge or an electrical short.

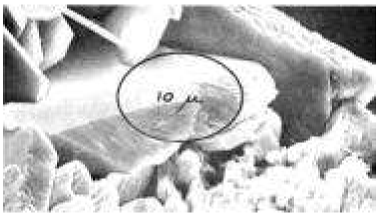
Another form of memory that occurs on some NiCd cells is the formation of an inter-metallic compound of nickel and cadmium, which ties up some of the needed cadmium and creates extra resistance in the cell. Reconditioning by deep discharge helps to break up this compound and reverses the capacity loss.

The memory phenomenon can be explained in layman’s terms as expressed by Duracell: “The voltage drop occurs because only a portion of the active materials in the cells is discharged and recharged during shallow or partial discharging. The active materials that have not been cycled change in physical characteristics and increase in resistance. Subsequent full discharge/charge cycling will restore the active materials to their original state.”

When NiMH was first introduced there was much publicity about its memory-free status. Today, it is known that this chemistry also suffers from memory but to a lesser extent than the NiCd. The positive nickel plate, a metal that is shared by both chemistries, is responsible for the crystalline formation.



New NiCd cell.
The anode is in fresh condition (capacity of 8.1Ah). Hexagonal cadmium hydroxide crystals are about 1 micron in cross section, exposing large surface area to the liquid electrolyte for maximum performance.



Cell with crystalline formation.
Crystals have grown to an enormous 50 to 100 microns in cross section, concealing large portions of the active material from the electrolyte (capacity of 6.5Ah). Jagged edges and sharp corners may pierce the separator, which can lead to increased self-discharge or electrical short.

Restored cell.
After pulsed charge, the crystals are reduced to 3 to 5 microns, an almost 100% restoration (capacity of 8.0A). Exercise or recondition are needed if the pulse charge alone is not effective.

Figure 10-1: Crystalline formation on NiCd cell.
Illustration courtesy of the US Army Electronics Command in Fort Monmouth, NJ, USA.

In addition to the crystal-forming activity on the positive plate, the NiCd also develops crystals on the negative cadmium plate. Because both plates are affected by crystalline formation, the NiCd requires more frequent discharge cycles than the NiMH. This is a non-scientific explanation of why the NiCd is more prone to memory than the NiMH.

The stages of crystalline formation of a NiCd battery are illustrated in Figure 10-1. The enlargements show the negative cadmium plate in normal crystal structure of a new cell, crystalline formation after use (or abuse) and restoration.

Lithium and lead-based batteries are not affected by memory, but these chemistries have their own peculiarities. Current inhibiting pacifier layers affect both batteries — plate oxidation on the lithium and sulfation and corrosion on the lead acid systems. These degenerative effects are non-correctible on the lithium-based system and only partially reversible on the lead acid.

How to Restore and Prolong Nickel-based Batteries

The effects of crystalline formation are most pronounced if a nickel-based battery is left in the charger for days, or if repeatedly recharged without a periodic full discharge. Since most applications do not use up all energy before recharge, a periodic discharge to 1V/cell (known as exercise) is essential to prevent the buildup of crystalline formation on the cell plates. This maintenance is most critical for the NiCd battery.

All NiCd batteries in regular use and on standby mode (sitting in a charger for operational readiness) should be exercised once per month. Between these monthly exercise cycles, no further service is needed. The battery can be used with any desired user pattern without the concern of memory.

The NiMH battery is affected by memory also, but to a lesser degree. No scientific research is available that compares NiMH with NiCd in terms of memory degradation. Neither is information on hand that suggests the optimal amount of maintenance required to obtain maximum battery life. Applying a full discharge once every three months appears right. Because of the NiMH battery's shorter cycle life, over-exercising is not recommended.

A hand towel must be cleaned periodically. However, if it were washed after each use, its fabric would wear out very quickly. In the same way, it is neither necessary nor advisable to discharge a rechargeable battery before each charge — excessive cycling puts extra strain on the battery.

Exercise and Recondition — Research has shown that if no exercise is applied to a NiCd for three months or more, the crystals ingrain themselves, making them more difficult to break up. In such a case, exercise is no longer effective in restoring a battery and reconditioning is required. Recondition is a slow, deep discharge that removes the remaining battery energy by draining the cells to a voltage threshold below 1V/cell.

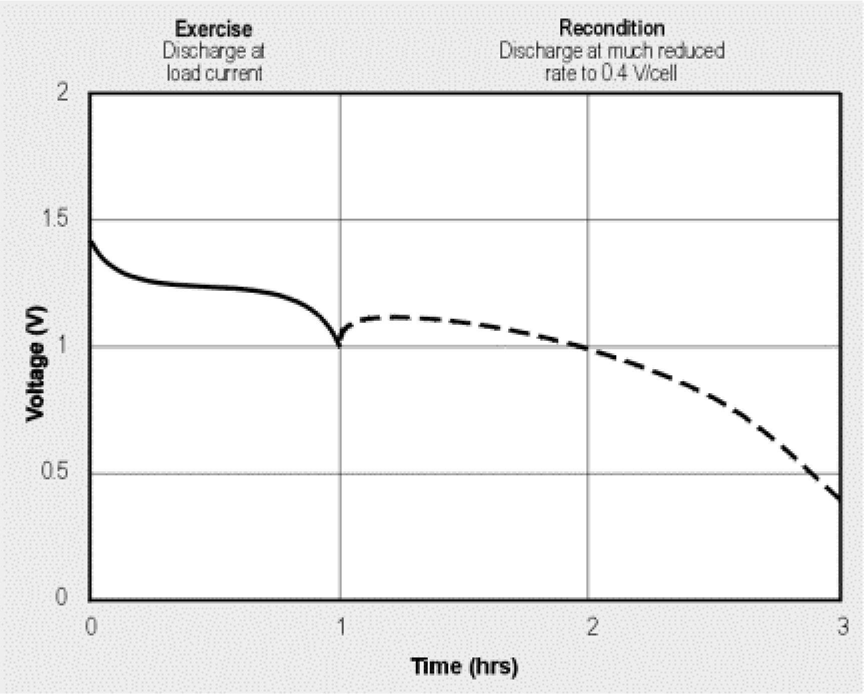


Figure 10-2: Exercising and reconditioning batteries on a Cadex battery analyzer. This illustration shows the battery voltage during a normal discharge to 1V, followed by the secondary discharge (recondition). Recondition consists of a discharge to 1V/cell at a 1C load current, followed by a secondary discharge to 0.4V at a much reduced current. NiCd batteries affected by memory often restore themselves to full service.

Tests performed by the US Army have shown that a NiCd cell needs to be discharged to at least 0.6V to effectively break up the more resistant crystalline formation. During recondition, the current must be kept low to prevent cell reversal. Figure 10-2 illustrates the battery voltage during normal discharge to 1V/cell followed by the secondary discharge (recondition).

Figure 10-3 illustrates the effects of exercise and recondition. Four batteries afflicted with various degrees of memory are serviced. The batteries are first fully charged, then discharged to 1V/cell. The resulting capacities are plotted on a scale of 0 to 120 percent in the first column. Additional discharge/charge cycles are applied and the battery capacities are plotted in the subsequent columns. The solid black line represents exercise, (discharge to 1V/cell) and the dotted line recondition (secondary discharge at reduced current to 0.4V/cell). On this test, the exercise and recondition cycles are applied manually at the discretion of the research technician.

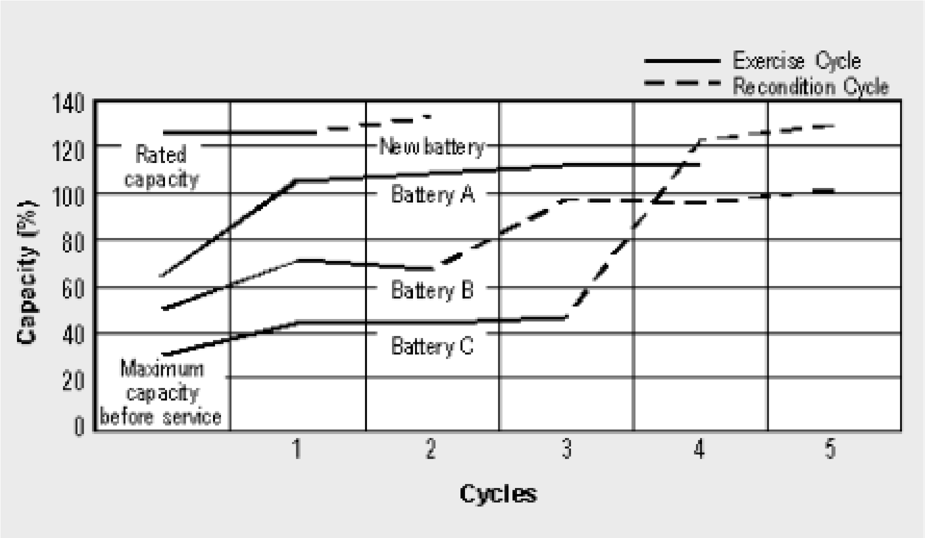


Figure 10-3: Effects of exercise and recondition.
Battery A improved capacity on exercise alone; batteries B and C required recondition. A new battery with excellent readings improved further with recondition.

Battery A responded well to exercise alone and no recondition was required. This result is typical of a battery that has been in service for only a few months or has received periodic exercise cycles. Batteries B and C, on the other hand, required recondition (dotted line) to restore their performance. Without the recondition function, these two batteries would need to be replaced.

After service, the restored batteries were returned to full use. When examined after six months of field use, no noticeable degradation in the restored performance was visible. The regained capacity was permanent with no evidence of falling back to the previous state. Obviously, the batteries would need to be serviced on a regular basis to maintain the performance.

Applying the recondition cycle on a new battery (top line on chart) resulted in a slight capacity increase. This capacity gain is not fully understood, other than to assume that the battery improved by additional formatting. Another explanation is the presence of early memory. Since new batteries are stored with some charge, the self-discharge that occurs during storage contributes to a certain amount of crystalline formation. Exercising and reconditioning reverse this effect. This is why the manufacturers recommend storing rechargeable batteries at about 40 percent charge.

The importance of exercising and reconditioning NiCd batteries is emphasized further by a study carried out by GTE Government Systems in Virginia, USA, for the US Navy. To determine the percentage of batteries needing replacement within the first year of use, one group of batteries received charge only, another group was exercised and a third group received recondition. The batteries studied were used for two-way radios on the aircraft carriers USS Eisenhower with 1500 batteries and USS George Washington with 600 batteries, and the destroyer USS Ponce with 500 batteries.

With charge only (charge-and-use), the annual percentage of battery failure on the USS Eisenhower was 45 percent (see Figure 10-4). When applying exercise, the failure rate was reduced to 15 percent. By far the best results were achieved with recondition. The failure rate dropped to 5 percent. Identical results were attained from the USS George Washington and the USS Ponce.

Maintenance Method	Annual Percentage of Batteries Requiring Replacement
Charge only (charge-and-use)	45%
Exercise only (discharge to 1V/cell)	15%
Reconditioning (secondary deep discharge)	5%

Figure 10-4: Replacement rates of NiCd batteries.
The annual percentage of NiCd batteries requiring replacement when used without any maintenance decreases with exercise and recondition. These statistics were drawn from batteries used by the US Navy on the USS Eisenhower, USS George Washington and USS Ponce.

The GTE Government System report concluded that a battery analyzer featuring exercise and recondition functions costing $2,500US would pay for itself in less than one month on battery savings alone. The report did not address the benefits of increased system reliability, an issue that is of equal if not greater importance, especially when the safety of human lives is at stake.

Another study involving NiCd batteries for defense applications was performed by the Dutch Army. This involved battery packs that had been in service for 2 to 3 years during the Balkan War. The Dutch Army was aware that the batteries were used under the worst possible conditions. Rather than a good daily workout, the packs were used for patrol duties lasting 2 to 3 hours per day. The rest of the time the batteries remained in the chargers for operational readiness.

After the war, the batteries were sent to the Dutch Military Headquarters and were tested with Cadex *7000 Series* battery analyzers. The test technician found that the capacity of some packs had dropped to as low as 30 percent. With the recondition function, 90 percent of the batteries restored themselves to full field use. The Dutch Army set the target capacity threshold for field acceptability to 80 percent. This setting is the pass/fail acceptance level for their batteries.

Based on the successful reconditioning results, the Dutch Army now assigns the battery maintenance duty to individual battalions. The program calls for a service once every two months. Under this regime, the Army reports reduced battery failure and prolonged service life. The performance of each battery is known at any time and any under-performing battery is removed before it causes a problem.

NiCd batteries remain the preferred chemistry for mobile communications, both in civil and defense applications. The main reason for its continued use is dependable and enduring service under difficult conditions. Other chemistries have been tested and found problematic in long-term use.

During the later part of the 1990s, the US Army switched from mainly non-rechargeable to the NiMH battery. The choice of chemistry was based on the benefit of higher energy densities as compared to NiCd. The army soon discovered that the NiMH did not live up to the expected cycle life. Their reasoning, however, is that the 100 cycles attained from a NiMH pack is still more economical than using a non-rechargeable equivalent. The army’s focus is now on the Li-ion Polymer, a system that is more predictable than NiMH and requires little or no maintenance. The aging issue will likely cause some logistic concerns, especially if long-term storage is required.

Simple Guidelines

Do not leave a nickel-based battery in a charger for more than a day after full charge is reached.

- Apply a monthly full discharge cycle. Running the battery down in the equipment may do this also.
- Do not discharge the battery before each recharge. This would put undue stress on the battery.
- Avoid elevated temperature. A charger should only raise the battery temperature for a short time at full charge, and then the battery should cool off.
- Use quality chargers to charge batteries.

The Effect of Zapping

To maximize battery performance, remote control (RC) racing enthusiasts have experimented with all imaginable methods available. One technique that seems to work is zapping the cells with a very high pulse current. Zapping is said to increase the cell voltage slightly, generating more power.

Typically, the racecar motor draws 30A, delivered by a 7.2V battery. This calculates to over 200W of power. The battery must endure a race lasting about four minutes.

According to experts, zapping works best with NiCd cells. NiMH cells have been tried but they have shown inconsistent results.

Companies specializing in zapping NiCd for RC racing use a very high quality Japanese NiCd cell. The cells are normally sub-C in size and are handpicked at the factory for the application. Specially labeled, the cells are delivered in a discharged state. When measuring the cell in empty state-of-charge (SoC), the voltage typically reads between 1.11 to 1.12V. If the voltage drops lower than 1.06V, the cell is considered suspect and zapping does not seem to enhance the performance as well as on the others.

The zapping is done with a 47,000mF capacitor that is charged to 90V. Best results are achieved if the battery is cycled twice after treatment, then is zapped again. After the battery has been in service for a while, zapping no longer seems to improve the cell’s performance. Neither does zapping regenerate a cell that has become weak.

The voltage increase on a properly zapped battery is between 20 and 40mV. This improvement is measured under a load of 30A. According to experts, the voltage gain is permanent but there is a small drop with usage and age.

There are no apparent side effects in zapping, however, the battery manufacturers remain silent about this treatment. No scientific explanations are available why the method of zapping improves battery performance. There is little information available regarding the longevity of the cells after they have been zapped.

How to Restore and Prolong Sealed Lead Acid Batteries

The sealed version of the lead acid battery is designed with a low over-voltage potential to prevent water depletion. Consequently, the SLA and VRLA systems never get fully charged and some sulfation will develop over time.

Finding the ideal charge voltage limit for the sealed lead acid system is critical. Any voltage level is a compromise. A high voltage limit produces good battery performance, but shortens the service life due to grid corrosion on the positive plate. The corrosion is permanent and cannot be reversed. A low voltage preserves the electrolyte and allows charging under a wide temperature range, but is subject to sulfation on the negative plate. (In keeping with portability, this book focuses on portable SLA batteries. Due to similarities between the SLA and VRLA systems, references to the VRLA are made where applicable).

Once the SLA battery has lost capacity due to sulfation, regaining its performance is often difficult and time consuming. The metabolism of the SLA battery is slow and cannot be hurried.

A subtle indication on whether an SLA battery can be recovered is reflected in the behavior of its discharge voltage. A fully charged SLA battery that starts its discharge with a high voltage and tapers off gradually can be reactivated more successfully than one on which the voltage drops rapidly when the load is applied.

Reasonably good results in regaining lost capacity are achieved by applying a charge on top of a charge. This is done by fully charging an SLA battery, then removing it for a 24 to 48 hour rest period and applying a charge again. This is repeated several times, then the capacity of the battery is checked with a full discharge. The SLA is able to accept some overcharge, however, too long an overcharge could harm the battery due to corrosion and loss of electrolyte.

The effect of sulfation of the plastic SLA can be reversed by applying an over-voltage charge of up to 2.50V/cell for one to two hours. During that time, the battery must be kept cool and careful observation is necessary. Extreme caution is required not to raise the cell pressure to venting point. Most plastic SLA batteries vent at 34 kPa (5 psi). Cell venting causes the membrane on some SLA to rupture permanently. Not only do the escaping gases deplete the electrolyte, they are also highly flammable!

The VRLA uses a cell self-regulating venting system that opens and closes the cells based on cell pressure. Changes in atmospheric pressure contribute to cell venting. Proper ventilation of the battery room is essential to prevent the accumulation of hydrogen gas.

Cylindrical SLA — The cylindrical SLA (made by Hawker) resembles an enlarged D sized cell. After long storage, the Hawker cell can be reactivated relatively easily. If affected by sulfation, the cell voltage under charge may initially raise up to 5V, absorbing only a small amount of current. Within about two hours, the small charging current converts the large sulfate crystals back into active material. The internal cell resistance decreases and the charge voltage eventually returns to normal. At a voltage between 2.10V and 2.40V, the cell is able to accept a normal charge. To prevent damage, caution must be exercised to limit the charge current.

The Hawker cells are known to regain full performance with the described voltage method, leaving few adverse effects. This, however, does not give credence to store this cell at a very low voltage. It is always best to follow the manufacturer’s recommended specifications.

Improving the capacity of an older SLA by cycling is mostly unsuccessful. Such a battery may simply be worn out. Cycling would just wear down the battery further. Unlike nickel-based batteries, the lead acid battery is not affected by memory.

SLA batteries are commonly rated at a 20-hour discharge. Even at such a slow rate, a capacity of 100 percent is difficult to obtain. For practical reasons, most battery analyzers use a 5-hour discharge when servicing SLA batteries. This typically produces 80 to 90 percent of the rated capacity. SLA batteries are normally overrated and manufacturers are aware of this.

Caution: When charging an SLA with over-voltage, current limiting must be applied to protect the battery. Always set the current limit to the lowest practical setting and observe the battery voltage and temperature during charge. Prevent cell venting.

Typically 50 to 70 percent of discarded NiCd batteries can be restored.

Important: In case of rupture, leaking electrolyte or any other cause of exposure to the electrolyte, flush with water immediately. If eye exposure occurs, flush with water for 15 minutes and consult a physician immediately.

Simple Guidelines

- Always keep the SLA charged. Never store below 2.10V/cell.
- Avoid repeated deep discharges. Charge more often.
- If repeated deep discharges cannot be avoided, use a larger battery to ease the strain.
- Prevent sulfation and grid corrosion by choosing the correct charge and float voltages.

How to Prolong Lithium-based Batteries

Today’s battery research is heavily focused on lithium chemistries, so much so that one could assume that all future batteries will be lithium systems. Lithium-based batteries offer many advantages over nickel and lead-based systems. Although maintenance free, no external service is known that can restore the battery’s performance once degraded.

In many respects, Li-ion provides a superior service to other chemistries, but its performance is limited to a defined lifespan. The Li-ion battery has a time clock that starts ticking as soon as the battery leaves the factory. The electrolyte slowly ‘eats up’ the positive plate and the electrolyte decays. This chemical change causes the internal resistance to increase. In time, the cell resistance raises to a point where the battery can no longer deliver the energy, although it may still be retained in the battery. Equipment requiring high current bursts is affected most by the increase of internal resistance.

Battery wear-down on lithium-based batteries is caused by two activities: actual usage or cycling, and aging. The wear-down effects by usage and aging apply to all batteries but this is more pronounced on lithium-based systems.

The Li-ion batteries prefer a shallow discharge. Partial discharges produce less wear than a full discharge and the capacity loss per cycle is reduced. A periodic full discharge is not required because the lithium-based battery has no memory. A full cycle constitutes a discharge to 3V/cell. When specifying the number of cycles a lithium-based battery can endure, manufacturers commonly use an 80 percent depth of discharge. This method resembles a reasonably accurate field simulation. It also achieves a higher cycle count than doing full discharges.

In addition to cycling, the battery ages even if not used. The amount of permanent capacity loss the battery suffers during storage is governed by the SoC and temperature. For best results, keep the battery cool. In addition, store the battery at a 40 percent charge level. Never fully charge or discharge the battery before storage. The 40 percent charge assures a stable condition even if self-discharge robs some of the battery’s energy. Most battery manufacturers store Li-ion batteries at 15°C (59°F) and at 40 percent charge.

Simple Guidelines

- Charge the Li-ion often, except before a long storage. Avoid repeated deep discharges.
- Keep the Li-ion battery cool. Prevent storage in a hot car. Never freeze a battery.
- If your laptop is capable of running without a battery and fixed power is used most of the time, remove the battery and store it in a cool place.
- Avoid purchasing spare Li-ion batteries for later use. Observe manufacturing date when purchasing. Do not buy old stock, even if sold at clearance prices.

The recovery rate for lead acid batteries is a low 15 percent.

The recovery rate of the NiMH is about 40 percent.

Battery Recovery Rate

The battery recovery rate by applying controlled discharge/charge cycles varies with chemistry type, cycle count, maintenance practices and age of the battery. The best results are achieved with NiCd. Typically 50 to 70 percent of discarded NiCd batteries can be restored when using the exercise and recondition methods of a Cadex battery analyzer or equivalent device.

Not all batteries respond equally well to exercise and recondition services. An older battery may show low and inconsistent capacity readings with each cycle. Another will get worse when additional cycles are applied. An analogy can be made to a very old man for whom exercise is harmful. Such conditions indicate instabilities caused by aging, suggesting that this pack should be replaced. In fact, some users of the Cadex analyzers use the recondition cycle as the acid test. If the battery gets worse, there is strong evidence that this battery would not perform well in the field. Applying the acid test exposes the weak packs, which can no longer hide behind their stronger peers.

Some older NiCd batteries recover to near original capacity when serviced. Caution should be applied when ‘rehiring’ these old-timers because they may exhibit high self-discharge. If in doubt, a self-discharge test should be carried out.

The recovery rate of the NiMH is about 40 percent. This lower yield is, in part, due to the NiMH’s reduced cycle count as compared to the NiCd. Some batteries may be afflicted by heat damage that occurs during incorrect charging. This deficiency cannot be corrected. Permanent loss of battery capacity is also caused by prolonged storage at elevated temperatures.

The recovery rate for lead acid batteries is a low 15 percent. Unlike nickel-based batteries, the restoration of the SLA is not based on reversing crystalline formation, but rather by reactivating the chemical process. The reasons for low capacity readings are prolonged storage at low terminal voltage, and poor charging methods. The battery also fails due to age and high cycle count.

Lithium-based batteries have a defined age limit. Once the anticipated cycles have been delivered, no method exists to improve the battery. The main reason for failure is high internal resistance caused by oxidation. Operating the battery at elevated temperatures will momentarily reduce this condition. When the temperature normalizes, the condition of high internal resistance returns.

The speed of oxidation depends on the storage temperature and the battery’s charge state. Keeping the battery in a cool place can prolong its life. The Li-ion battery should be stored at 40 percent rather than full-charge state.

A question that is commonly asked is, “Will a restored battery work as good as a new one?

An increasing number of modern batteries fall prey to the cut-off problem induced by a deep discharge. This is especially evident on Li-ion batteries for mobile phones. If discharged below 2.5V/cell, the internal protection circuit often opens. Many chargers cannot apply a recharge and the battery appears to be dead.

Some battery analyzers feature a boost, or wake-up function, to activate the protection circuit and enable a recharge if discharged too low. If the cell voltage has fallen too low (1.5V/cell and lower) and has remained in that state for a few days, a recharge should not be attempted because of safety concerns on the cell(s).

It is often asked whether a restored battery will work as good as a new one. The breakdown of the crystalline formation can be considered a full restoration. However, the crystalline formation will re-occur with time if the battery is denied the required maintenance.

When the defective component of a machine is replaced, only the replaced part is new; the rest of the machine remains in the same condition. If the separator of a nickel-based battery is damaged by excess heat or is marred by uncontrolled crystalline formation, that part of the battery will not improve.

Other methods, which claim to restore and prolong rechargeable batteries, have produced disappointing results. One method is attaching a strong magnet on the side of the battery; another is exposing the battery to ultrasound vibrations. No scientific evidence exists that such methods will improve battery performance, or restore an ailing battery.

Chapter 11: Maintaining Fleet Batteries

Unlike individual battery users, who come to know their batteries like a good friend, fleet users must share the batteries from a pool of unknown packs. While an individual user can detect even a slight reduction in runtime, fleet operators have no way of knowing the behavior or condition of the battery when pulling it from the charger. They are at the mercy of the battery. It's almost like playing roulette.

It is recommended that fleet battery users set up a battery maintenance program. Such a plan exercises all batteries on a regular basis, reconditions those that fall below a set target capacity and 'weeds out' the deadwood. Usually, batteries get serviced only when they no longer hold a charge or when the equipment is sent in for repair. As a result, battery-operated equipment becomes unreliable and battery-related failures often occur. The loss of adequate battery power is as detrimental as any other malfunction in the system.

Implementing a battery maintenance plan requires an effort by management to schedule the required service for the battery packs. This should become an integral component of an organization's overall equipment maintenance and repair activities. A properly managed program improves battery performance, enhances reliability and cuts replacement costs.

The maintenance plan should include all rechargeable batteries in use. Large organizations often employ a variety of batteries ranging from wireless communications, to mobile computing, to emergency medical equipment, to video cameras, portable lighting and power tools. The performance of these batteries is critical and there is little room for failure.

Whether the batteries are serviced in-house with their own battery analyzers or sent to an independent firm specializing in that service, sufficient spare batteries are required to replace those packs that have been temporarily removed. When the service is done on location and the batteries can be reinstated within 24 hours, only five spares in a fleet of 100 batteries are required. This calculation is based on servicing five batteries per day in a 20 workday month, which equals100 batteries per month. If the batteries are sent away, five spares are needed for each day the batteries are away. If 100 batteries are absent for one week, for example, 35 spare batteries are needed.

Manufacturers of portable equipment support battery maintenance programs. Not only does such a plan reduce unexpected downtime, a well-performing battery fleet makes the equipment work better. If the recurring problems relating to the battery can be eliminated, less equipment is sent to the service centers. A well-managed battery maintenance program also prolongs battery life, a benefit that looks good for the vendor.

Usually, batteries get serviced only when they no longer hold a charge or when the equipment is sent in for repair.

The ‘Green Light’ Lies

When charging a battery, the ready light will eventually illuminate, indicating that the battery is fully charged. The user assumes that the battery has reached its full potential and the battery is taken in confidence.

In no way does the ‘green light’ guarantee sufficient battery capacity or assure good state-of-health (SoH). Similar to a toaster that pops up the bread when brown (or black), the charger fills the battery with energy and ‘pops’ it to ready when full (or warm).

The rechargeable battery is a corrosive device that gradually loses its ability to hold a charge. Many users in an organization are unaware that their fleet batteries barely last a day with no reserve energy to spare. In fact, weak batteries can hide comfortably because little demand is placed on them in a routine day. The situation changes when full performance is required during an emergency. Total collapse of portable systems is common and such breakdowns are frequently related to poor battery performance. Figure 11-1 shows five batteries in various states of degradation.

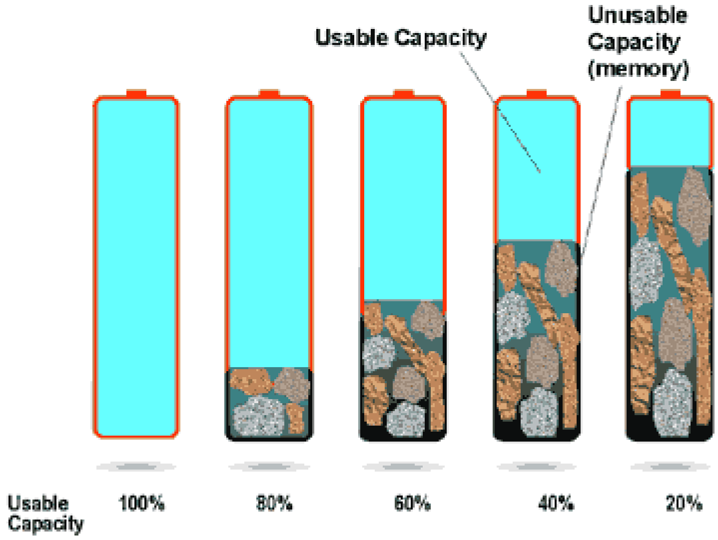
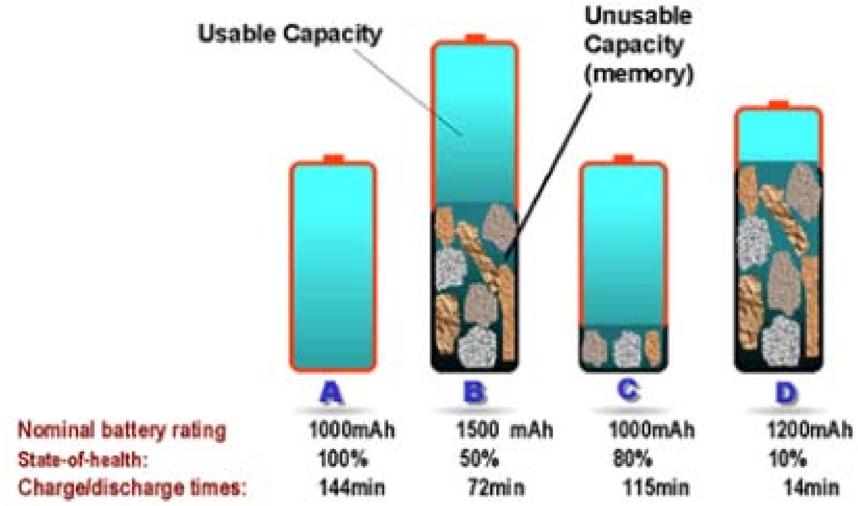


Figure 11-1: Progressive loss of charge acceptance.
The rechargeable battery is a corrosive device that gradually loses its ability to hold charge as part of natural aging, incorrect use and/or lack of maintenance. The unusable part of the battery that creeps in is referred to as ‘rock content’.

Carrying larger packs or switching to higher energy-dense chemistries does not assure better reliability if the weak batteries are not ‘weeded’ out at the appropriate time. Likewise, the benefit of using ultra-advanced battery systems offers little advantage if packs are allowed to remain in the fleet once their performance has dropped below an acceptable performance level.

The bad batteries tend to gravitate to the top. They become a target for the unsuspecting user.

Figure 11-2 illustrates four batteries with different ratings and SoH conditions. Batteries B, C and D show reduced performance because of memory problems and other deficiencies. The worst pack is Battery D. Because of its low charge acceptance, this battery might switch to ready after only 14 minutes of charge (assumed time). Ironically, this battery is a likely candidate to be picked when a fresh battery is required in a hurry. Unfortunately, it will last only for a brief moment. Battery A, on the other hand, has the highest capacity and takes the longest to charge. Because the ready light is not yet lit, this battery is least likely picked.



	A	B	C	D
Nominal battery rating	1000mAh	1500 mAh	1000mAh	1200mAh
State-of-health:	100%	50%	80%	10%
Charge/discharge times:	144min	72min	115min	14min

Figure 11-2: Comparison of charge and discharge times.
This illustration shows typical charge and discharge times for batteries with different ratings and SoH conditions. Carrying larger batteries or switching to high energy-dense chemistries does not necessarily assure longer runtime if deadwood is allowed to remain in the battery fleet.

The weak batteries are charged quicker and remain on ‘ready’ longer than the strong ones. The bad batteries tend to gravitate to the top. They become a target for the unsuspecting user. In an emergency situation that demands quick charge action, the batteries that show ready may simply be those that are deadwood.

A weak battery can be compared to a fuel tank with an indentation. Refueling this tank is quicker than a normal tank because it holds less fuel. Similar to the ‘green light’ on a charger, the fuel gauge in the vehicle will show full when filled to the brim, but the distance traveled before refueling will be short.

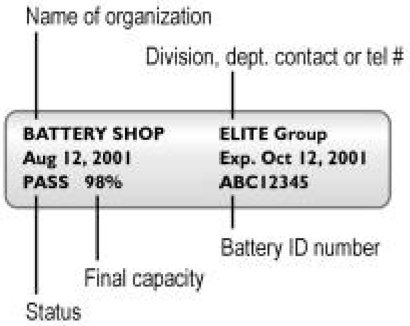
Battery Maintenance, a Function of Quality Control

The reliability of portable equipment relies almost entirely on the performance of the battery. A dependable battery fleet can only be assured if batteries are maintained on a periodic basis.

Battery maintenance also needs proper documentation. One simple method is attaching a color dot, each color indicating the month of service. A different color dot is applied when the battery is re-serviced the following month. A numbering system indicating the month of service also works well.

A better system is attaching a full battery label containing service date and capacity. Like the pending service on a car, the label shows the user when maintenance is due. For critical missions, the user will pick a battery with the highest capacity and the most recent service date. The label ensures a properly serviced replacement pack.

Battery analyzers are available that print a label revealing the organization, group, service date, expiry date (time to service the battery), battery capacity and ID number. The label is generated automatically when the battery is removed from the analyzer. Figure 11-3 illustrates such a label.



11-3: Sample battery label.
The battery label keeps track of the battery in the same way a service sticker on a car reminds the owner of pending service.

The battery labeling system is simple to manage. It is self-governing in the sense that the users would only pick a battery that is properly labeled and has recently been serviced. The system does not permit batteries to fall though the cracks and be forgotten. It is in the interest of the user to ensure continued reliability by bringing in batteries with dated labels for service.

Battery Maintenance Made Simple

Several methods are available to maintain a fleet of batteries. A simple, self-governing system is illustrated in Figure 11-4 to Figure 11-6. Only 30 minutes per day should be required for a technician to maintain the system. One or several battery analyzers are needed that are capable of producing battery labels.

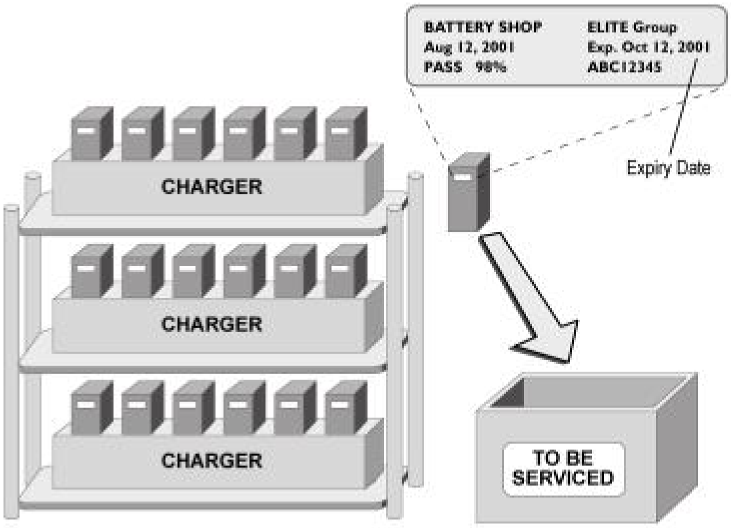


Figure 11-4: Sorting batteries for servicing.
Each time a battery is taken from the charger, the user checks the service date on the label attached to the battery. If the date has expired, the battery is placed in a box marked ‘To be serviced’.

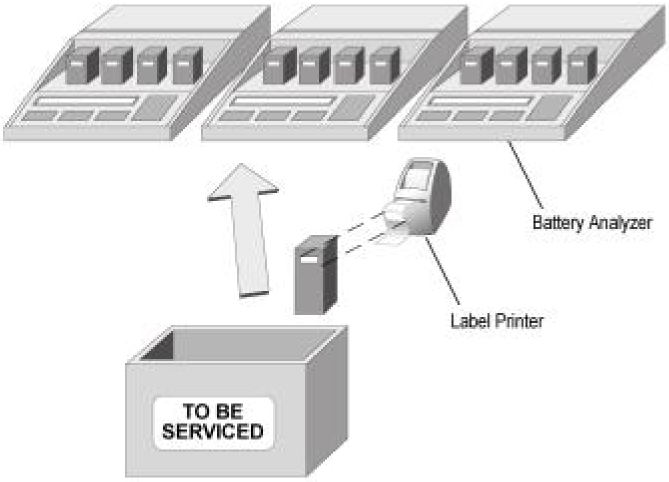


Figure 11-5: Servicing expired batteries.
Batteries with expired dates are exercised; those that do not recover to the preset target capacity are reconditioned. Batteries that pass are re-certified by attaching a new label with dates and capacity reading.

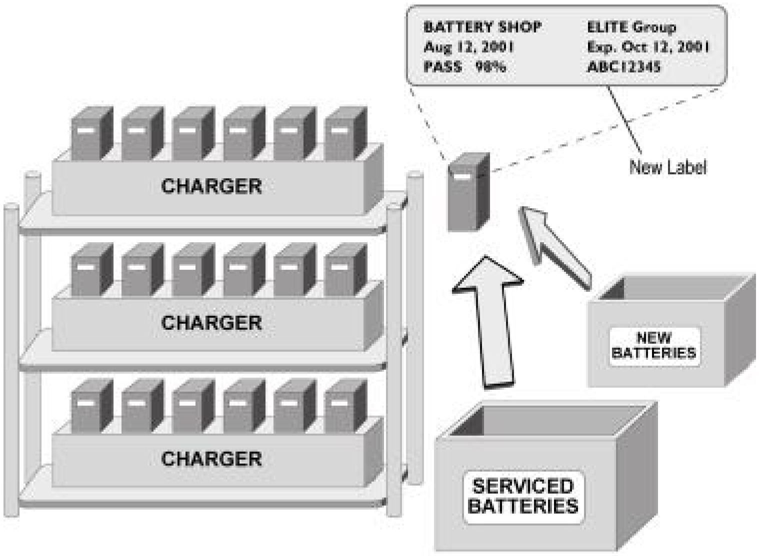


Figure 11-6: Returning batteries to circulation.
After servicing, the restored batteries are returned to the charger; those that failed are replaced with new ones. Battery maintenance assures that all packs perform at the expected capacity level.

When taking a battery from the charger, the user checks the service date on the battery label. If expired, the battery is placed into the box marked: ‘To be serviced’. Periodically, the box is removed and the batteries are serviced and re-certified with a battery analyzer.

After service, the batteries are re-labeled and returned to the charger. Those batteries that fail to meet the target capacity are replaced with new packs. All batteries in the charger are now certified to meet a required performance standard.

Battery maintenance has been simplified with the introduction of battery analyzers that offer a target capacity selection. All batteries must meet a user-defined performance test or target capacity to pass. Nickel-based batteries that fall short of the required capacity are automatically restored with the analyzer’s recondition cycle. Those packs that fail to recover are subsequently replaced with new packs.

Recondition is only effective for nickel-based batteries. It is worth noting that batteries with high self-discharge and/or shorted cells cannot be corrected with recondition; neither can a battery be restored that is worn out or has been damaged through abuse.

Another group of batteries that cannot be deep discharged by recondition are ‘smart’ batteries. This includes any pack that contains a microchip that must be maintained by a continuous voltage supply. Discharging these batteries below a certain voltage point will put the battery to sleep. A recharge often fails to wake up these batteries.

Battery Maintenance as a Business

Some entrepreneurs have come up with the novel idea of providing a service to test and restore rechargeable batteries. They operate in convenient locations such as downtown cores, shopping malls and transportation hubs. Customers bring in their batteries to have them serviced. The packs are tested and reconditioned with automated battery analyzers. A full performance report is issued with each battery serviced, showing service date, performance status and the date for the next service. The suggested fee per battery is $10.00US. Higher prices can be requested on specialty batteries which are expensive to replace.

The dealers are simply not equipped to handle the influx of returned batteries, neither is the staff trained to perform this task on a customer service level.

For organizations using a large number of batteries, a special pick-up and delivery service can be organized to provide scheduled maintenance. This ensures that fleet batteries used by organizations are regularly maintained. Such a service would benefit firms that do not want to bother with battery maintenance or do not have the expertise or resources to perform the task in-house.

Increasingly, dealers who sell mobile phones, laptops and camcorders also provide battery service. This activity increases traffic and helps foster good customer relations. A new battery is sold if the old one does not recover when serviced. By knowing that a battery can be checked and possibly restored, customers may try to salvage their weak batteries before investing in new ones. Some dealers may be reluctant to restore used batteries for fear of reduced battery sales.

Chapter 12: Battery Maintenance Equipment

With the increasing volume of batteries in circulation, battery manufacturing is outpacing the supply of suitable equipment to test these packs. This void is especially apparent in the mobile phone market where large quantities of batteries are being replaced under warranty without checking or attempting to restore them. The dealers are simply not equipped to handle the influx of returned batteries, neither is the staff trained to perform this task on a customer service level. Testing and conditioning these batteries is a complex procedure that lies outside the capabilities of most customer service clerks.

With the move to maintenance-free batteries and the need to test larger numbers of batteries, the function of battery test equipment is changing. Lengthy cycling is giving way to quick testing, improved battery preparation and better customer service. This shift in priority is especially apparent in the rapidly growing consumer market. In this chapter we examine modern battery analyzers and how they adapt to the changing needs of battery service.

Conditioning Chargers

Charging batteries is often not enough, especially when it comes to nickel-based chemistries. Periodic maintenance is needed to optimize battery life. Some innovative manufacturers offer chargers with conditioning features. The most basic charger models feature one or several bays with discharge opportunity. More advanced chargers include a display to reveal the capacity.

Some chargers offer pulse charge methods. This is done to improve charge efficiency and reduce the memory phenomenon on nickel-based batteries. Optimal charge performance is achieved by using a pulse charge that intersperses discharge pulses between charge pulses. Commonly referred to as ‘burp’ or ‘reverse load’ charge, this charge method promotes high surface area on the electrodes and helps in the recombination of the gases generated during charge.

Some manufacturers claim that the pulse charge method conditions and restores NiCd batteries and makes the periodic discharges redundant. Research carried out by the US Army has revealed that pulse charging does reduce the crystalline formation on the NiCd battery. If properly administered, batteries charged with these pulse chargers prolong service life. For batteries with advanced memory, however, the pulse charge method alone is not sufficient and a full discharge or recondition cycle is needed to break down the more stubborn crystalline formation.

Battery Analyzers

There are two types of battery analyzers: the fixed current units and the programmable devices. While fixed current units are less expensive and generally simpler to operate, programmable analyzers are more accurate and faster. Programmable units can better adapt to different battery needs and are more effective in restoring weak batteries. One of the main advantages of the programmable battery analyzer is the ability to test the batteries against preset parameters.

Fixed current analyzers perform well in organizations that use medium size batteries ranging from 600mAh to 1500mAh. If smaller or larger batteries are serviced, the charge and discharge currents are compromised and the program time is prolonged. Here is the reason why.

A fixed current battery analyzer with a current of 600mA, for example, services a 600mAh battery in about three hours, roughly one hour for each cycle starting with charge, followed by discharge and a final charge. Servicing an 1800mAh battery would take three times as long. On the low end of the scale, a problem may arise if a 400mAh battery is serviced. This battery may not be capable of accepting a charge rate higher than 1C and the battery could be damaged.

When purchasing a battery analyzer, there is a tendency to buy according to price. With the need to service a larger volume of batteries of a wider variety, second-generation buyers find the advanced features on upscale models worth the extra cost. These features manifest themselves in reduced operator time, increased, throughput, simpler operation and the use of less trained staff. Adaptation to new battery systems is also made easier. Figure 12-1 illustrates an advanced battery analyzer.

Figure 12-1: Cadex *7400* battery analyzer
The Cadex *7400* services NiCd, NiMH, SLA and Li-ion/polymer batteries and is programmable to a wide range of voltage and current settings. Custom battery adapters simplify the interface with different battery types. A quick test program measures battery state-of-health in three minutes, independent of charge. Nickel-based batteries are automatically restored if the capacity falls below the user-defined target capacity.

An advanced battery analyzer evaluates the condition of a battery and implements the appropriate service to restore the battery's performance. On nickel-based systems, a recondition cycle is applied automatically if a user-selected capacity level cannot be reached.

Battery chemistry, voltage and current ratings are user-programmable. These parameters are stored in interchangeable battery adapters and configure the analyzer to the correct function when the adapter is installed. In the Cadex *7000 Series* battery analyzers, for example, each adapter is preprogrammed with up to ten distinct configuration codes (C-codes) to enable service for all batteries with the same footprint.

Battery-specific adapters are available for all major batteries; user-programmable cables with alligator clips accommodate batteries for which no adapter is on hand. Batteries with shorted, mismatched or soft cells are identified in minutes and their deficiencies are displayed on the LCD panel.

User-selectable programs address different battery needs. The Cadex *7000 Series* features *'Prime'* to prepare a new battery for field use and *'Auto'* to test and recondition weak batteries from the field. *'Custom'* allows the setting of unique cycle sequences composed of charge, discharge, recondition, trickle charge or any combination, including rest periods and repeats.

More and more battery analyzers now measure the internal battery resistance, a feature that enables one to test a battery in a few seconds. The resistance check works best with lithium-based batteries because the level of internal cell resistance is in direct reflection to the performance. The resistance measurements can also be used for NiMH batteries but the readings do not fully disclose the battery's condition.

One of the most powerful features offered in modern battery analyzers is battery quick testing. Within two to five minutes, reasonably accurate state-of-health (SoH) readings are available. The test is independent of the state-of-charge (SoC). Some charge is needed, however, to facilitate the test.

New requirements of battery analyzers are the ultra-fast charge and quick prime features. When a battery is inserted, the analyzer evaluates the battery, applies an ultra-fast charge if needed, and prepares the battery for service within minutes. Such a feature helps the mobile phone industry, which receives a large number of batteries under warranty. With the proper equipment, many of these presumably faulty batteries can be jump-started instead of replaced.

To accurately test batteries that power digital equipment, a modern battery analyzer is capable of discharging a battery under a simulated digital load. The GSM waveform, for example, transmits voice data in 567 ms bursts with currents of 1.5A and higher. By simulating these pulses, the performance of a battery can be tested under these field conditions. Not all analyzers are capable of simulating such short current bursts. Instead, medium-priced battery analyzers use a slower motion to accommodate the load signals. Pulse duration of 5 ms, or ten times slower than the true GSM, is commonly used.

Another application involving uneven load demand is the so-called 5-5-90 program used to simulate the runtime of analog two-way radios. The battery is loaded 5 percent of the time on transmit, 5 percent on receive and 90 percent on standby. Other combinations are 10-10-80. Each stage can be programmed to the appropriate discharge current. Because of the different load conditions, calculating the predicted runtime in the absence of a battery analyzer would be difficult.

Easy operation is an important feature of any battery analyzer. This quality is appreciated because the user is confronted with an ever-increasing number of battery types. Displaying the battery capacity in percentage of the nominal capacity rather than in milliampere-hours (mAh) is preferred by many users. With the percentage readout, the user does not need to memorize the ratings of each battery tested because this battery information is stored in the system. The percentage readout allows an added level of automation by implementing a recondition cycle if the set target capacity level cannot be reached.

Some analyzers are capable of setting the appropriate battery parameters automatically when a battery is inserted. An intelligent battery adapter reads a passive code that is imbedded in most batteries. The code may consist of a jumper, resistor or specified thermistor value. Some battery packs contain a memory chip that holds a digital code. On recognition of the battery, the adapter assigns the correct service parameters. Automatic battery identification minimizes training and allows battery service by untrained staff.

> *The loss of battery capacity occurs gradually and often without the knowledge of the user.*

Most analyzers are capable of printing service reports and battery labels. This feature simplifies the task of keeping track of batteries. Marking batteries with the service date reminds the user when a battery is due for service. Labeling works well because the basic service history is attached right to the battery.

A battery analyzer should be automated and require minimal operator time. The task of the operator should be limited to scheduling incoming batteries for testing, marking the batteries after service, and replacing those that did not meet the performance criteria. Occasional selection of the correct current rating and chemistry may also be necessary. Properly used, a battery analyzer generates major cost savings in terms of longer battery life and more dependable service.

Battery Analyzers for Maintenance-Free Batteries

In the past, the purpose of battery analyzers was to restore NiCd batteries affected by ‘memory’. With today’s nickel-free batteries, memory is no longer a problem and the modern battery analyzer assumes duties other than conditioning weak batteries. In an environment with nickel-free batteries, the purpose of an analyzer is shifting to performance verification, quality control, quick testing and quick priming.

Common sense suggests that a new battery should always perform flawlessly. Yet even brand new batteries do not always meet manufacturer's specifications. With a battery analyzer, all incoming batteries can be checked as part of a quality control procedure and a warranty claim can be made if the capacity drops below the specified level toward the end of the warranty period.

The typical life of a Li-ion battery is 300 to 500 discharge/charge cycles or two to three years from the time of manufacturing. The loss of battery capacity occurs gradually and often without the knowledge of the user. The function of the battery analyzer is to identify weak batteries and “weed’ them out before they become a problem.

A battery analyzer can also trouble-shoot the cause of short runtimes. There are several reasons for this common deficiency. In some cases, the battery may not be properly formatted when first put in service; or the original charger does not provide a full charge. In other cases, the portable device draws more current than specified. Many of today’s battery analyzers can simulate the load signature of a digital device and verify the runtime according to the load requirements.

Lithium-based batteries are sensitive to aging. If stored fully charged and at elevated temperatures, this battery chemistry deteriorates to a 50 percent performance level in about one year. Similar performance degradation can be seen on NiMH batteries when used under these conditions. Although still considered new, the user will likely blame the equipment rather than the battery for its poor performance. The analyzer can isolate this problem.

Before adding new batteries to the battery fleet, a battery analyzer can be used to perform a spot check to ensure proper operation. If a battery shows low performance due to aging, the inventory practices may be changed to the ‘just in time’ method. Storage facilities with improved temperature control may also be sought.

An important new function of a battery analyzer is the ability to quick test batteries. No longer is it necessary to guess a battery’s condition by reading the terminal voltage, measuring the internal resistance or in enrolling lengthy charge and discharge cycles to determine its performance. Modern quick test programs using artificial intelligence are amazingly accurate and work independently of SoC.

Battery quick testing is finding a ready market niche with mobile phone dealers. This feature saves money because batteries returned under warranty can be tested. Replacements are only issued if a genuine problem is found. Once battery quick testing has been further refined,

One four-station analyzer is recommended for a fleet of 100 batteries.

this technology will also find applications in the fields of biomedical, broadcast, aviation and defense.

Battery Throughput

The quantity of batteries which an analyzer is capable of servicing depends on the number of battery bays available. The type of service programs and the conditions of the batteries serviced also play a role. Li-ion and lead acid batteries take longer to charge than nickel-based packs. Analyzers with fixed charge and discharge currents require added time, especially for larger batteries.

The four-station Cadex *7400* battery analyzer is capable of processing four nickel-based batteries every 4 to 8 hours on a full-service program. Based on two batches per day (morning and evening attendance) and 20 working days per month, one such analyzer can service 160 batteries every month. The throughput of batteries with ratings higher than 2000mA or those that need to be charged and discharged at lower C-rates will take longer. To allow extra analyzer capacity, including reconditioning of old batteries, one four-station analyzer is recommended for a fleet of 100 batteries.

When first servicing a fleet of batteries with a battery analyzer, extra runtime will be required, especially if a large number of batteries need to be restored with the recondition cycle. Once the user-defined target capacity has been reached, maintaining that level from then on will be easier and take less time. When first installing a battery maintenance program, some older packs will likely need replacing because not all batteries recover with exercise and recondition programs.

Quick test methods require the least amount of time. The Cadex *Quicktest*™ available on the Cadex *7000 Series* takes three minutes per battery. The time is prolonged if a brief charge or discharge is needed prior to testing. A charge or discharge is applied automatically if the battery resides outside the SoC requirements of 20 to 90 percent. Unlike the maintenance program, the Cadex *Quicktest*™ does not improve the battery's performance; it simply measures its SoH.

The *Ohmtest*™measurement of the Cadex *7000 Series* analyzer takes ten seconds to complete. Large numbers of batteries can be examined if the packs are charged prior to the test. Measuring the internal battery resistance works reasonably well if reference readings are on hand. However, there are batteries that measure good internal resistance but do not perform well. This is especially common with nickel-based chemistries.

There are a number of factors which affect the accuracy of the internal resistance readings, one of which is SoC and the settling time allowed immediately after a recharge. A newly charged battery exhibits higher resistance readings compared to one that has rested for a while. The increased interfacial resistance present after charging causes this. Allow the battery to rest for one hour or more before measurement. Temperature and the number of cells connected in series also affects the readings. Many batteries contain a protection circuit that distorts the readings further.

Battery Maintenance Software

Organizations servicing portable equipment need simplified battery testing. The difficulty of testing batteries is brought on by the proliferation of batteries, both in volume and diversity of models. With most standalone battery test equipment, servicing batteries with conventional methods is complex and time consuming. This task will only get more difficult as new battery models are added, almost weekly. New chemistries are being introduced which have different service requirements.

Manufacturers of battery test equipment are responding by introducing software packages that run on a PC. Many new systems enable operating the battery analyzers through a PC. Such products bring battery maintenance within reach of the untrained operator.

Cadex *Batteryshop™* is a system that integrates with the Cadex *7000 Series* battery analyzers. Although the analyzers are stand-alone units that can think on their own, the software overrides the analyzer to adjust the settings, and stores the test results obtained from the batteries. Figure 12-2 illustrates such a battery maintenance system.

Figure 12-2: Components of a battery maintenance system.
Cadex *Batteryshop™* stores the battery test results on the database. Point and click technology programs the analyzer by selecting the battery from a listing of over 2000 commercial batteries. The system accommodates up to 120 analyzers for simultaneous service of 480 batteries.

Here are examples of how a computer-assisted battery testing system can simplify operation. To service a battery with Cadex *Batteryshop™,* for example, the user selects the battery model from the database, clicks the mouse, and the analyzer is automatically configured to the correct battery parameters. Programming the analyzer by scanning the bar code identifying the battery's model number is also possible.

In the near future, the operator will be able to view a picture of the battery on a PC monitor. Clicking on the image will reveal the various models available in that battery family. Clicking on the correct model will program the analyzer.

For battery fleet operators, keeping track of a large battery fleet can be difficult, especially when observing the periodic maintenance requirements. With systems such as Cadex *Batteryshop™,* the battery test results can be stored in the database. This feature enables the operator to retain battery records from birth to retirement. Here is how this is done:

Each battery is marked with a permanent bar code label containing a unique battery ID number. When servicing the battery, the user scans the battery ID and the analyzer is automatically configured through the PC. All battery test results are stored and updated in the database under the assigned battery ID number. Any reference to this battery in terms of performance, maintenance history and even vendor information is available with a click of a mouse.

Delivering batteries with consistent high quality is a concern for all battery manufacturers and distributors. With advanced battery maintenance systems, battery batches can be tested and documented to satisfy quality control standards. Voltage, current and temperature information can be displayed in real-time graphics.

Cadex *Batteryshop*™, includes specialty programs that may not be available on other software products. For example, the program allows discharging a battery under a given pulsed current to simulate digital load requirements. Other programs include life cycling to evaluate the battery's longevity, self-discharge tests, quick formatting and priming. The Internet allows updating the battery database to include new entries, fetching battery matrix settings for quick testing, sending battery test results to a central location, and downloading of new firmware for the Cadex *7000 Series* battery analyzers.

Chapter 13: Making Battery Quick-Test Feasible

When Sanyo, one of the largest battery manufacturers in the world, was asked, "Is it feasible to quick test batteries?" the engineer replied decisively, "No". He based his conclusion on the difficulty of using a universal test formula that applies to all battery applications, — from wireless communications to mobile computing, and from power tools to forklifts and electric vehicles.

Several universities, research organizations and private companies, including Cadex, are striving to find a workable solution to battery quick testing. Many methods have been tried, and an equal number have failed because they were inaccurate, inconsistent and impractical.

When studying the characteristics relating to battery state-of-health and state-of-charge (SoH and SoC, respectively) some interesting effects can be observed. Unfortunately, these properties are cumbersome and non-linear, and worst of all, the parameters are unique for every battery type. This inherent complexity makes it difficult, if not impossible, to create a formula that works for all batteries.

In spite of these seemingly insurmountable odds, battery quick testing is possible. But the question is asked, "how accurate will it be, and how well will it adapt to continuously changing battery chemistries?" The cost of a commercial quick tester and the ease-of-use are other issues of concern.

Battery Specific Quick Testing

The secret of battery quick testing lies, to a large extent, in understanding how the battery is being loaded. Battery loads vary from short current bursts for a mobile phone using the GSM protocol, to long and fluctuating loads on laptops, and to intermittent heavy loads for power tools.

Because of these differences in loads, a battery for a digital mobile phone should be tested primarily for low impedance to assure a clean delivery of the current bursts, whereas a battery for a notebook should be examined mainly for the bulk in energy reserve. Ultra-low impedance is of less importance here. A battery for a power tool, on the other hand, needs both — low impedance and good power reserve.

Some quick testers simulate the equipment load and observe the voltage signature of the battery under these conditions. The readings are compared with the reference settings, which are stored in the tester. The resulting discrepancies are calculated against the anticipated or ideal settings and displayed as the SoH readings.

The first step in obtaining quick test readings is measuring the battery's internal resistance, often referred to as impedance. Internal resistance measurements take only a few seconds to complete and provide a reasonably accurate indication of the battery's condition, especially if a reference reading from a good battery is available for comparison.

Unfortunately, the impedance measurement alone provides only a rough sketch of the battery's performance. The readings are affected by various battery conditions, which cannot always be controlled. For example, a fully charged battery that has just been removed from the charger shows a higher impedance reading than one that has rested for a few hours after charge. The elevated impedance is due to the increased interfacial resistance present after charging. Allowing the battery to rest for an hour or two will normalize the battery. Temperature also affects the readings. In addition, the chemistry, the number of cells connected in series and the rating of a battery influence the results. Many batteries also contain a protection circuit that further distorts the readings.

Three-Point Quick Test

The *three-point quick test* uses internal battery impedance as a basis and adds the battery voltage under charge and discharge to the equation. The readings are evaluated and compared with reference settings stored in the tester. Let's explore each of these fundamentals closer to see what it entails:

Internal resistance — To measure the impedance, a battery must be at least 50 percent charged. An empty or nearly empty battery exhibits a high internal resistance. As the battery reaches 50 percent SoH, the resistance drops, then increases again towards full discharge or full charge. Figure 13-1 shows the typical internal resistance curve of a NiMH as a function of charge. Note the decrease of impedance after the battery has rested for a while. To obtain accurate results, allow the battery to rest after discharge and charge.

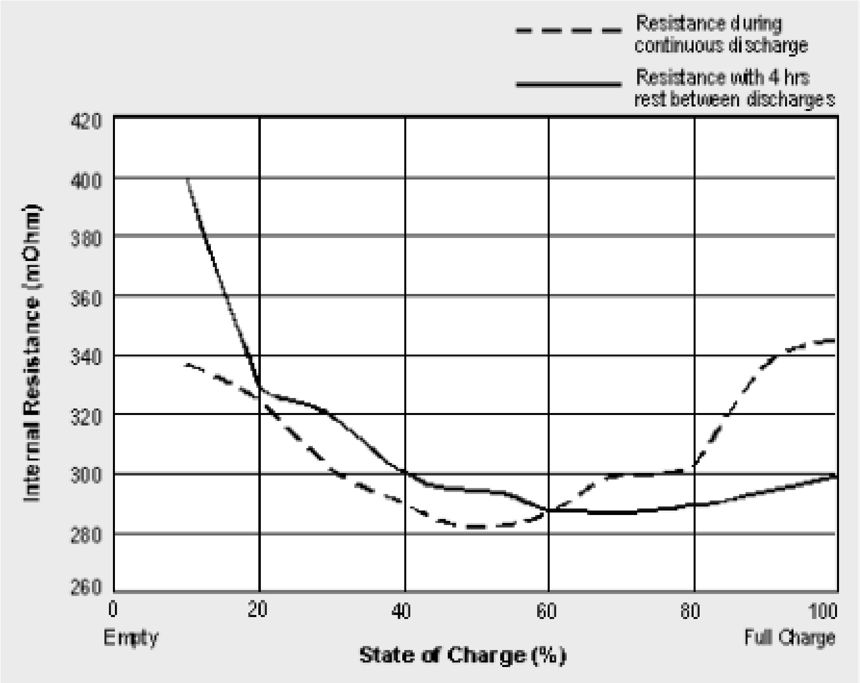


Figure 13-1: Internal resistance in a NiMH battery.
Note the higher readings immediately after a full discharge and full charge. To obtain accurate results, allow the battery to rest after discharge and charge.

Charge Voltage — During charge, the voltage of a battery must follow a narrow predetermined path relating to time. Anomalies such as too high and too low voltages are identified. For example, a fast initial rise reveals that the battery may be fully charged. If the voltage overshoots, the battery may be 'soft'. This condition often arises when one or more cells have developed dry spots. A frozen battery exhibits a similar effect. If, on the other hand, the voltage does not increase in the allotted time and remains constant, an electrical short is suspected.

Discharge Voltage — When applying a discharge, the voltage drops slightly, and then stabilizes for most of the period in which the energy is drawn. As the battery reaches the end-of-discharge point, the voltage drops rapidly. Observing the initial voltage drop and measuring the voltage delta during the flat part of the discharge curve provides some information as to the SoC. However, each battery type behaves differently and an accurate prediction is not easy. NiCd batteries that have a long flat voltage during most of the discharge period are more difficult to predict using this method than chemistries which exhibit a steady voltage drop under load.

Unfortunately, the battery's SoC affects the three-point quick test. Even within a charge range of 50 to 90 percent, fluctuations in the test results cannot be avoided. Internal resistance readings further influence the final outcome. If used as a linear correlation with capacity, internal resistance measurements can be highly unreliable, especially with NiCd and NiMH batteries. Figure 13-2 compares the accuracy of six batteries when tested with the three-point quick test. To establish the true capacity, each battery was analyzed by applying a full charge/discharge/charge cycle.

Often referred to as the 'Feel Good Battery Tester' because of overly optimistic readings, the three-point quick test method fails to provide the accuracy and repeatability that serious battery users demand.

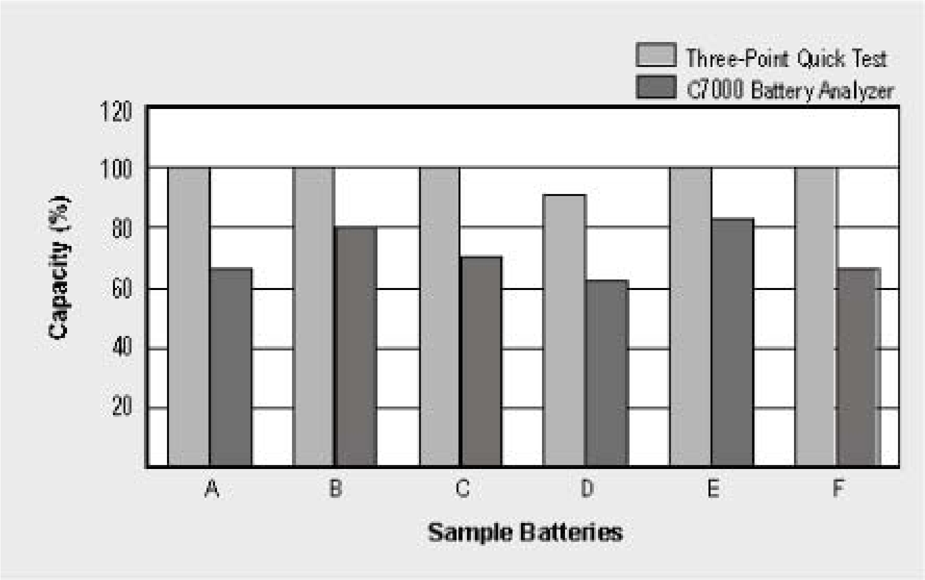


Figure 13-2: Comparison of battery quick test methods.
Six batteries with different state-of-health conditions were quick tested. The dark gray bars reflect the true state-of-health obtained with the Cadex *7000* Series battery analyzer by applying a full charge/discharge/ charge cycle; the light gray bars are readings derived using the Three-Point Quick Test.

The impression of casual battery users that this method is "better than nothing" will not stand up to the requirements of critical industries such as biomedical, law enforcement, emergency response, aviation and defense. Because of relatively low cost, the three-point tester finds a strong niche in the consumer market where a wrong reading is simply a nuisance and does not threaten human safety. Satisfactory readings are achieved in the mobile phone market where batteries are similar in format. It should be noted that the three-point quick test method provides better results than merely measuring the battery's internal resistance or voltage.

The Evolving Battery

The Li-ion battery has not yet matured. Chemical compositions change as often as once every six months. According to Moli Energy, a large manufacturer of Li-ion batteries, the chemical composition of Li-based batteries changes every six months. New chemicals are discovered that provide better load characteristics, higher capacities and longer storage life. Although beneficial to consumers, these improvements wreak havoc with battery testing

The Li-ion battery has not yet matured. Chemical compositions change as often as once every six months.

equipment that base quick test algorithms on fixed parameters. Why do these changes in battery composition affect the results of a quick tester?

The early Li-ion batteries, notably the coke-based variety, exhibited a gradual drop of voltage during discharge. With newer graphite-based Li-ion batteries, flatter voltage signatures are achieved. Such batteries provide a more stable voltage during most of the discharge cycle. The rapid voltage drop only occurs towards the end of discharge.

A ‘hardwired’ tester looks for an anticipated voltage drop and estimates the SoH according to fixed references. If the voltage-drop changes due to improved battery technology, erroneous readings will result.

Diverse metals used in the positive electrode also alter the open terminal voltage. Manganese, also referred to as spinel, has a slightly higher terminal voltage compared to the more traditional cobalt. In addition, spinel ages differently from cobalt. Although both cobalt and spinel systems belong to the Li-ion family, differences in readings can be expected when the batteries are quick tested side-by-side.

The Li-ion polymer has a dissimilar composition to the Li-ion and responds in a different way when tested. Instruments capable of checking Li-ion batteries may not provide reliable readings when quick testing Li-ion polymer batteries.

The Cadex Quicktest™ Method

A battery quick text must be capable of adapting to new chemical combinations as introduced from time to time. Cadex solves this by using a self-learning fuzzy logic algorithm. Used to measure analog variances in an assortment of applications, fuzzy logic is known to the industry as a universal approximator. Along with unique learning capabilities, this system can adapt to new trends. Similar to a student adapting to the complexity of a curriculum, the system learns with each battery tested. The more batteries that are serviced, the higher the accuracy becomes.

Cadex *Quicktest*™ is built on the new Cadex *7000 Series* battery analyzer platform. This system features interchangeable battery adapters that contain the battery configuration codes (C-codes). When installed, the adapter sets the analyzer to the correct battery parameters (chemistry, voltage rating, etc.).

To enable quick testing, the battery adapters must also contain the matrix settings for the serviced battery. While matrices for the most common batteries are included when acquiring the adapter, the user is asked to enter the information on those adapters that have not yet been prepared for quick testing. This can be done in the field by ‘scanning’ the working battery.

The *‘Learn’* program of the Cadex *7000 Series* battery analyzer performs this task by applying charge-discharge-charge activities on the test battery. Similar to downloading a program into a PC, the information derived from the battery sets the matrices and prepares the Cadex *Quicktest*™ function. The *‘Learn’* program completes its cycle within approximately four hours. One learning cycle is the minimal requirement to enable the Cadex *Quicktest*™ function.

With only one battery learned or scanned, the confidence level is ‘marginal’. Running additional batteries through the learning program will fill the matrix registers and the confidence level will increase to ‘good’ or ‘excellent’. Like a bridge that needs several pillars for proper support, the most accurate quick test results are achieved by scanning individual batteries that have SoH readings of around 100, 80 and 60 percent. The confidence level attained for a given battery adapter is indicated on the LCD panel of the analyzer.

The Cadex *Quicktest*™ can be performed with charge levels between 20 and 90 percent. Within this range, different charge levels do not affect the readings. If the battery is insufficiently charged, or has too high a charge, a message appears and the analyzer automatically applies the appropriate charge or discharge to bring the battery within testing range. Charging or discharging a battery immediately prior to taking the reading does not affect the Cadex *Quicktest*™ results.

The reader may ask whether the Cadex *Quicktest*™ system can also learn incorrectly. No — once the learning cycles have been completed for a given battery, the matrix settings are firm and resilient. Testing bad batteries will not affect the setting.

Spoilage is only possible if a number of bad batteries are purposely put through the *'Learn'* program in an attempt to alter the existing matrix. Such would be the case when scanning a batch of batteries that have not been properly formatted, have been in prolonged storage, or are of poor quality. To protect the existing matrix from spoilage when adding learning cycles, the system checks each new vector reading for its integrity before accepting the information as a valid reference. Learned readings obtained from defective batteries are rejected.

If a battery adapter has lost its integrity as part of 'bad learning', the matrix setting can be erased and re-taught. As an alternative, Cadex will make recommended matrices available on the Internet. Users may also want to exchange learned matrix information with each other. Copying battery adapters by inserting a recognized adapter into the analyzer will achieve this. Another method is 'Webcasting' the matrices over the Internet.

How does the Cadex Quicktest work?

The first stage of the Cadex *Quicktest*™analysis uses a waveform to gather battery information under certain stresses, establishing probability levels for the given battery. Since there are many battery types with several interacting variables, a set of rules is applied to further evaluate the data. The results are averaged and an estimated battery capacity is predicted. The initial inference to categorize the batteries is computed from a set of specialized shapes called membership functions. These membership functions are unique to every battery model and are developed using a specialized trend-learning algorithm.

The raw data, consisting of three or more items, flows through the input layer. Vectors leading from the input layer are weighted and the derived values are passed through a function in the hidden layer. Another vector set channels the information to the output.

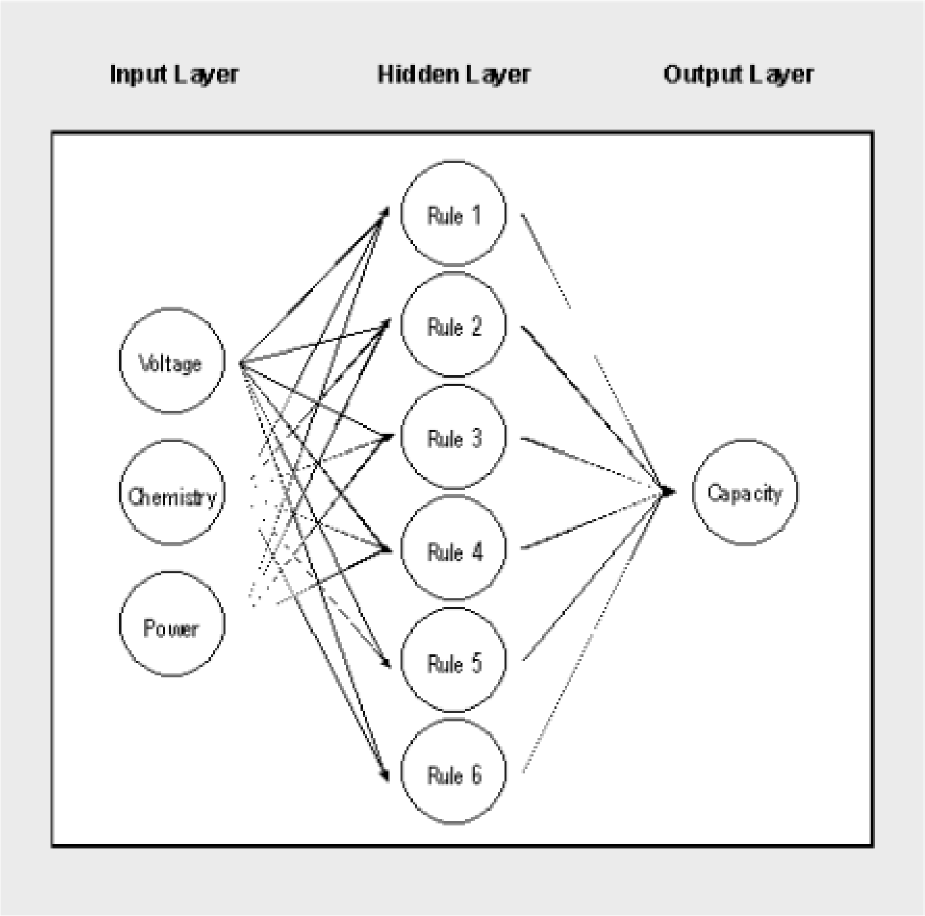


Figure 13-3: Flowchart of a neuro-network based on fuzzy logic.
The first three circles on the left are the inputs. The data entering is 'fuzzified' according to a set of curves called membership functions. A set of rules that depend on fixed knowledge is evaluated. The results of the rules are combined and distilled, or 'defuzzified'. The result is a crisp, non-fuzzy number.

> *"As complexity rises, precise statements lose meaning and meaningful statements lose precision."*

The weights are highly significant and function as the learning facility of the network. A run would proceed with a certain set of weights. If the result is off by a certain range, the weights are changed and the process is repeated until a certain number of iterations have passed or the algorithm produces the correct output.

The Cadex *Quicktest*™ requires less time than most other methods. While current quick test systems, such as those used in defense applications, need hundreds of learning cycles and run on large computers, the Cadex method requires minimal experience and can be performed on relatively simple hardware. Typically less than five learning cycles are necessary to achieve robust, model-specific solution sets, also known as matrices. This massive reduction in time is the result of a new self-learning algorithm that acquires numerous measures of the battery's characteristics. The algorithm uses a unique decision-making formula that determines the best solution set for each battery model.

Of course, artificial intelligence is a complicated subject, and is beyond the scope of this book. With respect to complexity, Dr. Lofti Zadeh spoke these famous words: "As complexity rises, precise statements lose meaning and meaningful statements lose precision."

Battery quick testing has raised the interest of manufacturers and users alike. The race is on to provide a product that is accurate, easy to use and cost effective. The true winner may not be an individual or organization that amasses the largest number of patents, but a company that can offer a product that is cost effective and truly works.

Battery Testing and the Internet

Increasingly, the Internet plays a pivotal role in battery testing. The ability to send all battery test results to a central global database is an exciting prospect. With this information on hand, battery manufacturers would be able to perform battery analysis based on battery type, geographic area and user pattern. Field failures could be identified quickly and appropriate corrections implemented.

Another application for the Internet is establishing a global database for all major battery types, complete with matrix settings. With compatible systems, users would be able to select and download battery information from a central database. *Batteryshop*™, a software product offered by Cadex, provides such a service. The database lists all common batteries, complete with battery specifications and matrix information. Point and click technology programs the battery analyzer to the correct battery parameters.

Collaborating with battery manufacturers enables Cadex to create the most accurate vector settings. Manufacturers welcome such a system because it reduces beta testing and puts the manufacturer in closer contact with the battery user. The aim is to reduce warranty returns and increase customer satisfaction.

Another powerful feature of the Internet is downloading new software for hardware upgrades. Since battery quick testing is still in its infancy, improved software will be made available in the future that allows upgrading existing equipment with the latest developments.

Electrochemical Impedance Spectroscopy

Electrochemical Impedance Spectroscopy (EIS) has been used for a number of years to test the SoH and SoC of industrial batteries. EIS is well suited for observing reactions in the kinetics of electrodes and batteries. Changes in impedance readings hint at minute intrusion of corrosion, which can be evaluated with the EIS methods. Impedance studies using the EIS technology have been carried out on lead acid, NiCd, NiMH, Li-ion and other chemistries. EIS test methods are also used to examine the cells on larger stationary batteries.

In its simplest manifestation, measurements of internal battery resistance can be taken by applying a load to a battery and observing the current-voltage characteristics. A secondary load of higher current is applied, again noting the voltage and current. The current and voltage relationship of the two loads can be utilized to provide the internal resistance using Ohm’s Law.

Rather than applying two load levels, an AC signal is injected. This AC voltage floats as a ripple on top of the battery DC voltage and charges and discharges the battery alternatively. The AC frequency varies from a low 100mHz to about 5kHz. 100mHz is a very low frequency that takes 10 seconds to complete a full cycle. In comparison, 5kHz completes 5000 cycles in one second. At about 1000Hz, the load behaves more like a DC resistance because the chemistry cannot follow the rapid changes between charge and discharge pulses. The information about electrolyte mass transport is ascertained at lower frequencies.

Additional information regarding the battery’s condition can be obtained by applying various frequencies. One can envision going through different layers of the battery and examining each level. Similar to tuning the dial on a broadcast radio, in which individual stations offer different types of music, so too does the battery provide different information of the internal processes. The EIS is an effective technique to analyze the mechanisms of interfacial structure and to observe the change in the formation when cycling the battery as part of everyday use.

It is one thing to amass a large amount of data, and another to make practical use of it.

When applying a sine wave to a battery, a phase shift between voltage and current occurs. The reactive load of the battery causes this phenomenon. The overall battery resistance consists of three resistance types: pure resistance, inductance and capacitance. Capacitance is responsible for the capacitor effect; and the inductance is accountable for the so-called magnetic field, or coil effect. The voltage on a capacitor lags behind the current. This process is reversed on a coil and the current lags behind the voltage. The level of phase shift that occurs when applying a current through a reactive load is used to provide information as to the battery's condition.

One of the difficulties with the EIS method is interpreting the information. It is one thing to amass a large amount of data, and another to make practical use of it. Although the derived information reflects aging and other deficiencies, the readings are not universal and do not apply in the same way to all battery makes and types. Rather, each battery type generates its own set of signatures. Without a library of well-defined reference readings with which to compare, the EIS method has little meaning.

Modern technology can help. The vector settings of a given battery type can be stored in the test instrument and translated into meaningful readings by software. The readings can further be analyzed by coupling impedance spectroscopy with a fuzzy neuro-adaptive algorithm.

Electrochemical Impedance Spectroscopy is commonly used to research batteries in a lab environment. Best results are obtained on a single cell. EIS is also used in aviation and in-flight analysis of satellite batteries. Closer to earth, the EIS method examines stationary batteries for grid corrosion and water loss. Further refined, the EIS technology has the potential for wider applications, such as testing portable batteries. EIS may one day test batteries in a matter of seconds and achieve higher accuracy than current methods.

Part Three

Knowing Your Battery

Chapter 14: Non-Correctable Battery Problems

Non-correctable battery problems are those that cannot be improved through external means such as giving the battery a full charge or by applying repeated charge/discharge cycles. Deficiencies that denote the non-correctable status are high internal resistance, elevated self-discharge, electrical short of one or several cells, lack of electrolyte, oxidation, corrosion and general chemical breakdown. These degenerative effects are not only caused by normal usage and aging, but they include less than ideal field conditions and an element of neglect. The user may have poor charging equipment, may operate and store the battery in adverse temperatures and, in the case of nickel-based batteries, may not maintain the battery properly.

New battery packs are not exempt from deficiency syndromes and early failure. Some batteries may be kept in storage too long and sustain age-related damage, others are returned by the customer because of incorrect user preparation.

In this section we examine the cause of non-correctable battery problems and explore why they occur. We also look at ways to minimize premature failure.

High Self-discharge

Self-discharge is a natural phenomenon of any battery. It is not a manufacturing defect per se, although poor manufacturing practices and improper maintenance and storage by the consumer enhance the problem.

The level of self-discharge differs with each chemistry and cell design. High-performance nickel-based batteries with enhanced electrode surface area and super conductive electrolyte are subject to higher self-discharge than the standard version cell with lower energy densities. Self-discharge is non linear and is highest right after charge when the battery holds full capacity.

NiCd and NiMH battery chemistries exhibit a high level of self-discharge. If left on the shelf, a new NiCd loses about 10 percent of its capacity in the first 24 hours after being removed from the charger. The rate of self-discharge settles to about 10 percent per month afterwards. At a higher temperature, the self-discharge rate increases substantially. As a rule, the rate of self-discharge doubles with every 10°C (18°F) increase in temperature. The self-discharge of the NiMH is about 30 percent higher than that of the NiCd.

A major contributor to high self-discharge on nickel and lead-based batteries is a high cycle count and/or old age. With increased cycles, the battery plates tend to swell. Once enlarged, the plates press more firmly against the delicate separator, resulting in increased self-discharge. This is common in aging NiCd and NiMH batteries but can also be seen in lead acid systems.

Loading less active materials on the plates can reduce the plate swelling on nickel-based batteries. This improves expansion and contraction while charging and discharging. In addition, the load characteristic is enhanced and the cycle life prolonged. The downside is lower capacity.

Metallic dendrites penetrating into the separator are another cause of high self-discharge. The dendrites are the result of crystalline formation, also known as memory. Once marred, the damage is permanent. Poorly designed chargers that ‘cook’ the batteries also increase the self-discharge. High cell temperature causes irreversible damage to the separator.

While the nickel-based systems can withstand some abuse and tolerate innovative or crude charge methods, the Li-ion demands tight charging and discharging regimes. Keeping the voltage and current within firm boundaries prevents the growth of dendrites. The presence of dendrites in lithium-based batteries has more serious implications than just an increase in self-discharge — dendrites can cause an electrical short, which could lead to venting with flame.

The self-discharge of the Li-ion battery is five percent in the first 24 hours after charge and averages 1 to 2 percent per month thereafter. In addition to the natural self-discharge through the chemical cell, the safety circuit draws as much as 3 percent per month. High cycle count and aging has little effect on self-discharge on lithium-based batteries.

An SLA self-discharges at a rate of only five percent per month or 50 percent per year. Repeated deep cycling increases the self-discharge. When deep cycling, the electrolyte is drawn into the separator, resulting in a crystalline formation similar to that of a NiCd battery.

The self-discharge of a battery is best measured with a battery analyzer. The procedure starts by charging the battery. The capacity is read by applying a controlled discharge. The battery is then recharged and put on a shelf for 24 hours, after which the capacity is measured again. The discrepancy between the capacity readings reveals the level of self-discharge.

More accurate self-discharge measurements can be obtained by allowing the battery to rest for at least 72 hours before taking the reading. The longer rest period compensates for the relatively high self-discharge immediately after charge. At 72 hours, the self-discharge should be between 15 and 20 percent. The most uniform self-discharge readings are obtained after seven days. On some battery analyzers, the user may choose to adjust the desired rest periods in which the self-discharge is measured.

Research is being conducted to find a way to measure the self-discharge of a battery in minutes, if not seconds. The accuracy and repeatability of such technology is still unknown. The challenge is finding a formula that applies to all major batteries and includes the common chemistries.

Low Capacity Cells

Even with modern manufacturing techniques, the capacity of a cell cannot be accurately predicted. As part of the manufacturing process, each cell is measured and segregated into categories according to their inherent capacity levels. The high capacity A cells are commonly sold for special applications at premium prices; the large mid-range B cells are used for commercial and industrial applications such as mobile communications; and the low-end C cells are mostly sold in supermarkets at bargain prices. Cycling will not significantly improve the capacity of the low-end cell. When purchasing rechargeable batteries at a reduced price, the buyer should be aware of the different capacity and quality levels offered.

As part of quality control, the battery assembler should spot-check each batch of cells to examine cell uniformity in terms of voltage, capacity and internal resistance. Failing to observe these simple rules will often result in premature battery failures. When buying quality cells from a well-known manufacturer, battery assemblers are able to relax the matching requirements somewhat.

Cell Mismatch

Cell mismatch can be found in brand-new as well as aged battery packs. Poor quality control at the cell manufacturing level and inadequate cell matching when assembling the batteries cause unevenly matched cells. If only slightly off, the cells in a new pack adapt to each other after a few charge/discharge cycles, like players in a winning sports team.

A weak cell holds less capacity and is discharged more quickly than the strong one. This imbalance causes cell reversal on the weak cell if the battery is discharged below 1V/cell. The weak cell reaches full charge first and goes into heat-generating overcharge while the stronger cell still accepts charge and remains cool. In both situations, the weak cell is at a disadvantage, making it weaker and contributing to a more acute cell mismatch condition. An analogy can be made with a high school bully who picks on the weaker kid.

High quality cells are more consistent in capacity than lower quality counterparts. During their life span, high quality cells degrade at about the same rate, helping to maintain the matching. Manufacturers of power tools choose high quality cells because of their durability under heavy load conditions and temperature extremes. Lower-cost cells have been tried, but early failure and consequent replacement is costlier than the initial investment.

The capacity matching between the cells in a battery pack should be within +/- 2.5 percent. Tighter tolerances are required on batteries with high cell counts that also must generate high load currents and are operating under adverse temperatures. There is a strong correlation between well-balanced cells and the longevity of a battery.

Lithium-based cells have tighter matching tolerances than their nickel-based cousins. Tight matching of all cells in a pack is especially important on lithium-based chemistries. All cells must reach the end-of-discharge voltage threshold at the same time. The full-charge point must be attained in unison by all cells. If the cells are allowed to get out of match, the weaker cell will be discharged to a lower voltage point before the cut-off occurs. On charge, this weak cell will attain the full-charge status before the others, causing the voltage to go higher than on the stronger cells. This larger voltage swing will put undue strain on the weak cell.

Each cell in a lithium-based pack is electronically monitored to assure proper cell matching during the battery’s life. An electronic circuit is added to some packs that compensate the differences in cell voltages. This is done by connecting a shunt across each cell string to consume the excess energy of the cells which are more energetic. The low-voltage cut-off occurs when the weakest cell reaches the end-of-discharge point.

The Li-ion battery is controlled down to the cell level to assure safety at all times. Because this chemistry is still relatively new and unpredictable under extreme conditions, manufacturers do not want to take undue risks. There have been a few failures but such irregularities are often kept a secret. This chemistry is considered very safe, considering the large number of Li-ion batteries that are in use.

Shorted Cells

Manufacturers are often unable to explain why some cells develop high electrical leakage or an electrical short while the batteries are still relatively new. There are a number of possible reasons that contribute to this irreversible form of cell failure.

The suspected culprit is foreign particles that contaminate the cells during manufacture. Another possible cause is rough spots on the plates that damage the separator. Better quality control at the raw material level and minimal human interface during the manufacturing process has greatly reduced the ‘infant mortality’ rate of the modern rechargeable cells.

Cell reversal caused by deep discharging also contributes to shorted cells. This commonly occurs if a nickel-based battery is being fully depleted under a heavy load. A NiCd battery is designed with some reverse voltage protection and a small reverse current in the magnitude of milliamperes can be tolerated. A high current, however, causes the reversed-polarized cell to develop a permanent electrical short. Another cause of a short circuit is marring the separator through uncontrolled crystalline formation.

Applying momentary high-current bursts in an attempt to repair shorted cells has had limited success. The short may temporarily evaporate but the damage to the separator material remains. The repaired cell often exhibits a high self-discharge and the short frequently returns.

Replacing a shorted cell in an aging pack is not recommended unless the new cell is matched with the others in terms of voltage and capacity. Otherwise, an imbalance may occur. One may remember the biblical verse “No one puts a patch of unshrunken cloth on an old garment. . .” or “No man would put new wine into old wineskins. . .” (Mt 9.16-17). Attempts to replace faulty cells have commonly lead to battery failures after about six months of use. It is best not to disturb the cells in a battery pack but allow them to age naturally. Maintaining the batteries while they are still in good working condition will help to prevent premature failure.

Shorts in a Li-ion cell are uncommon. Protection circuits monitor an ailing Li-ion cell and render the pack unusable if serious voltage irregularities are detected. Charging such a pack would (protection circuit permitting) generate excess heat. The battery’s temperature control circuits are designed to terminate the charge.

Loss of Electrolyte

Although sealed, battery cells may lose some electrolyte during their life. Typical loss of moisture occurs if the seal opens due to excessive pressure. This occurs if the battery is charged at very low or very high temperatures. Once vented, the spring-loaded seal of nickel-based cells may never properly close again, resulting in a deposit of white powder around the seal opening. Losses may also occur if the cell cap is not correctly sealed in the manufacturing process. The loss of electrolyte results in a decrease of capacity, a defect that cannot be corrected.

Permeation, or loss of electrolyte in sealed lead acid batteries, is a recurring problem. Overcharge is the main cause. Careful adjustment of charging and float voltages reduces loss

It is interesting to observe that batteries that are cared for by a single user generally last longer than those that operate in an open fleet system.

of electrolyte. In addition, the battery should operate at moderate temperatures. Air-conditioning is a prerequisite for VRLA batteries, especially in warmer climates.

Replenishing lost liquid in VRLA batteries by adding water has had limited success. Although lost capacity can often be regained with a catalyst, the performance of the stack is short-lived. After tampering with the cells, it was observed that the battery stack turned into high maintenance mode and needed to be closely supervised.

A properly designed, correctly charged Li-ion cell should never generate gases. As a result, the Li-ion battery does not lose electrolyte through venting.

But in spite of what is being said, the lithium-based cells can build up an internal pressure under certain conditions. Provisions are made to maintain safety of the battery and equipment should this occur. Some cells include an electrical switch that opens if the cell pressure reaches a critical level. Other cells feature a membrane that safely releases the gases if need be. Controlled release of the pressure prevents bulging of the cell during pressure buildup.

Most of the safety features of lithium-based batteries are one-way; meaning that once activated, the cells are inoperable thereafter. This is done for safety reasons.

Chapter 15: Caring for Your Batteries from Birth to Retirement

It is interesting to observe that batteries cared for by a single user generally last longer than those that operate in an open fleet system where everyone has access to, but no one is accountable for them. There are two distinct groups of battery users — the personal user and the fleet operator.

A personal user is one who operates a mobile phone, a laptop computer or a video camera for business or pleasure. He or she will most likely follow the recommended guidelines in caring for the battery. The user will get to know the irregularities of the battery. When the runtime gets low, the battery often gets serviced or replaced. Critical failures are rare because the owner adjusts to the performance of the battery and lowers expectations as the battery ages.

The fleet user, on the other hand, has little personal interest in the battery and is unlikely to tolerate a pack that is less than perfect. The fleet user simply grabs a battery from the charger and expects it to last through the shift. The battery is returned to the charger at the end of the day, ready for the next person. Little or no care is given to these batteries. Perhaps due to neglect, fleet batteries generally have a shorter service life than those in personal use.

How can fleet batteries be made to last longer? An interesting contrast in the handling of fleet batteries can be noted by comparing the practices of the US Army and the Dutch Army, both of which use fleet batteries. The US Army issues batteries with no maintenance program in place. If the battery fails, another pack is issued. Little or no care is given and the failure rate is high.

The Dutch Army, on the other hand, has moved away from the open fleet system by making the soldiers responsible for their batteries. This change was made in an attempt to reduce battery waste and improve reliability. The batteries are issued in the soldier’s name and the packs become part of their personal belongings. The results are startling. Since the Dutch Army adapted this new regime, the failure rate has dropped considerably and, at the same time, battery performance has increased. Unexpected down time has almost been eliminated.

It should be noted that the Dutch Army uses exclusively NiCd batteries. Each pack receives periodic maintenance to prolong service life. Weak batteries are systematically replaced. The

Batteries are a perishable product and start deteriorating right from the time they leave the manufacturing plant.

US Army, on the other hand, uses NiMH batteries. They are evaluating the Li-ion polymer for the next generation battery.

Because of the high failure rate of fleet batteries and the uncertain situations such failures create, some organizations assign a person to maintain batteries. This person checks all batteries on a scheduled basis, exercises them for optimum service life, and replaces those that fall below an accepted capacity level and do not recover with maintenance programs. Batteries perform an important function; giving them the care they deserve is appropriate.

Storage

Batteries are a perishable product and start deteriorating right from the time they leave the manufacturing plant. For this reason, it is not advisable to stock up on batteries for future use. This is especially true with lithium-based batteries. The buyer should also be aware of the manufacturing date. Avoid acquiring old stock.

Keep batteries in a cool and dry storage area. Refrigerators are recommended, but freezers must be avoided because most battery chemistries are not suited for storage in sub-freezing temperatures. When refrigerated, the battery should be placed in a plastic bag to protect it against condensation.

The NiCd battery can be stored unattended for five years and longer. For best results, a NiCd should be fully charged, then discharged to zero volts. If this procedure is impractical, a discharge to 1V/cell is acceptable. A fully charged NiCd that is allowed to self-discharge during storage is subject to crystalline formation (memory).

Most batteries are shipped with a state-of-charge (SoC) of 40 percent. After six months storage or longer, a nickel-based battery needs to be primed before use. A slow charge, followed by one or several discharge/charge cycles, will do. Depending on the duration of storage and temperature, the battery may require two or more cycles to regain full performance. The warmer the storage temperature, the more cycles will be needed.

The Li-ion does not like prolonged storage. Irreversible capacity loss occurs after 6 to 12 months, especially if the battery is stored at full charge and at warm temperatures. It is often necessary to keep a battery fully charged as in the case of emergency response, public safety and defense. Running a laptop (or other portable device) continuously on an external power source with the battery engaged will have the same effect. Figure 15-1 illustrates the recoverable capacity after storage at different charge levels and temperatures.

The combination of a full charge condition and high temperature cannot always be avoided. Such is the case when keeping a spare battery in the car for a mobile phone. The NiMH and Li-ion chemistries are most severely affected by hot storage and operation. Among the Li-ion family, the cobalt has an advantage over the manganese (spinel) in terms of storage at elevated temperatures.

Temperature	**40% charge level** (recommended storage charge level)	**100% charge level** (typical user charge level)
0°C	98% after 1 year	94% after 1 year
25°C	96% after 1 year	80% after 1 year
40°C	85% after 1 year	65% after 1 year
60°C	75% after 1 year	60% after 3 months

Figure 15-1: Non-recoverable capacity loss on Li-ion batteries after storage.
High charge levels and elevated temperatures hasten the capacity loss. Improvements in chemistry have increased the storage performance of some Li-ion batteries.

The recommended storage temperature of a lithium-based battery is 15°C (59°F) or less. A charge level of 40 percent allows for some self-discharge that naturally occurs; and 15°C is a practical and economical storage temperature that can be achieved without expensive climate control systems.

While most rechargeable batteries cannot be stored at freezing temperatures, some newer commercial Li-ion batteries can be kept at temperatures of -40°C without apparent side effects. Such temperature tolerances enable long and cost-effective storage in the arctic.

The SLA battery can be stored for up to two years but must be kept in a charged condition. A periodic topping charge, also referred to as ‘refreshing charge’, is required to prevent the open cell voltage from dropping below 2.10V. (Depending on the manufacturer, some lead acid batteries may be allowed to drop to lower voltage levels). When self-discharged below a critical voltage threshold, sulfation occurs on most lead acid batteries. Sulfation is an oxidation layer on the negative plate that alters the charge and discharge characteristics. Although cycling can often restore the capacity loss, the battery should be recharged before the open cell voltage drops below 2.10V.

The SLA cannot be stored below freezing temperatures. Once a pack has been frozen, it is permanently damaged and its service life is drastically reduced. A previously frozen battery will only be able to deliver a limited number of cycles.

Priming

Some nickel-based batteries do not perform well when new. This deficiency is often caused by lack of formatting at the time of manufacturing. Batteries that are not sufficiently formatted are destined to fail because the initial capacity is low. The full potential is only reached after the battery has been cycled a few times. In many cases, the user does not have the patience to wait until the expected performance is reached. Instead, the customer exercises the warranty return option.

The most critical time in a battery’s life is the so-called priming stage. An analogy can be drawn with breaking in a new car engine. The performance and fuel efficiency may not be best at first, but with care and attention, the engine will improve over time. If overstressed when new, the engine may never provide the economical and dependable service that is expected.

Some poorly formatted batteries are known to produce less than 10 percent of capacity at the initial priming stage. By cycling, the capacity increases, and the battery will become usable after three to five cycles. Maximum performance on a NiCd, for example, is reached after 50 to 100 full charge/discharge cycles. This priming function occurs while the battery is being used. The gradual capacity increase during the early life of a battery is normally hidden to the user.

Quality cells from major Japanese manufacturers do not need extended priming and can be used almost immediately. After five full cycles, the performance is predictable and fully repeatable.

The manufacturer's recommended priming procedure should be followed. In many cases, a 24-hour trickle charge is needed. Verifying the performance with a battery analyzer is advisable, especially if the batteries are used for critical applications.

Some nickel-based batteries are known to form a passivation layer if kept in prolonged storage. Little scientific knowledge is available on this subject and the battery manufacturers may deny the existence of such a layer. A full charge/discharge, followed by a complete recharge corrects the problem.

Li-ion cells need less priming than the nickel-based equivalent. Manufacturers of Li-ion cells insist that priming is not a requirement. The priming function on the Li-ion may be used to verify that the battery is fully functional and produces the capacity required.

In an earlier chapter, the question "Why are excessive quantities of batteries being returned under warranty?" was raised. This question has not been fully answered. It appears that all battery chemistries are represented among the packs being returned. It is unclear whether these batteries are inoperable as claimed. Perhaps the liberal warranty return offered by dealers provides an opportunity to acquire a new, and seemingly better, battery without charge. Some misuse of the warranty policy cannot be fully dismissed.

The internal protection circuit of lithium-based batteries may be the cause of some problems. For safety reasons, many of these batteries do not allow a recharge if the battery has been discharged below 2.5V/cell. If discharged close to 2.5V and the battery is not recharged for a while, self-discharge further discharges the pack below the 2.5V level. If, at this time, the battery is put into the charger, nothing may happen. The battery appears to have an open circuit and the user consequently demands a replacement.

Cadex has received a large number of supposedly dead Li-ion polymer batteries from various manufacturers. When measured, these batteries had no voltage at the terminals and appeared to be dead. Charging the packs in their respective chargers was unsuccessful. But after waking up the battery's control circuit with the '*Boost'* function of the Cadex *7000 Series* battery analyzer, most of these batteries accepted normal charge. After a full charge, the performance was checked. Almost all packs reached capacities of 80 percent and higher and the batteries were returned to service.

The Million Dollar Battery Problem

In today's surging mobile phone market, many batteries are returned to mobile phone carriers before the ink on the invoice has dried. The most common consumer complaint is 'less than expected' runtime.

Many batteries are returned to mobile phone carriers before the ink on the invoice has dried.

The reasons for this failure are multi-fold. The battery may not have been properly formatted at the factory. Perhaps the packs remained on the shelf too long or have been discharged too low. Incorrect customer preparation is also to blame. The true reason for such failure may never be known.

Dealers are not equipped to handle the influx of returned batteries. To fulfill the warranty obligations and satisfy the customer, the dealer hands out a new battery and sends the faulty pack to the manufacturer. Truckloads of 'worthless' batteries are transported, only to be stockpiled in warehouses for eventual testing or recycling at the manufacturer's expense. The cost of exchange, time lost by retail staff, shipping, warehousing and eventual disposal amounts to a million dollar problem.

On a recent visit to Europe, a Cadex staff member learned that a large phone manufacturer had received 17 tons of failed handset batteries in one year alone. The batteries were stockpiled in large barrels for recycling. He also discovered that 15,000 NiMH batteries were returned to the manufacturer within weeks after the release of a new phone. When spot-checking the failed batteries with a Cadex *7000 Series* battery analyzer, most packs appeared to be operational.

On another occasion, a total of 14,000 Li-ion batteries were returned to a North American mobile phone provider. Of these, only 700 (or 5 percent), were faulty. Of these, ten random batteries were sent to Cadex for further testing. The Cadex lab reported that each of these failed packs indeed had genuine faults.

A European service center sent 40 Li-ion polymer batteries to Cadex for evaluation. These packs had failed in the field and were returned to the service center by customers. When servicing the batteries on a Cadex *7000 Series* battery analyzer, 37 units were found to be fully functional with capacities of above 80 percent and impedances below 180mW.

Phone manufacturers report that 80 to 90 percent of returned batteries have no faults or can easily be repaired with battery analyzing equipment. The remaining 10 to 20 percent, which do not easily recover with basic service, can often be restored with extended programs. Only a small percentage of batteries returned under warranty exhibit non-correctable faults.

Not all batteries and portable equipment under warranty fail due to manufacturer’s defects. A service manager for a major mobile phone manufacturer hinted that submersion into a cup of coffee or soft drink is a sizable contributor to equipment and battery failures. Apparently, the acids in the beverages manage to corrode the electrical conductors. Submersion into coffee occurs when the user mistakes the coffee cup for the phone cradle.

In an effort to salvage returned batteries, a leading mobile phone manufacturer segregates battery packs according to purchase date. Packs returned within the thirty-day warranty period are marked as type B. The batteries are then sent to a regional service center where they are serviced with battery analyzers. If the batteries are clean, (have no coffee residue) and regain a capacity of 80 percent or higher, the packs are relabeled and sold as a B class product. Over 90 percent of their returned batteries have been reclaimed with this program.

On the strength of this success, some battery-refurbishing houses have extended the service to include batteries of up to one year old. The service center experiences a 40 to 70 percent restoration yield in repairing these older batteries. The battery-refurbishing centers are said to make a profit. Equally important, such programs reduce the environmental impact of battery disposal.

To the Service Counter, and No Further

Not all manufacturers and dealers offer battery-refurbishing centers. If not available, a program is gaining popularity in which the battery is serviced at the store level. When a customer returns a faulty battery, the pack goes no further than the store that sold the equipment.

The customer service clerk checks the battery on site with approved test equipment. An attempt is made to restore the battery. If not successful and a warranty replacement is needed, a service report is issued, which is sent to the manufacturer by fax or e-mail. After verifying the report, the manufacturer offers replacement batteries as part of the warranty replacement policy.

Warranty replacement can be further streamlined by using the Internet and compatible battery analyzers. Such a process will operate with a minimum of human resources and run independent of office hours and time zones. Here’s how it works:

Technology is not keeping pace in supplying the battery market suitable test equipment that is both cost effective and easy to use.

The manufacturer first sends each participating store an appropriate number of replacement batteries. When a customer returns a faulty battery, service personnel test the pack with the in-store analyzer. If restoration is unsuccessful, the analyzer e-mails a report to the manufacturer, stating the nature of the deficiency. Other information, such as the date of purchase, battery type and customer name are also included. The computer at the manufacturer's headquarters verifies the claim and, if valid, issues an inventory adjustment against the spare batteries allocated to the store. When the stock gets low, a re-stocking order is generated and additional batteries are sent out automatically.

Besides lowering overhead costs, a fully integrated warranty replacement system provides the manufacturer with accurate information regarding the nature of battery failures. User patterns leading to battery failure can be evaluated by geographic region. For example, a temperature related failure might be more likely to occur in warm climates than in cool ones. Batteries with higher temperature resiliency can be allocated for these regions. Recurring problems can be identified quickly and corrective measures implemented within months rather than years. Such measures can be as simple as providing the customer with better operating instructions in preparing a new battery before use.

One of the most difficult problems in servicing batteries at store-level is a lack of technical know-how by the customer service personnel. With the ever-increasing number of battery models, the task of identifying a battery type and setting the correct parameters is becoming increasingly more complex. Technology is not keeping pace in supplying the battery market with suitable test equipment that is both cost effective and easy to use.

To bring battery testing within reach of the untrained user, battery analyzers must be simple to operate and allow easy interface with all major battery types. Setting the correct battery parameters should be clear and concise. Uncertainties that can lead to errors must be minimized. The manufacturer of the battery test equipment should be aware that the task of operating a battery analyzer is not part of the clerk's job description.

The *Batteryshop*™ software by Cadex has been developed for the purpose of simplifying battery maintenance. When installed in a PC, the operator simply selects the desired battery from the database of over 2000 battery listings. With the Cadex *7000 Series* connected to the PC, the analyzer programs itself to the correct parameters with the click of the mouse. The user only needs to insert the battery into the appropriate battery adapter and everything else is done automatically.

Some batteries, such as those manufactured by Motorola, are equipped with bar code labels. If bar coded, the user can simply scan the bar code label and insert the battery into the analyzer. Here is how it works:

The scanned battery model number is matched with the battery listing in the database. Cadex *Batteryshop*™ then assigns the appropriate battery configuration code (C-code) to the battery and downloads it to the Cadex *7000 Series*. The analyzer is now programmed to the correct parameters, ready to service the battery.

Not all battery packs come with bar code identification. If not available, a label printer connected to the PC can generate the missing bar code. These labels can be attached to a separate sheet on the service counter. The bar code labels may also be placed next to an illustration of the battery. The clerk simply refers to the correct battery and scans the bar code label associated with the battery. The system is now set to service the battery.

In the near future it will be possible to view the picture of the battery on the PC monitor. Clicking the mouse on the image will reveal all model numbers associated with this battery. A click on the correct model will program the analyzer.

The expensive and wasteful battery exchange policies practiced today may no longer be acceptable in the future.

When training global staff, simplification and automation make common sense. With tools now available that do the thinking, employees no longer need to be battery experts. Similar to a checkout clerk in a supermarket who, in the pre-computer days, required full product knowledge can now rely on the embedded bar code information. The price of all items purchased is flashed on the screen and an up-to-the-second inventory status is available. Such simplifications are also possible in servicing commercial batteries.

The Quick Fix

Checking a battery and assessing its status within a few minutes is one thing — finding a solution and actually fixing the problem is another. Increasingly, customers and dealers alike are seeking an alternative solution to replacing the batteries under warranty. They want a quick fix.

Fully automated test procedures are being developed which check the battery and apply a quick-prime program to wake up a sleeping battery. The program will last from a few minutes for an easy wake-up call, to an hour or longer for the deep-sleepers.

Batteries with minor deficiencies will be serviced while the customer enjoys a cup of coffee or browses through the store. If the battery has an electrical short or does not accept a charge, the likelihood of revitalizing the battery is slim. This pack is eliminated within seconds to clear the test equipment for other batteries. If a pack requires extensive priming, which will take a few hours to complete, the customer is asked to come back later.

Some battery analyzers indicate the estimated service time after the battery has passed through the early assessment stages. The customer can decide to wait, buy a spare battery, or come back for the repaired battery the next day.

A complete battery cycle offers the best service. Such a service makes optimal use of the restorative abilities of a battery analyzer. A full cycle may take five to eight hours and can be applied overnight. Multi-bay analyzers that service several batteries at the same time increase the throughput. Such analyzers operate 24 hours without user intervention.

A customer may not have time to wait for the outcome of a battery test. The prospect of having to buy a new battery is even less appealing. In such a case, a class B or replacement battery may be the answer. This pack can be drawn from a pool of refurbished batteries, which the store has built up from previous returns. This could become a lucrative side business as customers begin to realize the cost saving potential, especially if the battery is accompanied by a performance report.

Some battery analyzers offer ultra-fast charge functions. The maximum permissible charge current that can be applied to a battery is dictated by the battery’s ability to absorb charge. A fit battery, or one that has a partial charge, would charge to the 70 percent level in 30 minutes or less. A 70 percent charge level is often sufficient to complete a performance test or quick-fill the battery for a hurried customer. The topping charge from there to full charge is what demands the long charge time.

Some late model battery analyzers also offer a quick priming program that services a battery in a little more than an hour. This program applies an ultra-fast charge and ultra-fast discharge to check the integrity of the battery. By virtue of cycling, some priming and conditioning activities occur.

Customers demand a quick turnaround when a mobile phone fails. Manufacturers and service providers realize that better methods are needed to handle customer returns. The expensive and wasteful battery exchange policies practiced today may no longer be acceptable in the future. Fierce competition and tight product margins are part of the reason. Returned batteries

> *"Where will the mountains of batteries go when spent?"*

account for a considerable after-sale burden. With modern technology, these costs can be reduced while improving customer service and enhancing satisfaction.

Battery Warranty

Some manufacturers of industrial batteries provide warranties of up to 18 months. A free exchange is offered if the battery fails to meet 80 percent of the rated capacity throughout the warranty period. (I hasten to mention that these warranty policies apply to markets other than mobile phones.)

But what happens if such a battery is returned for warranty? Will the dealer replace the pack without hesitation? Rarely.

With lack of battery standards, manufacturers are free to challenge warranty claims, even if a genuine problem exists. Many batteries reveal only the chemistry and voltage on the label and do not make reference to the milliampere-hour rating (mAh). How does the user know what capacity rating to use when testing the battery? What performance standards can be applied?

On battery packs that show the mAh rating, some battery manufacturers may have used the peak capacity rating. This is done for promotional reasons to make their packs look better than the competitor's. Peak capacity is based on a lower discharge rate because a battery produces higher readings if discharged slowly. For warranty purposes, a discharge of 1C should be used.

Regulatory authorities stress the importance of marking all batteries with the average capacity rating. Portable batteries with a capacity of up to about 2A should be rated at a 1C discharge. Batteries above that capacity may be rated at 0.5C. No true standard exists in term of capacity rating.

With the increased popularity of battery analyzers, battery manufacturers and dealers are urged to follow industry-accepted standards regarding battery ratings. In an attempt to lower warranty claims, some battery manufacturers have moderated the published ratings of some batteries to be more consistent with reality.

Manufacturers are concerned about the high cost of providing free replacement batteries and disposing of returned units. If a battery analyzer is used, failures due to fading capacity can mostly be corrected. Warranty claims are exercised only on those packs that develop a genuine failure. If fewer batteries returned, the vendor can offer better pricing.

Battery Recycling

Even though the emphasis in battery research has shifted away from NiCd to newer technologies, the NiCd battery continues to be one of the most used rechargeable batteries. Over 75 million NiCd batteries were sold in the US during the year 2000. Market reports indicate that the demand of NiCd batteries is expected to rise six percent per year until 2003. The demand for other chemistries, such as the NiMH and Li-ion family, is rising at a more rapid pace. Where will the mountains of batteries go when spent? The answer is recycling.

The lead acid battery has led the way in recycling. The automotive industry should be given credit in organizing ways to dispose of spent car batteries. In the USA, 98 percent of all lead acid batteries are recycled. Compared to aluminum cans (65 percent), newspaper (59 percent) and glass bottles (37 percent), lead acid batteries are reclaimed very efficiently, due in part to legislation.

Only one in six households in North America recycle rechargeable batteries. Teaching the public to bring these batteries to a recycling center is a challenging task. Homeowners have

It takes six to ten times the amount of energy to reclaim metals from recycled batteries than it would through other means.

the lowest return ratios, but this should improve once more recycling repositories become available and better environmental awareness is emphasized.

Careless disposal of the NiCd is very hazardous to the environment. If used in landfills, the cadmium will eventually dissolve itself and the toxic substance will seep into the water supply, causing serious health problems. Our oceans are already beginning to show traces of cadmium (along with aspirin, penicillin and antidepressants) but the source of the contamination is unknown.

Although NiMH batteries are considered environmentally friendly, this chemistry is also being recycled. The main derivative is nickel, which is considered semi-toxic. NiMH also contains an electrolyte that, in large amounts, is hazardous to the environment.

If no disposal service is available in an area, individual NiMH batteries can be discarded with other household wastes. If ten or more batteries are accumulated, the user should consider disposing the batteries in a secure waste landfill.

Lithium (metal) batteries contain no toxic metals, however, there is the possibility of fire if metallic lithium is exposed to moisture while the cells are corroding. Most lithium batteries are non-rechargeable and are used by defense organizations. For proper disposal, these batteries must be fully discharged in order to consume all the metallic lithium content. Li-ion batteries do not contain metallic lithium and the disposal problem does not exist. Most lithium systems, however, contain toxic and flammable electrolyte.

In 1994, the Rechargeable Battery Recycling Corporation (RBRC) was founded to promote the recycling of rechargeable batteries in North America. RBRC is a non-profit organization that collects batteries from consumers and businesses and sends them to Inmetco and Toxco for recycling. Inmetco specializes in recycling NiCd, but also accepts NiMH and lead-based batteries. Toxco, focuses on lithium metal and Li-ion system. Currently only intended to recycle NiCd batteries, RBRC will expand the program to include also NiMH, Li-ion and SLA batteries.

Programs to recycle spent batteries have been in place in Europe and Asia for many years. Sony and Sumitomo Metal in Japan have developed a technology to recycle cobalt and other precious metals from Li-ion batteries. The rest of Asia is progressing at a slower rate. Some movements in recycling spent batteries are starting in Taiwan and China, but no significant infrastructure exists.

Battery recycling plants require batteries to be sorted according to chemistries. Some sorting is done prior to the battery arriving at the recycling plants. NiCd, NiMH, Li-ion and lead acid are often placed in designated boxes at the collection point.

Sorting batteries adds to the cost of recycling. The average consumer does not know the chemistry of the batteries they are using. For most, a battery is a battery.

If a steady stream of batteries, sorted by chemistry, were available at no charge, recycling would be feasible with little cost to the user. The logistics of collection, transportation and labor to sort the batteries make recycling expensive.

The recycling process starts by removing the combustible material, such as plastics and insulation using a gas fired thermal oxidizer. Gases from the thermal oxidizer are sent to the plant’s scrubber where they are neutralized to remove pollutants. The process leaves the clean, naked cells which contain valuable metal content.

The cells are then chopped into small pieces, which are then heated until the metal liquefies. Non-metallic substances are burned off; leaving a black slag on top that is removed with a slag arm. The different alloys settle according to their weights and are skimmed off like cream from raw milk.

Cadmium is relatively light and vaporizes easily at high temperatures. In a process that appears like a pan boiling over, a fan blows the cadmium vapor into a large tube, which is cooled with water mist. This causes the vapors to condense. A 99.95 percent purity level of cadmium can be achieved using this method.

Some recyclers do not separate the metals on site but pour the liquid metals directly into what the industry refers to as ‘pigs’ (65 pounds) or ‘hogs’ (2000 pounds). The pigs and hogs are then shipped to metal recovery plants. Here, the material is used to produce nickel, chromium and iron re-melt alloy for the manufacturing of stainless steel and other high end products.

Current battery recycling methods requires a high amount of energy. It takes six to ten times the amount of energy to reclaim metals from recycled batteries than it would through other means. A new process is being explored, which may be more energy and cost effective. One method is dissolving the batteries with a reagent solution. The spent reagent is recycled without forming any atmospheric, liquid or solid wastes.

Who pays for the recycling of batteries? Participating countries impose their own rules in making recycling feasible. In North America, some recycling plants bill on weight. The rates vary according to chemistry. Systems that yield high metal retrieval rates are priced lower than those which produce less valuable metals. The highest recycling fees apply to NiCd and Li-ion batteries because the demand for cadmium is low and Li-ion batteries contain little in the way of retrievable metal. The recycling cost of alkaline is 33 percent lower than that of NiCd and Li-ion because the alkaline cell contains valuable iron. The NiMH battery yields the best return. Recycling NiMH produces enough nickel to pay for the process.

Not all countries base the cost of recycling on the battery chemistry; some put it on tonnage alone. The cost of recycling batteries is about $1,000 to $2,000US per ton. Europe hopes to achieve a cost per ton of $300US. Ideally, this would include transportation, however, moving the goods is expected to double the overall cost. For this reason, Europe sets up several smaller processing locations in strategic geographic locations.

Significant subsidies are sill required from manufacturers, agencies and governments to support the battery recycling programs. These subsidies are in the form of a tax added to each manufactured cell. RBRC is financed by such a scheme.

Caution: Under no circumstances should batteries be incinerated as this can cause them to explode.

Important: In case of rupture, leaking electrolyte or any other cause of exposure to the electrolyte, flush with water immediately. If eye exposure occurs, flush with water for 15 minutes and consult a physician immediately.

Chapter 16: Practical Battery Tips

Batteries seem to have a mind of their own. Their stubborn and unpredictable behavior has left many battery users in awkward situations. In fact, the British Army could have lost the Falkland War in 1982 because of uncooperative batteries. The army assumed that a battery would always follow rigid military specifications. Not so. When the order was given to launch the portable missiles, nothing happened and the missiles did not fly that day. Such battery-induced letdowns happen on a daily basis. Some are simply a nuisance, others have serious consequences.

In this section we examine what the user can reasonably expect from a battery. We learn how to cope with the many moods of a battery and how to come to terms with its limitations.

The best choice is not necessarily an oversized battery, but one that has a sufficient safety margin and is well maintained.

Personal Field Observations

While working with General Electric, I had the opportunity to examine the behavior of many NiCd batteries for two-way radios. I noticed a trend with these batteries that was unique to NiCd. These particularities repeated themselves in various other applications.

A certain organization continually experienced NiCd battery failure after a relatively short service time. Although the batteries performed at 100 percent when new, their capacity dropped to 20 percent and below within one year. We discovered that their two-way radios were under-utilized; yet the batteries received a full recharge after each short field use.

After replacing the batteries, we advised the organization to exercise the new batteries once per month by discharging them to one-volt-per cell with a subsequent recharge. The first exercise took place after the batteries had been in service for four months. At that stage, we were anxious to find out how much the batteries had deteriorated. Here is what we found:

On half of the batteries tested, the capacity loss was between 25 to 30 percent; on the other half, the losses were around 10 to 20 percent. With exercise — and some needed recondition cycles — all batteries were fully restored. Had maintenance been omitted for much longer, the probability of a full recovery would have been jeopardized.

On another occasion, I noticed that two-way radios used by construction workers experienced fewer NiCd battery problems than those used by security guards. The construction workers often did not turn off the radios when they put down their hammers. As a result, the batteries got their exercise and kept performing well until they fell apart from old age. In many cases the batteries were held together with electrician’s tape.

In comparison, the security guards pampered their batteries to death by giving them light duty and plenty of recharge. These batteries still looked new when they had to be discarded after only 12 months of service. Because of the advanced state of memory, recondition was no longer effective to restore these batteries.

On a further application, I studied the performance of a two-way radio that was available with batteries of different capacities. It soon was apparent that the smaller battery lasted much longer, whereas the larger packs needed replacing more often. The small battery had to work harder and received more exercise during a daily routine.

Equipment manufacturers are aware of the weak link — the battery. For a more reliable energy source, higher capacity batteries are recommended. Not only are oversized batteries bulky, heavy and expensive, they hold more residual charge prior to recharge than smaller units. If the residual energy is never fully consumed before a recharge, and no exercise is applied, the nickel-based battery will eventually lose its ability to hold charge due to memory.

On the lithium and lead-base systems, a slightly oversized battery offers an advantage because the pack is less stressed on deep discharges. The battery does not need to be discharged as low for the given application. A high residual charge before recharge is a benefit rather than a disadvantage for these chemistries.

The Correct Battery for the Job

What is the best battery choice? The requirements differ between personal users and fleet operators. The personal user can choose batteries in various sizes and chemistries. Cost is a factor for many. If a smaller and less energy-dense battery is chosen, a spare battery may be carried to assure continued service.

The energy requirements are quite different with fleet operators. The equipment is matched with a battery designed to run for a specified number of hours per shift. A degradation factor to compensate for battery aging is taken into account. A reserve capacity is added to allow for unforeseen activities. Allowing an aging degradation factor of 20 percent and providing a reserve capacity of 20 percent will reduce the usable battery capacity from 100 percent to 60 percent in a worst-case scenario. Such a large percentage of reserve capacity may not always be practical but the equipment manufacturers should consider these safety factors when fitting the portable devices with a battery.

The best choice is not necessarily an oversized battery, but one that has sufficient safety margin and is well maintained. This is especially true of NiCd batteries. When adding large safety margins, the reserve capacity should be depleted once per month, if this is not done already through normal use.

The NiMH also needs exercising but less often. Cycling lithium-based batteries is only recommended for the purpose of measuring the performance.

Many battery users have a choice of switching from NiCd to NiMH to obtain longer runtimes and/or reduce weight. Regulatory bodies advise using less toxic alternatives because of the environment. But will the NiMH battery perform as well as the NiCd in industries that require repetitive deep discharges?

The NiMH will not match the cycle count of the NiCd chemistry. This lower life expectancy has serious consequences on applications that need one or several recharges per day. However, in a recent study on battery choice for heart defibrillators for emergency applications, it was observed that a battery may cycle far less than anticipated. Instead of the expected 200-cycle count after two years of use, less than 60 cycles had been delivered. Such service information is now available with the use of ‘smart’ batteries. With fewer cycles needed, the switch to lighter and higher energy-dense batteries becomes practical for these applications.

In most cases, NiMH can be used as a direct replacement for NiCd. When doing so, the charger must be checked. A NiMH charger can charge NiCd batteries, but a charger designed only for the NiCd battery should not be used to charge NiMH. Battery damage may result due to inaccurate full-charge detection and excessive trickle charge while in ready mode. If no alternative exists, the battery should be removed as soon as the green ready light appears. Battery temperature during charge should also be observed.

Remote control racecar enthusiasts rely heavily on high current capabilities and quick charging. NiMH batteries are now available that can handle very high discharge currents. This makes the battery ideally suited for competitions, because the weight and size of the battery can be reduced.

For most hobbyists, the NiCd remains the preferred choice. The reasons are: more consistent performance, longer cycle life and lower cost. NiCd needs replacement less often than NiMH. RC racing experts claim that NiMH is fragile, temperamental, and can be hurt easily. The storage of the NiMH battery is also erratic. Some cells are flat after a few weeks of storage; others still retain a charge.

High load currents have been problematic for NiMH. Discharge currents of 0.5C and higher rob the battery of cycle life. In comparison, NiCd delivers repetitive high load currents with minimal side effects.

The ultra-high capacity NiCd does not perform as well compared to the standard version in terms of load characteristics and endurance. Packing more active material makes the NiCd behave more like a NiMH battery.

The Li-ion battery has limited current handling capabilities. In many cases, it cannot be used as a replacement for such applications as defibrillators and power tools, not to mention RC racing. In addition, Li-ion requires a different charging system than the nickel-based battery chemistries.

Battery Analyzers for Critical Missions

Occasionally, a customer will call Cadex because their battery analyzer appears faulty. The complaint: the battery no longer indicates correct capacity readings. In most cases, the customer has just purchased new batteries. When testing these new packs, the capacities read 50 to 70 percent. The customer assumes that, “Naturally, if two or more of these brand new batteries show low readings, it can only be the analyzer’s fault.”

Battery analyzers play a critical role in identifying non-performing batteries, new or old. Conventional wisdom says that a new battery always performs flawlessly. Yet many users realize that a fresh battery may not always meet the manufacturer's specifications. Weak batteries can be identified and primed. If the capacity does not improve, the packs can often be returned to the vendor for warranty replacement. Whole batches of new batteries have been sent back because of unacceptable performance. Had these batteries been released without prior inspection, the whole system would have been jeopardized, resulting in unpredictable performance and frequent down time.

In addition to getting new batteries field-ready, battery analyzers perform the important function of weeding out the deadwood in a battery fleet. Weak batteries can often hide among their peers. However, when the system is put to the test in an emergency, these non-performers become a real nuisance.

Organizations tend to postpone battery maintenance until a crisis situation develops. One fire brigade using two-way radios experienced chronic communication problems, especially during emergency calls which lasted longer than two hours. Although their radios functioned in the receive mode, they were not able to transmit and firefighters were left unaware that their calls did not get through.

The fire brigade acquired a Cadex battery analyzer and all batteries were serviced through exercise and recondition methods. Those batteries that did not recover to a preset target capacity were replaced.

Shortly thereafter, the firefighters were summoned to a ten-hour call that demanded heavy radio traffic. To their astonishment, none of the two-way radios failed. The success of this flawless operation was credited to the excellent performance of their batteries. The following day, the Captain of the fire brigade personally contacted the manufacturer of the battery analyzer and enthusiastically endorsed the use of the device.

Batteries placed on prolonged standby commonly fail. Such was the case when a Cadex representative was allowed to view the State Emergency Management Facility of a large US city. In the fortified underground bunker, over one thousand batteries were kept in chargers. The green lights glowed, indicating that the batteries where ready at a moment’s notice. The officer in charge stood tall and confidently said, “We are prepared for any emergency”.

The representative then asked the officer to hand over a battery from the charger to check the state-of-health (SoH). Within seconds, the battery analyzer detected a fail condition. In an effort to make good, the officer grabbed another battery from the charger bank but, it failed too. Subsequent batteries tested also failed.

Scenarios such as these are common but such flaws do not get rectified quickly. Political hurdles and lack of funding are often to blame. In the meantime, all the officer can do is pray that no emergency occurs.

Eventually, a new set of batteries is installed and the system returns to full operational readiness. However, the same scenario will reoccur, unless a program is implemented to exercise the batteries on a regular basis. Advanced battery analyzers, such as the Cadex *7000 Series*, apply a conditioning discharge every 30 days to prevent the memory phenomenon on nickel-based batteries.

Figure 16-1: Results of neglecting your battery's state-of-health.
Maintenance helps keep deadwood out of your arsenal.

The military also relies heavily on batteries. Defense organizations take great pride in employing the highest quality and best performing equipment. When it comes to rechargeable batteries, however, there are exceptions. The battery often escapes the scrutiny of a full military inspection and only its visual appearance is checked. Maintenance requirements are frequently ignored. Little effort is made in keeping track of the battery's state of health, cycle count and age. Eventually, weak batteries get mixed with new ones and the system becomes unreliable. This results in soldiers carrying rocks instead of batteries. A battery analyzer, when used correctly, keeps deadwood out of the arsenal.

The task of keeping a battery fleet at an acceptable capacity level has been simplified with battery analyzers that offer target capacity selection. This novel feature works on the basis that all batteries must pass a user-defined performance test. Batteries that fall short are restored with the recondition cycle. If they fail to recover, the packs are replaced.

The target capacity setting of a battery analyzer can be compared to a student entry-exam for college. Assuming that the passing mark is 80 percent, the students who do not obtain that level are given the opportunity to take a refresher course and are thereafter permitted to rewrite the exam. In our analogy, the refresher course is the recondition cycle that is applied to nickel-based batteries. If the passing mark is set to 90 percent, for example, fewer but higher qualified students are admitted.

A practical target capacity setting for batteries in public safety is 80 percent. Increasing the capacity requirement to 90 percent will provide an extra 10 percentage points of available energy. However, higher settings will yield fewer batteries since more packs will fail as they age.

Many organizations allocate the top performing batteries for critical applications and assign the lower performers for lighter duties. This makes full use of the available resources without affecting reliability.

Some battery analyzers display both the reserve capacity (motor fuel left in the tank before refill) and the full-charge capacity (full tank) of the batteries serviced. The user is then able to calculate how much energy was consumed during the day by subtracting the reserve from the full-charge capacity. To ensure a reasonable safety margin after a routine day, the reserve capacity should be about 20 percent. If less reserve capacity is available, the target capacity should be set higher. By allowing reasonable reserve capacity, unexpected downtime in an emergency or on extra-strenuous field activities can be eliminated.

Chapter 17: Did you know . . . ?

Technological advancements usually take off shortly after a major breakthrough has occurred. Electricity was discovered circa 1600 AD (or earlier). At that time, electric power had few other applications than creating sparks and experimenting with twitching frog legs. Once the relationship with magnetism was discovered in the mid 1800s, generators were invented that produced a steady flow of electricity. Motors followed that enabled mechanical movement and the Edison light bulb was invented to conquer the dark.

In the early 1900s, the electronic vacuum tube was invented, which enabled generating and amplifying signals. Soon thereafter broadcasting through the air by radio waves became possible. The discovery of the transistor in 1947 led to the development of the integrated circuit ten years later. Finally, the microprocessor ushered in the Information Age and revolutionized the way we live.

How much has the battery improved during the last 150 years when compared to other advancements? The progress has been moderate. A battery holds relatively little power, is bulky, heavy, and has a short life span. Battery power is also very expensive.

Yet humanity depends on the battery as a power source. In the year 2000, the total battery energy consumed globally by laptops and mobile phones alone is estimated to be 2,500MW. This equals 25,000 cars powered by a 100kW engine (134hp) driving at freeway speed.

Many travelers have experienced the exhilaration of take-off in a jumbo jet. At a full weight of over 396 tons, the Boeing 747 requires 90MW of energy to get airborne. The global battery power consumed by mobile phones and laptops could simultaneously lift off 28 jumbo jets. The energy consumption while cruising at high altitude is reduced to about half, or 45MW. The batteries that power our mobile phones and laptops could keep 56 Boeing 747s in the air.

The mighty Queen Mary, an 81,000 ton cruise ship measuring over 300 m (1000 ft) in length, was propelled by four steam turbine engines producing a total of 160,000hp. The energy consumed globally by mobile phones and laptops could power 20 Queen Mary ships, with 3000 passengers and crew aboard, traveling at a speed of 28.5 knots (52 km/hr). The Queen Mary was launched in 1934 and is now retired in Long Beach, California.

In this concluding chapter, we compare the cost of battery power against energy created by the combustion engine and the emerging fuel cell. We also examine the cost of electricity delivered through the electric utility system.

The Cost of Mobile Power

Among the common power sources, energy from non-rechargeable batteries is the most expensive. Figure 17-1 reflects the cost per kWh using non-rechargeable batteries, also referred to as primary batteries. In addition, non-rechargeable batteries have a high internal cell resistance, which limits their use to light loads with low discharge currents.

In the last few decades, there has been a shift from non-rechargeable to rechargeable batteries, also known as secondary batteries. The convenience of recharging, low cost and reliable operation have contributed to this. Another reason for the increased popularity of the secondary battery is the larger energy densities available. Some of the newer rechargeable lithium systems now approach or exceed the energy density of a primary battery.

	AAA Cell	AA Cell	C Cell	D Cell	9 Volt
Capacity (alkaline)	1100mAh	2500mAh	7100mAh	14,300mAh	600mAh
Energy (single cell)	1.4Wh	3Wh	9Wh	18Wh	4.2Wh
Cost per Cell (US$)	$1.25	$1.00	$1.60	$1.60	$3.10
Cost per KWh (US$)	$890	$330	$180	$90	$730

Figure 17-1: Energy and cost comparison of primary alkaline cells.
Energy from primary batteries is most expensive. The cost increases with smaller battery sizes.

Figure 17-2 compares the cost of power when using rechargeable batteries. The analysis is based on the purchase cost of the battery and the number of discharge-charge cycles it can endure before replacement is necessary. The cost does not include the electricity needed for charging, nor does it account for the cost of purchasing and maintaining the charging equipment.

	NiCd AA Cell	NiMH AA Cell	Lead Acid (typical pack)	Li-ion 18650 Cell	Reusable Alkaline AA Cell
Capacity	600mAh	1000mAh	2000mAh	1200mAh	1400mAh [1]
Battery Voltage	7.5V	7.5V	12V	7.2V	7.5V
Energy per cycle	4.5Wh	7.5Wh	24Wh	8.6Wh	6.3Wh
Cycle life	1500	500	250	500	10
Cost per battery (ref. only)	$50	$70	$50	$100	$6.00
Cost per kWh ($US)	$7.50	$18.50	$8.50	$24.00	$95.00

Figure 17-2: Energy and cost comparison using rechargeable cells.
Older battery technologies offer lower energy costs compared to new systems. In addition, larger cells are more cost-effective than small cells. The battery packs taken for comparison are for commercial applications at over-the-counter prices.

For this calculation, 840mA is used since subsequent capacities are rated at 840mA (60% of initial capacity). If the battery is discharged partially, a higher cycle life can be obtained.

Figure 17-3 evaluates the cost to generate 1kW of energy. We take into account the initial investment, add the fuel consumption and include the eventual replacement of each system.

Power obtained through the electrical utility grid is most cost effective. Consumers in industrialized countries pay between $0.05 and 0.15US per kWh. The typical daily energy consumption of a household is 25kWh.

	Investment of equipment to generate 1kW	**Lifespan** of equipment before major overhaul or replacement	**Cost of fuel** per kWh	**Total Cost** per kWh, incl. fuel, maintenance and equipment replacement
NiCd for portable use	$7,000, based on 7.2V, 1000mAh at $50/pack	1500 h, based on 1C discharge	$0.15 for electricity	$7.50
Gasoline Engine for mobile use	$30, based on $3,000/100kW (134hp)	4000 h	$0.10	$0.14
Diesel Engine for stationary use	$40, based on $4,000/100kW (134hp)	5000 h	$0.07	$0.10
Fuel Cell	$3,000 – 7,500		$0.35	
- for portable use		2000 h	-->	$1.85 – 4.10
- for mobile use		4000 h	-->	$1.10 – 2.25
- for stationary use		40,000 h	-->	$0.45 – 0.55
Electricity from electric grid	All inclusive	All inclusive	$0.10	$0.10

Figure 17-3: Cost of generating 1kW of energy.
This takes into account the initial investment, fuel consumption, maintenance and eventual replacement of the equipment. The most economical power source is by far the utility; the most expensive is portable batteries.

The fuel cell offers the most effective means of generating electricity, but is expensive in terms of cost per kWh. This high cost is made economical when comparing with portable rechargeable batteries. For mobile and stationary applications, the fuel cell is considerably more expensive than conventional methods.

Note: The costing information obtained on the fuel cell is based on current estimates and assumptions. It is anticipated that improvements and wider use of this technology will eventually lower the cost to be competitive with conventional methods.

The Fuel Cell

A fuel cell is an electrochemical device which combines hydrogen fuel with oxygen to produce electric power, heat and water. In many ways, the fuel cell resembles a battery. Rather than applying a periodic recharge, a continuous supply of oxygen and hydrogen is supplied from the outside. Oxygen is drawn from the air and hydrogen is carried as a fuel in a pressurized container. As alternative fuel, methanol, propane, butane and natural gas can be used.

The best choice is not necessarily an oversized battery, but one that has a sufficient safety margin and is well maintained.

The fuel cell does not generate energy through burning; rather, it is based on an electrochemical process. There are little or no harmful emissions. The only release is clean water. In fact, the water is so pure that visitors to Vancouver's Ballard Power Systems, the leader in the development of the proton exchange membrane fuel cell (PEMFC), drank clear water emitted from the tailpipes of buses powered by a Ballard fuel cell.

The fuel cell is twice as efficient in converting fuel to energy through a chemical process than combustion. Hydrogen, the simplest element consisting of one proton and one electron, is plentiful and is exceptionally clean as a fuel. Hydrogen makes up 90 percent of the composition of the universe and is the third most abundant element on the earth's surface. Such a wealth of fuel would provide an almost unlimited pool of energy at relatively low cost. But there is a price to pay. The fuel cell core (or 'stack'), which converts oxygen and hydrogen to electricity, is expensive to build.

Hydrogen must be carried in a pressurized bottle. If propane, natural gas or diesel are used, a reformer is needed to convert the fuel to hydrogen. Reformers for PEMFCs are bulky and expensive. They start slowly and purification is required. Often the hydrogen is delivered at low pressure and additional compression is required. Some fuel efficiency is lost and a certain amount of pollution is produced. However, these pollutants are typically 90 percent less than what comes from the tailpipe of a car.

The fuel cell concept was developed in 1839 by Sir William Grove, a Welsh judge and gentleman scientist. The invention never took off, partly because of the success of the internal combustion engine. It was not until the second half of the 20th century when scientists learned how to better utilize materials such as platinum and TeflonÔ, that the fuel cell could be put to practical use.

A fuel cell is electrolysis in reverse, using two electrodes separated by an electrolyte. Hydrogen is presented to the negative electrode (anode) and oxygen to the positive electrode (cathode). A catalyst at the anode separates the hydrogen into positively charged hydrogen ions and electrons. On the PEMFC system, the oxygen is ionized and migrates across the electrolyte to the anodic compartment where it combines with hydrogen. The byproduct is electricity, some heat and water. A single fuel cell produces 0.6 to 0.8V under load. Several cells are connected in series to obtain higher voltages.

The first practical application of the fuel cell system was made in the 1960s during the Gemini space program, when this power source was favored over nuclear or solar power. The fuel cell, based on the alkaline system, generated electricity and produced the astronauts' drinking water. Commercial application of this power source was prohibitive because of the high cost of materials. In the early 1990s, improvements were made in stack design, which led to increased power densities and reduced platinum loadings at the electrodes.

High cost did not hinder Dr. Karl Kordesch, the co-inventor of the alkaline battery, from converting his car to an alkaline fuel cell in the early 1970s. Dr. Kordesch drove the car for many years in Ohio, USA. The hydrogen tank was placed on the roof and the trunk was utilized to store the fuel cell and back-up batteries. According to Dr. Kordesch, there was "enough room for four people and a dog".

Types of fuel cells — Several variations of fuel cell systems have emerged. The most common are the previously mentioned and most widely developed PEMFC systems using a polymer electrolyte. This system is aimed at vehicles and portable electronics. Several developers are also targeting stationary applications. The alkaline system, which uses a liquid electrolyte, is the preferred fuel cell for aerospace applications, including the space shuttle. Molten carbonate, phosphoric acid and solid oxide fuel cells are reserved for stationary applications, such as power generating plants for electric utilities. Among these stationary systems, the solid oxide fuel cell system is the least developed but has received renewed attention due to breakthroughs in cell material and stack designs.

The PEMFC system allows compact designs and achieves a high energy to weight ratio. Another advantage is a quick start-up when hydrogen is applied. The stack runs at a low temperature of about 80°C (176°F). The efficiency is about 50 percent (in comparison, the internal combustion motor has an efficiency of about 15 percent).

The limitations of the PEMFC system are high manufacturing costs and complex water management issues. The stack contains hydrogen, oxygen and water. If dry, the input resistance is high and water must be added to get the system going. Too much water causes flooding.

The PEMFC has a limited temperature range. Freezing water can damage the stack. Heating elements are needed to keep the fuel cell within an acceptable temperature range. The warm-up is slow and the performance is poor when cold. Heat is also a concern if the temperature rises too high.

The PEMFC requires heavy accessories. Operating compressors, pumps and other apparatus consumes 30 percent of the energy generated. The PEMFC stack has an estimated service life of 4000 hours if operated in a vehicle. The relatively short life span is caused by intermittent operation. Start and stop conditions induce drying and wetting, which contribute to membrane stress. If run continuously, the stationary stack is good for about 40,000 hours. The replacement of the stack is a major expense.

Type of Fuel Cell	Applications	Advantages	Limitations	Status
Proton Exchange Membrane (PEMFC)	Mobile (buses, cars), portable power, medium to large-scale stationary power generation (homes, industry).	Compact design; relatively long operating life; adapted by major automakers; offers quick start-up, low temperature operation, operates at 50% efficiency.	High manufacturing costs, needs heavy auxiliary equipment and pure hydrogen, no tolerance for contaminates; complex heat and water management.	Most widely developed; limited production; offers promising technology.
Alkaline (AFC)	Space (NASA), terrestrial transport (German submarines).	Low manufacturing and operation costs; does not need heavy compressor, fast cathode kinetics.	Large size; needs pure hydrogen and oxygen; use of corrosive liquid electrolyte.	First generation technology, has renewed interest due to low operating costs.
Molten Carbonate (MCFC)	Large-scale power generation.	Highly efficient; utilizes heat to run turbines for co-generation.	Electrolyte instability; limited service life.	Well developed; semi-commercial.
Phosphoric Acid (PAFC)	Medium to large-scale power generation.	Commercially available; lenient to fuels; utilizes heat for co-generation.	Low efficiency, limited service life, expensive catalyst.	Mature but faces competition from PEMFC.
Solid Oxide (SOFC)	Medium to large-scale power generation.	High efficiency, lenient to fuels, takes natural gas directly, no reformer needed. Operates at 60% efficiency; utilizes heat for co-generation.	High operating temperature; requires exotic metals, high manufacturing costs, oxidation issues; low specific power.	Least developed. Breakthroughs in cell material and stack design sets off new research.
Direct Methanol (DMFC)	Suitable for portable, mobile and stationary applications.	Compact design, no compressor or humidification needed; feeds directly off methanol in liquid form.	Complex stack structure, slow load response times; operates at 20% efficiency.	Laboratory prototypes.

Figure שגיאה! הסימנייה אינה מוגדרת.-שגיאה! הסגנון אינו מוגדר.: Advantages and disadvantages of various fuel cell systems.
The PEMFC is the most widely developed system.

Figure 17-5: 1kW portable fuel cell generator.
The unit is a fully automated power system, which converts hydrogen fuel and oxygen from air directly into DC electricity. Water is the only by-product of the reaction. This fuel cell generator, which operates at low pressures, provides reliable, clean, quiet and efficient power. It is small enough to be carried to wherever power is needed. Illustration courtesy of Ballard Power Systems Inc., February 2001.

The SOFC is best suited for stationary applications. The system requires high operating temperatures (about 1000°C). Newer systems are being developed which can run at about 700°C.

A significant advantage of the SOFC is its leniency on fuel. Due to the high operating temperature, hydrogen is produced through a catalytic reforming process. This eliminates the need for an external reformer to generate hydrogen. Carbon monoxide, a contaminant in the PEMFC system, is a fuel for the SOFC. In addition, the SOFC system offers a fuel efficiency of 60 percent, one of the highest among fuel cells. The 60 percent efficiency is achieved with co-generation, meaning that the heat is utilized.

Higher stack temperatures add to the manufacturing cost because they require specialized and exotic materials. Heat also presents a challenge for longevity and reliability because of increased material oxidation and stress. High temperatures, however, can be utilized for co-generation by running steam generators. This improves the overall efficiency of this fuel cell system.

The AFC has received renewed interest because of low operating costs. Although larger in physical size than the PEMFC system, the alkaline fuel cell has the potential of lower manufacturing and operating costs. The water management is simpler, no compressor is usually needed, and the hardware is cheaper. Whereas the separator for the PEMFC stack costs between $800 and $1,100US per square meter; the equivalent of the alkaline system is almost negligible. (In comparison, the separator of a lead acid battery is $5 per square meter.) As a negative, the alkaline fuel cell needs pure oxygen and hydrogen to operate. The amount of carbon dioxide in the air can poison the alkaline fuel cell.

Applications — The fuel cell is being considered as an eventual replacement for the internal combustion engine for cars, trucks and buses. Major car manufacturers have teamed up with fuel cell research centers or are doing their own development. There are plans for mass-producing cars running on fuel cells. However, because of the low operating cost of the combustion engine, and some unresolved technical challenges of the fuel cell, experts predict that a large scale implementation of the fuel cell to power cars will not occur before 2015, or even 2020.

Large power plants running in the 40,000kW range will likely out-pace the automotive industry. Such systems could provide electricity to remote locations within 10 years. Many of these regions have an abundance of fossil fuel that could be utilized. The stack on these large power plants would last longer than in mobile applications because of steady use, even operating temperatures and absence of shock and vibration.

Residential power supplies are also being tested. Such a unit would sit in the basement or outside the house, similar to an air-conditioning unit of a typical middle class North American home. The fuel would be natural gas or propane, a commodity that is available in many urban settings.

Fuel cells may soon compete with batteries for portable applications, such as laptop computers and mobile phones. However, today's technologies have limitations in meeting the cost and size criteria for small portable devices. In addition, the cost per watt-hour is less favorable for small systems than large installations.

Let's examine once more the cost to produce 1kW of power. In Figure 17-5 we learned that the investment to provide 1kW of power using rechargeable batteries is around $7,000. This calculation is based on 7.2V; 1000mAh NiCd packs costing $50 each. High energy-dense batteries that deliver fewer cycles and are more expensive than the NiCd will double the cost.

The high cost of portable power opens vast opportunities for the portable fuel cell. At an investment of $3,000 to $7,500 to produce one kilowatt of power, however, the energy generated by the fuel cell is only marginally less expensive than that produced by conventional batteries.

> ***Ironically, the fuel cell does not eliminate the battery — it promotes it.***

The DMFC, the fuel cell designed for portable applications would not necessarily replace the battery in the equipment but serve as a charger that is carried separately. The feasibility to build a mass-produced fuel cell that fits into the form factor of a battery is still a few years away.

The advantages of the portable fuel cell are: relatively high energy density (up to five times that of a Li-ion battery), liquefied fuel as energy supply, environmentally clean, fast recharge and long runtimes. In fact, continuous operation is feasible. Miniature fuel cells have been demonstrated that operate at an efficiency of 20 percent and run for 3000 hours before a stack replacement is necessary. There is, however, some degradation during the service life of the fuel cell. Portable fuels cells are still in experimental stages.

Advantages and limitations of the fuel cell — A less known limitation of the fuel cell is the marginal loading characteristic. On a high current load, mass transport limitations come into effect. Supplying air instead of pure oxygen aggregates this phenomenon.

The issue of mass transport limitation is why the fuel cell operates best at a 30 percent load factor. Higher loads reduce the efficiency considerably. In terms of loading characteristics, the fuel cell does not match the performance of a NiCd battery or a diesel engine, which perform well at a 100 percent load factor.

Ironically, the fuel cell does not eliminate the chemical battery — it promotes it. Similar to the argument that the computer would make paper redundant, the fuel cell needs batteries as a buffer. For many applications, a battery bank will provide momentary high current loads and the fuel cell will serve to keep the battery fully charged. For portable applications, a supercapacitor will improve the loading characteristics and enable high current pulses.

The fuel cell is as revolutionary in transforming our technology as the microprocessor has been.

Most fuel cells are still handmade and are used for experimental purposes. Fuel cell promoters remind the public that the cost will come down once the cells are mass-produced. While an internal combustion engine requires an investment of $35 to $50 to produce one kilowatt of power, the equivalent cost in a fuel cells is still a whopping $3,000 to $7,500. The goal is a fuel cell that would cost the same or less than diesel engines.

The fuel cell will find applications that lie beyond the reach of the internal combustion engine. Once low cost manufacturing is feasible, this power source will transform the world and bring great wealth potential to those who invest in this technology.

It is said that the fuel cell is as revolutionary in transforming our technology as the microprocessor has been. Once fuel cell technology has matured and is in common use, our quality of life will improve and the environmental degradation caused by burning fossil fuels will be reversed. However, the maturing process of the fuel cell may not be as rapid as that of microelectronics.

The Electric Vehicle

In a bid to lower air pollution in big cities, much emphasis has been placed on the electric car. The notion of driving a clean, quiet and light vehicle appeals to many city dwellers. Being able to charge the car at home for only a dollar a day and escape heavy fuel taxes (at least for the time being) makes the electric car even more attractive.

The battery is still the main challenge in the development of the electric car. Distance traveled between recharge, charge time and the limited cycle count of the battery continue to pose major concerns. Unless the cycle life of the battery can be increased significantly, the cost per mile will be substantially higher than that of a fuel-powered vehicle. The added expense is the need to replace the battery after a given number of recharges. This could offset any advantage of lower energy costs or the absence of fuel taxes. Disposing the spent batteries also adds to the expenditure.

Another challenge associated with the electric vehicle is the high power demand that would be placed on the electric grid if too many cars were charged at a certain time. Each recharge consumes between 15 to 20kW of power, an amount that is almost as much as the daily power requirement of a smaller household. By adding one electric car per family, the amount of electric power a residence requires would almost double. Delayed charging could ease this problem by only drawing power during the night when the consumption is low.

A rapid shift to the electric car could create shortages of electric power. With the move to reduce the generation of electricity due environmental concerns, electricity would need to be imported at high costs. This would make the electric car less attractive.

If the electricity was generated with renewable energy such as hydroelectric generators and windmills, the electric vehicle would truly clear the air in big cities. The generation of electricity by means of nuclear power or fossil fuels simply shifts the pollution problem elsewhere. However, a central source of pollution is easier to contain than many polluting objects in a metropolitan area.

A hybrid car is an alternative to vehicles running solely on battery power. Here, a small combustion engine works in unison with an electric motor. During acceleration, both the electric and combustion engines are engaged. Because of superior torque, the electric motor takes precedence during acceleration. Once cruising, the combustion engine maintains the speed and keeps the batteries charged. Hybrid cars achieve fuel savings of 30 percent or better compared to the combustion engine alone.

A hybrid car is less strenuous on a battery than a conventional electric car because the battery is not being deeply discharged during regular use. A deep discharge only occurs on a long mountain climb where the small combustion engine could not sustain the load and would

With each incremental improvement of the battery, doors swing open for new products.

need assistance from the electric motor and its battery bank. Driving habits would, to a large extent, determine the service life of the battery. A light foot on the pedal will help the pocket book also with the hybrid car.

Another alternative to powering cars is the fuel cell. Although much cleaner running than the combustion engine, the fuel cell must solve a number of critical problems before the product can be offered to the consumer as an economical alternative. The major challenge is cost reduction. If fossil fuel remains as low-priced is it is today, many drivers owning high-powered cars, SUVs and trucks would be reluctant to switch to a new technology. Concerns over pollution only persuade a limited number of drivers to switch to a cleaner-running vehicle. With the slow and gradual progress in the fuel cell, it will be some time before this technology renders the combustion engine obsolete.

Europe is talking about the three-liter motor, an internal combustion engine running on gasoline or diesel fuel. Remarkably, ‘three’ does not denote the engine displacement but stands for liters of fuel consumed per 100 km traveled. There is talk about the one-liter engine also. Major car manufacturers are divided on the fuel that will power our cars in the future. Within one large auto manufacturer in Europe, opinions regarding the fuel cell and an economical three-liter engine are divided fifty-fifty.

Strengthening the Weakest Link

The speed at which mobility can advance hinges much on the battery. So important is this portable energy that engineers design handheld devices around the battery, rather than the other way around. With each incremental improvement of the battery, the doors swing open for new products and applications. It is the virtue of the battery that provides us the freedom to move around and stay in touch. The better the battery, the greater the freedom we can enjoy.

The longer runtime of newer portable devices is not only credited to higher energy-dense batteries. Much improvement has been made in reducing the power consumption of portable equipment. These advancements are, however, counteracted with the demand for more features and faster processing time. In mobile computing, for example, high speed CPUs, large screens and wireless interface are a prerequisite. These features eat up the reserve energy that the more efficient circuits save and the improved battery provides. The result is similar runtime to an older system, but with increased performance. It is predicted that the improvements in battery technology will keep par with better performance.

Wide-band mobile phones, dubbed G3 for third generation, are being offered as replacements for the digital voice phone. There is public demand for Internet access in a tiny handset that connects to the world by the push of a few buttons, twenty-four hours a day. But these devices require many times the power compared to voice only when operating on wideband. Higher capacity batteries are needed, preferably without added size and weight. In fact, the success of the G3 system could hinge on the future performance of the battery. G3 technology may be ready but the battery lags behind.

The battery has not leap-frogged at the same speed as microelectronics. Only 5 to 10 percent gains in capacity per year have been achieved during the last decades and the ultimate miracle battery is still nowhere in sight. As long as the battery is based on an electro-chemical process, limitations of power density and life expectancy must be taken into account.

The battery remains the ‘weak link’ for the foreseeable future. A radical turn will be needed to satisfy the unquenchable thirst for mobile power. What people want is an inexhaustible pool of energy in a small package. It is anyone’s guess whether the electro-chemical battery of the future, the fuel cell or some groundbreaking new energy storage device will fulfill this dream.

Part Four

Beyond Batteries

Cadex Products

Cadex products are built with one goal in mind — to make batteries run longer. Cadex has realized the importance of battery care and is offering equipment to charge, test, monitor, and restore batteries.

Cadex's core competence is engineering. Over 25 percent of the Cadex staff is active in the Engineering Department. Existing products are improved on a continual basis, and new and creative products are added to adjust to the changing demands of battery users. Key products include:

Figure 18-2: Cadex *7200* battery analyzer.
This compact two-station battery analyzer brings battery maintenance within reach of all battery users.

18-3: Cadex *7400* battery analyzer.
Provision to service four batteries simultaneously increases the service throughput. The Cadex *7400* offers parallel printer port and USB for easy interface to a PC.

Cadex *7000 Series* battery analyzers solve the common battery problems of uncertain service and short life. Pre-configured 'Snap Lock' adapters enable quick interface with all major batteries for wireless communications devices, laptops, biomedical equipment, video cameras and other portable devices. Irregular batteries connect by universal cables that can be programmed with the analyzer's menu function. The analyzer supports Li-ion/Polymer, NiMH, NiCd and Sealed Lead Acid (SLA) batteries.

The Cadex *7000 Series* features the self-learning Cadex *Quicktest*™ program that performs an in-depth battery diagnosis in three minutes. Other programs include: *'Boost'* to wake up low voltage batteries; *'Auto'* to recondition weak batteries and *'Prime'* to format new batteries. In addition, *'Self-Discharge'* verifies charge retention; *'CycleLife'* tests longevity and *'Custom'* enables user-defined programs. The Cadex *7200* services two batteries simultaneously; the Cadex *7400* accommodates four.

The battery voltage is programmable from 1.2 to 15V with a current range of 100mA to 24A. If set high, the analyzer automatically reduces the current to remain within the 4A per station handling capabilities. With a printer, service reports and battery labels can be generated. The unit operates as stand-alone or with a PC.

Figure 18-4: Cadex *Batteryshop*™.
This Windows-based software allows untrained users to perform accurate and expedient battery tests. With the same system, a design engineer can collect valuable battery information running customized test programs.

Cadex *Batteryshop*™ software provides a simple, yet powerful PC interface to control and monitor the Cadex *7000 Series* battery analyzers. Running on Windows 95, 98 and NT, the software enables untrained staff to test batteries as part of customer service. In addition, Cadex *Batteryshop*™ schedules periodic maintenance for fleet owners and assists battery manufacturers with quality control.

Cadex *Batteryshop*™ includes a database of over 2000 common battery models. Each battery listing contains the configuration code (C-code), the data that sets the analyzer to the correct parameters. A growing number of the battery listings also include matrices to perform Cadex *Quicktest*™.

Point and click technology selects the battery and programs the Cadex *7000 Series* analyzer. Scanning the battery's model number, if a bar code label is available, also programs the analyzer. Cadex *Batteryshop*™ supports up to 120 Cadex *7000 Series* battery analyzers. The test results can be displayed on screen in real time graphs and printed in customized reports.

Figure 18-5: The Cadex *SM1* battery charger.
This charger accommodates the widely used 202 format. Other batteries that fit the bay are the 2020, 1030, 1020, 210, 201, 36, 35, 30, 17 and 15. The Cadex *SM1* charger supports 'smart' and 'dumb' batteries.

Cadex *Smart Series* battery chargers offer the consumer a continuous supply of freshly charged batteries. Conforming to the SMBus Level 3, the Cadex *Smart Series* chargers accommodate Li-ion, NiMH and NiCd batteries. The charge time is 2 to 3 hours. If faulty batteries are identified, the charge is halted. On compatible footprint, the chargers also accommodate 'dumb' batteries. Typical uses are mobile computing, biomedical and survey devices.

The Cadex *SM1* charger is compact and charges one battery at a time. The Cadex *SM2+* charger services two packs simultaneously and doubles as conditioner and quality control system. The charger reads the data stored in the SMBus battery, calculates the previous power delivered and compares the results with the target capacity setting. Adjustable to 60, 70 and 80 percent, the charger flags batteries that fall below the set capacity reading.

Figure 18-6: The Cadex *SM2+* battery charger.
In addition to the features offered on the Cadex *SM1* charger, this unit serves as charger, quality control system and battery conditioner. SMBus batteries with low state-of-health are identified. Conditioning and calibration occurs by pressing a button.

Figure 18-7: Cadex *UCC1*, *MCC2* and *UCC6*.
The Cadex *UCC Series* chargers feature interchangeable battery adapters. The Cadex *MCC2* serves both as desktop and mobile charger.

Cadex *Universal Conditioning Chargers (UCC)* offer battery users an alternate source of chargers to those provided by the original equipment manufacturer (OEM). Available in one, two and six bay configurations, the chargers feature intelligent battery adapters. This concept allows easy adaptation to a variety of battery types without compromising charge performance.

The adapters allow service of different battery types in one unit. Reconfiguration to other battery types can be done in the field; the one and six-bay chargers are desktop and wall-mountable. The two-bay unit also serves as a vehicular charger built to military shock and vibration specifications.

Custom Battery Chargers — Cadex designs and manufactures a wide variety of custom chargers to serve public safety, law enforcement, emergency response, healthcare, mobile computing, broadcast and defence applications. Cadex covers all aspects of product development, from circuit design to power supply, from plastic housing to mechanical battery interface, to testing and manufacturing.

Custom Battery Packs — Cadex completes the line of portable power source by offering specialty battery packs. To provide added safety, Cadex has the capability of designing specialty protection circuits for lithium ion chemistries and other battery systems.

BATTERIES IN A PORTABLE WORLD

Home > File-Chap8-Page3 > Chapter 8 > Chapter 7 > Chapter 6 > Part 2 > Chapter 5 > Chapter 4 > Chapter 3 > Chapter 2 > Chapter 1 > Introduction

Home | Site Map| Contact Us

Table of Contents
Battery FAQ
New Articles
About the Author
Order Book
Links
Home

<< Previous Page

Next Page >>

Introduction

During the last few decades, rechargeable batteries have made only moderate improvements in terms of higher capacity and smaller size. Compared with the vast advancements in areas such as microelectronics, the lack of progress in battery technology is apparent. Consider a computer memory core of the sixties and compare it with a modern microchip of the same byte count. What once measured a cubic foot now sits in a tiny chip. A comparable size reduction would literally shrink a heavy-duty car battery to the size of a coin. Since batteries are still based on an electrochemical process, a car battery the size of a coin may not be possible using our current techniques.

Research has brought about a variety of battery chemistries, each offering distinct advantages but none providing a fully satisfactory solution. With today’s increased selection, however, better choices can be applied to suit a specific user application.

The consumer market, for example, demands high energy densities and small sizes. This is done to maintain adequate runtime on portable devices that are becoming increasingly more powerful and power hungry. Relentless downsizing of portable equipment has pressured manufacturers to invent smaller batteries. This, however, must be done without sacrificing runtimes. By packing more energy into a pack, other qualities are often compromised. One of these is longevity.

Long service life and predictable low internal resistance are found in the NiCd family. However, this chemistry is being replaced, where applicable, with systems that provide longer runtimes. In addition, negative publicity about the memory phenomenon and concerns of toxicity in disposal are causing equipment manufacturers to seek alternatives.

Once hailed as a superior battery system, the NiMH has also failed to provide the universal battery solution for the twenty-first century. Shorter than expected service life remains a major complaint.

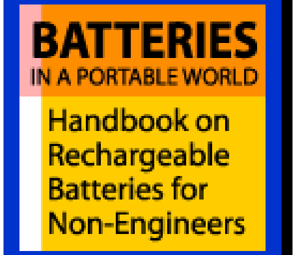
The lithium-based battery may be the best choice, especially for the fast-moving commercial market. Maintenance-free and dependable, Li-ion is the preferred choice for many because it offers small size and long runtime. But this battery system is not without problems. A relatively rapid aging process, even if the battery is not in use, limits the life to between two and three years. In addition, a current-limiting safety circuit limits the discharge current, rendering the Li-ion unsuitable for applications requiring a heavy load. The Li-ion polymer exhibits similar characteristics to the Li-ion. No major breakthrough has been achieved with this system. It does offer a very slim form factor but this quality is attained in exchange for slightly less energy density.

Search:

go

Advanced Search
Search Tips

? Find definitions of unfamiliar terms



BATTERIES
IN A PORTABLE WORLD
Handbook on Rechargeable Batteries for Non-Engineers

With rapid developments in technology occurring today, battery systems that use neither nickel, lead nor lithium may soon become viable. Fuel cells, which enable uninterrupted operation by drawing on a continuous supply of fuel, may solve the portable energy needs in the future. Instead of a charger, the user carries a bottle of liquid energy. Such a battery would truly change the way we live and work.

This book addresses the most commonly used consumer and industrial batteries, which are NiCd, NiMH, Lead Acid, and Li-ion/polymer. It also includes the reusable alkaline for comparison. The absence of other rechargeable battery systems is done for reasons of clarity. Some weird and wonderful new battery inventions may only live in experimental labs. Others may be used for specialty applications, such as military and aerospace. Since this book addresses the non-engineer, it is the author's wish to keep the matter as simple as possible.

<< Previous Page **Next Page >>**

Table of Contents | Battery FAQ | New Articles | About the Author | Links | Site Map | Contact Us