Part One - Basics every battery user should know

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Learning the basics about batteries - sponsored by Cadex Electronics Inc.

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Sharing battery knowledge

It is my pleasure bringing to you Battery University, the institution for Learning the basics about batteries. In each of the short commentaries you will read about the best battery choices, new battery technologies and ways to make your batteries last longer. Practical, down-to-earth battery information is sometimes hard to find. Battery manufacturers are often too optimistic with their promises and only emphasize positive features.

I have a background in radio communications and studied the behavior of rechargeable batteries in practical, everyday applications for several decades. In desiring to share this battery knowledge with you; I wrote several articles addressing the strength and limitations of the battery. These articles have been published in various trade magazines in the USA, Canada and Europe. I later compiled the material and wrote my first book entitled Batteries in a Portable World - A Handbook on Rechargeable Batteries for Non-Engineers.

The 88-page first edition appeared in 1997 and covered such topics as the memory effect of nickel-cadmium batteries and how to restore them. Some readers commented that I favored nickel-cadmium over nickel-metal-hydride. Perhaps this observation is valid and I have taken note. Having been active in the mobile radio industry for many years, much emphasis is placed on battery longevity, a quality that is true of nickel-cadmium. Today's battery users prefer small size and want maximum runtime. Longevity may be less important, especially in the fast-moving consumer market.

The second edition of Batteries in a Portable World was published in 2001. With 18 Chapters and 300 pages, this book has been extended to include new battery technologies and various field applications.

In May 2001, the Battery Information Website www.buchmann.ca was launched, making the contents of the book available to the world at large. Battery articles have been added to complement the book and serve readers of non-English languages. A search engine was installed to help you find topics of interest. The Battery Information Website is sponsored by Cadex Electronics Inc., the manufacturer of advanced battery analyzers chargers and PC software.

Out of sheer curiosity, I conducted a statistical analysis at the end of the year to find out which battery topics in the book are being requested most often. The winners are:

Number 1. Getting the Most from your Batteries Chapter 10
Number 2. Proper Charge Methods Chapter 4
Number 3. Internal Battery Resistance Chapter 9
Number 4. Choosing the Right Battery Chapter 8
Number 5. The 'Smart' Battery Chapter 7

Getting the Most from your Batteries has consistently been first choice. People want to know how to care for their batteries to get maximum runtime and dependable service. Proper Charge Methods is also very much in the hearts of the battery users. A surprise was Internal Battery Resistance in third position. This subject is of growing concern with digital equipment that puts high demands on the battery. A seemingly good battery often fails to deliver the heavy current bursts because of elevated internal resistance caused by aging batteries.

Battery University is based on the book Batteries in a Portable World and will address such issues as the choice of battery chemistries, physical battery packs, charge and discharge methods, runtime concerns, the 'smart' battery, internal battery resistance, getting the most of your batteries and much more.

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 protected lab environments 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 am prepared to accept the blame for any discrepancies. The book is available from www.buchmann.ca at $29.50US
I would like to hear your comments on Battery University. After all, battery technology is not black and white but has many shades of gray. I hope you will find these lessons interesting and helpful.

About the Author
Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world. Cadex Electronics is a manufacturer of advanced battery chargers, battery analyzers and PC software. For product information please visit www.cadex.com.
When was the battery invented?

One of the most important discoveries in the last 400 years has been electricity. You may ask, “Has electricity been around that long?” The answer is “yes”, and perhaps much longer. Surprisingly, electricity only became useful to humanity in the late 1800s.

The earliest known methods of generating electricity were by creating a static charge. Alessandro Volta (1745-1827) invented the so-called “electric pistol” by which 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 one Boolean bit. An iron wire supported by wooden poles was to be strung from Como to Milan in 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 cause a detonation to signal a coded event. This communications link was never built.

The next stage of generating electricity was through electrolysis. Volta discovered in 1800 that a continuous flow of electrical force was possible when using certain fluids as conductors to promote a chemical reaction between metals. Volta discovered further that the voltage would increase when voltaic cells were stacked. This led to the invention of the battery. From the availability of a battery, experiments were no longer limited to a brief display of sparks that lasted a fraction of a second. A seemingly endless stream of electric current was now available.

In the early 1800, 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 in which Napoleon Bonaparte was present. 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.

![Figure 1: Volta’s experimentations at the French National Institute in November of 1800 in which Napoleon Bonaparte was present.](image)

In 1802, Dr. William Cruickshank designed the first electric battery capable of mass production. Cruickshank arranged square sheets of copper soldered at their ends, intermixed 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 filled with an electrolyte of brine, or watered down acid.

New discoveries were made when Sir Humphry Davy 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. Witnesses reported that his voltaic arc lamp produced “the most brilliant ascending arch of light ever seen.”

All batteries at this time were 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, a chemistry that is still used today.
Figure 2: 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.

The third, and most significant, 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 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 and his research team succeeded in generating an endless electrical force as long as the movement between a coil and magnet continued.

In 1899, Waldmar Jungner from Sweden invented the nickel-cadmium battery. In 1947, Neumann succeeded in completely sealing the cell. These advances led to the modern sealed nickel-cadmium battery in use today.

Research of the nickel-metal-hydride system started in the 1970s but the metal hydride alloys were unstable in the cell environment. New hydride alloys were developed in the 1980s that improved the stability. nickel-metal-hydride became commercially available in the 1990s.

The first primary lithium batteries appeared in early 1970s. Attempts to develop rechargeable lithium batteries followed in the 1980s but failed due to safety problems. Because of inherent instability of lithium metal, especially during charging, research shifted to a non-metallic lithium battery using lithium ions. Although lower in energy density than lithium metal, lithium-ion is safe, provided certain precautions are made when charging and discharging. In 1991, the Sony Corporation commercialized the first lithium-ion battery.

As awkward and unreliable 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 200 years ago.

Created: April 2003, Last edited: July 2003

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**What's the best battery?**

Battery novices often brag about miracle batteries that offer very high energy densities, deliver 1000 charge/discharge cycles and are paper-thin. These attributes are indeed achievable but not on one and the same battery pack.

A certain battery may be designed for small size and long runtime, but this pack has a limited cycle life. Another battery may be built for durability but is big and bulky. A third pack may have high energy density and long durability but this version is too expensive for the consumer.

Battery manufacturers are aware of customer needs and offer packs that best suit the application. The mobile phone industry is an example of this clever adaptation. Here, small size and high energy density reign in favor of longevity. Short service life is not an issue because a device is often replaced before the battery is worn out.

Let's examine various battery designs, starting with nickel-metal-hydride. The cylindrical nickel-metal-hydride for commercial use offers a mid-range energy density of about 80Wh/kg and delivers roughly 400 cycles. The prismatic nickel-metal-hydride, a battery that is made for slim geometry, compromises on energy density and cycle count. This battery is rated at a moderate 60Wh/kg and offers around 300 cycles. Highly durable nickel-metal-hydride for industrial use are packaged in cylindrical cells, provide a modest 70Wh/kg but last for about 1000 cycles.

Similarly, lithium-ion batteries can be produced with various energy densities. Packing more energy into a cell compromises safety. While commercial lithium-ion batteries are safe, super-high capacity lithium-ion for defense applications are, for safety reasons, not approved for the public at large.

Below is a summary of the strength and limitations of today's popular battery systems. Although energy density is paramount, other important attributes are service life, load characteristics, maintenance requirements, self-discharge and operational costs. Since nickel-cadmium remains a standard against which batteries are compared, we evaluate alternative chemistries against this classic battery type.

- **Nickel-cadmium** - mature but has moderate energy density. nickel-cadmium is used where long life, high discharge rate and extended temperature range is important. Main applications are two-way radios, biomedical equipment and power tools. nickel-cadmium contains toxic metals.

- **Nickel-metal-hydride** - has a higher energy density compared to nickel-cadmium at the expense of reduced cycle life. There are no toxic metals. Applications include mobile phones and laptop computers.

- **Lead-acid** - most economical for larger power applications where weight is of little concern. Lead-acid is the preferred choice for hospital equipment, wheelchairs, emergency lighting and UPS systems.

- **Lithium-ion** - fastest growing battery system; offers high-energy density and low weight. Protection circuit are needed to limit voltage and current for safety reasons. Applications include notebook computers and cell phones.

- **Lithium-ion-polymer** - Similar to lithium-ion, this system enables slim geometry and simple packaging at the expense of higher cost per watt/hours. Main applications are cell phones.

- **Reusable Alkaline** - Its limited cycle life and low load current is compensated by long shelf life, making this battery ideal for portable entertainment devices and flashlights.

Table 1 summarizes the characteristics of the common batteries. The figures are based on average ratings at time of publication. Note that nickel-cadmium has the shortest charge time, delivers the highest load current and offers the lowest overall cost-per-cycle but needs regular maintenance.
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Nickel-cadmium</th>
<th>Nickel-metal-hydride</th>
<th>Lead-acid</th>
<th>Lithium-ion</th>
<th>Lithium-ion-polymer</th>
<th>Rechargeable alkaline</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gravimetric Energy Density (Wh/kg)</strong></td>
<td>45-50</td>
<td>60-120</td>
<td>30-50</td>
<td>110-160</td>
<td>100-150</td>
<td>80 (initial)</td>
</tr>
<tr>
<td><strong>Internal Resistance (includes peripheral circuits) in mΩ</strong></td>
<td>100 to 200†</td>
<td>200 to 300†</td>
<td>&lt;100†</td>
<td>150 to 250†</td>
<td>200 to 300†</td>
<td>200 to 200†</td>
</tr>
<tr>
<td><strong>Cycle Life (to 90% of initial capacity)</strong></td>
<td>160°F</td>
<td>300 to 500°F**</td>
<td>200 to 300°F</td>
<td>300 to 500°F</td>
<td>300 to 500°F</td>
<td>50°F (90% capacity)</td>
</tr>
<tr>
<td><strong>Fast Charge Time</strong></td>
<td>1 h typical</td>
<td>2 to 4 h</td>
<td>8 to 16 h</td>
<td>2 to 4 h</td>
<td>2 to 4 h</td>
<td>2 to 3 h</td>
</tr>
<tr>
<td><strong>Overcharge Tolerance</strong></td>
<td>moderate</td>
<td>low</td>
<td>high</td>
<td>very low</td>
<td>low</td>
<td>moderate</td>
</tr>
<tr>
<td><strong>Self-discharge / Month (room temperature)</strong></td>
<td>20%†</td>
<td>30%†</td>
<td>5%‡</td>
<td>10%‡</td>
<td>-10%‡</td>
<td>0.3%</td>
</tr>
<tr>
<td><strong>Cell Voltage (nominal)</strong></td>
<td>1.25V</td>
<td>1.25V</td>
<td>2V</td>
<td>3.6V</td>
<td>3.6V</td>
<td>1.6V</td>
</tr>
<tr>
<td><strong>Load Current peak</strong></td>
<td>20C</td>
<td>0C</td>
<td>0C</td>
<td>&gt;2C</td>
<td>1C</td>
<td>0.5C</td>
</tr>
<tr>
<td><strong>Operating Temperature (discharge only)</strong></td>
<td>-40 to 60°C</td>
<td>-20 to 60°C</td>
<td>-20 to 60°C</td>
<td>-20 to 60°C</td>
<td>0 to 60°C</td>
<td>0 to 80°C</td>
</tr>
<tr>
<td><strong>Maintenance Requirement</strong></td>
<td>30 to 60 days</td>
<td>60 to 90 days</td>
<td>3 to 6 months²</td>
<td>not required</td>
<td>not required</td>
<td>not required</td>
</tr>
<tr>
<td><strong>Typical Battery Cost</strong> (USD, reference only)</td>
<td>$500</td>
<td>$50</td>
<td>$25</td>
<td>$100</td>
<td>$100</td>
<td>$5</td>
</tr>
<tr>
<td><strong>Cost per Cycle (USD)</strong></td>
<td>$0.04</td>
<td>$0.12</td>
<td>$0.10</td>
<td>$0.14</td>
<td>$0.25</td>
<td>$0.10-0.50</td>
</tr>
<tr>
<td><strong>Toxicity</strong></td>
<td>Highly toxic, harmful to environment</td>
<td>Relatively low toxicity, should be recycled</td>
<td>Toxic lead and acids, harmful to environment</td>
<td>Low toxicity, can be disposed in small quantities</td>
<td>Low toxicity, can be disposed in small quantities</td>
<td>Low toxicity, may contain mercury</td>
</tr>
</tbody>
</table>

### Table 1: Characteristics of commonly used rechargeable batteries.

1) Internal resistance of a battery pack varies with cell rating, type of protection circuit and number of cells. Protection circuit of lithium-ion and lithium-ion-polymer adds about 100mΩ.
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, and then tapers off. The capacity of nickel-cadmium 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 as 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.

In subsequent columns I will describe the strength and limitation of each chemistry in more detail. We will examine charging techniques and explore methods to get the most of these batteries.

*Created: April 2003, Last edited: July 2003*

### About the Author

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The nickel-based battery, its dominance and the future

In this section we evaluate the strengths and limitations of various battery chemistries, beginning with the nickel. Each battery system offers unique advantages but none provides a fully satisfactory solution. With the increased selection of battery chemistries available today, better choices can be made to address specific battery needs. A careful evaluation of each battery's attribute is important. Because of similarities, both nickel-cadmium and nickel-metal hydride are covered in this paper.

The nickel-cadmium battery

Swedish Waldmar Jungner invented the nickel-cadmium battery in 1899. At that time, the materials were expensive compared to other battery types available 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 nickel-cadmium battery.

Rather than venting, the internal gases generated during charge were recombinated. These advances led to the modern sealed nickel-cadmium battery, which is in use today.

Nickel-cadmium prefers fast charge to slow charge and pulse charge to DC charge. It is a strong and silent worker; hard labor poses little problem. In fact, nickel-cadmium is the only battery type that performs well under rigorous working conditions. All other chemistries prefer a shallow discharge and moderate load currents.

Nickel-cadmium 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 nickel-cadmium will gradually lose its performance.

Among rechargeable batteries, nickel-cadmium remains a popular choice for two-way radios, emergency medical equipment and power tools. There is shift towards batteries with higher energy densities and less toxic metals but alternative chemistries cannot always match the superior durability and low cost of nickel-cadmium.

Here is a summary of the advantages and limitations of nickel-cadmium batteries.

Advantages

- Fast and simple charge, even after prolonged storage.
- High number of charge/discharge cycles - if properly maintained, nickel-cadmium provides over 1000 charge/discharge cycles.
- Good load performance - nickel-cadmium allows recharging at low temperatures.
- Long shelf life - five-year storage is possible. Some priming prior to use will be required.
- Simple storage and transportation - most airfreight companies accept nickel-cadmium without special conditions.
- Good low temperature performance.
- Forgiving if abused - nickel-cadmium is one of the most rugged rechargeable batteries.
- Economically priced - nickel-cadmium is lowest in terms of cost per cycle.
- Available in a wide range of sizes and performance options - most nickel-cadmium cells are cylindrical.

Limitations

- Relatively low energy density.
- Memory effect - nickel-cadmium must periodically be exercised (discharge/charge) to prevent memory.
- Environmentally unfriendly - nickel-cadmium contains toxic metals. Some countries restrict its use.
- Relatively high self-discharge - needs recharging after storage

The nickel-metal-hydride battery

Research on the nickel-metal-hydride system started in the 1970s as a means of storing hydrogen for the nickel hydrogen battery. Today, nickel hydrogen is used mainly for satellite applications. Nickel hydrogen batteries are bulky, require high-pressure steel canisters and cost thousands of dollars per cell.

In the early experimental days of nickel-metal hydride, 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 nickel-metal hydride slowed down. New hydride alloys were developed in the 1980s that were stable enough for use in a cell. Since then, nickel-metal hydride has steadily improved.
The success of nickel-metal hydride has been driven by high energy density and the use of environmentally friendly metals. The modern nickel-metal hydride offers up to 40% higher energy density compared to the standard nickel-cadmium. There is potential for yet higher capacities, but not without some negative side effects.

Nickel-metal hydride is less durable than nickel-cadmium. Cycling under heavy load and storage at high temperature reduces the service life. nickel-metal hydride suffers from high self-discharge, which is higher than that of nickel-cadmium.

Nickel-metal hydride has been replacing nickel-cadmium in markets such as wireless communications and mobile computing. Experts agree that nickel-metal hydride has greatly improved over the years, but limitations remain. Most shortcomings are native to the nickel-based technology and are shared with nickel-cadmium. It is widely accepted that nickel-metal hydride is an interim step to lithium-based battery technology.

Here is a summary of the advantages and limitations of nickel-metal hydride batteries.

**Advantages**

- 30-40% higher capacity than standard nickel-cadmium. Nickel-metal-hydride has potential for yet higher energy densities.
- Less prone to memory than nickel-cadmium - fewer exercise cycles are required.
- Simple storage and transportation - transport is not subject to regulatory control.
- Environmentally friendly - contains only mild toxins; profitable for recycling.

**Limitations**

- Limited service life - the performance starts to deteriorate after 200-300 cycles if repeatedly deeply cycled.
- Relatively short storage of three years. Cool temperature and a partial charge slows aging.
- Limited discharge current - although nickel-metal-hydride is capable of delivering high discharge currents, heavy load reduces the battery's cycle life.
- More complex charge algorithm needed - nickel-metal-hydride generates more heat during charge and requires slightly longer charge times than nickel-cadmium. Trickle charge settings are critical because the battery cannot absorb overcharge.
- High self-discharge - typically 50% higher than nickel-cadmium.
- Performance degrades if stored at elevated temperatures - nickel-metal-hydride should be stored in a cool place at 40% state-of-charge.
- High maintenance - nickel-metal hydride requires regular full discharge to prevent crystalline formation. nickel-cadmium should be exercised once a month, nickel-metal-hydride once in every 3 months.

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**Is lithium-ion the ideal battery?**

For many years, nickel-cadmium was the only suitable battery for portable applications from wireless communications to mobile computing. In 1990, the nickel-metal-hydride and lithium-ion emerged, offering higher capacities. Both chemistries fought nose to nose, each claiming better performance and smaller sizes. Today, lithium-ion has won the limelight and has become the most talked-about battery. It's the fastest growing and most promising battery chemistry of today.

**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 when the first non-rechargeable lithium batteries became commercially available. Lithium is the lightest of all metals, has the greatest electrochemical potential and provides the largest energy density for weight.

Attempts to develop rechargeable lithium batteries failed due to safety problems. 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, lithium-ion is safe, provided certain precautions are met when charging and discharging. In 1991, the Sony Corporation commercialized the first lithium-ion battery. Other manufacturers followed suit.

The energy density of lithium-ion is typically twice that of the standard nickel-cadmium. There is potential for higher energy densities. The load characteristics are reasonably good and behave similarly to nickel-cadmium in terms of discharge. The high cell voltage of 3.6 volts allows battery pack designs with only one cell. Most of today's mobile phones run on a single cell. A nickel-based pack would require three 1.2-volt cells connected in series.

Lithium-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 nickel-cadmium, making lithium-ion well suited for modern fuel gauge applications. Lithium-ion cells cause little harm when disposed.

Despite its overall advantages, lithium-ion 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 cell temperature is monitored to prevent temperature extremes. The maximum charge and discharge current is limited to between 1C and 2C. With these precautions in place, the possibility of metallic lithium plating occurring due to overcharge is virtually eliminated.

Aging is a concern with most lithium-ion batteries and many manufacturers remain silent about this issue. Some capacity deterioration is noticeable after one year, whether the battery is in use or not. The battery frequently fails after two or three years. It should be noted that other chemistries also have age-related degenerative effects. This is especially true for nickel-metal-hydride if exposed to high ambient temperatures.

Manufacturers are constantly improving lithium-ion. New and enhanced chemical combinations are introduced every six months or so. With such rapid progress, it is difficult to assess how well the revised battery will age.

Storage in a cool place slows the aging process of lithium-ion (and other chemistries). Manufacturers recommend storage temperatures of 15°C (59°F). In addition, the battery should be partially charged during storage. The manufacturer recommends a 40% charge.

The most economical lithium-ion battery in terms of cost-to-energy ratio is the cylindrical 18650 (18 is the diameter and 650 the length in mm). This cell is used for mobile computing
and other applications that do not demand ultra-thin geometry. If a slim pack is required, the prismatic lithium-ion cell is the best choice. These cells come at a higher cost in terms of stored energy.

**Advantages**

- High energy density - potential for yet higher capacities.
- Does not need prolonged priming when new. One regular charge is all that's needed
- Relatively low self-discharge - self-discharge is less than half that of nickel-based batteries.
- Low Maintenance - no periodic discharge is needed; there is no memory

**Limitations**

- Requires protection circuit to maintain voltage and current within safe limits.
- Subject to aging, even if not in use - storing the battery in a cool place and at 40% charge reduces the aging effect.
- Moderate discharge current - not suitable for heavy loads.
- Transportation restrictions - shipment of larger quantities 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 nickel-cadmium.
- Not fully mature - metals and chemicals are changing on a continuing basis.

**The Lithium-Polymer Battery**

The lithium-polymer differentiates itself from conventional battery systems in the type of electrolyte used. The original design, dating back to the 1970s, uses a dry solid polymer electrolyte. This electrolyte resembles a plastic-like film that does not conduct electricity but allows ions exchange (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. 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.

Unfortunately, the dry lithium-polymer suffers from poor conductivity. The internal resistance is too high and cannot deliver the current bursts needed to power modern communication devices and spin up the hard drives of mobile computing equipment. Heating the cell to 60°C (140°F) and higher increases the conductivity, a requirement that is unsuitable for portable applications.

To compromise, some gelled electrolyte has been added. Most of the commercial lithium-polymer batteries used today for mobile phones are a hybrid cells and contain gelled electrolyte. The correct term for this system is lithium-ion-polymer. This is the only functioning polymer battery for portable use today.

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

Lithium-ion-polymer has not caught on as quickly as some analysts had expected. Its superiority to other systems and low manufacturing costs has not been realized. No improvements in capacity gains are achieved - in fact, the capacity is slightly less than that of the standard lithium-ion battery. Lithium-ion-polymer finds its market niche in wafer-thin geometries, such as batteries for credit cards and other such applications.

**Advantages**

- Very low profile - batteries resembling 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.
- Lightweight - gelled electrolytes enable simplified packaging by 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 lithium-ion.
- Expensive to manufacture.
- No standard sizes. Most cells are produced for high volume consumer markets.
- Higher cost-to-energy ratio than lithium-ion.
Can the lead-acid battery compete in modern times?

The answer is YES. Lead-acid is the oldest rechargeable battery in existence. It has retained a market share in applications where newer battery chemistries would either be too expensive or the upkeep would be too demanding. There are simply no cost-effective alternatives for such applications as wheelchairs, scooters, golf carts, people movers and UPS systems.

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 holds a domineering position in automobiles, forklifts and large uninterruptible power supply (UPS) systems.

During the mid 1970s, researchers developed a maintenance-free lead-acid battery that 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 different market needs, two lead-acid systems emerged: the small sealed lead-acid (SLA), also known under the brand name of Gelcell, and the large valve-regulated lead-acid (VRLA). Technically, both batteries are the same. (Engineers may argue that the word ‘sealed lead acid’ is a misnomer because no rechargeable battery can be totally sealed.)

Unlike the flooded lead acid battery, both 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, these batteries can never be charged to their full potential.

Finding the ideal charge voltage limit is critical. Any voltage level is a compromise. A high voltage limit (above 2.40V/cell) produces good battery performance but shortens the service life due to grid corrosion on the positive plate. The corrosion is permanent. A low voltage (below 2.40V/cell) is safe if charged at a higher temperature but is subject to sulfation on the negative plate.

Lead-acid is not subject to memory. Leaving the battery on float charge for a prolonged time does not cause damage. The self-discharge is about 40% per year, one of the best on rechargeable batteries. In comparison, nickel-cadmium self-discharges this amount in three months. Lead-acid is relatively inexpensive to purchase but the operational costs can be more expensive than the nickel-cadmium if full cycles are required on a repetitive basis.

Lead-acid does not lend itself to fast charging. Typical charge time is 8 to 16 hours. The battery 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 nickel-cadmium, the lead-acid does not like deep cycling. A full discharge causes extra strain and each cycle robs the battery of a small amount of 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 battery is recommended.

Depending on the depth of discharge and operating temperature, the sealed lead-acid 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. Cycling does not prevent or reverse the trend.

The optimum operating temperature for the lead-acid battery is 25°C (77°F). As a guideline, every 8°C (15°F) rise in temperature will cut the battery life in half. VRLA, which would last
for 10 years at 25°C (77°F), will only be good for 5 years if operated at 33°C (95°F). Theoretically the same battery would endure a little more than one year at a desert temperature of 42°C (107°F).

Among modern rechargeable batteries, the lead-acid battery family has the lowest energy density, making it unsuitable for handheld devices that demand compact size. In addition, performance at low temperatures is poor.

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

In terms of disposal, the lead-acid is less harmful than nickel-cadmium but the high lead content and the electrolyte make the lead-acid environmentally unfriendly.

Advantages

- Inexpensive and simple to manufacture.
- Mature, reliable and well-understood technology - when used correctly, lead-acid is durable and provides dependable service.
- The self-discharge is among the lowest of rechargeable battery systems.
- Low maintenance requirements - no memory; no electrolyte to fill on sealed version.
- Capable of high discharge rates.

Limitations

- Low energy density - poor weight-to-energy ratio limits use to stationary and wheeled applications.
- Cannot be stored in a discharged condition - the cell voltage should never drop below 2.10V.
- Allows only a limited number of full discharge cycles - well suited for standby applications that require only occasional deep discharges.
- Lead content and electrolyte make the battery environmentally unfriendly.
- Transportation restrictions on flooded lead acid - there are environmental concerns regarding spillage. Thermal runaway can occur with improper charging.

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About the Author

Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world. Cadex Electronics is a manufacturer of advanced battery chargers, battery analyzers and PC software. For product information please visit www.cadex.com.
Will the reusable alkaline battery have a future?

The reusable alkaline was introduced in 1992 as an alternative to disposable batteries. The battery was promoted as a low-cost power source for consumer goods. Attempts were made to open markets for wireless communications, medical and defense. But the big breakthrough never came. Today, the reusable alkaline occupies only a small market and its use is limited to portable entertainment devices and flashlights. The lack of market appeal is regrettable when considering the environmental benefit of having to discard fewer batteries. It is said that the manufacturing cost of the reusable alkaline is only marginally higher than the primary cell.

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% of their total capacity. The number of recharges depends solely on the depth of discharge and is limited to a few cycles at best. With each recharge, the amount of capacity the cell can hold is reduced. There is a cautionary advisory. Charging ordinary alkaline batteries may generate hydrogen gas, which can lead to explosion. It is not prudent to charge ordinary alkaline unsupervised.

The reusable alkaline is designed for repeated recharge. Also here, there is a loss of 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 high capacity reading on the first discharge. In fact, the energy density was similar to that of nickel-metal-hydride. After the battery was fully discharged and recharged using the manufacturer’s charger, the reusable alkaline settled at 60%, a capacity slightly below that of nickel-cadmium. Repeat cycling in the same manner resulted in a fractional capacity loss with each cycle. The discharge current in the tests 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 high internal resistance, resulting in a load current capability of only 400mA (lower than 400mA provides better results). Although adequate for portable radios receivers, CD players, tape players and flashlights, 400mA is insufficient to power most mobile phones and video cameras.

The reusable alkaline is inexpensive to buy but the cost per cycle is high when compared to other rechargeable batteries. Whereas nickel-cadmium checks in at $0.04US 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 primary alkaline that provides a one-time use. By only partially discharging the reusable alkaline, an improved cycle life is possible. At 50% 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 reusable alkaline achieved measurable cost savings in the low/intensity care unit in which the flashlights were used only occasionally. The high-intensity care unit, which used the flashlights constantly, did not attain the same result. Deeper discharge and more frequent recharge reduced the service life and offset any cost advantage over the standard alkaline battery.

When considering reusable alkaline, one must realize that the initial energy is slightly lower than that of the standard alkaline. Each subsequent recharge/charge cycle causes the capacity to decrease. Cost savings are realized if the batteries are never fully discharged but have a change to be recharged often.

**Advantages**

- Inexpensive - can be used as a direct replacement for non-rechargeable (primary) cells.
- More economical than non-rechargeables - 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.
• 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.

*Created: March 2003, Last edited: July 2003*

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Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world. Cadex Electronics is a manufacturer of advanced battery chargers, battery analyzers and PC software. For product information please visit [www.cadex.com](http://www.cadex.com).

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Battery packaging - a look at old and new systems

In the 1700 and 1800s, battery cells were encased in large glass jars. Later, multi-cell batteries were developed using wooden containers treated with a sealant to prevent electrolyte leakage. With the need for portability, the cylindrical cell was developed. The sealed cylindrical cells became common after World War II. Continued downsizing called for smaller and more compact cell design and in the 1980s the button cell appeared. The early 1990s brought the prismatic cell, which was followed by the modern pouch cell. We are now examining the strength and limitation of each packaging system.

The cylindrical cell

The cylindrical cell continues to be the most widely used packaging. It is easy to manufacture, offers high energy density and provides good mechanical stability. The cylinder has the ability to withstand high internal pressures. Typical applications are wireless communication, mobile computing, biomedical instruments, power tools and applications that do not demand ultra-small size.

![Cylindrical cell diagram]

Most nickel cadmium systems come in cylindrical cells. Other chemistries also make use of the cylindrical design. The 18650 is among the most popular lithium-ion cells ('18' denotes the diameter and '650' the length in millimeters). Lead-based systems are also available in cylindrical design of which the Cyclone by Hawker is the most common.

Cylindrical cells are equipped with a resealable venting mechanism to release pressure under extreme conditions such as excessive overcharge. nickel-based cells can sustain a pressure of about 13.5 Bar or 200 pounds per square inch (psi). Venting occurs between 10-13.5 Bar or 150-200 psi.

The drawback of the cylindrical cell is poor space utilization. Because of fixed cell size, a battery pack must be designed around available cell sizes.
**The button cell**
The button cell was developed to reduce packs size and improve stacking. Non-rechargeable cells and are found in watches, hearing aids and memory backup.

(Photocourtesy of Sanyo; design courtesy of Panasonic)

The rechargeable button cells are mostly nickel-based and are found in older cordless telephones, biomedical devices and industrial instruments. Although inexpensive to manufacture, the main drawback is charge times of 10-16 hour and swelling if charged too rapidly. New designs claim faster charge capabilities. Button cells have no safety vent.

**The prismatic cell**
The prismatic cell was developed in the early 1990 to response to consumer demand for thinner geometry. Prismatic cells are commonly reserved for the lithium battery family. The polymer version is exclusively prismatic.

The prismatic cell comes in various sizes with capacities from 400mAh to 2000mAh and higher. No standard cell size exists; rather, prismatic cells are custom-made for cell phones and other high volume items.

The negative attributes of the prismatic cell are slightly lower energy densities and higher manufacturing costs than the cylindrical cell. In addition, the prismatic cell does not provide the same mechanical stability enjoyed by the cylindrical cell. Prismatic cells have no venting system. To prevent bulging on pressure build up, heavier gauge metal is used for the container. Some degree of bulging must be considered in equipment design.

**The pouch cell**
The introduction of the pouch cell in 1995 made a profound advancement in cell design. Rather than using expensive metallic enclosures and glass-to-metal electrical feed-troughs, a heat-sealable foil is used. The electrical contacts consist of conductive foil tabs that are welded to the electrode and sealed to the pouch material.

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 is light. The main application is cell phones. No standardized pouch cells exist, each manufacturer builds to a special application.
The pouch cell is exclusively used for lithium-based chemistries. Manufacturing cost is still higher than conventional systems and its reliability has not been fully proven. In addition, the energy density and load current are slightly lower. The cycle life is not well documented but remains less than that of other packaging systems.

A critical issue with the pouch cell is the swelling that occurs when gas is generated during charging or discharging. Allowance must be made for some expansion, even though battery manufacturers insist that the cells do not generate gas if correctly charged. It is best not to stack pouch cells, but lay them side-by-side.

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.

**Battery packs for portable devices**

Most manufacturers of cell phones, laptops and cameras develop their own battery packs. A model change often results in a redesigned battery. The typical contact arrangements of cell phone and video camera batteries are: battery positive, negative and temperature sensor. Additional contacts, if present, may serve as control switch or battery type identifier. 'Smart' batteries have extra contacts to provide state-of-charge indication and other information. There are no norms and standards for these batteries. Each manufacturer has its own design.

In the 1990s, the Smart Battery System (SBS) forum made a concerted effort to standardize on battery norms for laptops, survey equipment and medical instruments. Beside physical size, these batteries ran on a standard SMBus protocol. With miniaturizing and securing a lucrative battery replacement market, laptop manufacturers went their own way. The SMBus batteries (type 2020, 1030, 1020, 210, 202, 201, 36, 35, 30, 17 and 15) are still widely used today for specialty instruments. (See also "The 'smart' battery" in Part One and "How to service laptop batteries" in Part Two.)

*Created: April 2003, Last edited: January 2004*

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Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world. Cadex Electronics is a manufacturer of advanced battery chargers, battery analyzers and PC software. For product information please visit [www.cadex.com](http://www.cadex.com).

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Safety circuits for modern batteries

A modern battery is a delicate storage device that requires protection to safeguard against damage. The most basic protection is a fuse that opens on excess current. Some fuses disengage permanently and render the battery useless once the filament is broken; other safety devices are resettable. The Polyswitch™ is such a resettable fuse. Connected into the battery's current path, this device creates a high resistance on excess current. The Polyswitch™ reverts to the low ON position when the condition normalizes, allowing operation to resume.

Batteries used in hazardous areas must be intrinsically safe. Hazardous areas include oil refineries, mines, grain elevators and fuel handling at airports. These areas are typically serviced with two-way radios and computing devices. Intrinsically safe batteries prevent high heat and electric spark on equipment failure. Because of tight approval standards, intrinsically safe batteries carry twice to three-times the price tag of regular packs.

Another battery that contains high-level protection is lithium-ion. This is done to assure safety under all circumstances while in the hands of the public. Typically, a Field Effect Transistor (FET) opens if the charge voltage of any cell reaches 4.30V. A separate fuse opens 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 about 10 Bar (150 psi) is exceeded. To prevent the battery from over-discharging, the control circuit cuts off the current path at about 2.50V/cell. Prolonged storage at voltages of 1.5V/cell and lower damages the lithium-ion, causing safety problems if attempted to recharge.

Each parallel string of cells in a lithium-ion pack needs independent voltage monitoring. In addition, each cell in series must be monitored for voltage. 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 must be designed to add as little resistance as possible to the current path. The circuit of a cell phone battery often consists of two FET switches connected in series. One FET is responsible for high, the other for low voltage cut-off. The combined resistance of the FETs in the ON position is 50-100mili-Ohms (mΩ). This virtually doubles the internal resistance of a battery pack.

A major concern arises if static electricity or a faulty charger destroys the battery’s protection circuit. This may result in permanently fusing the solid-state switches in an ON position without the user’s knowledge. A battery with a faulty protection circuit may function normally but will not provide protection. If charged over a safe limit with a defective charger, venting with flame could occur. Such a situation must be avoided at all cost. Shorting such a battery could also be hazardous.

Small lithium-ion packs with spinel (manganese) chemistry containing one or two cells may only include a fuse as protection. Spinel is more tolerant to abuse than cobalt and the cells are deemed safe if below a certain size.

Although less expensive, the absence of a protection circuit introduces a new problem. Cell phone users have access to low-cost chargers that may rely on the battery’s protection circuit to terminate charge. Without the protection circuit, the cell voltage rises too high and damages the battery. Excess heat, even bulging can result. Discontinue using the battery and charger if a lithium-ion battery gets hot.

To maintain safe operation, manufacturers do not sell the lithium-ion cells by themselves but make them available in a battery pack, complete with protection circuit. The circuit is often subject to exact scrutiny before the manufacturers release cells to the pack assemblers. Although there are a few reported incidents of venting with flame, the lithium-ion battery is safe.

Created: April 2003, Last edited: July 2004
Serial and parallel battery configurations

Battery packs get their desired operating voltage by connecting several cells in series. If higher capacity and current handling is required, the cells are connected in parallel. Some packs have a combination of serial and parallel connections. A laptop battery may have four 3.6 volts lithium-ion cells connected in series to achieve 14.4V and two cells in parallel to increase the capacity from 2000mAh to 4000mAh. Such a configuration is called 4S2P, meaning 4 cell are in series and 2 in parallel.

Single cell applications

Single cell batteries are used in watches, memory back up and cell phones. The nickel-based cell provides a nominal cell voltage of 1.2V; alkaline is 1.5V; silver-oxide 1.6V, lead-acid 2V; primary lithium 3V and lithium-ion 3.6V. Spinel, lithium-ion polymer and other lithium-based systems sometimes use 3.7V as the designated cell voltage. This explains the unfamiliar voltages such as 11.1V if three cells are connected in series. Modern microelectronics makes it possible to operate cell phones and other low power portable communications devices from a single 3.6V lithium-ion cell. Mercury, a popular cell for light meters in the 1960s has been discontinued because of environmental concerns.

Nickel-based cells are either marked 1.2V or 1.25V. There is no difference in the cells but only preference in marking. Most commercial batteries are identified with 1.2V/cell; industrial, aviation and military batteries are still marked with 1.25V/cell.

Serial connection

Portable equipment with high-energy needs is powered with battery packs in which two or more cell are connected in series. Figure 1 shows a battery pack with four 1.2-volt cells in series. The nominal voltage of the battery string is 4.8V.

Figure 1: Serial connection of four cells.
Adding cells in a string increases the voltage but the current remains the same.

High voltage batteries have the advantage of keeping the conductor and switch sizes small. Medium-priced industrial power tools run on 12V to 19.2V batteries; high-end power tools go to 24V and 36V to get more power. The car industry will eventually increase the starter-light-ignition (SLI) battery from 12V (14V) to 36V, better known as 42V. These batteries have 18 lead-acid cells in series. The early hybrid cars are running on 148V batteries. Newer models feature batteries with 450-500V; mostly on nickel-based chemistry. A 480-volt nickel-metal-hydride battery has 400 cells in series. Some hybrid cars are also experimenting with lead acid.

42V car batteries are expensive and produce more arcing on the switches than the 12V. Another problem with higher voltage batteries is the possibility of one cell failing. Similar to a chain, the more links that are connected in series, the greater the odds of one failing. A faulty cell would produce a low voltage. In an extreme case, an open cell could break the current flow. Replacement of a faulty cell is difficult because of matching. The new cell will typically have a higher capacity than the aged cells.

Figure 2 illustrates a battery pack in which cell 3 produces only 0.6V instead of the full 1.2V. With the depressed operating voltage, the end-of-discharge point will be reached sooner than with a normal pack and the runtime is severely shortened. Once the equipment cuts off due to low voltage, the remaining three cells are unable to deliver the stored energy. Cell 3 could also exhibit a high internal resistance, causing the string to collapse under load. A
weak cell in a battery string is like a blockage in a garden hose that restricts water flow. Cell 3 could also be shorted, which would lower the terminal voltage to 3.6V, or be open and cut off the current. A battery is only as good as the weakest cell in the pack.

**Parallel connection**

To obtain higher ampere-hour (Ah) ratings, two or more cells are connected in parallel. The alternative to parallel connection is using a larger cell. This option is not always available because of limited cell selection. In addition, bulky cell sizes do not lend themselves to build specialty battery shapes. Most chemistries allows parallel connection and lithium-ion is one of the best suited. Figure 3 illustrates four cells connected in parallel. The voltage of the pack remains at 1.2V but the current handling and runtime are increased four fold

![Parallel connection of four cells.](image)

With parallel cells, the voltage stays the same but the current handling and runtime increases.

A high resistance or open cell is less critical in a parallel circuit than the serial configuration but the parallel pack will have reduced load capability and a shorter runtime. It's like an engine running only on three cylinders. An electrical short would be more devastating because the faulty cell would drain the energy from the other cells, causing a fire hazard. Figure 4 illustrates a parallel configuration with one faulty cell.

![Parallel connection with one faulty cell.](image)

A weak cell will not affect the voltage but provide a low runtime. A shorted cell could cause excessive heat and create a fire hazard.

**Serial/parallel connection**

Figure 5 illustrates a parallel/serial connection. This allows good design flexibility and attains the wanted voltage and current ratings by using a standard cell size. It should be noted that the total power does not change with different configurations. The power is the product of voltage times current.

![Serial/parallel connection of four cells.](image)

The configurations will not affect the overall power but provide the most suitable voltage and current source for the application.

Serial/parallel connections are common with lithium-ion. One of the most popular cells is the 18650 (18mm diameter; 650mm long). Because of the protection circuit, which must monitor each cell connected in series, the maximum practical voltage is 14.4V. The protection must also monitor strings placed in parallel.
Charging and discharging lithium-ion batteries

Lithium-ion batteries are safe when used as directed. The same safety cannot be assured if individual cells of unknown nature are connected in series and parallel to build a battery pack. Not all lithium-ion cells are suited for multi-cell packs. Only cells that meet tight voltage and capacity tolerances can be used for serial and parallel connection. Mismatched packs are subject to overcharge, resulting in venting with flame and fire. Check with the cell manufacturer if the cells are suitable for multi-cell packs.

In the past, single lithium-ion cells were only made available to authorized battery assembles. Today, imports are becoming readily available and often fall into the hands of the inexperienced. While most brand name cells are equipped with an internal cell disconnect that permanently opens the current path on high pressure, some brands do not provide this safeguard. Neither do many brands use a separator that is designed to shut down on high temperature. The internal safety features are omitted for cost reasons.

Please follow the following guidelines when charging and discharging lithium-ion cell(s) and packs. Failing to follow these rules could result in venting with flame, explosion, fire and personal injury.

**WARNING when charging lithium-ion cells and packs**

- Never connect cells in parallel and/or series that are not designed for that purpose. A cell mismatch may cause overcharge and venting with flame.

- Never charge or discharge the battery without connecting a working protection circuit. Each cell must be monitored individually and the current disconnected if an anomaly occurs.

- Always attach a temperature sensor when charging and discharging the battery. The temperature sensor must disconnect the current on excess temperature.

- Only connect cells that are matched and have the identical state-of-charge.

- Pay special attention when using an unknown brand. Not all brands contain intrinsic safety features that protect the cell when stressed.

- During experiments, place the test battery into a well-ventilated fireproof container.

- Never leave the battery unattended while under charge or discharge.

- Do not charge a battery hat has physical damage.

**Household batteries**

The serial and parallel connections of cells described above addresses rechargeable battery packs in which the cells are permanently welded together. The same rules apply to household batteries except that we are dealing here with single cells that are put into a battery holder and form a serial configuration. When using single cells, some basic guidelines must be observed:

- Keep the battery contacts clean. A four-cell configuration has eight contacts (cell to holder and holder to next cell). Each contact exhibits some resistance which, when added, can affect the overall battery performance.

- Never mix batteries. Replace all cells when weak. (Remember the 'weak link of a chain' and 'a battery is only as good as the weakest cell'.) Use the same cell type for the whole string.

- Do not recharge non-rechargeable batteries. Charging primary cells will generate hydrogen that can lead to an explosion.

- Observe the right polarity. A reversed cell will deduct rather than add the cell voltage to the string.

- Charging a secondary battery with a reversed polarity will cause the affected cell to develop an electrical short. If left unattended, the damaged cell will heat up and create a fire hazard.

- Remove fully discharged batteries from the equipment. Old cells tend to leak and cause corrosion. Alkaline is less critical than carbon-zinc.

- Remove the batteries when the equipment is not used for a while to prevent corrosion.

- Do not store a box of cells in a way that can create an electrical short. A short cell will
heat up and create a fire hazard. Place lose cells in small plastic bags for electrical insulation.

- Always keep batteries away from children.

- Primary batteries such as Alkaline can be disposed in regular trash. It is recommended, however, to bring the spent batteries to a depot for recycle or disposal.

About the Author
Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world.
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Charging nickel-based batteries

The reliability and longevity of a battery hinges, to a large extent, on the quality of the charger. Battery chargers are often given low priority, especially for consumer products. In this paper we address the charger as the quintessential provider and guardian of the battery. We look at various charge methods that will increase the performance of nickel-based batteries. Charging lithium and lead-based batteries are described on separate papers.

A battery should always remain cool during charging because high temperatures shorten battery life. Some temperature rise with nickel-based batteries cannot be avoided. The time during which the battery temperature remains elevated should be as short as possible. The temperature rise occurs in the second half of the charge cycle. The battery should cool to room temperature when on trickle charge. If the temperature remains above room temperature after a few hours in ready mode, the charger is performing incorrectly. In such a case, remove the battery when ready. The caution applies especially to nickel-metal-hydride because this chemistry cannot absorb overcharge well.

Nickel-based chargers are grouped into three categories:

- **Slow Charger** - Also known as 'overnight charger', the slow charger applies a fixed charge of about 0.1C* (one-tenth of the rated capacity) for as long as the battery is connected. Charge time is 14-16 hours. Slow chargers are found in cord-less phones, portable CD players and other consumer goods.

- **Quick Charger** - Also known as rapid charger, this charger serves the middle range, both in terms of charging time and price. Charging time is 3-6 hours. The charger switches the battery to trickle charge when ready. Quick-chargers are used for cell phones, laptops and camcorders.

- **Fast Charger** - Designed for nickel-based battery, the fast charger fills a pack in about one hour. Fast charging is preferred because of reduced crystalline formation (memory). Accurate full-charge detection is important. When full, the charger switches to topping and then trickle charge. Fast chargers are used for industrial devices such as two-way radios, medical devices and power tools.

New nickel-based batteries should be trickle-charged for 24 hours prior to use. Trickle charge brings all cells to equal charge level because each cell self-discharges at a different rate. Trickle charge also redistributes the electrolyte to remedy dry spots on the separator brought on by gravitation of the electrolyte during long storage.

* The C-rate is a unit by which charge and discharge currents are scaled. A charge current of 1000mAh, or 1C, will charge a 1000mAh battery in slightly more than one hour. A 1C discharge lasts one hour.

Some battery manufacturers do not fully form the cells before shipment. Full performance is reached after the battery has been primed through several charge/discharge cycles, either with a battery analyzer or through normal use. In some cases, 50-100 discharge/charge cycles are needed to obtain full performance. Properly formed cells perform to specification after 5-7 cycles.

Most rechargeable cells are equipped with a safety vent to release excess pressure if overcharged. The safety vent on a nickel-based cell opens between 10-13 Bar (150-200 psi). (The pressure of a car tire is about 2.3 Bar or 35 psi.) With a resealable vent, no damage occurs after venting. Some electrolyte is lost and the seal may leak afterwards. A white powder accumulating at the vent opening indicates venting activities.

**Charging nickel-cadmium**

The overall charge efficiency of nickel-cadmium is about 90% if fast charged at 1C. On a 0.1C overnight charge, the efficiency drops to 70% and the charge time is 14 hours or longer.
In the initial 70% of charge, the charge acceptance of a healthy nickel-cadmium battery is close to 100%. The battery remains cool because all energy is absorbed. Currents of several times the C-rating can be applied without heat buildup. Ultra-fast chargers use this phenomenon to charge a battery to the 70% level within minutes. Past 70%, the battery gradually loses the ability to accept charge. The pressure and temperature increase. Figure 1 illustrates the relationship of cell voltage, pressure and temperature while nickel-cadmium is being charged.

![Figure 1: Charge characteristics of a nickel-cadmium cell. The cell voltage, pressure and temperature characteristics are similar to nickel-metal-hydride.](image)

Ultra-high capacity nickel-cadmium batteries tend to heat up more than the standard version on fast-charge. This is partly due to increased internal cell resistance. To moderate the temperature buildup and achieve short charge times, advanced chargers apply a high current at the beginning and then lower the amount to harmonize with the charge acceptance.

Interspersing discharge pulses between charge pulses improves the charge acceptance of nickel-based batteries. Commonly referred to as burp or reverse load charging, this method promotes high surface area on the electrodes to improve the recombination of gases generated during charge. The results are better performance, reduced memory and longer service life.

Full-charge detection is based on a combination of voltage drop at full charge (negative delta V), rate-of-temperature-increase (dT/dt), absolute temperature and timeout timers. The charger utilizes whatever comes first to terminate the fast-charge.

After the initial fast charge, some fast-chargers apply a timed topping charged. In an attempt to gain a few extra capacity points, some chargers apply a measured amount of overcharge. The capacity gain is about 6%. The negative is shorter cycle life. The recommended trickle charge for nickel-cadmium is between 0.05C and 0.1C. Because of memory concerns and compatibility with nickel-metal-hydride, the trickle charge is set as low as possible.

**Charging nickel-metal-hydride**

Nickel-metal-hydride chargers require more complex electronics than nickel-cadmium systems. To begin with, nickel-metal-hydride produces a very small voltage drop at full charge and the NDV is almost non-existent at charge rates below 0.5C and elevated temperatures. Aging and degenerating cell match diminish the already minute voltage delta further. This makes full charge detection difficult.

A nickel-metal-hydride charger must respond to a voltage drop of 8-16mV per cell. Making the charger too sensitive may terminate the fast charge halfway through the charge due to voltage fluctuations and electrical noise. Most of today’s nickel-metal-hydride chargers use a combination of NDV, rate-of-temperature-increase (dT/dt), temperature sensing and timeout timers. The charger utilizes whatever comes first to terminate the fast-charge.

Nickel-metal-hydride should be rapid charged rather than slow charged. Because of poor overcharge absorption, the trickle charge must be lower than that of nickel-cadmium and is usually around 0.05C. This explains why the original nickel-cadmium charger cannot be used nickel-metal-hydride.
It is difficult, if not impossible, to slow-charge a nickel-metal-hydride. At a C-rate of 0.1-0.3C, the voltage and temperature profiles fail to exhibit defined characteristics to measure the full charge state accurately and the charger must rely on a timer. Harmful overcharge can occur if a partially or fully charged battery is charged with a fixed timer. The same occurs if the battery has aged and can only hold 50 instead of 100% charge. Overcharge could occur even though the battery feels cool to the touch.

Lower-priced chargers may not apply a fully saturated charge. Some will indicate full-charge immediately after a voltage or temperature peak is reached. These chargers are commonly sold on the merit of short charge time and moderate price.

**Simple Guidelines:**

- Avoid high temperature during charging. Discontinue the use of chargers that cook batteries.
- A charger for nickel-metal-hydride can also accommodate nickel-cadmium, but not the other way around. A charger designed for nickel-cadmium would overcharge the nickel-metal-hydride battery.
- Nickel-based batteries prefer fast-charge. Lingering slow charges cause crystalline formation (memory).
- Nickel- and lithium-based batteries require different charge algorithms. The two chemistries can normally not be interchanged in the same charger.
- If not used immediately, remove the battery from the charger and apply a topping-charge before use. Do not leave nickel-based battery in the charger for more than a few days, even if on trickle charge.

A well-designed charger is a reasonably complex device. Taking short cuts will cost the user in the long run. Choosing a well-engineered charger will return the investment in longer lasting and better performing batteries.

*Created: April 2003, Last edited: December 2003*

**About the Author**

Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world. Cadex Electronics is a manufacturer of advanced battery chargers, battery analyzers and PC software. For product information please visit [www.cadex.com](http://www.cadex.com).

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Charging lithium-ion batteries

There is only one way to charge lithium-based batteries. The so-called 'miracle chargers', which claim to restore and prolong batteries, do not exist for lithium chemistries. Neither does super-fast charging apply. Manufacturers of lithium-ion cells have very strict guidelines in charge procedures and the pack should be charged as per the manufacturers "typical" charge technique.

Lithium-ion is a very clean system and does not need priming as nickel-based batteries do. The 1st charge is no different to the 5th or the 50th charge. Stickers instructing to charge the battery for 8 hours or more for the first time may be a leftover from the nickel battery days.

Most cells are charged to 4.20 volts with a tolerance of +/−0.05V/cell. Charging only to 4.10V reduced the capacity by 10% but provides a longer service life. Newer cell are capable of delivering a good cycle count with a charge to 4.20 volts per cell. Figure 1 shows the voltage and current signature as the lithium-ion cell passes through the charge stages.

![Figure 1: Charge stages of a lithium-ion battery. Increasing the charge current on a lithium-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.](image)

The charge time of most chargers is about 3 hours. Smaller batteries used for cell phones can be charged at 1C; the larger 18650 cell used for laptops should be charged at 0.8C or less. The charge efficiency is 99.9% and the battery remains cool during charge. Full charge is attained after the voltage threshold has been reached and the current has dropped to 3% of the rated current or has leveled off.

Increasing the charge current does not shorten the charge time by much. Although the voltage peak is reached quicker with higher charge current, the topping charge will take longer.

Some chargers claim to fast-charge a lithium-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%. The topping charge typically takes twice as long as the initial charge.

No trickle charge is applied because lithium-ion is unable to absorb overcharge. A continuous trickle charge above 4.05V/cell would causes plating of metallic lithium that could lead to instabilities and compromise safety. Instead, a brief topping charge is provided to
compensate for the small self-discharge the battery and its protective circuit consume. Depending on the battery, a topping charge may be repeated once every 20 days. Typically, the charge kicks in when the open terminal voltage drops to 4.05V/cell and turns off at a high 4.20V/cell.

What happens if a battery is inadvertently overcharged? lithium-ion is designed to operate safely within their normal operating voltage but become unstable if charged to higher voltages. When charging above 4.30V, the cell causes plating of metallic lithium on the anode; the cathode material becomes an oxidizing agent, loses stability and releases oxygen. Overcharging causes the cell to heat up. If left unattended, the cell could vent with flame.

Much attention is focused to avoid over-charging and over-discharging. Commercial lithium ion packs contain a protection circuits that limit the charge voltage to 4.30V/cell, 0.10 volts higher than the voltage threshold of the charger. Temperature sensing disconnects the charge if the cell temperature approaches 90°C (194°F), and a mechanical pressure switch on many cells permanently interrupt the current path if a safe pressure threshold is exceeded. Exceptions are made on some spinel (manganese) packs containing one or two small cells.

Extreme low voltage must also be prevented. The safety circuit is designed to cut off the current path if the battery is inadvertently discharged below 2.50V/cell. At this voltage, most circuits render the battery unserviceable and a recharge on a regular charger is not possible. There are several safeguards to prevent excessive discharge. The equipment protects the battery by cutting off when the cell reaches 2.7 to 3.0V/cell. Battery manufacturers ship the batteries with a 40% charge to allow some self-discharge during storage. Advanced batteries contain a wake-up feature in which the protection circuit only starts to draw current after the battery has been activated with a brief charge. This allows prolonged storage.

In spite of these preventive measures, over-discharge does occur. Advanced battery analyzers (Cadex C7000 series) feature a 'boost' function that provides a gentle charge current to activate the safety circuit and re-energize the cells if discharged too deeply. A full charge and analysis follows.

If the cells have dwelled at 1.5V/cell and lower for a few days, however, a recharge should be avoided. Copper shunts may have formed inside the cells, leading a partial or total electrical short. The cell becomes unstable. Charging such a battery would cause excessive heat and safety could not be assured.

Battery experts agree that charging lithium-ion batteries is simpler and more straightforward than the nickel-based cousins. Besides meeting the tight voltage tolerances, the charge circuit can be designed with fewer variables to consider. Full-charge detection by applying voltage limits and observing the current saturations on full charge is simpler than analyzing many complex signatures, which nickel-metal-hydride produces. Charge currents are less critical and can vary. A low current still permits proper full charge detection. The battery simply takes longer to charge. The absence of topping and trickle charge also help in simplifying the charger. Best of all, there is no memory but aging issues are the drawback.

The charge process of a lithium-ion-polymer is similar to lithium-ion. These batteries use a gelled electrolyte to improve conductivity. In most cases, lithium-ion and lithium-ion-polymer share the same charger.

**Preparation new lithium-ion for use**

Unlike nickel and lead-based batteries, a new lithium-ion pack does not need cycling through charging and discharging. Priming will make little difference because the maximum capacity of lithium-ion is available right from the beginning. Neither does a full discharge improve the capacity of a faded pack. However, a full discharge/charge will reset the digital circuit of a 'smart' battery to improve the state-of-charge estimation.

**State-of-charge reading based on terminal voltage**

The open circuit voltage can be used to estimate the battery state-of-charge of lithium, alkaline and lead-based batteries. Unfortunately, this method cannot be used for nickel-based packs.

On a lithium-ion cell, 3.8V/cell indicates a state-of-charge of about 50%. It must be noted that utilizing voltage as a fuel gauge function is inaccurate because cells made by different manufacturers produce a slightly different voltage profile. This is due to the electrochemistry of the electrodes and electrolyte. Temperature also affects the voltage. The higher the temperature, the lower the voltage will be.
About the Author
Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world. Cadex Electronics is a manufacturer of advanced battery chargers, battery analyzers and PC software. For product information please visit www.cadex.com.
Charging the lead-acid battery

The charge algorithm for lead-acid batteries is similar to lithium-ion but differs from nickel-based chemistries in that voltage rather than current limiting is used. The charge time of a sealed lead-acid battery is 12-16 hours (up to 36 hours for larger capacity batteries). With higher charge currents and multi-stage charge methods, the charge time can be reduced to 10 hours or less. Lead-acid cannot be fully charged as quickly as nickel or lithium-based systems.

It takes about 5 times as long to recharge a lead-acid battery to the same level as it does to discharge. On nickel-based batteries, this ratio is 1:1, and roughly 1:2 on lithium-ion.

A multi-stage charger first applies a constant current charge, raising the cell voltage to a preset voltage (Stage 1 in Figure 1). Stage 1 takes about 5 hours and the battery is charged to 70%. During the topping charge in Stage 2 that follows, the charge current is gradually reduced as the cell is being saturated. The topping charge takes another 5 hours and is essential for the well being of the battery. If omitted, the battery would eventually lose the ability to accept a full charge. Full charge is attained after the voltage has reached the threshold and the current has dropped to 3% of the rated current or has leveled off. The final Stage 3 is the float charge, which compensates for the self-discharge.

Correct settings of the voltage limits are critical and range from 2.30V to 2.45V. Setting the voltage limit is a compromise. On one end, the battery wants to be fully charged to get maximum capacity and avoid sulfation on the negative plate. A continually over-saturated condition at the other end, however, would cause grid corrosion on the positive plate. It also promotes gassing, which results in venting and loss of electrolyte.

The voltage limit shifts with temperature. A higher temperature requires slightly lower voltages and vice versa. Chargers that are exposed to large temperature fluctuations should be equipped with temperature sensors to adjust the charge voltage for optimum charge. Figure 2 compares the advantages and limitations of various peak voltage settings.
The battery cannot remain at the peak voltage for too long; the maximum allowable time is 48 hours. When reaching full charge, the voltage must be lowered to maintain the battery at between 2.25 and 2.27V/cell. Manufacturers of large lead-acid batteries recommend a float charge of 2.25V at 25°C.

Car batteries and valve-regulated-lead-acid batteries (VRLA) are typically charged to between 2.26 and 2.36V/cell. At 2.37V, most lead-acid batteries start to gas, causing loss of electrolyte and possible temperature increases. The exceptions are small sealed lead acid batteries (SLA), which can be charged to 2.50V/cell without adverse side effect.

The cylindrical Cyclone by Hawker requires a very high peak voltage of 2.60V/cell. Failing to apply the recommended voltage threshold causes a gradual decrease in capacity due to sulfation. Follow manufacturer’s recommended settings on these lead-acid variations.

Large VRLA batteries are often charged with a float-charge current to 2.25V/cell. A full charge may take several days. It is interesting to observe that the current in float charge mode gradually increases as the battery ages in standby mode. The reasons may be electrical cell leakages and a reduction in chemical efficiency.

Aging affects each cell differently. Since the cells are connected in series, controlling the individual cell voltages during charge is virtually impossible. Even if the correct overall voltage is applied, a weak cell will generate its own voltage level and intensify the condition further.

Much has been said about pulse charging lead-acid batteries. Some experts believe there is a benefit in reduced cell corrosion but manufacturers and service technicians are not in full agreement on the effectiveness. There are also disagreements on the 'equalizing charge'. An equalizing charge raises the battery voltage for several hours above that specified by the manufacturer. Although beneficial in reversing sulfation, the side effects are elevated temperature, gassing and loss of electrolyte if the service is not administered correctly. A periodic discharge of about 10% is said to benefit the battery but little conclusive evidence is available.

Lead-acid batteries must always 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 on an SLA. Prolonged storage below the critical voltage causes sulfation, a condition that is difficult to reverse. (See also: "How to restore and prolong lead-acid batteries")

**Charging lead-acid batteries with a power supply**

Lead-acid batteries can be charged manually with a commercial power supply featuring voltage regulation and current limiting. Calculate the charge voltage according to the number of cells and desired voltage limit. Charging a 12-volt battery (6 cells) at a cell voltage limit of 2.40V, for example, would require a voltage setting of 14.40V.

The charge current for small lead-acid batteries should be set between 10% and 30% of the rated capacity (30% of a 2Ah battery would be 600mA). Larger batteries, such as those used in the automotive industry, are generally charged at lower current ratings. Cells constructed of a non-antimonial lead grid material allow higher charge currents but have a lower capacity. The cylindrical Cyclone is sealed and can sustain a pressure of up to 3.5 Bar (50 psi). A pressurized cell assists in the recombination of gases.

Observe the battery temperature, voltage and current during charge. Charge only at ambient temperatures and in a ventilated room. Once the battery is fully charged and the current has dropped to 3% of the rated current, the charge is completed. A good car battery will drop to about 40mA when fully charged; a bad battery may not fall below 100mA.

After full charge, remove the battery from the charger. If float charge is needed for operational readiness, lower the charge voltage to about 13.50V (2.25V/cell). Most chargers perform this function automatically. The float charge can be applied for an unlimited time.
State-of-charge reading based on terminal voltage

The state-of-charge of a lead-acid battery can, to a certain extent, be estimated by measuring the open terminal voltage. Prior to measuring, the battery must have rested for 4-8 hours after charge or discharge and reside at room temperature. A cold battery would show slightly higher voltages and a hot battery would be lower. Plate additions of calcium and antimony will also vary the open terminal voltage. Furthermore, AGM has a higher voltage plateau than the flooded lead acid and the readings on Figure 3 may not apply.

<table>
<thead>
<tr>
<th>Open circuit voltage</th>
<th>State-of-Charge in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.65V</td>
<td>100%</td>
</tr>
<tr>
<td>12.45V</td>
<td>75%</td>
</tr>
<tr>
<td>12.24V</td>
<td>50%</td>
</tr>
<tr>
<td>12.06V</td>
<td>25%</td>
</tr>
<tr>
<td>11.89V or less</td>
<td>Discharged</td>
</tr>
</tbody>
</table>

Figure 3: BCI standard for SoC estimation of a 12V flooded lead acid car battery.

Test the battery at room temperature. Allow 4-8 hour of rest after charge or discharge. Courtesy of BCI

Battery as a buffer

While dwelling on float-charge, an external load can be connected to a lead-acid battery. In such a case, the battery acts as a buffer. Micro-towers on cell sites work this way. During off-peak periods, the batteries get fully charged. On peak traffic times, the load exceeds the net supply provided by the rectifier (charger) and the battery supplies the extra energy. A car battery works in a similar way.

When configuring a battery as a buffer, make certain that the battery has the opportunity to fully charge between loads. The net charge must be greater than what is drawn from the battery. Some chargers switch to fast charge after a deep discharge, others simply use the float charge to recharge. Allow up to 48 hours to fully recharge on float charge. Deep discharges should be avoided if possible. Assure that the float charge voltage is set correctly.

Created: April 2003, Last edited: March 2005

About the Author

Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world. Cadex Electronics is a manufacturer of advanced battery chargers, battery analyzers and PC software. For product information please visit www.cadex.com.
Charging at high and low temperatures

Rechargeable batteries operate under a reasonably wide temperature range. This, however, does not automatically permit charging under these same temperature extremes. While operating batteries under hot or cold conditions cannot always be avoided, the user has some control over charging. Efforts must be made to charge the batteries at moderate temperatures.

In general, older battery technologies, such as nickel-cadmium, are more tolerant to charging at temperature extremes. Nickel-cadmium can be fast-charged in an hour or so, however, such a charge should only be applied within temperatures of 5°C and 45°C (41°F and 113°F). More moderate temperatures of 10°C to 25°C (50°F to 77°F) produce better results.

Charging below 5°C requires a reduce charge rate of 0.1C (one tenth of the rated current). This is in line with the rate at which the oxygen and hydrogen can be absorbed within the cell. Because of the decreased combination rate at low temperatures, too rapid a charge would cause excessive cell pressure, which would lead to cell venting. Such a battery would never reach full charge state under these conditions.

Industrial batteries that need to be fast-charged at low temperatures include a thermal blanket to maintain the battery at an acceptable temperature. Once a charging temperature is enabled, the very process of gas recombination, which occurs during charge, also generates some heat to assist the cold temperature charging. The ideal charger would adjust itself to obtain equilibrium between gas recombination and charge current.

Nickel-metal-hydride is less forgiving than the nickel-cadmium if charged under high and low temperatures. Nickel-metal-hydride cannot be fast charged below 10°C (45°F), neither can it be slow charged below 0°C (32°F). Some industrial chargers are designed to adjust the charge rate to existing temperatures. Price sensitivity does not permit elaborate temperature sensing on consumer chargers.

At higher temperatures, the charge acceptance of nickel-based batteries is drastically reduced. A battery that provides a capacity of 100% when charged at moderate room temperature can only accept 70% if charged at 45°C (113°F), and 45% if charged at 60°C (140°F). This demonstrates the poor summer performance of some vehicular chargers.

The lithium-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 lithium-ion cells prefer a lower charge current when the temperature drops down to 5°C (41°F) or colder. Charging below freezing must be avoided because plating of lithium metal could occur.

The lead-acid battery is reasonably forgiving on temperature extremes, as we are familiar with our car batteries. Part of this tolerance is credited to the sluggishness of the lead-acid system. Some battery brands permit freezing and low level charging, others sustain damage and deliver reduced capacity and a short service life.

To improve charge performance of lead-acid batteries at colder temperatures and avoid thermal runaway during heat spells, controlling the voltage limits, to which the battery is charged, is important. Implementing such a measure can prolong battery life by up to 15%. General guidelines suggest a compensation of approximately 3mV per degree Celsius. The voltage adjustment has a negative coefficient, meaning that the voltage threshold drops as the temperature increases.

Heat kills batteries. The warmer the cells, the shorter the life is. Elevated temperatures cannot always be prevented, especially during fast charging, but efforts must be made to keep this time brief. While 45°C (113°F) is acceptable if kept short, at 50°C (122°F) and above, the battery starts to suffer. Note that the cells inside the pack are always a few degrees warmer than the temperature of the housing.

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, nickel-cadmium 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% of the charge cycle.

In the second phase of the charge cycle, the charge current must be lowered. The efficiency to absorb charge is progressively reduced as the battery moves to a higher state-of-charge. If the charge current remains too high in the later part of the charge cycle, the excess energy turns into heat and high cell pressure. Eventually, venting will occur, releasing oxygen and hydrogen. Not only do the escaping gases deplete the electrolyte, they are highly flammable! A white powdery substance accumulating at the vent area indicates previous venting.

Ultra-fast charging can only be applied to batteries that are designed for fast charging. Applying a high current charge to regular cells will cause the conductive path to heat up. The contacts on portable packs also suffer if the current handling of the spring-loaded plunger contacts is underrated. These contacts may 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 often melts the plastic. Higher contact tensions improve the current flow.

Aged batteries with high internal resistance and mismatched cells do not lend themselves to ultra-fast charging, even if they are designed for it. Low cell conductivity turns into heat, which further deteriorates the cells. The weak cells holding less capacity are fully charged before the others and begin to heat up rapidly. Some batteries create sufficient heat to soften and distort the plastic housing. Temperature sensing is a prerequisite with fast and ultra-fast charging.

Several manufacturers offer pulse chargers. Interspersing brief discharge pulses between each charge pulse can further enhance charging. This method promotes recombination of oxygen and hydrogen gases, resulting in reduced pressure buildup and lower cell temperature. Pulse chargers are also known to reduce crystalline formation (memory) on nickel-based batteries. Most Cadex chargers for nickel-based batteries apply this feature.

Some advanced chargers regulate the charge current according to the battery's ability to accept charge. An empty battery will initially take a very high charge current. Towards the end of a charge, the current is tapered down. Aged batteries are given their due respect and are automatically charged at rates suitable to their condition.

About the Author
Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world. Cadex Electronics is a manufacturer of advanced battery chargers, battery analyzers and PC software. For product information please visit www.cadex.com.
How to charge - when to charge table

Batteries are ready to work in an instant (provided they are charged) and can be used in a reasonably wide temperature range. Charging, on the other hand, has limitations and the user should follow recommended guidelines on how and when to charge. Each battery chemistry has its own charging preference. Properly applied, the battery will provide better performance and will live longer.

Ideal handling is not always possible. Any deviation from a perfect condition will have a negative effect; some only marginally. Prolonged exposure to heat will likely be the largest enemy.

<table>
<thead>
<tr>
<th>x</th>
<th>Nickel-based (NiCd and NiMH)</th>
<th>Lithium-ion (Li-ion)</th>
<th>Lead-acid (Sealed or flooded)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Should I use up all battery energy before charging?</td>
<td>Yes, fully discharge once every 1-3 months to prevent memory. It is not necessary to deplete the battery before each charge. Over cycling wears down NiMH.</td>
<td>No, it is better to recharge more often; avoid frequent full discharges. Yes, on batteries with a fuel gauge, allow a full discharge once a month to enable reset.</td>
<td>No, it is better to recharge more often; avoid frequent full discharges. Deep cycles wear down the battery. Use a larger battery if full cycles are required.</td>
</tr>
<tr>
<td>Should I charge my battery partially or fully?</td>
<td>Allow full charge without interruptions. Repeated partial charge can cause heat buildup. (Many chargers terminate charge by heat. A fully charged battery will re-heat, causing overcharge.)</td>
<td>Does not matter. Charging in stages is acceptable. Full charge termination occurs by reading the voltage level and charge current. Charging a full battery is safe and does not cause harm.</td>
<td>Does not matter. Charging in stages is acceptable. Full charge termination occurs by reading the voltage level and charge current. Charging a full battery is safe and does not cause harm.</td>
</tr>
<tr>
<td>Should the battery be kept charged when not in use?</td>
<td>Not critical. Manufacturers recommend a 40% charge for long storage. (Open terminal voltage cannot determine state-of-charge.) Store in a cool place. Battery can be fully depleted and recharged. Priming may be needed.</td>
<td>Best to store at 40% charge or 3.75-3.80V/cell open terminal. Cool storage is more important than state-of-charge. Do not fully deplete battery because Li-ion may turn off its protection circuit.</td>
<td>IMPORTANT: always keep battery fully charged. A discharged battery causes sulfation (insulating layer in the cell). This condition is often irreversible.</td>
</tr>
<tr>
<td>Will the battery heat up during charge?</td>
<td>Yes, towards full charge. The battery must cool down when ready. Discontinue using a charger that keeps the battery warm on standby.</td>
<td>No, little heating is generated during charge. A large laptop battery may get lukewarm. Do not allow the battery to heat during charge.</td>
<td>No, the battery should remain cool or lukewarm to the touch. The battery must remain cold on maintenance charge.</td>
</tr>
<tr>
<td>What are the allowable charging temperatures?</td>
<td>Important: Rechargeable batteries can be used under a wide temperature range. This does not automatically permit charging at these extreme conditions. The maximum allowable charge temperatures are shown below:</td>
<td>Important: Optimum charge temperatures.</td>
<td>Important: Optimum charge temperatures.</td>
</tr>
<tr>
<td>Slow charge (0.1) Fast charge (0.5-1C)</td>
<td>0°C - 45°C (32°F - 113°F) 5°C - 45°C (41°F - 113°F)</td>
<td>Charging a hot battery decreases the charge time. The battery may not fully charge.</td>
<td>0°C - 45°C (32°F - 113°F) 5°C - 45°C (41°F - 113°F) Temperature sensor may prevent charge or cut off the charge prematurely.</td>
</tr>
<tr>
<td>What should I know about chargers?</td>
<td>Best results are achieved with a fast-charger that terminates the charge by other than temperature alone. Fastest full-charge time: Slightly over 1 hour.</td>
<td>Charger should apply full charge. Avoid economy chargers that advertise one-hours charge. Fastest full-charge time: 2-3 hours.</td>
<td>Multi-level chargers shorten charge time. Charge must be fully saturated. Failing to do so will gradually decrease the capacity. Fastest full-charge time: 8-14 hours.</td>
</tr>
</tbody>
</table>

Created: May 2003, last edited March 2003

About the Author
Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC.
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 lithium-ion performs better at high temperatures. Elevated temperatures temporarily counteract the battery’s internal resistance, which may have advanced as 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 lithium-ion polymer uses some moist electrolyte to enhance conductivity, the dry solid polymer version depends on heat to enable sufficient ion flow. This requires that the battery core be kept at an operation temperature of 60°C to 100°C (140°F to 212°F).

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 that is fed by the utility grid during normal operation. On a power outage, the battery would need to provide its own power to maintain the temperature. Although said to be long lasting, price is an obstacle.

Nickel-metal-hydride degrades rapidly if cycled at higher ambient temperatures. For example, if operated at 30°C (86°F), the cycle life is reduced by 20%. At 40°C (104°F), the loss jumps to a whopping 40%. 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 nickel-cadmium 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 nickel-metal-hydride, sealed lead-acid and lithium-ion battery cease to function, the nickel-cadmium can go down to -40°C (-40°F). At that frigid temperature, the nickel-cadmium 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 allow charging 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. Nickel-cadmium can be recharged at below freezing provided the charge rate is reduced to 0.1C.

Pulse discharge

Battery chemistries react differently to specific loading requirements. Discharge loads range from a low and steady current used in a flashlight, to sharp current pulses for digital communications equipment, to intermittent high current bursts in a power tool and 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.

Although lithium-ion battery packs are equipped with a current limiter for safety reasons, the cell is capable of delivering high current pulses of one second and less in duration. On applications with high current spikes, a special protection circuit will be needed that allows high-current pulses but provides protection on a continuous overload condition.

A lithium-ion battery manufacturer claims that their cells perform better on a pulse rather than DC load. The DC resistance of their 18650 cylindrical cell is ~110 mOhm. At 1 KHz AC, the impedance goes down to ~36 mOhm. As the pulses increase in frequency, the cell’s effective impedance goes down. This results in better performance and lower heat build-up. These two effects increase the life of the lithium-ion cell.
The internal resistance of the cobalt-based lithium-ion will increase with age and cause a problem when drawing heavy pulse currents. The manganese-based cell, on the other hand, will maintain the resistance at a low level throughout its service life. The cobalt-based lithium-ion cell provides a higher energy density but manganese is better suited for pulse load applications.

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. A discharge at 1C of the rated capacity yields the poorest efficiency. 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, affect the longevity of some battery chemistries. While nickel-cadmium and lithium-ion are robust and show minimal deterioration when pulse discharged, the nickel-metal-hydride exhibits a reduced cycle life when powering a digital load.

In a recent study, the longevity of nickel-metal-hydride was observed by discharging with analog and digital loads 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 and a standby current of 270mA. (Note that the GSM pulse for voice is about 550 ms every 4.5 ms).

With the analog discharge, the nickel-metal-hydride provided an above average service life. At 700 cycles, the battery still provided 80% capacity. By contrast, the cells faded more rapidly with a digital discharge. The 80% capacity threshold was reached after only 300 cycles. This phenomenon indicates that the kinetic characteristics for the nickel-metal-hydride deteriorate more rapidly with a digital rather than an analog load. Lithium and lead-acid systems are less sensitive to pulsed discharge than nickel-metal-hydride.

About the Author
Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world. Cadex Electronics is a manufacturer of advanced battery chargers, battery analyzers and PC software. For product information please visit www.cadex.com.
Discharge methods

The purpose of a battery is to store energy and release it at the appropriate time in a controlled manner. In this section we examine the discharge under different C-rates and evaluate the depth to which a battery can safely be discharged. We also observe how deep discharges affect battery life.

What is C-rate?

The charge and discharge current of a battery is measured in C-rate. Most portable batteries are rated at 1C. This means that a 1000mAh battery would provide 1000mA for one hour if discharged at 1C rate. The same battery discharged at 0.5C would provide 500mA for two hours. At 2C, the 1000mAh battery would deliver 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% is shown if a 1000mAh battery can provide this current for one hour. If the battery only lasts for 30 minutes before cut-off, 50% is indicated. A new battery sometimes provides more than 100% capacity.

When discharging a battery with a battery analyzer that allows the setting of 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 with a slower discharge, since the identical amount of energy is dispensed, only over a shorter time. Due to internal energy losses and a voltage drop that causes the battery to reach the low-end voltage cut-off sooner, the capacity reading may be lowered to 95%. Discharging the same battery at 0.5C, or 500mA over two hours may increase the capacity reading to about 105%. The discrepancy in capacity readings with different C-rates is related to the internal resistance of the battery.

One battery that does not perform well at a 1C discharge rate is the portable sealed lead-acid. To obtain a reasonably good capacity reading, manufacturers commonly rate these batteries at 0.05C or 20 hour discharge. Even at this slow discharge rate, a 100% capacity is hard to attain. To compensate for different readings at various discharge currents, manufacturers offer a capacity offset. Applying the offset to correct the capacity readout does not improve battery performance; it merely adjusts the capacity calculation if discharged at a higher or lower C-rate than specified.

Lithium-ion/polymer batteries are electronically protected against high load currents. Depending on battery type, the discharge is limited to between 1C and 2C. This protection makes the lithium ion unsuitable for biomedical equipment and power tools demanding high inrush currents.

Depth of discharge

The typical end-of-discharge voltage for nickel-based batteries is 1V/cell. At that voltage level, roughly 99% of the energy is spent and the voltage starts to drop rapidly if the discharge continued. 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, also known as cell reversal, will occur across a weaker cell if the discharge is allowed to continue uncontrolled. The more cells that are connected in series, the greater the likelihood of cell reversal occurring.

Nickel-cadmium can tolerate some 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 on the positive electrode leads to
pressure build-up and possible cell venting. If the cell is pushed further into voltage reversal, the polarity of both electrodes is being reversed and the cell produces an electrical short. Such a fault cannot be corrected.

Some battery analyzers apply a secondary discharge (recondition) that discharges the battery voltage to a very low voltage cut-off point. These instruments control the discharge current to assure that the maximum allowable current, while in sub-discharge range, does not exceed a safe limit. Should cell reversal develop, the current would be low enough not to cause damage. Cell breakdown through recondition is possible on a weak or aged pack.

If the battery is discharged at a rate higher than 1C, the end-of-discharge point of a nickel-based battery is typically lowered to 0.9V/cell. This compensates for the voltage drop induced by the internal resistance of the cells, wiring, protection devices and contacts. A lower cut-off point also produces better capacity readings when discharging a battery at cold temperatures.

Among battery chemistries, nickel-cadmium is least affected by repeated full discharge cycles. Several thousand charge/discharge cycles are possible. This is why nickel-cadmium performs well on power tools and two-way radios that are in constant use. nickel-metal-hydride is less durable in respect to repeated deep cycling.

Lithium-ion typically discharges to 3.0V/cell. The spinline and coke versions can be discharged to 2.5V/cell to gain a few extra percentage points. Since the equipment manufacturers do not specify the battery type, most equipment is designed for a 3-volt cut-off.

A discharge below 2.5V/cell may put the battery's protection circuit to sleep, preventing a recharge with a regular charger. These batteries can be restored with the Boost program available on the Cadex C7000 Series battery analyzers.

Some lithium-ion batteries feature an ultra-low voltage cut-off that permanently disconnects the pack if a cell dips below 1.5V. 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.

Manufacturers rate the lithium-ion battery at an 80% depth of discharge. Repeated full (100%) discharges would lower the specified cycle count. It is therefore recommended to charge lithium-ion more often rather than letting it discharge down too low. Periodic full discharges are not needed because lithium-ion is not affected by memory.

The recommended end-of-discharge voltage for lead-acid is 1.75V/cell. The discharge does not follow the preferred flat curve of nickel and lithium-based chemistries. Instead, Lead-acid has a gradual voltage drop with a rapid drop towards the end of discharge.

The cycle life of sealed lead-acid is directly related to the depth of discharge. The typical number of discharge/charge cycles at 25°C (77°F) with respect to the depth of discharge is:

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

The lead-acid battery should not be discharged beyond 1.75V per cell, nor should it be stored in a discharged state. The cells of a discharged lead-acid sulfate, a condition that renders the battery useless if left in that state for a few days. Always keep the open terminal voltage at 2.10V and higher.

**What constitutes a discharge cycle?**

There are no standard definitions that constitute a discharge cycle. Smart batteries that keep track of discharge cycles commonly use a depth-of-discharge of 70% to define a discharge cycle. Anything less than 70% does not count. The reason of the cycle count is to estimate the end-of-battery life.

A battery often receives many short discharges with subsequent recharges. With the smart battery, these cycles do not count because they stress the battery very little. On satellites, the depth-of-discharge is only about 10%. Such minute discharge cycles put the least amount of stress on the batteries in space. With shallow discharges, however, nickel-based batteries require a periodic deep discharge to eliminate memory.

Lithium and lead-based batteries do not require a periodic full discharge. In fact, it is better not to discharge them too deeply but charge them more often. Using a larger battery is one way to reduce the stress on a battery.

Created: April 2003, Last edited: January 2004
Calculating the battery runtime

A battery can either be discharged at a low current over a long time or at a high current for only a short duration. Table 1 illustrates the discharge characteristics of a lead acid battery at various loads as expressed in C-rate. At 1C, a 10Ah battery discharges at the nominal rating of 10A in less than one hour. At 0.1C, the same battery discharges at 1A for roughly 10 hours. While the discharge voltage of lead acid decreases in a rounded profile towards the end-of-discharge cut-off, nickel and lithium-based chemistries provide a more steady voltage level through most of the discharge and then drop rapidly at the end of discharge.

![Discharge Rate Characteristics](image)

Table 1: Typical discharge curves of lead acid as a function of C-rate.

The relationship between the discharge time (in amperes drawn) is reasonably linear on low loads. As the load increases, the discharge time suffers because some battery energy is lost due to internal losses. This results in the battery heating up. The table below indicates the typical discharge time of a 10Ah lead acid battery at various currents.

<table>
<thead>
<tr>
<th>Discharge current</th>
<th>C-Rate</th>
<th>Discharge time</th>
<th>End of discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5A</td>
<td>0.05C</td>
<td>20h</td>
<td>1.75V/cell</td>
</tr>
<tr>
<td>0.1A</td>
<td>0.1C</td>
<td>10h</td>
<td>1.75V/cell</td>
</tr>
<tr>
<td>2A</td>
<td>0.2C</td>
<td>5h</td>
<td>1.70V/cell</td>
</tr>
<tr>
<td>2.8A</td>
<td>0.28C</td>
<td>3f</td>
<td>1.64V/cell</td>
</tr>
<tr>
<td>6A</td>
<td>0.6C</td>
<td>1h</td>
<td>1.55V/cell</td>
</tr>
<tr>
<td>10A</td>
<td>1C</td>
<td>0.5h</td>
<td>1.40V/cell</td>
</tr>
</tbody>
</table>

Table 2: Typical discharge times of a 10Ah lead acid battery as a function of C-rate.

If the battery was a perfect energy source and behaved linearly, a 5A discharge would take two hours to discharge. At a load current of 10A, the same battery would provide energy of one hour. In reality, the relative discharge times are much shorter at higher currents. The losses increase progressively with load. To compensate somewhat, a high current discharge is allowed to terminate at a slightly lower volt per cell, as the forth column of the above table illustrates.

The Peukert number

The efficiency of a battery is expressed in the Peukert number. In essence, the Peukert number reflects the internal resistance of the battery. A value close to 1 indicates a well-performing battery with little losses. A higher number reflects a less efficient battery. The Peukert number of a battery is exponential and checks in between 1.3 and 1.4 for lead acid. The number is lower for nickel-based batteries.
Batteries are stressed the most if discharged at a steady load to the end-of-discharge point. This is the opposite of an internal combustion engine that operates most efficiently with a steady load. On a battery, the intermittent load allows a level of recovery of the very chemical reaction that produces the electrical energy. Because of the rather sluggish behavior, the quiescent rest period is especially important for lead acid. Table 3 illustrates the effective cell capacity of lead acid on a continuous discharge as opposed to an intermittent discharge.

Table 3: The Peukert Curve. The effective cell capacity fades with increased load. An intermittent discharge improves the capacity as it allows the chemical reaction to recover.
How does the internal battery resistance affect performance?

With the move from analog to digital, new demands are placed on the battery. Unlike analog portable devices that draw a steady current, the digital equipment loads the battery with short, heavy current spikes.

One of the urgent requirements of a battery for digital applications is low internal resistance. Measured in milliohms, 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 spikes. A high mW reading can trigger an early 'low battery' indication on a seemingly good battery because the available energy cannot be delivered in the required manner and remains in the battery.

Figure 1 demonstrates 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 dips, reflecting the load pulses. These pulses push the voltage towards the end-of-discharge line, resulting in a premature cut-off. As seen in the chart, the internal resistance governs much of the runtime.

As part of ongoing research to measure the runtime of batteries with various internal resistance levels, Cadex Electronics examined several cell phone batteries that had been in service for a while. All batteries were similar in size and generated good capacity readings when checked with a battery analyzer under a steady discharge load. The nickel-cadmium pack produced a capacity of 113%, nickel-metal-hydride checked in at 107% and the lithium-ion provided 94%. The internal resistance varied widely and measured a low 155 mOhm for nickel-cadmium, a high 778 mOhm for nickel-metal-hydride and a moderate 320 mOhm for lithium-ion. These internal resistance readings are typical of aging batteries with these chemistries.

Let’s now check how the test batteries perform on a cell phone. The maximum pulse current of a GSM (Global System for Mobile Communications) cell phone is 2.5 amperes. This represents a large current from a relatively small battery of about 800 milliamperes (mAh) hours. A current pulse of 2.4 amperes from an 800 mAh battery, for example, correspond to a C-rate of 3C. This is three times the current rating of the battery. Such high current pulses can only be delivered if the internal battery resistance is low.

![Battery Discharge Pulses](image)
Figures 2, 3 and 4 reveal the talk time of the three batteries under a simulated GSM current of 1C, 2C and 3C. One can see a direct relationship between the battery’s internal resistance and the talk time. nickel-cadmium performed best under the circumstances and provided a talk time of 120 minutes at a 3C discharge (orange line). nickel-metal-hydride performed only at 1C (blue line) and failed at 3C. lithium-ion allowed a moderate 50 minutes talk time at 3C.

**Figure 2:** Discharge and resulting talk-time of nickel-cadmium at 1C, 2C and 3C under the GSM load schedule. The battery tested has a capacity of 113%, the internal resistance is a low 155 mOhm.

**Figure 3:** Discharge and resulting talk-time of nickel-metal-hydride at 1C, 2C and 3C under the GSM load schedule. The battery tested has a capacity of 107%, the internal resistance is a high 778 mOhm.
Figure 4: Discharge and resulting talk-time of a lithium-ion battery at 1C, 2C and 3C under the GSM load schedule. The battery tested has a capacity of 94%, the internal resistance is 320 mOhm.

The internal resistance also varies with the state-of-charge of the battery. The largest changes are noticeable on nickel-based batteries. In Figure 5, we observe the internal resistance of nickel-metal-hydride when empty, during charge, at full charge and after a 4-hour rest period.

High readings are measured at low state-of-charge and immediately after charge. The resistance decreases at half charge and after a 4-hour rest period. Contrary to popular belief, the best battery performance is not achieved right after a full charge but after a rest period.

Usntac5: Internal resistance in nickel-metal-hydride. Note the higher readings immediately after a full discharge and full charge. Resting a battery before use produces the best results.

The internal resistance of lithium-ion is fairly flat from empty to full charge. The battery decreases asymptotically from 270 mW at 0% to 250 mW at 70%. The largest changes occur between a state-of-charge of 0% and 30%. The internal resistance of lead-acid typically measures 34 mW at 0%, 20 mW at 50% and 52 mW at 100%. Cold temperature increases the internal resistance on all batteries.

References: Shukla et al. 1998. Rodrigues et al. 1999

Created: April 2003, Last edited: July 2003

About the Author

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The 'smart' battery

The battery has the inherit problem of not being able to communicate with the user. Neither weight, color, nor size provides an indication of the battery's state-of-charge (SoC) and state-of-health (SoH). The user is at the mercy of the battery.

Help is at hand in breaking the code of silence. 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. Typical applications for 'smart' batteries are notebook computers and video cameras. Increasingly, these batteries are also used in biomedical devices and defense applications.

There are several types of 'smart' batteries, each offering different complexities and costs. The most basic 'smart' battery may contain nothing more than a chip that sets the charger to the correct charge algorithm. 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. In 1990, Benchmarq was the first company to commercialize the concept by offering fuel gauge technology. Today, several manufacturers produce such chips. They range from the single wire system, to the two-wire system to the System Management Bus (SMBus). Let's first look at the single wire system.

The Single Wire Bus

The single wire system delivers the data communications through one wire. This battery uses three wires: the common positive and negative battery terminals and one single data terminal, which also provides the clock information. For safety reasons, most battery manufacturers run a separate wire for temperature sensing. Figure 1 shows the layout of a single wire system.

![Figure 1: Single wire system of a 'smart' battery. Only one wire is needed for data communications. For safety reasons, most battery manufacturers run a separate wire for temperature sensing.](image)

The single wire system stores the battery code and tracks battery readings, including temperature, voltage, current and SoC. Because of relatively low hardware cost, the single wire system enjoys market acceptance for high-end two-way radios, camcorders and portable computing devices.

Most single wire systems do not provide 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 the 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 only feasible if the original battery is used. Any discrepancy in the battery will make the system unreliable or will provide false readings.

The SMBus

The SMBus is the most complete of all systems. It represents a large effort from the electronics industry to standardize on one communications protocol and one set of data. The Duracell/Intel SBS, which is in use today, was standardized in 1993. It is a two-wire interface system consisting of separate lines for the data and clock. Figure 2 shows the layout of the two-wire SMBus system.

Figure 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.

The objective 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 slave that must follow the dictates of the battery.

Battery-controlled charging makes sense when considering that some packs share the same footprint but contain different chemistries, requiring alternative charge algorithms. With the SMBus, each battery receives the correct charge levels and terminates full-charge with proper detection methods. Future battery chemistries will be able to use the existing chargers.

An SMBus battery contains permanent and temporary data. The permanent data is programmed into the battery at the time of manufacturing and includes 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 this information is 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 Level 2 application is a battery that contains the charging circuit within the pack. Level 3 is reserved for full-featured external chargers.

External Level 3 chargers are complex and expensive. Some lower cost chargers have emerged that accommodate SMBus batteries but are not fully SBS compliant. Manufacturers of SMBus batteries do not fully endorse this shortcut. Safety is always a concern, but customers buy them because of low cost. Serious industrial battery users operating biomedical instruments, data collection devices and survey equipment use Level 3 chargers with full-fledged charge protocol.

Among the most popular SMBus batteries are the 35 and 202 form-factors (Figure 3). Manufactured by Sony, Hitachi, GP Batteries, Moli Energy and others, these batteries work (should work) in all portable equipment designed for this system. Although the 35 has a smaller footprint than the 202, most chargers accommodate both sizes. A non-SMBus (‘dumb’) version with same footprint is also available. These batteries can only be charged with a regular charger, or one that accepts both types.
In spite of the agreed standard and given form factors, many computer manufacturers have retained their proprietary batteries. Safety, performance and form factor are the reasons. They argue that enduring performance can only be guaranteed if their own brand battery is used. This makes common sense but the leading motive may be pricing. In the absence of competition, these batteries can be sold for a premium price.

**Negatives of the 'smart' battery**

The 'smart' battery has some notable downsides, one of which is price. An SMBus battery costs about 25% 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 model.

A more serious drawback is the requirements for periodic calibration or capacity re-learning. The Engineering Manager of Moli Energy, a manufacturer of lithium-ion cell commented, "With lithium-ion we have eliminated the memory effect; but is the SMBus battery introducing digital memory?"

Why is calibration needed? The calibration corrects the tracking errors that occur between the battery and the digital sensing circuit while charging and discharging. The most ideal battery application, as far as fuel-gauge accuracy is concerned, would be a full charge followed by a full discharge at a constant current. In such a case, the tracking error would be less than 1% per cycle. In real life, however, a battery may be discharged for only a few minutes and the load pulses may be very short. Long storage also contributes to errors because the circuit cannot accurately compensate for self-discharge. Eventually, the true capacity of the battery no longer synchronizes with the fuel gauge and a full charge and discharge is needed to 're-learn' the battery.

How often is calibration needed? The answer lies in the battery application. For practical purposes, a calibration is recommended once every three months or after every 40 short cycles. Many batteries undergo periodic full discharges as part of regular use. If the portable device allows a deep enough discharge to reset the battery and this is done regularly, no additional calibration is needed. However, if no discharge reset has occurred for a few months, a deliberate full discharge is needed. This can be done on a charger with discharge function or a battery analyzer.

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 chemical cells rather than the electronic circuit. In this case, the battery will fully charge regardless of the fuel gauge setting and function normally, but the digital readout will become inaccurate. If not corrected, the fuel gauge simply becomes a nuisance.

An addition problem with the SMBus battery is non-compliance. Unlike other tightly regulated standards, the SMBus protocol allows some variations. This may cause problems with existing chargers and the SMBus battery should be checked for compatibility before use. The need to test and approve the marriage between a specific battery and charger is unfortunate, given the assurance that the SMBus battery is intended to be universal. Ironically, the more features offered on the SMBus charger and the battery, the higher the likelihood of incompatibilities.

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**About the Author**

Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world.
The battery fuel gauge

When the 'smart' battery was introduced in the 1990s, one of the main objectives was to enable communications between the battery and user. Adding a fuel gauge solved this. In this paper, we evaluate various fuel gauges, check how they work, and assess their advantages and limitations. Since the System Management Bus (SMBus) is most widely used, we will focus on this system.

The state-of-charge indicator

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

![Figure 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.](image)

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

The reserve capacity can only be established when the SoH is known. Figure 5 illustrates the three imaginary sections of a battery consisting of the empty zone, which can be refilled, available energy and unusable section or 'rock content' that can no longer store energy.

![Figure 5: 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.](image)

A battery fuel gauge should be able to disclose all three sections of the battery. Knowing the battery's SoH can do this. While the SoC is relatively simple to produce, 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% 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% setting. A perfect battery would indicate 100% on a calibrated fuel gauge. As the battery ages and the charge acceptance drops, the SoH decreases. The discrepancy between the factory-set 100% and the delivered coulombs on a fully discharged battery indicates the SoH.

Knowing the SoC and SoH, a simple linear display can be made. The SoC is indicated with green LEDs; the empty part remains dark; and the unusable part is shown with red LEDs. Figure 6 shows such a tri-state fuel gauge. As an alternative, a numeric display indicating SoH and SoC can be used. The practical location for the tri-state-fuel gauge is on the charger.
The target capacity selector

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

If a battery falls below target, the charger triggers the condition light. The user is prompted to press the condition button to calibrate and condition the battery by applying a charge/discharge/charge cycle. The green 'ready' light at the end of the service reveals full charge and assures that the battery meets the required performance level. If the battery does not recover, a fail light indicates that the battery should be replaced. Figure 7 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.

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 application, reliability and cost.

The nominal target capacity setting is 80%. Decreasing the threshold to 70% will lower the performance standard but pass more batteries. A direct cost saving will result. The 60% 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. It should be noted that the batteries are always charged to 100%, regardless of the target setting. The target capacity simply reveals the energy, which a fully charged battery can deliver.

'Smart' batteries enabling performance readings are reserved for high-end industrial applications. However, in spite of improvements made over the last ten years, the 'smart' battery, the SMBus in particular, has not received the anticipated acceptance. Some engineers go so far as to suggest that the SMBus battery is a 'misguided principal'.

Part of the problem is the periodic calibration that is needed to correct the tracking errors that occur between the battery and the digital sensing circuit. Notable errors transpire if a battery is charged and discharged for only brief moments and the load varies widely. Long storage also contributes to errors because the circuit cannot accurately compensate for self-discharge.

Regardless of these limitations, the 'smart' battery will continue to serve a critical market. It is conceivable that other methods will be introduced that do not rely on the in and out-flow of energy to establish energy reserve. But the importance of the fuel gauge has been established. There are simply no alternatives for users to whom unexpected downtime is no option.

*Created: April 2003, Last edited: July 2003*

**About the Author**  
Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC.
How to store batteries

Batteries are perishable products that start deteriorating right from the moment they leave the factory. There are simple preventive measures that battery users can apply to slow the aging process. This paper provides guidelines to reduce age-related capacity losses and how to prime new and stored batteries.

The recommended storage temperature for most batteries is 15°C (59°F). While lead-acid batteries must always be kept at full charge, nickel and lithium-based chemistries should be stored at 40% state-of-charge (SoC). This level minimizes age-related capacity loss, yet keeps the battery in operating condition even with some self-discharge. While the open terminal voltage of nickel-based batteries cannot be used to determine the SoC accurately, voltage fuel gauging works well for lithium-ion cells. However, differences in the electrochemistry of the electrodes and electrolyte between manufacturers vary the voltage profile slightly. A SoC of 50% reads about 3.0V; 40% is 3.75V. Store lithium-ion at an open terminal voltage of 3.75-3.80V. Allow the battery to rest 90 minutes after charge before taking the voltage reading.

Figure 1 illustrates the recoverable capacity at various storage temperatures and charge levels over one year.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Lithium-ion 40% charge level (recommended storage level)</th>
<th>Lithium-ion 100% charge level (typical user charge level)</th>
<th>Nickel-based recoverable capacity after 1 year of storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°C</td>
<td>98%</td>
<td>54%</td>
<td>99%</td>
</tr>
<tr>
<td>25°C</td>
<td>94%</td>
<td>50%</td>
<td>97%</td>
</tr>
<tr>
<td>40°C</td>
<td>85%</td>
<td>65%</td>
<td>91%</td>
</tr>
<tr>
<td>60°C</td>
<td>75%</td>
<td>60% (after 3 months)</td>
<td>70%</td>
</tr>
</tbody>
</table>

Figure 1: Non-recoverable capacity loss on lithium-ion and nickel-based batteries after storage. High charge levels and elevated temperatures hasten the capacity loss.

Among the lithium-ion family, cobalt has a slight advantage over manganese (spinel) in terms of storage at elevated temperatures. Nickel-based batteries are also affected by elevated temperature but to a lesser degree than lithium-ion.

Lithium-ion powers most of today's laptop computers. The battery compartment on many laptops rises to about 45°C (113°F) during operation. The combination of high charge level and elevated ambient temperature presents an unfavorable condition for the battery. This explains the short lifespan of many laptop batteries.

Nickel-metal-hydride can be stored for about three years. The capacity drop that occurs during storage is permanent and cannot be reversed. Cool temperatures and a partial charge slows aging. Nickel-cadmium stores reasonably well. Field test revealed that NICd batteries stored for five years still performed well after priming cycles. Alkaline and lithium batteries (primary) can be stored for up to 10 years. The capacity loss is minimal.

The sealed lead-acid battery can be stored for up to two years. A periodic topping charge, also referred to as 'refresh charge', is required to prevent the open cell voltage from dropping below 2.10V. (Some lead-acid batteries may allow lower voltage levels.) Insufficient charge induces sulfation, an oxidation layer on the negative plate that inhibits the current flow on charge and discharge. Topping charge and/or cycling may restore some of the capacity losses in the early stages.

Priming new batteries
Manufacturers recommend to trickle charge a nickel-based battery for 24 hours when new and after long storage. This service brings all cells to equal charge level and redistributes the electrolyte to remedy dry spots on the separator brought on by gravitation of the electrolyte. It is advisable to verify the capacity with a battery analyzer before use. This is especially important in critical applications.

Cycling (priming) is recommended to regain lost capacity after a nickel-based battery has been stored for 6 months or longer. A slow charge followed by one or several discharge/charge cycles will do this. The recovery rate is governed by the condition under which the battery was stored. The longer and warmer the storage temperature, the more cycles will be required. The Prime program of the Cadex battery analyzers automatically applies the number of cycles needed to regain full capacity.

Nickel-based batteries are not always fully formed when leaving the factory. Applying several charge/discharge cycles through normal use or with a battery analyzer completes the forming. The number of cycles needed to attain full capacity differs between cell manufacturers. Quality cells perform to specification after 5-7 cycles. Those lacking formation may need 50 or more cycles to reach acceptable capacity levels. What is the difference between priming and forming? For the user, both symptoms manifest themselves as insufficient capacity. The difference may be explained in that forming needs to be done only once when the battery is new, while priming must be repeated after each prolonged storage.

Lithium-ion batteries deliver full power after the initial charge. Manufacturers of lithium-ion cells insist that no priming is required. However, priming is beneficial as an initial start and to verify battery performance. Excessive cycling should be avoided because of wear-down effect.

The internal protection circuit of lithium-based batteries is known to cause some problems after a long storage. If the battery is left discharged after use, the self-discharge will further drain the pack and eventually drip the protection circuit at about 2.5 volts per cell. At this point, the charger will no longer recognize the battery and the pack appears dead. Advanced battery analyzers (Cadex) feature the Boost program that activates the protection circuit to enable a recharge. If the cell voltage has fallen below 1.5V/cell and has remained in that state for a few days, a recharge should be avoided for safety reasons.

To reduce the self-discharge on newly manufactured batteries, advanced lithium-ion packs feature a sleep mode that keeps the protection circuit off until activated by a brief charge. Once engaged, the battery remains operational and the advantage of the sleep mode no longer applies.

Lead-acid batteries should be primed by applying a full charge, followed by a discharge and recharge. Verifying the capacity through a discharge is important, especially if the battery is engaged in critical applications such as powering medical devices. Priming is also recommended after storing a battery for six months and longer. Battery analyzers provide the priming service automatically.

It is believed that a partial or full discharge applied once every six months or so enhances the performance of lead-acid batteries. Avoid too many full discharges, as this would wear down the battery unnecessarily.

While capacity loss during a battery's life cannot be eliminated, simple guidelines minimize the effect:

- Keep batteries in a cool and dry storage area. Refrigeration is recommended but freezers should be avoided. When refrigerated, the battery should be placed in a plastic bag to protect against condensation.
- Do not fully charge lithium and nickel-based batteries before storage. Keep them partially charged and apply a full charge before use. Store lithium-ion at about 40% state-of-charge (3.75-3.80V/cell open terminal). Lead-acid batteries must be stored fully charged.
- Do not store lithium-ion fully depleted. If empty, charge for about 30 minutes before storage. Self-discharge on a depleted battery may cause the protection circuit to trip, preventing a recharge.
- Do not stockpile lithium-ion batteries; avoid buying dated stock, even if offered at a reduced price. Observe the manufacturing date, if available.
- Never leave a nickel-based battery sitting on a charger for more than a few days. Prolonged trickle charge causes crystalline formation (memory).
- Always store a lead acid battery in full-charge condition. Observe the open terminal voltage and recharge the battery every 6 months or as recommended by the manufacturer.
Recycling batteries

Modern batteries are often promoted on their environmental qualities. Lithium-based batteries fall into this category. While nickel-cadmium presents an environmental problem on careless disposal, this chemistry continues to hold an important position among rechargeable batteries. Power tools are almost exclusively powered by nickel-cadmium. Lead-acid batteries continue to service designated market niches and these batteries also need to be disposed of in a proper manner. Lithium-ion would simply be too fragile to replace many of these older, but environmentally unfriendly, battery chemistries.

Our quest for portability and mobility is steadily growing, so is the demand for batteries. 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% of all lead-acid batteries are recycled. In comparison, only one in six households in North America recycle batteries.

Careless disposal of nickel-cadmium is hazardous to the environment. If used in landfills, the cadmium will eventually dissolve itself and the toxic substance can 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 nickel-metal-hydride is considered environmentally friendly, this chemistry is also being recycled. The main derivative is nickel, which is considered semi-toxic. Nickel-metal-hydride also contains electrolyte that, in large amounts, is hazardous. If no disposal service is available in an area, individual nickel-metal-hydride batteries can be discarded with other household wastes. If ten or more batteries are accumulated, the user should consider disposing of these packs in a secure waste landfill.

Lithium (metal) batteries contain no toxic metals, however, there is the possibility of fire if the metallic lithium is exposed to moisture while the cells are corroding. Most lithium batteries are non-rechargeable and are used in cameras, hearing aids and defense applications. For proper disposal, the batteries must first be fully discharged to consume the metallic lithium content.

Lithium-ion batteries used for cell phones and laptops do not contain metallic lithium and the disposal problem does not exist. Most lithium systems contain toxic and flammable electrolyte.

In 1994, the Rechargeable Battery Recycling Corporation (RBRC) was founded to promote recycling of rechargeable batteries in North America. RBRC is a non-profit organization that collects batteries from consumers and businesses and sends them to recycling organizations. Inmetco and Toxco are among the best-known recycling companies in North America. Europe and Asia have had programs to recycle spent batteries for many years. Sony and Sumitomo Metal in Japan have developed a technology to recycle cobalt and other precious metals from spent lithium-ion batteries.

Battery recycling plants require that the batteries be sorted according to chemistries. Some sorting must be done prior to the battery arriving at the recycling plants. Nickel-cadmium, nickel-metal-hydride, lithium-ion and lead acid are placed in designated boxes at the collection point. Battery recyclers claim that if a steady stream of batteries, sorted by chemistry, were available at no charge, recycling would be profitable. But preparation and transportation add to the cost.

The recycling process starts by removing the combustible material, such as plastics and insulation, with 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 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 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 and produces cadmium that is 99.95 percent pure.

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 require 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.

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.

Nickel-metal-hydride yields the best return. It produces enough nickel to pay for the process. The highest recycling fees apply to nickel-cadmium and lithium-ion because the demand for cadmium is low and lithium-ion contains little retrievable metal.

Not all countries base the cost of recycling on the battery chemistry; some put it on tonnage alone. The flat cost to recycle 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 still required from manufacturers, agencies and governments to support the battery recycling programs. This funding is in the form of a tax added to each manufactured cell. RBRC is financed by such a scheme.

Important: Under no circumstances should batteries be incinerated as this can cause explosion. If skin is exposed to electrolyte, flush with water immediately. If eye exposure occurs, flush with water for 15 minutes and consult a physician immediately.

Created: May 2003, Last edited: July 2003

About the Author
Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world. Cadex Electronics is a manufacturer of advanced battery chargers, battery analyzers and PC software. For product information please visit www.cadex.com.

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# Do and don’t battery table

Each battery has unique needs that must be met to obtain reliable service and long life. The Do and Don’t battery table summarizes these needs and advises proper handling of each battery type.

Optimal handling may not always be practical in real life. Deviations from the ideal are acceptable but will lower the life expectancy of the battery to some degree. Exposure to heat may be the larger deterrent.

<table>
<thead>
<tr>
<th>-</th>
<th>Nickel-cadmium (NiCd)</th>
<th>Nickel-metal-hydride (NiMH)</th>
<th>Lithium-ion (Li-ion)</th>
<th>Lead-acid (Sealed or flooded)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Used in</strong></td>
<td>Two-way radios, power tools, medical.</td>
<td>Similar application as NiCd; higher density.</td>
<td>Cell phones, laptops, video cameras.</td>
<td>Motorcycles, cars, wheelchairs, UPS.</td>
</tr>
<tr>
<td><strong>Charging</strong></td>
<td>Do run the battery fully down once per month; try to use up all energy before charging. Do not leave battery in charger for more than 2 days because of memory. Avoid getting battery too hot during charge. Charge methods: Constant current, followed by trickle charge when full. Fast charge preferred over slow charge. Slow charge = 16h; Rapid charge = 3h; Fast charge = 1h.</td>
<td>Do run the battery fully down once every 3 months. Over-cycling is not advised. Do not leave battery in charger for more than 2 days because of memory. Avoid getting battery too hot during charge. Charge methods: Constant current, followed by trickle charge when full. Slow charge not recommended. Battery will get warm towards full charge. Rapid charge = 3h; Fast charge = 1h.</td>
<td>Do charge the battery often. The battery lasts longer with partial rather than full discharges. Do not use if pack gets hot during charge. Check also charger. Charge methods: Constant voltage to 4.20V/cell (typical). No trickle-charge when full. Li-ion may remain in the charger (no memory). Battery must remain cool. No fast-charge possible. Rapid charge = 3h.</td>
<td>Do charge the battery immediately after use. Lead-acid must always be kept in a charged condition. The battery lasts longer with partial rather than full discharges. Over-cycling is not advised. Charge methods: Constant voltage to 2.40V/cell (typical), followed by float held at 2.25V/cell. Battery must remain cool. Fast charge not possible; can remain on float charge. Slow charge = 14h; Rapid charge = 10h.</td>
</tr>
<tr>
<td><strong>Discharging</strong></td>
<td>Full cycle does not harm NiCd. NiCd is one of the most hardy and durable chemistries. Avoid too many full cycles because of wear. Use 80% depth-of-discharge. NiMH has higher energy density than NiCd at the expense of shorter cycle life.</td>
<td>Avoid too many full cycles because of wear. Use 80% depth-of-discharge recommended. NiMH has higher energy density than NiCd at the expense of shorter cycle life.</td>
<td>Avoid full cycle because of wear. 80% depth-of-discharge recommended. Re-charge more often. Avoid full discharge. Low voltage may cut off safety circuit.</td>
<td>Avoid full cycle because of wear. Use 80% depth-of-discharge. Recharge more often or use larger battery. Low energy density limits lead-acid to wheeled applications.</td>
</tr>
<tr>
<td><strong>Service needs</strong></td>
<td>Discharge to 1V/cell every 1 to 2 months to prevent memory. Do not discharge before each charge.</td>
<td>Discharge to 1V/cell every 3 months to prevent memory. Do not discharge before each charge</td>
<td>No maintenance needed. Loses capacity due to aging whether used or not.</td>
<td>Apply topping charge every 6 months. Occasional discharge/charge may improve performance.</td>
</tr>
<tr>
<td><strong>Storage</strong></td>
<td>Best to store at 40% charge in a cool place. Open terminal voltage cannot determine state-of-charge. 5 years and longer storage possible. Prime battery if stored longer than 6 months. Store at 40% charge in a cool place. Open terminal voltage cannot determine state-of-charge. Prime battery if stored longer than 6 months.</td>
<td>Store at 40% charge in a cool place. Open terminal voltage cannot determine state-of-charge. Prime battery if stored longer than 6 months. Store at 40% charge in a cool place (40% state-of-charge reads 3.75-3.80V/cell at open terminal. Do not store at full charge and at warm temperatures because of accelerated aging.</td>
<td>Store always at a full state-of-charge. Do not store below 2.10V/cell; apply topping charge very 6 months.</td>
<td></td>
</tr>
<tr>
<td><strong>Disposal</strong></td>
<td>Do not dispose; contains toxic metals; must be recycled. Should be recycled. Low volume household NiMH may be disposed.</td>
<td>Should be recycled. Low volume household Li-ion may be disposed.</td>
<td>Should be recycled. Low volume household Li-ion may be disposed.</td>
<td>Do not dispose; must be recycled.</td>
</tr>
</tbody>
</table>

*Created: May 2003, Last edited: March 2004*
Part Two - Getting the most from your batteries

<< Click on the flag beside each article to view a German version.

**Part Two - Getting the most from your batteries**

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- Increasing internal resistance
- Elevated self-discharge
- Premature voltage cut-off

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The secrets of battery runtime

Is the runtime of a portable device directly related to the size of the battery? The answer should be ‘yes’ but in reality, the runtime is governed by other attributes than the specified capacity alone.

This paper examines the cause of unexpected downtime and short battery service life. We look at four renegades - declining capacity, increasing internal resistance, elevated self-discharge and premature voltage cut-off on discharge. We evaluate how these regenerative deficiencies affect nickel, lead and lithium-based batteries.

**Declining capacity**

The amount of charge a battery can hold gradually decreases due to usage and aging. Specified to deliver 100% capacity when new, the battery should be replaced when the capacity drops to below 80% of the nominal rating. Some organizations may use different end-capacities as a minimal acceptable performance threshold.

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 unusable part (rock content) that increases with aging. Figure 1 illustrates these three sections.

![Figure 1: Battery charge capacity. Three imaginary sections of a battery consisting of available energy, empty zone and rock content.](image)

In nickel-based batteries, the so-called *rock content* is present in form of crystalline formation, also known as memory. Restoration is possible with a full discharge to one volt per cell. However, if no service is done for four months and longer, a full repair becomes increasingly more difficult the longer service is withheld. To prevent memory, nickel-based batteries should be deep-cycled once every one or two months. Nickel-cadmium and nickel-metal-hydride batteries are used for two-way radios, medical instruments and power tools.

Performance degradation of the lead-acid battery is caused by sulfation and grid corrosion. Sulfation is a thin layer that forms on the negative cell plate if the battery is being denied a fully saturated charge. Sulfation can, in part, be corrected with cycling and/or topping charge. The grid corrosion, which occurs on the positive plate, is caused by over-charge. Lead-acid batteries are used for larger portable devices and wheeled applications.

Lithium-ion batteries lose capacity through cell oxidation, a process that occurs naturally during use and aging. The typical life span of lithium?ion is 2-3 years, whether the battery is used or not. Cool storage a 40% charge minimizes aging. An aged lithium-ion cannot be restored with cycling. Lithium-ion is found in cell phones and mobile computing.

**Increasing internal Resistance**

The capacity of a battery defines the stored energy - the internal resistance governs how much energy can be delivered at any given time. While a good battery is able to provide high current on demand, the voltage of a battery with elevated resistance collapses under a heavy load. Although the battery may hold sufficient capacity, the resulting voltage drop triggers the ‘low battery’ indicator and the equipment stops functioning. Heating the battery will momentarily increase the output by lowering the resistance.
A battery with high internal resistance may still perform adequately on a low current appliance such as a flashlight, portable CD player or wall clock. Digital equipment, on the other hand, draw heavy current bursts. Figure 2 simulates low and high internal resistance with a free-flowing and restricted tap.

![Figure 2: Effects of internal battery resistance. A battery with low internal resistance is able to provide high current on demand. With elevated resistance, the battery voltage collapses and the equipment cuts off.](image)

Nickel-cadmium offers very low internal resistance and delivers high current on demand. In comparison, nickel-metal-hydride starts with a slightly higher resistance and the readings increase rapidly after 300 to 400 cycles.

Lithium-ion has a slightly higher internal resistance than nickel-based batteries. The cobalt system tends to increase the internal resistance as part of aging whereas the manganese (spinel) maintains the resistance throughout its life but loses capacity through chemical reaction. Cobalt and manganese are used for the positive electrodes.

High internal resistance will eventually render the battery useless. The energy may still be present but can no longer be delivered. This condition is permanent and cannot be reversed with cycling. Cool storage at a partial state-of-charge (40%) retards the aging process.

The internal resistance of Lead-acid batteries is very low. The battery responds well to short current bursts but has difficulty providing a high, sustained load. Over time, the internal resistance increases through sulfation and grid corrosion.

**Elevated self-discharge**

All batteries suffer from self-discharge, of which nickel-based batteries are among the highest. The loss is asymptotical, meaning that the self-discharge is highest right after charge and then levels off. nickel-based batteries lose 10% to 15% of their capacity in the first 24 hours after charge, then 10% to 15% per month afterwards. One of the best batteries in terms of self-discharge is Lead-acid; it only self-discharges 5% per month. Unfortunately, this chemistry has the lowest energy density and is ill suited for portable applications.

lithium-ion self-discharges about 5% in the first 24 hours and 1-2% afterwards. Adding the protection circuit increases the discharge by another 3% per month. The protection circuit assures that the voltage and current on each cell does not exceed a safe limit. Figure 3 illustrates a battery with high self-discharge.

![Figure 3: Effects of high load impedance. Self-discharge increases with age, high cycle count and elevated temperature. Discard a battery if the self-discharge reaches 30% in 24 hours.](image)

The self-discharge on all battery chemistries increase at higher temperatures. Typically, the rate doubles with every 10°C (18°F). A noticeable energy loss occurs if a battery is left in a hot vehicle.

Aging and usage also affect self-discharge. nickel-metal-hydride is good for 300-400 cycles, whereas nickel-cadmium may last over 1000 cycles before high self-discharge affects the performance. An older nickel-based battery may lose its energy during the day through self-discharge rather than actual use. Discard a battery if the self-discharge reaches 30% in 24 hours.
Nothing can be done to reverse this deficiency. Factors that accelerate self-discharge are damaged separators induced by crystalline formation, allowing the packs to cook while charging, and high cycle count, which promotes swelling in the cell. Lead and lithium-based batteries do not increase the self-discharge with use in the same manner as their nickel-based cousins do.

**Premature voltage cut-off**

Not all stored battery power can be fully utilized. Some equipment cuts off before the designated end-of-discharge voltage is reached and precious battery energy remains unused. Applications demanding high current bursts push the battery voltage to an early cut-off. This is especially visible on batteries with elevated internal resistance. The voltage recovers when the load is removed and the battery appears normal. Discharging such a battery on a moderate load with a battery analyzer to the respective end-of-discharge threshold will sometimes produce residual capacity readings of 30% and higher, yet the battery is inoperable in the equipment. Figure 4 illustrates high cut-off voltage.

![Figure 4: Illustration of equipment with high cut-off voltage. Some portable devices do not utilize all available battery power and leave precious energy behind.](image)

High internal battery resistance and the equipment itself are not the only cause of premature voltage cut-off - warm temperature also plays a role by lowering the battery voltage. Other reasons are shorted cells in a multi-cell battery pack and memory on nickel-based batteries.

*Created: May 2003, Last edited: December 2003*

**About the Author**

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Non-Correctable Battery Problems

Some rechargeable batteries can be restored through external means, such as applying a full discharge. There are, however, many defects that cannot be corrected. These include high internal resistance, elevated self-discharge, electrical short, dry-out, plate corrosion and general chemical breakdown.

The performance loss of a battery occurs naturally as part of usage and aging; some is hastened by lack of maintenance, harsh field conditions and poor charging practices. This paper examines the cause of non-correctable battery problems and explores ways to minimize these breakdowns.

High Self-discharge
All batteries are affected by self-discharge. This is not a defect per se, although improper use enhances the condition. Self-discharge is asymptotical; the highest loss occurs right after charge, and then tapers off.

Nickel-based batteries exhibit a relatively high self-discharge. At ambient temperature, a new nickel-cadmium loses about 10% of its capacity in the first 24 hours after charge. The self-discharge settles to about 10% per month afterwards. Higher temperature increases the self-discharge substantially. As a general guideline, the rate of self-discharge doubles with every 10°C (18°F) increase in temperature. The self-discharge of nickel-metal-hydride is about 30% higher than that of nickel-cadmium.

The self-discharge increases after a nickel-based battery has been cycled for a few hundred times. The battery plates begin to swell and press more firmly against the separator. Metallic dendrites, which are the result of crystalline formation (memory), also increase the self-discharge by marring the separator. Discard a nickel-based battery if the self-discharge reaches 30% in 24 hours.

The self-discharge of the lithium-ion battery is 5% in the first 24 hours after charge, and then reduces to 1% to 2% per month thereafter. The safety circuit adds about 3%. High cycle count and aging have little effect on the self-discharge of lithium-based batteries. A lead-acid battery self-discharges at only 5% per month or 50% per year. Repeated deep cycling increases self-discharge.

The percentage of self-discharge can be measured with a battery analyzer but the procedure takes several hours. Elevated internal battery resistance often reflects in higher internal battery resistance, a parameter that can be measured with an impedance meter or the OhmTest program of the Cadex battery analyzers.

Cell matching

Even with modern manufacturing techniques, the cell capacities cannot be accurately predicted, especially with nickel-based cells. As part of manufacturing, 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 mid-range 'B' cells are used for commercial and industrial applications; and the low-end 'C' cells are sold at bargain prices. Cycling will not significantly improve the capacity of the low-end cells. When purchasing rechargeable batteries at a reduced price, the buyer should be prepared to accept lower capacity levels.

The cells in a pack should be matched within +/- 2.5%. Tighter tolerances are required on batteries with high cell count, those delivering high load currents and packs operating at cold temperatures. If only slightly off, the cells in a new pack will adapt to each other after a few charge/discharge cycles. There is a correlation between well-balanced cells and battery longevity.

Why is cell matching so important? A weak cell holds less capacity and is discharged more quickly than the strong one. This imbalance may cause cell reversal on the weak cell if discharged too low. On charge, the weak cell is ready first and goes into heat-generating
overcharge while the stronger cell still accepts charge and remains cool. In both cases, the weak cell is at a disadvantage, making it even weaker and contributing to a more acute cell mismatch.

Quality cells are more consistent in capacity and age more evenly than the lower quality counterparts. Manufacturers of high-end power tools choose high quality cells because of durability under heavy load and temperature extremes. The extra cost pays back on longer lasting packs.

Lithium-based cells are by nature closely matched when they come off the manufacturing line. Tight tolerances are important because all cells in a pack must reach the full-charge and end-of-discharge voltage thresholds at a unified time. A built-in protection circuit safeguards against cells that do not follow a normal voltage pattern.

**Shorted Cells**

Manufacturers are often unable to explain why some cells develop high electrical leakage or an electrical short while still relatively new. The suspected culprit is foreign particles that contaminate the cells during manufacturing. Another possible cause is rough spots on the plates that damage the separator. Better manufacturing processes have reduced the 'infant mortality' rate significantly.

Cell reversal caused by deep discharging also contributes to shorted cells. This may occur if a nickel-based battery is being fully depleted under a heavy load. Nickel-cadmium is designed with some reverse voltage protection. A high reverse current, however, will produce a permanent electrical short. Another contributor is marring of the separator through uncontrolled crystalline formation, also known as memory.

Applying momentary high-current bursts in an attempt to repair shorted cells offers 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.

**Loss of Electrolyte**

Although sealed, the cells may lose some electrolyte during their life, especially if venting occurs due to excessive pressure during careless charging. Once venting has occurred, the spring-loaded vent seal on nickel-based cells may never properly close again, resulting in a build-up of white powder around the seal opening. The loss of electrolyte will eventually lower the battery capacity.

Permeation, or loss of electrolyte in valve regulated lead-acid batteries (VRLA) is a recurring problem. Overcharging and operating at high temperatures are the causes. Replenishing lost liquid by adding water offers limited success. Although some capacity may be regained, the performance becomes unreliable.

If correctly charged, lithium-ion cell should never generate gases and cause venting. But in spite of what is said, the lithium-based cells can build up internal pressure under certain conditions. Some cells include an electrical switch that disconnects the current flow if the cell pressure reaches a critical level. Other cells rupture a membrane to release the gases in a controlled way. Lithium-ion-polymer in a pouch cell sometime grows to the shape of a small balloon because these cells do not include venting. Ballooning cell are known to damage the housing of the portable device.

*Figure 1:* lithium-ion-polymer cell in a pouch pack. Made ultra-slim, some cells generate hydrogen gas during charge and puff up. The force can damage the housing of the portable device.

*Created: April 2003, Last edited: July 2003*
Memory: myth or fact?

The word 'memory' was originally derived from 'cyclic memory'; meaning that a nickel-cadmium battery could remember how much energy was drawn on preceding discharges. On a longer than scheduled discharge, the voltage would rapidly drop and the battery would lose power. Improvements in battery technology have virtually eliminated this phenomenon.

The problem with nickel-cadmium is not so much the cyclic memory but the effects of crystalline formation. The active cadmium material is present in finely divided crystals. In a good cell, these crystals remain small, obtaining maximum surface area. With memory, the crystals grow and conceal the active material from the electrolyte. In advanced stages, the sharp edges of the crystals penetrate the separator, causing high self-discharge or electrical short.

When introduced in the early 1990s, nickel-metal-hydride was promoted as being memory-free. Today, we know that this chemistry is also affected but to a lesser degree than nickel-cadmium. The nickel plate, a metal that is shared by both chemistries, is partly to blame. While nickel-metal-hydride has only the nickel plate to worry about, nickel-cadmium also includes the memory-prone cadmium plate. This is a non-scientific explanation why nickel-cadmium is affected more than nickel-metal-hydride.

The stages of crystalline formation of a nickel-cadmium cell are illustrated in Figure 1. The enlargements show the cadmium plate in a proper functioning crystal structure, crystalline formation after use (or abuse) and restoration.

![New nickel-cadmium cell. The anode is in fresh condition. Hexagonal cadmium hydroxide crystals are about 1 micron in cross section, exposing large surface area to the electrolyte for maximum performance.](image1)

![Cell with crystalline formation. Crystals have grown to 50 to 100 microns in cross section, concealing large portions of the active material from the electrolyte. Jagged edges and sharp corners may pierce the separator, leading to increased self-discharge or electrical short.](image2)

![Restored cell. After pulsed charge, the crystals are reduced to 3 to 5 microns, an almost 100% restoration. Exercise or recondition are needed if the pulse charge alone is not effective.](image3)

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

How to restore and prolong nickel-based batteries

Crystalline formation is 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 all energy before recharge, a periodic discharge to 1 volt per cell (known as exercise) is essential to prevent memory.

Nickel-cadmium 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. No scientific research is available on the optimal exercise...
requirements of nickel-metal-hydride. Based on the reduced crystalline buildup, applying a full discharge once every three months appears right. Because of the shorter cycle life compared to nickel-cadmium, over-exercising is not recommended.

**Exercise and Recondition** - Research has shown that the crystals ingrain themselves if no exercise is applied to nickel-cadmium for three months or more. A full restoration with exercise becomes more difficult the longer service is withheld. In advanced cases ‘recondition’ is required.

Recondition is a slow, secondary discharge applied below the 1 volt/cell threshold. During this process, the current must be kept low to minimize cell reversal. Nickel-cadmium can tolerate a small amount of cell reversal but caution must be applied to stay within the allowable current limit.

Tests performed by the US Army have shown that a nickel-cadmium cell needs to be discharged to at least 0.6V to effectively break up the more resistant crystalline formation. Figure 2 illustrates the battery voltage during a discharge to 1V/cell, followed by the secondary discharge to 0.4V/cell.

![Figure 2: Exercise and recondition features of a Cadex battery analyzer.](image)

Figure 3 illustrates the effects of exercise and recondition. Four nickel-cadmium 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 capacity scale of 0 to 120% in the first column. Additional discharge/charge cycles are applied and the battery capacities are plotted in the subsequent columns. The green line represents ‘exercise’, and the blue line ‘recondition’. The exercise and recondition cycles are applied manually at the discretion of the research technician.

![Figure 3: Effects of exercise and recondition. Four batteries afflicted with memory are serviced. Battery ‘A’ improved capacity on exercise alone; batteries ‘B’ and ‘C’ required recondition. The new battery improved further with recondition.](image)
Battery 'A' responded well to exercise alone and no recondition was required. This battery may have been in service for only a few months or has received periodic exercise cycles. Batteries 'B' and 'C' required recondition to restore performance. Without recondition, these two batteries would have been discarded.

After service, the restored batteries were returned to full use. When examined after six months of field service, no noticeable degradation in the performance was visible. The regained capacity was permanent but periodic service will be needed to maintain the performance.

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

Recondition has its limitations. If no exercise had been applied for 6 to 12 months, permanent damage may have been inflicted. The capacity may not recover or the pack may suffer from high self-discharge caused by a marred separator. Older batteries may get worse with recondition. These packs can be compared to an old man to whom strenuous activity is harmful. Such batteries must be replaced.

Typically 50%-70% of discarded nickel-cadmium batteries can be restored when using the exercise and recondition methods of a Cadex battery analyzer or equivalent. The recovery rate of nickel-metal-hydride is about 40%. This lower yield is, in part, due to the battery's low cycle count.

**Field results on exercise and recondition**

After the Balkan War, the Dutch Army examined how many field batteries could be restored with a battery analyzer (Cadex). The army was aware that the packs were used under less than ideal conditions. They had been sitting in the chargers with only 2-3 hours use per day.

The capacity on some packs had dropped from 100% to 30%. With the analyzer's recondition function, 9 of 10 batteries were restored to 80% and higher. The nickel-cadmium batteries were 2-3 years old.

The importance of exercising and reconditioning is emphasized by another study carried out for the US Navy by GTE Government Systems. To determine the percentage of batteries needing replacement in the first year of use, one group of batteries received charge only (no maintenance), another group was periodically exercised and a third group received recondition. The batteries studied were used for two-way radios on US aircraft carriers.

With charge only (charge-and-use), the annual percentage of battery failure was 45% (Figure 4). With exercise, the failure rate was reduced to 15%. By far the best results were achieved with recondition. The failure rate dropped to 5%.

<table>
<thead>
<tr>
<th>Maintenance method</th>
<th>Annual % of batteries requiring replacement</th>
<th>Annual battery cost (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge-and-use only</td>
<td>45%</td>
<td>$40,500</td>
</tr>
<tr>
<td>Exercise</td>
<td>14%</td>
<td>$13,500</td>
</tr>
<tr>
<td>Recondition</td>
<td>5%</td>
<td>$4,500</td>
</tr>
</tbody>
</table>

The GTE report concluded that a battery analyzer featuring exercise and recondition functions costing $2,500US would return its investment in less than one month on battery savings alone.

**Simple Guidelines**

- Do not leave a nickel-based battery in a charger for more than a few days, even on trickle charge.
- Exercise nickel-cadmium every 1 to 2 months and nickel-metal-hydride every 3 months. Running the battery down in the equipment may do this also.
- Do not discharge the battery before each recharge. This puts undue stress on the battery.
- Avoid getting the battery too hot during charge. The temperature should only rise for a short moment at full charge, then cool off.
How to prolong lithium-based batteries

Battery research is focusing heavily on lithium chemistries, so much so that one could presume that all portable devices will be powered with lithium-ion batteries in the future. In many ways, lithium-ion is superior to nickel and lead-based chemistries and the applications for lithium-ion batteries are growing as a result.

Lithium-ion has not yet fully matured and is being improved continuously. New metal and chemical combinations are being tried every six months to increase energy density and prolong service life. The improvements in longevity after each change will not be known for a few years.

A lithium-ion battery provides 300-500 discharge/charge cycles. The battery prefers a partial rather than a full discharge. Frequent full discharges should be avoided when possible. Instead, charge the battery more often or use a larger battery. There is no concern of memory when applying unscheduled charges.

Although lithium-ion is memory-free in terms of performance deterioration, batteries with fuel gauges exhibit what engineers refer to as “digital memory”. Here is the reason: Short discharges with subsequent recharges do not provide the periodic calibration needed to synchronize the fuel gauge with the battery’s state-of-charge. A deliberate full discharge and recharge every 30 charges corrects this problem. Letting the battery run down to the cut-off point in the equipment will do this. If ignored, the fuel gauge will become increasingly less accurate. (Read more in ‘Choosing the right battery for portable computing’, Part Two.)

Aging of lithium-ion is an issue that is often ignored. Depending on the state-of-charge and storage temperature, lithium-based batteries have a typical lifetime of 2-3 years (longer if partially charged and kept cool). The clock starts ticking as soon as the battery comes off the manufacturing line. The capacity loss manifests itself in increased internal resistance caused by oxidation. Eventually, the cell resistance will reach a point where the pack can no longer deliver the stored energy, although the battery may still contain ample charge. Increasing internal resistance is common to cobalt-based lithium-ion, a chemistry that is found in laptops and cell phones. The lower energy dense manganese-based lithium-ion, also known as spinel, maintains the internal resistance through its life but loses capacity due to chemical decompositions.

The speed by which lithium-ion ages is governed by temperature and state-of-charge. Figure 1 illustrates the capacity loss as a function of these two parameters.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>40% charge level (recommended storage charge level)</th>
<th>100% charge level (typical user charge level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°C</td>
<td>98% after 1 year</td>
<td>94% after 1 year</td>
</tr>
<tr>
<td>25°C</td>
<td>90% after 1 year</td>
<td>83% after 1 year</td>
</tr>
<tr>
<td>40°C</td>
<td>85% after 1 year</td>
<td>65% after 1 year</td>
</tr>
<tr>
<td>80°C</td>
<td>75% after 1 year</td>
<td>60% after 3 months</td>
</tr>
</tbody>
</table>

**Figure 1: Permanent capacity loss of lithium-ion as a function of temperature and charge level.**

High charge levels and elevated temperatures hasten permanent capacity loss. Improvements in chemistry have increased the storage performance of lithium-ion batteries.

There are no remedies to restore lithium-ion once worn out. A momentary improvement in performance is noticeable when heating up the battery. This lowers the internal resistance but the condition reverts back to its former state when the temperature drops.

If possible, store the battery in a cool place at about a 40% state-of-charge. Some reserve charge is needed to keep the battery and its protection circuit operational during prolonged
storage. The most harmful combination is full charge at high temperature. This is the case when placing a cell phone or spare battery in a hot car. Running a laptop computer on the mains has a similar temperature problem. While the battery is kept fully charged, the inside temperature during operation rises to 45°C (113°F).

Removing the battery from the laptop when running on fixed power protects the battery from heat but some battery and laptop manufacturers caution against it. They say that dust and moisture accumulating inside the battery casing could damage the laptop. The dealers will be happy to provide you with a new pack when a replacement is needed a little sooner.

The question is often asked, should the laptop be disconnected from the main when not in use? With lithium-ion it does not matter. Once the battery is fully charged, no further charge is applied. It is recommended, however, to turn the laptop off overnight because heat harms the battery.

A large number of lithium-ion batteries for cell phones are being discarded under the warranty return policy. Some failed batteries are sent to service centers or the manufacturer, where they are refurbished. Studies show that 80%-90% of the returned batteries can be repaired and returned to service.

Some lithium-ion batteries fail due to excessive low discharge. If discharged below 2.5 volts per cell, the internal safety circuit opens and the battery appears dead. A charge with the original charger is no longer possible. Some battery analyzers (Cadex) feature a boost function that reactivates the protection circuit of a failed battery and enables a recharge. However, if the cell voltage has fallen below 1.5V/cell and has remained in that state for a few days, a recharge should be avoided because of safety concerns. To prevent failure, never store the battery fully discharged. Apply some charge before storage, and then charge fully before use.

All personal computers (and some other electronic devices) contain a battery for memory back up. This battery is commonly a small non-rechargeable lithium cell, which provides a small current when the device is turned off. The PC uses the battery to retain certain information when the power is off. These are the BIOS settings, current date and time, as well as resource assignment for Plug and Play systems. Storage does shorten the service life of the backup battery to a few years. Some say 1-2 years. By keeping the computer connected to the main, albeit turned off, a battery on the PC motherboards should be good for 5-7 years. A PC should give the advanced warning when battery gets low. A dead back-up battery will wipe out the volatile memory and erase certain settings. After battery is replaced, the PC should again be operational.

**Simple Guidelines**

- Avoid frequent full discharges because this puts additional strain on the battery. Several partial discharges with frequent recharges are better for lithium-ion than one deep one. Recharging a partially charged lithium-ion does not cause harm because there is no memory. (In this respect, lithium-ion differs from nickel-based batteries.) Short battery life in a laptop is mainly cause by heat rather than charge / discharge patterns.

- Batteries with fuel gauge (laptops) should be calibrated by applying a deliberate full discharge once every 30 charges. Running the pack down in the equipment does this. If ignored, the fuel gauge will become increasingly less accurate and in some cases cut off the device prematurely.

- Keep the lithium-ion battery cool. Avoid a hot car. For prolonged storage, keep the battery at a 40% charge level.

- Consider removing the battery from a laptop when running on fixed power. (Some laptop manufacturers are concerned about dust and moisture accumulating inside the battery casing.)

- Avoid purchasing spare lithium-ion batteries for later use. Observe manufacturing date. Do not buy old stock, even if sold at clearance prices.

- If you have a spare lithium-ion battery, use one to the fullest and keep the other cool by placing it in the refrigerator. Do not freeze the battery. For best results, store the battery at 40% state-of-charge.

**About the Author**
Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of
How to restore and prolong lead-acid batteries

The sealed lead-acid battery is designed with a low over-voltage potential to prohibit the battery from reaching its gas-generating state during charge. This prevents water depletion of the sealed system. Consequently, these batteries will never get fully charged and some sulfation will develop over time.

Finding the ideal charge voltage threshold is critical and any level is a compromise. A voltage limit above 2.40 volts per cell produces good battery performance but shortens the service life due to grid corrosion on the positive plate. The corrosion is permanent. A voltage below the 2.40V/cell threshold strains the battery less but the capacity is low and sulfation sets in over time on the negative plate.

Driven by diverse applications, two sealed lead-acid types have emerged. They are the sealed lead acid (SLA), and the valve regulated lead acid (VRLA). Technically, both batteries are the same. Engineers may argue that the word ‘sealed lead acid’ is a misnomer because no lead acid battery can be totally sealed.

The SLA has a typical capacity range of 0.2Ah to 30Ah and powers personal UPS units, local emergency lighting and wheelchairs. The VRLA battery is used for large stationary applications for power backup. We are looking at methods to restore and prolong these two battery systems separately.

The sealed lead-acid (SLA)

SLA batteries with mild sulfation can be restored but the work is time consuming and the results are mixed. Reasonably good results 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. The process is repeated several times and the capacity is checked with a final full discharge and recharge.

Another method of improving performance is by applying an equalizing charge, in which the charge voltage threshold is increased by about 100mV, typically from 2.40V to 2.50V. This procedure should last no longer than one to two hours and must be carried out at moderate room temperature. A careless equalize charge could cause the cells to heat up and induce venting due to excessive pressure. Observe the battery during the service.

The cylindrical SLA, made by Hawker and sold under the Cyclone name, requires slightly higher voltages to reverse sulfation. An adjustable power supply works best for the service. Set the current limit to the lowest practical setting and observe the battery voltage and temperature during charge. Initially, the cell voltage may rise to 5V, absorbing only a small amount of current. In about two hours, the small charging current converts the large sulfate crystals back into active material. The internal cell resistance decreases and the cell starts to clamp the voltage. At around 2.30V, the cell accepts charge. If the sulfation is advanced, this remedy does not work and the cell needs replacing.

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

Cycling an SLA on a battery analyzer may provide capacity readings that decrease with each additional cycle. A battery may start off at a marginal 88%, then go to 86%, 84% and 83%. This phenomenon can be corrected by increasing the charge voltage threshold from 2.40V to 2.45V and perhaps even 2.50V. Always consider the manufacturer’s recommended settings. Cyclone batteries require slightly higher voltage settings than the plastic version. Avoid setting the charge voltage threshold too high. In an extreme case, the limiting voltage may never be reached, especially when charging at elevated temperatures. The battery continues charging at full current and the pack gets hot. Heat lowers the battery voltage and works against a further voltage raise. If no temperature sensing is available to terminate the charge, a thermal runaway can be the result.
The recovery rate of SLA batteries is a low 15%. Other than reverse sulfation, there is little one can do to improve SLA. Because the SLA has a relatively short cycle life, many fail due to wear-out.

**Valve regulated lead-acid (VRLA)**

The charge voltage setting on VRLA is generally lower than SLA. Heat is a killer of VRLA. Many stationary batteries are kept in shelters with no air conditioning. Every 8°C (15°F) rise in temperature cuts the battery life in half. A VRLA battery, which would last for 10 years at 25°C (77°F), will only be good for 5 years if operated at 33°C (95°F). Once damaged by heat, no remedy exists to improve capacity.

The cell voltages of a VRLA battery must be harmonized as close as possible. Applying an equalizing charge every 6 months brings all cells to similar voltage levels. This is done by increasing the cell voltage to 2.50V/cell for about 2 hours. During the service, the battery must be kept cool and careful observation is needed. Limit cell venting. Most VRLA vent at 0.3 Bar (5 psi). Not only does escaping hydrogen deplete the electrolyte, it is highly flammable.

Water permeation, or loss of electrolyte, is a concern with sealed lead acid batteries. Adding water may help to restore capacity but a long-term fix is uncertain. The battery becomes unreliable and requires high maintenance.

**Simple Guidelines**

- Always store lead acid in a charged condition. Never let the open cell voltage drop much below 2.10V. Apply a topping charge every six months or when recommended.
- Avoid repeated deep discharges. Charge more often or use a larger battery.
- Prevent sulfation and grid corrosion by choosing the correct charge and float voltages.
- Avoid operating lead-acid at elevated ambient temperatures.

*Created: April 2003, Last edited: July 2003*

**About the Author**

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Battery performance as a function of cycling

As part of ongoing research to find the most durable battery system, Cadex has performed life cycle tests on nickel-cadmium, nickel-metal-hydride and lithium-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 cell phone batteries, of which one per chemistry was chosen for the charts below.

**Nickel-cadmium**

In terms of life cycling, standard nickel Cadmium is the most enduring battery. Figure 1 illustrates the capacity, internal resistance and self-discharge of a 7.2V, 900mA nickel-cadmium battery with standard cells. Due to time constraints, the test was terminated after 2300 cycles. The capacity remained steady, the internal resistance stayed flat at 75mW and the self-discharge was stable. This battery receives a grade ‘A’ for almost perfect performance. It should be noted that nickel-cadmium has a moderate energy density, requires periodic full discharges and contains toxic metals.

![Figure 1: Cycle performance of standard nickel-cadmium.](image)

7.2V, 900mAh This battery deserves an ‘A’ for almost perfect performance in terms of stable capacity, internal resistance and self-discharge over many cycles.

The ultra-high capacity nickel-cadmium offers up to 60% higher in energy density compared to the standard version at the expense of reduced cycle life. In Figure 2, we observe a steady drop of 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.

![Figure 2: Cycle performance of ultra-high nickel-cadmium.](image)

6V, 700mAh This battery offers higher energy density than the standard version at the expense of reduced cycle life.

**Nickel-metal-hydride**
Figure 3 examines nickel-metal-hydride. We observe good performance at first but past 300 cycles, the readings start to deteriorate rapidly. One can observe the swift increase in internal resistance and self-discharge after cycle count 700. Nickel-metal hydride has a higher energy density than nickel-cadmium and does not contain toxic metals. Some argue that nickel-metal-hydride is an interim step to lithium-ion.

![Capacity, Self-Discharge and Internal Resistance of a Nickel Metal Hydride Battery](chart)

**Figure 3: Cycle performance of nickel-metal-hydride**

6V, 950mAh. This battery offers good performance at first but past 300 cycles, the capacity, internal resistance and self-discharge start to deteriorate rapidly.

**Lithium-ion**

In Figure 4 we examine the capacity and internal resistance of a lithium-ion battery. A gentle and predictable capacity drop is observed over 1000 cycles and the internal resistance increases only slightly. Because of low readings, self-discharge has been omitted on this test. Lithium-ion offers the highest energy density of the above-mentioned chemistries and contains no toxic metals. Limited discharge current, the need for safety circuits and aging are negative attributes of this battery.

![Capacity and Internal Resistance of a Lithium Ion Battery](chart)

**Figure 4: Cycle performance of lithium-ion.**

3.6V, 500mAh. Lithium-ion offers good capacity and steady internal resistance over 1000 cycles. Self-discharge was omitted because of low readings.

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

Under a full cycle program, as conducted in this test, nickel-based batteries are not affected by crystalline formation (memory). Memory shortens battery life in everyday use if not properly maintained. Applying a full discharge/charge cycle once a month solves this problem. Nickel-cadmium is more prone to memory than nickel-metal-hydride.

Lithium-ion benefited from a controlled life cycle test because the aspect of aging plays a less significant role. The service life of lithium-ion in real life is a combination of cycle count and aging. All batteries are affected by aging in various degrees.

Another reason why life the lab cycling produced very positive readings is the controlled temperature environment in which the tests were carried out. In true life, the batteries meet much harsher treatment and are often exposed to heat. Furthermore, the batteries in our test were charged with a well-defined charge algorithm. Overcharge was minimized and damaging heat buildup prevented. Low-cost consumer chargers do not always service the battery optimally.

The type of load with which the batteries are discharged also plays a role. The above test consisted of an even DC discharge. Digital equipment loads the battery with heavy current bursts. Tests have shown reduced cycle life when a battery is discharged with sharp current pulses as opposed to DC, even though the delivered end-energy is the same. Cell phones, laptop computers, digital cameras are devices that draw such heavy current spikes.

In some other aspects, however, a lab test may be harder on the battery than actual field use. In our test, each cycle applied a full discharge. The nickel-based packs were drained to 1.0 volt and lithium-ion to 3.0 volts per cell. In typical field use, the discharge before re-
charge is normally shallower. A partial discharge puts less strain on the battery, which benefits lithium-ion and to some extent also nickel-metal-hydride. Nickel-cadmium is least affected by delivering full cycles. Manufacturers normally specify the cycle life of lithium-ion at an 80% depth-of-discharge.

**What is the best cycling pattern?**

I often get asked by the readers, "how deep can a battery be discharged and still achieve maximum service life?" There are no definite answers. Batteries are like us humans. Suppose we ate all the vegetables our mother heaped on our plates and do our daily exercise, would we live longer? Perhaps. But by how much, no one will know. Batteries lose capacity as part of aging, cycling and exposure to heat. Nickel-cadmium also loses capacity due to lack of exercise because of memory.

To maximize service life, satellite batteries are kept at a cool temperature and undergo a very shallow discharge of only 10% before recharge. Nickel-based batteries in space also receive a periodic full discharge. This regime allows ten of thousands of cycles. Closer to earth, the ideal charge/discharge patterns cannot be scheduled; neither is the temperature always perfect. As a result, a replacement will be required sooner or later.

If possible, do not discharge lithium-based batteries too deeply. Instead, recharge more often. Allow a nickel-cadmium battery to fully discharge once every 30 cycles or so. This also applies to nickel-metal-hydride but to a lesser extent. Exact data as to how often a nickel-based battery should be discharged is not available. Neither do we know low long a lithium-ion will last under different depth-of-discharge regimes. Manufacturers typically specify lithium-ion at an 80% depth-of-discharge.
Choosing the right battery for wireless communications

Research has brought about a variety of battery chemistries, each offering distinct advantages but none providing a fully satisfactory solution. With today’s variety of battery types, better choices can be made to suit specific user applications. This paper talks about the recommended battery chemistry for cell phones and two-way radios in terms of energy density, durability and price.

What's the best battery for cell phones?

Early cell phones were powered with nickel-based batteries but most newer phones are now equipped with lithium-ion. This chemistry is lightweight, offers high energy density and lasts long enough to span the typical life of the product. Lithium-ion contains no toxic metals. To obtain thin geometry, some cell phone manufacturers switched to lithium-ion-polymer.

This satisfied consumer requests for slim designs. In the meantime, technological advancements also made low profile lithium-ion possible. Lithium-ion packs are now available in 3 mm, a profile that suits most designs. Lithium-ion has the advantage of lower manufacturing cost, better performance and longer cycle life than the polymer version.

Lithium-ion is a low maintenance battery. No periodic discharge is needed and charging can be done at random. A random charge means that the battery does not need to be fully depleted before recharge. In fact, it is better to recharge before the battery gets too low. Full discharges put an unnecessary strain on the battery. A recharge on a partially charged battery does not cause memory because there is none.

Charging lithium-ion is simpler and cleaner than nickel-based batteries but the chargers require tighter tolerances. Lithium-ion cannot absorb overcharge and no trickle charge is applied on full charge. This allows lithium-ion to be kept in the chargers until used. Some chargers apply a topping charge every week or so to replenish the capacity lost through self-discharge while the battery sits idle in the charger. Repeated insertion into the charger or cradle does not damage the battery though overcharge. If the battery is full, no charge is applied. The battery voltage determines the need to charge.

On the negative side, lithium-ion gradually loses charge acceptance as part of aging, even if not used. Lithium-ion batteries should not be stored for long periods but be rotated like perishable food. The buyer should be aware of the manufacturing date when purchasing a replacement battery. Aging affects battery chemistries at different degrees.

Counterfeit cell phone batteries

The number of substandard batteries being sold by street vendors or on the Web is growing. Cell phone manufacturers have issued warnings, saying that these batteries are unsafe. Some lithium-ion packs offered do not include a safety circuit to shut off the power source when reaching full charge and the battery overheats. Enough heat is generated to melt the phone’s plastic casing and destroy the phone's internal circuits.

Cell phone manufacturers advise customers to replace the battery with a recommended brand. Failing to do so may void the warranty. The problem with counterfeit cell phone batteries has become acute since the beginning of 2003, especially in Asia, Africa and Europe.

Most cell phone manufacturers act out of genuine concern for safety, rather than using scare tactics to persuade customers to buy their own accessories. They do not object to batteries and chargers being offered by third party suppliers as long as the products are well built and are functioning properly.

The buyer often cannot distinguish between an original and a counterfeit cell phone battery because the labeling may hint to a bona fide brand. Some packs are labeled to contain lithium-ion but contain lower cost nickel-based cells. Battery analyzers are able to identify most counterfeit batteries.
Caution should also be exercised in purchasing counterfeit chargers. Some units do not terminate the battery correctly or they rely on the battery's internal safety circuit to cut off the power on full charge. Counterfeit batteries, and those with damaged safety circuits, may not terminate the fast-charge. The battery may heat to the point of venting with flame.

**What's the best battery for two-way radios?**

Most two-way radios use nickel-cadmium. These batteries are durable and forgiving if abused. But nickel-cadmium batteries have only moderate energy density and are environmentally unfriendly. Environmental agencies have been discouraging its use, especially in Europe. The recommended alternative is nickel-metal-hydride, a battery that has higher energy density and contains no toxic metals. nickel-metal-hydride has been tested in two-way radios for a number of years but the results are mixed. Shorter than expected service life is the major drawback.

For two-way radios, nickel-metal-hydride has a cycle life, which is half that of standard nickel-cadmium. nickel-metal-hydride 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 and sharp pulse currents shorten battery life.

To compare the longevity of nickel-metal-hydride under different load condition, a test was carried out in which batteries of the same type were discharged with a DC and digital load. In both tests, the batteries were discharged to 1.04 volts per cell. The DC load was a steady 500mA; the digital load simulated the Global System for Mobile Communications (GSM) at 1.65 ampere peak for 12 ms every 100 ms with 270 mA standby. (Note that the GSM pulse for voice is about 550 ms every 4.5 ms).

With the DC discharge, nickel-metal-hydride wore out gradually, providing an above average service life. At 700 cycles, the battery still provided 80% capacity. By contrast, the same battery type faded more rapidly with a digital discharge and the 80% capacity threshold was reached after only 300 cycles. This phenomenon indicates that the kinetic characteristics for nickel-metal-hydride deteriorate more rapidly with a digital than analog load. Although the test was simulating a GSM cell phone, Tetra and other digital two-way radios have similar loading.

Let's briefly compare the characteristics of nickel-cadmium and nickel-metal-hydride. nickel-cadmium has the advantage of maintaining steady high capacity and low internal resistance through most of its service life. nickel-metal-hydride, on the other hand, starts with good capacity and low internal resistance but the resistance increases after a few hundred cycles, causing the voltage to drop on a load. Even though the energy may still be present, the battery cannot deliver the high current during transmit and the message cuts off. The radio becomes unreliable.

Nickel-based batteries are high in maintenance. Periodic discharge cycles are needed to prevent crystalline formation on the cell plates, also known as memory. nickel-cadmium is more receptive to memory than nickel-metal-hydride because both nickel and cadmium plates are affected by memory.

nickel-cadmium should be exercised once every 1 to 2 months, whereas nickel-metal-hydride can get by with a deliberate full discharge once every 3 months. Without proper maintenance, the advantage of nickel-cadmium over nickel-metal-hydride in terms of cycle life cannot be realized.

Lithium-ion has been tested for two-way radios and the results are positive. Substituting lithium-ion with nickel-based will require chargers specifically suited for this chemistry. While nickel-cadmium and nickel-metal-hydride can often share the same charger, lithium-ion uses a different charge algorithm. There is also a cost premium for lithium-ion. Future two-way radios will undoubtedly be fitted with lithium-ion.

**About the Author**

Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world. Cadex Electronics is a manufacturer of advanced battery chargers, battery analyzers and PC software. For product information please visit www.cadex.com.
Choosing the right battery for portable computing

Laptops are known to be tough hosts on their batteries. The host demands a stream of uninterrupted power but offers a poor working environment in return. As a result, the battery cannot provide the promised runtime and the service cuts short, often with little notice. In this paper we address the unhappy marriage between the host and battery, and examine what causes a battery to deteriorate faster than in other portable devices.

What's the best battery for laptops?

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

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 for 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.

The energy density of modern batteries improves by about 10% per year. However, the benefit of better battery performance is eaten up by higher power requirements of laptops. This results in the same runtime but more powerful laptops.

During the last few years, batteries have improved in terms of energy density. But any benefit in better battery performance is being eaten up by the higher power requirements of the laptops. This trend is continuing and the net effect will be the same runtimes but more powerful laptops.

Most laptops are powered by lithium-ion. This chemistry has a high energy density and is lightweight. There is no immediate breakthrough on the horizon of a miracle battery that would provide more power than the current electro-chemical battery.

Fuel cells, when available, will offer a continued stream of power by allowing the exchange of fuel cartridges when empty. Unfortunately, commercial fuel cells for laptops and other portable devices are still several years away. Power handling, size and cost remain the biggest hurdles. The early fuel cells will function more like a portable charger than a battery replacement. The fuel cells currently in use have the difficulty in providing spontaneous high power on demand.

The runtime of a laptop battery is based on the activity of the computer. The basic housekeeping, which the computer needs to stay alive, draws less power than, for example, reading, writing, computations and searching for files. Manufacturers prefer using idle time when specifying runtime.

A battery in a laptop ages more quickly than in other applications because of heat. During use, the inside temperature of a laptop rises to 45°C (113°F). The combination of high temperature and full state-of-charge promotes cell oxidation, a condition that cannot be reversed once present. The battery's life expectancy when operating at high temperature is half compared to running at a more moderate 20°C (68°F) or lower. Leaving the laptop in a parked car under the hot sun will also aggravate the situation. All batteries suffer permanent capacity loss as part of elevated temperatures but lithium-ion is affected more than other batteries.
Some Japanese computer manufacturers have introduced a number of sub-notebooks in which the battery is mounted externally, forming part of the housing. This design improves battery life because the battery is kept at room temperature. Some models carry several size batteries to accommodate different user demands.

Lithium-ion is well suited for laptop users who continually switch from fixed power to battery use. This user pattern is typical for those in the sales, service and medical field. Here is the reason why:

With nickel-based batteries, the charger applies a full charge each time the portable device is connected to fixed power. The battery is put on charge until a signal is received indicating that the battery is full. This signal is in form of a voltage change or rising temperature. Because of the sluggish response, permanent capacity loss occurs caused by overcharge and elevated temperature. Lithium-ion only receives charge if the voltage is low.

**How to calibrate the battery**

Most laptop batteries are ‘smart’; meaning that they know how much energy is left. Such a feature has definite benefits but the readings are often inaccurate. A laptop may indicate 30 minutes of remaining runtime when suddenly the screen goes dark. Here is the reason why:

With use and time, a tracking error occurs between the chemical battery and the digital sensing circuit. The most ideal use of the ‘smart’ battery, as far as fuel-gauge accuracy is concerned, is a full charge followed by a full discharge at a constant current. In such a case, the tracking error would be less than 1% per cycle. In real life, however, a battery may be discharged for only a few minutes and the load may vary widely. Long storage also contributes to errors because the circuit cannot accurately compensate for self-discharge. Eventually, the true capacity of the battery no longer synchronizes with the fuel gauge and a deliberate full charge and discharge is needed to ‘re-learn’ or calibrate the battery.

What happens if no battery calibration is done? Can such a battery be used in confidence? Most ‘smart’ battery chargers obey the dictates of the chemical cells rather than the electronic circuit. In this case, the battery will fully charge regardless of the fuel gauge setting and function normally, but the digital readout will become increasingly more inaccurate. If not corrected, the fuel gauge simply becomes a nuisance.

At what point of a discharge does the reset occur? Lithium-ion is considered fully discharged between 2.5 and 3.0 volts per cell. The electronic circuit in the battery is designed to reset between these voltage levels. A problem occurs if the laptop cuts off before this low voltage can be reached. In such a case, an external charger with discharge function may be used. Cadex Electronics manufactures ‘smart’ chargers and battery analyzers, both of which can be used to test and calibrate the ‘smart’ battery.
Choosing the right battery for industrial applications

Industrial applications have unique power needs and the choice of battery is important. While consumer products demand high energy density to obtain slim and elegant designs, industry focuses on durability and reliability. Industrial batteries are commonly bulkier than those used in consumer products but achieve a longer service life.

Batteries are electro-chemical devices that 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 attribute reflects in good load characteristics.

Discharge loads range from a low and steady current flow of a flashlight to intermittent high current bursts in a power tool, to sharp current pulses on digital communications equipment, laptops and cameras. In this paper we evaluate how the various battery chemistries perform in a given application.

What’s the best battery for video cameras?

Nickel-cadmium batteries continue to power a large percentage of professional cameras. This battery provided reliable service and performs well at low temperature. nickel-cadmium is one of the most enduring batteries in terms of service life but has only moderate energy density and needs a periodic full discharge.

The need for longer runtimes is causing a switch to nickel-metal-hydride. This battery offers up to 50% more energy than nickel-cadmium. However, the high current spikes drawn by digital cameras have a negative affect and the nickel-metal-hydride battery suffers from short service life.

There is a trend towards lithium-ion. Among rechargeables, this chemistry has the highest energy density and is lightweight. A steep price tag and the inability to provide high currents are negatives.

The 18650 cylindrical lithium-ion cell offers the most economical power source. "18" defines the cell's diameter in millimeters and "650" the length. No other lithium-ion cell, including prismatic or polymer types, offers a similar low cost-per-watt ratio.

Over the years, several cell versions of 18650 cells with different Ah ratings have emerged, ranging from 1.8Ah to well above 2Ah. The cells with moderate capacities offer better temperature performance, enable higher currents and provide a longer service life than the souped up versions.

The typical 18650 for industrial use is rated at 2Ah at 3.60 volts. Four cells are connected in series to obtain the roughly 15 volts needed for the cameras. Paralleling the cells increases the current handling by about 2A per cell. Three cells in parallel would provide about 6A of continuous power. Four cells in series and three in parallel is a practical limit for the 18650 system.

Lithium-ion requires a protection circuit to provide safe operations under all circumstances. Each cell in series is protected against voltage peaks and dips. In addition, the protection circuit limits each cell to a current about 2A. Even if paralleled, the current of a lithium-ion pack is not high enough to drive digital cameras requiring 10 to 15A peak current. Tests conducted at Cadex Electronics have shown that the 18650 allows short current peaks above the 2A/cell limit. This would allow the use of lithium-ion on digital cameras, provided the current bursts are limited to only a few seconds.

What’s the best battery for still cameras?

The power requirement of a professional digital camera is sporadic in nature. Much battery power is needed to take snapshots, some with a powerful flash. To view the photo, the backlit color display draws additional power. Transmitting a high-resolution image over the air depletes another portion of the energy reserve.

Most non-professional cameras use a primary lithium battery. This battery type provides the highest energy density but cannot be recharged. This is a major drawback for professional use. Rechargeable batteries are the answer and lithium-ion fits the bill but faces similar challenges to the video cameras.

What is the best battery for medical devices?
One of the most energy-hungry portable medical devices is the heart defibrillator. The battery draws in excess of 10 amperes during preparation stages. Several shocks may be needed to get the patient's heart going again. The battery must not hamper the best possible patient care.

Most defibrillators are powered by nickel-cadmium. nickel-metal-hydride is also being used but there is concern of short service life. In a recent study, however, it was observed that a defibrillator battery cycles far less than expected. Instead of the anticipated 200?cycles after two years of seemingly heavy use, less than 60 cycles had been delivered on the battery examined. 'Smart' battery technology makes such information possible. With fewer cycles needed, the switch to higher energy-dense batteries becomes a practical alternative.

Sealed lead-acid batteries are often used to power defibrillators intended for standby mode. Although bulky and heavy, the Lead-acid has a low self-discharge and can be kept in prolonged ready mode without the need to recharge. Lead-acid performs well on high current spurts. During the rest periods the battery disperses the depleted acid concentrations back into the electrode plate. Lead-acid would not be suitable for a sustained high load.

The medical industry is moving towards lithium-ion. The robust and economical 18650 cells make this possible. The short but high current spurts needed for defibrillators are still a challenge. Parallelizing the cells and adding current-limiting circuits that allow short spikes of high current will help overcome this hurdle.

**What is the best battery for power tools?**

Power tools require up to 50 amperes of current and operate in an unfriendly environment. The tool must perform at sub zero temperatures and endure in high heat. The batteries must also withstand shock and vibration.

Most power tools are equipped with nickel-cadmium batteries. nickel-metal-hydride has been tried with limited success. Longevity is a problem but new designs have improved. lithium-ion is too delicate and could not provide the high amperage. Lead-acid is too bulky and lacks persistent power delivery. The power tool has simply no suitable alternatives to the rugged and hard-working nickel-cadmium.

In an attempt to pack more energy into power tools, the battery voltage is increased. Because of heavy current and application at low temperatures, cell matching is important. Cell matching becomes more critical as the number of cell connected in series increases. A weak cell holds less capacity and is discharged more quickly than the strong ones. This imbalance causes cell reversal on the weak cell if the battery is discharged at high current below 1V/cell. An electrical short occurs in the weak cell if exposed to reverse current and the pack needs to be replaced. The higher the battery voltage, the more likely will a weak cell get damaged.

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About the Author

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*Learning the basics about batteries - sponsored by Cadex Electronics Inc.*
What's the best battery for wheeled and stationary applications?

Consumer products have benefited the most from the advancements in battery technology. The size and weight reductions achieved for the high-end cell phones, PDA's and laptops have not trickled down to batteries for wheeled and stationary applications in an expected fashion. Only marginal improvements have been gained on larger batteries. One of the reasons for the apparent lack in progress is the loyalty to the classic sealed lead-acid battery.

The wheeled and stationary industries have several reasons for their unwillingness to change: [1] lead-acid is mature and inexpensive. [2] The low energy density is no major drawback because the battery is either on wheels or is stationary. [3] The limited cycle life can, to some extent, be compensated by using larger batteries. Unlike portable devices, most wheeled and stationary batteries are replaced due to age rather than wear out effect induced by high cycle count.

What's the best battery for wheelchairs?

Wheelchairs and scooters are almost exclusively powered by sealed lead-acid batteries. Regular car batteries are sometimes used for cost reasons. There is, however, a danger of spillage if overturned. Neither are regular car batteries designed for deep cycling. The demanding cycling regimens of wheelchairs and scooters cause an undue strain on these batteries and shorten their lives. nickel-based batteries would be lighter than lead-acid but are more expensive and maintenance prone. Lithium-ion would simply be too delicate, not to mention the high cost.

A new generation of wheelchair is being developed that is able to 'stand up' and climb chairs. These high-tech devices use gyroscopes for balancing. To obtain the extra power needed to run its internal computer and electric motors without adding too much weight, nickel-based batteries are used. The two-wheeled Segway scooter being touted to solve city transportations problems also uses nickel-based batteries.

What's the best battery for the electric bicycle?

Anyone serious about the electric bicycle would use nickel-based batteries. Sealed lead-acid is simply too heavy and does not provide the cycle count needed to satisfy daily use. In addition, lead-acid requires a long charge time of 10 hours and more. Lithium-ion would simply be too expensive and delicate. The lack of a suitable battery that is light, durable and inexpensive is, in my opinion, delaying the public acceptance of the electric bicycle.

What's the best battery for the electric vehicle?

The electric vehicle will gain public acceptance as soon as a battery emerges that is inexpensive and provides 10 years of reliable service. The high cost and limited cycle life of the batteries used in hybrid vehicles negate the savings achieved in burning less fuel. The benefits are more environmental in nature rather than in cost savings. Higher fuel prices could change this equilibrium.

nickel and lithium-based batteries have been tried but both chemistries have problems with durability and stability. lithium-ion has an advantage in weight but this gain is offset by a high price. Similarly, nickel-metal-hydride used for the hybrid vehicle is expensive and requires forced air-cooling. No battery manufacturer is willing to commit to a 10-year warranty. After excursions into new battery chemistries, design engineers always come back to the old but proven lead-acid.

The fuel cell may still be two decades away before offering a viable alternative for cars. An executive from Ford stated recently that the fuel cell may never be feasible to replace the internal combustion engine. Cost and longevity remain major drawbacks.

Since the invention in 1839 by Sir William Grove, the advancements in the fuel cell have been slow. Much attention was then placed on improving the internal combustion engine. It was not until the Gemini and Apollo programs in the 1960s that the fuel cell was used to
provide power and water in space. During the 1990s, renewed activities took place and the fuel cell stocks soared. Unlike the rapid developments in microelectronics, which generated income in its early stages, fuel cell research continues to depend on government grants and public investors. It is our hope that one day the fuel cell will become a viable option to the polluting combustion engine.

What's the best battery for stationary applications?

Until the mid 1970s, most stationary batteries were flooded lead-acid. The Valve Regulated Lead Acid (VRLA) allowed batteries to be installed in smaller confinements because the cells could be stacked and mounted in any position. Although VRLA are less durable than flooded lead-acid, simple mounting and lower cost make them the preferred battery system for small and medium sized installations. Most UPS systems repeater stations for cell phones use VRLA. Large installations, such as internet hubs, hospitals, banks and airports still use the flooded lead-acid.

Heat is the main killer of batteries. Many outdoor installations for communication systems lack proper venting, not to mention air conditioning. Instead of the expected 10-year service life, the batteries need replacement after 2 to 5 years. Many batteries in the field are in such bad conditions that they could only provide power for a short time, should a major power outage occur. Stationary batteries are often installed and forgotten.

A Canadian manufacturer of lithium-polymer batteries is taking advantage of the heat problem. They offer lithium-polymer for standby applications, a battery that needs heat to operate. The dry lithium-polymer lacks conductivity at ambient temperature and must be heated. The battery includes heating elements to keep its core temperature at 60°C (140°F). The mains provide the energy for heating. On a power outage, the battery must also provide power for heating the core. To conserve energy, the battery is well insulated. Unlike the VRLA, the high ambient heat does not shorten the lithium-polymer battery. The high cost remains a drawback and only a few lithium-polymer batteries are used for stationary applications today.

Flooded nickel-cadmium batteries have been used for many years in applications that must endure hot and cold temperatures. This battery system is substantially more expensive than Lead-acid but the improved longevity makes up for the higher investment cost. The flooded nickel-cadmium batteries are non-sintered and do not suffer from memory. It should be noted that only the sintered sealed nickel-cadmium cells are affected by memory and need regular discharges.

About the Author

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<<PREVIOUS LESSON NEXT LESSON>>
Rapid-testing of batteries

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

In spite of these seemingly insurmountable odds, battery rapid testing is possible. But the questions are asked, how accurate will the test results be and how will the system adapt to different battery types. Instrument cost and ease-of-use are also concerns. This paper evaluates currently used methods, which include the load test, AC conductance test and the six-point test developed by Cadex.

The load test

The load test provides important battery information consisting of open battery voltage, voltage under load and internal resistance. nickel-based batteries should always indicate an open terminal voltage of about 1.1V/cell, even if empty. The electro-chemical reaction of the different metals in the cell generates this voltage potential. A depressed voltage may indicate high self-discharge or a partial electrical short.

A lead-based battery must always have a charge and the open terminal voltage should read 2.0V/cell and higher. If below 2 volts, a sulfation layer builds up that makes a recharge difficult, if impossible. An open terminal voltage of 2.10V/cell indicates that the battery is roughly 50% charged.

The voltage of a lithium-based battery can, to some extent, indicate SoC. A fully charged cell reads about 4.0V/cell and a partially charged cell measures between 3.0 and 4.0V/cell. The load test applies a momentary load, during which the voltage is measured. Voltage over current equals the resistance. More accurate results are obtained by applying a two-stage load. Figure 1 illustrates the voltage pattern of such a two-stage load test.

![Figure 1: DC load test.](image)

The AC conductance test

An alternative method of measuring the internal battery resistance is the AC conductance test. An alternating current of 50 to 1000 Hertz is applied to the battery terminals. The battery’s reactance causes a phase shift between voltage and current, which reveals the condition of the battery. AC conductance works best on single cells. Figure 2 demonstrates the relation of voltage and current on a battery.
Some AC resistance meters evaluate only the load factor and disregard the phase shift information. This technique behaves similar to the pulse method in that the AC voltage is superimposed on the battery's DC voltage and acts as brief charge and discharge pulses. The amplitude of the ripple is utilized to calculate the internal battery resistance.

There are some discrepancies in the resistance readings between the 'load test' and 'AC conductance test'. The differences are more apparent on marginal than on good batteries. So which reading is correct? In many aspects, the AC conductance is superior to the load test, however, one single frequency cannot provide enough data to evaluate the battery adequately. Multi-frequency devices are being developed but their complexity rises exponentially with the number of frequencies used.

Resistance measurement, as a whole, provides only a rough sketch of the battery’s performance because various battery conditions affect the readings. For example, a battery that has just been charged shows a higher resistance reading than one that has rested for a few hours. An empty or nearly empty battery also exhibits elevated internal resistance. To obtain reliable readings, a battery must be at least 50% charged.

Temperature further affects the internal resistance readings. A hot battery reads a lower resistance than one at ambient temperature or one that is cold. In addition, the chemistry, the number of cells connected in series and the current rating (size in mAh) of a battery influence the results. Many batteries also contain a protection circuit that further distorts the readings.

The Cadex QuickTest™
Cadex Electronics has developed a method to measure the state-of-health (SoH) of a battery in 3 minutes. QuickTest™ uses a patent-pending inference algorithm to fuse data from 6 variables, which are: capacity, internal resistance, self-discharge, charge acceptance, discharge capabilities and mobility of electrolyte. The data is combined with a trend-learning algorithm to provide an accurate SoH reading in percent. Figure 3 illustrates general structure of such a network.

**Figure 2: AC load test.** The AC method measures the phase shift between voltage and current. The battery's reactance and/or voltage deflections are used to calculate the impedance.
QuickTest™ is built into the Cadex C7000-Series battery analyzers and services nickel, lithium and lead-based batteries for two-way radios, cell phones, laptops, scanners and medical devices. The analyzers are user-programmable and also perform battery priming, reconditioning, fast-charging, life-testing and boosting functions.

QuickTest™ uses battery specific matrices that are obtained with the analyzer's trend learning process. The ability to learn allows adapting to new batteries in the field. The matrices are stored in the battery adapters and automatically configure the analyzer to the correct battery setting. The adapters commonly include the matrix at time of purchase. If missing, the matrix can be added in the field by scanning two or more batteries on the analyzer's Learn program. The required charge level to perform QuickTest™ is 20-90%. If outside this range, the analyzer automatically applies a brief charge or discharge.

What is the definition of state-of-health and when should a battery be replaced? SoH reveals the overall battery conditions based on the above mentioned variables, which are capacity, internal resistance, self-discharge, charge acceptance, discharge capabilities and mobility of electrolyte. If any of these variables provide marginal readings, the end result will be affected. A battery may have a good capacity but the internal resistance is high. In this case, the end SoH reading will be lowered accordingly. Similar demerit points are added if the battery has high self-discharge or exhibits other chemical deficiencies. The battery should be replaced if the SoH falls below 80%.

Created: May 2003

About the Author
Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world. Cadex Electronics is a manufacturer of advanced battery chargers, battery analyzers and PC software. For product information please visit www.cadex.com.

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Rapid testing automotive and stationary batteries

Portable batteries for cell phones, laptops and cameras may be rapid-tested by applying a number of load pulses while observing the relationship between voltage and current. Ohm’s Law is used to calculate the internal resistance. Comparing the readings against a table of values estimates the battery’s state-of-health.

This load pulse method does not work well for larger batteries and AC conductance is commonly used. An AC voltage is applied to the battery terminals that floats as a ripple on top of the battery’s DC voltage and charges and discharges the battery alternatively.

AC conductance has been incorporated into a number of hand-held testers to check batteries for vehicular and stationary batteries. To offer simple and low-cost units, these testers load the battery with pulses rather than injecting sinusoidal signals. The pulses are commonly not voltage controlled and the thermal battery voltage* may be surpassed. The thermal voltage threshold of a lead-acid battery is 25mV per cell. Exceeding this voltage is similar to over-driving an audio amplifier. Amplified noise and distortion is the result.

AC conductance provides accurate readings, provided the battery is fully charged, has rested or has been briefly discharged prior to taking the reading. AC conductance tends to become unreliable on low charge and sometimes fails a good battery. At other times, a faulty battery may pass as good. The correlation to the battery’s state-of-charge is a common complaint by users. AC conductance works best in identifying batteries with definite deficiencies.

AC conductance is non-invasive, quick and the test instruments are relatively inexpensive. There are, however, some fundamental problems. Most commercial testers use only one frequency, which is commonly below 100 Hertz. Multi-frequency systems would be more accurate but require complex data interpretation software and expensive hardware. In this paper we focus on Electrochemical Impedance Spectroscopy (EIS), a method that overcomes some of the shortcomings of AC conductance.

* Batteries are non-linear systems. The equations, which govern the battery’s response becomes linear below 25mV/cell at 25°C. This voltage is called the battery thermal voltage.

Electrochemical Impedance Spectroscopy (EIS)

EIS evaluates the electrochemical characteristics of a battery by applying an AC potential at varying frequencies and measuring the current response of the electrochemical cell. The frequency may vary from about 100 micro Hertz (µHz) to 100 kilo Hertz (kHz). 100µHz is a very low frequency that takes more than two hours to complete one full cycle. In comparison, 100kHz completes 100,000 cycles in one second.

Applying various frequencies can be envisioned as going through different layers of the battery and examining its characteristics at all levels. Similar to tuning the dial on a broadcast radio, in which individual stations offer various types of music, so also does the battery provide different information at varying frequencies.

Battery resistance consists of three types, which are: pure resistance, inductance and capacitance. Figure 1 illustrates the classic Randles model, which represents a typical battery.

Figure 1: Randles model of a lead acid battery. The overall battery resistance consists of pure Ohmic resistance, inductance and capacitance. There are many other models.

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.
On a magnetic coil, on the other hand, the current lags behind the voltage. When applying a sine wave to a battery, the reactive resistance produces a phase shift between voltage and current. This information is used to evaluate the battery.

EIS has been used for a number of years to perform in-flight analysis of satellite batteries, as well as estimating grid corrosion and water loss on aviation and stationary batteries. EIS gives the ability to observe the kinetic reaction of the electrodes and allows analyzing changes of analyze changes that occur in everyday battery usage. Increases in impedance readings hint at minute intrusion of corrosion and other deficiencies. Impedance studies using the EIS methods have been carried out on lead-acid, nickel-cadmium, nickel-metal-hydride and lithium-ion batteries. Best results are obtained on a single cell.

One of the difficulties of EIS is data interpretation. It is easy to amass a large amount of data; making practical use of it is more difficult. Analyzing the information is further complicated by the fact that the readings are not universal and do not apply equally to all battery makes and types. Rather, each battery type generates its own set of signatures. Without well-defined reference readings and software to interpret the results, gathering information has little meaning for the ordinary person.

Modern technology can help by storing characteristic settings of a given battery type in the test instrument. Advanced digital signal processors are able to carry out millions of instructions per second. Software translates the data into a single reading. EIS has the potential of becoming a viable alternative to AC conductance in checking automotive, traction and stationary batteries. Noteworthy advancements are being made in this field.

**Commercializing Electrochemical Impedance Spectroscopy**

Cadex is developing a battery rapid test method incorporating EIS based techniques. Trademarked Spectro™, the system injects sinusoidal signals at multiple frequencies. The signals are voltage controlled and remain below the thermal battery voltage.

Spectro™ is being tested on randomly sampled automotive batteries of various states-of-health conditions. Automotive batteries serve the purpose well because of easy availability. To demonstrate the accuracy, we tested six typical automotive batteries (A, B, C, D, E, and F) with various state-of-health conditions. The batteries are flooded lead acid of the same model.

Prior to testing, the batteries were fully charged and the actual Cold Cranking Ampere (CCA) reading was established using standards developed under SAE J537. The batteries were then re-tested using the AC conductance and Spectro™ methods. The Spectro™ approximations were conducted using model-specific matrices.

![Figure 2: Comparison readings of CCA and Spectro™ using battery-specific matrices.](image)

*The blue markers compare readings with AC conductance. Spectro™ follows the CCA measurements very closely.*

Batteries arrive for testing in all conditions, including low state-of-charge (SoC). With AC conductance, the charge level affects the CCA readings to such a degree that the test results may become meaningless. To demonstrate SoC immunity of Spectro™, Spectro was used to estimate CCA at different charge levels. The results are shown in Figure 3.
Figure 3: CCA rapid-tests at various SoC.
Spectro™ provides robust readings from 40-100% SoC. The AC conductance readings are strongly affected by the charge level.

Ideally, the line should be perfectly horizontal. Spectro™ departs only moderately within the 40-100% SoC range. In comparison, the CCA approximations using AC conductance show a strong departure from the horizontal line, caused by the charge level.

Although early test results conducted with the Spectro™ based technology demonstrate strong advantages over existing test methods, the electrical requirements and complexities are demanding. Injecting multi-frequency sinusoidal signals at controlled levels and processing reams of data will add cost.

Cadex plans to release the first commercial Spectro™ units in a hand-held tester for automotive batteries towards the end of 2003. Testers for stationary batteries are scheduled for 2004. Research is continuing to include a broad range of battery sizes and chemistries, and to reduce the test time from two minutes to about 20 seconds per battery test. Patents for Spectro™ have been applied for.

Created: March 2003, Last edited: July 2003

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Why do different test methods provide dissimilar readings?

During the last 20 years, three basic battery rapid test methods have emerged: DC load, AC conductance and multi-frequency electro-chemical impedance spectroscopy (EIS). All methods are resistance based, a characteristic that reveals the battery's ability to deliver load current. Internal resistance provides useful information in detecting problems and indicating when a battery should be replaced. However, the battery often drops below the critical 80% level set by IEEE before the condition can effectively be detected. Neither does resistance alone provide a linear correlation to the battery's capacity. Rather, the increase of cell resistance relates to aging.

When measuring the internal resistance of brand new VRLA cells from the same batch, variations of 8% between cells are common. Manufacturing process and materials used contribute to the discrepancies. Rather than relying on an absolute resistance reading, service technicians are asked to take a snapshot of the cell resistances when the battery is installed and then measure the subtle changes as the cells age. A 25% increase in resistance over the baseline indicates a performance drop from 100% to about 80%. Battery manufacturers honor warranty replacements if the internal resistance increases by 50%. Before analyzing the different test methods, let's briefly brush upon internal resistance and impedance, terms that are often used incorrectly when addressing the conductivity of a battery.

Resistance is purely resistive and has no reactance. There is no trailing phase shift because the voltage and current are in unison. A heating element is such a pure resistive load. It works equally well with direct current (DC) and alternating current (AC). Most electrical loads, including the battery, contain a component of reactance. The reactive part of the load varies with frequency. For example, the capacitive reactance of a capacitor decreases with rising frequency. A capacitor is an insulator to DC and no current can pass through. The inductor, on the other hand, acts in the opposite way and its reactance increases with rising frequency. DC presents an electrical short. A battery combines ohmic resistance, as well as capacitive and inductive reactance. The term impedance represents all three types.

The battery may be viewed as a set of electrical elements. Figure 1 illustrates Randles' basic lead-acid battery model in terms of resistors and a capacitor (R1, R2 and C). The inductive reactance is commonly omitted because it plays a negligible role in a battery at low frequency.

Battery rapid test methods and how they work

Let's now look at the different battery test methods and evaluate their strengths and limitations. It is important to know that each method provides a different internal resistance reading when measured on the same battery. Neither reading is right or wrong. For example, a cell may read higher resistance readings with the DC load method than with a 1000-hertz AC signal. This simply implies that the battery performs better on an AC than DC load. Manufacturers accept all variations as long as the readings are taken with the same type of instrument.
**DC load method:** The pure ohmic measurement is one of the oldest and most reliable test methods. The instrument applies a load lasting a few seconds. The load current ranges from 25-70 amperes, depending on battery size. The drop in voltage divided by the current provides the resistance value. The readings are very accurate and repeatable. Manufacturers claim resistance readings in the 10 micro-ohm range. During the test, the unit heats up and some cooling will be needed between measurements on continuous use.

The DC load blends R1 and R2 of the Randles model into one combined resistor and ignores the capacitor. C is a very important component of a battery and represents 1.5 farads per 100 Ah cell capacity.

**AC conductance method:** Instead of a DC load, the instrument injects an AC signal into the battery. A frequency of between 80-100 hertz is chosen to minimize the reactance. At this frequency, the inductive and capacitive reactance converges, resulting in a minimal voltage lag. Manufacturers of AC conductance equipment claim battery resistance readings to the 50 micro-ohm range. AC conductance gained momentum in 1992; the instruments are small and do not heat up during use.

The single frequency technology sees the components of the Randles model as one complex impedance, called the modulus of Z. The majority of the contribution is coming from the conductance of the first resistor.

**Multi-frequency electro-chemical impedance spectroscopy (EIS):** Cadex Electronics has developed a rapid-test method based on EIS. Called Spectro™, the instrument injects 24 excitation frequencies ranging from 20-2000 Hertz. The sinusoidal signals are regulated at 10mV/cell to remain within the thermal battery voltage of lead acid. This allows consistent readings for small and large batteries.

With multi-frequency impedance Spectroscopy, all three resistance values of the Randles model can be established. A patented process evaluates the fine nuances between each frequency to enable an in-depth battery analysis.

Spectro™ is the most complex of the three methods. The 20-second test processes 40 million transactions. The instrument is capable of reading to a very low micro-ohms level. With stored matrices as reference, Spectro™ is capable of providing battery capacity in Ah, conductivity (CCA) and state-of-charge.

The EIS concept is not new. In the past, EIS systems were hooked up to dedicated computers and diverse laboratory equipment. Trained electrochemists were required to interpret the data. Advancements in data analysis automated this process and high-speed signal processors shrunk the technology into a handheld device.

**Capacity measurements**

DC load and AC conductance have one major limitation in that these methods cannot measure capacity. With the growing demand of auxiliary power on cars and trucks and the need to assess performance of stationary batteries non-invasively, testers are needed that can estimate battery capacity. Cadex has succeeded in doing this with car batteries. The company is working on applying this technology to stationary batteries.

Figure 5 reveals the reserve capacity (RC) readings of 24 car batteries, arranged from low to high on the horizontal axis. The batteries were first tested according to the SAE J537.
standard, which includes a full charge, a rest period and a 25A discharge to 1.75V/cell during which the reserve capacity was measured (black diamonds). The tests were then repeated with Spectro™ (purple squares) using battery-specific matrices. The derived results approach laboratory standards, as the chart reveals.

![Figure 5: Reserve capacity of 24 batteries with a model-specific matrix.](image)

The black diamonds show capacity readings derived by a 25A discharge; the purple squares represent the Spectro™ readings.

Some people claim a close relationship between battery conductivity (ohmic values) and capacity. Others say that internal ohmic readings are of little practical use and have no relation to capacity. To demonstrate the relationship between resistance and capacity, Cadex Electronics has carried out an extensive test involving 175 automotive batteries in which the cold cranking amps (CCA) were compared with the RC readings. CCA represents the conductivity of the battery and is closely related with the internal resistance. Figure 6 shows the test results. The CCA readings are plotted on the vertical Y-axis and the RC on the horizontal X-axis. For ease of reading, the batteries are plotted as a percentage of their nominal value and are arranged from low-to-high on the X-axis.

![Figure 6: CCA as a function of reserve capacity (RC).](image)

Internal resistance (represented by CCA) and capacity do not follow the red line closely and fail to provide accurate capacity readings.

Note: The CCA and RC readings were obtained according to SAE J537 standards. CCA is defined as a discharge of a fully charged battery at -18°C at the CCA-rated current. If the voltage remains at or above 7.2V after 30 seconds, the battery passes. The RC is based on a full charge, rest period and a discharge at 25A to 1.75V/cell. If the internal resistance (CCA) were linear with capacity, then the blue diamonds would be in close proximity of the red reference line. In reality, CCA and RC wander off left and right. For example, the 90% CCA battery produces an RC of only 38%, whereas the 71% CCA delivers a whopping 112% capacity (green dotted line).

An important need is fulfilled

Cadex has packaged the EIS technology into an elegant hand-held tester that is currently being beta-tested in the USA, Canada, Europe and Japan. (Please visit [http://www.cadex.com/prod_testers_ca12.asp](http://www.cadex.com/prod_testers_ca12.asp))
Being able to obtain battery capacity makes the EIS technology one of the most sought-after test systems for automotive, marine, aviation, defense, wheeled mobility, traction and UPS batteries. Capacity fading due to aging and other deficiencies can be tracked and a timely replacement scheduled.

Created: July 2004, Last edited: October 2004

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What causes car batteries to fail?

Driving habits rather than battery defect may be the cause.
A German manufacturer of luxury cars reveals that of 400 car batteries returned under warranty, 200 are working well and have no problem. Low charge and acid stratification are the most common causes of the apparent failure. The car manufacturer says that the problem is more common on large luxury cars offering power-hungry auxiliary options than on the more basic models.

In Japan, battery failure is the largest complaint among new car owners. The average car is only driven 13 km (8 miles) per day and mostly in a congested city. As a result, the batteries will never get fully charged and sulfation occurs. The batteries in Japanese cars are small and only provide enough power to crank the engine and perform some rudimentary functions. North America may be shielded from these battery problems, in part because of long distance driving.

Good battery performance is important because problems during the warranty period tarnish customer satisfaction. Any service requirement during that time is recorded and the number is published in trade magazines. This data is of great interest among prospective car buyers throughout the world.

Battery malfunction is seldom caused by a factory defect; driving habits are the more common culprits. The heavy auxiliary power drawn during a short distance driven never allows the periodic fully saturated charge that is so important for the longevity of a lead acid battery. According to a leading European manufacturer of car batteries, factory defects amount to less than 7 percent.

Acid stratification, a problem with luxury cars

A common cause of battery failure is acid stratification. The electrolyte on a stratified battery concentrates on the bottom, causing the upper half of the cell to be acid poor. This effect is similar to a cup of coffee in which the sugar collects on the bottom when the waitress forgets to bring the stirring spoon. Batteries tend to stratify if kept at low charge (below 80%) and never have the opportunity to receive a full charge. Short distance driving while running windshield wiper and electric heaters contributes to this. Acid stratification reduces the overall performance of the battery.

Figure 1 illustrates a normal battery in which the acid is equally distributed from top to bottom. This battery provides good performance because the correct acid concentration surrounds the plates. Figure 2 shows a stratified battery in which the acid concentration is light on top and heavy on the bottom. A light acid limits plate activation, promotes corrosion and reduces performance. High acid concentration on the bottom, on the other hand, artificially raises the open circuit voltage. The battery appears fully charged but provides a low CCA. High acid concentration also promotes sulfation and decreases the already low conductivity further. If unchecked, such a condition will eventually lead to battery failure.

Figure 1: Normal battery
The acid is equally distributed from the top to the bottom in the cell and provides maximum CCA and capacity.
Allowing the battery to rest for a few days, applying a shaking motion or tipping the unit over tends to correct the problem. A topping charge by which the 12-volt battery is brought up to 16 volts for one to two hours also reverses the acid stratification. The topping charge also reduces sulfation caused by high acid concentration. Careful attention is needed to keep the battery from heating up and losing excessive electrolyte through hydrogen gassing. Always charge the battery in a well-ventilated room. Accumulation of hydrogen gas can lead to an explosion. Hydrogen is odorless and can only be detected with measuring devices.

**The challenge of battery testing**

During the last 20 years, battery testing lagged behind other technologies. The reason: the battery is a very difficult animal to test, short of applying a full charge, discharge and recharge. The battery behaves similar to us humans. We still don't know why we perform better on certain days than others.

Even by using highly accurate charge and discharge equipment, lead acid batteries produce disturbingly high capacity fluctuations on repetitive measurements. To demonstrate the variations, Cadex tested 91 car batteries with diverse performance levels (Figure 3). We first prepared the batteries by giving them a full charge and a 24-hour rest period. We then measured the capacity by applying a 25A discharge to 10.50V or 1.75V/cell (black diamonds).

This procedure was repeated for a second time and the resulting capacities were plotted (purple squared). This produced a whooping +/-15% variation in capacity readings across the full population. Some batteries had higher readings the second time; others were lower. Other chemistries appear to be more consistent in capacity readings than lead acid.

**Figure 3: Capacity fluctuations.** Capacities of 91 car batteries measured with a conventional discharge method show a fluctuation of +/-15%.

From the beginning, load testers have been the standard test method for car batteries. The year 1992 brought us AC conductance, a method that simplified battery testing. Now we are experimenting with multi-model electrochemical impedance spectroscopy (EIS) in a portable version at an affordable price.

Getting a fast and dependable assessment of a failing battery is difficult. Most battery testers in use only take cold cranking amps (CCA) and voltage readings. Capacity, the most important measurement of a battery, is unavailable. While taking the CCA reading alone is relatively simple, measuring the capacity is very complex and instruments offering this feature are expensive.

The Spectro CA-12 by Cadex Electronics is the first in a series of high-end battery testers capable of measuring capacity, CCA and state-of-charge (SoC) in a single, non-invasive test. The technology is based on multi-model electrochemical impedance spectroscopy (EIS). The
The system injects 24 excitation frequencies ranging from 20 to 2000 Hertz. The sinusoidal signals are regulated at 10mV/cell to remain within the thermal battery voltage of lead acid. This achieves stable readings for small and large batteries.

During the 30-second test, over 40 million transactions are completed. A patented algorithm analyses the data and the final results are displayed in capacity, CCA and state-of-charge. (For more information, please visit http://www.cadex.com/prod_testers_ca12.asp.

EIS is very complex and until recently required dedicated computers and expensive laboratory equipment, not to mention chemists and engineers to interpret the readings. The hardware of a full EIS system is commonly mounted on racks and the installation runs into tens of thousands of dollars.

**The tough choice**

No battery tester solves all problems. Entry-level testers are low cost, simple to use and capable of servicing a broad range of batteries. However, these units only provide a rough indication of the battery condition. A lab test at Cadex demonstrates that a battery tester based on EIS is four times more accurate in detecting weak batteries than AC conductance. Conventional testers often misjudge the battery on account of low state-of-charge. Many batteries are replaced when they should have been recharged, while others are given a clean bill of health when it should have been replaced.

Acid stratification is difficult to measure, even with the EIS technology. Non-invasive testers simply take a snapshot, average the measurements and spit out the results. Stratified batteries tend to show higher state-of-charge readings because of elevated voltage. On preliminary tests, the Spectro CA-12 also shows slightly higher CCA and capacity readings than normal. After letting the battery rest, the capacity tends to normalize. This may be due to diffusion effects in the stratified as a result of resting. Little information is available on how long a stratified battery needs to rest to improve the condition, other than to note that higher temperatures will hasten the diffusion process.

Ideally, a battery tester should indicate the level of acid stratification; sulfation, surface charge and other such condition and display how to correct the problem. This feature is not yet possible. Much research is being done in finding a solution that offers a more complete battery evaluation without the need for a full discharge. The knowledge gained on lead acid batteries can then be applied to other battery systems, such as traction, military, marine, aviation and stationary batteries.

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Learning the basics about batteries - sponsored by Cadex Electronics Inc. [Cadex]
Starting is easy... but can I steer and brake?
A look at emerging technologies capable of estimating battery reserve capacity

AC conductance testing was introduced in 1992 as a new way of measuring the cold cranking amps (CCA) of a car battery. This non-invasive method was hailed as a major breakthrough and, to a large degree, eliminates load testing to measure battery performance. The test only takes a few seconds; the readings are displayed in digital numbers and a message spells out the condition of the battery. There are no sparks at the battery terminals and the instrument remains cool.

But single frequency AC conductance has limitations. It does not measure CCA according to SAE standards but offers an approximation relating to the battery’s power output capability. This relative power figure often varies with state-of-charge and other battery conditions. At times, a good battery fails and a faulty one passes by error. But the most significant drawback is its inability to read the reserve capacity (RC). Despite these shortcomings, AC conductance has become an accepted standard for predicting battery life and determining when to replace an old battery before it becomes a nuisance.

What is the difference between CCA and RC?
A good battery needs high CCA and high capacity readings but these attributes reflect differently depending on the application. A high CCA reading assures good battery conductivity and provides strong cranking ability. High CCA goes hand-in-hand with a low internal battery resistance. Figure 1 compares high CCA with a large, open tap that allows unrestricted flow.

Reserve capacity governs the amount of energy the battery can store. A new battery is rated at a nominal capacity of 100%. As the battery ages, the reserve capacity drops and the battery eventually needs replacing when the reserve capacity falls below 70%. The RC reading always refers to a fully charged battery; the state-of-charge (SoC) should not affect the readings when measured with a rapid-tester.

A battery may provide a good CCA reading and start a car well but be low on reserve capacity. This battery would be run down in no time when drawing auxiliary power. Figure 2 illustrates such a battery. The so-called ‘rock content’ that builds up as the battery ages is permanent and cannot be reversed.

Figure 3 illustrates a battery with good reserve capacity but low CCA. This battery has a difficult task turning the starter and needs replacing even though it could be used for low load applications.
Figure 3: Battery with low CCA but high reserve capacity.
The low CCA of this battery provides poor cranking although the reserve capacity is high.

Capacity measurements, the most comprehensive battery test
With increased demand for auxiliary power on vehicles, measuring energy reserve is more relevant than CCA. The slogan goes: "Starting is easy... but can I steer and brake?" Modern battery testers must adapt to this new requirement and also include RC measurement. European car manufacturers place heavy emphasis on reserve capacity, while in North America CCA is still the accepted standard to assess battery performance. Most modern battery testers also provide state-of-charge readings (SoC).

Measuring reserve capacity is more complex than CCA. Many methods have been tried, including multi-frequency conductance, but most have limitations. One of the main obstacles is processing large volumes of data received when scanning a battery with multiple frequencies. Collecting the data is easy; making practical use of the information is the problem. The cost of high-speed microprocessors and processing difficulties has put the price tag on such battery testers out of range. Put changes are coming.

Cadex Electronics has developed a method that enables the processing of a large volume of data received through multi-model electro-chemical impedance spectroscopy (EIS). Trademarked Spectro™, the system injects 24 excitation frequencies ranging from 20 to 2000 Hertz. The signals are regulated at 10mV to remain within the thermal battery voltage of lead acid. This permits stable readings for small and large batteries. The test takes 20 seconds, during which about 40 million transactions are completed.

Normally, EIS requires dedicated equipment and a computer to analyze the obtained data. To permit such analyses in a hand held unit, high-speed digital signal processing is used. In 2005, the Spectro™ invention received a patent (US patent 6,778,913, Jörn Tinnemeyer).

Spectro™ has primarily been demonstrated on 12V lead-acid batteries, automotive in particular. The large pool of available car batteries provides an excellent platform to verify the technology. The same technology can also be used on nickel and lithium-based batteries.

On the strength of our invention, Cadex has developed a battery rapid-tester (CA-12) for automotive batteries. One of the strongest features of Spectro™ is its ability to reveal CCA, reserve capacity and state-of-charge on a single measurement. Displaying RC has been on the wish list of battery manufacturers and service centers for many years. In fact, this will be the first time such information can be obtained non-invasively with a commercial hand-held tester. Figure 4 shows the suggested display format.

The battery needs to be charged for testing. The typical test band is 50% to 100% SoC. Early tests provide stable results over a wide temperature range. There is good immunity to electrical noise. Parasitic loads of up to 30A have been tried without notable side effects. Furthermore, Spectro™ appears to be less sensitive to surface charge than single frequency AC conductance and the CCA readings are more consistent. The tester tolerates some acid stratification but chemical additives may affect the readings. Figure 5 illustrates the CA-12 tester.
Early test results on Reserve Capacity

Verifying the accuracy and repeatability of a new invention takes much time and effort. To test Spectro™, Cadex assembled a test bed of 91 car batteries with diverse performance levels. The preparation consisted of a fully saturated charge, followed by a 24-hour rest period and a 25A discharge to 10.50V (1.75V/cell), during which the reserve capacity was measured. This procedure produced an astonishing +/-15% variation in capacity readings across the full population. When comparing the capacity obtained through a conventional discharge and by non-invasive means, one must take into account the vulnerability of lead acid in producing varied readings even when using highly accurate charges and load banks.

Figure 6 compares the reserve capacities of 38 randomly chosen car batteries. The black diamonds show the reserve capacity derived through a full discharge; the purple squares represent Spectro™ estimations using a generic matrix.

How can the RC readings be further improved? Best results are achieved by sorting the batteries according to architecture and CCA rating. We developed a model specific matrix and tested a group of same-model batteries. Figure 7 shows the reserve capacity readings derived through a conventional full discharge and Spectro™. With specific matrices, the readings approach laboratory standards in terms of accuracy.

Although the test results in Figure 6, and in particular Figure 7, look very encouraging, we need to be reminded that Spectro™ is not a universal battery tester capable of measuring...
any battery that comes along. It cannot be compared to a photocopier that duplicates any
document or flat object by simply pressing the copy button. Rather, Spectro™ needs a
battery specific matrix as a reference. To a large extent, the quality of the matrix governs
the accuracy. The matrices are stored in the tester and need selecting together with the Ah
and/or CCA rating. We are currently making gains in establishing generic matrices that may
be used for CCA and RC measurements.

Price is another issue. Because of added complexity and higher parts count compared to
single frequency AC conductance, the Spectro™ technology will command a higher price. We
are not competing directly with currently available battery testers; rather, we offer a
solution for those needing a better technology because the present method may be
insufficient.

Summary
Technology has advanced to a point where measuring battery performance through non-
invasive means will become the acceptable standard. Applying a full discharge for the
purpose of obtaining the reserve capacity is impractical and stresses the battery. Multi-
model electrochemical impedance spectroscopy with improved data processing algorithms
will bring this task one step closer to reality.

Multi-frequencies EIS not only makes RC estimations possible; it also improves the CCA
readings. Rather than providing a reference numbers relating to battery conductivity, EIS
can give actual CCA equivalents. The technology also improves state-of-charge estimations.
Typical applications include verifications of battery warranty returns, assessing the state-of-
life of stationary batteries and checking the capacity for batteries in defense and marine
applications. EIS is also an indispensable tool in examining batteries for wheelchair, golf
carts, robots, boats and forklifts.

Created: June, 2005

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Advanced battery analyzers

How are batteries checked and serviced? This article describes the advancements of the modern battery analyzer and explains how these instruments are used in the industry. While organizations such as public safety have been using battery analyzers for the last two decades to restore and prolong nickel-cadmium batteries, analyzers have made their way also into the cell phone, portable computing, medical and defense markets. The early models were impractical and did not adapt well to changing battery chemistries. In addition, the analyzers provided limited service and did not offer the quick test results and restoration capabilities customers demand today.

The last few years have brought a rebirth of the battery analyzer. With the move from the high-maintenance nickel-based batteries to the maintenance-free lithium-based packs, the duty of a battery analyzer is changing from life-extending cycling to rapid testing and boosting.

Fixed current analyzers
There are two basic types of battery analyzers: the fixed current and programmable versions. Fixed current units are the lower priced of the two, and charge and discharge a battery at a preset current of about 600mA. Smaller batteries get serviced reasonably fast but larger batteries are slow. The service time of an 1800mAh battery is three times that of a 600mAh pack. The capacity readout is in mAh and reflects the length of discharge. The fixed-current analyzers are the predecessors of the programmable units.

Programmable analyzers
The programmable analyzers allow servicing the battery against preset parameters. The charge and discharge currents are adjusted according to the battery rating, and the voltage is set to flag batteries with incorrect voltages. These analyzers provide more accurate readings and enable higher battery throughput than fixed current units. In addition, programmable analyzers are better suited to service new battery systems and have proven to be more effective in restoring weak batteries. The Cadex C7000-Series are such programmable battery analyzers.

Battery adapters
Interfacing the batteries has always been a challenge with battery analyzers. Technicians have invented contraptions with springs and levers so complicated that only they themselves are able to operate. Everybody else stays away from them of fear.

Cadex solved the battery interface issue with the custom adapters for common batteries and the universal adapters for specialty packs. The custom adapters are the easiest to use and provide the most accurate test results. User-programmable cables accommodate larger batteries or assist when no adapter is on hand. Smaller batteries can be serviced with the Cadex FlexArm™. Two contact probes mounted on flexible arms provide the connection when lowered to the battery terminals. Magnetic guides keep the battery in position and a temperature sensor safeguards the battery. Figure 1 illustrates the Cadex FlexArm™.

**Figure 1: Cadex FlexArm™.**
Snapped into the Cadex 7000-Series battery analyzers, the FlexArm™ establishes contact by lowering the arms to the battery. Magnetic guides keep the battery in position. The FlexArm™ stores up to 10 battery types, each of which can be given a unique name.
The Cadex adapters contain a memory chip that configures the analyzer to the correct setting. Each adapter stores 10 battery configuration codes to service 10 different battery types. The parameters can be edited with a few keystrokes on the analyzer's keypad.

**Service programs**
Advanced battery analyzers are capable of evaluating battery conditions and implementing corrective service to restore weak performance. The Cadex system, for example, automatically applies a recondition cycle to nickel-based packs if a user-selected target capacity cannot be reached. Other programs include Prime to prepare a new battery for field use, Charge to allow fast-charge and Custom to apply unique cycles composed of charge, discharge, recondition, trickle charge or any combination, including rest periods and repeats.

Many modern analyzers also offer battery rapid test programs. This often requires entering the battery voltage and rating (in mAh). To obtain accurate readings, a battery-specific matrix may also be required. The Cadex QuickTest™ stores the matrix in the battery adapter, together with the configuration code. Installing the adapter sets the analyzer to the correct parameters, transparent to the user.

With the Cadex system, the matrix is commonly included when purchasing the adapter. If missing, scanning several batteries with various state-of-health conditions creates the matrix. The test time is 3 minutes and requires a charge level of 20-90%. If outside this range, the analyzer automatically applies a brief charge or discharge.

Many batteries are discarded, even when restoration is possible. Cell phone dealers have confirmed that 80-90% of returned mobile phone batteries can be repaired with a battery analyzer. However, most dealers are not equipped to handle the influx of warranty batteries and the packs are returned to the manufacturers for replacement or are discarded. Rapid test enables checking the battery while the customer waits. Minor battery problems can be corrected on the spot.

A typical failure of lithium-ion batteries is excessive low discharge. If discharged below 2.5 volts per cell, the internal safety circuit deactivates and the battery no longer accepts charge with a regular charger. An excessive low discharge can occur if the battery is not recharged for some time after a full discharge through extensive use.

The Cadex battery analyzers feature Boost, a program, which reactivates batteries that appear dead. Boost works by applying a gentle current to the battery to re-energize the safety circuit and raise the cell voltage. After reaching the operating voltage, the battery can be charged and tested normally. Boosted batteries perform flawlessly as long as a repeat deep discharge is avoided.

**Printing**
Most analyzers are capable of printing service reports and battery labels. This feature simplifies maintenance, especially in a fleet environment where the operators must observe periodic service requirements. Printed reports also benefit customer service staff and engineers.

![Label printer](image)

**Figure 2: Label printer.**
The label printer automatically spits out a label with each battery serviced. The labels contain the service date; service due date, battery capacity and internal battery resistance.

Labeling the batteries with service date and test results is self-governing in the sense that the user only picks a properly labeled battery and has recently been serviced. Batteries with past due service date are segregated for service. With such a system, the user has full confidence that the battery will last through the shift, with energy to spare. Weak batteries are weeded out.

Created: February 2003
Computerized battery testing

Keeping track of batteries can be difficult, especially when encountering continuously changing battery types and observing periodic maintenance needs. To assist, several manufacturers of battery analyzers are offering software to enable PC interface. While a PC is helpful for battery service, the available software is often not refined enough to satisfy most market requirements.

Describing the features of software packages is difficult, if not outright boring. For this reason, this paper takes BatteryShop™ by Cadex as the example of a fully functioning, multi-tasking battery maintenance system. Developed during the last 10 years, BatteryShop™ is a mature product that meets today’s battery service requirements.

BatteryShop™ works in conjunction with Cadex C7000 Series battery analyzers. Although the analyzers work as stand-alone units, the software overrides the analyzers when connected to a PC. BatteryShop™ is equally proficient in supporting one analyzer or a fully extended system of 120 units.

To simplify the service of batteries, BatteryShop™ includes a database of over 2000 batteries for wireless communications, portable computing, medical, broadcast and defense. The listing includes the battery configuration codes, known as C-Codes. The newer battery listings also contain the QuickTest™ matrix to enable rapid testing. The user can extend the library by adding new models or downloading the updates from www.cadex.com. The Internet allows sharing the C-Codes and QuickTest™ matrices with the global battery community. In addition, battery manufacturers can prepare and publish the service parameters before releasing a new battery.

To service a battery, the user selects the battery model from the database and clicks the mouse. The PC sets the analyzer to the correct parameters, ready to service the battery. Programming the analyzer by scanning the battery model is also possible. Figure 1 illustrates a typical setup with two analyzers.

![Figure 1: BatteryShop™ provides a simple, yet powerful PC-interface to control and monitor Cadex battery analyzers. The Internet allows the use of common test parameters and sharing of test results. The software accommodates up to 128 battery analyzers.](image)

Software is commonly written to accommodate a broad range of applications, even though a customer may never use more than one function. BatteryShop™ is designed to service cell phone batteries at store fronts, check batteries in large repair centers, assist in the scheduled maintenance of fleet batteries, and tend to engineers in research labs. Here are a few examples how the PC software can be used:

**Cellular dealers**

When testing a cell phone battery at point-of-sale with BatteryShop™, the service clerk selects the battery from the database, clicks the mouse and connects the pack. To simplify the selection, photo images of the pack can also be shown on the monitor. The service programs range from QuickTest™ to check a battery in three minutes, Boost to wake up a seemingly dead battery, Prime to prepare a new battery and verify its performance, Charge
to fast-charge, and Auto to exercise and recondition a battery. Systems such as these prevent the liberal replacement of batteries returned by frivolous customers who complain about reoccurring problems with a handset.

Battery software can also be integrated into rapid test stations capable of examining the basic functions of a complete cell phone at storefronts. Willtek Communications offers such a system. With the use of these test instruments, only handsets with genuine problems are sent in for repair. Cell phone dealers have indicated that less that 20% of cell phones brought in for service have real problems with the handset or the battery. The cost savings by pre-testing the handsets and batteries are considerable.

**Cellular service Centers**

Not all batteries are tested at point-of-sale. Many cell phone manufactures use strategically placed service centers to repair handsets and batteries. A large service center may repair as many as 50,000 units per month. The database for such an organization can be tailored to include only those batteries that are being handled by that organization. The test results can be used for statistical analyses or sent to a central location for evaluation. Enabling access to vital test information allows battery manufacturers to correct recurring battery problems quickly and effectively.

**Battery fleet owners**

Service software is especially helpful in tracking the maintenance requirements of fleet batteries. All packs are first marked with a unique battery ID number. The ID number is printed on a label in bar code format and permanently attached to the battery. BatteryShop™ generates these labels. To perform the scheduled maintenance, the user scans the battery ID and the PC automatically configures to the analyzer to the correct setting. On completion of the service, the battery test results are stored in the database under the assigned battery ID number. All references to the battery in terms of vendor information, purchase date, custodian, maintenance schedules, performance history and planned replacement are available with a click of the mouse.

**Manufacturers and pack assemblers**

Battery service software assists battery manufacturers and pack assemblers in terms of life cycle testing, batch checking for quality control and verifying warranty claims. Chemistry, voltage and current setting can be entered manually through the PC. Charge and discharge voltages are displayed in real-time graphics. The graphs also include battery temperature and internal resistance readings that are recoded during charge and discharge cycles. All test data can be stored for future reference.

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**About the Author**

Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world. Cadex Electronics is a manufacturer of advanced battery chargers, battery analyzers and PC software. For product information please visit [www.cadex.com](http://www.cadex.com).

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Definitions

**Ambient temperature:**
The average temperature of the battery's surrounding medium, typically air.

**Ampere-hours (Ah):**
A measure of energy that is provided to or drawn from a battery. (A current of one ampere for one hour equals 1Ah).

**Battery cycle:**
A full charge followed by a full discharge (or the other way around).

**Button cell:**
A miniaturized battery. Most rechargeable button cells are NiCd or NiMH.

**C-code:**
Abbreviation of ‘configuration code.’ This information is typically stored in a battery adapter and configures the analyzer to the correct battery settings when installed.

**C-rate:**
Unit by which charge and discharge times are scaled. A battery rated at 1000mAh provides 1000mA for one hour if discharged at 1C. A discharge of 1C draws a current equal to the rated capacity. The same battery discharged at 0.5C would provide 500mA for two hours.

**Capacity:**
The electrical energy content of a battery as expressed in ampere-hours. The energy is measured by observing the time to discharge a battery at a constant current until a specified cut-off voltage is reached.

**Capacity offset:**
A correction factor applied to the rating of a battery if discharged under different C-rates from the one rated.

**Cell mismatch:**
Cells within a battery pack containing different capacity and voltage levels.

**Cell reversal:**
The stronger cells of a battery (several cells connected in series) impose a voltage of reverse polarity across a weaker cell during a deep discharge.

**Charge:**
The process of replenishing or replacing the electrical charge in a rechargeable cell or battery.

**Co-generation:**
The utilization of heat produced as byproduct in converting oxygen and hydrogen to electricity in a fuel cell. The heat is used to drive steam turbines.

**Coulomb:**
A unit of electric charge used to measure the ingoing and outgoing discharge current of a battery. One coulomb (1C) is equal to the electricity transferred by a current of one ampere in one second. (The maximum energy a molecular weight of a chemical system can deliver is one faraday of energy or 96495.7C which is the equivalent of 26.8Ah of capacity.)

**Coke:**
Coal from which most of the gases have been removed by heating. Coke is used as an industrial fuel.

**Current-limiting chargers:**
A charger that keeps the charge current constant during the charge process but allows the voltage to fluctuate (typically used on NiCd and NiMH chargers).

**Cycle:**
A process consisting of a single charge and discharge of a rechargeable battery.

**Cycle life:**
The number of cycles a battery provides before it is no longer usable. (A battery is considered non-usable if its nominal capacity falls below 60 to 80 percent).

**Cylindrical cell:**
The positive and negative plates are rolled up and placed into a cylindrical container.

**Double layer capacitor:**
Capacitor with high farad rating. The high capacity is made possible by a double layer formed near the carbon electrode surface.

**Dumb battery:**
A battery which contains no electronic circuitry with which to communicate digitally.

**Electrochemical Impedance Spectroscopy (EIS):**
Used to investigate electrochemical characteristics of batteries. The method applies an AC potential at varying frequencies to an electrochemical cell and the current response is measured.

**Electrode:**
Conducting element within a cell in which an electrochemical reaction occurs. Normally includes active materials plus conductive and supportive elements.

**Electrolyte:**
A non-metallic conductor of electricity (typically liquid) between the positive and negative electrodes of a battery. The current is carried by the physical movement of ions.

**Energy:**
Voltage multiplied by current expressed in watts.

**Energy density:**
The amount of energy a cell can contain. Gravimetric energy is the watt-hours a battery is capable of providing per given weight (pound or kilogram), and volumetric energy is the watt-hours per given size (cubic inch or cubic centimeter). The energy is defined as nominal battery voltage multiplied by rated capacity.

**Equalizing Charge:**
With time, the charge levels of individual cells of a large battery tend to become slightly unbalanced. The equalizing charge applies an elevated charge voltage for a few hours to balance the cells. Used mainly for large lead acid cells.

**Exercise:**
Commonly understood as one or several discharge cycles to 1V/cell with subsequent recharge. Used to maintain NiCd & NiMH batteries.

**Fast charge:**
Typical fast charge time for a nickel-based battery is 1 hour; lithium-based is 3 hours. The fast-charger detects the state-of-charge and switches to trickle charge when full-charge is reached.

**Float charge:**
Similar to trickle charge. Compensates for the self-discharge on a lead acid battery.

**Fuel cell:**
An electrochemical device that generates electricity by converting oxygen and hydrogen into water.

**Fuzzy logic:**
A mathematical technique used to obtain an approximate output reading derived from various analog inputs. Fuzzy logic can be utilized to quick-test batteries.

**Graphite:**
A form of carbon.

**Hydrogen battery:**
A rechargeable battery commonly used for space applications.

**Internal resistance:**
Resistance to electrical current inside a cell or battery pack.

**Impedance:**
Resistance to electrical current created by reactance and ohmic resistance

**Intelligent battery:**
Also known as a ‘smart’ battery. The battery pack contains internal circuitry to enable communication between the battery and the user.

**Intrinsically Safe:**
A battery with built-in protection circuitry. These batteries are used primarily in explosive environments.

**Ion:**
A charged particle that is combined with a particle of opposite charge to produce a chemical salt.

**Lead acid battery:**
Rechargeable battery commonly used for wheeled and stationary applications. The plates consist of lead-antimony alloy.

**Lithium battery:**
A battery using lithium metal as negative electrode. Most lithium batteries are non-rechargeable.

**Lithium ion battery:**
A battery dependent on the flow of lithium ions. The lithium metal on the negative electrode is replaced with carbon to improve safety.

**Lithium ion polymer:**
A rechargeable battery similar to the Li?ion but with a solid polymer as electrolyte. Some gelled conductive material is added to promote conductivity.

**Lithium polymer:**
A rechargeable battery using solid polymer as electrolyte. Most lithium polymer batteries require heat to promote conductivity.

**Load current:**
The discharge current delivered to a battery-powered device.

**Matrix:**
The set of battery parameters stored in the battery adapter to enable the Cadex Quicktestä function.

**Manganese:**
A metallic chemical element.

**Maintenance Requirements:**
Battery maintenance prolongs battery life. Nickel-based batteries need a periodic full discharge to eliminate ‘memory’. Lead acid batteries require periodic equalizing charge. Lithium-based batteries need little maintenance.

**Memory:**
Reversible capacity loss in NiCd and NiMH batteries. The modern definition of memory commonly refers to a change in crystalline formation from the desirable small size to a large size. Memory is often used to describe any reversible capacity loss on nickel-based batteries.

**Milliampere-hour:**
A battery capacity or rating. A battery that provides a current of 1000mA for 1 hour is rated at 1000mAh (or 1Ah).

**Negative delta V (NDV):**
A drop in battery voltage, which occurs when a sealed NiCd or NiMH battery reaches the full charge state and goes into overcharge.

**Nickel cadmium battery:**
A rechargeable battery using cadmium as the negative electrode.

**Nominal voltage:**
The cell voltage that is accepted as an industrial standard. (Cell voltages of 1.20 and 1.25V are used for NiCd and NiMH batteries).

**Ohmic resistance:**
Electrical resistance void of reactance.

**Ohmtest™:**
A measurement that reflects the internal resistance of a battery.

**Organic:**
Carbon-based solvent.

**Overcharge:**
Charging a battery after it reaches full charge. On overcharge, the battery can no longer absorb charge and the battery heats up.

**Passivation layer:**
A resistive layer that forms in some cells after prolonged storage. This layer must be broken to enable proper operation. Applying charge/discharge cycles often help in preparing the battery for use.

**Polymer:**
An ionic conductor that is an electrical insulator put passes ions.

**Pouch cell:**
A battery in which the typical metallic cylinder and glass-to-metal electrical feed-through is replaced with a flexible, heat-sealable foil package.

**Primary battery:**
A non-rechargeable battery. The active materials of a primary battery undergo an irreversible change during discharge.

**Prismatic cell:**
The positive and negative plates are stacked rather than rolled.

**Protection circuit:**
Circuitry built into the battery pack to maintain the safety of the battery and equipment in case of improper handling.

**Quick charger:**
A charger that charges a battery in 3 to 6 hours.

**Quicktest™:**
A method to quick test the state-of-health of a battery.

**Rapid charge:**
Same terminology as quick charger.

**Reactance:**
The presence of inductive and capacitive resistance.

**Recondition:**
A deep discharge below 1.0V/cell with a controlled current, causing a change to the molecular structure of the cell and a rebuilding of its chemical composition. Recondition helps break down large crystals to a more desirable small size, often restoring the battery to its full capacity. Applies to nickel-based batteries.

**Resistance:**
Opposition to electrical current flow. Batteries with high internal resistance are not able to deliver heavy current pulses or elevated loads.

**Residual capacity:**
The charge capacity remaining in a battery prior to charge.

**Reverse load charge:**
A charge method that intersperses discharge pulses between charge pulses to promote the recombination of gases generated during fast charge. Reverse load charge also helps to reduce memory.

**Secondary battery:**
A battery that is rechargeable by reversing its chemical reaction.

**Self-discharge:**
Capacity loss during storage due to the internal leakage between the positive and negative cell plates.

**Single wire bus:**
Simplified ‘smart’ battery using only one wire for digital communications to the outside world.

**Slow charge:**
Typically an over-night charge lasting 10 to 16 hours at a charge current of 0.1C. A battery does not require instant removal when fully charged.

**'Smart' battery:**
Also known as an ‘intelligent battery.’ A battery pack containing internal circuitry that enables communication between the battery and the user.

**Soft cell:**
A cell whose voltage rises above its defined boundaries during charging. This voltage rise may be caused by high cell impedance, cold battery temperature or lack of electrolyte.

**Spectroscopy:**
Same terminology as Electrochemical Impedance Spectroscopy.

**Spinel:**
A family of compounds that have a specific chemical structure. In lithium-ion batteries, the structure is manganese-based.

**State-of-Charge (SoC):**
A measurement that reflects the state-of-charge of a battery. The SoC alone is not a valid indicator of the battery's runtime. The SoC readings will indicate 100 percent, even if a battery whose acceptance has dropped to 50 percent is fully charged.

**State-of-Health (SoH):**
A measurement that reflects the state-of-health of a battery, taking into account charge acceptance, internal resistance, voltage and self-discharge.

**Sulfation:**
The growth of lead sulfate crystals in lead acid batteries, which inhibits current flow. Sulfation is caused by storage at low state-of-charge.

**Supercapacitor:**
A capacitor that can store a high amount of energy. Supercapacitors hold about one tenth the energy of a nickel or lithium-based battery.

**System Management Bus (SMBus):**
A commonly used protocol for the 'smart' battery.

**Thermal battery voltage:**
Batteries are non-linear systems. The equations, which govern the battery's response, becomes linear below 25mV/cell at 25°C. This voltage is called the battery thermal voltage.

**Thermal runaway:**
A condition whereby an electrochemical cell will overheat and destroy itself through internal heat generation. This may be caused by overcharge or high current discharge and other abusive conditions.

**Trickle charge:**
Maintenance charge to compensate for the battery's self-discharge.

**Topping Charge:**
To complete the fast charge, a topping charge is applied that continues charging the battery for 30 minutes or longer at a lower current. Typically used for nickel-based batteries.

**Voltage delay:**
During open circuit storage, some battery systems develop a passivation film on the surface of the active material. On the initial discharge, these batteries demonstrate a momentarily lower than normal voltage until this film is removed by the discharge.

**Voltage limit:**
The voltage value beyond which a battery is not permitted to rise on charge or fall on discharge.

**Voltage-limiting charger:**
A charger that limits the maximum voltage to a battery but allows the current to drop towards the end of charge. A voltage-limiting charge may also include current-limiting. (Typically used on lead acid and Li?ion battery chargers).

**Zapping:**
The process of applying a momentary high current pulse to a battery to improve performance. Zapping is said to improve new NiCd batteries but does not restore weak packs.

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**About the Author**
Isidor Buchmann is the founder and CEO of Cadex Electronics Inc., in Vancouver BC. Mr. Buchmann has a background in radio communications and has studied the behavior of rechargeable batteries in practical, everyday applications for two decades. Award winning author of many articles and books on batteries, Mr. Buchmann has delivered technical papers around the world. Cadex Electronics is a manufacturer of advanced battery chargers, battery analyzers and PC software. For product information please visit [www.cadex.com](http://www.cadex.com).
Bibliography


Created: January 2003, Last edited: July 2003

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