Sharing battery knowledge (BU1)

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? *(BU2)*

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.

![Figure 1: Prehistoric batteries](image1)

Clay jar with iron rod surrounded by copper cylinder. When filled with vinegar + an electrolytic solution produces 1.1 volts DC (circa. 250 BC to 640 AD). It is believed that the Parthians who ruled Baghdad (circa 250 BC) used batteries to electroplate silver. The Egyptians are said to have electroplated antimony onto copper over 4300 years ago.

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.

![Figure 2: Volta and his battery.](image2)

In 1800, Alessandro Volta invented the first modern electric battery. Volta demonstrated that an electrical current is generated when metals and chemicals come into contact.

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.

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 met when

<table>
<thead>
<tr>
<th>Year</th>
<th>Inventor</th>
<th>Event</th>
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<tbody>
<tr>
<td>1600</td>
<td>Gilbert (UK)</td>
<td>Establishment of electrochemistry study</td>
</tr>
<tr>
<td>1791</td>
<td>Galvani (Italy)</td>
<td>Discovery of ‘animal electricity’</td>
</tr>
<tr>
<td>1800</td>
<td>Volta (Italy)</td>
<td>Invention of the voltaic cell</td>
</tr>
<tr>
<td>1802</td>
<td>Cruickshank (UK)</td>
<td>First electric battery capable of mass production</td>
</tr>
<tr>
<td>1820</td>
<td>Ampère (France)</td>
<td>Electricity through magnetism</td>
</tr>
<tr>
<td>1833</td>
<td>Faraday (UK)</td>
<td>Announcement of Faraday’s Law</td>
</tr>
<tr>
<td>1836</td>
<td>Daniell (UK)</td>
<td>Invention of the Daniell cell</td>
</tr>
<tr>
<td>1839</td>
<td>Grove (UK)</td>
<td>Invention of fuel cell (H2/O2)</td>
</tr>
<tr>
<td>1859</td>
<td>Planté (France)</td>
<td>Invention of the lead acid battery</td>
</tr>
<tr>
<td>1888</td>
<td>Leclanché (France)</td>
<td>Invention of the Leclanché cell</td>
</tr>
<tr>
<td>1888</td>
<td>Gassner (USA)</td>
<td>Completion of the dry cell</td>
</tr>
<tr>
<td>1899</td>
<td>Jungner (Sweden)</td>
<td>Invention of the nickel-cadmium battery</td>
</tr>
<tr>
<td>1901</td>
<td>Edison (USA)</td>
<td>Invention of the nickel-iron battery</td>
</tr>
<tr>
<td>1932</td>
<td>Slich &amp; Ackermann (Germany)</td>
<td>Invention of the sintered pole plate</td>
</tr>
<tr>
<td>1947</td>
<td>Neumann (France)</td>
<td>Successfully sealing the nickel-cadmium battery</td>
</tr>
<tr>
<td>Mid 1960</td>
<td>Union Carbide (USA)</td>
<td>Development of primary alkaline battery</td>
</tr>
<tr>
<td>Mid 1970</td>
<td></td>
<td>Development of valve regulated lead acid battery</td>
</tr>
<tr>
<td>1990</td>
<td></td>
<td>Commercialization of nickel-metal-hydride battery</td>
</tr>
<tr>
<td>1991</td>
<td>Sony (Japan)</td>
<td>Commercialization of lithium-ion battery</td>
</tr>
</tbody>
</table>
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.
What's the best battery? *(BU3)*

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 has a limited cycle life. Another pack may be built for durability and is big and bulky. A third may have high energy density and long durability but is made for a special application and is too expensive for the average consumer. A lithium-based battery can be designed for maximum energy density but its safety would be compromised.

Battery manufacturers are aware of customer needs and offer packs that best suit the application. The mobile phone industry is a good 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.

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 costs and safety. Nickel-cadmium is the first rechargeable battery in small format and forms a standard against which other chemistries are commonly compared. The trend is towards lithium-based systems.

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. NiMH is viewed as steppingstone to lithium-based systems.

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. Lead acid is inexpensive and rugged. It serves a unique niche that would be hard to replace with other 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. High current versions are available for power tools and medical devices.

Table 1 summarizes the characteristics of the common batteries. The figures are based on average ratings at time of publication. Lithium-ion is divided into three versions: The traditional cobalt that is commonly used in cell phones, cameras and laptops; the manganese (spinel) that power
High-end power tools and the new phosphate that competes head-on with spinel. Lithium-ion polymer is not listed as a separate system. Its unique construction performs in a same way to cobalt-based lithium-ion.

Table 1: Characteristics of commonly used rechargeable batteries.

<table>
<thead>
<tr>
<th></th>
<th>Nickel-cadmium</th>
<th>Nickel-metal-hydride</th>
<th>Lead-acid sealed</th>
<th>Lithium-ion cobalt</th>
<th>Lithium-ion manganese</th>
<th>Lithium-ion phosphate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gravimetric Energy Density (kWh/kg)</strong></td>
<td>45-80</td>
<td>60-120</td>
<td>30-50</td>
<td>150 - 190</td>
<td>100 - 135</td>
<td>90 - 120</td>
</tr>
<tr>
<td><strong>Internal Resistance in mΩ</strong></td>
<td>100 to 200 (^1) 6V pack</td>
<td>200 to 300 (^1) 6V pack</td>
<td>(&lt;100)^(^1) 12V pack</td>
<td>150 - 300 (^1) pack 100 - 130 per cell</td>
<td>25 – 75(^2) per cell</td>
<td>25 – 50(^2) per cell</td>
</tr>
<tr>
<td><strong>Cycle Life</strong> (to 80% of initial capacity)</td>
<td>1500(^2)</td>
<td>300 to 500(^3)</td>
<td>200 to 300(^3)</td>
<td>300 – 500(^4)</td>
<td>Better than 300 – 500(^4)</td>
<td>(&gt;1000) lab conditions</td>
</tr>
<tr>
<td><strong>Fast Charge Time</strong></td>
<td>1 hr typical</td>
<td>2 to 4 hr</td>
<td>8 to 16 hr</td>
<td>1.5 - 3 hr</td>
<td>1 hr or less</td>
<td>1 hr or less</td>
</tr>
<tr>
<td><strong>Overcharge Tolerance</strong></td>
<td>moderate</td>
<td>low</td>
<td>high</td>
<td>Low</td>
<td>Cannot tolerate trickle charge.</td>
<td></td>
</tr>
<tr>
<td><strong>Self-discharge / Month (room temperature)</strong></td>
<td>20(^%)(^5)</td>
<td>30(^%)(^5)</td>
<td>5(^%)</td>
<td>(&lt;10)^(^%)(^6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cell Voltage</strong></td>
<td>Nominal Average 1.25V</td>
<td>1.25V</td>
<td>2V</td>
<td>3.6V</td>
<td>Nominal 3.6V</td>
<td>3.3V</td>
</tr>
<tr>
<td><strong>Load Current</strong> peak best result</td>
<td>20C 1C</td>
<td>5C 0.5C or lower</td>
<td>5C 0.2C</td>
<td>&lt;3C 1C or lower</td>
<td>&lt;30C 10C or lower</td>
<td>&gt;30C 10C or lower</td>
</tr>
<tr>
<td><strong>Operating Temperature</strong>(^10) (discharge only)</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></td>
<td></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 months(^11)</td>
<td>not required</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td>Thermally stable, fuse recommended</td>
<td>Thermally stable, fuse recommended</td>
<td>Thermally stable</td>
<td>Protection circuit mandatory; stable to 150°C</td>
<td>Protection circuit recommended; stable to 250°C</td>
<td>Protection circuit recommended; stable to 250°C</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></td>
<td></td>
</tr>
</tbody>
</table>

1) Internal resistance of a battery pack varies with mAh rating, wiring and number of cells. Protection circuit of lithium-ion adds about 100mW.
2) Based on 18650 cell size. Cell size and design determines internal resistance. Larger cells can have an impedance of \(<15\)mOhms.
3) 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.
4) Cycle life is based on the depth of discharge. Shallow discharges provide more cycles than deep discharges.
5) The self-discharge is highest immediately after charge, and then tapers off. The capacity loss...
of nickel-cadmium is 10% in the first 24h, then declines to about 10% every 30 days thereafter. High temperature increases self-discharge.
6) Internal protection circuits typically consume 3% of the stored energy per month.
7) The traditional nominal voltage is 1.25V; 1.2V is more commonly used to harmonize with lithium-ion (3 in series = 3.6V).
8) Lithium-ion is often rated higher than the nominal 3.6V. Based on average voltage under load.
9) Capable of high current pulses; needs time to recuperate.
10) Applies to discharge only; charge temperature range is more confined. Delivers lower capacity at lower temperatures.
11) Maintenance may be in the form of ‘equalizing’ or ‘topping’ charge to prevent sulphation.

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.
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 recombined. 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.
Is lithium-ion the ideal battery? *(BUS)*

For many years, nickel-cadmium had been the only suitable battery for portable equipment from wireless communications to mobile computing. Nickel-metal-hydride and lithium-ion emerged in the early 1990s, fighting nose-to-nose to gain customer's acceptance. Today, lithium-ion is the fastest growing and most promising battery chemistry.

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 on most packs are 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. At the same time, lithium-ion packs are known to have served for five years in some applications.

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.
- Specialty cells can provide very high current to applications such as power tools.

Limitations
- Requires protection circuit to maintain voltage and current within safe limits.
- Subject to aging, even if not in use - storage in a cool place at 40% charge reduces the aging effect.
- Transportation restrictions - shipment of larger quantities may be subject to regulatory control. This restriction does not apply to personal carry-on batteries. (See last section)
- 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. The commercial cells use a separator/ electrolyte membrane prepared from the same traditional porous polyethylene or polypropylene separator filled with a polymer, which gels upon filling with the liquid electrolyte. Thus the commercial lithium-ion polymer cells are very similar in chemistry and materials to their liquid electrolyte counter parts.

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

Restrictions on lithium content for air travel

Air travelers ask the question, "How much lithium in a battery am I allowed to bring on board?" We differentiate between two battery types: Lithium metal and lithium-ion.

Most lithium metal batteries are non-rechargeable and are used in film cameras. Lithium-ion packs are rechargeable and power laptops, cellular phones and camcorders. Both battery types, including spare packs, are
allowed as carry-on but cannot exceed the following lithium content:
- 2 grams for lithium metal or lithium alloy batteries
- 8 grams for lithium-ion batteries

Lithium-ion batteries exceeding 8 grams but no more than 25 grams may be carried in carry-on baggage if individually protected to prevent short circuits and are limited to two spare batteries per person.

_How do I know the lithium content of a lithium-ion battery?_ From a theoretical perspective, there is no metallic lithium in a typical lithium-ion battery. There is, however, equivalent lithium content that must be considered. For a lithium-ion cell, this is calculated at 0.3 times the rated capacity (in ampere-hours).

**Example:** A 2Ah 18650 Li-ion cell has 0.6 grams of lithium content. On a typical 60 Wh laptop battery with 8 cells (4 in series and 2 in parallel), this adds up to 4.8g. To stay under the 8-gram UN limit, the largest battery you can bring is 96 Wh. This pack could include 2.2Ah cells in a 12 cells arrangement (4s3p). If the 2.4Ah cell were used instead, the pack would need to be limited to 9 cells (3s3p).

Restrictions on shipment of lithium-ion batteries

- Anyone shipping lithium-ion batteries in bulk is responsible to meet transportation regulations. This applies to domestic and international shipments by land, sea and air.
- Lithium-ion cells whose equivalent lithium content exceeds 1.5 grams or 8 grams per battery pack must be shipped as "Class 9 miscellaneous hazardous material." Cell capacity and the number of cells in a pack determine the lithium content.
- Exception is given to packs that contain less than 8 grams of lithium content. If, however, a shipment contains more than 24 lithium cells or 12 lithium-ion battery packs, special markings and shipping documents will be required. Each package must be marked that it contains lithium batteries.
- All lithium-ion batteries must be tested in accordance with specifications detailed in UN 3090 regardless of lithium content (UN manual of Tests and Criteria, Part III, subsection 38.3). This precaution safeguards against the shipment of flawed batteries.
- Cells & batteries must be separated to prevent short-circuiting and packaged in strong boxes.
The high-power lithium-ion (BU5A)

Most lithium-ion batteries for portable applications are cobalt-based. The system consists of a cobalt oxide positive electrode (cathode) and a graphite carbon in the negative electrode (anode). One of the main advantages of the cobalt-based battery is its high energy density. Long run-time makes this chemistry attractive for cell phones, laptops and cameras.

The widely used cobalt-based lithium-ion has drawbacks; it offers a relatively low discharge current. A high load would overheat the pack and its safety would be jeopardized. The safety circuit of the cobalt-based battery is typically limited to a charge and discharge rate of about 1C. This means that a 2400mAh 18650 cell can only be charged and discharged with a maximum current of 2.4A. Another downside is the increase of the internal resistance that occurs with cycling and aging. After 2-3 years of use, the pack often becomes unserviceable due to a large voltage drop under load that is caused by high internal resistance. Figure 1 illustrates the crystalline structure of cobalt oxide.

In 1996, scientists succeeded in using lithium manganese oxide as a cathode material. This substance forms a three-dimensional spinel structure that improves the ion flow between the electrodes. High ion flow lowers the internal resistance and increases loading capability. The resistance stays low with cycling, however, the battery does age and the overall service life is similar to that of cobalt. Spinel has an inherently high thermal stability and needs less safety circuitry than
Figure 2: Cathode crystalline of lithium manganese oxide has a 'three-dimensional framework structure'. This spinel structure, which is usually composed of diamond shapes connected into a lattice, appears after initial formation. This system provides high conductivity but lower energy density.

The spinel battery also has weaknesses. One of the most significant drawbacks is the lower capacity compared to the cobalt-based system. Spinel provides roughly 1200mAh in an 18650 package, about half that of the cobalt equivalent. In spite of this, spinel still provides an energy density that is about 50% higher than that of a nickel-based equivalent.

Figure 3: Format of 18650 cell. The dimensions of this commonly used cell are: 18mm in diameter and 65mm in length.

Types of lithium-ion batteries
Lithium-ion has not yet reached full maturity and the technology is continually improving. The anode in today's cells is made up of a graphite mixture and the cathode is a combination of lithium and other choice metals. It should be noted that all materials in a battery have a theoretical energy density. With lithium-ion, the anode is well optimized and little improvements can be gained in terms of design changes. The cathode, however, shows promise for further enhancements. Battery research is therefore focusing on the cathode material. Another part that has potential is the electrolyte. The electrolyte serves as a reaction medium between the anode and the cathode.

The battery industry is making incremental capacity gains of 8-10% per year. This trend is expected to continue. This, however, is a far cry from Moore's Law that specifies a doubling of transistors on a chip every 18 to 24 months. Translating this increase to a battery would mean a doubling of capacity every two years. Instead of two years, lithium-ion has doubled its energy capacity in 10 years.

Today's lithium-ion comes in many "flavours" and the differences in the composition are mostly related to the cathode material. Table 1 below summarizes the most commonly used lithium-ion on the market today. For simplicity, we summarize the chemistries into four groupings, which are Cobalt, Manganese, NCM and Phosphate.
Table 1: Most common types of lithium-ion batteries.

<table>
<thead>
<tr>
<th>Chemistry</th>
<th>Nominal V</th>
<th>Charge V limit</th>
<th>Charge &amp; discharge C-rates</th>
<th>Energy density Wh/kg</th>
<th>Applications</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>3.60V</td>
<td>4.20V</td>
<td>1C limit</td>
<td>110-190</td>
<td>Cell phone, cameras; laptops</td>
<td>Since 1990s, most commonly used for portable devices; has high energy density.</td>
</tr>
<tr>
<td>Manganese (spinel)</td>
<td>3.7-3.80V</td>
<td>4.20V</td>
<td>10C cont. 40C pulse</td>
<td>110-120</td>
<td>Power tools, medical equipment</td>
<td>Low internal resistance; offers high current rate and fast charging but lower energy density.</td>
</tr>
<tr>
<td>NCM (nickel-co 3.70V</td>
<td>4.10V*</td>
<td>~5C cont. 30C pulse</td>
<td>95-130</td>
<td>Power tools, medical equipment</td>
<td>Nickel, cobalt, manganese mix: provides compromise between high current rate and high capacity.</td>
<td></td>
</tr>
<tr>
<td>Saphion®</td>
<td>3.2-3.30V</td>
<td>3.60V*</td>
<td>35C cont.</td>
<td>95-140</td>
<td>Power tools, medical equipment</td>
<td>New, high current rate, long cycle life. Higher charge V increase capacity but shorten cycle life.</td>
</tr>
</tbody>
</table>

* Higher voltages provide more capacity but reduce cycle life

The cobalt-based lithium-ion appeared first in 1991, introduced by Sony. This battery chemistry gained quick acceptance because of its high energy density. Possibly due to lower energy density, spinel-based lithium-ion had a slower start. When introduced in 1996, the world demanded longer runtime above anything else. With the need for high current rate on many portable devices, spinel has now moved to the frontline and is in hot demand. The requirements are so great that manufacturers producing these batteries are unable to meet the demand. This is one of the reasons why so little advertising is done to promote this product. E-One Moli Energy (Canada) is a leading manufacturer of the spinel lithium-ion in cylindrical form. They are specializing in the 18650 and 26700 cell formats. Other major players of spinel-based lithium-ion are Sanyo, Panasonic and Sony.

Sony is focusing on the nickel-cobalt manganese (NCM) version. The cathode incorporates cobalt, nickel and manganese in the crystal structure that forms a multi-metal oxide material to which lithium is added. The manufacturer offers a range of different products within this battery family, catering to users that either needs high energy density or high load capability. It should be noted that these two attributes could not be combined in one and the same package; there is a compromise between the two. Note that the NCM charges to 4.10V/cell, 100mV lower than cobalt and spinel. Charging this battery chemistry to 4.20V/cell would provide higher capacities but the cycle life would be cut short. Instead of the customary 800 cycles achieved in a laboratory environment, the cycle count would be reduced to about 300.

The newest addition to the lithium-ion family is the A123 System in which nano-phosphate materials are added in the cathode. It claims to have the highest power density in W/kg of a commercially available lithium-ion battery. The cell can be continuously discharged to 100% depth-of-discharge at 35C and can endure discharge pulses as high as 100C. The phosphate-based system has a nominal voltage of about 3.3V/cell and peak charge voltage is 3.60V. This is lower than the cobalt-based lithium-ion and the battery will require a designated charger.
Valance Technology was the first to commercialize the phosphate-based lithium-ion and their cells are sold under the Saphionâ name.

In Figure 4 we compare the energy density (Wh/kg) of the three lithium-ion chemistries and place them against the traditional lead acid, nickel-cadmium, nickel-metal-hydride. One can see the incremental improvement of Manganese and Phosphate over older technologies. Cobalt offers the highest energy density but is thermally less stable and cannot deliver high load currents.

**Figure 4:**
Energy densities of common battery chemistries.

Lithium-cobalt enjoys the highest energy density. Manganese and phosphate systems are terminally more stable and deliver high load currents than cobalt.

Definition of Energy Density and Power Density

Energy Density (Wh/kg) is a measure of how much energy a battery can hold. The higher the energy density, the longer the runtime will be. Lithium-ion with cobalt cathodes offer the highest energy densities. Typical applications are cell phones, laptops and digital cameras.

Power Density (W/kg) indicates how much power a battery can deliver on demand. The focus is on power bursts, such as drilling through heavy steel, rather than runtime. Manganese and phosphate-based lithium-ion, as well as nickel-based chemistries, are among the best performers. Batteries with high power density are used for power tools, medical devices and transportation systems.

An analogy between energy and power densities can be made with a water bottle. The size of the bottle is the energy density, while the opening denotes the power density. A large bottle can carry a lot of water, while a large opening can pore it quickly. The large container with a wide mouth is the best combination.

Confusion with voltages
For the last 10 years or so, the nominal voltage of lithium-ion was known to be 3.60V/cell. This was a rather handy figure because it made up for three nickel-based batteries (1.2V/cell) connected in series. Using the higher cell voltages for lithium-ion reflects in better watt/hours readings on paper and poses a marketing advantage, however, the equipment manufacturer will continue assuming the cell to be 3.60V. The nominal voltage of a lithium-ion battery is calculated by taking a fully charged battery of about 4.20V, fully discharging it to about 3.00V at a rate of 0.5C while measuring the average voltage.

Because of the lower internal resistance, the average voltage of a spinel system will be higher than that of the cobalt-based equivalent. Pure spinel has the lowest internal resistance and the nominal cell voltage is 3.80V. The exception again is the phosphate-based lithium-ion. This system deviates the furthest from the conventional lithium-ion system.

Prolonged battery life through moderation

Batteries live longer if treated in a gentle manner. High charge voltages, excessive charge rate and extreme load conditions have a negative effect on battery life. The longevity is often a direct result of the environmental stresses applied. The following guidelines suggest ways to prolong battery life.

- The time at which the battery stays at 4.20/cell should be as short as possible. Prolonged high voltage promotes corrosion, especially at elevated temperatures. Spinel is less sensitive to high voltage.

- 3.92V/cell is the best upper voltage threshold for cobalt-based lithium-ion. Charging batteries to this voltage level has been shown to double cycle life. Lithium-ion systems for defense applications make use of the lower voltage threshold. The negative is a much lower capacity.

- The charge current of Li-ion should be moderate (0.5C for cobalt-based lithium-ion). The lower charge current reduces the time in which the cell resides at 4.20V. A 0.5C charge only adds marginally to the charge time over 1C because the topping charge will be shorter. A high current charge tends to push the voltage into voltage limit prematurely.

- Do not discharge lithium-ion too deeply. Instead, charge it frequently. Lithium-ion does not have memory problems like nickel-cadmium batteries. No deep discharges are needed for conditioning.

- Do not charge lithium-ion at or below freezing temperature. Although accepting charge, an irreversible plating of metallic lithium will occur that compromises the safety of the pack.

Not only does a lithium-ion battery live longer with a slower charge rate; moderate discharge rates also help. Figure 5 shows the cycle life as a function of charge and discharge rates. Observe the improved laboratory performance on a charge and discharge rate of 1C compared to 2 and 3C.
Battery experts agree that the longevity of lithium-ion is shortened by other factors than charge and discharge rates. Even though incremental improvements can be achieved with careful use, our environment and the services required are not always conducive for optimal battery life. In this respect, the battery behaves much like us humans - we cannot always live a life that caters to achieve maximum life span.
Lithium-ion safety concerns (BUSB)

When Sony introduced the first lithium-ion battery in 1991, they knew of the potential safety risks. A recall of the previously released rechargeable metallic lithium battery was a bleak reminder of the discipline one must exercise when dealing with this high energy-dense battery system.

Pioneering work for the lithium battery began in 1912, but it was not until the early 1970's when the first non-rechargeable lithium batteries became commercially available. Attempts to develop rechargeable lithium batteries followed in the eighties. These early models were based on metallic lithium and offered very high energy density. However, inherent instabilities of lithium metal, especially during charging, put a damper on the development. The cell had the potential of a thermal runaway. The temperature would quickly rise to the melting point of the metallic lithium and cause a violent reaction. A large quantity of rechargeable lithium batteries had to be recalled in 1991 after the pack in a cellular phone released hot gases and inflicted burns to a man's face.

Because of the inherent instability of lithium metal, research shifted to a non-metallic lithium battery using lithium ions. Although slightly lower in energy density, the lithium-ion system is safe, providing certain precautions are met when charging and discharging. Today, lithium-ion is one of the most successful and safe battery chemistries available. Two billion cells are produced every year.

Lithium-ion cells with cobalt cathodes hold twice the energy of a nickel-based battery and four-times that of lead acid. Lithium-ion is a low maintenance system, an advantage that most other chemistries cannot claim. There is no memory and the battery does not require scheduled cycling to prolong its life. Nor does lithium-ion have the sulfation problem of lead acid that occurs when the battery is stored without periodic topping charge. Lithium-ion has a low self-discharge and is environmentally friendly. Disposal causes minimal harm.

Long battery runtimes have always been the wish of many consumers. Battery manufacturers responded by packing more active material into a cell and making the electrodes and separator thinner. This enabled a doubling of energy density since lithium-ion was introduced in 1991.

The high energy density comes at a price. Manufacturing methods become more critical the denser the cells become. With a separator thickness of only 20-25µm, any small intrusion of metallic dust particles can have devastating consequences. Appropriate measures will be needed to achieve the mandated safety standard set forth by UL 1642. Whereas a nail penetration test could be tolerated on the older 18650 cell with a capacity of 1.35Ah, today's high-density 2.4Ah cell would become a bomb when performing the same test. UL 1642 does not require nail penetration. Lithium-ion batteries are nearing their theoretical energy density limit and battery manufacturers are beginning to focus on improving manufacturing methods and increasing safety.

Recall of lithium-ion batteries

With the high usage of lithium-ion in cell phones, digital cameras and
laptops, there are bound to be issues. A one-in-200,000 failure rate triggered a recall of almost six million lithium-ion packs used in laptops manufactured by Dell and Apple. Heat related battery failures are taken very seriously and manufacturers chose a conservative approach. The decision to replace the batteries puts the consumer at ease and lawyers at bay. Let's now take a look at what's behind the recall.

Sony Energy Devices (Sony), the maker of the lithium-ion cells in question, says that on rare occasions microscopic metal particles may come into contact with other parts of the battery cell, leading to a short circuit within the cell. Although battery manufacturers strive to minimize the presence of metallic particles, complex assembly techniques make the elimination of all metallic dust nearly impossible.

Figure 1: Lithium-ion battery damages a laptop.

Safety issues are enticing battery manufacturers to change the manufacturing process. According to Sony, contamination of Cu, Al, Fe and Ni particles during the manufacturing process may cause an internal short circuit.

A mild short will only cause an elevated self-discharge. Little heat is generated because the discharging energy is very low. If, however, enough microscopic metal particles converge on one spot, a major electrical short can develop and a sizable current will flow between the positive and negative plates. This causes the temperature to rise, leading to a thermal runaway, also referred to 'venting with flame.'

Lithium-ion cells with cobalt cathodes (same as the recalled laptop batteries) should never rise above 130°C (265°F). At 150°C (302°F) the cell becomes thermally unstable, a condition that can lead to a thermal runaway in which flaming gases are vented.

During a thermal runaway, the high heat of the failing cell can propagate to the next cell, causing it to become thermally unstable as well. In some cases, a chain reaction occurs in which each cell disintegrates at its own timetable. A pack can get destroyed within a few short seconds or linger on for several hours as each cell is consumed one-by-one. To increase safety, packs are fitted with dividers to protect the failing cell from spreading to neighboring cells.

Safety level of lithium-ion systems

There are two basic types of lithium-ion chemistries: cobalt and manganese (spinel). To achieve maximum runtime, cell phones, digital cameras and laptops use cobalt-based lithium-ion. Manganese is the newer of the two chemistries and offers superior thermal stability. It can sustain temperatures of up to 250°C (482°F) before becoming unstable. In addition, manganese has a very low internal resistance and can
deliver high current on demand. Increasingly, these batteries are used for power tools and medical devices. Hybrid and electric vehicles will be next.

The drawback of spinel is lower energy density. Typically, a cell made of a pure manganese cathode provides only about half the capacity of cobalt. Cell phone and laptop users would not be happy if their batteries quit halfway through the expected runtime. To find a workable compromise between high energy density, operational safety and good current delivery, manufacturers of lithium-ion batteries can mix the metals. Typical cathode materials are cobalt, nickel, manganese and iron phosphate.

Let me assure the reader that lithium-ion batteries are safe and heat related failures are rare. The battery manufacturers achieve this high reliability by adding three layers of protection. They are: [1] limiting the amount of active material to achieve a workable equilibrium of energy density and safety; [2] inclusion of various safety mechanisms within the cell; and [3] the addition of an electronic protection circuit in the battery pack.

These protection devices work in the following ways: The PTC device built into the cell acts as a protection to inhibit high current surges; the circuit interrupt device (CID) opens the electrical path if an excessively high charge voltage raises the internal cell pressure to 10 Bar (150 psi); and the safety vent allows a controlled release of gas in the event of a rapid increase in cell pressure. In addition to the mechanical safeguards, the electronic protection circuit external to the cells opens a solid-state switch if the charge voltage of any cell reaches 4.30V. A fuse cuts the current flow if the skin temperature of the cell approaches 90°C (194°F). To prevent the battery from over-discharging, the control circuit cuts off the current path at about 2.50V/cell. In some applications, the higher inherent safety of the spinel system permits the exclusion of the electric circuit. In such a case, the battery relies wholly on the protection devices that are built into the cell.

We need to keep in mind that these safety precautions are only effective if the mode of operation comes from the outside, such as with an electrical short or a faulty charger. Under normal circumstances, a lithium-ion battery will simply power down when a short circuit occurs. If, however, a defect is inherent to the electrochemical cell, such as in contamination caused by microscopic metal particles, this anomaly will go undetected. Nor can the safety circuit stop the disintegration once the cell is in thermal runaway mode. Nothing can stop it once triggered.

What every battery user should know

A major concern arises if static electricity or a faulty charger has destroyed the battery's protection circuit. Such damage can permanently fuse the solid-state switches in an ON position without the user knowing. A battery with a faulty protection circuit may function normally but does not provide protection against abuse.

Another safety issue is cold temperature charging. Consumer grade lithium-ion batteries cannot be charged below 0°C (32°F). Although the packs appear to be charging normally, plating of metallic lithium occurs on the anode while on a sub-freezing charge. The plating is permanent
and cannot be removed. If done repeatedly, such damage can compromise the safety of the pack. The battery will become more vulnerable to failure if subjected to impact, crush or high rate charging.

Asia produces many non-brand replacement batteries that are popular with cell phone users because of low price. Many of these batteries don’t provide the same high safety standard as the main brand equivalent. A wise shopper spends a little more and replaces the battery with an approved model. Figure 1 shows a cell phone that was destroyed while charging in a car. The owner believes that a no-name pack caused the destruction.

![Figure 1: A cell phone destroyed by a no-name battery while charging in a car.](image)

Figure 2: A cell phone with a no-brand battery that vented with flame while charging in the back of a car.

To prevent the infiltration of unsafe packs on the market, most manufacturers sell lithium-ion cells only to approved battery pack assemblers. The inclusion of an approved safety circuit is part of the purchasing requirement. This makes it difficult for a hobbyist to purchase single lithium-ion cells off-the-shelf in a store. The hobbyist will have no other choice than to revert to nickel-based batteries. I would caution against using an unidentified lithium-ion battery from an Asian source, if such cells is available.

The safety precaution is especially critical on larger batteries, such as laptop packs. The hazard is so much greater than on a small cell phone battery if something goes wrong. For this reason, many laptop manufacturers secure their batteries with a secret code that only the matching computer can access. This prevents non-brand-name batteries from flooding the market. The drawback is a higher price for the replacement battery. Readers of www.BatteryUniversity.com often ask me for a source of cheap laptop batteries. I have to disappoint the shoppers by directing them to the original vendor for a brand name pack.

Considering the number of lithium-ion batteries used on the market, this energy storage system has caused little harm in terms of damage and personal injury. In spite of the good record, its safety is a hot topic that gets high media attention, even on a minor mishap. This caution is good for the consumer because we will be assured that this popular energy storage device is safe. After the recall of Dell and Apple laptop batteries, cell manufacturers will not only try packing more energy into the pack but will attempt to make it more bulletproof.
Can the lead-acid battery compete in modern times? (BU6)

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.
Will the reusable alkaline battery have a future? *(BU7)*

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.
What's the role of the Supercapacitor? *(BU8)*

The supercapacitor resembles a regular capacitor with the exception that it offers very high capacitance in a small package. Energy storage is by means of static charge rather than of an electro-chemical process that is inherent to the battery. Applying a voltage differential on the positive and negative plates charges the supercapacitor. This concept is similar to an electrical charge that builds up when walking on a carpet. The supercapacitor concept has been around for a number of years. Newer designs allow higher capacities in a smaller size.

Whereas a regular capacitor consists of conductive foils and a dry separator, the supercapacitor crosses into battery technology by using special electrodes and some electrolyte. There are three types of electrode materials suitable for the supercapacitor. They are: high surface area activated carbons, metal oxide and conducting polymers. The high surface area electrode material, also called Double Layer Capacitor (DLC), is least costly to manufacture and is the most common. It stores the energy in the double layer formed near the carbon electrode surface.

The electrolyte may be aqueous or organic. The aqueous variety offers low internal resistance but limits the voltage to one volt. In contrast, the organic electrolyte allows 2.5 volts of charge, but the internal resistance is higher.

To operate at higher voltages, supercapacitors are connected in series. On a string of more than three capacitors, voltage balancing is required to prevent any cell from reaching over-voltage.

The amount of energy a capacitor can hold is measured in microfarads or µF. (1µF = 0.000,001 farad). While small capacitors are rated in nano-farads (1000 times smaller than 1µF) and pico-farads (1 million times smaller than 1µF), supercapacitors come in farads.

The gravimetric energy density of the supercapacitor is 1 to 10Wh/kg. This energy density is high in comparison to a regular capacitor but reflects only one-tenth that of the nickel-metal-hydride battery. Whereas the electro-chemical battery delivers a fairly steady voltage in the usable energy spectrum, the voltage of the supercapacitor is linear and drops evenly from full voltage to zero volts. Because of this, the supercapacitor is unable to deliver the full charge.

If, for example, a 6V battery is allowed to discharge to 4.5V before the equipment cuts off, the supercapacitor reaches that threshold within the first quarter of the discharge cycle. The remaining energy slips into an unusable voltage range. A DC-to-DC converter could correct this problem but such a regulator would add costs and introduce a 10 to 15 percent efficiency loss.

Rather than operate as a main battery, supercapacitors are more commonly used as memory backup to bridge short power interruptions. Another application is improving the current handling of a battery. The supercapacitor is placed in parallel to the battery terminal and provides current boost on high load demands. The supercapacitor will also find a ready market for portable fuel cells to enhance peak-load performance. Because of its ability to rapidly charge, large supercapacitors are used for regenerative braking on vehicles. Up to 400 supercapacitors are connected in series to obtain the required energy storage capacity.
The charge time of a supercapacitor is about 10 seconds. The ability to absorb energy is, to a large extent, limited by the size of the charger. The charge characteristics are similar to those of an electrochemical battery. The initial charge is very rapid; the topping charge takes extra time. Provision must be made to limit the current when charging an empty supercapacitor.

In terms of charging method, the supercapacitor resembles the lead-acid battery. Full charge occurs when a set voltage limit is reached. Unlike the electrochemical battery, the supercapacitor does not require a full-charge detection circuit. Supercapacitors take as much energy as needed. When full, they stop accepting charge. There is no danger of overcharge or 'memory'.

The supercapacitor can be recharged and discharged virtually an unlimited number of times. Unlike the electrochemical battery, there is very little wear and tear induced by cycling and age does not affect the supercapacitor much. In normal use, a supercapacitor deteriorates to about 80 percent after 10 years.

The self-discharge of the supercapacitor is substantially higher than that of the electro-chemical battery. Supercapacitors with an organic electrolyte are affected the most. In 30 to 40 days, the capacity decreases from full charge to 50 percent. In comparison, a nickel-based battery discharges about 10 percent during that time.

Supercapacitors are relatively expensive in terms of cost per watt. Some design engineers argue that the money would be better spent in providing a larger battery by adding extra cells. But the supercapacitor and chemical battery are not necessarily in competition. Rather, they enhance one another.

Advantages

- Virtually unlimited cycle life - can be cycled millions of time.
- Low impedance - enhances load handling when put in paralleled with a battery.
- Rapid charging - supercapacitors charge in seconds.
- Simple charge methods - no full-charge detection is needed; no danger of overcharge.

Limitations

- Linear discharge voltage prevents use of the full energy spectrum.
- Low energy density - typically holds one-fifth to one-tenth the energy of an electrochemical battery.
- Cells have low voltages - serial connections are needed to obtain higher voltages. Voltage balancing is required if more than three capacitors are connected in series.
- High self-discharge - the rate is considerably higher than that of an electrochemical battery.

Information provided by Maxwell Technologies, Inc

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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.

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.

(Photo courtesy 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.)
Safety circuits for modern batteries *(BU10)*

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 excessive heat buildup and the danger of an 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.

![Figure 1: A common safety circuit for cellular phone applications. Because of improved thermal stability of manganese-based lithium-ion, manufacturers relax the need for an external safety circuit on packs with two cells in series.](image)

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 50-100 milli Ohms (mW). 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 voltage limit (4.20V/cell should not be exceeded) 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.

Low-cost cell phone batteries have infiltrated the world market since the beginning of 2003. These counterfeit batteries often do not have an approved protection circuit and can vent with flame if the charger malfunctions. Cell phone manufacturers strongly advise customers to replace the battery with an approved brand. Failing to do so may void the warranty. It is also highly recommended to only use approved chargers. (See photos of an exploded cell phone with a clone battery that was on charge.)

![Figure 2: Damaged cell phone. A cell phone with a no-brand battery vented with flame while charging in the back of a car.](image)

When advising on the choice of batteries and chargers, 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 third parties as long as the products are well built and safe. The buyer can often not distinguish between an original and a counterfeit battery because the label may appear bona fide.

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.
Figure 3: Budging of a lithium-ion cell.
Prismatic Lithium-ion cells are subject to budging, causing stress on the battery compartment of portable devices.

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.
Serial and parallel battery configurations *(BU10A)*

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.](image)

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.

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.

![Figure 4: Parallel connection with one faulty cell. 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.

![Figure 5: Serial/parallel connection of four cells. 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 that 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 loose 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.
Charging nickel-based batteries *(BU11)*

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 case, remove the battery when ready. The caution applies especially to nickel-metalhydride 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 over-charged. 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.

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.
Charging lithium-ion batteries (BU12)

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.

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.

Preparing 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.

Hints to long battery life

- Limit the time at which the battery stays at 4.20/cell. Prolonged high voltage promotes corrosion, especially at elevated temperatures. (Spinel is less sensitive to high voltage than cobalt-based systems).

- 3.92V/cell is the best upper voltage threshold for cobalt-based lithium-ion. Charging batteries to this voltage level has been shown to double cycle life. Lithium-ion systems for defense applications make use of the lower voltage threshold. The negative is reduced capacity.

- The charge current of Li-ion should be moderate (0.5C for cobalt-based lithium-ion). The lower charge current reduces the time in which the cell resides at 4.20V. It should be noted that a 0.5C charge only adds marginally to the charge time over 1C because the topping charge will be shorter. A high current charge tends to push the voltage up and forces it into the voltage limit prematurely.
Note: In respect to fast-charging and topping charge, the charge behavior of lithium-ion is similar to lead acid. Here, the voltage threshold of 2.35V/cell during regular charge needs to be lowered to 2.27V/cell when the VRLA is on standby. Keeping the voltage at the high threshold would contribute to corrosion. A similar effect occurs with lithium-ion.
Charging the lead-acid battery *(BU13)*

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.

![Figure 1: Charge stages of a lead-acid battery. The battery charges at a constant current to a set voltage threshold (Stage 1). As the battery saturates, the current drops (Stage 2). The float charge compensates for the self-discharge (Stage 3).](image)

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.

<table>
<thead>
<tr>
<th>Voltage Limit</th>
<th>2.30V to 2.35V/cell</th>
<th>2.40V to 2.45V/cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantage</td>
<td>Maximum service life, battery remains cool during charge; ambient charge temperature may exceed 30°C (86°F).</td>
<td>Faster charge times; good, consistent capacity readings; less inclined to sulfation.</td>
</tr>
<tr>
<td>Disadvantage</td>
<td>Slow charge time, capacity readings may be inconsistent and declining with each cycle. Sulfation can occur if no topping charge is applied.</td>
<td>Not suitable for charging at high room temperatures. A hot battery may fail to reach the voltage limit, causing severe overcharge. Subject to corrosion.</td>
</tr>
</tbody>
</table>

Figure 2: Effects of charge voltage on a small lead-acid battery (SLA). Cylindrical lead-acid cells have higher voltage settings but are lower for VRLA and car batteries.

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 resided at a steady 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 with calcium being a little higher than antimony. Furthermore, AGM has a higher voltage plateau than the flooded lead acid and the readings on Figure 3 may not apply for AGM systems. Due to surface charge, a brief charge will raise the terminal voltage and provide inflated state-of-charge reading. For example, a 30 minute charge could wrongly indicate 100% SoC if no rest is applied.
With sufficient rest and stable temperature, voltage measurements provide an amazingly accurate SoC estimation for lead acid batteries. It is important that the battery is free of polarization. If connected in a system, such as in a car, there are steady auxiliary loads, not to mention frequent starting and driving.

<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*

Note: The BCI readings apply to flooded batteries with antimony doping. Calcium will raise the voltage by 5 - 8%. Calcium is commonly used for maintenance-free lead acid batteries. After charge or discharge, allow the battery to rest for a minimum of eight hours before assessing the state-of-charge by measuring the terminal voltage.

**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.
Charging at high and low temperatures (BU14)

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.

Nickel-cadmium: In general, older battery technologies 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 reduced 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.

Lithium-ion offers good charging performance at cold and hot temperatures. The acceptable charge range is 0°C to 45°C (32°F to 113°F). It is recommended, however, to reduce the charge rate to less than 1C at temperatures of 5°C to 0°C (41°F to 32°F).

It is important to know that consumer grade lithium-ion batteries cannot be charged below 0°C (32°F). Although the packs appear to be charging normally at freezing temperatures, the cell impedance goes up and the acceptance of the ions on the anode is drastically reduced.

What is most troubling is the plating of metallic lithium that occurs on the anode. The higher the charge rate, the more pronounced the plating will be. A prolonged charge at cold temperatures will eventually compromise the safety of the pack. The plating is permanent and no
amount of cycling can reverse this effect. Unknown to the user, such a battery will become more vulnerable to failure if subjected to impact, crush or high rate charging. Venting with flame could be the result.

Quality chargers reduce the charge current at cold temperatures and avert a charge altogether below 0°C (32°F). When charging a cold battery, allow the pack to warm up before putting it into the charger. Discharging a lithium-ion battery at cold temperature does not cause any harm. The lower performance will only be noticeable while the pack is dwelling in the cold state.

There are specialty Li-ion batteries that allow low-temperature charging. These packs are made for military and aerospace applications. The lower viscosity of the electrolyte of these batteries may reduce the rate capability and decrease the cycle life. Beside lower performance, the high purchase price is another concern for the consumer.

There are also safety concerns when using lithium-ion at high temperatures, especially in cells containing cobalt and/or nickel electrodes. Raising the temperature of a fully charged cell, or applying an overcharge, could cause a spontaneous thermal runaway. The higher the state-of-charge, the less heat is required to induce a thermal runaway. Manganese based cells [spinel] are thermally more stable and the thermal stability is the same whether fully charged or overcharged.

Lead-acid 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 cell 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.

**How to charge - when to charge table (BU14A)**

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.

Batteries behave like humans; some live to a great old age, others die early. Exposure to heat is likely the biggest enemy. Steps can be taken to prolong battery life but an ideal world will not be possible. The table below provides basic instruction in maximizing battery performance from cradle to grave.
<table>
<thead>
<tr>
<th><strong>How should I prepare my new battery?</strong></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><strong>Can I damage my battery if incorrectly prepared?</strong></td>
<td>No; without priming, the performance will be low at first, then gradually improve with use.</td>
<td>No; Li-ion is forgiving to partial and full charge. No priming is needed when new.</td>
<td>Lead acid needs a fully saturated charge to keep good performance. A charge can take over 10h.</td>
</tr>
<tr>
<td><strong>How do I prepare a battery with charge indication?</strong></td>
<td>Fully charge and discharge battery. Repeat when readings get inaccurate.</td>
<td>Fully charge and discharge battery. Repeat when readings get inaccurate.</td>
<td>Larger lead acid use different charge indicator to nickel &amp; lithium-based chemistries.</td>
</tr>
<tr>
<td><strong>Should I use up all battery energy before charging?</strong></td>
<td>Yes, fully discharge once every 1-3 months to prevent memory. It is not necessary to deplete the battery before each charge.</td>
<td>No, it is better to recharge more often; avoid frequent full discharges.</td>
<td>No, it is better to recharge more often; avoid frequent full discharges.</td>
</tr>
<tr>
<td><strong>Should I charge my battery partially or fully?</strong></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><strong>Should the battery be kept charged when not in use?</strong></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><strong>Will the battery heat up during charge?</strong></td>
<td>Yes, towards full charge. The battery must cool down when ready. Necessary to use a charger that keeps the battery warm on standby.</td>
<td>No, little heating is generated during charging. 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 cool on standby.</td>
</tr>
<tr>
<td><strong>What are the allowable charging temperatures?</strong></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>0°C - 45°C (32°F - 113°F)</td>
<td>0°C - 45°C (32°F - 113°F)</td>
</tr>
<tr>
<td><strong>Slow charge (0.1)</strong></td>
<td>0°C - 45°C (32°F - 113°F)</td>
<td>0°C - 45°C (32°F - 113°F)</td>
<td>0°C - 45°C (32°F - 113°F)</td>
</tr>
<tr>
<td><strong>Fast charge (0.5-1C)</strong></td>
<td>5°C - 45°C (41°F - 113°F)</td>
<td>5°C - 45°C (41°F - 113°F)</td>
<td>5°C - 45°C (41°F - 113°F)</td>
</tr>
<tr>
<td><strong>Charging a hot battery decreases the charge time. The battery may not fully charge.</strong></td>
<td><strong>Temperature sensor may prevent charge or cut off the charge.</strong></td>
<td><strong>Temperature sensor may prevent charge or cut off the charge.</strong></td>
<td><strong>Temperature sensor may prevent charge or cut off the charge.</strong></td>
</tr>
<tr>
<td><strong>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.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>A float charge of about 2.27V/cell is advisable. Do not allow the open cell voltage to drop below 2.10V/cell while in storage. (Not used for laptops)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Apply a topping charge to the pack when the battery is fully charged. A laptop may be connected to the AC when not in use.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Larger lead acid use different charge indicator to nickel &amp; lithium-based chemistries.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Discontinue using a charger that keeps the battery warm on standby.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Heat during charge. A fully charged battery can be harmful. (Laptops use Lithium-ion)</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Temperature sensor may prevent charge or cut off the charge.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Battery must cool down when ready. Necessary to use a charger that keeps the battery warm on standby.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>No, it is better to recharge more often; avoid frequent full discharges.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Do not allow the open cell voltage to drop below 2.10V/cell while in storage. (Not used for laptops)</strong></td>
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</tr>
<tr>
<td><strong>A float charge of about 2.27V/cell is advisable. Do not allow the open cell voltage to drop below 2.10V/cell while in storage. (Not used for laptops)</strong></td>
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<tr>
<td><strong>Apply a topping charge to the pack when the battery is fully charged. A laptop may be connected to the AC when not in use.</strong></td>
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<tr>
<td><strong>Larger lead acid use different charge indicator to nickel &amp; lithium-based chemistries.</strong></td>
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<tr>
<td><strong>Discontinue using a charger that keeps the battery warm on standby.</strong></td>
<td></td>
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</tr>
<tr>
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</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 charges 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 September 2005*
Discharging at high and low temperature *(BU15)*

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.

Lithium-ion works within the discharge temperature limits of -20°C to 60°C (-4°F to 140°F). The performance is temperature based, meaning that the rate capability at or below -20°C is reduced due to the increased impedance of the electrolyte. Discharging at low temperatures does not harm the battery. Lithium-ion may be used down to -30°C (-22°F) with acceptable results. Larger packs will be necessary to compensate for the
reduced capacity at these temperatures. It is not recommended to discharge lithium-ion at temperatures above 60°C. A high discharge rates combined with elevated temperatures can cause self-heating, an effect that could permanently damage the separator and electrodes of the cells.

It is not recommended to discharge lithium-ion at temperatures above 60°C. A high discharge rates combined with elevated temperatures can cause self-heating, an effect that could permanently damage the separator and electrodes of the cells.

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.
Discharge methods *(BU16)*

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 spinel 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.

Discharge currents and load signatures

Rechargeable batteries are tolerant to wide range of load signatures. In terms of cycle life, a constant current discharge is better than a digital load. Figure 1 reveals the number of cycles a nickel-metal-hydride battery provides at different load conditions. As can be seen, the capacity loss is greatest on a digital load, such as a cell phone. Increased internal resistance is the principal cause of premature failure.

![Figure 1: Cycle life of nickel-metal-hydride batteries under different operating conditions. (Zhang, 1998)](image)

Although rechargeable batteries provide good overall loading capabilities, the cycle count is higher if the discharge current is kept moderate. Figures 2 shows permanent capacity losses under a 1C, 1.3C and 2C discharge. The test was performed on a lithium-ion battery. Other chemistries show a similar wear-and-tear phenomenon at loads above 1C.
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.
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.

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 intermitted 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? *(BU17)*

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.

![Battery Discharge Pulses](image)

*Figure 1: Discharge curve on a pulsed load with diverse internal resistance. This chart demonstrates the runtime of 3 batteries with same capacities but different internal resistance levels.*

Talk-time as a function of internal resistance

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 phones is 2.5 amperes. This represents a large current from a relatively small battery of about 800 milliampere (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.

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.](image)
**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.

Internal resistance as a function of state-of-charge
The internal resistance 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. The resistance levels are highest at low state-of-charge and immediately after charging. Contrary to popular belief, the best battery performance is not achieved immediately after a full charge but following a rest period of a few hours. During discharge, the internal battery resistance decreases, reaches the lowest point at half charge and starts creeping up again (dotted line).

![Figure 5: 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. References: Shukla et al. 1998. Rodrigues et al. 1999.](image)

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% state-of-charge. The largest changes occur between 0% and 30% SoC.

The resistance of lead acid goes up with discharge. This change is caused by the decrease of the specific gravity, a depletion of the electrolyte as it becomes more watery. The resistance increase is almost linear with the decrease of the specific gravity. A rest of a few hours will partially restore the battery as the sulphate ions can replenish themselves. The resistance change between full charge and discharge is about 40%. Cold temperature increases the internal resistance on all batteries and adds about 50% between +30°C and -18°C to lead acid batteries. Figure 6 reveals the increase of the internal resistance of a gelled lead acid battery used for wheelchairs.
Figure 6: Typical internal resistance readings of a lead acid wheelchair battery. The battery was discharged from full charge to 10.50V. The readings were taken at open circuit voltage (OCV). Cadex battery laboratories.

Created: April 2003, Last edited: October 2006
The 'smart' battery *(BU18)*

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 Benchmark 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.

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
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.
The battery fuel gauge (BU19)

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.

![State-of-charge readout of a 'smart' battery.](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.

![Battery charge capacity.](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.

![Figure 6: Tri-state fuel gauge. The Battery Health Gauge reads the 'learned' battery information available on the SMBus and displays it on a multi-colored LED bar. The illustration shows a partially discharged battery of 50% SoC with a 20% empty portion and an unusable portion of 30%.](image)

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.
Figure 7: The Cadex SM2+ charger This Level 3 charger serves as charger, conditioner and quality control system. It reads the battery’s true state-of-health and flags those that fall below the set target capacity. Each bay operates independently and charges nickel-cadmium, nickel-metal-hydride and lithium?ion chemistries in approximately three hours. 'Dumb' batteries can also be charged but no SoH information is available.

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.
How to store batteries (BU20)

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 3.8V; 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>94%</td>
<td>99%</td>
</tr>
<tr>
<td>25°C</td>
<td>96%</td>
<td>80%</td>
<td>97%</td>
</tr>
<tr>
<td>40°C</td>
<td>85%</td>
<td>65%</td>
<td>95%</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 dip 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 \((BU21)\)

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 requires a high amount of energy. It takes six to ten times the amount of energy to reclaim metals from recycled batteries than it would through other means.

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 sill 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
Do and don’t battery table *(BU22)*

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>Used in</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>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>
<td></td>
</tr>
</tbody>
</table>

**Charging**

<table>
<thead>
<tr>
<th>Do and Don’t</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>Do run the battery fully down once per month; try to use up all energy before charging.</td>
<td>Do run the battery fully down once every 3 months. Over-cycling is not advised.</td>
<td>Do charge the battery often. The battery lasts longer with partial rather than full discharges.</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.</td>
<td></td>
</tr>
<tr>
<td>Do not leave battery in charger for more than 2 days because of memory.</td>
<td>Do not leave battery in charger for more than 2 days because of memory.</td>
<td>Do not use if pack gets hot during charge. Check also charger.</td>
<td>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.</td>
<td></td>
</tr>
<tr>
<td>Avoid getting battery too hot during charge.</td>
<td>Avoid getting battery too hot during charge.</td>
<td>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>Rapid charge = 3h</td>
<td></td>
</tr>
<tr>
<td>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>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>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.</td>
<td>Rapid charge = 3h</td>
<td></td>
</tr>
</tbody>
</table>

**Discharging**

<table>
<thead>
<tr>
<th>Do and Don’t</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>Full cycle does not harm NiCd. NiCd is one of the most hardy and durable chemistries.</td>
<td>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 full cycle because of wear. 80% depth-of-discharge recommended. Recharge 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>
<td></td>
</tr>
</tbody>
</table>

**Service needs**

<table>
<thead>
<tr>
<th>Do and Don’t</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>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. Lose capacity due to aging whether used or not.</td>
<td>Apply topping charge every 6 months. Occasional discharge/charge may improve performance.</td>
<td></td>
</tr>
</tbody>
</table>

**Storage**

<table>
<thead>
<tr>
<th>Do and Don’t</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>Best to store at 40% charge in a cool place. Open terminal voltage cannot determine state-of-charge. 5</td>
<td>Store at 40% charge in a cool place. Open terminal voltage cannot determine state-of-charge.</td>
<td>Store at 40% charge in a cool place (40% state-of-charge reads 3.75-3.80V/cell at open terminal.</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>Disposal</td>
<td>Low volume household NiMH 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>
<td>Prime battery if stored longer than 6 months.</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-------------------------------------------</td>
<td>---------------------------------------------------------------</td>
<td>---------------------------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>Do not dispose; contains toxic metals; must be recycled.</td>
<td>Should be recycled.</td>
<td>Should be recycled.</td>
<td>Do not dispose; must be recycled.</td>
<td>Prime battery if stored longer than 6 months.</td>
</tr>
</tbody>
</table>