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Law Enforcement and Corrections Standards and Testing Program

NEW TECHNOLOGY BATTERIES GUIDE

NIJ Guide 200-98

ABOUT THE LAW ENFORCEMENT AND CORRECTIONS STANDARDS AND TESTING PROGRAM

The Law Enforcement and Corrections Standards and Testing Program is sponsored by the Office of Science and Technology of the National Institute of Justice (NIJ), U.S. Department of Justice. The program responds to the mandate of the Justice System Improvement Act of 1979, which created NIJ and directed it to encourage research and development to improve the criminal justice system and to disseminate the results to Federal, State, and local agencies.

The Law Enforcement and Corrections Standards and Testing Program is an applied research effort that determines the technological needs of justice system agencies, sets minimum performance standards for specific devices, tests commercially available equipment against those standards, and disseminates the standards and the test results to criminal justice agencies nationally and internationally.

The program operates through:

The *Law Enforcement and Corrections Technology Advisory Council* (LECTAC) consisting of nationally recognized criminal justice practitioners from Federal, State, and local agencies, which assesses technological needs and sets priorities for research programs and items to be evaluated and tested.

The *Office of Law Enforcement Standards* (OLES) at the National Institute of Standards and Technology, which develops voluntary national performance standards for compliance testing to ensure that individual items of equipment are suitable for use by criminal justice agencies. The standards are based upon laboratory testing and evaluation of representative samples of each item of equipment to determine the key attributes, develop test methods, and establish minimum performance requirements for each essential attribute. In addition to the highly technical standards, OLES also produces technical reports and user guidelines that explain in nontechnical terms the capabilities of available equipment.

The *National Law Enforcement and Corrections Technology Center* (NLECTC), operated by a grantee, which supervises a national compliance testing program conducted by independent laboratories. The standards developed by OLES serve as performance benchmarks against which commercial equipment is measured. The facilities, personnel, and testing capabilities of the independent laboratories are evaluated by OLES prior to testing each item of equipment, and OLES helps the NLECTC staff review and analyze data. Test results are published in Equipment Performance Reports designed to help justice system procurement officials make informed purchasing decisions.

Publications are available at no charge from the National Law Enforcement and Corrections Technology Center. Some documents are also available online through the Internet/World Wide Web. To request a document or additional information, call 800-248-2742 or 301-519-5060, or write:

National Law Enforcement and Corrections Technology Center
P.O. Box 1160
Rockville, MD 20849-1160
E-mail: *asknlectc@nlectc.org*
World Wide Web address: *http://www.nlectc.org*

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National Institute of Justice

Jeremy Travis
Director

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Enforcement Standards (OLES) of the
National Institute of Standards and Technology (NIST)
under the direction of A. George Lieberman,
Program Manager for Communications Systems,
and Kathleen M. Higgins, Director of OLES.
The work resulting in this guide was sponsored by
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Director, Office of Science and Technology.

FOREWORD

The Office of Law Enforcement Standards (OLES) of the National Institute of Standards and Technology furnishes technical support to the National Institute of Justice program to strengthen law enforcement and criminal justice in the United States. OLES's function is to conduct research that will assist law enforcement and criminal justice agencies in the selection and procurement of quality equipment.

OLES is: (1) subjecting existing equipment to laboratory testing and evaluation, and (2) conducting research leading to the development of several series of documents, including national standards, user guides, and technical reports.

This document covers research conducted by OLES under the sponsorship of the National Institute of Justice. Additional reports as well as other documents are being issued under the OLES program in the areas of protective clothing and equipment, communications systems, emergency equipment, investigative aids, security systems, vehicles, weapons, and analytical techniques and standard reference materials used by the forensic community.

Technical comments and suggestions concerning this report are invited from all interested parties. They may be addressed to the Director, Office of Law Enforcement Standards, National Institute of Standards and Technology, Gaithersburg, MD 20899.

David G. Boyd, Director
Office of Science and Technology
National Institute of Justice

BACKGROUND

The Office of Law Enforcement Standards (OLES) was established by the National Institute of Justice (NIJ) to provide focus on two major objectives: (1) to find existing equipment which can be purchased today, and (2) to develop new law-enforcement equipment which can be made available as soon as possible. A part of OLES's mission is to become thoroughly familiar with existing equipment, to evaluate its performance by means of objective laboratory tests, to develop and improve these methods of test, to develop performance standards for selected equipment items, and to prepare guidelines for the selection and use of this equipment. All of these activities are directed toward providing law enforcement agencies with assistance in making good equipment selections and acquisitions in accordance with their own requirements.

As the OLES program has matured, there has been a gradual shift in the objectives of the OLES projects. The initial emphasis on the development of standards has decreased, and the emphasis on the development of guidelines has increased. For the significance of this shift in emphasis to be appreciated, the precise definitions of the words "standard" and "guideline" as used in this context must be clearly understood.

A "standard" for a particular item of equipment is understood to be a formal document, in a conventional format, that details the performance that the equipment is required to give, and describes test methods by which its actual performance can be measured. These requirements are technical, and are stated in terms directly related to the equipment's use. The basic purposes of a standard are (1) to be a reference in procurement documents created by purchasing officers who wish to specify equipment of the "standard" quality, and (2) to identify objectively equipment of acceptable performance.

A standard is not intended to inform and guide the reader; that is the function of a guideline

Note that a standard is not intended to inform and guide the reader; that is the function of a "guideline." Guidelines are written in non-technical language and are addressed to the potential user of the equipment. They include a general discussion of the equipment, its important performance attributes, the various models currently on the market, objective test data where available, and any other information that might help the reader make a rational selection among the various options or alternatives available to him or her.

This battery guide is provided to inform the reader of the latest technology related to battery composition, battery usage, and battery charging techniques.

Kathleen Higgins
National Institute of Standards and Technology
March 27, 1997

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COMMONLY USED SYMBOLS AND ABBREVIATIONS

A	ampere	H	henry	nm	nanometer
ac	alternating current	h	hour	No.	number
AM	amplitude modulation	hf	high frequency	o.d.	outside diameter
cd	candela	Hz	hertz (c/s)	Ω	ohm
cm	centimeter	i.d.	inside diameter	p.	page
CP	chemically pure	in	inch	Pa	pascal
c/s	cycle per second	ir	infrared	pe	probable error
d	day	J	joule	pp.	pages
dB	decibel	L	lambert	ppm	part per million
dc	direct current	L	liter	qt	quart
°C	degree Celsius	lb	pound	rad	radian
°F	degree Fahrenheit	lbf	pound-force	rf	radio frequency
dia	diameter	lbf·in	pound-force inch	rh	relative humidity
emf	electromotive force	lm	lumen	s	second
eq	equation	ln	logarithm (natural)	SD	standard deviation
F	farad	log	logarithm (common)	sec.	section
fc	footcandle	M	molar	SWR	standing wave ratio
fig.	figure	m	meter	uhf	ultrahigh frequency
FM	frequency modulation	min	minute	uv	ultraviolet
ft	foot	mm	millimeter	V	volt
ft/s	foot per second	mph	mile per hour	vhf	very high frequency
g	acceleration/gravity	m/s	meter per second	W	watt
g	gram	N	newton	λ	wavelength
gr	grain	N·m	newton meter	wt	weight

area=unit^2 (e.g., ft^2, in^2, etc.); volume=unit^3 (e.g., ft^2, m^3, etc.)

PREFIXES

d	deci (10^{-1})	da	deka (10)
c	centi (10^{-2})	h	hecto (10^{2})
m	milli (10^{-3})	k	kilo (10^{3})
µ	micro (10^{-6})	M	mega (10^{6})
n	nano (10^{-9})	G	giga (10^{9})
p	pico (10^{-12})	T	tera (10^{12})

COMMON CONVERSIONS (See ASTM E380)

ft/s×0.3048000=m/s	lb×0.4535924=kg
ft×0.3048=m	lbf×4.448222=N
ft·lbf×1.355818=J	lbf/ft×14.59390=N/m
gr×0.06479891=g	lbf·in×0.1129848=N·m
in×2.54=cm	lbf/in^2×6894.757=Pa
kWh×3600000=J	mph1.609344=km/h
	qt×0.9463529=L

Temperature: $(T_{^\circ F} - 32)\times 5/9 = T_{^\circ C}$
Temperature: $(T_{^\circ C} \times C9/5) + 32 = T_{^\circ F}$

1. Fundamentals of Battery Technology

1.1 WHAT IS A BATTERY?

A battery, in concept, can be any device that stores energy for later use. A rock, pushed to the top of a hill, can be considered a kind of battery, since the energy used to push it up the hill (chemical energy, from muscles or combustion engines) is converted and stored as potential kinetic energy at the top of the hill. Later, that energy is released as kinetic and thermal energy when the rock rolls down the hill.

Common use of the word, “battery,” however, is limited to an electro-chemical device that converts chemical energy into electricity, by use of a galvanic cell. A galvanic cell is a fairly simple device consisting of two electrodes (an anode and a cathode) and an electrolyte solution. Batteries consist of one or more galvanic cells.

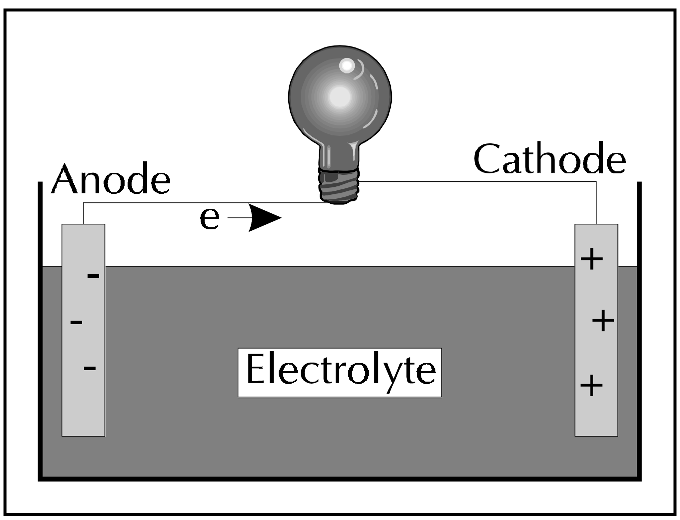

Figure 1. Conceptual diagram of a galvanic cell.

1.2 HOW DOES A BATTERY WORK?

Figure 1 shows a simple galvanic cell. Electrodes (two plates, each made from a different kind of metal or metallic compound) are placed in an electrolyte solution. External wires connect the electrodes to an electrical load (a light bulb in this case). The metal in the anode (the negative terminal) oxidizes (*i.e.*, it “rusts”), releasing negatively charged electrons and positively charged metal ions. The electrons travel through the wire (and the electrical load) to the cathode (the positive terminal). The electrons combine with the material in the cathode. This combination process is called reduction, and it releases a negatively charged metal-oxide ion. At the interface with the electrolyte, this ion causes a water molecule to split into a hydrogen ion and a hydroxide ion. The positively charged hydrogen ion combines with the negatively charged metal-oxide ion and becomes inert. The negatively charged hydroxide ion flows through the electrolyte to the anode where it combines with the positively charged metal ion, forming a water molecule and a metal-oxide molecule.

In effect, metal ions from the anode will “dissolve” into the electrolyte solution while hydrogen molecules from the electrolyte are deposited onto the cathode.

When the anode is fully oxidized or the cathode is fully reduced, the chemical reaction will stop and the battery is considered to be discharged.

Recharging a battery is usually a matter of externally applying a voltage across the plates to reverse the chemical process. Some chemical reactions, however, are difficult or impossible to reverse. Cells with irreversible reactions are commonly known as primary cells, while cells with reversible reactions are known as secondary cells. It is dangerous to attempt to recharge primary cells.

The amount of voltage and current that a galvanic cell produces is directly related to the types of materials used in the electrodes and electrolyte. The length of time the cell can produce that voltage and current is related to the amount of active material in the cell and the cell's design.

Every metal or metal compound has an electromotive force, which is the propensity of the metal to gain or lose electrons in relation to another material. Compounds with a positive electromotive force will make good anodes and those with a negative force will make good cathodes. The larger the difference between the electromotive forces of the anode and cathode, the greater the amount of energy that can be produced by the cell. **Table 1** shows the electromotive force of some common battery components.

Table 1. The Electromotive Series for Some Battery Components

Anode Materials (Listed from worst [most positive] to best [most negative])	**Cathode Materials** (Listed from best [most positive] to worst [most negative])
Gold	Ferrate
Platinum	Iron Oxide
Mercury	Cuprous Oxide
Palladium	Iodate
Silver	Cupric Oxide
Copper	Mercuric Oxide
Hydrogen	Cobaltic Oxide
Lead	Manganese Dioxide
Tin	Lead Dioxide
Nickel	Silver Oxide
Iron	Oxygen
Chromium	Nickel Oxyhydroxide
Zinc	Nickel Dioxide
Aluminum	Silver Peroxide
Magnesium	Permanganate
Lithium	Bromate

Over the years, battery specialists have experimented with many different combinations of material and have generally tried to balance the potential energy output of a battery with the costs of manufacturing the battery. Other factors, such as battery weight, shelf life, and environmental impact, also enter into a battery's design.

1.3 Galvanic Cells vs. Batteries

From earlier discussion, we know that a battery is one or more galvanic cells connected in series or in parallel.

A battery composed of two 1.5 V galvanic cells connected in series, for example, will produce 3 V. A typical 9 V battery is simply six 1.5 V cells connected in series. Such a series battery, however, will produce a current that is the equivalent to just one of the galvanic cells.

A battery composed of two 1.5 V galvanic cells connected in parallel, on the other hand, will still produce a voltage of 1.5 V, but the current provided can be double the current that just one cell would create. Such a battery can provide current twice as long as a single cell.

A battery is one or more galvanic cells connected in series or in parallel

Many galvanic cells can be thus connected to create a battery with almost any current at any voltage level.

1.4 Primary Battery

A primary battery is a battery that is designed to be cycled (fully discharged) only once and then discarded. Although primary batteries are often made from the same base materials as secondary (rechargeable) batteries, the design and manufacturing processes are not the same.

Battery manufacturers recommend that primary batteries not be recharged. Although attempts at recharging a primary battery will occasionally succeed (usually with a diminished capacity), it is more likely that the battery will simply fail to hold any charge, will leak electrolyte onto the battery charger, or will overheat and cause a fire. It is unwise and dangerous to recharge a primary battery.

1.5 Secondary Battery

A secondary battery is commonly known as a rechargeable battery. It is usually designed to have a lifetime of between 100 and 1000 recharge cycles, depending on the composite materials.

Secondary batteries are, generally, more cost effective over time than primary batteries, since the battery can be recharged and reused. A single discharge cycle of a primary battery, however, will provide more current for a longer period of time than a single discharge cycle of an equivalent secondary battery.

1.6 Battery Labels

The American National Standards Institute (ANSI) Standard, ANSI C18.1M-1992, lists several battery features that must be listed on a battery's label. They are:

- **Manufacturer --** The name of the battery manufacturer.
- **ANSI Number --** The ANSI/NEDA number of the battery.
- **Date --** The month and year that the battery was manufactured or the month and year that the battery "expires" (*i.e.*, is no longer guaranteed by the manufacturer).
- **Voltage --** The nominal battery voltage.

- **Polarity --** The positive and negative terminals. The terminals must be clearly marked.
- **Warnings --** Other warnings and cautions related to battery usage and disposal.

2. Available Battery Types

2.1 General

2.1.1 Acid vs. Alkaline

Batteries are often classified by the type of electrolyte used in their construction. There are three common classifications: acid, mildly acid, and alkaline.

Acid-based batteries often use sulphuric acid as the major component of the electrolyte. Automobile batteries are acid-based. The electrolyte used in mildly acidic batteries is far less corrosive than typical acid-based batteries and usually includes a variety of salts that produce the desired acidity level. Inexpensive household batteries are mildly acidic batteries.

Alkaline batteries typically use sodium hydroxide or potassium hydroxide as the main component of the electrolyte. Alkaline batteries are often used in applications where long-lasting, high-energy output is needed, such as cellular phones, portable CD players, radios, pagers, and flash cameras.

2.1.2 Wet vs. Dry

"Wet" cells refer to galvanic cells where the electrolyte is liquid in form and is allowed to flow freely within the cell casing. Wet batteries are often sensitive to the orientation of the battery. For example, if a wet cell is oriented such that a gas pocket accumulates around one of the electrodes, the cell will not produce current. Most automobile batteries are wet cells.

"Dry" cells are cells that use a solid or powdery electrolyte. These kind of electrolytes use the ambient moisture in the air to complete the chemical process. Cells with liquid electrolyte can be classified as "dry" if the electrolyte is immobilized by some mechanism, such as by gelling it or by holding it in place with an absorbent substance such as paper.

In common usage, "dry cell" batteries will usually refer to zinc-carbon cells (Sec. 2.3.1) or zinc-alkaline-manganese dioxide cells (Sec. 2.3.2), where the electrolyte is often gelled or held in place by absorbent paper.

Some cells are difficult to categorize. For example, one type of cell is designed to be stored for long periods without its electrolyte present. Just before power is needed from the cell, liquid electrolyte is added.

2.1.3 Categories

Batteries can further be classified by their intended use. The following sections discuss four generic categories of batteries; "vehicular" batteries (Sec. 2.2), "household" batteries (Sec. 2.3), "specialty" batteries (Sec. 2.4), and "other" batteries (Sec. 2.5). Each section will focus on the general properties of that category of battery.

Note that some battery types (acidic or alkaline, wet or dry) can fall into several different *categories*. For this guideline, battery types are placed into the category in which they are most likely to be found in commercial usage.

2.2 Vehicular Batteries

This section discusses battery types and configurations that are typically used in motor vehicles. This category can include batteries that drive electric motors directly or those that provide starting energy for combustion engines. This category will also include large, stationary batteries used as power sources for emergency building lighting, remote-site power, and computer back up.

Vehicular batteries are usually available off-the-shelf in standard designs or can be custom built for specific applications.

Battery manufacturing is the single largest use for lead in the world.

2.2.1 Lead-Acid

Lead-acid batteries, developed in the late 1800s, were the first commercially practical batteries. Batteries of this type remain popular because they are relatively inexpensive to produce and sell. The most widely known uses of lead-acid batteries are as automobile batteries. Rechargeable lead-acid batteries have become the most widely used type of battery in the world—more than 20 times the use rate of its nearest rivals. In fact, battery manufacturing is the single largest use for lead in the world.[1]

[1] *Encyclopedia of Physical Science and Technology*, Brooke Schumm, Jr., 1992.

Equation 1 shows the chemical reaction in a lead-acid cell.

$$PbO_2 + Pb + 2H_2SO_4 \blacktriangleright\blacktriangleright\blacktriangleright 2PbSO_4 + 2H_2O$$

Equation 1. The chemical reaction in a lead-acid battery.

Lead-acid batteries remain popular because they can produce high or low currents over a wide range of temperatures, they have good shelf life and life cycles, and they are relatively inexpensive to manufacture. Lead-acid batteries are usually rechargeable.

Lead-acid batteries come in all manner of shapes and sizes, from household batteries to large batteries for use in submarines. The most noticeable shortcomings of lead-acid batteries are their relatively heavy weight and their falling voltage profile during discharge (Sec. 3.5).

2.2.2 Sealed vs. Flooded

In “flooded” batteries, the oxygen created at the positive electrode is released from the cell and vented into the atmosphere. Similarly, the hydrogen created at the negative electrode is also vented into the atmosphere. The overall result is a net loss of water (H_2O) from the cell. This lost water needs to be periodically replaced. Flooded batteries must be vented to prevent excess pressure from the build up of these gases. Also, the room or enclosure housing the battery must be vented, since a concentrated hydrogen and oxygen atmosphere is explosive.

In sealed batteries, however, the generated oxygen combines chemically with the lead and then the hydrogen at the negative electrode, and then again with reactive agents in the electrolyte, to recreate water. The net result is no significant loss of water from the cell.

2.2.3 Deep-Cycle Batteries

Deep-cycle batteries are built in configurations similar to those of regular batteries, except that they are specifically designed for prolonged use rather than for short bursts of use followed by a short recycling period. The term "deep-cycle" is most often applied to lead-acid batteries. Deep-cycle batteries require longer charging times, with lower current levels, than is appropriate for regular batteries.

As an example, a typical automobile battery is usually used to provide a short, intense burst of electricity to the automobile's starter. The battery is then quickly recharged by the automobile's electrical system as the engine runs. The typical automobile battery is not a deep-cycle battery.

A battery that provides power to a recreational vehicle (RV), on the other hand, would be expected to power lights, small appliances, and other electronics over an extended period of time, even while the RV's engine is not running. Deep-cycle batteries are more appropriate for this type of continual usage.

2.2.4 Battery Categories for Vehicular Batteries

Vehicular, lead-acid batteries are further grouped (by typical usage) into three different categories:

✔ **Starting-Lighting-Ignition (SLI) --** Typically, these batteries are used for short, quick-burst, high-current applications. An example is an automotive battery, which is expected to provide high current, occasionally, to the engine's starter.

✔ **Traction --** Traction batteries must provide moderate power through many deep discharge cycles. One typical use of traction batteries is to provide power for small electric vehicles, such as golf carts. This type of battery use is also called **Cycle Service**.

✔ **Stationary --** Stationary batteries must have a long shelf life and deliver moderate to high currents when called upon. These batteries are most often used for emergencies. Typical uses for stationary batteries are in uninteruptable power supplies (UPS) and for emergency lighting in stairwells and hallways. This type of battery use is also called **Standby** or **Float**.

2.3 "HOUSEHOLD" BATTERIES

"Household" batteries are those batteries that are primarily used to power small, portable devices such as flashlights, radios, laptop computers, toys, and cellular phones. The following subsections describe the technologies for many of the formerly used and presently used types of household batteries.

Typically, household batteries are small, 1.5 V cells that can be readily purchased off the shelf. These batteries come in standard shapes and sizes as shown in **Table 2**. They can also be custom designed and molded to fit any size battery compartment (*e.g.*, to fit inside a cellular phone, camcorder, or laptop computer).

Table 2. Various Popular Household-Battery Sizes

Size	Shape and Dimensions	Voltage
D	Cylindrical, 61.5 mm tall, 34.2 mm diameter.	1.5 V
C	Cylindrical, 50.0 mm tall, 26.2 mm diameter.	1.5 V
AA	Cylindrical, 50.5 mm tall, 14.5 mm diameter.	1.5 V
AAA	Cylindrical, 44.5 mm tall, 10.5 mm diameter	1.5 V
9 Volt	Rectangular, 48.5 mm tall, 26.5 mm wide, 17.5 mm deep.	9 V

Note: Three other standard sizes of household batteries are available, AAAA, N, and 6-V (lantern) batteries. It is estimated that 90% of portable, battery-operated devices require AA, C, or D battery sizes.

Most of the rest of this guideline will focus on designs, features, and uses of household batteries.

2.3.1 Zinc-carbon (Z-C)

Zinc-carbon cells, also known as “Leclanché cells” are widely used because of their relatively low cost. **Equation 2** shows the chemical reaction in a Leclanché cell. They were the first widely available household batteries. Zinc-carbon cells are composed of a manganese dioxide and carbon cathode, a zinc anode, and zinc chloride (or ammonium chloride) as the electrolyte.

$$Zn + 2MnO_2 + 2NH_4Cl \rightarrow Zn(NH_3)_2Cl_2 + 2MnOOH$$

Equation 2. The chemical reaction in a Leclanché cell.

Generally, zinc-carbon cells are not rechargeable and they have a sloping discharge curve (*i.e.*, the voltage level decreases relative to the amount of discharge). Zinc-carbon cells will produce 1.5 V, and they are mostly used for non-critical uses such as small household devices like flashlights and portable personal radios.

One notable drawback to these kind of batteries is that the outer, protective casing of the battery is made of zinc. The casing serves as the anode for the cell and, in some cases, if the anode does not oxidize evenly, the casing can develop holes that allow leakage of the mildly acidic electrolyte which can damage the device being powered.

2.3.2 Zinc-Manganese Dioxide Alkaline Cells (“Alkaline Batteries”)

When an alkaline electrolyte—instead of the mildly acidic electrolyte—is used in a regular zinc-carbon battery, it is called an “alkaline” battery. An alkaline battery can have a useful life of five to six times that of a zinc-carbon battery. One manufacturer estimates that 30% of the household batteries sold in the world today are zinc-manganese dioxide (*i.e.*, alkaline) batteries.[2,3]

2.3.3 Rechargeable Alkaline Batteries

Like zinc-carbon batteries, alkaline batteries are not generally rechargeable. One major battery manufacturer, however, has designed a "reusable alkaline" battery that they market as being rechargeable "25 times or more."[4]

This manufacturer states that its batteries do not suffer from memory effects as the Ni-Cd batteries do, and that their batteries have a shelf life that is much longer than Ni-Cd batteries—almost as long as the shelf life of primary alkaline batteries.

Also, the manufacturer states that their rechargeable alkaline batteries contain no toxic metals, such as mercury or cadmium, to contribute to the poisoning of the environment.

Rechargeable alkaline batteries are most appropriate for low- and moderate-power portable equipment, such as hand-held toys and radio receivers.

2.3.4 Nickel-Cadmium (Ni-Cd)

Nickel-cadmium cells are the most commonly used rechargeable household batteries. They are useful for powering small appliances, such as garden tools and cellular phones. The basic galvanic cell in a Ni-Cd battery contains a cadmium anode, a nickel hydroxide cathode, and an alkaline electrolyte. **Equation 3** shows the chemical reaction in a Ni-Cd cell. Batteries made from Ni-Cd cells offer high currents at relatively constant voltage and they are tolerant of physical abuse. Nickel-cadmium batteries are also tolerant of inefficient usage cycling. If a Ni-Cd battery has incurred memory loss (Sec. 3.4), a few cycles of discharge and recharge can often restore the battery to nearly "full" memory.

$$Cd + 2H_2O + 2NiOOH \rightarrow 2Ni(OH)_2 + Cd(OH)_2$$

Equation 3. The chemical reaction in a nickel-cadmium battery.

Unfortunately, nickel-cadmium technology is relatively expensive. Cadmium is an expensive metal and is toxic. Recent regulations limiting the disposal of waste cadmium (from cell manufacturing or from disposal of used batteries) has contributed to the higher costs of making and using these batteries.

These increased costs do have one unexpected advantage. It is more cost effective to recycle and reuse many of the components of a Ni-Cd battery than it is to recycle components of other types of batteries. Several of the major battery manufacturers are leaders in such recycling efforts.

[2] *The Story of Packaged Power*, Duracell International, Inc., July, 1995.

[3] Certain commercial companies, equipment, instruments, and materials are identified in this report to specify adequately the technical aspects of the reported results. In no case does such identification imply recommendation or endorsement by the National Institute of Justice, or any other U.S. Government department or agency, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

[4] *Household Batteries and the Environment*, Rayovac Corporation, 1995.

2.3.5 Nickel-Metal Hydride (Ni-MH)

Battery designers have investigated several other types of metals that could be used instead of cadmium to create high-energy secondary batteries that are compact and inexpensive. The nickel-metal-hydride cell is a widely used alternative.

The anode of a Ni-MH cell is made of a hydrogen storage metal alloy, the cathode is made of nickel oxide, and the electrolyte is a potassium hydroxide solution.

According to one manufacturer, Ni-MH cells can last 40% longer than the same size Ni-Cd cells and will have a life-span of up to 600 cycles.[5] This makes them useful for high-energy devices such as laptop computers, cellular phones, and camcorders.

Lithium will ignite or explode on contact with water.

Ni-MH batteries have a high self-discharge rate and are relatively expensive.

2.3.6 Nickel-Iron (Ni-I)

Nickel-iron cells, also known as the Edison battery, are much less expensive to build and to dispose of than nickel-cadmium cells. Nickel-iron cells were developed even before the nickel-cadmium cells. The cells are rugged and reliable, but do not recharge very efficiently. They are widely used in industrial settings and in eastern Europe, where iron and nickel are readily available and inexpensive.

2.3.7 Nickel-Zinc (Ni-Z)

Another alternative to using cadmium electrodes is using zinc electrodes. Although the nickel-zinc cell yields promising energy output, the cell has some unfortunate performance limitations that prevent the cell from having a useful lifetime of more than 200 or so charging cycles. When nickel-zinc cells are recharged, the zinc does not redeposit in the same “holes” on the anode that were created during discharge. Instead, the zinc redeposits in a somewhat random fashion, causing the electrode to become misshapen. Over time, this leads to the physical weakening and eventual failure of the electrode.

2.3.8 Lithium and Lithium Ion

Lithium is a promising reactant in battery technology, due to its high electro-positivity. The specific energy of some lithium-based cells can be five times greater than an equivalent-sized lead-acid cell and three times greater than alkaline batteries.[6] Lithium cells will often have a starting voltage of 3.0 V. These characteristics translate into batteries that are lighter in weight, have lower per-use costs, and have higher and more stable voltage profiles. **Equation 4** shows the chemical reaction in one kind of lithium cell.

[5] *The Story of Packaged Power*, Duracell International, Inc., July, 1995.

[6] *Why Use Energizer AA Lithium Batteries?*, Eveready Battery Company, Inc., 1993.

$$Li + MnO_2 \blacktriangleright\blacktriangleright\blacktriangleright LiMnO_2$$

Equation 4. The chemical reaction in a lithium-manganese dioxide cell.

Unfortunately, the same feature that makes lithium attractive for use in batteries—its high electrochemical potential—also can cause serious difficulties in the manufacture and use of such batteries. Many of the inorganic components of the battery and its casing are destroyed by the lithium ions and, on contact with water, lithium will react to create hydrogen which can ignite or can create excess pressure in the cell. Many fire extinguishers are water based and will cause disastrous results if used on lithium products. Special D-class fire extinguishers must be used when lithium is known to be within the boundaries of a fire.[7]

Lithium also has a relatively low melting temperature for a metal, 180 °C (356 °F). If the lithium melts, it may come into direct contact with the cathode, causing violent chemical reactions.

Because of the potentially violent nature of lithium, the Department of Transportation (DOT) has special guidelines for the transport and handling of lithium batteries. Contact them to ask for DOT Regulations 49 CFR.

Some manufacturers are having success with lithium-iron sulfide, lithium-manganese dioxide, lithium-carbon monoflouride, lithium-cobalt oxide, and lithium-thionyl cells.

In recognition of the potential hazards of lithium components, manufacturers of lithium-based batteries have taken significant steps to add safety features to the batteries to ensure their safe use.

Lithium primary batteries (in small sizes, for safety reasons) are currently being marketed for use in flash cameras and computer memory. Lithium batteries can last three times longer than alkaline batteries of the same size.[8] But, since the cost of lithium batteries can be three times that of alkaline batteries, the cost benefits of using lithium batteries are marginal.

Button-size lithium batteries are becoming popular for use in computer memory back-up, in calculators, and in watches. In applications such as these, where changing the battery is difficult, the longer lifetime of the lithium battery makes it a desirable choice.

One company now produces secondary lithium-ion batteries with a voltage of 3.7 V, "four times the energy density of Ni-Cd batteries," "one-fifth the weight of Ni-Cd batteries," and can be recharged 500 times.[9]

In general, secondary (rechargeable) lithium-ion batteries have a good high-power performance, an excellent shelf life, and a better life span than Ni-Cd batteries. Unfortunately, they have a very high initial

[7] Battery Engineering Web Site, http://www.batteryeng.com/, August 1997.

[8] *Navy Primary and Secondary Batteries. Design and Manufacturing Guidelines*, NAVSO P-3676, September 1991.

[9] Battery Engineering Web Site, http://www.batteryeng.com/, August 1997.

cost and the total energy available per usage cycle is somewhat less than Ni-Cd batteries.

2.4 SPECIALTY BATTERIES ("BUTTON" AND MINIATURE BATTERIES)

"Button" batteries are the nickname given to the category of batteries that are small and shaped like a coin or a button. They are typically used for small devices such as cameras, calculators, and electronic watches.

Miniature batteries are very small batteries that can be custom built for devices, such as hearing aids and electronic "bugs," where even button batteries can be too large. Industry standardization has resulted in five to ten standard types of miniature batteries that are used throughout the hearing-aid industry.

Together, button batteries and miniature batteries are referred to as specialty batteries.

Most button and miniature batteries need a very high energy density to compensate for their small size. The high energy density is achieved by the use of highly electro-positive—and expensive—metals such as silver or mercury. These metals are not cost effective enough to be used in larger batteries.

Several compositions of specialty batteries are described in the following sections.

2.4.1 Metal-Air Cells

A very practical way to obtain high energy density in a galvanic cell is to utilize the oxygen in air as a "liquid" cathode. A metal, such as zinc or aluminum, is used as the anode. The oxygen cathode is reduced in a portion of the cell that is physically isolated from the anode. By using a gaseous cathode, more room is available for the anode and electrolyte, so the cell size can be very small while providing good energy output. Small metal-air cells are available for applications such as hearing aids, watches, and clandestine listening devices.

Metal-air cells have some technical drawbacks, however. It is difficult to build and maintain a cell where the oxygen acting as the cathode is completely isolated from the anode. Also, since the electrolyte is in direct contact with air, approximately one to three months after it is activated, the electrolyte will become too dry to allow the chemical reaction to continue. To prevent premature drying of the cells, a seal is installed on each cell at the time of manufacture. This seal must be removed by the customer prior to first use of the cell. Alternately, the manufacturer can provide the battery in an air-tight package.

2.4.2 Silver Oxide

Silver oxide cells use silver oxide as the cathode, zinc as the anode, and potassium hydroxide as the electrolyte. Silver oxide cells have a moderately high energy density and a relatively flat voltage profile. As a result, they can be readily used to create specialty batteries. Silver oxide cells can provide higher currents for longer periods than most other specialty batteries, such as those designed from metal-air technology. Due to the high cost of silver, silver oxide technology is currently limited to use in specialty batteries.

2.4.3 Mercury Oxide

Mercury oxide cells are constructed with a zinc anode, a mercury oxide cathode, and potassium hydroxide or sodium hydroxide as the electrolyte. Mercury oxide cells have a high energy density and flat voltage profile resembling the energy density and voltage profile of silver oxide cells. These mercury oxide cells are also ideal for producing specialty batteries. The component, mercury, unfortunately, is relatively expensive and its disposal creates environmental problems.

2.5 OTHER BATTERIES

This section describes battery technology that is not mature enough to be available off-the-shelf, has special usage limitations, or is otherwise impractical for general use.

2.5.1 Nickel-Hydrogen (Ni-H)

Nickel-hydrogen cells were developed for the U.S. space program. Under certain pressures and temperatures, hydrogen (which is, surprisingly, classified as an alkali metal) can be used as an active electrode opposite nickel. Although these cells use an environmentally attractive technology, the relatively narrow range of conditions under which they can be used, combined with the unfortunate volatility of hydrogen, limits the long-range prospects of these cells for terrestrial uses.

2.5.2 Thermal Batteries

A thermal battery is a high-temperature, molten-salt primary battery. At ambient temperatures, the electrolyte is a solid, non-conducting inorganic salt. When power is required from the battery, an internal pyrotechnic heat source is ignited to melt the solid electrolyte, thus allowing electricity to be generated electrochemically for periods from a few seconds to an hour. Thermal batteries are completely inert until the electrolyte is melted and, therefore, have an excellent shelf life, require no maintenance, and can tolerate physical abuse (such as vibrations or shocks) between uses.

Thermal batteries can generate voltages of 1.5 V to 3.3 V, depending on the battery's composition. Due to their rugged construction and absence of maintenance requirements, they are most often used for military applications such as missiles, torpedoes, and space missions and for emergency-power situations such as those in aircraft or submarines.

The high operating temperatures and short active lives of thermal batteries limit their use to military and other large-institution applications.

2.5.3 Super Capacitor

This kind of battery uses no chemical reaction at all. Instead, a special kind of carbon (carbon aerogel), with a large molecular surface area, is used to create a capacitor that can hold a large amount of electrostatic energy.[10] This energy can be released very quickly, providing a specific energy of up to 4000 Watt-hours per kilogram (Wh/kg), or it can be regulated to provide smaller currents typical of many commercial devices such as flashlights, radios, and toys. Because there are no chemical reactions, the battery can be recharged hundreds of thousands of times without degradation. Other potential advantages of this kind of cell are its low cost and wide temperature range. One disadvantage, however, is its high self-discharge rate. The voltage of some prototypes is approximately 2.5 V.

[10] PolyStor Web Page, http://www.polystor.com/, August, 1997.

2.5.4 The Potato Battery

One interesting science experiment involves sticking finger-length pieces of copper and zinc wire, one at a time, into a raw potato to create a battery. The wires will carry a very weak current which can be used to power a small electrical device such as a digital clock.

One vendor sells a novelty digital watch that is powered by a potato battery. The wearer must put a fresh slice of potato in the watch every few days.

2.5.5 The Sea Battery

Another interesting battery design uses a rigid framework, containing the anode and cathode, which is immersed into the ocean to use sea water as the electrolyte. This configuration seems promising as an emergency battery for marine use.

2.5.6 Other Developments

Scientists are continually working on new combinations of materials for use in batteries, as well as new manufacturing methods to extract more energy from existing configurations.

3. Performance, Economics and Tradeoffs

3.1 ENERGY DENSITIES

The energy density of a battery is a measure of how much energy the battery can supply relative to its weight or volume. A battery with an energy density twice that of another battery should, theoretically, have an active lifetime twice as long.

The energy density of a battery is mainly dependent on the composition of its active components. A chemist can use mathematical equations to determine the theoretical maximum voltage and current of a proposed cell, if the chemical composition of the anode, cathode, and electrolyte of the cell are all known. Various physical attributes, such as purity of the reactants and the particulars of the manufacturing process can cause the measured voltage, current, and capacity to be lower than their theoretical values.

3.2 ENERGY PER MASS

Figure 2 compares the gravimetric energy densities of various dry cell systems discharged at a constant rate for temperatures between -40 °C (-40 °F) and 60 °C (140 °F).

Of the systems shown, the zinc-air cell produces the highest gravimetric energy density. Basic zinc-carbon cells have the lowest gravimetric energy density.

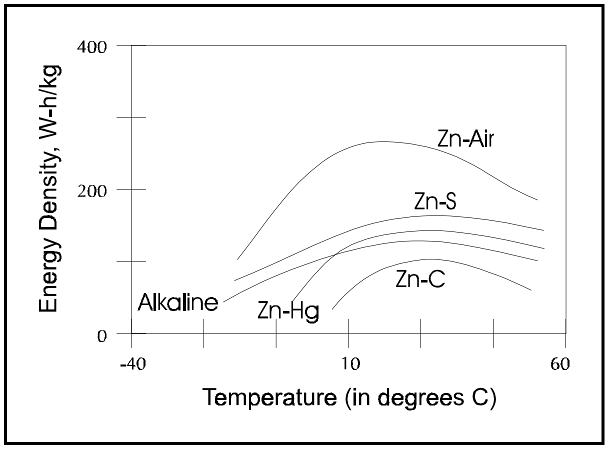

Figure 2. Energy densities, W·h/kg, of various battery types (adapted from NAVSO P-3676).

3.3 ENERGY PER VOLUME

Figure 3 compares the volumetric energy densities of various dry cell systems discharged at a constant rate for temperatures between -40 °C (-40 °F) and 60 °C (140 °F).

Of the systems shown, the zinc-air cell produces the highest volumetric energy density. Basic zinc-carbon cells have the lowest volumetric energy density. The curves for secondary battery cells are not shown in the tables.

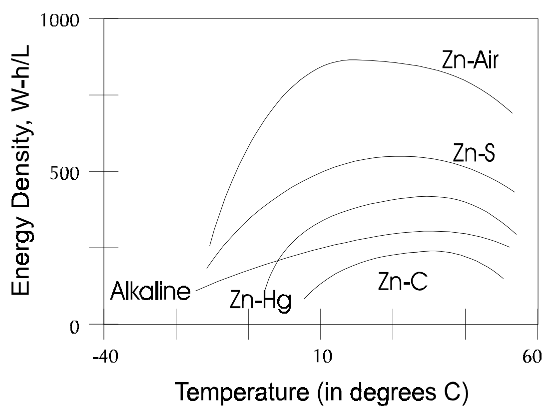

Figure 3. Energy densities, W·h/L, of various battery types (adapted from NAVSO P-3676).

Of the major types of secondary cells, Ni-Cd batteries and wet-cell lead-acid batteries have approximately the same volumetric energy density. Ni-MH batteries have approximately twice the volumetric energy density of Ni-Cd batteries.

3.4 Memory Effects

As a rechargeable battery is used, recharged, and used again, it loses a small amount of its overall capacity. This loss is to be expected in all secondary batteries as the active components become irreversibly consumed.

Ni-Cd batteries, however, suffer an additional problem, called the memory effect. If a Ni-Cd battery is only partially discharged before recharging it, and this happens several times in a row, the amount of energy available for the next cycle will only be slightly greater than the amount of energy discharged in the cell's most-recent cycle. This characteristic makes it appear as if the battery is "remembering" how much energy is needed for a repeated application.

The physical process that causes the memory effect is the formation of potassium-hydroxide crystals inside the cells. This build up of crystals interferes with the chemical process of generating electrons during the next battery-use cycle. These crystals can form as a result of repeated partial discharge or as a result of overcharging the Ni-Cd battery.

The build up of potassium-hydroxide crystals can be reduced by periodically reconditioning the battery. Reconditioning of a Ni-Cd battery is accomplished by carefully controlled power cycling (*i.e.*, deeply discharging and then recharging the battery several times). This power cycling will cause most of the crystals to redissolve back into the electrolyte. Several companies offer this reconditioning service, although battery users can purchase a reconditioner and recondition their own batteries. Some batteries can be reconditioned without a special reconditioner by completely draining the battery (using the battery powered device itself or a resistive circuit designed to safely discharge the battery) and charging it as normal.

3.5 Voltage Profiles

The voltage profile of a battery is the relationship of its voltage to the length of time it has been discharging (or charging). In most primary batteries, the voltage will drop steadily as the chemical reactions in the cell are diminished. This diminution leads to an almost-linear drop in voltage, called a sloping profile. Batteries with sloping voltage profiles provide power that is adequate for many applications such as flashlights, flash cameras, and portable radios.

Ni-Cd batteries provide a relatively flat voltage profile. The cell's voltage will remain relatively constant for more than ⅔ of its discharge cycle. At some point near the end of the cycle, the voltage drops sharply to nearly zero volts. Batteries with this kind of profile are used for devices that require a relatively steady operating voltage.

One disadvantage of using batteries with a flat voltage profile is that the batteries will need to be replaced almost immediately after a drop in voltage is noticed. If they are not immediately replaced, the batteries will quickly cease to provide any useful energy.

Figure 4 shows the conceptual difference between a flat discharge rate and a sloping discharge rate.

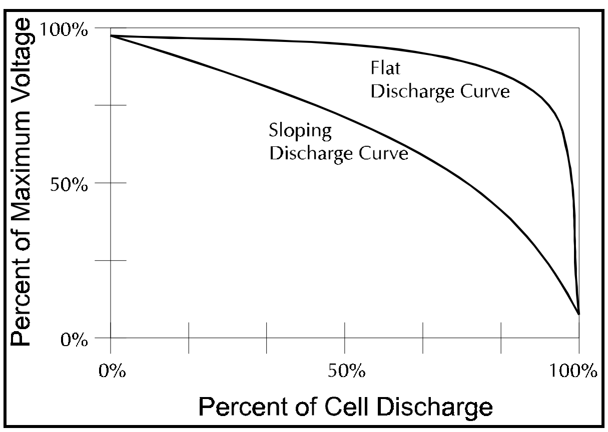

Figure 4. Flat discharge curve vs. sloping discharge curve.

Figure 5 (Sec. 5) shows actual voltage profiles for several common battery types.

3.6 SELF-DISCHARGE RATES

All charged batteries (except thermal batteries and other batteries specifically designed for a near-infinite shelf life) will slowly lose their charge over time, even if they are not connected to a device. Moisture in the air and the slight conductivity of the battery housing will serve as a path for electrons to travel to the cathode, discharging the battery. The rate at which a battery loses power in this way is called the self-discharge rate.

Ni-Cd batteries have a self-discharge rate of approximately 1% per day. Ni-MH batteries have a much higher self-discharge rate of approximately 2% to 3% per day. These high discharge rates require that any such battery, which has been stored for more than a month, be charged before use.

Primary and secondary alkaline batteries have a self-discharge rate of approximately 5% to 10% per *year*, meaning that such batteries can have a useful shelf life of several years. Lithium batteries have a self-discharge rate of approximately 5% per month.

3.7 OPERATING TEMPERATURES

As a general rule, battery performance deteriorates gradually with a rise in temperature above 25 °C (77 °F), and performance deteriorates rapidly at temperatures above 55 °C (131 °F). At very low temperatures -20 °C (-4 °F) to 0 °C (32 °F), battery performance is only a fraction of that at 25 °C (77 °F). **Figure 2** and **Figure 3** show the differences in energy density as a function of temperature.

At low temperatures, the loss of energy capacity is due to the reduced rate of chemical reactions and the increased internal resistance of the electrolyte. At high temperatures, the loss of energy capacity is due to the increase of unwanted, parasitic chemical reactions in the electrolyte.

Ni-Cd batteries have a recommended temperature range of +17 °C (62 °F) to 37 °C (98 °F). Ni-MH have a recommended temperature range of 0 °C (32 °F) to 32 °C (89 °F).

3.8 CYCLE LIFE

The cycle life of a battery is the number of discharge/recharge cycles the battery can sustain, with normal care and usage patterns, before it can no longer hold a useful amount of charge.

Ni-Cd batteries should have a normal cycle life of 600 to 900 recharge cycles. Ni-MH batteries will have a cycle life of only 300 to 400 recharge cycles. As with all rechargeable batteries, overcharging a Ni-Cd or Ni-MH battery will significantly reduce the number of cycles it can sustain.

3.9 CAPACITY TESTING

Many battery manufacturers recommend the constant-load test to determine the capacity of a battery. This test is conducted by connecting a predetermined load to the battery and then recording the amount of time needed to discharge the battery to a predetermined level.

Another recommended test is the intermittent- or switching-load test. In this type of test, a predetermined load is applied to the battery for a specified period and then removed for another period. This load application and removal is repeated until the battery reaches a predetermined level of discharge. This kind of test simulates the battery usage of a portable radio.

A comparison of these two kinds of tests was performed on five commonly available types of batteries.[11] The data shows that the five tested batteries all had a constant-load duration of 60 to 80 minutes, which indicates that the five batteries had similar capacities.

But, intermittent-load testing of those same five batteries showed that the duration of the batteries ranged from 8.5 hours to 12 hours. There was no correlation of the results of the two tests, meaning that batteries that performed best under constant-load testing did not necessarily perform well under intermittent-load testing. The study concluded that the ability of a battery to recover itself between heavy current drains cannot be made apparent through a constant-load test.

3.10 BATTERY TECHNOLOGY COMPARISON

Table 3 shows a comparison of some of the performance factors of several common battery types.

The *initial capacity* of a battery refers to the electrical output, expressed in ampere-hours, which the fresh, fully charged battery can deliver to a specified load. The *rated capacity* is a designation of the total electrical output of the battery at typical discharge rates; e.g., for each minute of radio transceiver operation, 6 seconds shall be under a transmit current

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[11] *Batteries Used with Law Enforcement Communications Equipment: Chargers and Charging Techniques*, W. W. Scott, Jr., U.S. Department of Justice, LESP-RPT-0202.00, June 1973.

drain, 6 seconds shall be under a receive current drain and 48 seconds shall be under a standby current drain.

The *self-discharge* rate is the rate at which the battery will lose its charge during storage or other periods of non-use. The *cycle life* is the number of times that the rechargeable battery can be charged and discharged before it becomes no longer able to hold or deliver any useful amount of energy.

The *initial cost* is the relative cost of purchasing the battery. The *life-cycle cost* is the per-use relative cost of the battery.

Table 4 shows a more detailed comparison of many of the available battery types.

Table 3. Battery Technology Comparison (adapted from *Design Note: Renewable Reusable Alkaline Batteries*)

(See Sec. 3.10)	Ni-Cd	Ni-MH	Primary Alkaline	Secondary Alkaline
Initial Capacity	❍	◗◗	✪✪✪✪	●●●
Rated Capacity	✪✪✪✪	●●●	◗◗	❍
Self-Discharge	◗◗	❍	✪✪✪✪	✪✪✪✪
Cycle Life	✪✪✪✪	✪✪✪✪	❍	●●●
Initial Cost*	◗◗	❍	✪✪✪✪	●●●
Life-Cycle Cost*	●●●	●●●	❍	●●●

Worst Performance = ❍, Low Performance = ◗◗,
Good Performance= ●●●, Best Performance =✪✪✪✪
*A better performance ranking means lower costs.

Table 4. A Comparison of Several Popular Battery Types

Cell Type*	Basic Type**	Anode material	Cathode Material	Main Electrolyte Material	Volts per Cell	Advantages & Applications	Disadvantages
Carbon-Zinc (“Leclanché”)	P	Zinc	Manganese dioxide	Ammonium chloride, zinc chloride	1.5	Low cost, good shelf life. Useful for flashlights, toys, and small appliances.	Output capacity decreases as it drains; poor performance at low temperatures.
Zinc Chloride	P	Zinc	Manganese dioxide	Zinc Chloride	1.5	Good service at high drain, leak resistant, good low-temperature performance. Useful for flashlights, toys, and small appliances.	Relatively expensive for novelty usage.
“Alkaline” (Zinc-Manganese Dioxide)	P or S	Zinc	Manganese dioxide	Potassium hydroxide	1.5	High efficiency under moderate, continuous drains, long shelf life, good low-temperature performance. Useful for camera flash units, motor-driven devices, portable radios.	Primary cells are expensive for novelty usage. Secondary cells have a limited number of recharge cycles.
Car Battery (Lead-Acid)	S	Lead	Lead dioxide	Sulfuric acid	2	Low cost, spill resistant (sealed batteries). Useful for automobiles and cordless electric lawn mowers.	Limited low-temperature performance. Vented cells require maintenance. Cells are relatively heavy.

* -- Common name, ** -- P=Primary, S=Secondary (Rechargeable)

Table 4 (continued)

Cell Type*	**Basic Type****	**Anode material**	**Cathode Material**	**Main Electrolyte Material**	**Volts per Cell**	**Advantages & Applications**	**Disadvantages**
"Ni-Cd" (Nickel-Cadmium)	S	Cadmium	Nickel hydroxide	Potassium hydroxide	1.25	Excellent cycle life; flat discharge curve; good high- and low-temperature performance; high resistance to shock and vibration. Useful for small appliances that have intermittent usage, such as walkie-talkies, portable hand tools, tape players, and toys. When batteries are exhausted, they can be recharged before the next needed use.	High initial cost; only fair charge retention; memory effect.
Mercuric Oxide	P	Zinc	Mercuric oxide	Potassium hydroxide	1.35	Relatively flat discharge curve; relatively high energy density; good high-temperature performance; good service maintenance. Useful for critical appliances, such as paging, hearing aids, and test equipment.	Poor low-temperature performance in some situations.

* -- Common name, ** -- P=Primary, S=Secondary (Rechargeable)

Table 4 (continued)

Cell Type*	Basic Type**	Anode material	Cathode Material	Main Electrolyte Material	Volts per Cell	Advantages & Applications	Disadvantages
"Ni-MH" (Nickel-Metal Hydride)	S	Hydrogen storage metal	Nickel oxide	Potassium hydroxide	1.5	No memory effects (such as Ni-Cd has), good high-power performance, good low-temperature performance. Useful for portable devices where the duty cycle varies from use to use.	High initial cost, relatively high rate of self-discharge.
Silver Oxide	P or S	Zinc	Silver oxide	Potassium hydroxide	1.5	High energy density; flat discharge curve. Useful for very small appliances such as calculators, watches, and hearing aids.	Silver is very expensive; poor storage and maintenance characteristics. Rechargeable cells have a very limited number of cycles.
Zinc-Air	P	Zinc	Oxygen	Potassium hydroxide	1.25	High energy density in small cells. Flat discharge rate.	Dries out quickly.
Lithium	P	Lithium	Iron sulfide	Lithium salts in ether	1.0 - 3.6	Good energy density.	Limited high-rate capacities; safety concerns.

* -- Common name, ** -- P=Primary, S=Secondary (Rechargeable)

4. Selecting the Right Battery for the Application

Batteries come in many different shapes, sizes, and compositions. There is no one "ideal" battery that can satisfy all possible requirements equally. Different battery technologies have been developed that will optimize certain parameters for specific battery uses.

In general, the energy output of a battery is related only to its size and material composition. Different battery designs and different manufacturing methods (for the same type, size, and composition of battery) will, in general, lead to only minor differences in the batteries' electrical output. Battery-industry standards have contributed to the fact that batteries (of the same type, composition, and size) from different manufacturers are quite interchangeable.

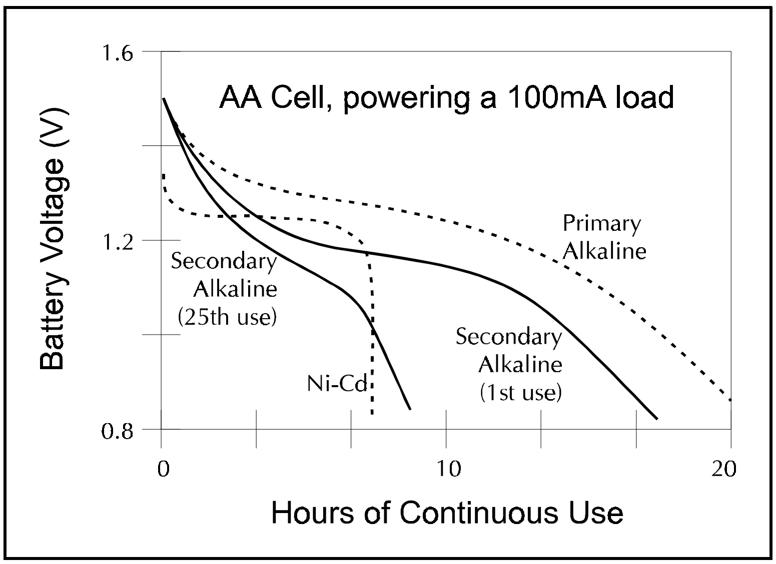

Figure 5. Performance comparison of primary and secondary alkaline and Ni-Cd batteries (adapted from *Design Note: Renewable Reusable Alkaline Batteries*).

However, the small differences that do exist between batteries made by different manufacturers, can be significant when using a multi-cell array of *matched* cells. In these cases, potential replacement cells must be graded to see if the cells properly match the capacity of the existing cells.

Even for non-matched, multi-cell applications, such as flashlights, portable radios, *etc.*, it is still a good rule of thumb to avoid mixing batteries from different manufacturers within one device. Small variances in voltage and current, between different brands of battery, can slightly shorten the useful life span of all of the batteries.

Do not mix batteries of different *types* (*e.g.*, do not mix rechargeable alkaline batteries with Ni-Cd batteries) within a single device or within an array of batteries.

Figure 5 shows some discharge curves for several popular AA size battery types. Two of the curves (secondary alkaline [1st use] and [25th use]) show that secondary alkaline batteries rapidly lose their capacity as they are used and recharged. Only one Ni-Cd curve is shown, since its curve remains essentially the same throughout most its life span.

4.1 BATTERY PROPERTIES

Battery applications vary, as do considerations for selecting the correct battery for each application. Some of the important factors that customers might consider when selecting the right battery for a particular application are listed below:

- **Chemistry --** Which kind of battery chemistry is best for the application? Different chemistries will generate different voltages and currents.
- **Primary or Secondary --** Primary batteries are most appropriate for applications where infrequent, high-energy output is required. Secondary batteries are most appropriate for use in devices that see steady periods of use and non-use (pagers, cellular phones, etc.).
- **Standardization and Availability --** Is there an existing battery design that meets the application needs? Will replacement batteries be available in the future? Using existing battery types is almost always preferable to specifying a custom-made battery design.
- **Flexibility --** Can the battery provide high or low currents over a wide range of conditions?
- **Temperature Range --** Can the battery provide adequate power over the expected temperature range for the application?
- **Good Cycle Life --** How many times can the rechargeable battery be discharged and recharged before it becomes unusable?
- **Costs --** How expensive is the battery to purchase? Does the battery require special handling?
- **Shelf Life --** How long can the battery be stored without loss of a significant amount of its power?
- **Voltage --** What is the voltage of the battery? [Most galvanic cells produce voltages of between 1.0 and 2.0 V.]
- **Safety --** Battery components range from inert, to mildly corrosive, to highly toxic or flammable. The more hazardous components will require additional safety procedures.
- **Hidden Costs --** Simpler manufacturing processes result in lower cost batteries. However, if a battery contains toxic or hazardous components, extra costs will be incurred to dispose of the battery safely after its use.

Table 5 shows a short list of different battery types and the kinds of application that are appropriate for each.

4.2 ENVIRONMENTAL CONCERNS

All battery components, when discarded, contribute to the pollution of the environment. Some of the components, such as paperboard and carbon powder, are relatively organic and can quickly merge into the ecosystem without noticeable impact. Other components, such as steel, nickel, and plastics, while not actively toxic to the ecosystem, will add to the volume of a landfill, since they decompose slowly.

Table 5. Recommended Battery Types for Various Usage Conditions

Battery Type	Device Drain Rate	Device Use Frequency
Primary Alkaline	High	Moderate
Secondary Alkaline	Moderate	Moderate
Primary Lithium	High	Frequent
Secondary Ni-Cd	High	Frequent
Primary Zn-C ("Heavy Duty")	Moderate	Regular
Primary Zn-C ("Standard")	Low	Occasional

Of most concern, however, are the heavy-metal battery components, which, when discarded, can be toxic to plants, animals, and humans. Cadmium, lead, and mercury are the heavy-metal components most likely to be the target of environmental concerns.

Many of the major battery manufacturers have put significant efforts into the recycling of discarded batteries.

Several of the major battery manufacturers have taken steps to reduce the amount of toxic materials in their batteries. One manufacturer reports the reduction of the mercury content of their most-popular battery from 0.75%, in 1980, to 0.00%, in 1996.[12] Other manufacturers report that their current battery formulas contain no mercury. The U.S. Department of Mines, in 1994, estimated that, for the U.S. production of household batteries, mercury usage had fallen from 778 tons in 1984 to (a projected) 10 tons in 1995.[13]

Many of the major battery manufacturers have put significant efforts into the recycling of discarded batteries. According to one manufacturer, it takes six to ten times more energy to recycle a battery than to create the battery components from virgin materials. Efforts are underway that could improve the recycling technology to make recycling batteries much more energy efficient and cost effective.[14]

The use of secondary (rechargeable) batteries is more cost efficient than the use of primary batteries. Such use will reduce the physical volume of discarded batteries in landfills, because the batteries can be recharged and reused 25 to 1000 times before they must be discarded.

[12] *Eveready and the Environment*, Eveready Battery Company, Inc., 1995.

[13] Eveready *and the Environment*, Eveready Battery Company, Inc., 1995.

[14] *Eveready and the Environment*, Eveready Battery Company, Inc., 1995.

The most popular secondary batteries, however, contain cadmium. Many manufacturers, responding to customer requests and legislative demands, are designing nickel-metal hydride, lithium-ion, and rechargeable-alkaline secondary batteries that contain only trace amounts of cadmium, lead, or mercury.

4.3 STANDARDIZATION

Existing off-the-shelf batteries are often preferred to batteries that require special design and manufacturing. Some benefits of using off-the-shelf batteries are listed below:

- The use of a proven design can reduce the risk of the battery not working properly.
- The use of tested technology eliminates costly and time-consuming development efforts.
- The use of a proven design reduces unit production costs because of competitive, multi-source availability.
- The use of tested technology reduces operations and support costs through commonality of training, documentation, and replacement efforts.

4.4 TESTING CAPACITIES

One method of estimating battery capacity requirements for a specific battery-powered device is to calculate the current drawn during the typical duty cycle for the device.

Standard duty cycles for battery service life and capacity determinations are defined in EIA/TIA Standard 603[15] for land mobile radio communications and NIJ Standard-0211.01[16] for hand-held portable radio applications. Specifically, in an average 1 minute period of mobile-radio usage, 6 seconds (10%) is spent receiving, 6 seconds (10%) is spent transmitting and 48 seconds (80%) is spent in the idle mode. Table 8 provides an example of a transceiver drawing an average current of 8.0 + 6.2 + 32.5 = 46.7 mA. For a typical duty cycle composed of 8 hours of operation (followed by 16 hours of rest) a minimum battery capacity of 374 mAh is required. One manufacturer of portable communications equipment recommends that batteries be replaced if they fail to deliver 80% or more of their original rated capacity. Below 80% batteries are usually found to deterioriate quickly. Because a minimum requirement of 374 mAh is 75% of the rated capacity of a 500 mAh battery, the latter should adequately provide power for the entire duty described.[17]

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[15] *Land Mobile FM or PM Communications Equipment, Measurement and Performance Standard*, Electronics Industry Association/Telecommunications Industry Association, Publication EIA/TIA 603, 1993.

[16] *Rechargeable Batteries for Personal/ Portable Transceivers*, National Institute of Justice, NIJ Standard-0211.01, 1995.

[17] *Batteries Used with Law Enforcement Communications Equipment: Chargers and Charging Techniques*, W.W. Scott, Jr., National Institute of Justice, LESP-RPT-0202.00, June 1973.

Table 6. Typical Usage of Portable Telecommunications Equipment.

	Standby Mode	Receive Mode	Transmit Mode
Percent of Duty Cycle	80% (48 minutes of each hour)	10% (6 minutes of each hour)	10% (6 minutes of each hour)
Current Drain for Mode	10 mA	62 mA	325 mA
Average Current for Mode	8.0 mA	6.2 mA	32.5 mA

Similar calculations can be performed for any battery in any battery-powered device by using the data relevant to the device and the proposed battery. The manufacturers should either provide such appropriate information with the batteries and devices, or they should be able to provide those data on request.

4.5 Mobile Radios

As reported above, mobile radios have a typical duty cycle of 10% transmit, 10% receive, and 80% standby. The maximum current drain will occur during the transmit cycle. Each radio, typically, will have a daily cycle of 8 hours of use and 16 hours of non-use. The non-use hours may be used to charge the radio's batteries.

Most commercial, off-the-shelf mobile-radio units include a battery. But, since many radio units are in service 7 days a week, 52 weeks a year, and since the batteries are discharged and recharged daily, each set of batteries should wear out approximately once every two years (~700 recharge cycles). Replacement batteries should be purchased as directed by the user manual for the unit.

4.6 Cellular Phones and PCS Phones

Most commercial, off-the-shelf cellular phones contain a battery when purchased. Charging units may be supplied with the phone or may be purchased separately.

Typical usage for cellular telephones will vary significantly with user, but, the estimate for mobile radio usage (10% of the duty cycle is spent in transmit mode, 10% in receive mode, and 80% in standby mode) is also a reasonable estimate for cellular phone usage. At the end of each usage cycle, the user places the battery (phone) on a recharging unit that will charge the battery for the next usage cycle. This usage pattern is appropriate for Ni-Cd or Ni-MH batteries. Ni-Cd batteries should be completely discharged between uses to prevent memory effects created by a recurring duty cycle.

When a replacement or spare battery is needed, only replacements, recommended by the phone manufacturer should be used.

Batteries and battery systems from other manufacturers may be used if the batteries are certified to work with that particular brand and model of phone. Damage to the phone may result if non-certified batteries are used.

Several battery manufacturers make replacement battery packs that are designed to work with a wide variety of cellular phones. Because of the variety of phones available, battery manufacturers must design and sell several dozen different types of batteries to fit the hundreds of models of cellular phones from dozens of different manufacturers.[18] The user is advised to check battery inter-operability charts before purchasing a replacement battery.

One battery manufacturer offers a battery replacement system that allows a phone owner to use household primary batteries, inserted into a special housing (called a refillable battery pack), to replace the phone's regular rechargeable battery pack. This refillable pack, says the manufacturer, is designed for light-use customers, who require that their phone's batteries have the long shelf life of primary batteries. This refillable pack can also be used in emergencies, for example, where the phone's rechargeable battery pack is exhausted and no recharged packs are available. Primary household batteries can be readily purchased (or borrowed from other devices), inserted into the refillable pack, and used to power the phone.[19]

4.7 LAPTOP COMPUTERS

Most commercial, off-the-shelf laptop computers have a built-in battery system. In addition to the battery provided, most laptops will have a battery adapter that also serves as a battery charger.

The expected usage of a laptop computer is that the operator will use it several times a week, for periods of several hours at a time. The computer will drain the battery at a moderate rate when the computer is running, and at the self-discharge rate when the computer is shut off. Quite often, the user will use the computer until the "low battery" alarm sounds. At this point, the battery will be drained of 90% of its charge before the user recharges it. The computer will also register regular periods of non-use, during which the battery can be recharged. Secondary Ni-Cd batteries are most appropriate for this usage pattern.

When a laptop-computer battery reaches the end of its life cycle, it should be replaced with a battery designed specifically for that laptop computer. Using other types of batteries may damage the computer. The user's manual for the laptop computer will list one or more battery types and brands that may be used. If in doubt, the user is advised to contact the manufacturer of the laptop computer and ask for a battery-replacement recommendation.

4.8 CAMCORDERS

Almost all commercial, off-the-shelf camcorders come with a battery and a recharging unit when purchased.

The camcorder is typically operated continuously for several minutes or hours (to produce a video recording of some event). This use will require that the battery provide approximately 2 hours of non-stop recording time. The electric motor driving the recording tape through the camcorder requires a moderately high amount of power throughout the entire recording period.

Rechargeable Ni-Cd or Ni-MH batteries or primary lithium batteries are usually the only choice for camcorder use. Several battery manufacturers produce Ni-Cd or Ni-MH

[18] *Easy to Choose, Easy to Use*, Eveready Battery Corporation, 1997.

[19] *Cellular Duracell Rechargeable Batteries*, Duracell, 1996.

batteries that are specially designed for use in camcorders. Due to the lack of sufficient standardization for these kind of batteries, the battery manufacturers must design and sell approximately 20 different camcorder batteries to fit at least 100 models of camcorders from over a dozen manufacturers.[20]

Camcorder batteries are usually designed to provide 2 hours of service, but larger batteries are available that can provide up to 4 hours of service.

Lithium camcorder batteries can provide three to five times the energy of a single cycle of secondary Ni-Cd batteries. These lithium batteries, however, are primary batteries and must be properly disposed of at the end of their life cycle. Secondary lithium-ion camcorder batteries are being developed.

4.9 Summary

There are six varieties of batteries in use, each with its own advantages and disadvantages. Below is a short summary of each variety:

- **Lead-Acid --** Secondary lead-acid batteries are the most popular worldwide. Both the battery product and the manufacturing process are proven, economical, and reliable.
- **Nickel-Cadmium --** Secondary Ni-Cd batteries are rugged and reliable. They exhibit a high-power capability, a wide operating temperature range, and a long cycle life. They have a self-discharge rate of approximately 1% per day.
- **Alkaline --** The most commonly used primary cell (household) is the zinc-alkaline manganese dioxide battery. They provide more power-per-use than secondary batteries and have an excellent shelf life.
- **Rechargeable Alkaline --** Secondary alkaline batteries have a long shelf life and are useful for moderate-power applications. Their cycle life is less than most other secondary batteries.
- **Lithium Cells --** Lithium batteries offer performance advantages well beyond the capabilities of conventional aqueous electrolyte battery systems. However, lithium batteries are not widely used because of safety concerns.
- **Thermal Batteries --** These are special batteries that are capable of providing very high rates of discharge for short periods of time. They have an extremely long shelf life, but, because of the molten electrolyte and high operating temperature, are impractical for most household uses.

[20] *Camcorder Battery Pocket Guide*, Eveready Battery Company, 1996.

5. Battery Handling and Maintenance

The following guidelines offer specific advice on battery handling and maintenance. This advice is necessarily not all inclusive. Users are cautioned to observe specific warnings on individual battery labels and to use common sense when handling batteries.

5.1 Battery Dangers

✔ To get help, should someone swallow a battery, immediately call **The National Battery Ingestion Hot Line** collect at (202) 625-3333. Or, call **911** or a state/local **Poison Control Center**.

✔ Batteries made from lead (or other heavy metals) can be very large and heavy and can cause damage to equipment or injuries to personnel if improperly handled.

✔ When using lithium batteries, a “Lith-X” or D-Class fire extinguisher should always be available. Water-based extinguishers must **not** be used on lithium of any kind, since water will react with lithium and release large amounts of explosive hydrogen.

✫ Before abusively testing a battery, contact the manufacturer of the battery to identify any potential dangers.

✔ Vented batteries must be properly ventilated. Inadequate ventilation may result in the build up of volatile gases, which may result in an explosion or asphyxiation.

✫ Do not attempt to solder directly onto a terminal of the battery. Attempting to do so can damage the seal or the safety vent.

✫ When disconnecting a battery from the device it is powering, disconnect one terminal at a time. If possible, first remove the ground strap at its connection with the device’s framework. Observing this sequence can prevent an accidental short circuit and also avoid risking a spark at the battery. In most late-model, domestic automobiles, the battery terminal labeled “negative” is usually connected to the automobile’s framework.

✫ Do not attempt to recharge primary batteries. This kind of battery is not designed to be recharged and may overheat or leak if recharging is attempted.

✔ When recharging secondary batteries, use a charging device that is approved for that type of battery. Using an approved charging device can prevent overcharging or overheating the battery. Many chargers have special circuits built into them for correctly charging specific types of batteries and will not work properly with other types.

- Do not use secondary (rechargeable) batteries in smoke detectors. Secondary batteries have a high self-discharge rate. Primary batteries have a much longer shelf life and are much more dependable in emergencies. Consult the smoke detector's user manual for the recommended battery types.

- Do not attempt to refill or repair a worn-out or damaged battery.

- Do not allow direct bodily contact with battery components. Acidic or alkaline electrolyte can cause skin irritation or burns. Electrode materials such as mercury or cadmium are toxic. Lithium can cause an explosion if it comes into contact with water. Other components can cause a variety of short-term (irritation and burns) or long-term (nerve damage) maladies.

- Do not lick a 9 V battery to see if it is charged. You will, of course, be able to determine whether or not the battery is charged, but such a test may result in a burn that may range from simply uncomfortable to serious.

- Do not dispose of batteries in a fire. The metallic components of the battery will not burn and the burning electrolyte may splatter, explode, or release toxic fumes. Batteries may be disposed of, however, in industrial incinerators that are approved for the disposal of batteries.

- Do not carry batteries in your pocket. Coins, keys, or other metal objects can short circuit a battery, which can cause extreme heat, acid leakage, or an explosion.

- Do not wear rings, metal jewelry, or metal watchbands while handling charged cells. Severe burns can result from accidentally short circuiting a charged cell. Wearing gloves can reduce this danger.

- Do not use uninsulated tools near charged cells. Do not place charged cells on metal workbenches. Severe arcing and overheating can result if the battery's terminals are shorted by contact with such metal objects.

The Straight Dope
by Cecil Adams, *The Chicago Reader*

Is it true that refrigerating batteries will extend shelf life? If so, why does a cold car battery cause slower starts? The answer will help me sleep better. — Kevin C., Alexandria, Virginia

Whatever it takes, dude. Refrigerating batteries extends shelf life because batteries produce electricity through a chemical reaction. Heat speeds up any reaction, while cold slows it down. Freeze your [car battery] and you'll extend its life because the juice won't leak away—but it'll also make those volts a little tough to use right away. That accounts for the belief occasionally voiced by mechanics that if a battery is left on the garage floor for an extended period, the concrete will "suck out the electricity." It does nothing of the kind, but a cold floor will substantially reduce a battery's output. The cure: warm it up first.

(Reprinted, with permission, from *Return of the Straight Dope*.

5.2 Extending Battery Life

- ✔ Read the instructions for the device before installing batteries. Be sure to orient the battery's positive and negative terminals correctly when inserting them.
- ✔ In a device, use only the type of battery that is recommended by the manufacturer of the device.
- ✔ To find a replacement battery that works with a given device, call the manufacturer of the device or ask the retailer to check the manufacturer's battery cross-reference guide.
- ✔ Store batteries in a cool, dark place. This helps extend their shelf life. Refrigerators are convenient locations. Although some battery manufacturers say that refrigeration has no positive effect on battery life, they say it has no negative effect either. Do not store batteries in a freezer. Always let batteries come to room temperature before using them.
- ✔ Store batteries in their original boxes or packaging materials. The battery manufacturer has designed the packaging for maximum shelf life.
- ✔ When storing batteries, remove any load or short circuit from their terminals.
- ✔ When storing battery-powered devices for long periods (*i.e.*, more than a month), remove the batteries. This can prevent damage to the device from possible battery leakage. Also, the batteries can be used for other applications while the batteries are still "fresh."

✔ Use a marking pen to indicate, on the battery casing, the day and year that the battery was purchased. Also, keep track of the number of times the battery has been recharged. Avoid writing on or near the battery terminals.

✔ Do not mix batteries from different manufacturers in a multi-cell device (*e.g.*, a flashlight). Small differences in voltage, current, and capacity, between brands, can reduce the average useful life of all the batteries.

✔ When using secondary batteries in a multi-cell device (*e.g.*, a flashlight), try to use batteries of the same age and similar charging histories. This kind of matching will make it more likely that all the batteries will discharge at the same rate, putting less stress on any individual battery.

✔ When using single-cell rechargeable Ni-Cd batteries, be sure to discharge the cell completely before recharging it, thus counteracting the "memory" effect.

✔ Secondary Ni-Cd batteries can sometimes be reconditioned to reduce the impact of "memory" effects. Completely discharge the battery and recharge it several times.

☼ Do not use batteries in high-temperature situations (unless the battery is designed for that temperature range). Locate batteries as far away from heat sources as possible. The electrical potential of the battery will degrade rapidly if it is exposed to temperatures higher than those recommended by the manufacturer.

6. Battery Chargers and Adapters

6.1 BATTERY CHARGERS

Secondary (rechargeable) batteries require a battery charger to bring them back to full power. The charger will provide electricity to the electrodes (opposite to the direction of electron discharge), which will reverse the chemical process within the battery, converting the applied electrical energy into chemical potential energy.

Table 7. Charge Rate Descriptions

Description	Charge Rate (Amperes)	Nominal Charge Time (Hours)
Standby (Trickle)	0.01 C to 0.03 C	100 to 33
Slow (Overnight)	0.05 C to 0.1 C	20 to 10
Quick	0.2 C to 0.5 C	5 to 2
Fast	1 C and more	1 and less

"C" is the theoretical current needed to completely charge the fully discharged battery in one hour.

Batteries should only be recharged with chargers that are recommended, by the manufacturer, for that particular type of battery. In general, however, battery-industry standards ensure that any off-the-shelf battery charger, specified for one brand, size, and type of battery, will be able to charge correctly any brand of battery of that same *size* and *type*.

Do not, however, use a charger designed for one *type* of battery to charge a different *type* of battery, even if the sizes are the same. For example, do not use a charger designed for charging "D"-sized Ni-Cd batteries to charge "D"-sized rechargeable alkaline batteries. If in doubt, use *only* the exact charger recommended by the battery manufacturer.

Recharging a battery without a recommended charger is dangerous. If too much current is supplied, the battery may overheat, leak, or explode. If not enough current is applied, the battery may never become fully charged, since the self-discharge rate of the battery will nullify the charging effort.

It is not recommended that battery users design and build their own charging units. Many low-cost chargers are available off-the-shelf that do a good job of recharging batteries. Specific, off-the-shelf chargers are identified and recommended, by each of the major battery manufacturers, for each type of secondary battery they produce.

6.2 Charge Rates

The current that a charger supplies to the battery is normally expressed as a fraction of the theoretical current (for a given battery) needed to charge the battery completely in 1 hour. This theoretical current is called the nominal battery capacity rating and is represented as "C." For example, a current of 0.1 C is that current which, in 10 hours, theoretically, would recharge the battery fully. **Table 7** shows some common charging rates for various styles of recharging.

6.3 Charging Techniques

In general, lower charge rates will extend the overall life of the battery. A battery can be damaged or degraded if too much current is applied during the charging process. Also, when a battery is in the final stages of charging, the current must be reduced to prevent damage to the battery. Many chargers offer current-limiting devices that will shut off or reduce the applied current when the battery reaches a certain percent of its charged potential.

The key issue in charging a battery is knowing when to stop charging.

Slow charge rates (between 0.05 C and 0.1 C) are the most-often recommended charge rate, since a battery can be recharged in less than a day, without significant probability of damaging or degrading the battery. Slow charge rates can be applied to a battery for an indefinite period of time, meaning that the battery can be connected to the charger for days or weeks with no need for special shut-off or current-limiting equipment on the charger.

Trickle chargers (charge rates lower than 0.05 C) are generally insufficient to charge a battery. They are usually only applied after a battery is fully charged (using a greater charge rate) to help offset the self-discharge rate of the battery. Batteries on a trickle charger will maintain their full charge for months at a time. It is usually recommended that batteries on a trickle charger be fully discharged and recharged once every 6 to 12 months.

Quick and fast charging rates (over 0.2 C) can be used to charge many kinds of secondary batteries. In such cases, however, damage or deterioration can occur in the battery if these high charge rates are applied after the battery has approximately 85% of its charge restored. Many quick and fast chargers will have current-limiters built into them that will slowly reduce the current as the battery is charged, thereby preventing most of this deterioration.

The recharge times shown in **Table 7** may be somewhat lower than the actual times required to recharge batteries at the associated charge rates. Various elements, such as temperature, humidity, initial charge state, and the recharge history of the cell, will each act to extend the time needed to charge the cell fully.

6.4 Charging Lead-Acid Batteries

Constant potential charging, with current limiting, is usually recommended for sealed lead-acid cells. Due to the sloping voltage profile of a lead-acid battery, the voltage of the battery is a reliable indicator of its state of charge. Current limiting may be accomplished through the use of a current-limiting resistor. One manufacturer uses a miniature light bulb as a current-limiting resistor. The brightness of the bulb will provide a visual indication of the state of charge of the battery. In modern practice, however, current limiting is accomplished with integrated circuits.

6.5 Charging Ni-Cd Batteries

During their recharge cycle, nickel-cadmium batteries react in a manner different from other batteries. Nickel-cadmium batteries will actually absorb heat during the first 25% of the charge cycle (as opposed to most secondary batteries, which generate heat all through their recharge cycle). Beyond that first quarter of the charge cycle, a Ni-Cd battery will generate heat. If constant current is applied past the point when the battery reaches approximately 85% of its fully charged state, the excess heat will cause "thermal runaway" to occur. Under thermal runaway conditions, the excess heat in the battery will cause its voltage to drop. The drop in voltage will cause the charge rate to increase (according to Ohm's Law), generating more heat and accelerating the cycle. The temperature and internal pressure of the battery will continue to rise until permanent damage results.

When using trickle or slow chargers to charge Ni-Cd batteries, the heat build-up is minimal and is normally dissipated by atmospheric convection before thermal runaway can occur. Most chargers supplied with, or as a part of, rechargeable devices (sealed flashlights, mini-vacuums, *etc.*) are slow chargers.

Quick or fast battery chargers, designed especially for Ni-Cd batteries, will usually have a temperature sensor or a voltage sensor that can detect when the battery is nearing thermal-runaway conditions. When near-runaway conditions are indicated, the charger will reduce or shut off the current entering the battery.

6.6 Timed-Charge Charging

Most charging methods, described so far in this guide, allow the user to begin charging a cell regardless of its current state of charge. One additional method can be used to charge Ni-Cd cells, but only if the cell is *completely* discharged. It is called the timed-charged method.

One characteristic of Ni-Cd cells is that they can accept very large charge rates (as high as 20 C), provided that the cell is not forced into an overcharge condition.

The timed-charge charger will provide high-rate current to the cell for a very specific period. A timer will then cut off the charging current at the end of that period. Some cells can be charged completely in as little as 10 minutes (as opposed to 8 hours on a slow charger).

Great care should be exercised when using a timed-charge charger, because there is no room for error. If the cell has any charge in it at all at the beginning of the charge cycle, or if the cell's capacity is less than anticipated, the cell can quickly reach the fully charged state, proceed into thermal-runaway conditions, and cause the explosion or destruction of the cell.

Some timed-charge chargers have a special circuit designed to discharge the cell completely before charging it. These are called dumped timed-charge chargers, since they dump any remaining charge before applying the timed charge.

6.7 Pulsed Charge-Discharge Chargers

This method of charging Ni-Cd cells applies a relatively high charge rate (approximately 5 C) until the cell reaches a voltage of 1.5 V. The charging current is then removed and the cell is rapidly discharged for a brief period of time (usually a few seconds). This action depolarizes the cell components and dissipates any gaseous buildup within the cell. The cell is then rapidly charged back to 1.5 V. The process is repeated several more times until the cell's maximum charge state is reached.

Unfortunately, this method has some difficulties. The greatest difficulty is that the maximum voltage of a Ni-Cd cell will vary with several outside factors such as the cell's recharge history and the ambient temperature at the charger's location. Since the cell's maximum potential voltage is variable, the level to which it must be charged is also variable. Integrated circuits are being designed, however, that may compensate for such variations.

6.8 Charging Button Batteries

Secondary cylindrical (household) cells will usually have a safety seal or vent built into them to allow excess gases, created during the charging process, to escape. Secondary, button-type batteries do not have such seals and are often hermetically sealed.

When cylindrical cells are overcharged, excess gases are vented. If a button battery is inadvertently overcharged, the excess gases cannot escape. The pressure will build up and will damage the battery or cause an explosion. Care should be taken not to overcharge a secondary button battery.

6.9 Internal Chargers

For some applications, the charger may be provided, by the battery manufacturer, as an integral part of the battery itself. This design has the obvious advantage of ensuring that the correct charger is used to charge the battery, but this battery-charger combination may result in size, weight and cost penalties for the battery.

6.10 Battery Testers

A battery tester is a device that contains a small load and attaches across the terminals of a battery to allow the user to see if the battery is sufficiently charged. A simple battery tester can be made from a flashlight bulb and two pieces of wire. Flashlight bulbs are ideal for testing household batteries, since the voltage and current required to light the bulb is the same as that of the battery. This kind of flashlight-bulb tester can also be used to drain a secondary battery safely before fully charging it.

Some off-the-shelf household batteries are sold with their own testers. These testers are attached to the packaging material or to the battery itself. The active conductor in the tester is covered by a layer of heat-sensitive ink. As the ends of the tester are pressed against the battery terminals, a small amount of current will flow through the material under the ink, heating it. The heating will cause the ink to change color, indicating that the battery still has energy.

Using a simple battery tester to test a Ni-Cd battery can be somewhat misleading, since a Ni-Cd battery has a flat voltage profile. The tester will indicate near-maximum voltage whether the battery is 100% charged or 85% discharged.

6.11 "SMART" BATTERIES

Many battery-powered devices require the use of multi-cell battery packs (*i.e.*, several ordinary battery cells strapped together to be used as a single unit). The individual cells cannot be charged or measured separately, without destroying the battery pack.

A new development in rechargeable battery technology is the use of microelectronics in battery-pack cases to create "intelligent" battery packs. These "smart" battery packs contain a microprocessor, memory, and sensors that monitor the battery's temperature, voltage, and current. This information can be relayed to the device (if the device is designed to accept the information) and used to calculate the battery's state of charge at any time or to predict how much longer the device can operate. The microprocessor on a battery pack may also record the history of the battery and display the dates and number of times that it has been charged.

To get the maximum potential from a secondary battery, the user must adopt a strict regimen of noting certain information about the battery and acting upon that information. For example, if a battery is already partially discharged, using it in a device will obviously not allow the device to be used for its entire duty cycle. Attempting to charge a battery when the ambient temperature is too high is another example of suboptimal battery usage, since the battery will not hold as much charge as it would have had it been charged at the recommended temperature.

Most battery users are not sufficiently diligent in matters of battery maintenance. "Smart" batteries allow the battery itself to record all pertinent information and make it available to the user at a glance.

6.12 END OF LIFE

All secondary batteries will eventually fail due to age, expended components, or physical damage. A battery, when properly maintained, will fail through gradual loss of capacity. To the user, this gradual failure will appear as a frequent need to change and charge the batteries. Sudden failure, usually due to physical abuse, will prevent the battery from holding any charge at all.

The physical manifestations of a gradual failure of the battery can be seen as a degradation of the separator material, dendritic growth or other misshapening of the electrodes, and permanent material loss of the active components.

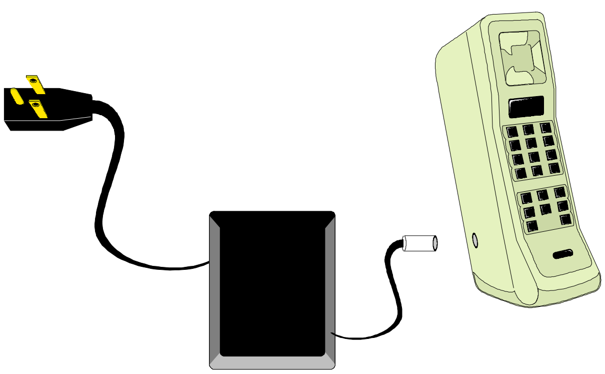
The physical manifestations of a sudden failure, can be seen as the destruction of the battery components. Open-circuit failure can be induced by an applied shock to or excess vibration of the battery. As a result, the internal components of the battery may become loose or detached, causing a gap in the electrical circuit.

Short-circuit failure can be caused by an applied shock. It can also be caused by overheating or overcharging the battery. In a short-circuit failure, some part of one of the electrodes pierces (caused by shock) or grows through (caused by overcharging) the separator material in the electrolyte. This piercing effect will cause the electrical path to be shorted.

If a battery and its replacements seem to be suffering repeated premature failures, in reoccurring and similar circumstances, the failed batteries should be sent to a laboratory for dissection and analysis. The problem may lie in faulty equipment, inappropriate battery usage, or in physical abuse to the device and its batteries. Resolution of the problem will save time and money in future battery designs and applications.

6.13 Battery Adapters

A battery adapter is a device that can be used instead of a battery to provide current to a battery-powered device.



Most battery adapters will convert 60 Hz, 110 V, alternating current (*i.e.*, typical house current) into direct current (dc) for use by battery-powered devices. Other adapters are designed to be powered by 12 V automobile batteries, usually by insertion of a plug into the automobile’s cigarette lighter.

An adapter will usually have a dc-output plug that is inserted into the battery-powered device to provide dc current to the device.

Usually, manufacturers of the more expensive battery-powered devices (*e.g.*, cellular phones, laptop computers) will provide the customer with a battery adapter designed especially for that device. The adapter will plug into a special connector in the device to provide it power. If designed to do so, the battery adapter will charge the device’s batteries as well.

Other manufacturers make generic battery adapters. These adapters will have a battery-shaped appendage that plugs into a battery-powered device in place of a real battery and will provide energy equivalent to a real battery. While this kind of adapter has some advantages (it can be used for *any* battery powered device, it can be used when no charged batteries are available, *etc.*), those advantages are usually outweighed by the disadvantages (the power cord is inconvenient and negates the portability of the device, the battery cover cannot be replaced while the cord is attached, a multiple-battery device would require multiple adapters, *etc.*).

7. Products and Suppliers

Table 8. Some On-Line Information Available via the World Wide Web

Battery Manufacturers	Web Address
Battery Engineering	http://www.batteryeng.com/
Duracell Batteries	http://www.duracell.com/
Eveready Batteries	http://www.eveready.com/
Kodak Corporation	http://www.kodak.com/
NEXcell	http://www.battery.com.tw/
Panasonic Batteries	http://www.panasonic-batteries.be/home.html
PolyStor Corporation	http://www.polystor.com/
Radio Shack	http://www.radioshack.com/
Rayovac Batteries	http://www.rayovac.com/
Sony Corporation	http://www.sel.sony.com/SEL/rmeg/batteries/
Battery Distributors	**Web Address**
Battery-Biz, Inc.	http://www.battery-biz.com/battery-biz/
Battery Depot	http://www.battery-depot.com/
Battery Network	http://batnetwest.com/
Batteries Plus	http://www.spromo.com/battplus/
E-Battery	http://e-battery.com/
Powerline	http://www.powerline-battery.com/

All Web information was verified in August, 1997.

Batteries and battery manufacturers and suppliers listed or mentioned in this section, and elsewhere in this guideline, are listed for the convenience of the reader. The name of a specific product or company does not imply that the product or company is, necessarily, the best for any particular application or device. The lists are, necessarily, not all-inclusive. The list of Web pages was compiled following a Web search performed in August, 1997. New Web pages may have appeared since then and some which appear in this list may no longer be available. Other Web pages, that were not listed in the Web-search database at that time, will also not appear in this list.

7.1 Battery Manufacturers

The battery manufacturers listed below are some of the manufacturers of household batteries. They are presented in alphabetical order. All information was verified in August, 1997.

7.1.1 Battery Engineering

Postal Address:
Battery Engineering, Inc.
100 Energy Drive
Canton, MA 02001
Phone Number:
(617) 575-0800
Web Page:
http://www.batteryeng.com
Email Address:
info@batteryeng.com

7.1.2 Duracell

Postal Address:
Duracell, Inc.
Berkshire Corp Park
Bethel, CT 06801
Phone Number:
1 (800) 551-2355
Web Page:
http://www.duracell.com/

7.1.3 Eveready

Postal Address:
Eveready Battery Company, Inc.
Checkerboard Square
St. Louis, MO 63164-0001
Phone Number:
1 (800) 383-7323
Web Page:
http://www.eveready.com/
Email Address:
bunny@chas.ts.maritz.com

7.1.4 Rayovac

Postal Address:
Rayovac Corporation
P.O. Box 44960
Madison, WI 53744-4960
Phone Number:
1 (800) 237-7000
Web Page:
http://www.rayovac.com/
Email Address:
customers@rayovac.com

8. A Glossary of Battery Terms

✎ **Ampere-Hour --** One ampere-hour is equal to a current of one ampere flowing for one hour. A unit-quantity of electricity used as a measure of the amount of electrical charge that may be obtained from a storage battery before it requires recharging.

✎ **Ampere-Hour Capacity --** The number of ampere-hours which can be delivered by a storage battery on a single discharge. The ampere-hour capacity of a battery on discharge is determined by a number of factors, of which the following are the most important: final limiting voltage; quantity of electrolyte; discharge rate; density of electrolyte; design of separators; temperature, age, and life history of the battery; and number, design, and dimensions of electrodes.

✎ **Anode --** In a primary or secondary cell, the metal electrode that gives up electrons to the load circuit and dissolves into the electrolyte.

✎ **Aqueous Batteries --** Batteries with water-based electrolytes.

✎ **Available Capacity --** The total battery capacity, usually expressed in ampere-hours or milliampere-hours, available to perform work. This depends on factors such as the endpoint voltage, quantity and density of electrolyte, temperature, discharge rate, age, and the life history of the battery.

✎ **Battery --** A device that transforms chemical energy into electric energy. The term is usually applied to a group of two or more electric cells connected together electrically. In common usage, the term “battery” is also applied to a single cell, such as a household battery.

✎ **Battery Types --** There are, in general, two type of batteries: primary batteries, and secondary storage or accumulator batteries. Primary types, although sometimes consisting of the same active materials as secondary types, are constructed so that only one continuous or intermittent discharge can be obtained. Secondary types are constructed so that they may be recharged, following a partial or complete discharge, by the flow of direct current through them in a direction opposite to the current flow on discharge. By recharging after discharge, a higher state of oxidation is created at the positive plate or electrode and a lower state at the negative plate, returning the plates to approximately their original charged condition.

✎ **Battery Capacity --** The electric output of a cell or battery on a service test delivered before the cell reaches a specified final electrical condition and may be expressed in ampere-hours, watt-hours, or similar units. The capacity in watt-hours is equal to the capacity in ampere-hours multiplied by the battery voltage.

✎ **Battery Charger --** A device capable of supplying electrical energy to a battery.

✎ **Battery-Charging Rate --** The current expressed in amperes at which a storage battery is charged.

✎ **Battery Voltage, final --** The prescribed lower-limit voltage at which battery discharge is considered complete. The cutoff or final voltage is usually chosen so that the useful capacity of the battery is realized. The cutoff voltage varies with the type of battery, the rate of discharge, the temperature, and the kind of service in which the battery is used. The term "cutoff voltage" is applied more particularly to primary batteries, and "final voltage" to storage batteries. Synonym: **Voltage, cutoff**.

✎ **C_i --** The rated capacity, in ampere-hours, for a specific, constant discharge current (where *i* is the number of hours the cell can deliver this current). For example, the C_5 capacity is the ampere-hours that can be delivered by a cell at constant current in 5 hours. As a cell's capacity is not the same at all rates, C_5 is usually less than C_{20} for the same cell.

✎ **Capacity --** The quantity of electricity delivered by a battery under specified conditions, usually expressed in ampere-hours.

✎ **Cathode --** In a primary or secondary cell, the electrode that, in effect, oxidizes the anode or absorbs the electrons.

✎ **Cell --** An electrochemical device, composed of positive and negative plates, separator, and electrolyte, which is capable of storing electrical energy. When encased in a container and fitted with terminals, it is the basic "building block" of a battery.

✎ **Charge --** Applied to a storage battery, the conversion of electric energy into chemical energy within the cell or battery. This restoration of the active materials is accomplished by maintaining a unidirectional current in the cell or battery in the opposite direction to that during discharge; a cell or battery which is said to be charged is understood to be fully charged.

✎ **Charge Rate --** The current applied to a secondary cell to restore its capacity. This rate is commonly expressed as a multiple of the rated capacity of the cell. For example, the C/10 charge rate of a 500 Ah cell is expressed as,

$$C/10 \text{ rate} = 500 \text{ Ah} / 10 \text{ h} = 50 \text{ A}.$$

✎ **Charge, state of --** Condition of a cell in terms of the capacity remaining in the cell.

✎ **Charging --** The process of supplying electrical energy for conversion to stored chemical energy.

✎ **Constant-Current Charge --** A charging process in which the current of a storage battery is maintained at a constant value. For some types of lead-acid batteries this may involve two rates called the starting and finishing rates.

✎ **Constant-Voltage Charge --** A charging process in which the voltage of a storage battery at the terminals of the battery is held at a constant value.

✎ **Cycle --** One sequence of charge and discharge. Deep cycling requires that all the energy to an end voltage established for each system be drained from the cell or battery on each discharge. In shallow cycling, the energy is partially drained on each discharge; *i.e.*, the energy may be any value up to 50%.

✎ **Cycle Life --** For secondary rechargeable cells or batteries, the total number of charge/discharge cycles the cell can sustain before it becomes inoperative. In practice, end of life is usually considered to be reached when the cell or battery delivers approximately 80% of rated ampere-hour capacity.

✎ **Depth of Discharge --** The relative amount of energy withdrawn from a battery relative to how much could be withdrawn if the battery were discharged until exhausted.

✎ **Discharge --** The conversion of the chemical energy of the battery into electric energy.

✎ **Discharge, deep --** Withdrawal of all electrical energy to the end-point voltage before the cell or battery is recharged.

✎ **Discharge, high-rate --** Withdrawal of large currents for short intervals of time, usually at a rate that would completely discharge a cell or battery in less than one hour.

✎ **Discharge, low-rate --** Withdrawal of small currents for long periods of time, usually longer than one hour.

✎ **Drain --** Withdrawal of current from a cell.

✎ **Dry Cell --** A primary cell in which the electrolyte is absorbed in a porous medium, or is otherwise restrained from flowing. Common practice limits the term “dry cell” to the Leclanché cell, which is the common commercial type.

✎ **Electrochemical Couple --** The system of active materials within a cell that provides electrical energy storage through an electrochemical reaction.

✎ **Electrode --** An electrical conductor through which an electric current enters or leaves a conducting medium, whether it be an electrolytic solution, solid, molten mass, gas, or vacuum. For electrolytic solutions, many solids, and molten masses, an electrode is an electrical conductor at the surface of which a change occurs from conduction by electrons to conduction by ions. For gases and vacuum, the electrodes merely serve to conduct electricity to and from the medium.

✎ **Electrolyte --** A chemical compound which, when fused or dissolved in certain solvents, usually water, will conduct an electric current. All electrolytes in the fused state or in solution give rise to ions which conduct the electric current.

✎ **Electropositivity --** The degree to which an element in a galvanic cell will function as the positive element of the cell. An element with a large electropositivity will oxidize faster than an element with a smaller electropositivity.

✎ **End-of-Discharge Voltage --** The voltage of the battery at termination of a discharge.

✎ **Energy --** Output capability; expressed as capacity times voltage, or watt-hours.

✎ **Energy Density --** Ratio of cell energy to weight or volume (watt-hours per pound, or watt-hours per cubic inch).

✎ **Float Charging --** Method of recharging in which a secondary cell is continuously connected to a constant-voltage supply that maintains the cell in fully charged condition.

✎ **Galvanic Cell --** A combination of electrodes, separated by electrolyte, that is capable of producing electrical energy by electrochemical action.

✎ **Gassing --** The evolution of gas from one or both of the electrodes in a cell. Gassing commonly results from self-discharge or from the electrolysis of water in the electrolyte during charging.

✎ **Internal Resistance --** The resistance to the flow of an electric current within the cell or battery.

✎ **Memory Effect --** A phenomenon in which a cell, operated in successive cycles to the same, but less than full, depth of discharge, temporarily loses the remainder of its capacity at normal voltage levels (usually applies only to Ni-Cd cells).

✎ **Negative Terminal --** The terminal of a battery from which electrons flow in the external circuit when the cell discharges. See **Positive Terminal**.

✎ **Nonaqueous Batteries --** Cells that do not contain water, such as those with molten salts or organic electrolytes.

✎ **Ohm's Law --** The formula that describes the amount of current flowing through a circuit.
Voltage = Current × Resistance.

✎ **Open Circuit --** Condition of a battery which is neither on charge nor on discharge (*i.e.*, disconnected from a circuit).

✎ **Open-Circuit Voltage --** The difference in potential between the terminals of a cell when the circuit is open (*i.e.*, a no-load condition).

✎ **Oxidation --** A chemical reaction that results in the release of electrons by an electrode's active material.

✎ **Parallel Connection --** The arrangement of cells in a battery made by connecting all positive terminals together and all negative terminals together, the voltage of the group being only that of one cell and the current drain through the battery being divided among the several cells. See **Series Connection**.

✎ **Polarity --** Refers to the charges residing at the terminals of a battery.

✎ **Positive Terminal --** The terminal of a battery toward which electrons flow through the external circuit when the cell discharges. See **Negative Terminal**.

✎ **Primary Battery --** A battery made up of primary cells. See **Primary Cell**.

✎ **Primary Cell --** A cell designed to produce electric current through an electrochemical reaction that is not efficiently reversible. Hence the cell, when discharged, cannot be efficiently recharged by an electric current. **Note:** When the available energy drops to zero, the cell is usually discarded. Primary cells may be further classified by the types of electrolyte used.

✎ **Rated Capacity --** The number of ampere-hours a cell can deliver under specific conditions (rate of discharge, end voltage, temperature); usually the manufacturer's rating.

✎ **Rechargeable --** Capable of being recharged; refers to secondary cells or batteries.

✎ **Recombination --** State in which the gases normally formed within the battery cell during its operation, are recombined to form water.

✎ **Reduction --** A chemical process that results in the acceptance of electrons by an electrode's active material.

✎ **Seal --** The structural part of a galvanic cell that restricts the escape of solvent or electrolyte from the cell and limits the ingress of air into the cell (the air may dry out the electrolyte or interfere with the chemical reactions).

✎ **Secondary Battery --** A battery made up of secondary cells. See **Storage Battery; Storage Cell**.

✎ **Self Discharge --** Discharge that takes place while the battery is in an open-circuit condition.

✎ **Separator --** The permeable membrane that allows the passage of ions, but prevents electrical contact between the anode and the cathode.

✎ **Series Connection --** The arrangement of cells in a battery configured by connecting the positive terminal of each successive cell to the negative terminal of the next adjacent cell so that their voltages are cumulative. See **Parallel Connection**.

✎ **Shelf Life --** For a dry cell, the period of time (measured from date of manufacture), at a storage temperature of 21°C (69°F), after which the cell retains a specified percentage (usually 90%) of its original energy content.

✎ **Short-Circuit Current --** That current delivered when a cell is short-circuited (*i.e.*, the positive and negative terminals are directly connected with a low-resistance conductor).

✎ **Starting-Lighting-Ignition (SLI) Battery --** A battery designed to start internal combustion engines and to power the electrical systems in automobiles when the engine is not running. SLI batteries can be used in emergency lighting situations.

✎ **Stationary Battery --** A secondary battery designed for use in a fixed location.

✎ **Storage Battery --** An assembly of identical cells in which the electrochemical action is reversible so that the battery may be recharged by passing a current through the cells in the opposite direction to that of discharge. While many non-storage batteries have a reversible process, only those that are economically rechargeable are classified as storage batteries. Synonym: **Accumulator; Secondary Battery.** See **Secondary Cell**.

✎ **Storage Cell --** An electrolytic cell for the generation of electric energy in which the cell after being discharged may be restored to a charged condition by an electric current flowing in a direction opposite the flow of current when the cell discharges. Synonym: **Secondary Cell**. See **Storage Battery**.

✎ **Taper Charge --** A charge regime delivering moderately high-rate charging current when the battery is at a low state of charge and tapering the current to lower rates as the battery becomes more fully charged.

✎ **Terminals --** The parts of a battery to which the external electric circuit is connected.

✎ **Thermal Runaway --** A condition whereby a cell on charge or discharge will destroy itself through internal heat generation caused by high overcharge or high rate of discharge or other abusive conditions.

✎ **Trickle Charging --** A method of recharging in which a secondary cell is either continuously or intermittently connected to a constant-current supply that maintains the cell in fully charged condition.

✎ **Vent --** A normally sealed mechanism that allows for the controlled escape of gases from within a cell.

✎ **Voltage, cutoff --** Voltage at the end of useful discharge. (See **Voltage, end-point**.)

- ✎ **Voltage, end-point --** Cell voltage below which the connected equipment will not operate or below which operation is not recommended.

- ✎ **Voltage, nominal --** Voltage of a fully charged cell when delivering rated current.

- ✎ **Wet Cell --** A cell, the electrolyte of which is in liquid form and free to flow and move.

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