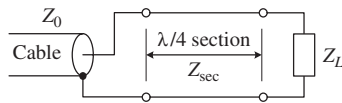**QUARTER-WAVE SECTION**

QUARTER-WAVE SECTION

FIGURE 3.22

A transmission line with characteristic impedance Z_0 can be matched with a load with impedance Z_L by inserting a wire segment that has a length equal to one quarter of the transmitted signal's wavelength ($\lambda/4$) and which has an impedance equal to

$$Z_{sec} = \sqrt{Z_0 Z_L}$$

To calculate the segment's length, you must use the formula $\lambda = v/f$, where v is the velocity of propagation of a signal along the cable and f is the frequency of the signal. To find v, use

$$v = c/\sqrt{k}$$

where $c = 3.0 \times 10^8$ m/s, and k is the dielectric constant of the cable's insulation.

For example, say you wish to match a 50-Ω cable that has a dielectric constant of 1 with a 200-Ω load. If you assume the signal's frequency is 100 MHz, the wavelength then becomes

$$\lambda = \frac{v}{f} = \frac{c/\sqrt{k}}{f} = \frac{3 \times 10^8/1}{100 \times 10^6} = 3 \text{ m}$$

To find the segment length, you plug λ into $\lambda/4$. Hence the segment should be 0.75 m long. The wire segment also must have an impedance equal to

$$Z_{sec} = \sqrt{(50)(200)} = 100 \ \Omega$$

STUBS

Short-circuited stub

Pair of open-ended matching stubs
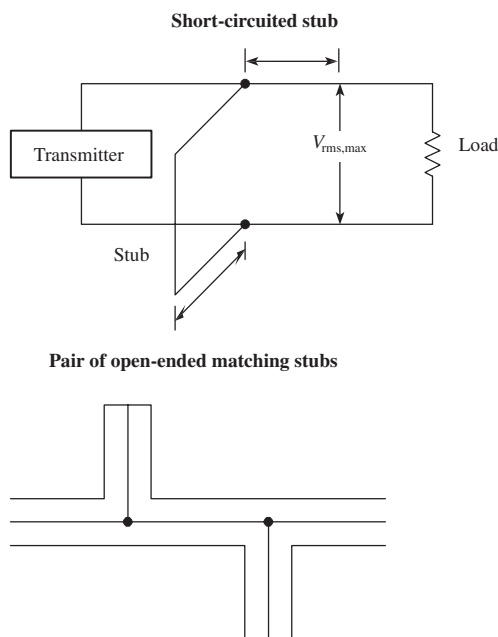
A short length of transmission line that is open ended or short-circuit terminated possesses the property of having an impedance that is reactive. By properly choosing a segment of open-circuit or short-circuit line and placing it in shunt with the original transmission line at an appropriate position along the line, standing waves can be eliminated. The short segment of wire is referred to as a *stub*. Stubs are made from the same type of cable found in the transmission line. Figuring out the length of a stub and where it should be placed is fairly tricky. In practice, graphs and a few formulas are required. A detailed handbook on electronics is the best place to learn more about using stubs.

FIGURE 3.23

3.2 Batteries

A battery is made up of a number of *cells*. Each cell contains a positive terminal, or *cathode*, and a negative terminal, or *anode*. (Note that most other devices treat *anodes* as positive terminals and *cathodes* as negative terminals.)
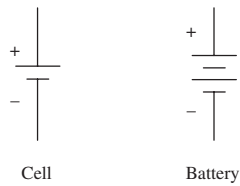
Cell Battery

FIGURE 3.24

When a load is placed across a cell's terminals, a conductive bridge is formed that initiates chemical reactions within the cell. These reactions produce electrons in the anode material and remove electrons from the cathode material. As a result, a potential is created across the terminals of the cell, and electrons from the anode flow through the load (doing work in the process) and into the cathode.

A typical cell maintains about 1.5 V across its terminals and is capable of delivering a specific amount of current that depends on the size and chemical makeup of the cell. If more voltage or power is needed, a number of cells can be added together in either series or parallel configurations. By adding cells in series, a larger-voltage battery can be made, whereas adding cells in parallel results in a battery with a higher current-output capacity. Figure 3.25 shows a few cell arrangements.
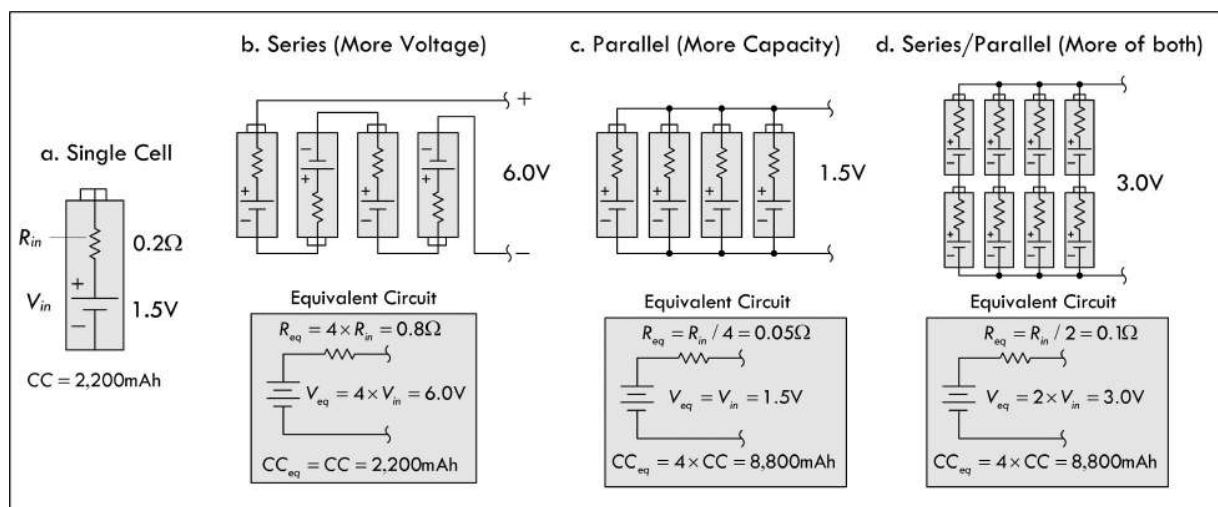

FIGURE 3.25

Battery cells are made from a number of different chemical ingredients. The use of a particular set of ingredients has practical consequences on the battery's overall performance. For example, some cells are designed to provide high open-circuit voltages, whereas others are designed to provide large current capacities. Certain kinds of cells are designed for light-current, intermittent applications, whereas others are designed for heavy-current, continuous-use applications. Some cells are designed for pulsing applications, where a large burst of current is needed for a short period of time. Some cells have good shelf lives; others have poor shelf lives. Batteries that are designed for one-time use, such as carbon-zinc and alkaline batteries, are called *primary batteries*. Batteries that can be recharged a number of times, such as nickel metal hydride and lead-acid batteries, are referred to as *secondary batteries*.

3.2.1 How a Cell Works

A cell converts chemical energy into electrical energy by going through what are called *oxidation-reduction reactions* (reactions that involve the exchange of electrons).

The three fundamental ingredients of a cell used to initiate these reactions include two chemically dissimilar metals (positive and negative electrodes) and an electrolyte (typically a liquid or pastelike material that contains freely floating ions). The following is a little lecture on how a simple lead-acid battery works.

For a lead-acid cell, one of the electrodes is made from pure lead (Pb); the other electrode is made from lead oxide (PbO_2); and the electrolyte is made from a sulfuric acid solution ($H_2O + H_2SO_4 \rightarrow 3H^+ + SO_4^{2-} + OH^-$).
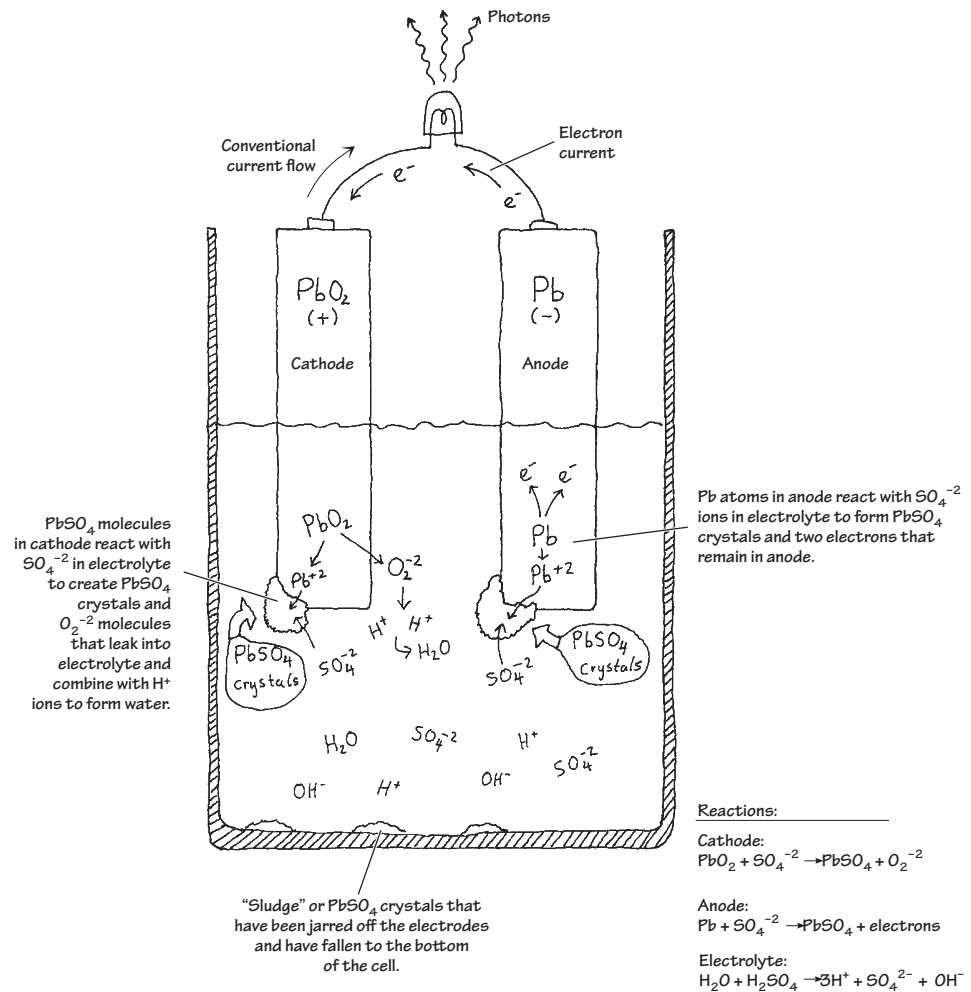
FIGURE 3.26

When the two chemically dissimilar electrodes are placed in the sulfuric acid solution, the electrodes react with the acid (SO_4^{-2}, H^+ ions), causing the pure lead electrode to slowly transform into $PbSO_4$ crystals. During this transformation reaction, two electrons are liberated within the lead electrode. Now, if you examine the lead oxide electrode, you also will see that it too is converted into $PbSO_4$ crystals. However, instead of releasing electrons during its transformation, it releases O_2^{-2} ions. These ions leak out into the electrolyte

solution and combine with the hydrogen ions to form H_2O (water). By placing a load element, say, a lightbulb, across the electrodes, electrons will flow from the electron-abundant lead electrode, through the bulb's filament, and into the electron-deficient lead oxide electrode.

As time passes, the ingredients for the chemical reactions run out (the battery is drained). To get energy back into the cell, a reverse voltage can be applied across the cell's terminals, thus forcing the reactions backward. In theory, a lead-acid battery can be drained and recharged indefinitely. However, over time, chunks of crystals will break off from the electrodes and fall to the bottom of the container, where they are not recoverable. Other problems arise from loss of electrolyte due to gasing during electrolysis (a result of overcharging) and due to evaporation.

3.2.2 Primary Batteries

Primary batteries are one-shot deals—once they are drained, it is all over. Common primary batteries include carbon-zinc batteries, alkaline batteries, mercury batteries, silver oxide batteries, zinc air batteries, and silver-zinc batteries. Here are some common battery packages:
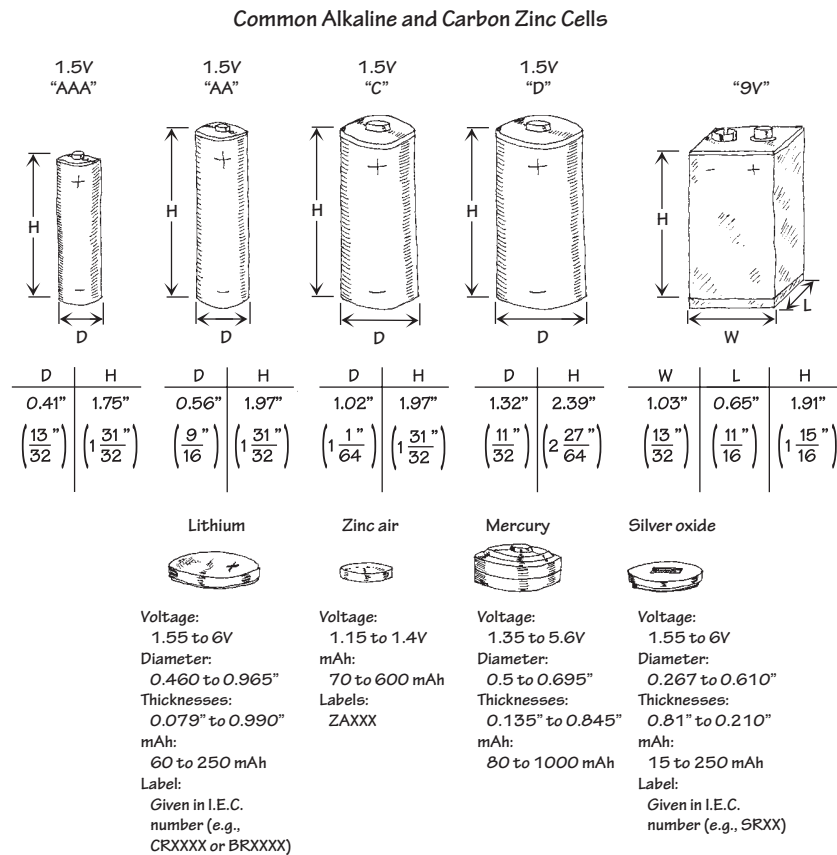

Common Alkaline and Carbon Zinc Cells

	1.5V "AAA"		1.5V "AA"		1.5V "C"		1.5V "D"		"9V"		
D	**H**	**D**	**H**	**D**	**H**	**D**	**H**	**W**	**L**	**H**
0.41"	1.75"	0.56"	1.97"	1.02"	1.97"	1.32"	2.39"	1.03"	0.65"	1.91"
$\left(\frac{13}{32}"\right)$	$\left(1\frac{31}{32}"\right)$	$\left(\frac{9}{16}"\right)$	$\left(1\frac{31}{32}"\right)$	$\left(1\frac{1}{64}"\right)$	$\left(1\frac{31}{32}"\right)$	$\left(\frac{11}{32}"\right)$	$\left(2\frac{27}{64}"\right)$	$\left(\frac{13}{32}"\right)$	$\left(\frac{11}{16}"\right)$	$\left(1\frac{15}{16}"\right)$

Lithium

Voltage:
  1.55 to 6V
Diameter:
  0.460 to 0.965"
Thicknesses:
  0.079" to 0.990"
mAh:
  60 to 250 mAh
Label:
  Given in I.E.C.
  number (e.g.,
  CRXXXX or BRXXXX)

Zinc air

Voltage:
  1.15 to 1.4V
mAh:
  70 to 600 mAh
Labels:
  ZAXXX

Mercury

Voltage:
  1.35 to 5.6V
Diameter:
  0.5 to 0.695"
Thicknesses:
  0.135" to 0.845"
mAh:
  80 to 1000 mAh

Silver oxide

Voltage:
  1.55 to 6V
Diameter:
  0.267 to 0.610"
Thicknesses:
  0.81" to 0.210"
mAh:
  15 to 250 mAh
Label:
  Given in I.E.C.
  number (e.g., SRXX)

FIGURE 3.27

3.2.3 Comparing Primary Batteries

Carbon-Zinc Batteries

Carbon-zinc batteries ("standard-duty") are general-purpose primary-type batteries that were popular back in the 1970s, but have become obsolete with the advent of alkaline batteries. These batteries are not suitable for continuous use (only for intermittent use) and are susceptible to leakage. The nominal voltage of a carbon-zinc cell is about 1.5 V, but this value gradually drops during service. Shelf life also tends to be poor, especially at elevated temperatures. The only really positive aspect of these batteries is their low cost and wide size range. They are best suited to low-power applications with intermittent use, such as in radios, toys, and general-purpose low-cost devices. Don't use these cells in expensive equipment or leave them in equipment for long periods of time—there is a good chance they will leak. Standby applications and applications that require a wide temperature range should also be avoided. In all, these batteries are to be avoided, if you can even find them.

Zinc-Chloride Batteries

Zinc-chloride batteries ("heavy-duty") are a heavy-duty version of the carbon-zinc battery, designed to deliver more current and provide about 50 percent more capacity. Like the carbon-zinc battery, zinc-chloride batteries are essentially obsolete as compared to alkaline batteries. The terminal voltage of a zinc-chloride cell is initially about 1.5 V, but drops as chemicals are consumed. Unlike carbon-zinc batteries, zinc-chloride batteries perform better at low temperatures, and slightly better at higher temperatures, too. The shelf life is also longer. They tend to have lower internal resistance and higher capacities than carbon-zinc, allowing higher currents to be drawn for longer periods. These batteries are suited to moderate, intermittent use. However, an alkaline battery will provide better performance in similar applications.

Alkaline Batteries

Alkaline batteries are the most common type of household battery you can buy—they have practically replaced the carbon-zinc and zinc-chloride batteries. They are relatively powerful and inexpensive. The nominal voltage of an alkaline cell is again 1.5 V, but doesn't drop as much during discharge as the previous two battery types. The internal resistance is also considerably lower, and remains so until near the end of the battery's life cycle. They have very long shelf lives and better high- and low-temperature performance, too. General-purpose alkaline batteries don't work particularly well on high-drain devices like digital cameras, since the internal resistance limits output current flow. They will still work in your device, but the battery life will be greatly reduced. They are well suited to most general-purpose applications, such as toys, flashlights, portable audio equipment, digital cameras, and so on. Note that there is a rechargeable version of an alkaline battery, as well.

Lithium Batteries

Lithium batteries use a lithium anode, one of a number of different kinds of cathodes, and an organic electrolyte. They have a nominal voltage of 3.0 V—twice that of most

other primary cells—that remains almost flat during the discharge cycle. They also have a very low self-discharge rate, giving them an excellent shelf life—as much as 10 years. The internal resistance is also quite low, and remains so during discharge. It performs well in both low and high temperatures, and advanced versions of this battery are used on satellites, on space vehicles, and in military applications. They are ideal for low-drain applications such as smoke detectors, data-retention devices, pacemakers, watches, and calculators.

Lithium-Iron Disulfide Batteries

Unlike other lithium cells that have chemistries geared to obtaining the greatest capacity in a given package, lithium-iron disulfide cells are a compromise. To match existing equipment and circuits, their chemistry has been tailored to the standard nominal 1.5-V output (whereas other lithium technologies produce double that). These cells are consequently sometimes termed *voltage-compatible lithium* batteries. Unlike other lithium technologies, lithium-iron disulfide cells are not rechargeable. Internally, the lithium-iron disulfide cell is a sandwich of a lithium anode, a separator, and an iron disulfide cathode with an aluminum cathode collector. The cells are sealed but vented. Compared to the alkaline cells—with which they are meant to compete—lithium-iron disulfide cells are lighter (weighing about 66 percent of same-size alkaline cells) and higher in capacity, and they have a much longer shelf life—even after 10 years on the shelf, lithium disulfide cells still retain most of their capacity. Lithium iron-disulfide cells operate best under heavier loads. In high-current applications, they can supply power for a duration exceeding 260 percent of the time that a similar-sized alkaline cell can supply. This advantage diminishes at lower loads, however, and at very light loads may disappear or even reverse. For example, under a 20-mA load, a certain manufacturer rates its AA-size lithium-disulfide cells to provide power for about 122 hours while its alkaline cells will last for 135 hours. However, under a heavy load of 1 A, the lithium disulfide cell overshadows the alkaline counterpart by lasting 2.1 hours versus only 0.8 hours for the alkaline battery.

Mercury Cells

Zinc-mercuric oxide, or "mercury," cells take advantage of the high electrode potential of mercury to offer a very high energy density combined with a very flat discharge curve. Mercuric oxide forms the positive electrode, sometimes mixed with manganese dioxide. The nominal terminal voltage of a mercury cell is 1.35 V, and this remains almost constant over the life of the cell. They have an internal resistance that is fairly constant. Although made only in small button sizes, mercury cells are capable of reasonably high-pulsed discharge current and are thus suitable for applications such as quartz analog watches and hearing aids as well as voltage references in instruments, and the like.

Silver Oxide Batteries

The silver oxide battery is the predominate miniature battery found on the market today. Silver oxide cells are made only in small button sizes of modest capacity

but have good pulsed discharge capability. They are typically used in watches, calculators, hearing aids, and electronic instruments. This battery's general characteristics include higher voltage than comparable mercury batteries, flatter discharge curve than alkaline batteries, good low-temperature performance, good resistance to shock and vibration, essentially constant internal resistance, excellent service maintenance, and long shelf life—exceeding 90 percent charge after storage for five years. The nominal terminal voltage of a silver oxide cell is slightly over 1.5 V and remains almost flat over the life of the cell. Batteries built from cells range from 1.5 V to 6.0 V and come in a variety of sizes. Silver oxide hearing aid batteries are designed to produce greater volumetric energy density at higher discharge rates than silver oxide watch or photographic batteries. Silver oxide photo batteries are designed to provide constant voltage or periodic high-drain pulses with or without a low drain background current. Silver oxide watch batteries, using a sodium hydroxide (NaOH) electrolyte system are designed primarily for low-drain continuous use over long periods of time—typically five years. Silver oxide watch batteries using potassium hydroxide (KOH) electrolyte systems are designed primarily for continuous low drains with periodic high-drain pulse demands, over a period of about two years.

Zinc Air Batteries

Zinc air cells offer very high energy density and a flat discharge curve, but have relatively short working lives. The negative electrode is formed of powdered zinc, mixed with the potassium hydroxide electrolyte to form a paste. This is retained inside a small metal can by a separator membrane that is porous to ions, and on the other side of the membrane is simply air to provide the oxygen (which acts as the positive electrode). The air/oxygen is inside an outer can of nickel-plated steel that also forms the cell's positive connection, lined with another membrane to distribute the oxygen over the largest area. Actually there is no oxygen or air in the zinc-oxygen cell when it's made. Instead, the outer can has a small entry hole with a covering seal, which is removed to admit air and activate the cell. The zinc is consumed as the cell supplies energy, which is typically for around 60 days. The nominal terminal voltage of a zinc-oxygen cell is 1.45 V, and the discharge curve is relatively flat. The internal resistance is only moderately low, and they are not suitable for heavy or pulsed discharging. They are found mainly in button and pill packages, and are commonly used in hearing aids and pagers. Miniature zinc air batteries are designed primarily to provide power to hearing aids. In most hearing aid applications, zinc air batteries can be directly substituted for silver oxide or mercuric oxide batteries and will typically give the longest hearing aid service of any common battery system. Notable characteristics include high capacity-to-volume ratio for a miniature battery, more stable voltage at high currents when compared to mercury or silver oxide batteries, and essentially constant internal resistance. They are activated by removing the covering (adhesive tab) from the air access hole, and they are most effective in applications that consume battery capacity in a few weeks.

TABLE 3.5   Primary Battery Comparison Chart

| TYPE (CHEMISTRY)	COMMON NAME(S)	NOMINAL CELL VOLTS	INTERNAL RESISTANCE	MAXIMUM DISCHARGE RATE	COST	PROS AND CONS	TYPICAL APPLICATIONS
Carbon-zinc	Standard-duty	1.5	Medium	Medium	Low	Low cost, various sizes, but terminal voltage drops steadily during cell life	Radios, toys, and general-purpose electrical equipment
Zinc-chloride	Heavy-duty	1.5	Low	Medium to high	Low to medium	Low cost at higher discharge rates and at lower temperature; terminal voltage still drops	Motor-driven portable devices, clocks, remote controls
Alkaline zinc-manganese dioxide	Alkaline	1.5	Very low	High	Medium to high	Better for high continuous or pulsed loads and at low temperatures, but terminal voltage drops	Photoflash units, battery shavers, digital cameras, handheld transceivers, portable CD players, etc.
Lithium-manganese dioxide	Lithium	3.0	Low	Medium to high	High	High energy density, very low self-discharge rate (excellent shelf-life), good temperature tolerance	Watches, calculators, cameras (digital and film), DMMs, and other test instruments
Zinc-mercuric oxide	Mercury cell	1.35	Low	Low	High	High energy density (compact), very flat discharge curve, good at higher temperatures	Calculators, pagers hearing aids, watches, test instruments
Zinc-silver oxide	Silver oxide cell	1.5	Low	Low	High	Very high energy density (very compact), very flat discharge curve, reasonable at lower temperatures	Calculators, pagers, hearing aids, watches test instruments
Zinc-oxygen	Zinc air cell	1.45	Medium	Low	Medium	High energy density, very lightweight, flat discharge curve, but must have access to air	Hearing aids and pagers
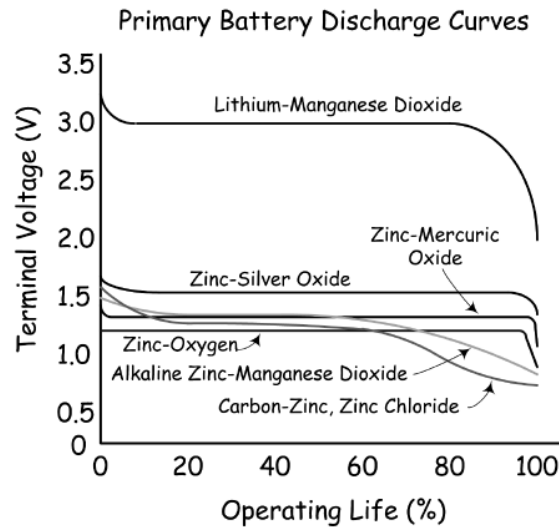
FIGURE 3.28

3.2.4 Secondary Batteries

Secondary batteries, unlike primary batteries, are rechargeable by nature. The actual discharge characteristics for secondary batteries are similar to those of primary batteries, but in terms of design, secondary batteries are made for long-term, high-power-level discharges, whereas primary batteries are designed for short discharges at low power levels. Most secondary batteries come in packages similar to those of primary batteries, with the exception of, say, lead-acid batteries and special-purpose batteries. Secondary batteries are used to power such devices as laptop computers, portable power tools, electric vehicles, emergency lighting systems, and engine starting systems.

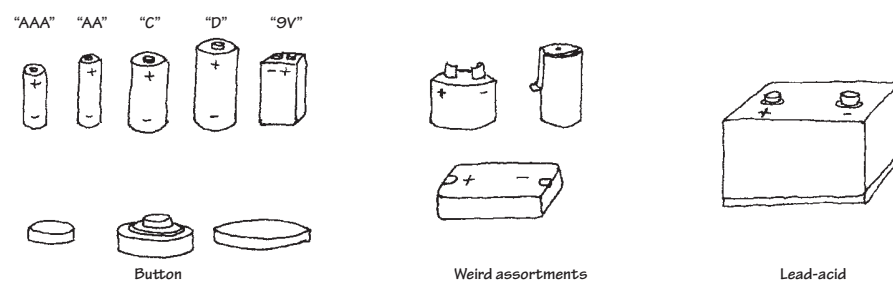Here are some common packages for secondary batteries:

FIGURE 3.29

Comparing Secondary (Rechargeable) Batteries

LEAD-ACID BATTERIES

Lead-acid batteries are typically used for high-power applications, such as motorized vehicle power and battery backup applications. There are basically three types of lead-acid batteries: flooded lead-acid, valve-regulated lead-acid (VRLA), and

sealed lead-acid (SLA). The flooded types must be stood upright and tend to lose electrolytes while producing gas over time. The SLA and VRLA are designed for a low overvoltage potential to prohibit the battery from reaching its gas-generating potential during discharge. However, SLA and VRLA can never be charged to their full potential. VRLA is generally used for stationary applications, while the SLA can be used in various positions. Lead-acid batteries typically come in 2-V, 4-V, 6-V, 8-V, and 12-V versions, with capacities ranging from 1 to several thousand amp-hours. The flooded lead-acid battery is used in automobiles, forklifts, wheelchairs, and UPS devices.

An SLA battery uses a gel-type electrolyte rather than a liquid to allow it to be used in any position. However, to prevent gas generation, it must be operated at a lower potential—meaning it's never fully charged. This means that it has a relatively poor energy density—the lowest for all sealed secondary batteries. However, they're the cheapest secondary, making them best suited for applications where low-cost, stationary power storage is the main concern. SLA batteries have the lowest self-discharge rate of any of the secondary batteries (about 5 percent per month). They do not suffer from memory effect (as displayed in NiCad batteries), and they perform well with shallow cycling; in fact, they tend to prefer it to deep cycling, although they perform well with intermittent heavy current demands, too. SLA batteries aren't designed for fast charging—typically 8 to 16 hours for full recharge. They must also always be stored in a charged state. Leaving them in a discharged state can lead to sulfation, a condition that makes the batteries difficult, if not impossible, to recharge. Also, SLA batteries have an environmentally unfriendly electrolyte.

The basic technique for recharging lead-acid batteries, be they flooded, sealed, or valve-regulated, is to read the technical directions that come with them. If you don't know what you're doing—say, trying to make your own battery recharger—you may run into a serious problem, such as blowing up batteries with too much pressure, melting them, or destroying the chemistry. (The procedure for charging lead-acid batteries is different from that for NiCad and NiMH batteries in that voltage limiting is used instead of current limiting.)

NICKEL-CADMIUM (NiCAD) BATTERIES

Nickel-cadmium batteries are made using nickel hydroxide as the positive electrode and cadmium hydroxide as the negative electrode, with potassium hydroxide as the electrolyte. Nickel-cadmium batteries have been a very popular rechargeable battery over the years; however, with the introduction of NiMH batteries, they have seen a decline in use. In practical terms, NiCad batteries don't last very long before needing a recharge. They put out less voltage (per cell) than a standard alkaline (1.2 V versus 1.5 V for alkaline). This means that applications that require four or more alkaline batteries might not work at all with comparable-sized NiCad batteries. During discharge, the average voltage of a sealed NiCad cell is about 1.2 V per cell. At nominal discharge rates, the characteristic is very nearly flat until the cell approaches full discharge. The battery provides most of its energy above 1.0 V per cell. The self-discharge rate of a NiCad is not great, either—around two to three months. However, like SLAs, sealed NiCads can be used in virtually any position. NiCads have a higher energy density than SLAs (about twice as much), and with

a relatively low cost, they are popular for powering compact portable equipment: cordless power tools, model boats and cars, and appliances such as flashlights and vacuum cleaners. NiCads suffer from memory effect and are therefore not really suitable for applications that involve shallow cycling or spending most of their time on a float charger. They perform best in situations where they're deeply cycled. They have a high number of charge/discharge cycles—around 1000.

Use a recommended charger—a constant current–type charger with due regard for heat dissipation and wattage rating. Improper charging can cause heat damage or even high-pressure rupture. Observe proper charging polarity. The safe charge rate for sealed NiCad cells for extended charge periods is 10 hours, or C/10 rate.

NICKEL METAL HYDRIDE (NiMH) BATTERIES

NiMH batteries are very popular secondary batteries, replacing NiCad batteries in many applications. NiMH batteries use a nickel/nickel hydroxide positive electrode, a hydrogen-storage alloy (such as lanthanum-nickel or zirconium-nickel) as a negative electrode, and potassium hydroxide as the electrolyte. They have a higher energy density than standard NiCad batteries (about 30 to 40 percent higher) and don't require special disposal requirements, either. The nominal voltage of a NiMH battery is 1.2 V per cell, which must be taken into consideration when substituting them into devices that use standard 1.5-V cells such as alkaline cells. They self-discharge in about two to three months and do display some memory effect, but not as bad as NiCad batteries. They are not as happy with a deep discharge cycle as a NiCad battery, and they tend to have a shorter work life. Best results are achieved with load currents of 0.2-C to 0.5-C (one-fifth to one-half of the rated capacity). Typical applications include remote-control vehicles and power tools (although NiMH batteries are rapidly being superceded by Li-ion and LiPo batteries).

Recharging NiMH batteries is a bit complex due to significant heat generation; the charge uses a special algorithm that requires trickle charging and temperature sensing. Unlike NiCad batteries, NiMH batteries have little memory effect. The batteries require regular full discharge to prevent crystalline formation.

Li-ION BATTERIES

Lithium is the lightest of all metals and has the highest electrochemical potential, giving it the possibility of an extremely high energy density. However, the metal itself is highly reactive. While this isn't a problem with primary cells, it poses an explosion risk with rechargeable batteries. For these to be made safe, lithium-ion technology had to be developed; the technology uses lithium ions from chemicals such as lithium-cobalt dioxide, instead of the metal itself. Typical Li-ion batteries have a negative electrode of aluminum coated with a lithium compound such as lithium-cobalt dioxide, lithium-nickel dioxide, or lithium-manganese dioxide. The positive electrode is generally of copper, coated with carbon (generally either graphite or coke), while the electrolyte is a lithium salt such as lithium-phosphorous hexafluoride, dissolved in an organic solvent such as a mixture of ethylene carbonate and dimethyl carbonate. Li-ion batteries have roughly twice the energy density of NiCads, making them the most compact rechargeable yet in terms of energy storage. Unlike NiCad or NiMH batteries, they are not subject to memory effect, and have a relatively low self-discharge rate—about 6 percent per month, less than half

that of NiCads. They are also capable of moderately deep discharging, although not as deep as NiCads, as they have a higher internal resistance. On the other hand, Li-ion batteries cannot be charged as rapidly as NiCads, and they cannot be trickle or float charged, either. They also are significantly more costly than either NiCads or NiMH batteries, making them the most expensive rechargeables of all. Part of this is that they must be provided with built-in protection against both excessive discharging and overcharging (both of which pose a safety risk). Most Li-ion batteries are therefore supplied in self-contained battery packs, complete with "smart" protective circuitry. They are subject to aging, even if not used, and have moderate discharge currents. The main applications for Li-ion batteries are in places where as much energy as possible needs to be stored in the smallest possible space, and with as little weight as possible. They are found in laptop computers, PDAs, camcorders, and cell phones.

Li-ion batteries require special voltage-limiting recharging devices. Commercial Li-ion battery packs contain a protection circuit that prevents the cell voltage from going too high while charging. The typical safety threshold is set to 4.30 V/cell. In addition, temperature sensing disconnects the charging device if the internal temperature approaches 90°C (194°F). Most cells feature a mechanical pressure switch that permanently interrupts the current path if a safe pressure threshold is exceeded. The charge time of all Li-ion batteries, when charged at a 1-C initial current, is about three hours. The battery remains cool during charge. Full charge is attained after the voltage has reached the upper voltage threshold and the current has dropped and leveled off at about 3 percent of the nominal charge current. Increasing the charge current on a Li-ion charger does not shorten the charge time by much. Although the voltage peak is reached more quickly with higher current, the topping charge will take longer.

LITHIUM POLYMER (Li-POLYMER) BATTERIES

The lithium polymer batteries are a lower-cost version of the Li-ion batteries. Their chemistry is similar to that of the Li-ion in terms of energy density, but uses a dry solid polymer electrolyte only. This electrolyte resembles a plastic-like film that does not conduct electricity but allows an exchange of ions (electrically charged atoms or groups of atoms). The dry polymer is more cost effective during fabrication, and the overall design is rugged, safe, and thin. With a cell thickness measuring as little as 1 mm, it is possible to use this battery in thin compact devices where space is an issue. It is possible to create designs which form part of a protective housing, are in the shape of a mat that can be rolled up, or are even embedded into a carrying case or piece of clothing. Such innovative batteries are still a few years away, especially for the commercial market.

Unfortunately, the dry Li-polymer suffers from poor ion conductivity, due to high internal resistance; it cannot deliver the current bursts needed for modern communication devices. However, it tends to increase in conductivity as the temperature rises, a characteristic suitable for hot climates. To make a small Li-polymer battery more conductive, some gelled electrolyte may be added. Most of the commercial Li-polymer batteries used today for mobile phones are hybrids and contain gelled electrolytes.

The charge process of a Li-polymer battery is similar to that of the Li-ion battery. The typical charge time is around one to three hours. Li-polymer batteries with gelled electrolyte, on the other hand, are almost identical to Li-ion batteries. In fact, the same charge algorithm can be applied.

NICKEL-ZINC (NiZn) BATTERIES

Nickel-zinc batteries are commonly used in light electric vehicles. They are considered the next generation of batteries used for high-drain applications, and are expected to replace sealed lead-acid batteries due to their higher energy densities (up to 70 percent lighter for the same power). They are also relatively cheap compared to NiCad batteries.

NiZn batteries are chemically very similar to NiCad batteries; both use an alkaline electrolyte and a nickel electrode, but they differ significantly in their voltage. The NiZn cell delivers more than 0.4 V of additional voltage both at open circuit and under load. With the additional 0.4 V per cell, multicell batteries can be constructed in smaller packages. For example, a 19.2-V pack can replace a 14.4-V NiCad pack, representing a 25 percent lower cell space and delivering higher power and a 45 percent lower impedance. They are also less expensive than most rechargeables. They are safe (abuse-tolerant). The life cycle is a bit better than for NiCad batteries for typical applications. They have superior shelf life when compared to lead-acid. Also, they are considered environmentally green—both nickel and zinc are nontoxic and easily recycled.

In terms of recharge times, it takes less than two hours to achieve full recharge; there is an 80 percent charge in one hour. This feature makes them useful in cordless power tools. Their high energy density and high discharge rate make them suitable for applications that demand large amounts of power in small, lightweight packages. They are found in cordless power tools, UPS systems, electric scooters, high-intensity dc lighting and the like.

NICKEL-IRON (NiFe) BATTERIES

Nickel-iron batteries, also called nickel alkaline or NiFe batteries, were introduced in 1900 by Thomas Edison. These are very robust batteries that are tolerant of abuse and can have very long life spans (30 years or more). The open-circuit voltage of these cells is 1.4 V, and the discharge voltage is about 1.2 V. They withstand overcharge and over-discharge. They accept high depth of discharge (deep cycling) and can remain discharged for long periods without damage, unlike lead-acid batteries that need to be stored in a charged state. They are, however, very heavy and bulky. Also, the low reactivity of the active components limits high-discharge performance. The cells take a charge slowly, give it up slowly, and have a steep voltage dropoff with state of charge. Furthermore, they have a low energy density compared to other secondary batteries, and a high self-discharge rate. NiFe batteries are used in applications similar to those for lead-acid batteries, but oriented toward a necessity of longevity. (A typical lead-acid battery will last around five years, compared to around 30 to 80 years for a NiFe battery.)

TABLE 3.6 Rechargeable Battery Comparison Chart

TYPE (CHEMISTRY)	NOMINAL CELL VOLTS (APPROX.)	ENERGY DENSITY (Wh/Kg)	CYCLE LIFE	CHARGE TIME	MAX. DISCHARGE RATE	COST	PROS AND CONS	TYPICAL APPLICATIONS
Sealed lead-acid	2.0	Low (30)	Long (shallow cycles)	8–16 h	Medium (0.2 C)	Low	Low cost, low self-discharge, happy float charging, but prefers shallow charging	Emergency lighting, alarm systems solar power systems, wheelchairs, etc.
Rechargeable alkaline-manganese	1.5	High (75 initial)	Short to medium	2–6 h (pulsed)	Medium (0.3 C)	Low	Low cost, low self-discharge, prefer shallow cycling, no memory effect but short cycle life	Portable emergency lighting, toys, portable radios, CD players, test instruments, etc.
NiCad	1.2	Medium (40–60)	Long (deep cycles)	14–16 h (0.1 C) or <2 h with care (1 C)	High (>2 C)	Medium	Prefer deep cycling, good pulse capacity, but have memory effect, fairly high self-discharge rate, environmentally unfriendly	Portable tools and appliances, model cars and boats, data loggers, camcorders, portable transceivers, and test equipment
NiMH	1.2	High (60–80)	Medium	2–4 h	Medium (0.2–0.5 C)	Medium	Very compact energy source, but have some memory effect, high self-discharge rate	Remote control vehicles, cordless mobile phones, personal DVD and CD players, power tools
NiZn	1.65	High (>170)	Medium to high	1–2 h	—	Medium	Low cost, environmentally green, twice energy density of NiCad	Exceptional performance, no memory, long shelf-life
NiFe	1.4	High (>200)	Extremely long	Long	—	Low	High cycle life, incredibly long life up to 80 years, environmentally friendly	Forklifts and other, similar SLA-like applications, but where longevity is important
Li-ion/LiPo	3.6	Very high (>100)	Medium	3–4 h (1 C– 0.03 C)	Med/high (<1 C)	High	Very compact, low maintenance, low self-discharge, but needs great care with charging	Compact cell phones and notebook PCs, digital cameras, and similar very small portable device

RECHARGEABLE ALKALINE-MANGANESE (RAM) BATTERIES

Rechargeable alkaline-manganese, or RAM, batteries are the rechargeable version of primary alkaline batteries. Like the primary technology, they use a manganese dioxide positive electrolyte and potassium hydroxide electrode, but the negative electrode is now a special porous zinc gel designed to absorb hydrogen during the charging process. The separator is also laminated to prevent it being pierced by zinc dendrites. These are often considered a poor substitute for a rechargeable, as compared to a NiCad or NiMH battery. RAM batteries have a tendency to plummet in capacity over few recharge cycles. It is feasible for a RAM battery to lose 50 percent of its capacity after only eight cycles. On the positive side, they are inexpensive and readily available. They can usually be used as a direct replacement for non-rechargeable batteries, but they usually have a lower nominal voltage, making them unsuitable for some devices, but not in high-drain devices like digital cameras. They have a low self-discharge rate and can be stored on standby for up to 10 years. Also, they are environmentally friendly (no toxic metals are used) and maintenance-free; there is no need for cycling or worrying about memory effect. On the short side, they have limited current-handling capability and are limited to light-duty applications such as flashlights and other low-cost portable electronic devices that require shallow cycling. Recharging a RAM battery requires a special recharger; if you charge them in a standard charger, they may explode.
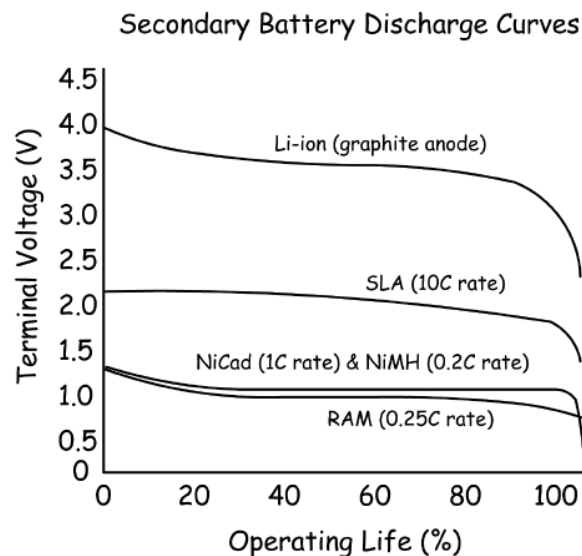

FIGURE 3.30

THE SUPERCAPACITOR

The supercapacitor isn't really a battery but a cross between a capacitor and a battery. It resembles a regular capacitor, but uses special electrodes and some electrolytes. There are three kinds of electrode material found in a supercapacitor: high-surface-area-activated carbons, metal oxide, and conducting polymers. The one using high-surface-area-activated carbons is the most economical to manufacture. This system is also called double layer capacitor (DLC) because the energy is stored in the double

layer formed near the carbon electrode surface. The electrolyte may be aqueous or organic. The aqueous electrolyte offers low internal resistance but limits the voltage to 1 V. In contrast, the organic electrolyte allows 2 and 3 V of charge, but the internal resistance is higher.

To make the supercapacitor practical for use in electronic circuits, higher voltages are needed. Connecting the cells in series accomplishes this task. If more than three or four capacitors are connected in series, voltage balancing must be used to prevent any cell from reaching overvoltage.

Supercapacitors have values from 0.22 F upwards to several F. They have higher energy storage capacity than electrolytic capacitors, but a lower capacity than a battery (approximately $\frac{1}{10}$ that of a NiMH battery). Unlike electrochemical batteries that deliver a fairly steady voltage, the voltage of a supercapacitor drops from full voltage to zero volts without the customary flat voltage curve characteristic of most batteries. For this reason, supercapacitors are unable to deliver the full charge. The percentage of charge that is available depends on the voltage requirements of the applications. For example, a 6-V battery is allowed to discharge to 4.5 V before the equipment cuts off; the supercapacitor reaches that threshold with the first quarter of the discharge. The remaining energy slips into an unusable voltage range.

The self-discharge of the supercapacitor is substantially higher than that of the electrochemical battery. Typically, the voltage of the supercapacitor with an organic electrolyte drops from full charge to the 30 percent level in as little as 10 hours. Other supercapacitors can retain the charged energy longer. With these designs, the capacity drops from full charge to 85 percent in 10 days. In 30 days, the voltage drops to roughly 65 percent, and to 40 percent after 60 days.

The most common supercapacitor applications are memory backup and standby power for real-time clock ICs. Only in special applications can the supercapacitor be used as a direct replacement for a chemical battery. Often the supercapacitor is used in tandem with a battery (placed across its terminals, with a provision in place to limit high influx of current when equipment is turned on) to improve the current handling of the battery: during low load current the battery charges the supercapacitor; the stored energy of the supercapacitor kicks in when a high load current is requested. In this way the supercapacitor acts to filter and smooth pulsed load currents. This enhances the battery's performance, prolongs the runtime, and even extends the longevity of the battery.

Limitations include an inability to use the full energy spectrum—depending on the application, not all energy is available. A supercapacitor has low energy density, typically holding $\frac{1}{5}$ to $\frac{1}{10}$ the energy of an electrochemical battery. Cells have low voltages—serial connections are needed to obtain higher voltages. Voltage balancing is required if more than three capacitors are connected in series. Furthermore, the self-discharge is considerably higher than that of an electrochemical battery.

Advantages include a virtually unlimited life cycle—supercapacitors are not subject to the wear and aging experienced by electrochemical batteries. Also, low impedance can enhance pulsed current demands on a battery when placed in parallel with the battery. Supercapacitors experience rapid charging—with low-impedance versions reaching full charge within seconds. The charge method is simple—the voltage-limiting circuit compensates for self-discharge.

Selecting the Right Battery (Comparison Chart)

Legend: ● Yes   ○ Borderline   (blank) No

	Carbon Zinc	Zinc Chloride	Alkaline	Lithium	Zinc air	Silver Oxide	Mercury	RAM	Lead Acid (SLA)	NiCad	NiMH	Lithium Ion	Lithium Polymer	NiZn	Supercapacitor
Characteristics of single cell															
Obsolete (not recommended)	●	●						●							
Rechargeable								●	●	●	●	●	●	●	●
Stable voltage				●	●	●	●			●	●	●	●		
High energy density (Wh/kg)		○	●	●	●	●	●	●			○	●	●	●	
High capacity rating (mAh)														●	
High peak load-current rating	○	●	●	●				●	●	●	●	○	○	●	
High pulsed discharge current		●	●	●		●	●		●	●		●	●	●	●
Low self-discharge rate			●	●					●	●	○	●	●	●	
Good at high temperatures		○	●	●			●								
Good at low temperatures		●	●	●		●									
High cycle life									●	●	●	●	●	●	●
Miniature				●	●	●	●							●	
Memory effect										●	○				
Expensive (cost)				●	●	●	●			●	●	●	●	○	
Environmentally unfriendly									●	●					
Applications															
Very small portable devices				●	●	●	●					●	●		
Pagers, hearing aids (h), watches (w)				●	h	w	●								
Radios, toys, general purpose	●	●	●					●							
Small motorized items		●	●				○				●				
Camcorders, digital cameras, test equipment			●							●	●				
Remotes, clocks, calculators		●	●	●			●								
Cellphones, mobile phones, laptops			○							○	●	●	●		
Low-self discharge (smoke detectors, data loggers)				●			●								
Power tools, model cars, electric toothbrush, etc.										●	●			●	
Motorized vehicles (electric bike, scooters, trolling motors, power tools, mower)									●	●	●			●	
High-power battery backup (emergency lighting, solar power storage, UPS)									●						
Power backup for short-term primary power outages (e.g. CMOS RAM, motor start, etc.)				●	●										●
Standard cell and battery packages															
AAA	●	●	●	●				●		●	●				
AA	●	●	●	●				●		●	●				
C	●	●	●	●				●		●	●				
D	●	●	●	●				●		●	●				
9V	●	●	●	●						●	●				
6V Lantern	●	●	●												
Button (coin)				●	●	●	●								●
Special battery pack				●	●				●	●	●	●	●	●	
Plastic Box									●					●	
PCB mount				●											●

FIGURE 3.31

3.2.5   Battery Capacity

Batteries are given a capacity rating that indicates how much electrical energy they are capable of delivering over a period of time. The capacity rating is specified in terms of ampere-hours (Ah) and millampere-hours (mAh). Knowing the battery capacity, it is possible to estimate how long the battery will last before being considered dead. The following example illustrates this.

Example: A battery with a capacity of 1800 mAh is to be used in a device that draws 120 mA continuously. Ignoring possible loss in capacity as a result of load current magnitude, how long should the battery be able to deliver power?

Answer: Ideally, this would be:

$$t = \frac{1800 \text{ mAh}}{120 \text{ mA}} = 15 \text{ h}$$

Note: In reality, you must consult the battery manufacturer's data sheets and analyze their discharge graphs (voltage as a function of time and of load current) to get an accurate determination of actual discharge time. As the load current increases, there is an apparent loss in battery capacity caused by internal resistance.

Typical capacity ratings for AAA, AA, C, D, and 9-V NiMH batteries are 1000 mAh (AAA), 2300 mAh (AA), 5000 mAh (C), 8500 mAh (D), 250 mAh (9).

C Rating

The charge and discharge currents of a battery are measured in capacity rating or C rating. The capacity represents the efficiency of a battery to store energy and its ability to transfer this energy to a load. Most portable batteries, with the exception of lead-acid, are rated at 1 C. A discharge rate of 1 C draws a current equal to the rated capacity that takes one hour (h). For example, a battery rated at 1000 mAh provides 1000 mA for 1 hour if discharged at 1 C rate. The same battery at 0.5 C provides 500 mA for 2 hours. At 2 C, the same battery delivers 2000 mA for 30 minutes. 1 C is often referred to as a 1-hour discharge; 0.5 C would be 2 hours, and 0.1C would be a 10-hour discharge. The discrepancy in C rates between different batteries is largely dependent on the internal resistance.

Example: Determine the discharge time and average current output of a battery with a capacity rating of 1000 mAh if it is discharged at 1 C. How long would it take to discharge at 5 C, 2 C, 0.5 C, 0.2 C, and 0.05 C?

Answer: At 1 C, the battery is attached to a load drawing 1000 mA (rated capacity/ hour), so the discharge time is:

$$t = 1 \text{ hC/C rating} = 1 \text{ hC/1 C} = 1 \text{ h}$$

At 5 C, the battery is attached to a load drawing 5000 mA (five times rated capacity/ hour), so the discharge time is:

$$t = 1 \text{ hC/C rating} = 1 \text{ hC/5 C} = 0.2 \text{ h}$$

At 2 C, the battery is attached to a load drawing 2000 mA (two times rated capacity/ hour), so the discharge time is:

$$t = 1 \text{ hC/C rating} = 1 \text{ hC/2 C} = 0.5 \text{ h}$$

At 0.5 C, the battery is attached to a load drawing 500 mA (half the rated capacity/ hour), so the discharge time is:

$$t = 1 \text{ hC/C rating} = 1 \text{ hC/0.5 C} = 2 \text{ h}$$

At 0.2 C, the battery is attached to a load drawing 200 mA (20 percent rated capacity/hour) so the discharge time is:

$$t = 1 \text{ hC}/\text{C rating} = 1 \text{ hC}/0.2 \text{ C} = 5 \text{ h}$$

At 0.05 C, the battery is attached to a load drawing 50 mA (5 percent rated capacity/hour) so the discharge time is:

$$t = 1 \text{ hC}/\text{C rating} = 1 \text{ hC}/0.05 \text{ C} = 20 \text{ h}$$

Again, note that these values are estimates. When load currents increase (especially when C values get large), the capacity level drops below nominal values—due to nonideal internal characteristics such as internal resistance—and must be determined using manufacturer's discharge curves and Peurkert's equation. Do a search of the Internet, using "Peurkert's equation" as a keyword, to learn more.

3.2.6   Note on Internal Voltage Drop of a Battery

Batteries have an internal resistance that is a result of the imperfect conducting elements that make up the battery (resistance in electrodes and electrolytes). Though the internal resistance may appear low (around 0.1 Ω for an AA alkaline battery, or 1 to 2 Ω for a 9-V alkaline battery), it can cause a noticeable drop in output voltage if a low-resistance (high-current) load is attached to it. Without a load, we can measure the open-circuit voltage of a battery, as shown in Fig. 3.32a. This voltage is essentially equal to the battery's rated nominal voltage—the voltmeter has such a high input resistance that it draws practically no current, so there is no appreciable voltage drop. However, if we attach a load to the battery, as shown in Fig. 3.32, the output terminal voltage of the battery drops. By treating the internal resistance R_{in} and the load resistance R_{load} as a voltage divider, you can calculate the true output voltage present across the load—see the equation in Fig. 3.32b.
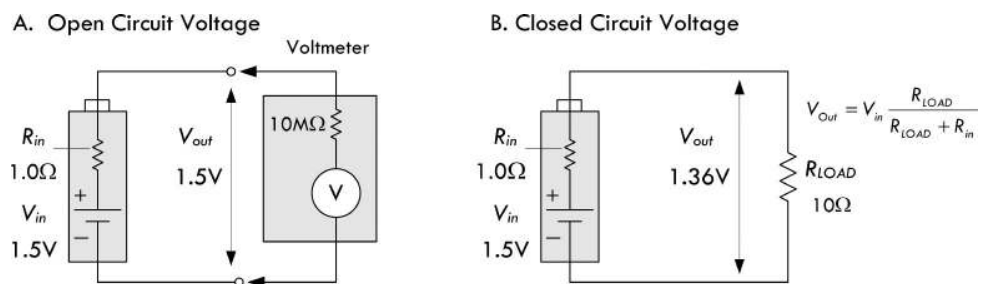

FIGURE 3.32

Batteries with large internal resistances show poor performance in supplying high current pulses. (Consult the battery comparison section and tables to determine which batteries are best suited for high-current, high-pulse applications.) Internal

resistance also increases as the battery discharges. For example, a typical alkaline AA battery may start out with an internal resistance of 0.15 Ω when fresh, but may increase to 0.75 Ω when 90 percent discharged. The following list shows typical internal resistance for various batteries found in catalogs. The values listed should not be assumed to be universal—you must check the specs for your particular batteries.

9-V zinc carbon	35 Ω
9-V lithium	16 to 18 Ω
9-V alkaline	1 to 2 Ω
AA alkaline	0.15 Ω (0.30 Ω at 50 percent discharge)
AA NiMH	0.02 Ω (0.04 Ω at 50 percent discharge)
D Alkaline	0.1 Ω
D NiCad	0.009 Ω
D SLA	0.006 Ω
AC13 zinc air	5 Ω
76 silver	10 Ω
675 mercury	10 Ω

Battery OK / LOW Indicator
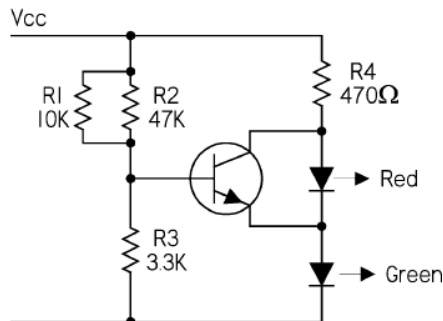

Here a green LED is used to indicate that the battery is okay. This stays on all the time to indicate that the battery is live, and the red LED comes on when the battery voltage falls below the set threshold. A green LED has around 2.0 V across it when it is illuminated. This value varies a bit with different manufacturers, but is pretty well matched within any batch. Add the base emitter voltage, and you need 2.6 V on the base of the right transistor (i.e., across the R_3) to turn on the transistor. 2.6 V across R_3 needs 9.1 across the supply rail. Below this threshold voltage, the transistor is off and the red LED is on. Above this voltage, the red LED is off. By adjusting the values of the three resistors, you can alter the threshold level. We'll discuss transistors and LEDs later on in this book.

FIGURE 3.33

3.3 Switches

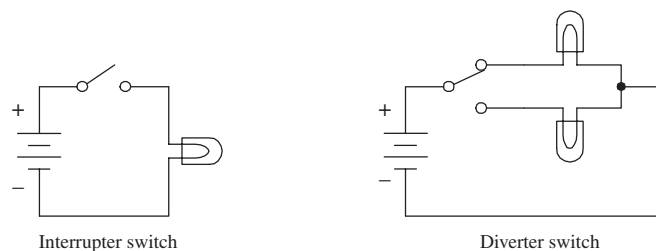A *switch* is a mechanical device that interrupts or diverts electric current flow within a circuit.

Interrupter switch   Diverter switch

FIGURE 3.34