Battery requirements

Estimated power requirements at 2 Amps when device is measuring (not including GPS and Cellular features). The device will be up 12 times per hour taking measurements for 30 seconds per measurement maximum. A CGR18650C is rated more than 2000 mAh and will last for 1 hour of continuous use or 12 hours. To stretch it to 24 hours, will have to limit to 6 measurements per hour. Note that the LDs are pulsed for 1-10us in a sequence. As a result, the draw large currents like 1Amp from the battery with some dead time in between. If dark is inter-sampled, the dead period will be 50-67% duty cycle. Li Ion batteries will provide 4.2 V in a single cell and enough capacity while pulse operation is ideal.

Capacity: 2A x (30 sec / 3600 sec/h) x 12 = 0.25 Ah = 250 mAh
Usage: 30 sec x 12 per hour x 24 hours = 2.4 hours /day

Battery Cell Comparison

Model Number	Nominal Voltage (v)	Typical* Capacity (mAh)	Diameter Inch (mm)	Height Inch (mm)	Thickness Inch (mm)	Approx. Weight oz (g)
CGR17500	3.6	830	0.67 + 0/-0.03 (16.9 + 0/-0.7)	1.95 + 0/-0.04 (49.6 + 0/-1.0)	---	0.88 (25)
CGR18650HG	3.6	1800	0.73 + 0/-0.03 (18.5 + 0/-0.7)	2.56 + 0/-0.02 (65.0 + 0/-0.6)	---	1.48 (42)
CGR18650A	3.6	2000	0.73 + 0/-0.03 (18.5 + 0/-0.7)	2.56 + 0/-0.02 (65.0 + 0/-0.6)	---	1.52 (43)
CGR18650C	3.6	2150	0.73 +0/-0.03 (18.6 +0/-0.7)	2.57 +0/-0.04 (65.2 +0/-1.0)	---	1.57 (44.5)
* 4.2 V Charge						

Li Ion

Technical Data - Table 1				
Model Number	V	Diameter in. (mm)	Height in. (mm)	Av.Wt. oz (gms)
*AM-1PI (Size "D")	1.5	1.312 (33.3)	2.407 (61.1)	4.97 (141)
*AM-2PI (Size "C")	1.5	1.004 (25.5)	1.969 (50.0)	2.47 (70)
*AM-3PI (Size "AA")	1.5	.571 (14.50)	1.988 (50.50)	0.84 (24)
*AM-4PI (Size "AAA")	1.5	.413 (10.49)	1.752 (44.50)	0.42 (12)
*Manufactured in the U.S.A				

Alkaline Standard Sizes

Technical Data - Table 2 - Prismatic Type - Aluminum Housing						
Model Number	Nominal Voltage (v)	Typical* Capacity (mAh)	Width Inch (mm)	Height Inch (mm)	Thickness Inch (mm)	Approx. Weight oz (g)
CGA523436[1]	3.6	710	1.34 +0/-0.02 (34.0 +0/-0.6mm)	1.42 +0/-0.04 (36.0 +0/-1.0mm)	0.20 +0/-0.02 (5.2 +0/-0.6mm)	0.51 (14.5g)
CGA523450A[1]	3.6	940	1.34 +0/-0.02 (34.0 +0/-0.6mm)	1.97 +0/-0.04 (50.0 +0/-1.0mm)	0.21 +0/-0.02 (5.25 +0/-0.6mm)	0.69 (19.5g)

CGA633450A[1]	3.6	1035	1.34 + 0/-0.02 (34.0 + 0/-0.6)	1.97 + 0/-0.04 (50.0 + 0/-1.0)	0.25 + 0/-0.02 (6.35 + 0/-0.6)	.85 (24)
CGA103450A	3.6	1950	1.34 + 0/-0.02 (34.0 + 0/-0.6)	1.97 + 0/-0.04 (50.0 + 0/-1.0)	0.41 + 0/-0.02 (10.5 + 0/-0.6)	1.38 (39)
[1] Not intended for use in multi-cell packs. (Use in single cell packs only) * 4.2 V Charge						

Li Ion Rectangular

Battery Stuff

http://www.batteryuniversity.com/parttwo.htm
Created: June 2003, Last edited: May 2004

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

Discharging at high and low temperature

Batteries function best at room temperature. Operating batteries at an elevated temperature dramatically shortens their life. Although a lead-acid battery may deliver the highest capacity at temperatures above 30°C (86°F), prolonged use under such conditions decreases the life of the battery. Similarly, a lithium-ion performs better at high temperatures. Elevated temperatures temporarily counteract the battery's internal resistance, which may have advanced as a result of aging. The energy gain is short-lived because elevated temperature promotes aging by further increasing the internal resistance.

There is one exception to running a battery at high temperature - it is the lithium-polymer with dry solid polymer electrolyte, the true 'plastic battery'. While the commercial lithium-ion polymer uses some moist electrolyte to enhance conductivity, the dry solid polymer version depends on heat to enable sufficient ion flow. This requires that the battery core be kept at an operation temperature of 60°C to 100°C (140°F to 212°F).

The dry solid polymer battery has found a niche market as backup power in warm climates. The battery is kept at the operating temperature with built-in heating elements that is fed by the utility grid during normal operation. On a power outage, the battery would need to provide its own power to maintain the temperature. Although said to be long lasting, price is an obstacle.

Nickel-metal-hydride degrades rapidly if cycled at higher ambient temperatures. For example, if operated at 30°C (86°F), the cycle life is reduced by 20%. At 40°C (104°F), the loss jumps to a whopping 40%. If charged and discharged at 45°C (113°F), the cycle life is only half of what can be expected if used at moderate room temperature. The nickel-cadmium is also affected by high temperature operation, but to a lesser degree.

At low temperatures, the performance of all battery chemistries drops drastically. While -20°C (-4°F) is threshold at which the nickel-metal-hydride, sealed lead-acid and lithium-ion battery cease to function, the nickel-cadmium can go down to -40°C (-40°F). At that frigid temperature, the nickel-cadmium is limited to a discharge rate of 0.2C (5 hour rate). There are new types of Li?ion batteries that are said to operate down to -40°C.

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

Pulse discharge

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

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

A lithium-ion battery manufacturer claims that their cells perform better on a pulse rather than DC load. The DC resistance of their 18650 cylindrical cell is ~110 mOhm. At 1 KHz AC, the impedance goes down to ~36 mOhm. As the pulses increase in frequency, the cell's effective impedance goes down. This results in better performance and lower heat build-up. These two effects increase the life of the lithium-ion cell.

The internal resistance of the cobalt-based lithium-ion will increase with age and cause a problem when drawing heavy pulse currents. The manganese-based cell, on the other hand, will maintain the resistance at a low level throughout its service life. The cobalt-based lithium-ion cell provides a higher energy density but manganese is better suited for pulse load applications.

The lead-acid battery performs best at a slow 20-hour discharge. A pulse discharge also works well because the rest periods between the pulses help to disperse the depleted acid concentrations back into the electrode plate. A discharge at 1C of the rated capacity yields the poorest efficiency. The lower level of conversion, or increased polarization, manifests itself in a momentary higher internal resistance due to the depletion of active material in the reaction.

Different discharge methods, notably pulse discharging, affect the longevity of some battery chemistries. While nickel-cadmium and lithium-ion are robust and show minimal deterioration when pulse discharged, the nickel-metal-hydride exhibits a reduced cycle life when powering a digital load.

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

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

Discharge methods

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

What is C-rate?

The charge and discharge current of a battery is measured in C-rate. Most portable batteries are rated at 1C. This means that a 1000mAh battery would provide 1000mA for one hour if discharged at 1C rate. The same battery discharged at 0.5C would provide 500mA for two hours. At 2C, the 1000mAh battery would deliver 2000mA for 30 minutes. 1C is often referred to as a one-hour discharge; a 0.5C would be a two-hour, and a 0.1C a 10-hour discharge.
The capacity of a battery is commonly measured with a battery analyzer. If the analyzer's capacity readout is displayed in percentage of the nominal rating, 100% is shown if a 1000mAh battery can provide this current for one hour. If the battery only lasts for 30 minutes before cut-off, 50% is indicated. A new battery sometimes provides more than 100% capacity.

When discharging a battery with a battery analyzer that allows the setting of different discharge C-rates, a higher capacity reading is observed if the battery is discharged at a lower C-rate and vice versa. By discharging the 1000mAh battery at 2C, or 2000mA, the analyzer is scaled to derive the full capacity in 30 minutes. Theoretically, the capacity reading should be the same as with a slower discharge, since the identical amount of energy is dispensed, only over a shorter time. Due to internal energy losses and a voltage drop that causes the battery to reach the low-end voltage cut-off sooner, the capacity reading may be lowered to 95%. Discharging the same battery at 0.5C, or 500mA over two hours may increase the capacity reading to about 105%. The discrepancy in capacity readings with different C-rates is related to the internal resistance of the battery.

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

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

Depth of discharge

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

Since the cells in a battery pack cannot be perfectly matched, a negative voltage potential, also known as cell reversal, will occur across a weaker cell if the discharge is allowed to continue uncontrolled. The more cells that are connected in series, the greater the likelihood of cell reversal occurring.

Nickel-cadmium can tolerate some cell reversal, which is typically about 0.2V. During that time, the polarity of the positive electrode is reversed. Such a condition can only be sustained for a brief moment because hydrogen evolution on the positive electrode leads to pressure build-up and possible cell venting. If the cell is pushed further into voltage reversal, the polarity of both electrodes is being reversed and the cell produces an electrical short. Such a fault cannot be corrected.

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

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

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

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

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

Some lithium-ion batteries feature an ultra-low voltage cut-off that permanently disconnects the pack if a cell dips below 1.5V. A very deep discharge may cause the formation of copper shunt, which can lead to a partial or total electrical short. The same occurs if the cell is driven into negative polarity and is kept in that state for a while.

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

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

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

150 - 200 cycles with 100% depth of discharge (full discharge)

400 - 500 cycles with 50% depth of discharge (partial discharge)

1000 and more cycles with 30% depth of discharge (shallow discharge)
The lead-acid battery should not be discharged beyond 1.75V per cell, nor should it be stored in a discharged state. The cells of a discharged lead-acid sulfate, a condition that renders the battery useless if left in that state for a few days. Always keep the open terminal voltage at 2.10V and higher.

What constitutes a discharge cycle?

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

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

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

Calculating the battery runtime

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

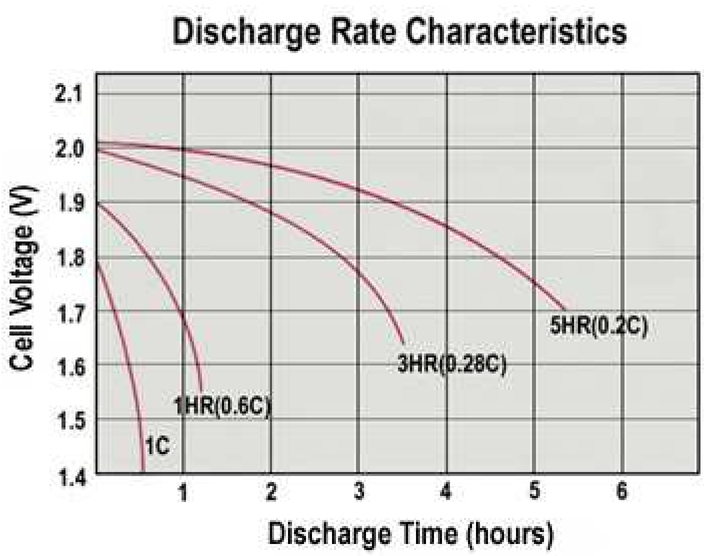

Table 1: Typical discharge curves of lead acid as a function of C-rate.

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

Discharge current C-Rate Discharge time End of discharge   Table 2: Typical discharge times of a 10Ah lead acid battery as a function of C-rate.

0.5A 0.05C 20h 1.75V/cell
0.1A 0.1C 10h 1.75V/cell
2A 0.2C 5h 1.70V/cell
2.8A 0.28C 3f 1.64V/cell
6A 0.6C 1h 1.55V/cell
10A 1C 0.5h 1.40V/cell

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

The Peukert number
The efficiently of a battery is expressed in the Peukert number. In essence, the Peukert number reflects the internal resistance of the battery. A value close to 1 indicates a well-performing battery with little losses. A higher number reflects a less efficient battery. The Peukert number of a battery is exponential and checks in between 1.3 and 1.4 for lead acid. The number is lower for nickel-based batteries.

Batteries are stressed the most if discharged at a steady load to the end-of-discharge point. This is the opposite of an internal combustion engine that operates most efficiently with a steady load. On a battery, the intermittent load allows a level of recovery of the very chemical reaction that produces the electrical energy. Because of the rather sluggish behavior, the quiescent rest period is especially important for lead acid. Table 3 illustrates the effective cell capacity of lead acid on a continuous discharge as opposed to an intermitted discharge.

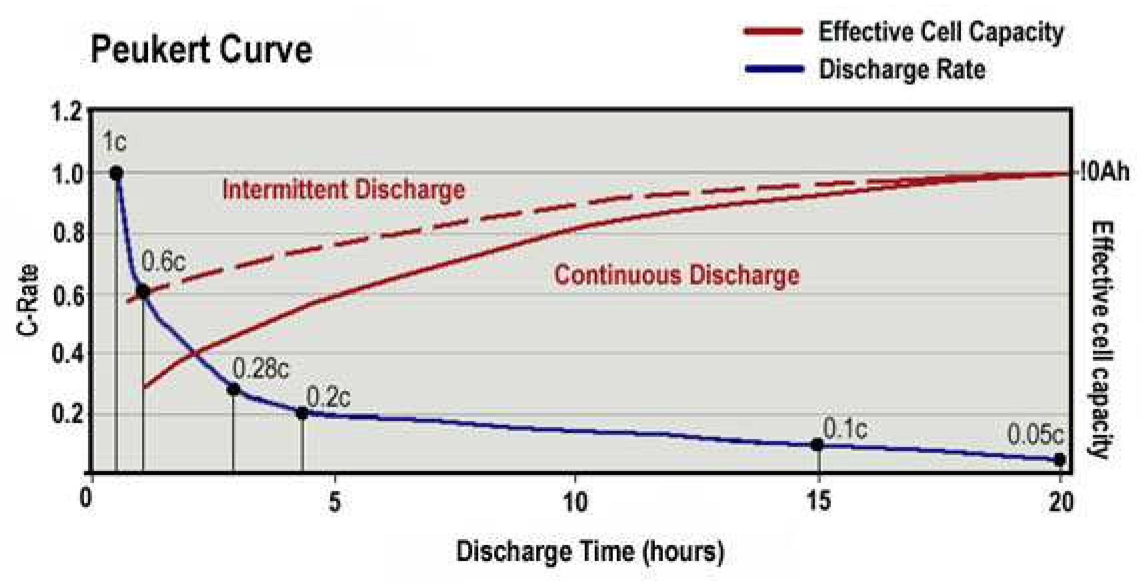

Table 3: The Peukert Curve. The effective cell capacity fades with increased load. An intermittent discharge improves the capacity as it allows the chemical reaction to recover.

How does the internal battery resistance affect performance?

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

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

Figure 1 demonstrates the voltage signature and corresponding runtime of a battery with low, medium and high internal resistance when connected to a digital load. Similar to a soft ball that easily deforms when squeezed, the voltage of a battery with high internal resistance modulates the supply voltage and leaves dips, reflecting the load pulses. These pulses push the voltage towards the end-of-discharge line, resulting in a premature cut-off. As seen in the chart, the internal resistance governs much of the runtime.

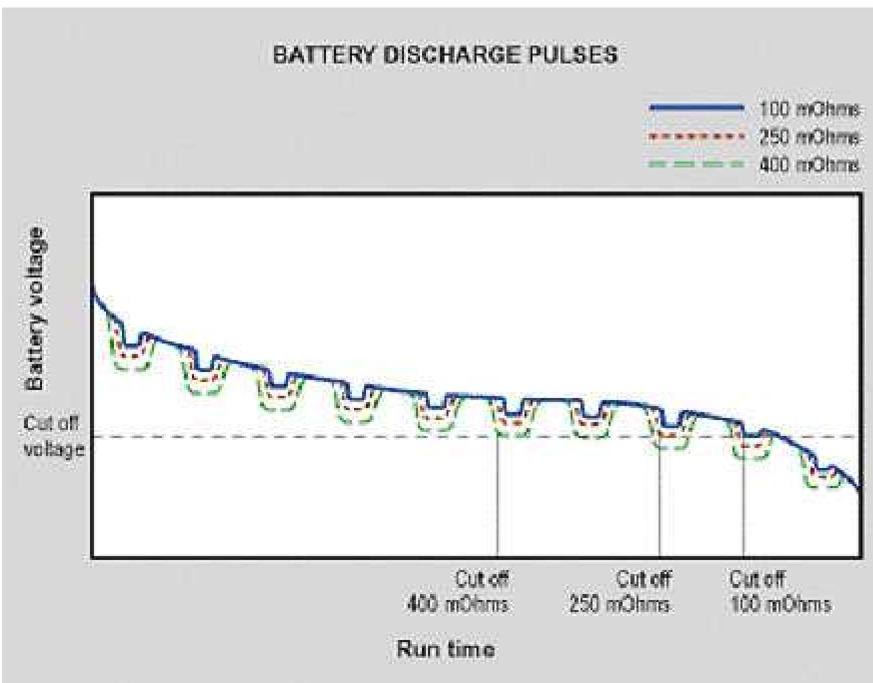

Figure 1: Discharge curve on a pulsed load with diverse internal resistance. This chart demonstrates the runtime of 3 batteries with same capacities but different internal resistance levels.

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

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

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

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

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

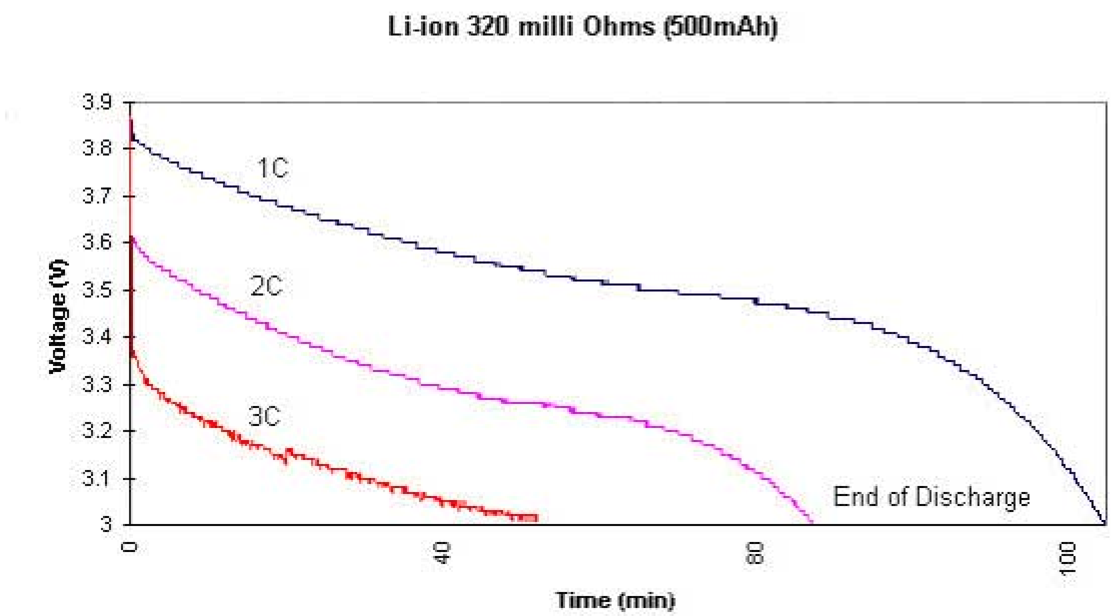

Figure 4: Discharge and resulting talk-time of a lithium-ion battery at 1C, 2C and 3C under the GSM load schedule. The battery tested has a capacity of 94%, the internal resistance is 320 mOhm.

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

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

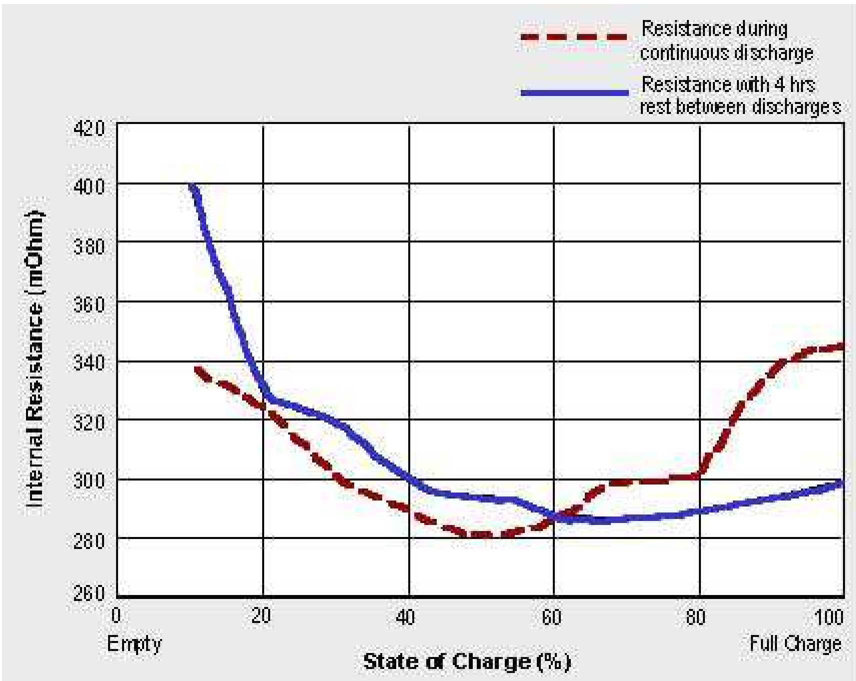

Figure 5: Internal resistance in nickel-metal-hydride. Note the higher readings immediately after a full discharge and full charge. Resting a battery before use produces the best results.

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

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

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

There are several types of 'smart' batteries, each offering different complexities and costs. The most basic 'smart' battery may contain nothing more than a chip that sets the charger to the correct charge algorithm. In the eyes of the Smart Battery System (SBS) forum, these batteries cannot be called 'smart'.

What then makes a battery 'smart'? Definitions still vary among organizations and manufacturers. The SBS forum states that a 'smart' battery must be able to provide SoC indications. In 1990, Benchmarq was the first company to commercialize the concept by offering fuel gauge technology. Today, several manufacturers produce such chips. They range from the single wire system, to the two-wire system to the System Management Bus (SMBus). Let's first look at the single wire system.

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

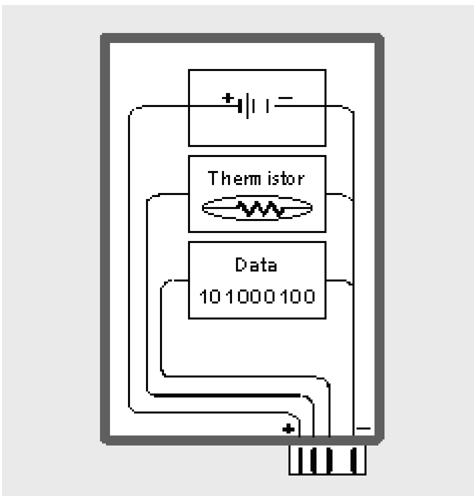

Figure 1: Single wire system of a 'smart' battery.Only one wire is needed for data communications. For safety reasons, most battery manufacturers run a separate wire for temperature sensing.

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

Most single wire systems do not provide a common form factor; neither do they lend themselves to standardized SoH measurements. This produces problems for a universal charger concept. The Benchmarq single wire solution, for example, cannot measure the current directly; it must be extracted from a change in capacity over time. In addition, the single wire bus allows battery SoH measurement only when the host is 'married' to a designated battery pack. Such a fixed host-battery relationship is only feasible if the original battery is used. Any discrepancy in the battery will make the system unreliable or will provide false readings.

The SMBus

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

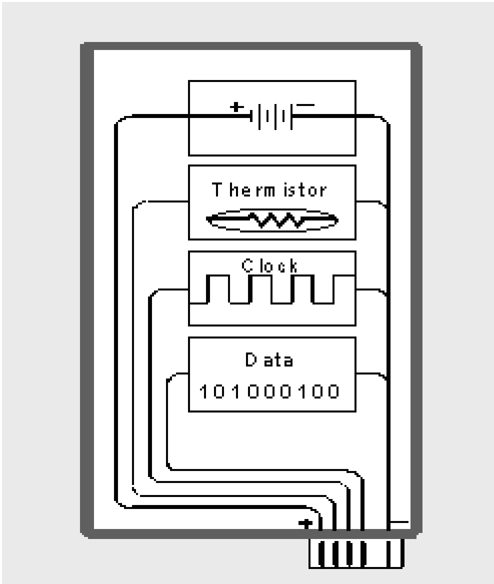

Figure 2: Two-wire SMBus system.The SMBus is based on a two-wire system using a standardized communications protocol. This system lends itself to standardized state-of-charge and state-of-health measurements.

The objective behind the SMBus battery is to remove the charge control from the charger and assign it to the battery. With a true SMBus system, the battery becomes the master and the charger serves as slave that must follow the dictates of the battery.

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

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

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

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

Among the most popular SMBus batteries are the 35 and 202 form-factors (Figure 3). Manufactured by Sony, Hitachi, GP Batteries, Moli Energy and others, these batteries work (should work) in all portable equipment designed for this system. Although the 35 has a smaller footprint than the 202, most chargers accommodate both sizes. A non-SMBus ('dumb') version with same footprint is also available. These batteries can only be charged with a regular charger, or one that accepts both types.

Figure 3: 35 and 202 series 'smart' batteries featuring SMBus.Available in nickel-cadmium, nickel-metal-hydride and lithium-ion chemistries, these batteries are used for laptops, biomedical instruments and survey equipment. A non-SMBus ('dumb') version with same footprint is also available.

In spite of the agreed standard and given form factors, many computer manufacturers have retained their proprietary batteries. Safety, performance and form factor are the reasons. They argue that enduring performance can only be guaranteed if their own brand battery is used. This makes common sense but the leading motive may be pricing. In the absence of competition, these batteries can be sold for a premium price.

Negatives of the 'smart' battery

The 'smart' battery has some notable downsides, one of which is price. An SMBus battery costs about 25% more than the 'dumb' equivalent. In addition, the 'smart' battery was intended to simplify the charger but a full-fledged Level 3 charger costs substantially more than a regular model.

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

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

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

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

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

How to store batteries

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

The recommended storage temperature for most batteries is 15°C (59°F). While lead-acid batteries must always be kept at full charge, nickel and lithium-based chemistries should be stored at 40% state-of-charge (SoC). This level minimizes age-related capacity loss, yet keeps the battery in operating condition even with some self-discharge. While the open terminal voltage of nickel-based batteries cannot be used to determine the SoC accurately, voltage fuel gauging works well for lithium-ion cells. However, differences in the electrochemistry of the electrodes and electrolyte between manufacturers vary the voltage profile slightly. A SoC of 50% reads about 3.8V; 40% is 3.75V. Store lithium-ion at an open terminal voltage of 3.75-3.80V. Allow the battery to rest 90 minutes after charge before taking the voltage reading.

Temperature	**Lithium-ion 40% charge level** (recommended storage level) Recoverable capacity after 1 year of storage	**Lithium-ion 100% charge level** (typical user charge level) Recoverable capacity after 1 year of storage	**Nickel-based** Recoverable capacity after 1 year of storage
0°C	98%	94%	99%
25°C	96%	80%	97%
40°C	85%	65%	95%
60°C	75%	60% (after 3 months)	70%

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

Figure 1: Non-recoverable capacity loss on lithium-ion and nickel-based batteries after storage. High charge levels and elevated temperatures hasten the capacity loss.
Among the lithium-ion family, cobalt has a slight advantage over manganese (spinel) in terms of storage at elevated temperatures. nickel-based batteries are also affected by elevated temperature but to a lesser degree than lithium-ion.

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

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

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

Priming new batteries

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

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

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

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

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

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

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

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

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

Keep batteries in a cool and dry storage area. Refrigeration is recommended but freezers should be avoided. When refrigerated, the battery should be placed in a plastic bag to protect against condensation

Do not fully charge lithium and nickel-based batteries before storage. Keep them partially charged and apply a full charge before use. Store lithium-ion at about 40% state-of-charge (3.75-3.80V/cell open terminal). Lead-acid batteries must be stored fully charged.

Do not store lithium-ion fully depleted. If empty, charge for about 30 minutes before storage. Self-discharge on a depleted battery may cause the protection circuit to trip, preventing a recharge.

Do not stockpile lithium-ion batteries; avoid buying dated stock, even if offered at a reduced price. Observe the manufacturing date, if available.

Never leave a nickel-based battery sitting on a charger for more than a few days. Prolonged trickle charge causes crystalline formation (memory).

Always store a lead acid battery in full-charge condition. Observe the open terminal voltage and recharge the battery every 6 months or as recommended by the manufacturer.