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# BATTERIES

**Contents**



Figures:

## CTI Batteries

This White Paper has been prepared to provide you with information about the wide range of battery technologies that are available for use with City Theatrical products. While City Theatrical and our customers have used a variety of battery technologies for various projects, our current standard battery products are all based on Sealed Lead Acid (SLA) battery technology, because the cost and performance characteristics of SLA batteries are the best fit for current CTI standard applications, so we begin this White Paper with a section on the care and use of CTI SLA batteries.

### Charging and Discharging SLA Batteries

SLA batteries should always be stored fully charged, and should be recharged immediately after use. <u>Storing a discharged SLA battery will reduce the unit's usable life.</u>

### Charging and Discharging the CTI 6280 Battery Base

The CTI 5640 Autocharger can be used with a CTI 5656 Anderson Twofer to charge both of the Batteries in the Battery Base at the same time; however you should check each battery by connecting it separately to the charger when the twofer-charge is completed, to assure that each battery is fully topped off. For faster charging, one Autocharger can be used for each of the batteries in the Battery Base.

A fully charged Battery Base in new condition will measure over 24VDC at the fixture when connected to a complete live MasterBlast system (as displayed in the MasterBlast Main Menu).

The 7.2 AH 12VDC batteries in the CTI Battery Base are rated for 250 charge/discharge cycles at 100% depth of discharge, which is 10.5VDC for each battery, or 21VDC total when both batteries are measured in series. CTI Battery life estimates are based on this maximum discharge value.

For maximum battery life, the batteries in the CTI Battery Base should not be discharged beyond 100% depth of discharge. If batteries are discharged beyond 100% depth of discharge (10.5/21VDC), battery life may be reduced. The symptom of over-discharge is that the batteries will not re-charge to full voltage and they will not achieve the charge life that was available when they were new. Worn out or damaged batteries may be replaced for a service charge by CTI; contact City Theatrical for details.

## For Best Battery Life:

- DO charge batteries immediately after use
- DO top off each battery individually after parallel charge is complete
- DO NOT store discharged batteries
- DO NOT discharge batteries below 10.5Vdc each

Not following these instructions will reduce battery life

## Introduction

Batteries come in many different shapes, sizes, chemistries, and serve many different functions. While most people are familiar with disposable Duracell and Eveready batteries available at your local grocery store or market, rechargeable batteries are less well known. Due to the growth of technical applications, rechargeables have become much more commonplace. They are more cost effective than disposables, but only if one knows how to apply and use them appropriately.

## What is a Battery?

A battery is two (or more) electromechanical cells which store chemical energy and make it available in an electrical form. The principle behind an electromechanical cell is galvanic chemistry where two unlike metal plates are immersed in an electrolyte (acid) and produce a charge. As the battery drains, the metal plates become chemically more alike and the acid becomes weaker. Luigi Galvani and Alessandro Volta pioneered this technology in the late 1700's and Gaston Plante built the first lead acid battery, which to this day is the most common type of rechargeable battery.

While chemistry differentiates types of batteries, they can all be measured in amp-hours and voltage. A battery is simply a means of storing electrical energy in a way that it can be harnessed very easily. While coal and gasoline provide electrical energy, they are not effective backstage to provide power for lighting effects, props, and so forth for obvious reasons. The battery industry today is being driven by the large increase in the number of electronic portable devices. For years the motor vehicle industry grew the technology behind today's lead acid battery, which has created a very large market of diverse lead acids for us to choose from. Now we have cell phones, digital cameras, PDA's, laptops, motorized scooters and wheelchairs, hybrid vehicles, universal power supplies, among other devices all calling for a greater variety of rechargeable batteries to serve our needs. Theatre technicians and electricians can draw upon all of these options to fulfill the technical effects sought after in today's shows.

## Factors in Choosing the Right Battery

- Cost: This includes the initial cost to purchase the battery as well as the charger to recharge the battery. If one were only interested in one-time use batteries, this would eliminate the need for the charger. On the other hand, shows usually run repeatedly and it is more cost effective to buy one battery and one charger rather than many batteries. Over time, however, the batteries will wear out and may need replacing. This is a cost not apparent at first, but will come into play over the course of months or years of battery use.

- Performance and Ease of Use: Some batteries are more rugged and durable than others, some are easier to maintain than others. This varies from situation to situation, and can only truly be assessed case by case. While some batteries may offer more in a smaller package, they might take more work to maintain and cost more for replacement. Hopefully this primer will provide the technician with the knowledge basis to assess their specific battery needs.

- Energy Density (power to weight or volume ratio): This is one means of measuring the differences between battery chemistries. The same power and run-time can be achieved with different chemistries, therefore battery size, weight, and durability are dictated by chemistry. Typically batteries with a higher energy density will cost more

- Load Factor: How powerful a battery do you need? How much voltage does your application need? What kind of current draw will you have? Estimate this too low and your battery won't be sufficient, estimate this too high and you will be paying extra for a larger battery. The worst case would be a battery just powerful enough to run the effect, but lacking power contingency. In this instance, the battery would appear to serve the user's needs, but would be susceptible to premature failure. This is explained more clearly later on in the section on causes of battery failure.

- Cycle Load: This is the number of cycles (defined as one drain and recharge of a battery), the rate at which batteries will be cycled (time between charge and discharge), and the depth of discharge (charging battery from near death to full, or 75% charge to 100%, etc.) required for your application. The cumulative affect of cycling a battery can have varying effects depending on how frequently this is done and whether the battery has time to rest between charges and discharges. Assuming the battery and load are matched appropriately and the correct charger is used (more can be found on chargers in our Charger White Paper), some batteries will perform better than others over time and you will get more life out of them. Typically, a battery that performs more consistently over time costs more, but this is dependent on maintenance and use. Any battery that is abused, not charged properly, or drained too low repeatedly will fail quicker and be less reliable.

- Safety: Batteries can explode if not used properly. They can also leak acid, swell, cause sparks, shock, and so forth. Remember, all of the dangers inherent to electricity apply to batteries.

- Environmental Impact: All batteries contain heavy metals (mercury, cadmium, and lead) and are very hazardous for the environment. They will need to be disposed of at some point in their life, and recycling is the best means of doing so. Improperly disposing of batteries will lead to bigger problems down the road, including the restriction of their use (this happened with mercury batteries used in the 70's). Newer battery technologies offer more in the way of energy density, cycle load, and load factor, but recycling options for them may be limited.. Due to the prevalence of lead acid batteries, numerous places will collect and recycle them, and about 97% of the lead is recyclable. The Home Depot and Lowes will collect NiMH and NiCAD batteries, while cell phone and consumer electronics stores will oftentimes collect Li-Ion batteries.

**Battery Types**

Batteries come in many styles and can be differentiated by application type as well as chemistry. While new chemistries are being explored, older chemistries are being applied in different ways to achieve various results.

**Types by Function or Application**

Primary cells are single use and include alkalines. These are manufactured by Duracell, Eveready, Rayovac and so forth and include button, AAA, AA, C, and D cells. Secondary cells are rechargeables and are the ones we are most concerned with here. They cost more per battery compared to primary cells, but can be used over and over again and are available in larger sizes.

Deep cycle batteries are intended to be discharged and charged frequently. They are also designed to provide a steady amount of current over a long period of time. A deep cycle battery can provide a surge of electricity on occasion, but repeated surges will lead to faster deterioration. Instead, its design enables it to be deeply discharged over and over again. The construction of a deep cycle battery involves fewer and thicker plates submerged in the acid.

Car batteries (also called SLIs, or start lights ignition) on the other hand need to give a large surge of energy, but can't handle being deeply discharged.

A car's battery is designed to provide a very large amount of current for a short period of time. This surge of current is needed to turn the engine over during starting. Once the engine starts, the alternator provides all the power that the car needs, so a car battery may go through its entire life without ever being drained more than 20 percent of its total capacity. Used in this way, a car battery can last a number of years. To achieve a large amount of current, a car battery uses thin plates in order to increase its surface area.

Uninterruptible power supplies are used as back ups for servers, computers, and so forth. These batteries are only used while being tested or in the event of a power outage, but when they are used they are drained down. The complication for these batteries is they can go bad or fail when called upon if they are not tested or maintained properly.

Industrial/military types of batteries exist for very specific and sometimes experimental purposes, but these tend to be very costly and application specific. These are not easy to find, they make use of the more esoteric chemistries, and are only mentioned as a reference to other technologies which are being developed on the fringes of the industry.

**Types by Chemistry**
*Alkaline:* Used for primary batteries and easily available over the counter in stores.

*Lead Acid*: Historically the most common rechargeables and have set the benchmark by which all other types are measured. Because of their commercial availability, these usually strike the best balance between the factors listed above when it comes to higher load applications. These batteries include several different styles including:

1. Wet Cell (flooded type)
2. Serviceable – open battery that you can add water to
3. Maintenance Free – a type of sealed battery that doesn't allow you to add water
4. Gel Cell – instead of liquid, the solution is a gel that is more stable. These can be turned over and are safer
5. SLA – Sealed Lead Acid. The battery case is sealed preventing acid from leaking out. This is basically a maintenance free battery.
6. VRLA – Valve Regulated Lead Acid. This is a variation on the SLA, but it includes a valve which regulates the pressure inside the case.
7. AGM – Absorbed Glass Mat, a type of Sealed VRLA. The Absorbed Glass Mat construction allows the electrolyte to be suspended in close proximity with the plate's active material. In theory, this enhances both the discharge and recharge efficiency.

97% of the lead is recyclable and an extensive recycling infrastructure exists for these types of batteries, so while batteries are hazardous, lead acids can be easily recycled.

*Nickel cadmium (NiCAD)* batteries have been in common use for over twenty years. They are popular in cordless tools and have proven reliable in abusive and demanding applications. They handle temperature variations nicely and they store well (although they lose their charge over the course of a few days to a few weeks). They are generally three to four times more expensive than lead acid, there are fewer options for recycling them (although it is improving), and they are only available in the low to moderate power range. Other chemistries are taking the lead and will surpass NiCADs, but for now they are still quite common.

*Nickel metal-hydride (NiMH)* have grown significantly over the past few years, especially due to their use in hybrid vehicles. They are projected to have a long cycle life, but they have not been in use long enough to really prove that function. They are also toxic, and recycling options are quite limited for these batteries. Their cost factor is about ten to twenty-five times that of a lead acid.

*Lithium ion (Li-Ion)* batteries have become the “next best thing” for battery technology. This includes polymer and liquid varieties of lithium ion. They are considerably more costly than lead, but have excellent discharge curves, charge rates, and cycle lives. Their popularity has been driven by the cell phone and laptop industries, and is being adopted into the cordless tool industry. Its availability for larger load applications is limited at this time, but expanding. While these batteries are more effective than older chemistries, they have very specific needs for charging and require foresight and planning. If not matched with the right charger, these batteries can be overcharged very easily which leads to thermal runaway, combustion, and so forth. Because they are relatively new to the market, recycling options are very limited but can be expected to grow.

**Battery Basics**

The Lead Acid battery is made up of plates, lead, and lead oxide (various other elements are used to change density, hardness, porosity, etc.) with a 35% sulfuric acid and 65% water solution. This solution is called electrolyte which causes a chemical reaction that produce electrons. When you test a battery with a hydrometer you are measuring the amount of sulfuric acid in the electrolyte. If your reading is low, that means the chemistry that makes electrons is lacking. So where did the sulfur go? It is resting to the battery plates and when you recharge the battery the sulfur returns to the electrolyte.

8. Always store batteries charged in a cool, dry environment. The longer a battery stays uncharged, the greater the chance of crystals forming on the internal components of the battery. This shortens the life of the battery and severely affects its runtime. Generally, batteries like to be fully charged.
9. Do not fully drain a battery. As soon as it ceases to provide a useful current, the load be removed and the battery should be charged.
10. Memory effect only occurs to some batteries in very unique situations, primarily in cases of repetitive light use such as cordless phones and electric shavers. Sporadic use and higher current draw on batteries prevent this from happening.
11. Temperature has a huge affect on batteries. They all have specific ranges where they perform better (per manufacturer), but generally these fall between 45 and 90 deg F. As a battery is drained, it can generate heat (increased current draw will increase heat

generated). As a battery is charged, it can also generate heat. In any event, the average consumer battery should not get so hot you can't hold it in your hand.

12. Battery chemistry basically affects the size, weight, and durability of a battery, not necessarily its power or run time.
13. For optimum performance, be aware of the recommended cutoff voltage for your battery. The cutoff voltage is that at which the discharge is terminated, and it is specified by the manufacturer as a function of discharge rate and temperature. In effect, different loads will require different cutoff voltages. Consistently over-discharging a battery past the recommended cutoff voltage will shorten the battery's life leading to reduced run time and poor performance.
14. Always use a charger that is designed for your battery. These vary between manufacturers and battery chemistries, so do a little research before buying just any charger.
15. Don't skimp on your charger. The battery is only half of the equation; the charger is the other half. The life and performance quality of a battery is directly related to the quality and effectiveness of the charger. Generally, a charger with circuitry controlling the current and voltage in response to its metering of the battery's output is ideal.

**Battery Testing**

Battery Testing can be done in more than one way. The most popular is measurement of specific gravity and battery voltage. To measure specific gravity buy a temperature compensating hydrometer and measure voltage, use a digital D.C. Voltmeter. A good digital load tester may be a good purchase if you need to test sealed batteries.

You must first have the battery fully charged. The surface charge must be removed before testing. If the battery has been sitting at least several hours (I prefer at least 12 hours) you may begin testing. To remove surface charge the battery must experience a load of 20 amps for 3 plus minutes. Turning on the headlights (high beam) will do the trick. After turning off the lights you are ready to test the battery.

| State of Charge | Specific Gravity | Voltage | |
|---|---|---|---|
| | | 12V | 6V |
| 100% | 1.265 | 12.7 | 6.3 |
| *75% | 1.225 | 12.4 | 6.2 |
| 50% | 1.190 | 12.2 | 6.1 |
| 25% | 1.155 | 12.0 | 6.0 |
| Discharged | 1.120 | 11.9 | 6.0 |

*Sulfation of Batteries starts when specific gravity falls below 1.225 or voltage measures less than 12.4 (12v Battery) or 6.2 (6 volt battery). Sulfation hardens the battery plates reducing and eventually destroying the ability of the battery to generate Volts and Amps.

Load testing is yet another way of testing a battery. Load test removes amps from a battery much like starting an engine would. A load tester can be purchased at most auto parts stores. Some battery companies label their battery with the amp load for testing. This number is usually 1/2 of the CCA rating. For instance, a 500CCA battery would load test at 250 amps for 15 seconds. A load test can only be performed if the battery is near or at full charge.

The results of your testing should be as follows:

Hydrometer readings should not vary more than .05 differences between cells.

Digital Voltmeters should read as the voltage is shown in this document. The sealed AGM and Gel-Cell battery voltage (full charged) will be slightly higher in the 12.8 to 12.9 ranges. If you have voltage readings in the 10.5 volts range on a charged battery, that indicates a shorted cell.

If you have a maintenance free wet cell, the only ways to test are voltmeter and load test. Most of the maintenance free batteries have a built in hydrometer that tells you the condition of 1 cell of 6. You may get a good reading from 1 cell but have a problem with other cells in the battery.

When in doubt about battery testing, call the battery manufacturer. Many batteries sold today have a toll free number to call for help.

**Battery life and performance**

Average battery life has become shorter as energy requirements have increased. Two phrases I hear most often are "my battery won't take a charge, and my battery won't hold a charge". Only 30% of batteries sold today reach the 48-month mark. In fact 80% of all battery failure is related to sulfation build-up. This build up occurs when the sulfur molecules in the electrolyte (battery acid) become so deeply discharged that they begin to coat the battery's lead plates. Before long the plates become so coated that the battery dies. The causes of sulfation are numerous:

- Batteries sit too long between charges. As little as 24 hours in hot weather and several days in cooler weather.
- Battery is stored without some type of energy input.
- "Deep cycling" an engine starting battery. Remember these batteries can't stand deep discharge.
- Undercharging of a battery, to charge a battery (let’s say) to 90% of capacity will allow sulfation of the battery using the 10% of battery chemistry not reactivated by the incomplete charging cycle.
- Heat of 100 plus F., increases internal discharge. As temperatures increase so does internal discharge. A new fully charged battery left sitting 24 hours a day at 110 degrees F for 30 days would most likely not start an engine.
- Low electrolyte level - battery plates exposed to air will immediately sulfate.
- Incorrect charging levels and settings. Most cheap battery chargers can do more harm than good. See the section on battery charging.
- Cold weather is also hard on the battery. The chemistry does not make the same amount of energy as a warm battery. A deeply discharged battery can freeze solid in sub zero weather.
- Parasitic drain is a load put on a battery with the key off. More info on parasitic drain will follow in this document.

**Battery Charging**
Remember you must put back the energy you use immediately. If you don't the battery sulfates and that affects performance and longevity. The alternator is a battery charger. It works well if the battery is not deeply discharged. The alternator tends to overcharge batteries that are very low and the overcharge can damage batteries. In fact an engine starting battery on average has only about 10 deep cycles available when recharged by an alternator. Batteries like to be charged in a certain way, especially when they have been deeply discharged. This type of charging is called 3 step regulated charging. Please note that only special smart chargers using computer technology can perform 3 step charging techniques. You don't find these types of chargers in parts stores and Wal-Marts. The first step is bulk charging where up to 80% of the battery energy capacity is replaced by the charger at the maximum voltage and current amp rating of the charger. When the battery voltage reaches 14.4 volts this begins the absorption charge step. This is where the voltage is held at a constant 14.4 volts and the current (amps) declines until the battery is 98% charged. Next comes the Float Step. This is a regulated voltage of not more than 13.4 volts and usually less than 1 amp of current. This in time will bring the battery to 100% charged or close to it. The float charge will not boil or heat batteries but will maintain the batteries at 100% readiness and prevent cycling during long term inactivity. Some gel cell and AGM batteries may require special settings or chargers.

**How a Battery Works**

A battery stores electricity for future use. It develops voltage from the chemical reaction produced when two unlike materials, such as the positive and negative plates, are immersed in the electrolyte, a solution of sulfuric acid and water. In a typical lead-acid battery, the voltage is approximately 2 volts per cell, for a total of 12 volts. Electricity flows from the battery as soon as there is a circuit between the positive and negative terminals. This happens when any load that needs electricity, such as the radio, is connected to the battery.

Most people don't realize that a lead-acid battery operates in a constant process of charge and discharge. When a battery is connected to a load that needs electricity, such as the starter in your car, current flows from the battery. The battery begins to be discharged.
In the reverse process, a battery becomes charged when current flows back into it, restoring the chemical difference between the plates. This happens when you're driving without any accessories and the alternator puts current back into the battery.
As a battery discharges, the lead plates become more chemically alike, the acid becomes weaker, and the voltage drops. Eventually the battery is so discharged that it can no longer deliver electricity at a useful voltage.

You can recharge a discharged battery by feeding electrical current back into it. A full charge restores the chemical difference between the plates and leaves the battery ready to deliver its full power.
This unique process of discharge and charge in the lead-acid battery means that energy can be discharged and restored over and over again. This is what's known as the cycling ability in a battery.

If the battery won't start your car, you usually refer to it as "dead," even though that's not technically correct. A battery that's merely discharged - from leaving your headlights on or from a damaged alternator -- can be recharged to its full capacity. But a battery that's at the end of its service life can't be recharged enough to restore it to a useful power level. Then it truly is dead, and must be replaced.

Lead-acid
Advantages: This chemistry has been proven over more than 140 years. Batteries of all shapes and sizes, available in sealed and maintenance-free products, are mass-produced today. In their price range, lead-acid batteries provide the greatest energy density (the amount of energy produced) per pound, have the longest life cycle and a large environmental advantage in that they are recycled at an extraordinarily high rate. (Ninety-seven percent of the lead is recycled and reused in new batteries.). No other chemistry can touch the infrastructure that exists for collecting, transporting and recycling lead-acid batteries.
Disadvantages: Lead is heavier than other metals and can be toxic.

Lithium-ion
*Advantages:* It has a high specific energy (the number of hours of operation for a given weight) making it a huge success for mobile applications such as phones and notebook computers.

Disadvantages: More expensive than lead. The cost differential is not as apparent with small batteries for phones and computers, and owners of these devices may not realize that they are paying much more per stored kilowatt hour than other chemistries. However, because automotive batteries are larger, the cost becomes more significant. In addition, currently there is no established system for recycling large lithium-ion batteries.

Nickel-cadmium
*Advantages:* This chemistry is reliable, can operate in a range of temperatures, tolerates abuse well and performs well after long periods of storage.

*Disadvantages:* It is three to five times more expensive than lead-acid, its materials are toxic and the recycling infrastructure for larger nickel-cadmium batteries is very limited.

Nickel-metal hydride
*Advantages:* It is reliable and lightweight. In hybrid vehicles, these batteries are projected to have very long cycle life, equal to 100,000 miles.

Disadvantages: The metals in the battery are 25 times more expensive than lead. Nickel has been identified as a carcinogen. Hybrid vehicles have not been on the road long enough to allow the batteries to prove their projected cycle life. No significant recycling capability exists.
Note: The Advanced Lead-Acid Battery Consortium has developed a lead-acid battery system that operates at the very high rates necessary for a hybrid vehicle and recently equipped a Honda Insight with this system. If it proves to be capable of reasonable life, the lead-acid batteries will challenge the very expensive nickel metal hydride system in hybrid vehicles today.

**Battery Electrical Characteristics**

Internal Resistance. In general, internal resistance will rise during discharge due to the active materials within the battery being used. However, the rate of change during discharge is not consistent. Batery chemistry, depth of discharge, drain rate and the age of the battery can all impact internal resistance during discharge.

Cold temperatures cause the electrochemical reactions that take place within the battery to slow down and will reduce ion mobility in the electrolyte. Subsequently, internal resistance will rise as ambient temperatures drop.

A battery can be simply modeled as a perfect voltage source (i.e. one with zero internal resistance) in series with a resistor. The voltage source depends mainly on the chemistry of the battery, not on whether it is empty or full. When a battery runs down, its internal resistance increases. When the battery is connected to a load (e.g. a light bulb), which has its own resistance, the resulting voltage across the load depends on the ratio of the battery's internal resistance to the resistance of the load. When the battery is fresh, its internal resistance is low, so the voltage across the load is almost equal to that of the battery's internal voltage source. As the battery runs down and its internal resistance increases, the voltage drop across its internal resistance increases, so the voltage at its terminals decreases, and the battery's ability to deliver power to the load decreases.

Internal resistance is a concept that helps model the electrical consequences of the complex chemical reactions inside a battery. It is impossible to directly measure the internal resistance of a battery, but it can be calculated from current and voltage data measured from a circuit. When a load is applied to a battery the internal resistance can be calculated from the following equations:

$$R_B = \left(\frac{Vs}{I}\right) - R_L$$

or

$$R_B = \left(\frac{V_S - V}{I}\right)$$

where

$R_B$ is the internal resistance of the battery

$V_S$ is the battery voltage without a load

$V$ is the battery voltage with a load

$R_L$ is the total resistance of the circuit

$I$ is the total current supplied by the battery

Internal resistance varies with the age of a battery, but for most commercial batteries the internal resistance is on the order of 1 ohm.

The capacity of a battery defines the stored energy - the internal resistance governs how much energy can be delivered at any given time. While a good battery is able to provide high current on demand, the voltage of a battery with elevated resistance collapses under a heavy load. Although the battery may hold sufficient capacity, the resulting voltage drop triggers the 'low battery' indicator and the equipment stops functioning. Heating the battery will momentarily increase the output by lowering the resistance.

A battery with high internal resistance may still perform adequately on a low current appliance such as a flashlight, portable CD player or wall clock. Digital equipment, on the other hand, draw heavy current bursts. Figure 2 simulates low and high internal resistance with a free-flowing and restricted tap.

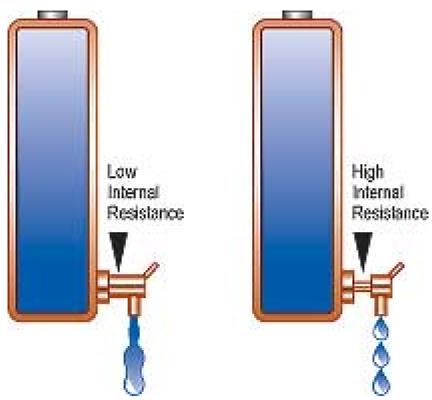


*Figure 2: Effects of internal battery resistance.A battery with low internal resistance is able to provide high current on demand. With elevated resistance, the battery voltage collapses and the equipment cuts off.*

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

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

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

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

Lack of maintenance on nickel-based batteries can increase the internal resistance.

When measuring the battery with a voltmeter after the equipment has cut off and the load is removed, the terminal voltage commonly recovers and the voltage reading appears normal. This is especially true of nickel-based batteries. Measuring the open terminal voltage is an unreliable method to establish the state-of-charge (SoC) of the battery.

A battery with high impedance may perform well if loaded with a low DC current such as a flashlight, portable CD player or wall clock. With such a gentle load, virtually all of the stored energy can be retrieved and the deficiency of high impedance is masked.

Elevated self-discharge

All batteries suffer from self-discharge, of which nickel-based batteries are among the highest. The loss is asymptotical, meaning that the self-discharge is highest right after charge and then levels off. nickel-based batteries lose 10% to 15% of their capacity in the first 24 hours after charge, then 10% to 15% per month afterwards. One of the best batteries in terms of self-discharge is Lead-acid; it only self-discharges 5% per month. Unfortunately, this chemistry has the lowest energy density and is ill suited for portable applications.
lithium-ion self-discharges about 5% in the first 24 hours and 1-2% afterwards. Adding the protection circuit increases the discharge by another 3% per month. The protection circuit assures that the voltage and current on each cell does not exceed a safe limit. Figure 3 illustrates a battery with high self-discharge.

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

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

Aging and usage also affect self-discharge. nickel-metal-hydride is good for 300-400 cycles, whereas nickel-cadmium may last over 1000 cycles before high self-discharge affects the performance. An older nickel-based battery may lose its energy during the day through self-discharge rather than actual use. Discard a battery if the self-discharge reaches 30% in 24 hours.

Nothing can be done to reverse this deficiency. Factors that accelerate self-discharge are damaged separators induced by crystalline formation, allowing the packs to cook while charging, and high cycle count, which promotes swelling in the cell. Lead and lithium-based batteries do not increase the self-discharge with use in the same manner as their nickel-based cousins do.

Premature voltage cut-off

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

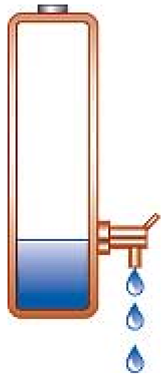

*Figure 4: Illustration of equipment with high cut-off voltage.Some portable devices do not utilize all available battery power and leave precious energy behind.*

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

Calculating how long a battery will last at a given rate of discharge is not as simple as "amp-hours" - battery capacity *decreases* as the rate of discharge *increases*. For this reason, battery manufacturers prefer to rate their batteries at very low rates of discharge, as they last longer and get higher ratings that way. That is fine if you're building a low-power application, but if your contraption really "sucks juice", you won't be getting the amp-hours you paid for.

The formula for calculating how long a battery will really last has the charming name of "Peukert's Formula". It is...

$$T = C / I^n$$

where C is *theoretical* capacity (in amp-hours, equal to actual capacity at one amp), I is current (in amps), T is time (in hours), and n is the Peukert number for the battery. The Peukert number shows how well the battery holds up under high rates of discharge - most range from 1.1 to 1.3, and the closer to 1, the better. The Peukert number is determined empirically, by testing the battery at different rates.

## Depth of Discharge and Life Expectancy

Batteries don't last forever - their lifetimes are measured in cycles, or how many times they can be discharged and recharged before they will no longer take a full charge. The depth of discharge (D.O.D.) has a major effect on the life expectancy of a battery - discharging only 80% of the total capacity of the battery will typically get you 25% more cycles than total discharges, and discharging to only 20% will make the battery last essentially forever. Car batteries, however, have to be treated differently - they're not designed to discharge even 20%, and will be damaged if they're deeply discharged. A "deep cycle" battery, on the other hand, can typically survive 400 full discharges.

## Declining capacity

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

The energy storage of a battery can be divided into three imaginary sections consisting of: available energy, the empty zone that can be refilled, and the unusable part (rock content) that increases with aging.

Lithium-ion batteries lose capacity through cell oxidation, a process that occurs naturally during use and aging. The typical life span of lithium-ion is 2-3 years under normal use. Cool storage a 40% charge minimizes aging. An aged lithium-ion cannot be restored with cycling.

**Battery Failure**

Ageing:  Battery performance gradually deteriorates with time due to unwanted chemical reactions and physical changes to the active chemicals. This process is generally not reversible and eventually results in battery failure. The following are some examples:-

- Corrosion consumes some of the active chemicals in the cell leading to increased impedance and capacity loss.
- Chemical loss through evaporation. Gaseous products resulting from over charging are lost to the atmosphere causing capacity loss.
- Change in physical characteristics (morphology) of the working chemicals.
- Crystal formation. Over time the crystal structure at the electrode surface changes as larger crystals are formed. This reduces the effective area of the electrodes and hence their current carrying and energy storage capacity.
- Dendritic growth. This is the formation of small crystals or treelike structures around the electrodes in what should be an aqueous solution. Initially these dendrites may cause an increase in self discharge. Ultimately they can pierce the separator causing a short circuit.
- Passivation. This is a resistive layer which builds up on the electrodes impeding the chemical action of the cell.
- Shorted cells. Cells which were marginally acceptable when new may have contained latent defects which only become apparent as the ageing process takes its toll. This would include poor cell construction, contamination, burrs on metal parts which can all cause the electrodes to come into contact with each other causing a short circuit.

- Electrode cracking Some solid electrolyte cells such as Lithium polymer can fail because of cracking of the electrolyte.

The ageing process outlined above is accelerated by elevated temperatures.

Uncontrolled operating conditions

Good batteries are not immune to failure which can be provoked by the way they are used or abused. High cell temperature is the main killer and this can be brought about in the following situations:

- Bad applications design
- Unsuitable cell for the application
- Unsuitable charging profile
- Overcharging
- Physical damage
- High ambient temperatures. Lack of cooling.
- High storage temperature

Most of these conditions result in overheating of the cell which is what ultimately kills it.

Abuse

Abuse does not just mean deliberate physical abuse by the end user. It also covers accidental abuse which may be unavoidable. This may include dropping, crushing, penetrating, impacts, immersion in fluids, freezing or contact with fire, any of which could occur to an automotive battery for instance. It is generally accepted that the battery may not survive all these trials, however the battery should not itself cause an increased hazard or safety problem in these circumstances.

How Cells Fail

The actions or processes outlined above cause the cells to fail in the following ways:

- Active chemicals exhausted. In primary cells this is not classed as a failure since this is to be expected but with secondary cell we expect the active chemicals to be restored through recharging. As noted above however ageing will cause the gradual depletion of the active mass.
- Change in molecular structure. Even though the chemical composition of the active chemicals may remain unchanged, changes in their morphology which take place as the cell ages can impede the chemical actions from taking place, ultimately rendering the cell unusable.
- Increased internal impedance. The cell internal impedance tends to increase with age as the larger crystals form, reducing the effective surface area of the electrodes.
- Reduced capacity. This is another consequence of cell ageing and crystal growth. Is is sometimes recoverable through reconditioning the cell by subjecting the cell to one or more deep discharges.
- Increased self discharge. The changing crystal structure of the active chemicals as noted above can cause the electrodes to swell increasing the pressure on the separator and, as a consequence, increasing the self discharge of the cell. As with all chemical reactions this increases with temperature. Unfortunately these changes are not usually reversible.
- Gassing. Gassing is generally due to over charging. This leads to loss of the active chemicals but In many cases this can also be dangerous. In some cells the released

gases may be explosive. Lead acid cells for instance give off oxygen and hydrogen when overcharged.

- Pressure build up. Gassing and expansion of the chemicals due to high temperatures lead to the build up of pressure in the cell and this can be dangerous as noted above. In sealed cells it could lead to the rupture or explosion of the cell due to the pressure build up unless the cell has a release vent to allow the escape of the gasses.
- Swelling. Before the pressure in the cell builds up to dangerous limits, some cells are prone to swelling due to overheating. This is particularly true of Lithium polymer pouch cells. This can lead to problems in fitting the cell into the battery enclosure.
- Overheating. Overheating is always a problem and is a contributing factor in nearly all cell failures. It has many causes and it can lead to irreversible changes to the chemicals used in the cells, gassing, expansion of the materials, swelling and distortion of the cell casing. Preventing a cell from overheating is the best way of extending its life.
- Thermal runaway. The rate at which a chemical action proceeds doubles for every 10°C increase in temperature. The current flow through a cell causes its temperature to rise. As the temperature rises the electro-chemical action speeds up and at the same time the impedance of the cell is reduced leading to even higher higher currents and higher temperatures which could eventually lead to destruction of the cell unless precautions are taken.

Consequences of Cell Faults

The failure mechanisms noted above to not always lead to immediate and complete failure of the cell. The failure will often be preceded by a deterioration in performance. This may be manifest in reduced capacity, increased internal impedance and self discharge or overheating. If a degraded cell continues in use, higher cell heat dissipation may result in premature voltage cut off by the protection circuits before the cell is fully charged or discharged reducing the effective capacity still further.

Measurement of the State of Health of the cells can provide an advance warning of impending failure of the cell. There are several possible failure modes associated with the complete breakdown of the cell, but it is not always possible to predict which one will occur. It depends very much on the circumstances.

- Open circuit. This is a fail safe mode for the cell but may be not for the application. Once the current path is cut and the battery is isolated, the possibility of further damage to the battery is limited. This may not suit the user however. If one cell of a multicell battery goes open circuit then the whole battery will be out of commission.
- Short circuit. If one cell of a battery chain fails because of a short circuit, the rest of the cells may be slightly overloaded but the battery will continue to provide power to its load. This may be important in emergency situations.
- Explosion. - This is to be avoided at all costs and the battery must incorporate protection circuits or devices to prevent this situation from occurring.
- Fire. This is also possible and as above the battery should be protected from this possibility.

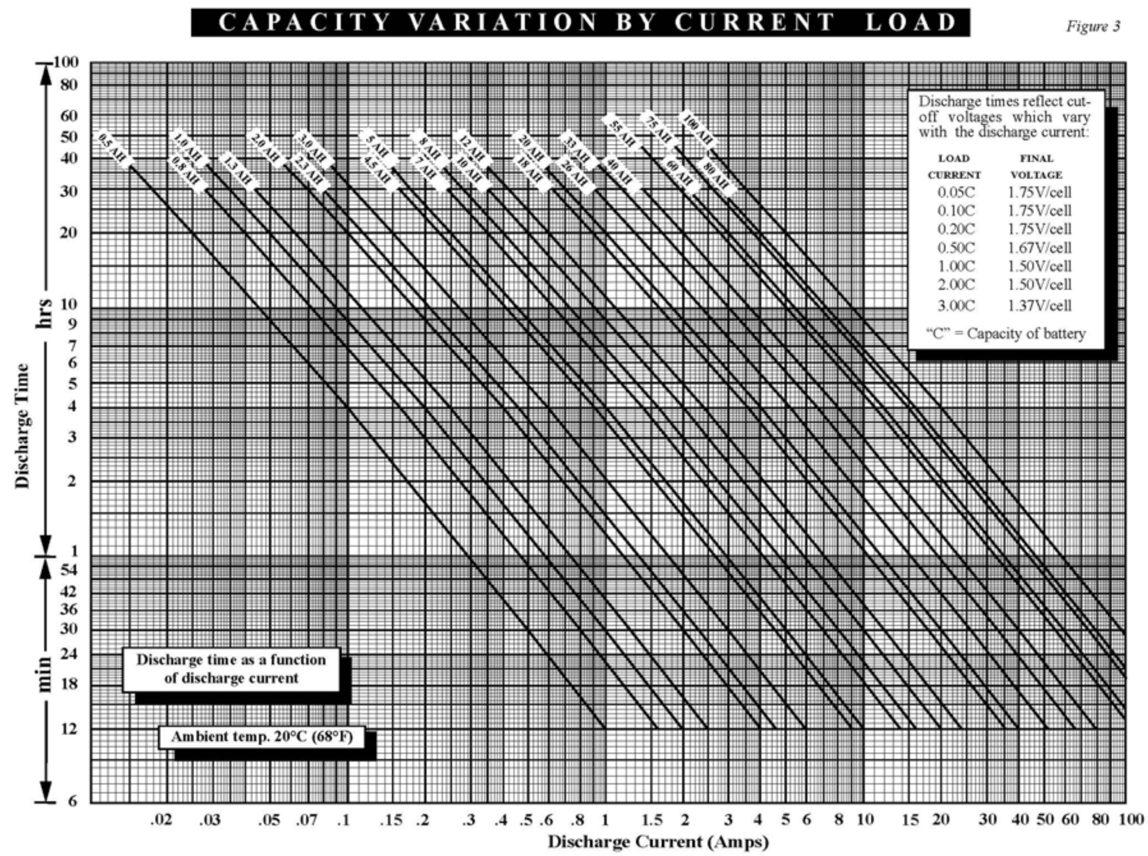


**Figure 1 , Capacity Variation by Current Load**

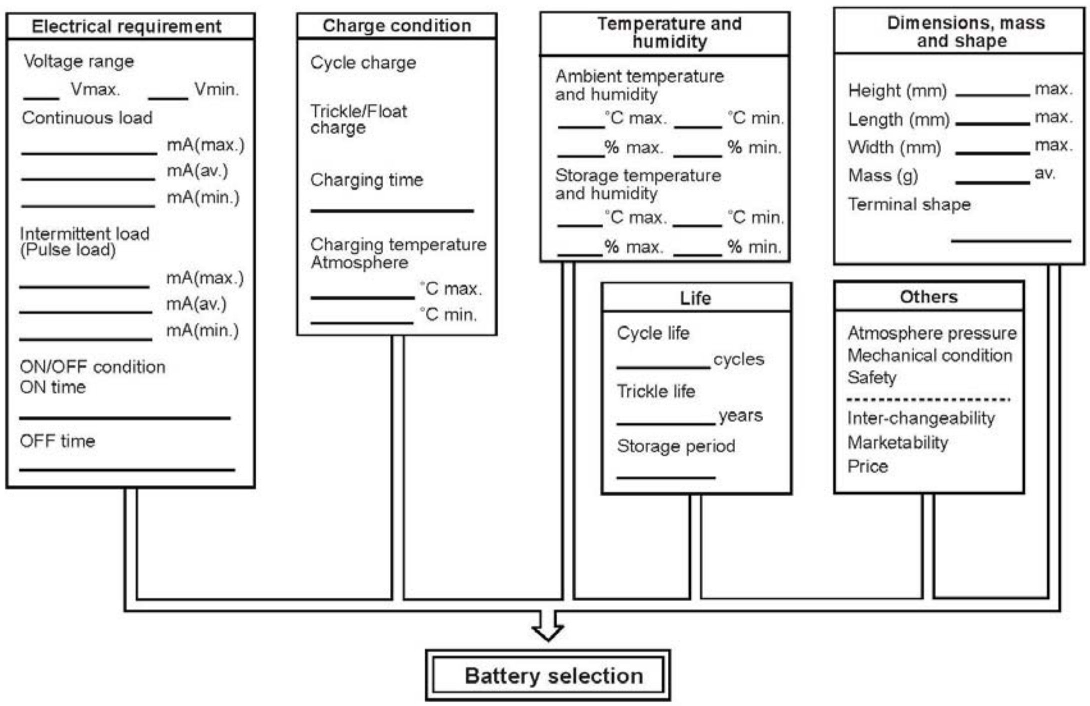


**Figure 2 Battery Selection Table**

| Rated Capacity | @ 0.05C rate (20 Hr. Rate.) | | @0.1C rate (9 Hr. Rate) | | @0.2C rate (4 Hr. Rate) | | @0.5C rate (1.3 Hr. Rate) | | @1C rate (33 Min. Rate) | | @2C rate (12 Min. Rate) | | @3C rate (7.2 Min. Rate) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Current Amps. | Capacity Amp. Hrs | Current Amps. | Capacity Amp. hrs. | Current Amps. | Capacity Amp.Hrs | Current Amps. | Capacity Amp. Hrs. | Current Amps. | Capacity Amp. hrs. | Current Amps. | Capacity Amp. Hrs. | Current Amps. | Capacity Amp. Hrs. |
| 0.5AH | 0.025 | 0.50 | 0.05 | 0.45 | 0.10 | 0.40 | 0.25 | 0.325 | 0.50 | 0.28 | 1.00 | 0.20 | 1.50 | 0.18 |
| 0.8AH | 0.04 | 0.80 | 0.08 | 0.72 | 0.16 | 0.64 | 0.40 | 0.52 | 0.80 | 0.44 | 1.60 | 0.32 | 2.40 | 0.29 |
| 1.0AH | 0.05 | 1.00 | 0.10 | 0.90 | 0.20 | 0.80 | 0.50 | 0.65 | 1.00 | 0.56 | 2.00 | 0.40 | 3.00 | 0.36 |
| 1.3AH | 0.065 | 1.30 | 0.13 | 1.17 | 0.26 | 1.04 | 0.65 | 0.845 | 1.30 | 0.715 | 2.60 | 0.52 | 3.90 | 0.47 |
| 2.3AH | 0.115 | 2.30 | 0.23 | 2.07 | 0.46 | 1.84 | 1.15 | 1.495 | 2.30 | 1.288 | 4.60 | 0.92 | 6.90 | 0.83 |
| 3.0AH | 0.15 | 3.00 | 0.30 | 2.70 | 0.60 | 2.40 | 1.50 | 1.95 | 3.00 | 1.65 | 6.00 | 1.20 | 9.00 | 1.08 |
| 3.2AH | 0.16 | 3.20 | 0.32 | 2.88 | 0.64 | 2.56 | 1.60 | 2.08 | 3.20 | 1.76 | 6.40 | 1.28 | 9.60 | 1.15 |
| 4.5AH | 0.22 | 4.40 | 0.45 | 4.05 | 0.90 | 3.60 | 2.25 | 2.92 | 4.5 | 2.47 | 9.00 | 1.80 | 13.50 | 1.62 |
| 5.0AH | 0.25 | 5.00 | 0.50 | 4.50 | 1.00 | 4.00 | 2.50 | 3.25 | 5.00 | 2.80 | 10.00 | 2.00 | 15.00 | 1.80 |
| 6.5AH | 0.325 | 6.50 | 0.65 | 5.85 | 1.30 | 5.20 | 3.25 | 4.23 | 6.50 | 3.64 | 13.00 | 2.60 | 19.50 | 2.34 |
| 7.0AH | 0.35 | 7.00 | 0.70 | 6.30 | 1.40 | 5.60 | 3.50 | 4.55 | 7.00 | 3.85 | 14.00 | 2.80 | 21.00 | 2.52 |
| 8.0AH | 0.40 | 8.00 | 0.80 | 7.20 | 1.60 | 6.40 | 4.00 | 5.20 | 8.00 | 4.48 | 16.00 | 3.20 | 24.00 | 2.88 |
| 9.0AH | 0.45 | 9.00 | 0.90 | 8.10 | 1.80 | 7.20 | 4.50 | 5.85 | 9.00 | 5.04 | 18.00 | 3.60 | 27.00 | 3.24 |
| 10.0AH | 0.50 | 10.00 | 1.00 | 9.00 | 2.00 | 8.00 | 5.00 | 6.50 | 10.00 | 5.60 | 20.00 | 4.00 | 30.00 | 3.60 |
| 12.0AH | 0.60 | 12.00 | 1.20 | 10.80 | 2.40 | 9.60 | 6.00 | 7.80 | 12.00 | 6.72 | 24.00 | 4.80 | 36.00 | 4.32 |
| 18.0AH | 0.90 | 18.00 | 1.80 | 16.20 | 3.06 | 14.40 | 9.00 | 11.70 | 18.00 | 9.90 | 36.00 | 7.20 | 54.00 | 6.48 |
| 20.0AH | 1.00 | 20.00 | 2.00 | 18.00 | 4.00 | 16.00 | 10.00 | 13.00 | 20.00 | 11.20 | 40.00 | 8.00 | 60.00 | 7.20 |
| 26.0AH | 1.30 | 26.00 | 2.60 | 23.40 | 5.20 | 20.80 | 13.00 | 16.90 | 26.00 | 14.30 | 52.00 | 10.40 | 78.00 | 9.36 |
| 28.0AH | 1.40 | 28.00 | 2.80 | 25.20 | 5.40 | 21.60 | 14.00 | 18.20 | 28.00 | 15.40 | 54.00 | 10.88 | 84.00 | 10.08 |
| 33.0AH | 1.65 | 33.00 | 3.30 | 29.70 | 6.60 | 26.40 | 16.50 | 21.45 | 33.00 | 18.15 | 66.00 | 13.20 | 99.00 | 11.88 |
| 40.0AH | 2.00 | 40.00 | 4.00 | 36.00 | 8.00 | 32.00 | 20.00 | 26.00 | 40.00 | 22.40 | 80.00 | 16.00 | 120.00 | 14.40 |
| 55.0AH | 2.75 | 55.00 | 5.50 | 49.50 | 11.00 | 44.00 | 27.50 | 35.75 | 55.00 | 30.25 | 110.00 | 22.00 | 165.00 | 19.80 |
| 60.0AH | 3.00 | 60.00 | 6.00 | 54.00 | 12.00 | 48.00 | 30.00 | 39.00 | 60.00 | 33.60 | 120.00 | 24.00 | 180.00 | 21.60 |
| 75.0AH | 3.75 | 75.00 | 7.50 | 67.50 | 15.00 | 60.00 | 37.50 | 48.75 | 75.00 | 41.25 | 150.00 | 30.00 | 225.00 | 27.00 |
| 80.0AH | 4.00 | 80.00 | 8.00 | 72.00 | 16.00 | 64.00 | 40.00 | 52.00 | 80.00 | 44.80 | 160.00 | 32.00 | 240.00 | 28.80 |
| 100.0 AH | 5.00 | 100.00 | 10.00 | 90.00 | 20.00 | 80.00 | 50.00 | 65.00 | 100.00 | 55.00 | 200.00 | 40.00 | 300.00 | 36.00 |

**Figure 3 Current vs Discharge Rate**

**Glossary**

AH (Amp Hour) – A battery capacity or rating. If a battery is rated at 100 amp hours it should deliver 5 amps for 20 hours, 20 amps for 5 hours, etc. The amp hour rating tells you how much amperage is available when discharged evenly over a 20 hour period. The amp hour rating is cumulative, so in order to know how many constant amps the battery will output for 20 hours, you have to divide the amp hour rating by 20. Example: If a battery has an amp hour rating of 75, dividing by 20 = 3.75. Such a battery can carry a 3.75 amp load for 20 hours before dropping to 10.5 volts. (10.5 volts is the fully discharged level, at which point the battery needs to be recharged.) A battery with an amp hour rating of 55 will carry a 2.75 amp load for 20 hours before dropping to 10.5 volts.

Active material - Constituents of a cell that participate in the electrochemical charge/discharge reaction.

Battery - Two or more cells electrically connected to form a unit. Under common usage, the term "battery" also applies to a single cell.

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

CCA (Cold Cranking Amps) – A measurement of the number of amps that a battery can produce at 32 degrees F (0 degrees C) for 30 seconds and not drop below 7.2 volts. Basically, a high CCA rating is good in cold weather. This is a measurement usually reserved for SLI (automotive) type batteries.

CA (Cranking Amps) - Cranking amps measured at 32 degrees F. This rating is also called marine cranking amps (MCA). Hot cranking amps (HCA) is seldom used any longer but is measured at 80 ° F. This is a measurement usually reserved for SLI (automotive) type batteries.

Cell - Basic electrochemical unit used to store electrical energy. *See Primary Cell and Secondary Cell below.*

Cell Reversal – When the stronger cells of a battery impose a voltage of reverse polarity across a weaker cell during a deep discharge.

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

Current - Flow of electrons equal to one coulomb of charge per second, usually expressed in amperes

Cutoff voltage - Cell or battery voltage at which the discharge is terminated. The cutoff voltage is specified by the manufacturer and is a function of discharge rate and temperature.

Cycle - The discharge and subsequent charge of a secondary battery such that it is restored to its fully charged state.

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

Duty cycle - Operating parameters of a cell or battery including factors such as charge and discharge rates, depth of discharge, cycle length, and length of time in the standby mode.

Depth of Discharge (DOD) – Degree to which a battery is discharged, usually rated as a percentage of a battery's full charge. Degree of discharge will affect the overall health of the battery and different batteries are rated for different discharge limits.

Electrode – Electrical conductor and the associated active materials at which an electrochemical reaction occurs. Also referred to as the positive and negative plates in a secondary cell. Normally includes active materials plus conductive and supportive elements.

Electrolysis – Chemical dissociation of water into hydrogen and oxygen gas caused by the passage of an electrical current.

Electrolyte - Medium which provides the ion transport function between the positive and negative electrodes of a cell.

Equalizing charge - Charge applied to a battery which is greater than the normal float charge and is used to completely restore the active materials in the cell, bringing the cell float voltage and the specific gravity of the individual cells back to equal values. With time, the charge levels of individual cells of a large battery tend to become slightly unbalanced. The equalizing charge applies an elevated charge voltage for a few hours to balance the cells. Used mainly for large lead acid cells.

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

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

Float Charge – Method of charging in which a secondary cell is continuously connected to constant-voltage supply that maintains the cell in a fully charged condition. This is similar to trickle charge and compensates for the self-discharge on a lead acid battery.

Gassing - Evolution of gas from one or more electrodes resulting from electrolysis of water during charge or from self-discharge. Significant gassing occurs when the battery is nearing the fully charged state while recharging or when the battery is on equalizing charge.

Grid corrosion – Occurs on the positive plate of a lead-acid battery due to being over charged.

Internal Resistance - Resistance to electrical current inside a cell or battery pack.

Lead Acid Battery - Rechargeable battery commonly used for wheeled and stationary applications. The plates consist of lead-antimony alloy.

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

Lithium Ion Battery - A battery dependent on the flow of lithium ions. The lithium metal on the negative electrode is replaced with carbon to improve safety.

Lithium Ion Polymer - A rechargeable battery similar to the Lithium-ion but with a solid polymer as electrolyte. Some gelled conductive material is added to promote conductivity.

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

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

Nickel Cadmium Battery (NiCd) - A rechargeable battery using cadmium as the negative electrode and nickel oxyhydroxide (NiOOH) as the positive electrode.

Nickel Metal Hydride (NiMH) – A rechargeable battery similar to NiCd, except that it uses a hydrogen-absorbing alloy for the negative electrode instead of cadmium. Due to the absence of cadmium, this battery is less prone to memory effects than NiCd batteries.

Nominal Voltage - The cell voltage that is accepted as an industrial standard. Cell voltages of 1.20 and 1.25V are used for NiCd and NiMH batteries. A cell voltage of 2V is used for lead-acid batteries, 1.5V for alkalines, 3V for Lithium, and 3.6V for Lithium-Ion and Lithium-polymer.

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

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

Peukert's Law – Expresses the capacity of a lead-acid battery in terms of the rate at which it is discharged. As the rate increases, the battery's capacity decreases, although its actual capacity tends to remain fairly constant.

$$C_p = I^k t$$

$C_p$ is the capacity according to Peukert, at a one-ampere discharge rate, expressed in Ah

I is the discharge current, expressed in A

k is the Peukert constant, dimensionless

t is the time of discharge, expressed in hours

The ideal battery would have a constant k of 1. The constant k varies with age and battery type.

Potential difference - Work which must be done against electrical forces to move a unit charge from one point to the other, also known as electromotive force (EMF).

Power Capacity – How much power a battery holds. This is listed as ampere-hours (Ah) or milliampere-hours (mAh). To convert this to watt-hours (Wh), multiply by the voltage. Available capacity refers to ampere-hours that can be discharged from a battery based on its state of charge, rate of discharge, ambient temperature, and specified cut-off voltage. Rated Capacity ("C") is the discharge capacity the manufacturer says may be obtained at a given discharge rate and temperature.

Power Capability or Rated Capacity – The rate at which a battery can deliver its power without wasting energy, denoted by C and measured in amps. The C of a battery is proportional to the capacity, so a 1Ah capacity battery with 0.1C capability can supply 100mA of current. Capability depends on chemistry. Lead acid batteries are rated at 10C, Alkalines at .1C, Lithiums at .01C, and Lithium-ions (and Lithium-polymers) at 1C.

Power Density (Energy Density) – How much power (or energy) a battery supplies for its weight, expressed in watt-hours per kilogram (Wh/kg). Gravimetric energy is expressed in watt-hours, volumetric energy is the watt-hours given size.

Primary cell or battery - Cell or battery which is not rechargeable and is discarded when the cell or battery has delivered its useful capacity.

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

Reserve Capacity - The number of minutes that the battery at 80 ° F can deliver 25 amps while keeping its voltage above 10.5 volts. (10.5 volts is the fully discharged level, at which point the battery needs to be recharged.)

Reserve Minutes - Reserve minutes is the number of minutes a battery will carry a 25 amp load before dropping to 10.5 volts. (10.5 volts is the fully discharged level, at which point the battery needs to be recharged.)

Residual Capacity - The charge capacity remaining in a battery prior to charge.

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

Secondary battery - A battery that after discharge may be restored to its charged state by passage of an electrical current through the cell in the opposite direction to that of discharge. (Also called storage or rechargeable.)

Self-discharge - Capacity loss during storage due to the internal leakage between the positive and negative cell plates. Self-discharge rates differ between battery chemistries.

Separator - Electrically insulating layer of material which physically separates electrodes of opposite polarity. Separators must be permeable to ions in the electrolyte and may also have the function of storing or immobilizing the electrolyte.

SLI – Starting, lighting, and ignition – Refers to batteries used in automobiles and engine generator sets.

Specific gravity - Ratio of the weight of a solution to an equal volume of water at a specified temperature. Used as an indicator of the state of charge of a cell or battery, especially with lead-acids.

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

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

Sulfation - Formation of lead sulfate crystals on the negative cell plates of a lead-acid battery. Occurs when the battery is denied a fully saturated charge (essentially storage at low state-of-charge). Can partially be corrected with cycling and/or topping charge.

Terminal - External electric connections of a cell or battery, also referred to as "terminal post" or "post."

Thermal runaway - A condition whereby an electrochemical cell will overheat and destroy itself through internal heat generation. This can cause failure through cell dry-out, shortened life, and/or melting of the battery. This may be caused by overcharge or high current discharge and other abusive conditions.

Traction Battery – typically used for electric or hybrid vehicles, forklifts, and electric carts. These batteries have a high capacity to weight and volume ratio and are designed to be deep cycled.

Trickle charge - Method of charging in which a secondary cell is either continuously or intermittently connected to a constant current supply in order to maintain the cell in fully or nearly fully charged condition.

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

UPS – Uninterruptible Power Supply – A device which maintains a continuous supply of electric power to connected equipment by supplying power from a separate source when utility power is not available.

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

Voltage Limit - The voltage value beyond which a battery is not permitted to rise on charge or fall on discharge.

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