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Solar Electric Power for Instruments at Remote Sites

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1. INTRODUCTION

Small photovoltaic (PV) systems are the preferred method to power instruments operating at permanent locations away from the electric power grid. These systems, unlike backup power systems or PV power systems for homes, are lightly loaded. There is a shallow battery discharge each night. At high latitudes or where seasonal weather variations limit sunlight, deep battery discharge may occur.

The low-power PV power system consists of a solar panel or small array of panels, lead-acid batteries, and a charge controller. Solar panels are rated from ten to several hundred watts. Battery storage capacity runs from tens to hundreds of ampere hours. Charge controllers vary from simple diodes to microprocessor-based devices. The output from these systems is usually 12 volts DC. The load current relative to the system storage capacity is small and these PV systems are able to operate from weeks to months without sunlight.

Even though the small PV power system is simple, the job of supplying power at a remote site can be very demanding. The equipment is often exposed to harsh conditions. The site may be inaccessible part of the year or difficult and expensive to reach at any time. Yet the system must provide uninterrupted power with minimum maintenance at low cost. This requires good design. Local conditions complicate the design process. Weather and obstructions at the instrument site cause variations in sunlight making it difficult to balance loads, storage and power input. Successful small PV systems often require modifications by a knowledgeable fieldworker to adapt to conditions at the site.

Much information is available in many places about solar panels, lead-acid batteries, and charging systems but very little of it applies directly to low power instrument sites. The discussion here aims to close some of the gap. Each of the major components is described in terms of this application with particular attention paid to batteries. Site problems are investigated. Finally, maintenance and test procedures are given.

This document assumes that the reader is engaged in planning or maintaining low-power PV sites and has basic electrical and electronic knowledge. The area covered by the discussion is broad. To help the reader with the many terms and acronyms used, they are highlighted when first introduced and a glossary is provided at the end of the paper.

2. SOLAR PANELS

Solar panels are referred to by the industry as solar electric modules or photovoltaic (PV) modules. Module or panel, they are flat arrangements of series-connected silicon solar cells. There are generally 30 to 36 solar cells per module. The modules can be wired as series or parallel arrays to produce higher voltages and currents. Typical small PV systems use a single panel to charge a 12 volt battery.

Solar panel packaging and mounting vary to suit a wide variety of conditions. Solar panels are used at locations from homes to outer space. All sorts of packages, from the heavy duty marine to the "lite" models are deployed with success at remote instrument sites.

There are three types of silicon solar cells used in solar panels. In order of decreasing efficiency and manufacturing cost, they are the single crystal cell, the semi-crystalline cell, and the amorphous (non crystalline) cell. Lower efficiency means that larger surface area is required to produce the required power. Semi-crystalline panels are 20 to 30% bigger than single crystal types. Amorphous cell panels are about twice the size of the other types. Amorphous cell panels are not now used to power instruments at remote sites but this could change if efficiency improves. Photovoltaic materials other than silicon are under development but panels based on these materials are not yet commercially available.

The electrical characteristics of a solar panel follow from the characteristics of the silicon solar cell. Here is a brief description of how solar cells work.

The Solar Cell

Fundamentally, a solar cell is a silicon photo diode. It is a photo diode whose PN junction is designed to capture sunlight. The diode is very thin and flat so that maximum surface area is presented to the sun. The top layer of P material is so thin that it is easily penetrated by sunlight. Photons passing through the top layer can be absorbed by the atoms of the junction depletion region. Atoms absorbing photons ionize and create free electron-hole pairs. The hole and the electron are separated by the electric field of the depletion region so that charge accumulates across the diode. A small additional charge is available from minority carriers produced near the depletion region. The total charge tends to forward bias the diode and is available to produce current in an external circuit (Ohanion, 1985, p. 653-654).

The simplified equivalent circuit of a solar cell is shown in *Figure 1 A* . It is a current source driving a diode (Wilson and Hawkes, 1983, p. 309). The output of the current source is set by the intensity of the sunlight on the solar cell's PN junction and the size of the junction. With no external load, the charge across the cell forward biases the diode so that the voltage across the cell is the silicon diode voltage of about 0.6 V.
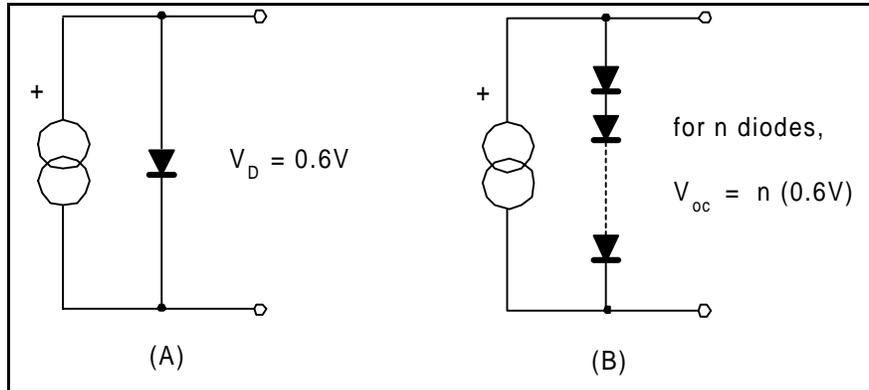
Figure 1.. (A) Solar cell equivalent circuit and (B) solar panel equivalent circuit.

Solar Panel Characteristic Curves

A solar panel is a stack of solar cells connected in series. The equivalent circuit of a solar panel is the sum of the solar cell equivalent circuits connected in series. It can be represented as a single large current source driving a string of diodes, see *Figure 1 B.*

With sunlight on the panel and no external load, all the current from the source is through the series diodes. The output voltage of the panel is the sum of the voltages across the diodes. This is the solar panel **open-circuit voltage, V_{oc}**.

With sunlight on the panel and a short-circuit load, all the current from the current source is through the short. This is the solar panel **short-circuit current, I_{sc}**.

The curve of *Figure 2* shows the change in current and voltage of a solar panel as the resistance of the load across it changes. When the resistance is very low (short circuit), the panel produces very little voltage but maximum current, I_{sc}. In this condition all the solar cell current flows through the load. As the resistance of the load increases, the voltage across the panel increases, but the current to the load stays almost constant and the curve is flat. Current is constant because the voltage produced at the load is too low to activate the diode string. When the product of load current and resistance creates a voltage large enough to forward bias the diodes, current to the load begins to decrease. This produces the bend in the curve. As the diodes become more forward biased, less current flows through the load and more flows through the diode string. When the diodes are fully forward biased, the load current decreases rapidly to zero at $V_{oc,}$ when all the current flows through the diodes.
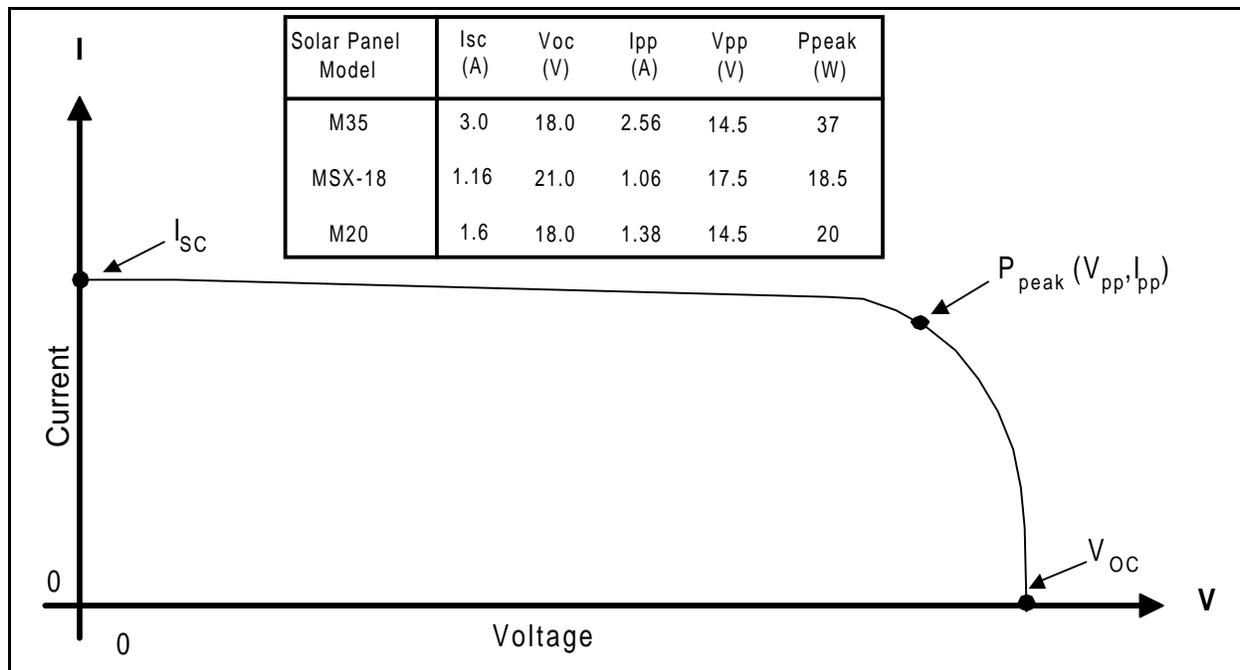
Solar Panel Model	Isc (A)	Voc (V)	Ipp (A)	Vpp (V)	Ppeak (W)
M35	3.0	18.0	2.56	14.5	37
MSX-18	1.16	21.0	1.06	17.5	18.5
M20	1.6	18.0	1.38	14.5	20

Figure 2.. Solar Panel Characteristic Curve. The table shows Standard Test Condition (STC) values for three small solar panels.

The point, P_{peak}, on the knee of the curve, marks the value of current and voltage at which the panel delivers the greatest power for a given level of sunlight. Under **standard test conditions (STC)**, the current (I_{pp}) and voltage (V_{pp}) at P_{peak} define the rated power of the panel. Standard test conditions allow different panels to be compared. STC is an irradiance of 1000 W/m^2 at 25°C with a defined spectrum. STC does not represent typical operating conditions. Most operating conditions produce lower power outputs from the panel than the STC rated power.

The table in *Figure 2* shows I_{sc}. V_{oc}, I_{pp}, V_{pp}, and P_{peak} for three solar panels commonly used in small PV systems and illustrates some differences between them. Notice that the MSX-18 has higher values of V_{oc} and V_{pp} than the M20, even though the M20 has more output power. The MSX-18 characteristic voltages are higher because it has 36 solar cells in series while the M20 has 30 cells. The M20 has similar dimensions to the MSX-18 and collects about the same amount of sunlight but has higher power output in spite of lower voltage. This is because the M20 uses more efficient single crystal solar cells that produce more current than the semi-crystalline cells of the MSX-18. The M35 has the same number of cells as the M20 and the same values of V_{oc} and V_{pp} but has twice the power output because each cell has twice the surface area of the M20's cells.

Figure 3 A shows how the solar panel voltage and current characteristic curve changes with light level. The radiometric term, **irradiance (W/m^2)**, is usually used to describe the level of light on a solar panel. Output current is linear with irradiance when the panel is operating in the constant current part of the curve (Horowitz and Hill, 1989, p. 932).
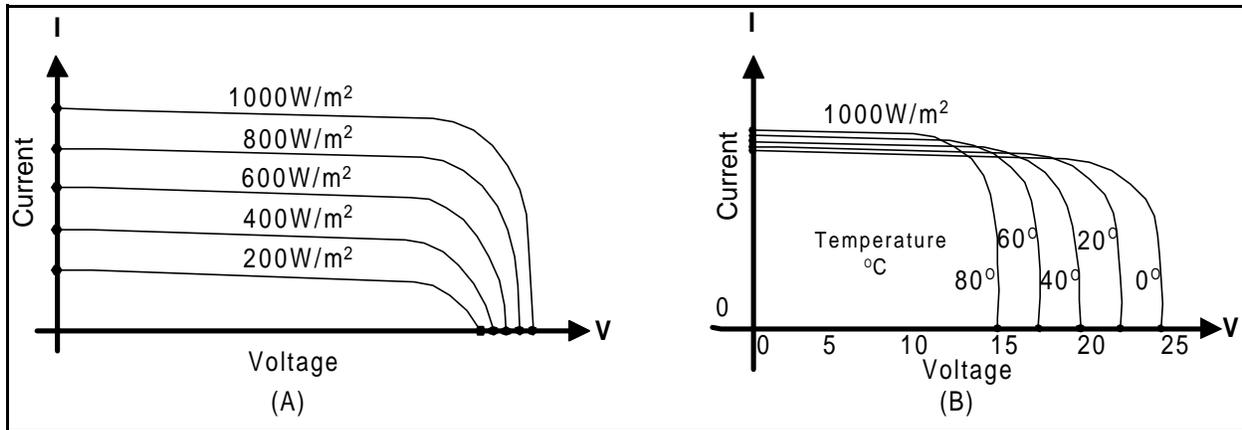
Figure 3. (A) Changes to Solar Panel Characteristic Curves with light level and (B) changes to the characteristic curves as the temperature of the panel changes (From Horowitz and Hill, 1989, p. 932-933).

As might be expected from a semiconductor junction device, the voltages described by the solar panel characteristic curve are temperature sensitive. They have the same temperature dependence as any other silicon diode of approximately -2 mV/°C per cell. Consequently, a 36 cell panel has a temperature dependence of about -72 mV/°C (*Figure 3 B).*

Solar panels are often described in terms of their output voltage, however the voltage and current characteristic curve of *Figure 2* is the curve of a constant current power source and not that of a voltage source. A 12 volt solar panel is not a 12 V source. It is a constant current source suitable for supplying power to a 12 volt power system. As will be seen when charge control is discussed in part 3, the actual voltage of a low-power PV system primarily depends on the state of charge of the battery.

Most small PV power systems have solar panels mounted in a fixed position facing the equator. As the direction of the sun with respect to the panel changes throughout the day, the effective area or **aperture** of the panel will change. At dawn, very little sunlight reaches the active surface of the panel and the aperture of the panel is near zero. As the sun goes higher in the sky, the panel intercepts more sunlight until maximum aperture is reached when the sun is at right angles to the plane of the active surface of the panel. The aperture then decreases as the sun falls in the sky.

Solar panel output depends on the amount of sunlight available and on how much of this light the solar panel collects. The largest possible aperture collects the most light. When the angle of the sun is low with respect to the panel, not only is the aperture small but the loss due to reflection from the surface of the panel increases. Most energy collection occurs when the incident light is within 45° of a right angle to the plane of the panel.

The effective dimensions of the panel changes as the sun moves through the day. The effective vertical dimension also changes as the peak height of the sun in the sky changes during the year.
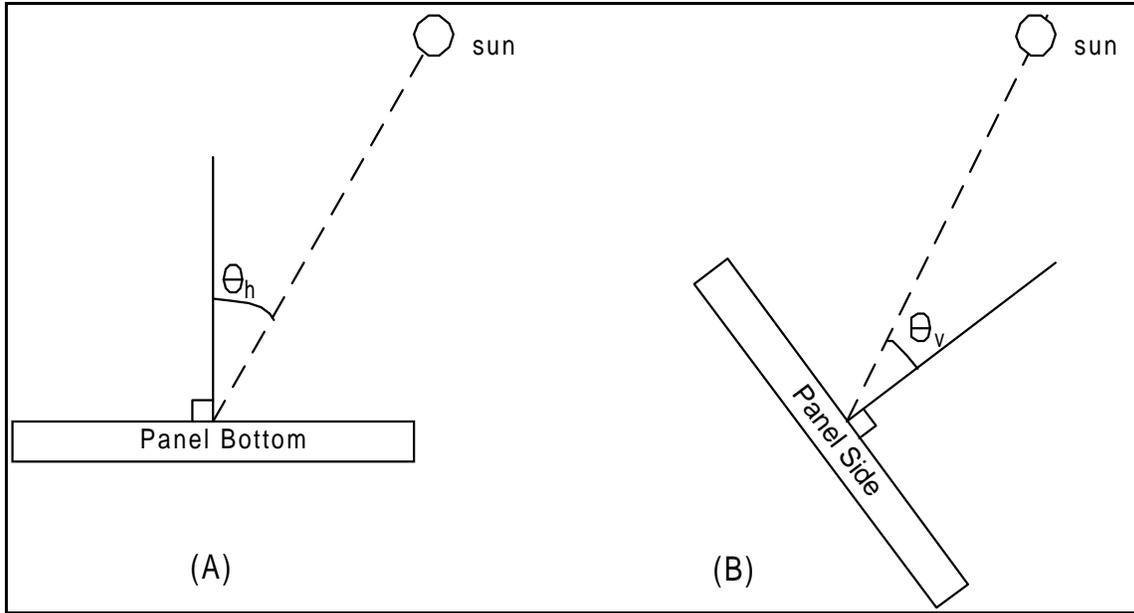
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Figure 4. (A) The horizontal dimension of the aperture changes as the cosine of θ_h. (B) The vertical dimension changes as the cosine of θ_v. The approximate area of the aperture is
A= $\cos(\theta_h)$(Length of Bottom) x $\cos(\theta_v)$(Length of Side).

This yearly change is greatest at high latitudes. The effective horizontal and vertical dimensions of the aperture are proportional to the cosine of the angle of incidence as shown in *Figure 4*.

Table 1 shows solar panel output current averaged over 24 hours as a fraction of the daily peak current for days with differing lengths. *Table 2* shows some typical charging currents for panels in full sun. *Table 2* can be used with *Table 1* to estimate the ampere-hours (Ah) a system will produce per day with continuous bright sun. For example, from *Table 2,* an M20 produces a peak current of 1.1 amps. If there are 16 hours of daylight, *Table 1* shows the 24 hour fraction of peak current is 0.4. The average current for 24 hours is 0.44 A (0.4 × 1.1 A) or 10.56 ampere-hours per day (0.44 A × 24 h). This calculation assumes that the sun is at right angles to the plane of the panel at peak output and estimates the best performance of a system. Weather and other local conditions can cause actual performance to be much less than this.

HOURS OF DAYLIGHT	6	8	10	12	14	16
FRACTION OF PEAK	0.15	0.20	0.25	0.30	0.35	0.40

Table 1. Daily averaged current as a fraction of peak solar panel current as the hours of sunlight change.

SIEMENS MODEL	NUMBER OF CELLS	RATED POWER (W)	CHARGE CURRENT 42 °C, 800 mW/m^2 (A)
M55	36	53	2.6
M45	36	48	2.4
M75	33	48	2.5
M40	33	40	2.1
M65	30	43	2.3
M35	30	37	2.0
M20	30	20	1.1

Table 2. Typical battery charging currents from clean solar panels in bright sun at 42 °C with the sun at right angles to the plane of the panel producing an irradiance of 800 W/m^2 (Siemens, 1990, p.2).

3. LEAD-ACID BATTERIES

Small PV power systems require some means of storing the electrical energy collected by solar panels. The usual choice for this job is the lead-acid battery. While far from perfect, lead-acid batteries offer good performance over a wide temperature range when compared to other battery types. They are also relatively inexpensive and widely available.

There are many types of lead-acid battery and new ones are under development. The differences between one type and another are not always obvious. The following is a condensed guide to lead-acid batteries and is far from complete. If further information is required, there are standard references such as "Handbook of Batteries" (Linden, 1995) and manufacturers will supply data sheets.

The Lead-Acid Cell

The basic unit of the battery is the electrochemical cell. Charged cells can release energy because the active materials participating in the reaction have a higher free energy than the reaction products. The cell has three parts, a **negative electrode**, a **positive electrode**, and an **electrolyte**. When an external load is connected across the positive and negative electrodes of a charged cell, chemical reactions between the electrolyte and each electrode occur that produce free electrons at the negative electrode and the ability to accept electrons at the positive. Current flows through the load and stored chemical energy is released. Internally the circuit is completed by the ionic current carriers of the electrolyte.

In a charged lead-acid cell, the **active material** of the negative electrode is lead (Pb). The active material of the positive electrode is lead dioxide (PbO_2). The lead-acid cell's electrolyte is sulfuric acid (H_2SO_4) in a solvent of water. The acid ionizes to form two positive hydrogen ions ($2H^{+1}$) and the negative sulfate ion (SO_4^{+2}).

The overall reaction of a lead-acid cell is shown in *Figure 5*. During discharge, the active materials of both electrodes change to lead sulfate ($PbSO_4$). The electrolyte loses sulfate ions to both electrodes and gains oxygen from the positive electrode which combines with electrolyte hydrogen to form additional water. This decreases the concentration of acid in the electrolyte.

Charging the cell reverses this process. On the negative electrode, lead sulfate loses its sulfate ion to become lead. On the positive electrode, the lead sulfate loses its sulfate ion and gains oxygen to become lead dioxide. The concentration of acid in the electrolyte increases as sulfate ions return from the electrodes and water is broken down to supply oxygen at the positive electrode and restore hydrogen ions to the electrolyte.

It is important to note that the chemical reactions of the cell are interdependent. Discharge stops when the reaction at either electrode runs out of active material or the electrolyte can no longer

supply sulfate ions. Charging stops when lead sulfate can no longer be converted to the active material of either electrode.
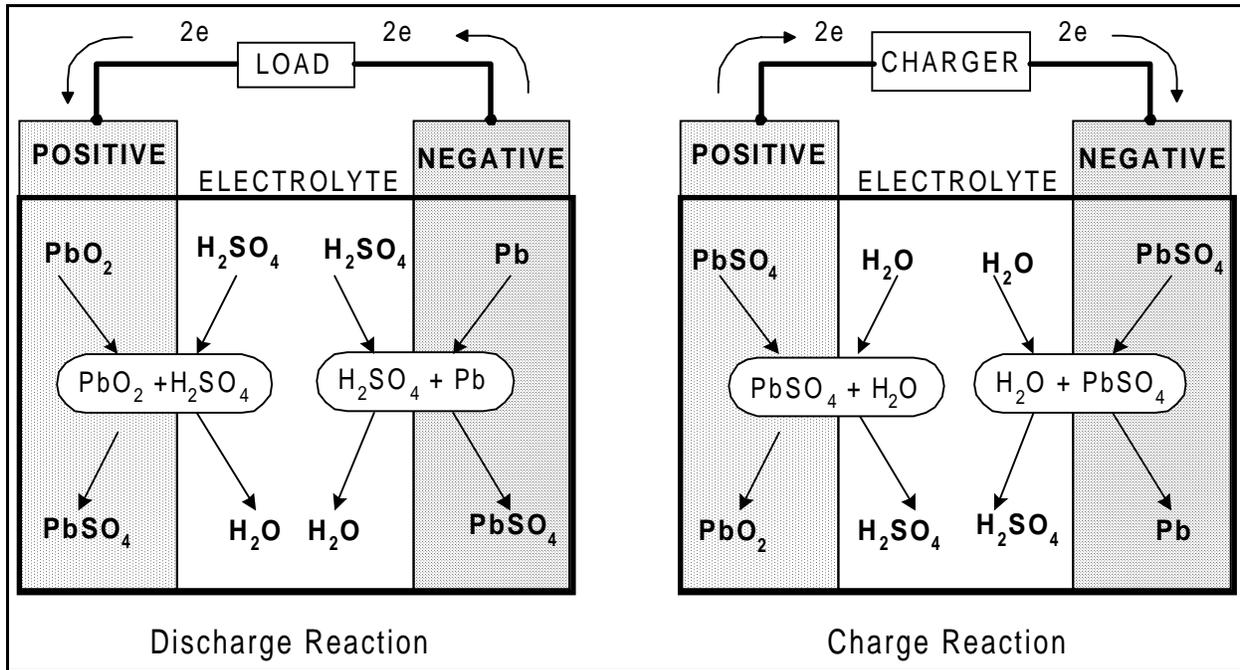

Figure 5. Overall lead-acid battery discharge and charge chemical reactions.

Cell Characteristics

The quantity of free energy stored by the cell depends on the quantity of the chemical reactants in the cell. This ability of a cell to hold energy is called its **capacity (C)**. Cell capacity is specified electrically in units of **amphere hours (Ah)**. The usual way to determine capacity is through a constant current discharge of a fully charged cell. Time is measured from the start of discharge until the potential across the loaded cell has reached a specified cutoff voltage.

When testing the capacity of a lead-acid cell at low to moderate discharge currents, a cutoff voltage of 1.75 volts/cell is used. This cutoff voltage is chosen because it is safe. Discharging a cell at low or moderate rates below 1.75 volts can damage it. For example, large lead-acid batteries are often rated for a 20 hour discharge. In this case, a six cell battery with a nominal capacity of 90 Ah is discharged at a constant 4.5 amps (90Ah / 20 hours) until the voltage across the battery reaches 10.50 volts (6×1.75 V). If the time of the discharge was 19 hours, the measured capacity of the battery is 85.5 Ah (4.5 amps $\times$ 19 hours). Sometimes capacity is expressed as percent of nominal or full capacity. In the example, the battery capacity is 95% (($85.5 / 90) \times 100\%$) of nominal capacity.

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The rate at which the cell can release or store energy depends on how much material can react simultaneously at the electrodes. It is often convenient to scale charge and discharge currents to the capacity of the cell. Instead of describing these currents in amperes, they are described in terms of the cell's nominal capacity. For example, if a cell with an 80 Ah capacity is discharged at its 20 hour rate, the current is 80 Ah/ 20 h or 4 A. If a 10 Ah battery is charged at the 20 hour rate its charge current is 0.5 A. Both rates are described as C/20.

The chemical reactions at the cell's electrodes produce an electric potential across them. The nominal value of a lead-acid cell's potential is 2 volts. The actual voltage depends on temperature and whether the cell is charging, discharging, or reached its **stable open-circuit voltage (V_{soc})**.

The stable open-circuit voltage is proportional to the concentration of the acid in the electrolyte. The concentration of acid is usually determined by measuring the **specific gravity (SG)** of the electrolyte. *Figure 6* shows the relationship between open-circuit voltage and specific gravity at 25°C. Lead-acid cells operate primarily in the linear portion of this curve, so that for each cell (Johnson Controls, 1994 a, p. 2)
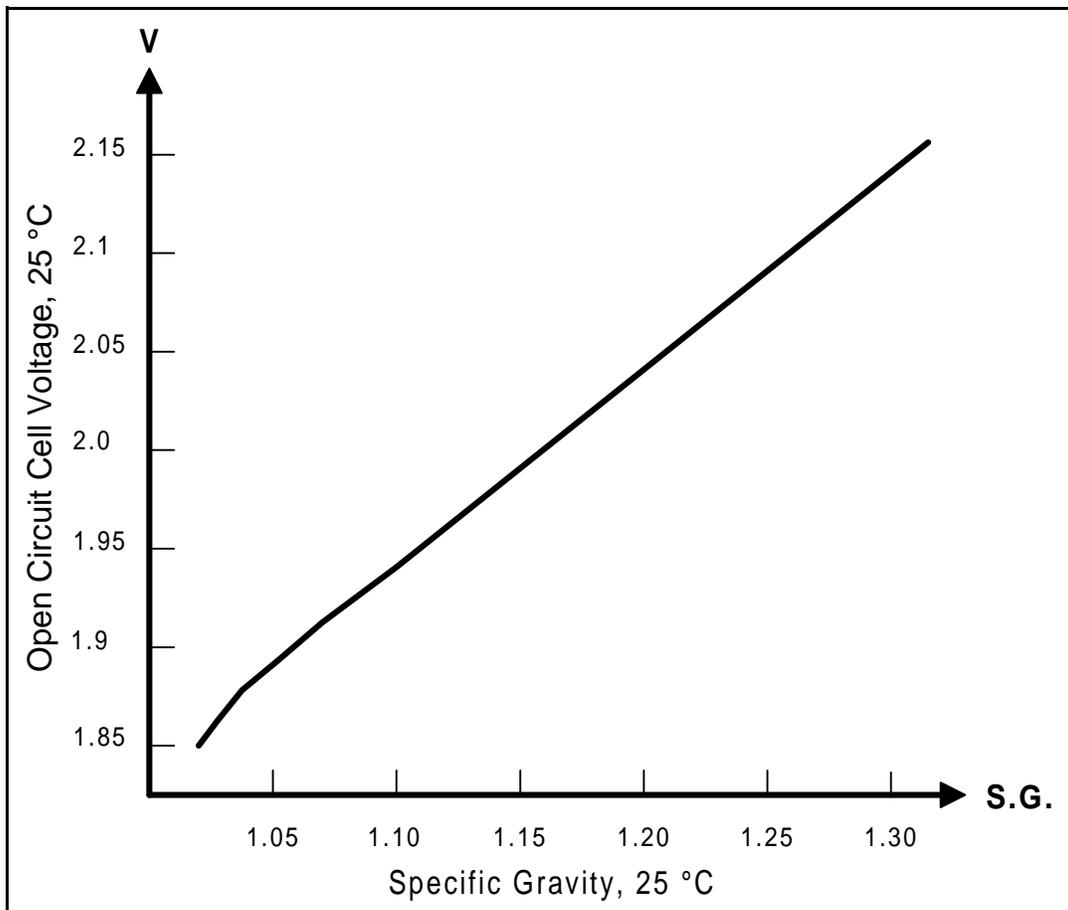
$$V_{SOC} = SG + 0.84.$$

Figure 6. Cell open-circuit voltage depends on electrolyte specific gravity (after Linden, 1995, Figure 24.4).

During discharge, the cell's electrolyte loses sulfate ions to the electrodes and gains water. This decreases the electrolyte's specific gravity and as a consequence the stable open-circuit voltage decreases. The opposite occurs when the cell charges, so that V_{SOC} indicates the cell's **state of charge**. Not all lead-acid batteries use the same range of specific gravities. Some cell designs have higher full-charge specific gravities and open-circuit voltages than others, nor is the specific gravity at full discharge the same for all cell designs.

The voltage of a charging or discharging cell is complex. The open circuit voltage combines with voltage losses caused by charging or discharging and causes the cell voltage to be greater than the open circuit voltage while charging and less than the open circuit voltage while discharging. The change from open circuit values depends on the rate of charge or discharge. There are two causes of voltage loss, polarization effects and electrical resistance in the cell current path (Linden, 1995, p 24.10).

Polarization losses occur because reactants from the electrolyte must be transported to the surface of the electrode before they can react with the electrode's active materials. There are two factors that inhibit this process. First, electrolyte solvent molecules at the surface of the electrode form a barrier to the passage of ions. The barrier is known as the electrical double layer.

Overcoming this barrier requires additional electric potential called the activation polarization voltage (Linden, 1995, p. 2.10-2.15). Second, as the reaction at the electrode surface proceeds, the quantity of electrolyte reactants near the electrode surface decreases and creates a concentration gradient between the electrode and the bulk electrolyte. This gradient produces a loss in voltage at the electrode called the concentration polarization voltage. The concentration polarization voltage increases exponentially with current (Linden, 1995, p. 2.16-2.18).

The activation polarization voltage and the concentration polarization voltage combine as the electrode polarization potential. Energy is lost through polarization and is dissipated as heat. The size of the polarization loss depends on the amount of current through the cell, the specific gravity of the electrolyte and on the physical structure of the electrodes. For the lead-acid batteries and the loads used in low power PV power systems, the polarization potential ranges from tens to several hundred millivolts per cell.

In addition to the loss due to electrode polarization potential, the internal resistance of the cell produces a voltage proportional to current, an **IR loss**. The current path through the cell includes the electrolyte's ionic current carriers, the active material of the electrodes, the electrode current collectors attached to the active materials, and the tabs for making external connection to the electrodes. All of these and the connections between them have electrical resistance and produce an IR loss when current moves through the cell. The internal resistance of the battery and electrode polarization both oppose current flow and the combination of this opposition is the **internal impedance** of the cell.
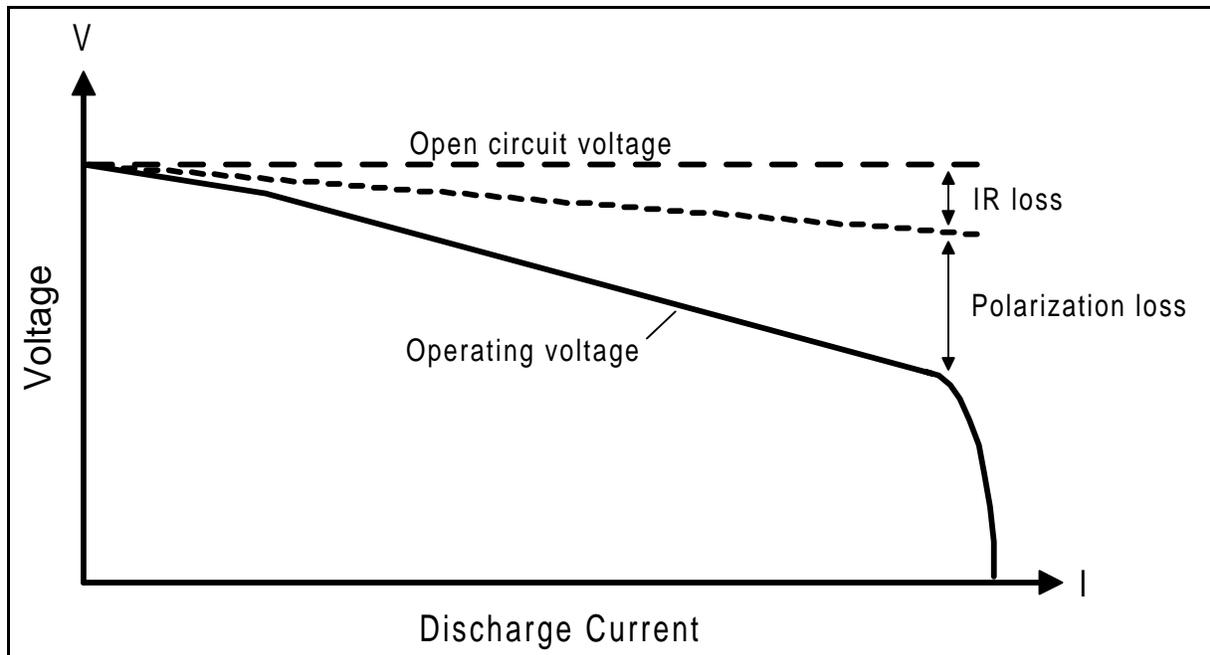
Figure 7. Battery operating voltage is the result of voltage losses from current moving through the internal resistance of the battery (IR loss) and electrode polarization potential (After Linden, 1995, Figure 2.1).

Figure 7 shows the electrode polarization potential and the IR loss combining to decrease the open-circuit voltage of a cell when it is discharging. When charging the cell, the charging source must supply a voltage greater than the open-circuit voltage of the cell to overcome similar polarization and IR losses. The smaller loss at lower current means that the cell will deliver more of its stored chemical energy to the load at lower discharge rates. Consequently, cell capacity increases as the discharge current decreases.

When a cell stops charging or discharging, the voltage of the cell moves toward its stable open-circuit value. The IR component of the voltage difference from the stable open-circuit value disappears immediately. The concentration polarization potential decreases as new reactants from the bulk electrolyte diffuse toward the electrodes. At the same time, the activation polarization potential is decreasing as voltage equalizes across the electrical double layer. The change in cell voltage, caused by polarization changes, is similar to the voltage change across a charging capacitor (Linden, 1995, p. 2.25-2.27). Charge stored because of electrode polarization is called **surface charge**. The cell reaches chemical equilibrium and its stable open circuit voltage when the surface charge is dissipated. It can take several hours for this to occur in a lead-acid cell (Linden, 1995, p. 24.11) and exact measurements are usually made after 24 hours.

The chemical activity and electrical characteristics of the lead acid cell are temperature dependent. As the temperature decreases, the cell's maximum current and storage capacity decrease as chemical activity decreases. The stabilized open-circuit voltage, (V_{soc}), has a complex dependence on temperature. The specific gravity of the electrolyte increases as the temperature decreases and this acts to raise (V_{soc}), but the decrease in chemical activity offsets this increase. Overall, for the range of specific gravities used for battery electrolytes, the temperature

coefficient of the stabilized open-circuit voltage is about +0.2 mV/°C per cell (Linden, 1995, p. 24.10).

Changes in chemical activity with temperature cause charging voltage temperature dependence. Temperature compensation of the end of charge voltage is required to correctly charge a cell. At 50 °C the temperature compensation is -3.5 mV/°C per cell, while at 0 °C it is -6 mV/°C per cell (Linden, 1995, Table 24.19). Commercial battery chargers with temperature compensation often use -5 mV/°C per cell to cover the recommended temperature range for battery charging. Discharge voltages have a similar temperature dependence.

A charged lead-acid cell is thermodynamically unstable and will **self-discharge** even though no load is connected across it. The rate of self-discharge depends on temperature, acid concentration, and the presence of metal ions, especially antimony (Linden, 1995, p. 24.11-24.12). At 25 °C the self-discharge rate can be as low as 0.05% per day. For cells contaminated with metal ions, the self-discharge rate can be as high as 5% per day. The voltage from a charging source required to replace the self-discharge current and maintain the cell at full charge is called the **float voltage**. The current from the float voltage source is called the **float current.** The temperature coefficient of the float voltage at 25 °C is -2 mV/°C.

Battery Design

Designers have been working on the lead-acid cell for over 100 years. This development process results in wide variety of lead-acid battery types and sizes which cover many applications. To understand how a battery will perform in a small PV power system, it is necessary to describe some of the differences in lead-acid battery types.

Most lead-acid batteries used in small PV power systems are similar in appearance to automotive batteries. These box-shaped batteries are constructed from a row of **prismatic** cells. In the prismatic cell, the electrodes are shaped into large flat **plates**. Positive and negative plates alternate and are stacked in parallel. Between the positive and negative plates there is separator material which prevents contact between them (*Figure 8)*. The stack of plates and separators is immersed in the battery electrolyte. Prismatic cell design is used when large, high capacity batteries are required.

There may be as many as 30 plates in a stack. Cells designed for high current discharges have many thin plates to maximize the amount of plate area. Cells with fewer, thicker plates have greater storage capacity and the plates are stronger than thin plates. An electrical connection is made with plate straps so that all the positive plates form a large surface area positive electrode. A similar connection turns the negative plates into a large negative electrode. The positive and negative connections are brought out of the cell casing where they can be connected to the other cells of the battery. The cells are connected in series to produce the battery's nominal voltage. A 12 V battery is made from six 2 V cells.

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The plates are not simple sheets of active material. One technique for making both positive and negative plates starts with pasting a mixture of lead oxide (PbO), acid, water and additives onto
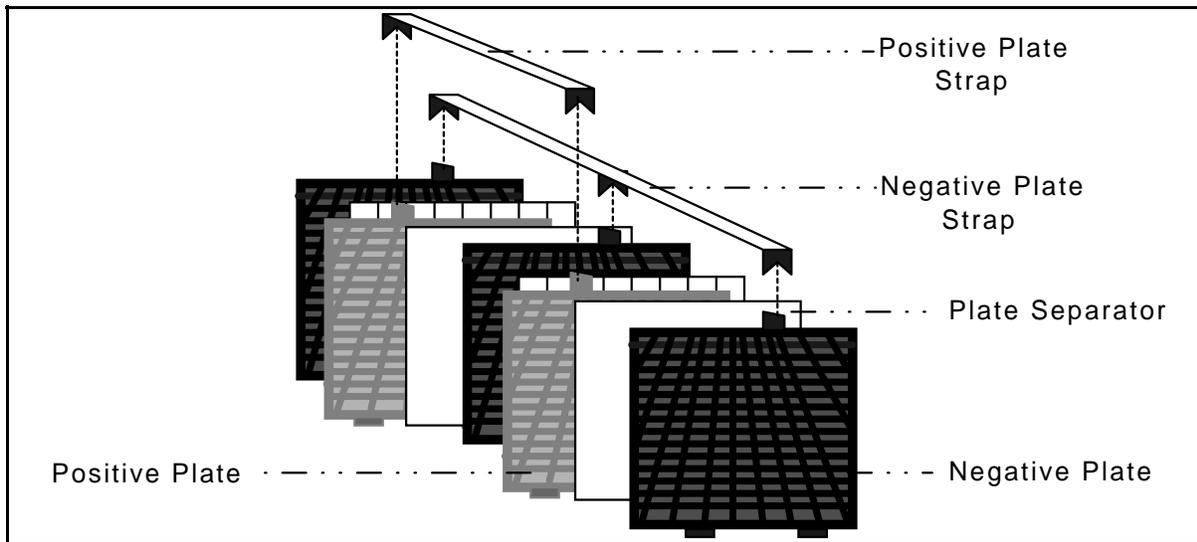

Figure 8. Prismatic cell design uses a stack of positive and negative plates. Short-circuits between the plates are prevented by plate separators. The mesh drawn on the plates represents the plate grids (From BCI, 1995, p. 12).

 a mesh support. When the lead oxide paste is cured it binds to the mesh creating a stiff porous plate structure. Positive and negative plates are then formed from the lead oxide by charging. At the negative plate, lead oxide becomes lead and at the positive plate, it becomes lead dioxide. This method produces porous lead dioxide and spongy lead. Both of these have large surface areas for the cell's chemical reactions.

The mesh structure is called the **plate grid**. The grid not only supports the plate active materials but also conducts current from the cell. Unfortunately, most metal conductors are easily attacked by acid. Pure lead resists corrosion but is too soft and weak to use as a grid for most applications. The problem is solved by using lead alloys.

Antimony is a common grid alloy metal but it has the unfortunate characteristic of migrating from the positive plate grid to the negative plate active material. The antimony deposit on the negative plate increases water loss during charging and self-discharge during battery storage. Recent grid designs minimize antimony and substitute other materials. The newest grid formulations eliminate antimony and use calcium as the lead alloy. Tin is sometimes used with calcium. Calcium strengthens and stiffens the grid. Tin increases corrosion resistance and strength. Batteries with lead calcium grids are better in small solar power storage systems than other types because less water is lost from the electrolyte during charging and self-discharge rates are lower.

Plate **separators** are electrical insulators with many small holes in them. They stop the plates from touching each other and short circuiting, while allowing the electrolyte to pass through the pores. Any restriction of electrolyte ion flow slows the reaction rate and is electrically the same

as increasing the internal impedance of the battery. However, larger pore areas allow a greater possibility of short-circuits so there is a trade-off between low impedance and insulation effectiveness.

The material of the separator must resist acid corrosion as well as providing the desired pore size and density. The materials in common use are rubber, cellulose, PVC, polyethylene, glass fiber, and micro-glass. Some separators include glass fiber mats whose purpose is to prevent the active plate material from falling out of the plate grid (**plate shedding**). Some separators encapsulate plates in an envelope of polyethylene.

One of the primary characteristics of a lead-acid battery design is the balance between the amount of active material in the plates and the number and concentration of the electrolyte ions. The discharge reaction of a battery stops when either of the plates run out of active material (**plate-limited**) or when the electrolyte runs out of sulfate ions (**electrolyte-limited**).

The specific gravity of a fully discharged cell depends on whether discharge is plate-limited or electrolyte-limited. This affects how the battery behaves in different applications. For example, a plate-limited battery is easier to recharge after a very deep discharge because the higher concentration of acid in the electrolyte makes it a better electrical conductor than an electrolyte-limited battery which has lost most of its sulfate ions from the electrolyte. A discharged plate-limited battery is less likely to freeze in cold weather than an electrolyte-limited battery because the higher acidity of the plate-limited battery electrolyte lowers the freezing temperature. On the other hand, an electrolyte-limited battery has reduced plate stress. This is an advantage when batteries are frequently and rapidly recharged from deep discharge.

The other major electrolyte characteristic is its full-charge specific gravity. There are two ways to increase the quantity of ions in the electrolyte. The volume of the electrolyte can be increased or the concentration of acid can be increased. Once again there are trade-offs. Batteries with higher full-charge specific gravities can supply larger currents with smaller IR and polarization losses but at the cost of reduced life because corrosion increases with acidity. Batteries with low concentrations of acid have longer lives but to provide the same storage capacity as batteries with higher specific gravities, must have greater electrolyte volumes. This makes them weigh more and requires more space. See *Table 3* for some typical electrolyte specific gravities.

BATTERY TYPE	AUTO-MOTIVE	DEEP-CYCLE	STATIONARY FLOAT SERVICE	GEL CELL	ABSORBED GLASS MAT
FULL-CHARGE SPECIFIC GRAVITY (typical, 25°C)	1.265	1.280	1.215	1.280	1.300

Table 3. The full-charge specific gravity of some lead-acid batteries.

Prismatic batteries are classified by whether or not the electrolyte is sealed inside the battery or is accessible for servicing through **vents** in each cell. The traditional lead-acid battery is vented and its electrolyte is a free flowing liquid. Batteries with electrolytes in this form are called **wet** or **flooded** lead-acid batteries. Some wet lead-acid batteries are sealed but most sealed lead-acid battery designs have immobile electrolytes. There are two ways to immobilize the electrolyte. **Gel-cell** electrolytes are set with a gelling agent. Absorbed glass mat (**AGM**) batteries use micro-glass fiber matting to hold their electrolytes like a damp cloth holds water.

A battery charging at a fast rate, or connected to a charging source at too high a voltage, can release gases due to overcharge. In unsealed wet lead-acid batteries these gases are lost, causing the electrolyte to dry out. Gel cells and AGM batteries recycle these gases. This is such an important characteristic of these batteries that they are classed together and called valve regulated lead-acid (**VRLA**) batteries. The valve regulates the internal pressure of the battery by releasing gas when the pressure is between 4 and 100 x 10^3 Pa (0.58 to 14.5 psi).

During overcharge, oxygen and hydrogen gases are formed by the decomposition of electrolyte water. In a VRLA battery, the oxygen generated at the positive plate flows through cracks in the gel or unfilled pores of the glass mat to the negative plate where it reacts with lead to form lead oxide. The lead oxide then reacts with the electrolyte to form lead sulfate and restore water to the electrolyte. Meanwhile, hydrogen, which would have evolved as a gas at the negative plate when water decomposed, reacts instead with lead sulfate to return lead to the negative plate and sulfate ions to the electrolyte. This forms a closed cycle which restores most water that would have been lost as long as the gas pressure stays below the valve release pressure.

Not all sealed prismatic batteries recombine decomposed water. Sealed, "maintenance-free", automotive batteries are often sealed wet batteries. In wet batteries, very little oxygen travels from the positive to the negative plate to start the recombination process. Most of it bubbles out of the liquid electrolyte before it can reach the negative plate. Unlike vented wet batteries, water lost by the electrolyte of sealed wet batteries cannot be replaced. Sealed wet automotive batteries are designed for automotive charging systems and perform poorly in small PV power systems. However, there are some sealed wet lead-acid batteries which are designed for energy storage systems. The cells of these batteries have large reservoirs of electrolyte to replace water lost during overcharge.

Before leaving the topic of battery construction, it is worth mentioning another type of sealed cell. Unlike the prismatic VRLA cell these cells are cylindrical and are called **SLA** (sealed lead-acid) cells. Thin lead and tin alloy grids are used to support the active plate materials of these cells. The flexible plates are spirally wound with glass mat separators and inserted into a plastic casing. The casing is then filled with electrolyte and the plates are formed by charging. Next the casing is sealed with a top that includes a pressure relief valve and openings for the plate terminals. The whole is then put inside a metal can that provides mechanical support.

In general the rectangular prismatic construction provides more energy in a given space than the cylinder but the cylindrical shape is a better pressure container for a sealed battery design and SLA batteries operate at 2 to 4 x 10^5 Pa (29 to 58 psi). Until recently the cylindrical cell was only seen in smaller batteries for portable equipment but there is now a car battery based on a six pack of plastic cylinders. Small PV power systems may one day use such a battery.

Battery Application Types

Lead-acid battery development has created three broad classifications of lead-acid battery designs. They are **starting, lighting and ignition (SLI); deep-cycle service; and float service**. Multi-purpose, valve regulated lead-acid (VRLA) battery designs blur and extend these traditional categories. Nevertheless, this classification serves to group applications and illustrates the specialization of lead-acid battery design.

The **SLI** battery is optimized to produce the high short-duration currents required to start an internal combustion engine. It has many thin, highly porous plates so that big areas of active material can react simultaneously and produce high peak currents. The grids and internal conductors are large to minimize internal resistance and IR loss. Separators are selected that allow as much ion current flow as possible. Moderately high specific gravity wet electrolytes minimize polarization losses while avoiding the corrosion problems caused by very acid electrolytes. The price the SLI battery pays for producing large currents is reduced storage capacity, and poor deep discharge recovery. Automotive batteries are the largest application for SLI batteries but SLI design principles are used when other applications require very large currents.

For a number of reasons, wet lead-acid batteries rather than VRLA batteries dominate SLI applications. Gel cell VRLA batteries have too high an internal impedance to deliver the high peak current required by most SLI applications. Absorbed glass mat (AGM) VRLA batteries can provide high current but at considerably higher cost. Wet lead-acid batteries have higher energy density than VRLA batteries and their more compact size is an advantage in the crowded engine compartment of a modern car.

Deep-cycle batteries are intended as the primary power source for an application and are designed to produce sustained moderate currents with intermittent heavy loading. Energy is stored for short periods and recharging is frequent. Most deep-cycle batteries are electrolyte-limited. The traditional large deep-cycle battery is called a **traction battery** because of its application in electric vehicles. Deep-cycle batteries range from large forklift traction batteries

with typically 500 Ah capacity to boat trolling motor batteries with 50 Ah capacity. Hundreds of deep discharge - charge cycles are expected from deep-cycle batteries. PV power systems that experience deep discharges each night require deep-cycle batteries. Small sealed portable instrument batteries must have good deep-cycle performance.

Deep-cycle battery designs require more storage capacity than SLI designs but the primary goal is repeated recovery from discharges of up to 80% of the rated capacity. There are fewer, thicker, and denser plates than in SLI batteries so that as much active material as possible is packed into each cell. The grids are designed for strength and this often means using antimony alloys in lower-cost batteries. Deep-cycle service causes stress on the active material of the positive plate, so separators often include glass fiber mats to prevent plate shedding. To further reduce plate stress, deep-cycle battery discharge is electrolyte-limited.

Deep-cycle applications are served by both AGM and gel cell VRLA batteries. The type "B" gel cell produces the greatest number of charge-discharge cycles before failure. AGM batteries have less than half the cycle life of "B" gel cells but have far superior high-rate discharge characteristics and are used with high current loads. PV power systems that must produce high power often use AGM batteries. In some cases, AGM batteries sold for these systems are labeled "photovoltaic batteries". The overall deep-cycle performance of VRLA batteries is not as good as wet deep-cycle designs but the spill-proof sealed VRLA is often preferred when installation and safety are considered.

Float service batteries operate in parallel with another power source and are idle until the other source fails. While active, the other source supplies float current to the float service battery that is just enough to replace self-discharge current. Energy storage is the primary purpose of float service batteries. In addition to storage capacity, long life and reduced maintenance are the battery characteristics most desired for float service.

Wet lead-acid batteries designed for float service are called **stationary batteries**. The plates, like deep-cycle batteries, are thicker than SLI designs and the active materials are denser. The grids are made of lead or lead calcium so that self-discharge and electrolyte dry out are minimized. Separators with small pores are used to prevent short-circuits and prolong battery life. Stationary batteries have large volumes of low specific gravity electrolyte to reduce corrosion and increase the time before electrolyte water replacement is required. Discharge is limited by the amount of active material on the plates. Float batteries range from large stationary batteries with 1600 Ah capacities to small VRLA designs with 1 Ah ratings. Special stationary batteries developed by the telecommunications industry have life expectancies of over 30 years while VRLA designs last 5 years (Power Sonic, 1996, p. 6).

Design Type	SLI	Deep-cycle	FLOAT
Applications	Engine starting High Power UPS	Wheel chair Golf cart Boat trolling motors RV electrical power Home PV systems	Security UPS Emergency Comm. Emergency Lighting Instrument Standby
Battery Types	Vented auto batteries Maintenance-free auto Marine AGM type VRLA	Traction batteries Type B VRLA Gel RV24, RV27 Marine	Stationary batteries AGM type VRLA Type A Gel, VRLA

Table 4. Battery applications and types.

Many float service applications are now served by VRLA batteries. In particular the AGM battery is increasingly popular. This may seem surprising, since it would be hard to imagine two more different battery designs. The traditional stationary battery is optimized for long life with a low specific gravity electrolyte while AGM batteries have the highest specific gravity of all the battery designs discussed. The reason for the change is that it is often less expensive to simply change AGM batteries than to support the maintenance program required to get the longer service life expected from traditional stationary batteries.

The uninterruptible power systems (UPS), which have spread with the increased use of personal computers, depend on the good high-rate performance of AGM batteries. The type "A" gel cell is made for float service but at room temperature has no advantages over AGM batteries and its high-rate performance is not as good (Johnson Controls, 1994 b, p.5).

Table 4 matches battery types to some applications. The RV24 and RV27 batteries listed are wet deep-cycle batteries. The marine battery referred to is used for both starting marine engines and supplying power when the engine is off. It consequently has some SLI and deep-cycle characteristics.

Batteries for Low-Power PV Systems

Small PV systems at remote instrument sites are primarily float systems with small discharges occurring at night and recharge the following day. There is a deep discharge at higher latitudes in winter or when weather conditions prevent recharge. At most, the battery will experience a dozen deep discharges and a battery designed for hundreds of deep-cycles is not required. Low-power PV systems are not required to produce high current discharges so SLI battery characteristics are not needed. It would seem that float service batteries are the best fit for small PV systems but the truth is that batteries from each design class are used in this application. This is because battery design characteristics are often outweighed by cost, availability, and site factors.

The least likely battery for this application is the automotive battery. The SLI design has poor deep-cycle performance and quickly loses capacity after a few deep discharges. The design uses

large pore separators with thin, tightly spaced plates. Consequently short circuited cells are much more likely than with other designs. However, some sites have strong sun all year and the battery never discharges deeply. The low cost of a car battery may compensate for a short service life. In these circumstances, car batteries may be used with caution. In some parts of the world they may be the only choice because better batteries are unavailable. Sealed wet "maintenance-free" automotive batteries should be avoided because they are unable to tolerate the overcharge conditions common to PV systems.

Vented wet deep-cycle traction batteries such as the Battery Council International (BCI) group numbers RV24 and RV27 are almost as inexpensive as car batteries and are much more durable. They are a good choice for low-power PV systems when it is possible to refill electrolytes that have lost water from overcharge. Vented deep-cycle marine batteries are similar. These batteries are widely available.

Wet deep-cycle batteries have longer service lives in low-power PV systems than SLI batteries because they have more durable plate structures and separators with smaller pores. These features make deep-cycle batteries less likely to short circuit than SLI batteries when overcharge leads to increased corrosion and plate shedding.

The vented wet stationary batteries used for emergency instrument power in power stations, for emergency communications, and as telecommunications batteries are rarely found at small PV system field sites. These batteries are designed for long float service, but regular maintenance and careful charging are required to achieve long lifetimes. This not possible at most remote instrument sites so stationary batteries have no special advantage. Further, the low specific gravities that give them long service lives make them more likely to freeze in winter.

The AC Delco Corporation makes a series of sealed wet lead-acid batteries called "Delco Freedom". The series includes SLI, deep-cycle, and float service designs. The SLI and deep-cycle designs cannot cope with the overcharge from a small PV system and should not be used. However, the Delco S2000 battery is designed for energy storage applications and performs well in small PV systems. The S2000 is influenced by traditional stationary battery design. Each cell has 430 cc (15 oz) of reserve electrolyte to avoid dry out from overcharge. Upright operation is necessary because the liquid electrolyte can spill from a vent in the electrolyte reservoir. The plate structures are similar to VRLA designs and use lead calcium grids. Envelope style separators prevent shed material from shorting plates at the bottom of the cell. The cost of an S2000 is between vented wet deep-cycle batteries and VRLA batteries.

The gel cell was the first VRLA battery and often sealed prismatic lead-acid batteries are assumed to be gel cells when they are actually AGM batteries. The mistake is understandable. These batteries are interchangeable in many applications. Manufacturers that make both types often use the same casings and similar labels.

Despite appearances, there are some fundamental differences between gel cells and AGM batteries. The two different ways of immobilizing the electrolyte, gelling versus absorption, leads to different separator systems. Gel cells have plastic or glass separators that are distinct from the

electrolyte gel. In the AGM battery, the glass mat that absorbs the AGM electrolyte, also functions as the separator. This separator system gives AGM batteries a much lower opposition to electrolyte ion flow than gel cells and consequently better high current rate performance because of lower impedance.

The lower impedance of the AGM battery combines with a more effective gas recombination cycle to give them a 50% higher float current than gel cells. Glass mats are less effective at conducting heat away from the plates than gelled electrolytes. The higher float current and lower heat conduction cause higher float operating temperatures (Johnson Controls, 1994 b, p. 1-4). Finally, AGM batteries are electrolyte-limited designs while gel cells are plate-limited. Other than high current rate performance, none of these differences between gel cells and AGM batteries matter very much for applications which operate at room temperature.

Where the differences do matter is in the field when batteries are subject to temperature extremes. Freezing a battery electrolyte usually ruins it. Electrolytes freeze at higher temperatures as the battery discharges and the specific gravity of the electrolyte decreases. Electrolyte-limited batteries will continue to discharge far beyond their rated capacity. These very deep discharges produce very low specific gravity electrolytes with higher freezing points than plate-limited designs. Without some form of deep discharge protection, electrolyte-limited AGM batteries are more likely to freeze than plate-limited gel cells. A further advantage of the plate-limited design is that such batteries recharge more easily from deep discharge because the higher specific gravity of the discharged electrolyte is a better electrical conductor (Globe-Union, no date, p. 2). If conditions at a field site are likely to produce very deep battery discharges at low temperatures, gel cells are less likely to freeze and more likely to recharge than AGM batteries.

At high temperatures, gel cells have a different advantage, longer service life. The life expectancy of a battery at constant voltage decreases by 50% for every 10°C increase in temperature above 25°C. AGM batteries have a higher operating temperature than other lead-acid battery types. The effects of higher temperatures accumulate and shorten battery life (Johnson Controls, 1994 c, p. 1-4). The fact that AGM electrolytes have a slightly higher full-charge specific gravity than gel cells also tends to diminish their service life because higher acidity increases corrosion. Wet batteries have the best thermal conductivity, and if temperature is the only factor, the longest potential life.

Does the better performance of gel cells at temperature extremes make AGM batteries a poor choice for low-power PV sites? No. The freezing and slow recharge problems caused by low specific gravity when AGM batteries are discharged can be prevented by use of a charge controller that disconnects the load before the battery is very deeply discharged. The shortened service life due to higher temperature operation can be partially overcome with temperature compensated charge controllers. Unless ambient temperatures are well above 25°C most of the time, other charge control problems at field sites are more likely to contribute to early battery failure than the higher operating temperature of AGM batteries.

This VRLA battery comparison gives a slight edge to gel cells over AGM batteries, but which gel cell is better? There are two types, "A" and "B". The type "B" deep-cycle gel cell is often

recommended for PV power systems but it is not the best choice for remote low-power PV systems. Phosphoric acid is added to the type "B" electrolyte. This additive inhibits plate shedding and increases the number of deep discharge cycles a battery can endure before failure. Unfortunately, the additive prevents the battery from developing full capacity until it has completed 20 deep discharge - charge cycles or spent a year on float charge. Given the small number of deep discharges expected at low-power PV sites during the life time of the battery, it is unlikely that the type "B" gel cell will ever develop full capacity before other charging problems reduce it. This is only a small flaw since 90% of full capacity is immediately available from the type "B" gel cell but it is enough to make the type "A" gel cell the VRLA battery of choice in low-power PV power systems.

The answer to the question of which battery to use depends on what trade-offs the user is willing to make. VRLA battery electrolytes should never need maintenance but overcharge from poor charge control will destroy a sealed battery when all that a vented wet lead-acid battery requires is a refill with a little water. Vented wet lead-acid batteries cost half as much as VRLA batteries but the periodic need to add water to the electrolyte can remove this cost advantage. VRLA batteries are spill-proof and can be installed in any position but vented wet lead-acid batteries waste no space on glass mats or gelling agents and are smaller and weigh less for the same capacity.

The sealed wet lead-acid Delco S2000 combines many good characteristics of vented wet lead-acid batteries and VRLA batteries. It costs less than a VRLA but has a similar lead calcium plate structure. It is "maintenance-free" and the liquid electrolyte of the S2000 gives it good high-temperature performance. However, the liquid electrolyte requires upright operation to avoid reservoir spills. The electrolyte reservoir takes space so that the S2000 is bigger and weighs more than a vented wet battery of the same capacity although it weighs less than a similar VRLA battery. *Table 5* summarizes the some of the characteristics of batteries considered useful at low-power PV sites.

BATTERY TYPE	ADVANTAGES	DISADVANTAGES
Automotive	Lowest cost, greatest availability.	Low capacity, poor deep discharge recovery, short service life, upright operation.
Vented Wet Deep-cycle RV24, RV27, Marine	Highest energy density, durable, low cost, good availability, can be topped up.	Electrolyte requires topping up, upright operation only.
Sealed Wet "Stationary" Delco S2000	Lowest cost sealed battery, no water replacement, surplus electrolyte, lead calcium grids.	Upright operation only.
VRLA Absorbed Electrolyte (AGM)	Best VRLA high-rate performance, low maintenance, operate in any position, lead calcium grids.	Inferior high and low temperature characteristics, higher float current than gel, requires careful charge control.
VRLA Gelled Electrolyte type "A"	Highest initial gel cell capacity, low maintenance, operate in any position, lead calcium grids.	Requires careful charge control.
VRLA Gelled Electrolyte type "B"	Best VRLA deep-cycle performance, low maintenance, operate in any position, lead calcium grids.	Requires careful charge control, lower initial capacity than type "A".

Table 5. Summary of battery comparison.

4. CHARGE CONTROL

Batteries are often blamed for power system failures, but batteries are only the most vulnerable part of the system. No battery can overcome the faults of a bad charging system. Best battery performance is achieved when the characteristics of the battery are matched to the charging source. This is the job of the charge control system.

Small PV power systems at remote sites face two charge control problems that indoor float systems connected to the power grid do not. First, the amount of solar power is highly variable and influenced by uncontrollable factors such as the weather. Second, the power system may have to cope with temperature extremes. Both of these can cause too much or too little battery charging. Premature battery failure is the result.

A battery becomes **overcharged** when it is forced to accept more current than it can chemically store. This happens either when charging currents are too high or when the battery is fully charged and current continues to flow through the battery. Overcharging damages batteries through electrolyte water loss and grid corrosion.

One of the ways a battery dissipates overcharge current is to use it to decompose electrolyte water. Water is broken down into hydrogen and oxygen gases. This process is referred to as **gassing**. Unless the gases are recycled or the water is replaced, the loss is permanent. In wet batteries, water loss causes plate damage by exposing them to air. If too much water is lost in VRLA batteries, the electrolyte will no longer support sufficient ion current flow or supply the hydrogen and oxygen required by the cell's chemical reactions. In both cases, battery capacity is permanently lost when the electrolyte dries out.

The decomposition of water creates stronger concentrations of acid in the electrolyte and free oxygen. These, together with the heat produced by the excess current, accelerate grid corrosion. When a plate grid corrodes, the lead in the grid is changed to lead dioxide. Lead dioxide requires 37% more space than lead, so the grid expands. As the grid swells, electrical contact with the active material of the plate is lost and the battery loses capacity. Mechanical contact between the grid and the active material is harmed by expansion and active material can fall from the plate (plate shedding). Material shed from plates can form conductive bridges that poke through plate separator pores or accumulate below the plates and short circuit the cell. In extreme cases, grid expansion can cause battery casings to swell and even rupture.

VRLA batteries have an additional failure mode caused by overcharging, thermal runaway. The recombination of oxygen that restores water to the electrolyte produces heat. Unless the heat is dissipated, the battery temperature will rise. The amount of excess current a battery draws from a voltage source has a positive temperature coefficient so there is positive feedback. The battery continues to heat until it self destructs. This is a bigger problem for AGM batteries than for other types because AGM batteries have poor thermal conductivity. However, thermal runaway is unlikely at a small PV site. The solar panels do not supply enough current to sustain thermal runaway unless the ambient temperature is already very high.

The battery industry pays less attention to **undercharging** than to overcharging. Most industrial battery users are connected to the power grid and have the ability to recharge batteries whenever it is required. This is not true for PV systems whose only source of power is the sun. In small PV systems, undercharging is as responsible as overcharging for early battery failure (Hund, 1997, p. 1).

The problem with undercharging is **sulfation**. As a battery discharges, the active material on both plates is changed to lead sulfate. When the battery recharges, the lead sulfate is changed back to active material and sulfate ions return to the electrolyte. Sulfate ions do this easily if they are not part of a larger lead sulfate crystal structure. However, if recharge is delayed, there is time for crystal growth and it can become difficult or impossible to change all the lead sulfate back into active material. Battery self-discharge contributes to crystal growth. By delaying full recharge, undercharging allows lead sulfate to form more perfect crystal structures. In extreme cases, whole plates are blocked by surface lead sulfate crystal barriers and the battery is unable to recharge. Such a battery is said to have "sulfated" because its plates have "hardened".

Batteries gradually lose capacity through sulfation because lead sulfate crystal structures decrease the amount of active material on the plates and the number of sulfate ions in the electrolyte. It is possible to restore some of this lost capacity. Overcharging after full charge can break up lead sulfate crystals. The sulfate barrier of badly sulfated batteries is sometimes broken by applying higher than usual charging voltages. However, immediate full recharge is the only way to avoid losing some capacity to sulfation. This is often impossible at most remote PV sites, so charge control systems should have a way of coping with sulfation.

Electrolyte stratification is an additional undercharging problem for wet lead acid batteries. Electrolytes stratify when denser, more highly concentrated regions of the electrolyte form at the bottom of the cell. Regions of strong acid are more likely to participate in cell reactions leaving upper sections of plates in weaker areas to sulfate while lower sections in strong acid regions corrode. The cure for electrolyte stratification is a controlled degree of overcharge after full charge. The gas bubbles which form during overcharge mix the liquid electrolyte.

If loads remain connected to the battery, lengthy periods of undercharging can lead to extremely deep battery discharge. The battery may never recover from very deep discharge because the high resistivity of the electrolyte at low acid concentrations retards charging. Electrolyte freezing is another problem caused by severe undercharging. Electrolytes with low specific gravities freeze at higher temperatures. Frozen electrolytes expand and injure plates. Sometimes battery casings are cracked by frozen electrolytes. *Table 5* shows the freezing point of electrolytes with different specific gravities.

Batteries are caught between the devil of overcharging and the deep blue sea of undercharging. At PV sites winter undercharge is often followed by summer overcharge and batteries suffer early failure from both. Charge control systems at small PV sites attempt to minimize the damage.

SPECIFIC GRAVITY	FREEZING POINT °C	SPECIFIC GRAVITY	FREEZING POINT °C
1.300	-70	1.180	-21
1.280	-68	1.160	-16
1.260	-58	1.140	-12
1.240	-44	1.120	-10
1.220	-34	1.100	-08
1.200	-25	1.000	0

Table 5. Electrolyte freezing point at various specific gravities (BCI, 1995, Figure 6).

Charge Characteristics

There are two basic ways to charge a battery. One is from a voltage source and the other is from a current source. As previously described, a solar panel is a current source. However, it is necessary to include voltage source charging in this discussion for three reasons. First, line-powered voltage source charging is the way most batteries are charged and is the method recommended by battery manufactures (Johnson Controls, no date, Dynasty Charging Manual, p. 1-2). Second, voltage source chargers are important tools for maintaining batteries. Third, most solar panel charge control schemes rely on voltage sensing to detect the battery's state of charge and share some common characteristics with voltage source chargers.

Figure 9 shows typical current and voltage curves for a medium-power voltage source charging a 100 Ah battery from full discharge. There are three regions of the charge curves. The first region is labeled **Bulk Charge**. In this region the voltage source is in current limit because the battery can accept more current than the charger is able to produce. Consequently the output voltage of the charger is below the charger's constant voltage set point of 14.75 volts.

At the end of the bulk charge period, the charger's output voltage reaches set point. The battery is 80 to 90% charged and can no longer store all the current the charger can produce. This is the **Finishing Charge** region. During this period, the current from the charger decreases rapidly as the plates have less and less lead sulfate to convert to active material. The charger output voltage remains constant. At the end of the finishing charge period the battery is fully charged.

The output of the charger is above the battery gassing voltage so the battery continues to draw current after the finishing charge period even though it can no longer store it as charge. The battery is in overcharge and electrolyte water is decomposing. This is the **Excess Charge** period.
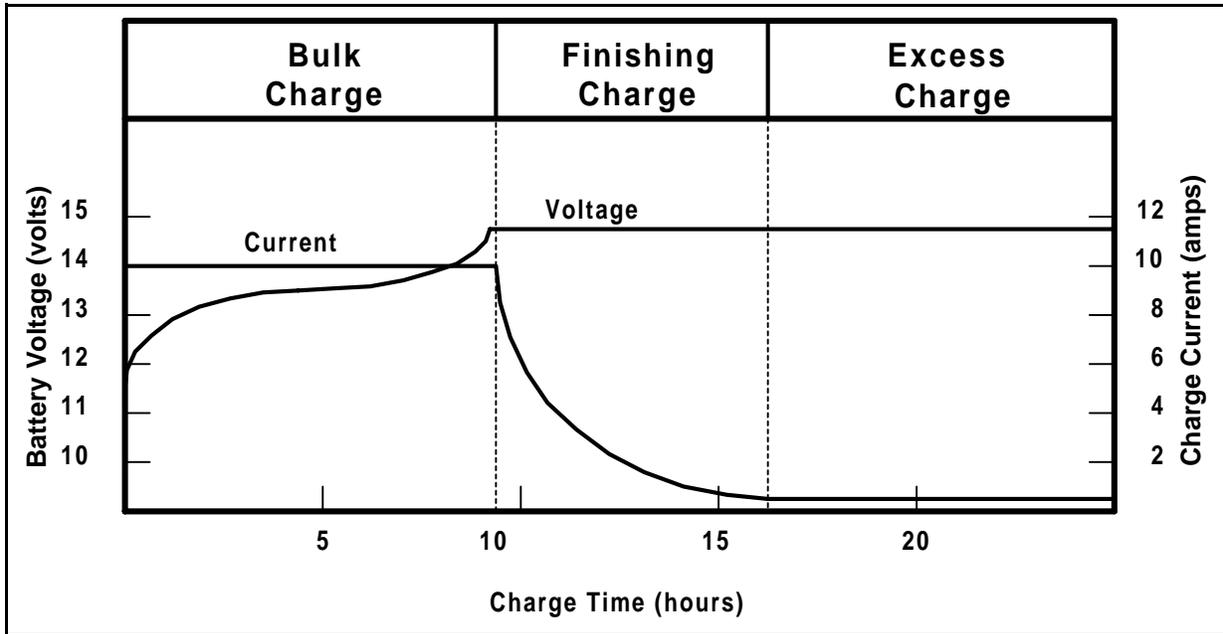
Figure 9. Medium-power constant voltage charger characteristics (Power Sonic, 1996, p. 8).

The degree of gassing depends on factors besides the charger voltage. It depends on temperature and contamination from metals such as antimony. Prolonged charging at voltages higher than the gassing voltage will cause premature battery failure. At room temperature this is about 14.4 volts for a six cell battery. *Table 6* shows the gassing voltage for other temperatures.

Some overcharge is beneficial. It can restore capacity by breaking down sulfate crystals. It mixes stratified electrolytes in wet lead-acid batteries. Battery cells do not necessarily finish charging at the same time. Some overcharge allows time for the charge to equalize among all cells of the battery. Often battery manufacturers specify an equalization voltage for a particular battery type and recommend an equalization charge period of up to 24 hrs (Johnson Controls, 1995, p.1). However, prolonged overcharge dries out electrolytes and increases grid corrosion and should be used with caution.

Various charger designs treat overcharge in different ways. In simple chargers, the battery gases until the user switches it off. Automatic chargers switch off when the full-charge condition is detected and switch on again when self-discharge lowers the battery voltage past a threshold level. Some VRLA chargers change their set point after full charge is detected. There is a "fast charge" to a fairly high output voltage followed by reducing the output below the gassing voltage so that the battery floats at a voltage that allows self-discharge replacement current to flow without gassing.

TEMPERATURE °C	GASSING VOLTAGE 6 CELLS V	TEMPERATURE °C	GASSING VOLTAGE 6 CELLS V
50	13.80	10	14.82
40	13.98	0	15.24
30	14.19	-10	15.90
25	14.34	-20	17.82
20	14.49		

Table 6. Gassing voltage change with temperature (From Linden, 1995, Table 24.19).

Detecting the full-charge condition is the problem with automatic battery chargers. In the previous discussion of the lead-acid cell, it was stated that the stabilized open-circuit voltage, Vsoc, was proportional to the state of charge. Unfortunately, the terminal voltage of a charging battery is not Vsoc. The terminal voltage of a charging battery includes charge rate dependent voltages caused by IR and polarization losses. *Figure 9* shows that the constant voltage charger output reaches its set point value well before the battery is fully charged so this event alone cannot be used to switch the charger. Full charge is detected when the set point voltage is reached and the charging current falls below a preset low level (Power-Sonic, 1996, p. 8). Both conditions must be met for a well designed automatic charger to detect full charge and finish the charge cycle.

Voltage and current sensing of full charge is effective as long as the battery under charge is in good condition. When a badly sulfated battery is charged, its terminal voltage rises rapidly at low charging currents and an automatic charger will switch off before it can remove sulfation and charge the battery. Batteries with shorted cells never finish charging either because the charger set point voltage is never reached or the charge current remains high. It is worth noting that automatic chargers used as float service power sources can cause overcharge when current to the external load is high enough to keep the charger in "fast charge" mode.

Solar panel charge controllers cannot use the full-charge detection method used by automatic constant voltage battery chargers because solar panels are current sources. A solar panel's output current is set primarily by the amount of sunlight on the panel and not by the battery's state of charge. The panel will try to force the battery to accept current regardless of its state of charge. Consequently, it is not possible to use the battery current level to help detect full charge when the charging source is a solar panel.

Figure 10 shows the terminal voltage and state of charge for sealed lead-acid batteries charging at two constant current rates. The voltages shown are scaled up from single cell data and the state of charge shown is the ratio of charge returned from discharge so that different charge rates can be compared directly (from Linden, 1995, figure 25.42). Wet lead-acid batteries show similar curves.

The curve labeled "C/100" corresponds to a 100 Ah battery charging at a 1 A constant current. It shows two well defined slopes as the state of charge increases from zero. The first part of the curve shows a slow increase in voltage as the battery charges. During this time the battery is able to store all the current from the source. At about 95% of full capacity the voltage rises steeply because the battery is running out of lead sulfate to convert to active materials and can no longer store all the current it is forced to accept from the source. Full charge is reached at about 14.7 volts on this steep slope.
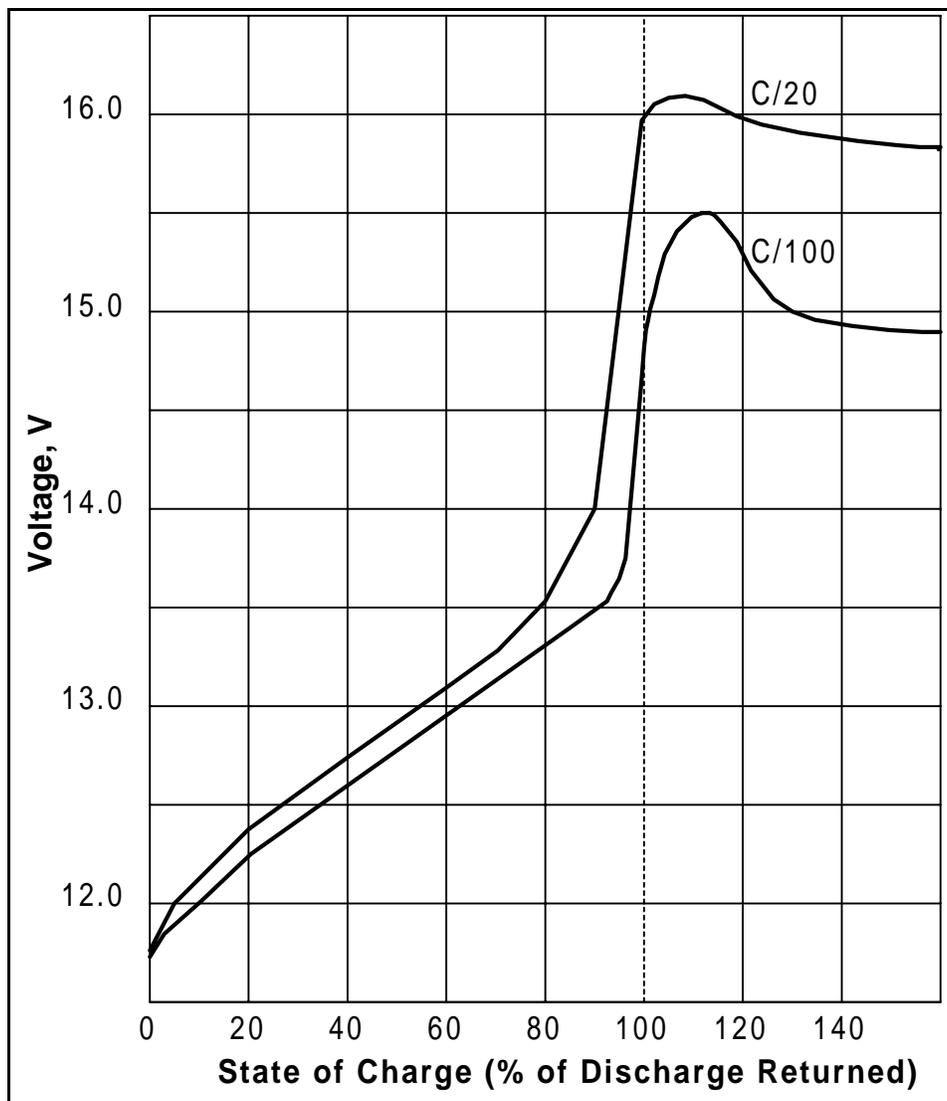

Figure 10. Voltage versus state of charge at two different constant current charge rates.

Compare this to the curve labeled "C/20" which corresponds to a 5 A constant current charge of the same battery. The C/20 curve is at higher voltage because greater IR and polarization losses occur at the higher current. Full charge occurs at a much higher voltage, about 16 volts.

Suppose that a simple controller attempts to switch off current from the source when the full-charge voltage is reached. These two curves show that the full-charge voltage depends on the rate of charge. If the lower curve's full-charge voltage is selected as the switch point then undercharging occurs when charge rates are higher than C/100. If the C/20 curve's full-charge voltage is picked as the switch point, then the higher voltage produces overcharging for lower charge rates.

The paradox of using simple voltage level sensing and a switch for charge control is that larger currents lead to more undercharging and smaller currents to more overcharging. In the field, adding a larger solar panel to a power system with this control system could make an undercharging problem worse.

Temperature is another obstacle to using battery terminal voltage for charge control. The values of voltages on the curves of *Figure 10* are temperature dependent at about -30 mV/°C (-5 mV/°C per cell). Over a ±20 °C temperature range, the full-charge voltage changes ±0.6 volts. A fixed switching voltage will cause undercharging in cold temperatures and overcharging when it is hot.

The full-charge voltage is also determined by the type of lead-acid battery under charge. The difference between the stable full-charge open circuit voltage for an AGM type VRLA and an automotive battery is 0.2 volts. If polarization and IR losses are equal, this is also the difference in their full-charge set point voltages.

Variable charge rates, temperature changes, and battery type make the full-charge voltage into a moving target for solar panel charge controllers. The problem is a serious one because small undercharges cause a progressive loss of capacity through sulfation while repeated overcharges cause accelerated grid corrosion and electrolyte water loss. However, because it is simple to implement, voltage sensing is the usual method used by active PV charge controllers.

Self Regulation

One method of charge control, self-regulation, avoids the problem of detecting the full-charge voltage by avoiding active control of the solar panel. Recall the previous discussion of solar panel characteristic curves. As shown in *Figure 11*, current is constant and depends primarily on light level until a knee is reached and the output current rapidly declines. It is possible to minimize overcharging by making use of this characteristic.

In the early stages of charging, a battery can accept large currents and is a low impedance load on the solar panel. Consequently the battery forces the solar panel to operate in the constant current portion of its curve. Towards the end of charge, the battery can no longer store all the current from the solar panel. This is the same as saying that the impedance of the battery increases and
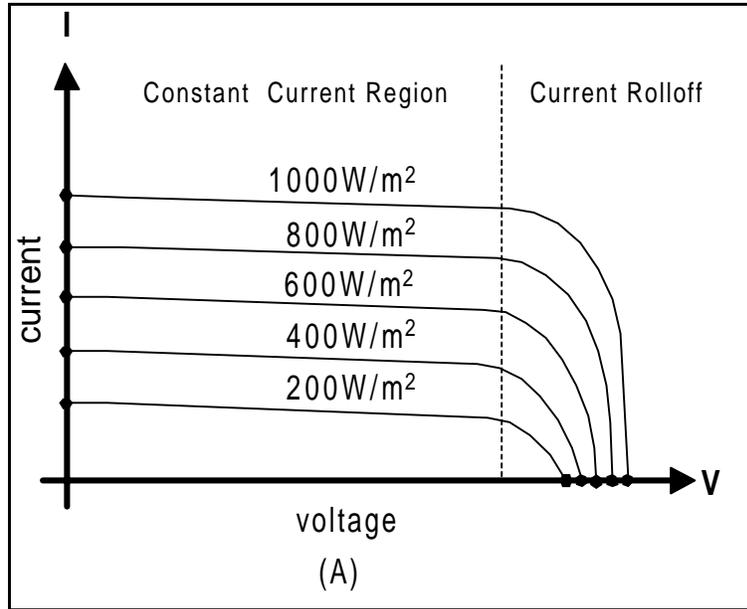
Figure 11. Solar panel roll-off limits overcharge current.

that the operating point of the battery shifts along the curve of the solar panel. The system will regulate if the solar panel current can be made to decrease as the battery finishes charging. The voltage at which the solar panel current rolls off depends on the number of solar cells in series. By selecting a panel with the right number of solar cells, overcharge is limited by the panel.

The Siemens M20, M35, and M65 solar panels are designed for self regulation (Siemens, 1990, p. 7). They use 30 cells in series to produce a current roll-off in the 14 to 16 volts region. These panels can be directly connected to the battery. Usually a diode is placed between the solar panel and the battery to block the small discharge through the panel at night. This biases the panel one diode drop above the battery and causes the current roll-off to begin at a lower battery voltage.

There is no set point voltage with self regulation. The panel is never switched off. Consequently, the battery recharges fully in the shortest possible time for the panel size. The battery voltage rises as a product of battery impedance and the current available from the solar panel. Batteries that have high impedances because of sulfation will receive the higher voltages necessary to breakdown sulfate crystals and recover from winter undercharging.

When the battery is fully charged and charging continues above C/500, the overcharge will reduce battery life. Solar panel output is not continuous, so higher intermittent end of charge currents can be tolerated. A slight overcharge is better than undercharging and does little harm to vented wet lead-acid batteries if they are refilled with water before the plates become exposed. Sealed batteries suffer permanent water loss and should only be used with self-regulating PV systems if the overcharge is known to be small.

Solar panel and battery temperature coefficients tend to track (Horowitz and Hill, 1989, p. 933). The solar panel open-circuit voltage changes at about -0.33%/°C. The temperature coefficient for the float voltage of a charged battery is -0.18%/°C. This increases to -0.25%/°C for a battery that is actively charging.

The solar panel current roll-off is not a precise regulating mechanism. Consequently, the battery capacity and solar panel charging ability must be matched. If battery capacity is too large relative to the solar panel output, then undercharging will ruin the battery through sulfation. Too much solar panel output produces electrolyte water loss and grid corrosion. In very hot climates, the temperature coefficient of a 30 cell panel can produce undercharging in bright sunlight because the panel operates too far down the roll-off of its characteristic curve.

Self regulation is not used as often as active charge control. The match between battery and solar panel can be upset by variations in current draw from loads and changes in weather patterns that alter available sunlight and temperatures.

Active Charge Control

Almost all PV charge controllers use current switching rather than linear voltage regulation. Series linear voltage regulators are inefficient when a battery is bulk charging and this increases the time it takes to recharge a battery. Linear shunt voltage regulators, such as zener diodes, must be able to dissipate the full solar panel output power when the battery is fully charged and require high power devices with heat sinks. Switched-current charge controllers allow current to flow from the solar panel to the battery with minimum loss and dissipate little power when current flow to the battery is stopped.

Small PV charge controllers use either series or shunt switches to route current. A series switch is located in the current path from the solar panel to the battery and closes when charging is desired. This is shown in *Figure 12 (A).* A shunt switch connects across the solar panel output. It short circuits the solar panel when it closes and opens to charge the battery as shown in *Figure 12 (B).* Many small controllers with output currents less than 10 amps use shunt-switching because of lower circuit cost. Proponents of series-switching controllers claim that their greater reliability is worth the expense (Gerken and Welsh, 1997, p. 12).

No matter what type of switching is used, all switching charge controller designs have the problem of set point uncertainty caused by the dependence of the full-charge voltage on variable solar panel charge rates and temperature. What follows is a description of three charge control schemes that try to solve this problem in different ways.
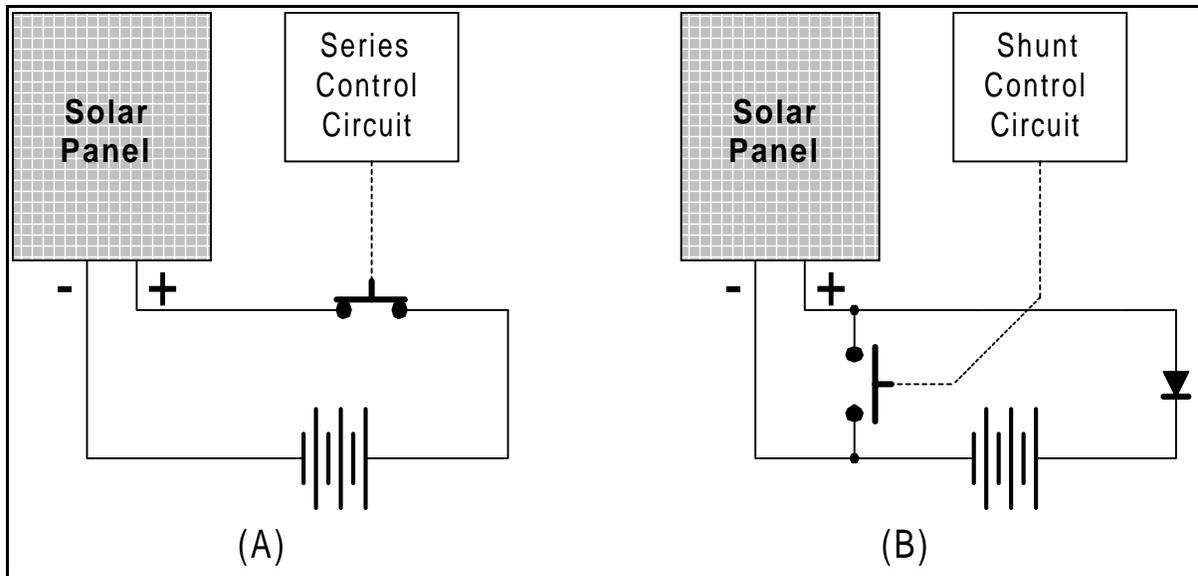
Figure 12. Solar panel current control switches. (A)The series switch is closed to charge the battery. (B) The shunt switch is open to charge the battery. The switch element is usually a field-effect transistor.

ON/OFF Controllers. One of the most popular type of charge controllers uses a simple ON/OFF shunt switch. The state of the switch is determined by two voltage thresholds. When the battery is bulk charging, the switch is open and the full solar panel output is applied to the battery through a diode as shown in *Figure 12 (B)*. When the upper threshold is reached, the switch closes and short circuits the solar panel depriving the battery of charge current. The battery discharges through the load until the lower threshold is reached and the switch opens allowing the battery to charge once again.

During the day, this controller cycles between the upper threshold and the lower threshold as it attempts to keep the battery near full-charge *(Figure 13)*. For a battery in good condition, the cycle rate depends on the load current, temperature and solar panel output current. It usually requires several minutes to cycle between these two levels. Damaged batteries have large polarization or IR losses and cycle more quickly. The upper threshold is typically 14.3 volts, which is just below the gassing voltage at room temperature. The lower threshold is typically 13.2 volts.

The ON/OFF control method prevents overcharging and gassing but at charge rates greater than C/100 it is unlikely that the controller will ever fully charge a battery. The upper switch point is too low and is not held long enough to develop a finishing charge. As seen in *Figure 10*, a battery under modest charge has a higher full-charge voltage than 14.3 volts. The lower threshold of 13.2 volts is too low. It is below the float voltage for VRLA batteries so these batteries will actually discharge stored chemical energy in full sun while the solar panel output current is cut off. This is
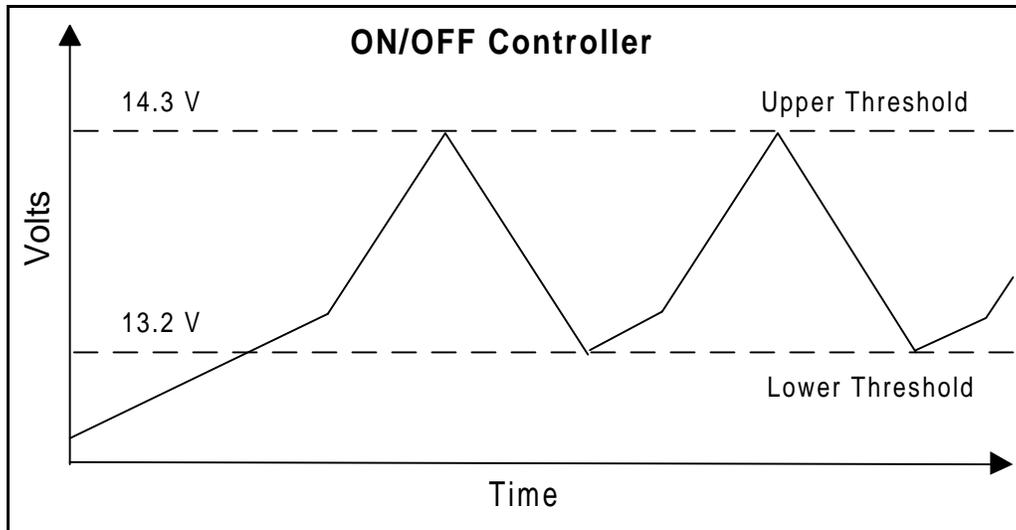
Figure 13. ON/OFF controller voltages**.**

not very efficient. ON/OFF charge control does not do a good job of recovering capacity from sulfation because the controller stops charging as soon as the upper threshold is reached and there is little time for sulfate crystals to break down.

One study estimates that batteries with ON/OFF charge control systems average between 55 and 60% of full charge (Gerkin and Welsh, 1997, p.24). This is a serious undercharge condition which will lead to premature battery failure (Hund, 1997, p.1). Temperature compensation and adjustable thresholds are sometimes offered as options but they do not overcome the main flaw in this control system. The problem is that solar panels are variable current sources but the upper voltage threshold is correct for only one charge rate.

Dual Set Point Controllers. Dual set point controllers have a more complex control action than ON/OFF controllers. The controllers are similar during bulk charging. Both apply full solar panel output to the battery until an upper battery voltage is reached. But unlike ON/OFF controllers, this voltage is a set point and not a switching threshold *(Figure 14)*. When the set point is reached, dual set point controllers hold this voltage for a fixed period by cycling the solar panel on and off. This allows time for the battery to finish charging.

After the finishing charge period, the battery voltage drops to a second set point. The second set point is at the battery float voltage. Once the float voltage is reached, the controller turns the solar panel on and off to maintain this voltage and supply current to the load without discharging stored chemical energy. If the solar panel output is too low and the controller is unable to hold the battery at the float voltage, the controller applies full solar panel output to the battery until it charges to the upper set point. This is how the controller resets itself.
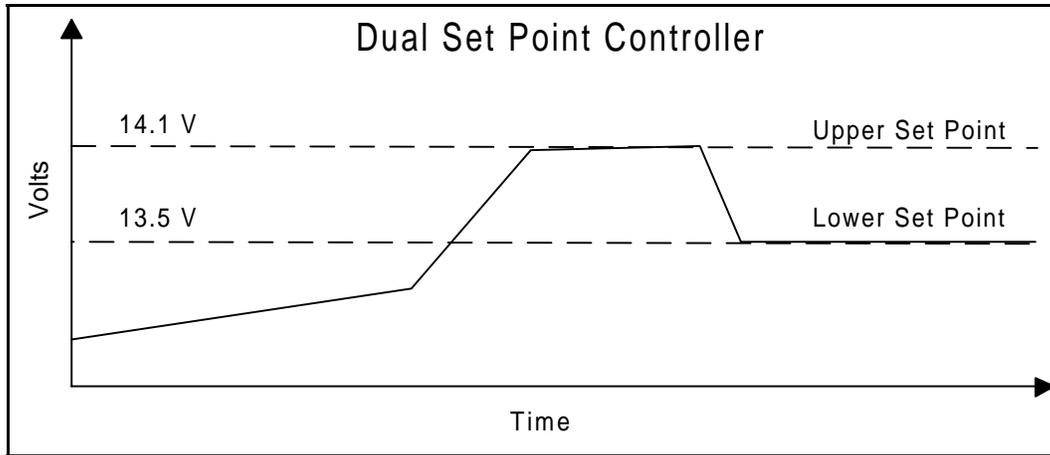
Figure 14. Dual set point controller voltages.

The C12 from Trace Engineering (5916 195th NE, Arlington, WA, 98223, USA), is a dual set point controller. In addition to the control action described, it has some other important features. The set points are adjustable and can be varied with the type of battery used. This recognizes that wet lead-acid batteries have lower float voltages and can tolerate higher upper set points than VRLA batteries. There is a programmed monthly overcharge for vented wet lead-acid batteries that restores capacity lost to sulfation, mixes stratified electrolytes and equalizes the charge among cells. The unit includes a low voltage disconnect that switches off the load when the battery reaches its cutoff voltage and prevents extremely deep battery discharge. Temperature compensation is an option.

Constant Voltage Controllers. Constant voltage PV controllers set out to mimic the current and voltage response of constant voltage source chargers. A solar panel is a current source and its output current does not diminish when battery impedance rises as it approaches full charge. So the controller does the job and decreases the current after the battery reaches set point. This is done through pulse-width modulation. The duty cycle of the pulse is adjusted to keep the battery voltage at the set point while supplying current for the load. As shown in *Figure 15*, this set point is held constant as the battery finishes charging and the average current tapers off as the ability of the battery to store charge decreases (Gerkin and Welsh, 1997, p. 26).

Careful set point selection and regulation is necessary for this control method. The set point is chosen to be above the battery float voltage but below the gassing voltage. The set point is above the float voltage to make sure that the battery reaches full charge quickly. It must remain below the gassing voltage to limit overcharge to acceptable levels. As a consequence, set point control must be accurate and temperature compensated.
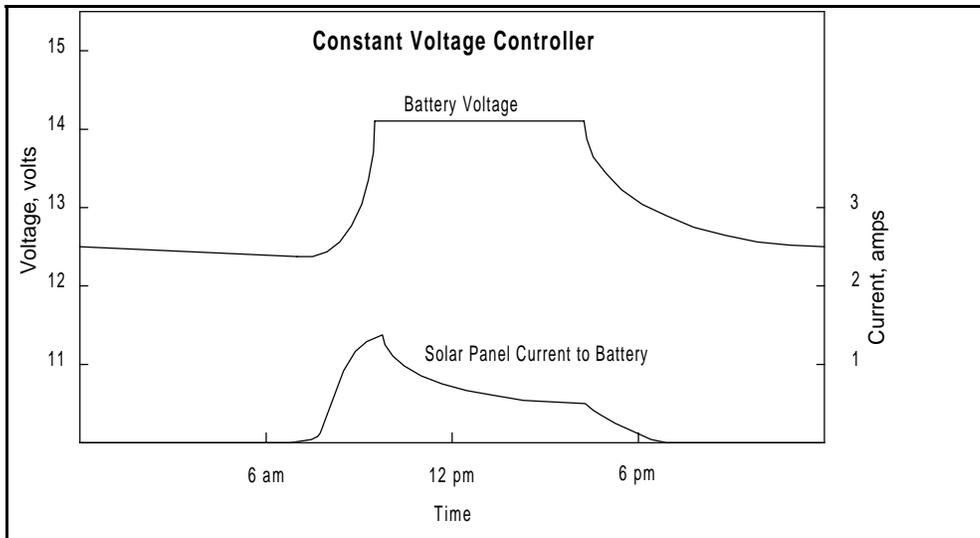
Figure 15. Typical Constant Voltage Charge Controller current and voltage control characteristics (From Gerkin and Welsh, 1997, Figure 7).

Pulse-width modulation is said to restore lost capacity by increasing charge acceptance and that lead sulfate crystals may be broken down by pulsing at the set point (Gerkin and Welsh, 1997, p. 26). These benefits from pulse charging may or may not apply at low-power instrument sites but the slight overcharge from these controllers will help to equalize cells and remove sulfation.

The Morningstar Corporation (1098 Washington Crossing Road, Washington Crossing, PA, 18977, USA) makes two constant voltage PV controllers, the ProStar and the SunSaver. The ProStar is a microcontroller based design while the SunSaver is a simpler design intended as a less expensive, rugged controller for small unattended PV systems. It comes with battery type selection that changes the set point for VRLA or wet battery operation. The VRLA battery set point is at 14.1 volts to reduce gassing but is raised to 14.3 volts for the more tolerant wet lead-acid battery. Temperature compensation is provided and most models come with low voltage load disconnection.

Charge Control Summary

The problems of ON/OFF charge controllers are now recognized (Gerkin and Welsh, 1997, p. 3). The US Department of Energy has funded the Photovoltaic Balance of Systems Program to try and improve PV systems. Design of the Morningstar SunSaver was partially funded under this program.

Dual set point controllers like the C12, and constant voltage controllers like the SunSaver, are welcome developments. How much improvement in battery life they will bring to remote instrument sites remains to be seen, but in most circumstances these new charge control methods should do a better job than the ON/OFF controllers of the past.

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All switching controllers can produce noise in load circuits. Aside from the circuit noise of the controllers, there is an unavoidable noise source that arises from current switching through the combined resistance of the external wiring and the internal resistance of the battery. Usually this resistance is a few tens of milliohms but even this amount of resistance produces tens of millivolts when 1 A is switched. The low resistance of the noise source makes it hard to filter and "battery capacitance" does not remove it. This low-level noise voltage is not a problem if the load circuits are well regulated. However, some older equipment designed for operation from primary batteries has no regulation and is sensitive to this noise. The 300 to 400 Hz pulse rate of the SunSaver is particularly annoying when it modulates unregulated radio telemetry transmitters.

Self regulation with lower voltage solar panels and vented wet lead-acid batteries is a good option when sites are visited at regular intervals. The advantage of this method is that there is no controller to buy and maintain and there is no switching noise. A self-regulating system with a small overcharge can be constructed that will operate for up to two years without refilling the batteries with water. However, if longer unattended operation is desired or VRLA batteries are used, it is best to use one of the newer dual set point or constant voltage controllers.

5. SITE FACTORS

Ideally, we would now be in a position to specify the components of a small PV power system. From the site's latitude and climate, we could calculate the irradiation expected during the year. Given the load, a simple formula could be used to select a solar panel and battery. Unfortunately the conditions at most remote instrument sites are far from this ideal. Sites are usually selected for some other purpose than providing the best possible solar power conditions. Vegetation and terrain block solar panels. Weather is frustratingly local rather than grandly "climatic". A hundred meters of elevation can mean the difference between good solar conditions and persistent cloud cover.

Experience can be a more reliable guide than calculations. Successful sites are the prototypes for similar sites that can be further adapted to meet local conditions. As an alternative to calculations, this discussion will turn to those site factors that most influence PV power system performance. Understanding site performance is required to adjust a site to changing conditions or modify the system for a new location. If no previous experience with a site is available, then start with a 30 watt solar panel and a 100 Ah battery for each 2 watts of average load. Use one of the newer charge controllers. Self regulation is not for the inexperienced unless the site is visited regularly.

Solar Panel Output

Aside from uncontrollable factors like the weather, the field performance of a solar panel is dictated primarily by the path of the sun and the **orientation** and **tilt** of the panel. In most cases it is desirable to maximize the panel output. Maximum output is found when the panel is oriented to face the equator and the tilt of the panel is adjusted for latitude according to *Table 7*.

LATITUDE	ANGLE FROM HORIZONTAL
0 - 4°	10°
5 - 20°	Latitude + 5°
21 - 45°	Latitude + 10°
45 - 65°	Latitude + 15°
65 - 75°	80°

Table 7. Solar panel tilt angles for various latitudes (Solarex MSX-Lite, 1988, p.3).

There are situations in which the recommended orientation and tilt do not give the best result. Sometimes, it is better to mount panels in a more vertical position than the recommended tilt angle if the steeper slope clears the panel more rapidly of snow, dust, or volcanic ash.

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Features of the visible horizon may require a different panel orientation if terrain or immoveable objects like buildings block the sun. Aim the panel so that it faces the sun for the longest possible time at all seasons of the year.

The amount of energy collected at a site depends directly on the size of the solar panel aperture and the length of time the sun is in the aperture. Changes from recommended values of tilt and orientation may require the use of more or larger panels to replace lost aperture. For example, a solar panel deployed in the tropics during a volcanic eruption is mounted at a tilt of 60° from horizontal so that ash slides from it. This is about a 60° angle of incidence when the sun is at its maximum height at low latitudes. As stated in the previous discussion on solar panels, the effective vertical dimension of the aperture is proportional to cosine of the angle of incidence as shown in *Figure 4*. This tilt angle decreases the aperture of the panel by about half (cos 60°). A second panel at the same tilt is required to compensate for lost output.

If there is any choice in the matter, locate solar panels on hilltops or on hillsides that face the equator. This becomes more important as the latitude increases because of the lower angle of the winter sun. Sites that have abundant sunlight in the summer can have almost no solar panel output in the winter if they are on the wrong side of hills or ridges. Sites located in craters have shortened days because of the high visible horizon at all times of the year and may require larger solar panels to compensate.

Local obstructions like snow, dust, or vegetation can reduce solar panel output to near zero regardless of the amount of sun at the site or the size of the panel. If possible, avoid places where recurrent local obstructions are likely. Hill and ridge tops have lower accumulations of snow and are more likely to have winds that will blow snow or dust from a solar panel than a more sheltered place. However, rime ice can block panels in windy locations during wet freezing weather. Vegetation that shades solar panels must be periodically removed.

Battery Performance

The chemical processes that store and release energy are temperature sensitive and battery performance in the field depends on temperature. Charge and discharge rates, capacity, and service life are all strongly influenced by temperature. Low-power instrument sites do not produce big charge or discharge currents so the influence of temperature on current rate performance is unimportant. However, charging efficiency is poor when batteries are cold but increased solar panel efficiency at lower temperatures partially compensates for this.

The effect of temperature on battery capacity at the C/20 discharge rate is shown in *Table 8* (Johnson Controls, no date, Figure 1). Above 20 °C, capacity increases 4% for each 10° rise in temperature. Below 10°C, capacity drops off more and more quickly as temperature decreases. At -35 °C, half of a battery's capacity is lost.

TEMPERATURE °C	50	40	30	20	10	0	-10	-20	-30	-40
CAPACITY %	112	108	104	100	94	86	78	67	56	45

Table 8. Capacity versus temperature at C/20.

At discharge rates lower than C/20, batteries have more than their nominal capacity. Batteries are more efficient at low currents because lower discharge rates produce lower internal losses. Capacity, for discharges less than C/20, increases by about 10% each time the discharge rate decreases by half. At C/640 this is an increase of 50%.

At low-power instrument sites, the loss of capacity with falling temperatures is offset by increased capacity because of small loads. Consider a 100 Ah battery operating at -35 °C providing 150 mA to its load. This discharge rate is about C/640 so a 50% increase in capacity is expected but the low temperature reduces capacity by the same amount and the battery produces 100% of nominal capacity. In fact, when evaluating low-power PV system battery capacity at low temperatures, it is good to assume that nominal capacity is available.

Operation at temperatures over 20 °C causes an increase in capacity in comparison to the nominal value but at the cost of reduced service life. Higher temperatures increase chemical activity including corrosion and sulfation. In general, battery life decreases by half for each 10 °C above 20 °C (Power Sonic, 1996, Figure 11). Over time, the loss of capacity from increased corrosion and sulfation offsets the gain in capacity caused by higher temperatures. Once again it is best to use nominal capacity for estimating battery requirements rather than making a positive adjustment for higher temperature.

Temperature is an important factor when comparing the performance of different sites. Reduced capacity due to cold may explain power system faults when similar sites in warmer locations do not fail. On the other hand, cold slows self discharge and sulfation, and batteries are more likely to recover if a prolonged discharge occurs at low temperature. Operation at high-temperature shortens battery life, which should be considered when planning battery replacement.

Additional Power and Storage

The typical low-power instrument site has one solar panel and a single battery. However, site conditions such as low irradiance, cold temperatures, or larger loads can require additional power input or storage.

One of the most common small PV system problems is power failure during seasonally bad weather. Adding more lead-acid battery storage capacity to "get the site through the bad period" is often perceived as the solution to this problem. As often as not this is a mistake. Small PV

systems require a balance between power input and storage. What goes out of the system must be replaced. The problem with too much storage is a long recharge period and premature battery failure due to sulfation. In general, it is unwise to increase lead-acid battery storage without increasing the ability of the site to collect solar energy. Enlarging the total solar panel aperture with bigger or more solar panels provides more output in low light conditions as well as shortening recharge time when conditions improve.

A small PV system can be expanded by installing a larger solar panel and connecting additional batteries in parallel. However, there are advantages to expanding the power system by connecting the extra battery and solar panel as a separate charging system. *Figure 16* shows two independent PV systems both connected to the load through diodes. Charge controllers are not shown but may be connected between the solar panel and the battery. The diodes act like switches allowing the battery with the most positive voltage to supply current to the load. There are three advantages to this arrangement. First, the systems are isolated from each other. Failure on one side does not affect the other. Second, solar panel mounting is flexible. The panels can be given different orientations to optimize energy collection and two smaller panels on separate mountings suffer less from wind loading than a single large panel. Third, the batteries are charged separately rather than in parallel.

Charging batteries from separate sources produces better charge control because the solar panel output can be controlled to meet the particular requirements of a battery. When batteries are recharged in parallel, current divides between them with the most current going to the battery with the lowest impedance. This delays the recharge of the other batteries and increases the chance of permanent sulfation. Connecting different types, sizes, and ages of batteries in parallel makes the situation worse.
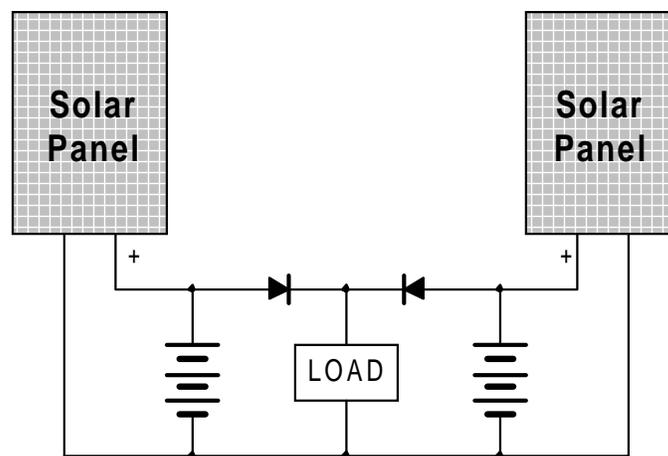

Figure 16. Independent charging systems.

The advantages of independent solar charging systems may or may not suit a particular installation but the technique of switching separate power sources through diodes is useful in a variety of circumstances. At some sites, the seasonal reduction in sunlight is so great that adding more solar panels is insufficient to provide uninterrupted operation. In these cases, power must be taken from another source. Primary batteries are frequently used for back up power. These are usually large zinc/air or air/alkaline batteries also known as "air cells". These air cells store 1000 to 1200 Ah and can preserve their energy while idle for long periods.

Figure 17 shows a combined PV and air cell power system. The nine air cells are connected in series to produce about 12 volts. One of the benefits of this combination of PV and primary battery power systems is that the discharge of the lead-acid batteries is limited by the primary batteries. The lead-acid battery will discharge only until its voltage equals that of the primary batteries. Consequently the lead-acid battery is prevented from deep discharge and remains in good condition, able to quickly recharge and supply power when there is enough sunlight.
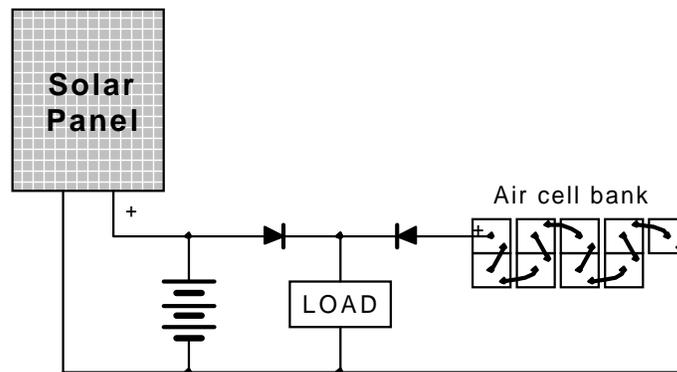

Figure 17. Solar power system with "air cell" primary battery backup system.

Diode switching is not limited to two power sources and can be used to connect a variety of power systems. Line powered DC supplies, thermoelectric generators, and wind power generators can all be coupled to low-power loads with diodes. The source with the highest output voltage powers the load. The diode switch consumes some power but the loss is at roughly constant voltage and therefore is a fixed fraction of the total power drawn by the load. A Schottky diode dissipates only about 2 to 4% of the total power. Usually this is not a large price to pay for making additional power available when it is needed. Only the diode that is ON dissipates power so there is no penalty for connecting several systems. Load currents are limited by diode ratings. The 1N5819 is a 1 amp Schottkey diode while the 1N5820 is rated at 3 amps.

Overcharge from too much solar panel input is a problem for self-regulated PV systems but is not a concern for systems using charge controllers. The newer charge controllers along with more powerful solar panels offer a solution to the undercharging that afflicts many small PV systems. Better charge control means that batteries are in good condition and fully charged when they begin seasonal periods of low light. More energy, from larger solar collection areas, shortens the

length of time that batteries are undercharged, while effective charge control avoids overcharging from more powerful panels during sunny periods. Many of the new charge controllers provide low voltage disconnection of the load. This prevents very deep discharge which damages batteries and increases their recharging time.

In spite of their bulk and weight, batteries are the most fragile component in a low-power PV system. Every system fault damages the battery. Because of this, batteries offer the best clues to system performance. These clues can be discovered in the process of maintaining the system and through systematic battery testing. There may not be instruments to measure and log the solar energy input at a site, but knowing whether a battery failed from undercharging or overcharging provides the information required to modify the site's power system.

6. SYSTEM MAINTENANCE

Approaches to maintenance vary between two extremes. Some say, "Don't fix it if it ain't broke." Others aim at zero failures through complete preventative maintenance. Where a maintenance program sits in this range should depend on the balance between the consequences of site failure and the time and money which can be spent on maintenance. The battery maintenance program of a large public utility is going to be different from that of a small scientific project. What follows is aimed at the small end of the scale. Good maintenance practices are required in this situation to minimize costs and down time even though zero failure preventative maintenance is not a cost effective option.

Safety

Lead-acid batteries pose several hazards. They are heavy. The 100 Ah batteries often used in this application weigh between 23 and 32 kg (50 to 70 lbs). The electrolyte is sulfuric acid and highly corrosive. The gases released during charging are explosive and some batteries release the toxic gases arsine and stibine (Linden, 1995, p. 24.80)

Some simple precautions can make working with lead-acid batteries much safer.

- Use correct lifting and carrying methods.

- When working with wet lead-acid batteries, wear protective clothing and safety glasses and have a supply of fresh water nearby for flushing acid from eyes, skin or clothing. Get immediate medical attention for acid contact with eyes. Spills can be neutralized with a 100 g/l solution of bicarbonate of soda (baking soda).

- Always charge batteries in a well ventilated area and avoid making live connections or disconnections which could produce a spark.

Further safety information is available in the manuals and data sheets supplied by battery and charging equipment manufacturers. In some countries, including the USA, batteries are classed as hazardous materials for transportation by aircraft and require special handling.

Field Maintenance

Field sites operate in a wide variety of conditions, so this description is necessarily general. Special situations, such as extremes of temperature and humidity, may well require measures not mentioned here. No matter where a site is located, it is essential to examine wiring and exposed electrical connections. Wiring strain reliefs should be checked and wire runs securely tied down to prevent wind damage. Electrical connections must be tight and free of corrosion. If corrosion is a persistent problem, steps should be taken to control it. Grease, battery sealant, and clear acrylic sprays can all be used to seal connections. If crimp connections are corroding, make new connections and seal them with solder.

Solar Panel Field Checks. Inspect solar panels for physical damage. Panel mountings should orient the panel with the correct direction and tilt to maximize energy collection. The panel fastenings should be tight. Clear obstructions such as vegetation, snow and ice, or dust.

If the sun is shining, the electrical operation of the solar panel can be checked by measuring its open-circuit voltage (V_{OC}) and the short-circuit current (I_{SC}). Disconnect the panel from the charging system and measure the open-circuit voltage. As discussed previously, the open-circuit voltage will vary with the number of cells in the panel, the panel temperature and the amount of light on the panel. The operating temperature of the panel in full sun with no wind is often well above the ambient temperature which can reduce the expected open-circuit voltage by as much as 3 volts. The voltage measured when the sun is bright and shining on the panel is approximately

$$V_{OC} = 0.6 \text{ V} \times \textbf{(the number of solar cells in the panel)}.$$

The short-circuit current is measured by putting a meter with a suitable current range across the panel or using a low value resistor as a load and measuring the voltage across it. A one ohm resistor provides a simple voltage to current scaling. If bright sun is shining within 45° of directly over the solar panel then it should produce a short-circuit current of about

$$I_{SC} = 0.05 \text{ A} \times \textbf{(watts of STC rated power)}.$$

In the field, V_{OC} and I_{SC} measurements will vary considerably with the amount of light on the panel and temperature. However, it is usually possible to use them to decide if a solar panel is functioning correctly.

Charge Controller Field Tests. Correct operation of a charge controller is verified by observing its control action. If the battery is fully charged, a controller will cycle around its set point(s). Do not rely on controller LED indicators. Observe controller switching by looking at the voltage across the solar panel when the controller is cycling. *Figure 12* shows the two types of controller current switching. When a shunt-switching controller stops charging the battery, it short circuits the solar panel driving its voltage to a low value. When a series-switching controller removes charge current, the switch opens and the solar panel voltage increases to its open-circuit value. Pulse-width modulation for PWM controllers can be seen with an oscilloscope or AC voltmeter across the solar panel input to the controller.

If the battery is not fully charged, the controller should provide a low resistance path to the battery. The battery voltage and the solar panel output voltage should be about the same. For shunt type controllers the solar panel will be a Schottky diode drop, 0.3 V above the battery voltage. Series switches show very little difference between battery and panel voltages. Excessive voltage differences between the battery and the solar panel while charging indicates a faulty controller switch element. If the controller indicates that the battery is fully charged, discharge it slightly and observe the battery and solar panel voltages during the recharge.

Battery Field Checks. Inspect lead-acid battery casings for damage. Cracks or signs of swelling

indicate that the battery has frozen or that serious overcharging has caused extensive grid corrosion. Whatever the cause, a battery with a swollen or cracked case must be replaced.

Check the electrolyte levels in wet lead-acid batteries and fill the cells with clean water to the correct level. If plates are exposed above the electrolyte then the capacity of the exposed plate areas has been lost and cells will likely develop short-circuits because of plate shedding. Batteries with exposed plates should be replaced and tested in the shop.

It is important to clean at least the top of the battery. Dirt, corrosion and moisture between battery terminals can combine to form conductive paths and discharge the battery. Use clean water or sodium bicarbonate solution to remove dirt. Scrape corrosion from battery terminals and the wiring that connects to them. Use battery sealer or petroleum jelly to control terminal corrosion. Sealers prevent the gases which form during battery charging from reacting with terminal metals to produce acid salts which contribute to leakage paths across the battery.

While a battery is connected to the charging system, its voltage indicates little about the condition of the battery. Batteries accumulate surface charge even when they are incapable of chemically storing electrical energy. To check a battery in the field by measuring its voltage, disconnect it from the charging system and apply a moderate load for enough time to bleed off the surface charge. A 40 watt, 12 volt, soldering iron is a useful piece of field equipment and is a good load for testing batteries. The hot iron can also be used for repairing wiring while the battery is under test.

To perform the field test, connect a voltmeter to the battery and disconnect the charging system. Connect the test load to the battery and observe the change in voltage. The voltage will decrease like a capacitor discharging through a resistor as the surface charge is removed. When the battery begins to release chemically-stored energy, the voltage will stabilize and may increase slightly for a short time.

The voltage at the point where the discharge of chemically-stored energy begins depends on the battery type, its condition, temperature, state of charge and the size of the load. In uncontrolled field conditions, this loaded voltage test cannot produce a decisive result. However, with a test current of 3 to 4 A, a battery which is half-charged and in good condition will stabilize above 11.6 V. A good, fully charged, VRLA or wet deep-cycle battery at moderate temperatures will stabilize above 12.2 V; an automotive battery in the same condition above 12.0 V.

Leave a 3 to 4 ampere test load connected for about 15 minutes for a 1% discharge of a fully charged 100 Ah battery. If a temperature-controlled soldering iron is used as a load, it will cycle ON and OFF around its set point temperature and the battery voltage will change as the iron switches. It takes a temperature controlled iron longer to draw 1% of capacity than a continuous load.

At the end of the test period measure the loaded voltage. Disconnect the test load and observe the increase in battery voltage as it recovers from the discharge. There is an immediate increase in voltage because there is no longer an IR loss from load current flowing through the battery. This

is followed by a slow rise in voltage as the battery recovers from polarization losses. After a minute, the total voltage increase should be less than 1 volt from the loaded value. Large changes between loaded and unloaded voltages indicate a battery in poor condition that should be replaced and tested in the shop.

Reconnect the charging system to the battery and observe the rise in battery voltage as the battery recharges. After the initial rise in voltage when the charging system is reconnected, a slow increase in battery voltage indicates chemical storage of charge is occurring. A quick increase in voltage to the upper set point of the charging system indicates a sulfated battery. Remove badly sulfated batteries for shop tests and servicing.

Battery voltage field checks are strongly influenced by uncontrollable factors, consequently there is no simple interpretation of the results. The question is, "Do the measurements show a correctly functioning power system given the operating conditions?" For example, if the battery undergoes seasonal discharge, expect voltage measurements to be different in early spring than they are at the end of summer. If a battery is operating correctly, then the slow voltage changes which occur when energy is moving in and out of chemical storage during charge and discharge should be observed. This does not show that the battery has full capacity, only that it has some capacity.

Knowledge of battery age and site history can help determine if it is time to replace a battery. If the battery is old and the site has a record of intermittent failure, reduced battery capacity is indicated and the battery should be replaced despite field voltage test results. In fact, it is a good idea to always replace the battery at a site where power failure is suspected. Knowing that a site has a good battery assists further troubleshooting. The battery that was removed can be tested in the shop and if it is good, serviced and used elsewhere.

Backup Systems. If a site has a backup power system, it should be disconnected while the solar power system is checked. Then test the backup system by using it to provide power and make the appropriate measurements.

Typically the backup system is a bank of zinc/air primary cells, often called "air cells". The older type of wet air cell has a clear plastic case that allows the zinc bars, electrolyte, and the lime bed to be viewed. The zinc bars are at the top of the cell and decrease in size as the cell discharges from use or aging. The electrolyte should cover the bars. The lime bed, at the bottom of the cell, is white when new and darkens as the cell discharges. The remaining capacity of the cell can be estimated from the size of the bars and the color of the lime bed. Air cell electrolyte levels decrease because of evaporation. Fill the electrolyte with clean water when necessary. Use gloves because the electrolyte is caustic potassium hydroxide.

Newer versions of the air cell have a gelled electrolyte. It does not require a lime bed, and the zinc is powdered and mixed with the electrolyte. These gelled air cells are smaller and easier to use than the wet type but it is not possible to estimate remaining capacity by inspection. *Figure 18* shows the discharge characteristic of a gelled air-alkaline cell and a gelled zinc-air cell. In addition to zinc, the air - alkaline cell uses manganese dioxide to improve the cell's pulse
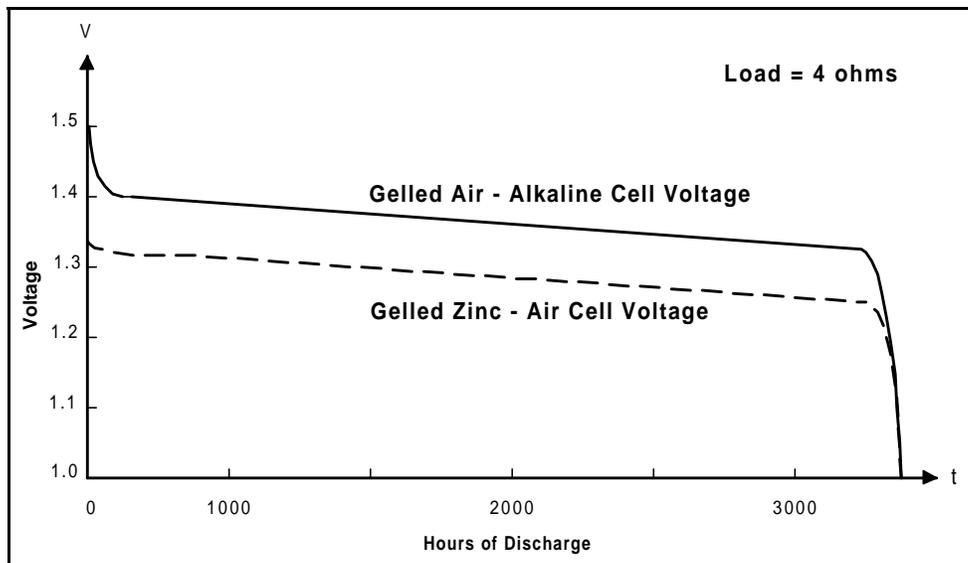
Figure 18. Gelled air cell discharge characteristics, 20°C (From Linden, 1995, Figure 38.9 and Celair Corp, no date, AS10-2 data sheet).

discharge ability. The effects of the air-alkaline hybrid cathode are shown in the discharge curve by the initial drop from 1.5 V and in the higher discharge voltage. However, at low discharge rates the chemistry of the hybrid cell is essentially the same as the zinc-air cell and produces similar capacity (Linden, 1995, p. 38.10). Reduced voltage under load is the only sign that it is time to replace these cells.

Shop Procedures

Batteries are too often neglected when they are no longer in the field. The temptation is to leave the battery in the truck or in the corner of the shed until it is needed for the next field visit. Then the battery is plugged into a high-rate charger while the rest of the field gear is organized. The battery is load tested with a "battery meter" and returned to the field if the meter reads in the green "Good" region.

This is bad practice. Batteries will quickly sulfate if they are stored uncharged. High-rate charging does not provide an adequate finishing charge. A "battery meter" can tell you if a battery will start a car but says nothing about how much energy it can store. Unless better service and test procedures than these are used, batteries in poor condition will likely return to field sites and cause further problems.

Battery Charging. Almost any 12 volt lead-acid battery charger will supply a bulk charge to a 12 volt lead-acid battery. Where batteries differ is in their finishing charge requirements. By design, different battery types have different concentrations of acid in their electrolytes and consequently have different full-charge and float voltages. The wrong charger selection can cause undercharging or overcharging. As previously discussed, wet lead-acid cells require some overcharge to equalize cells, mix the electrolyte, and break up sulfate crystals but the same

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degree of overcharge will damage both AGM and gelled VRLA batteries.

The amount of damage a charger can do is proportional to the amount of current it can supply. High-rate chargers that can supply 100 amps or more are not a sensible choice for this application. They are expensive, require close supervision, and encourage hasty, inadequate charging. High-rate chargers are also more dangerous since both explosive gas concentrations and strong arcs are more likely at high currents.

A 10 to 15 amp battery charger will charge a 100 Ah battery overnight, which is fast enough in most cases. This size of charger is widely sold for charging car batteries and is relatively inexpensive. These chargers have a variety of features. Look for the following:

- Automatic and Manual mode selection. It is useful to have the charger switch itself OFF but there are times when the automatic circuits must be bypassed. Manual mode is sometimes called "Pre-charge" or is the "Start" selection when the charger assists in starting cars.

- Battery type selection. Automotive battery chargers often have provision for deep-cycle and/or maintenance-free battery charging. Both of these battery types have higher full-charge voltages than the conventional car battery and the switch sets up the automatic charging circuit for these battery types.

- Current meter. It is essential to observe the current at various times in the charge cycle. A built in meter makes this safe and convenient.

- Temperature compensation. This is an important feature if charging is done at a temperature outside a range of 15 to 30 °C.

Wet Lead-acid Battery Charging. The medium-power chargers described above are designed to charge wet lead-acid batteries. If there is very little sulfation and the electrolyte is not stratified and all the cells recharge at the same rate, then the automatic circuits will charge the battery to full capacity. However, this is not a realistic assumption if the battery has been in the field or sat in storage for more than a few months. Even a recently purchased battery may have self-discharged and been damaged by sulfation at the store.

It is good practice to overcharge a wet lead-acid battery after automatic charging. Set the charger to manual mode and let the battery bubble gas for 3 to 4 hours. Delco recommends an equalization voltage of 15.5 volts for the sealed wet S2000 battery (AC Delco, no date, p. 2). At the end of the gassing period, test vented batteries with a hydrometer. Interpretation of hydrometer readings is discussed in a following section.

Overcharging wet lead-acid batteries causes accelerated grid corrosion so it is best not to do this for too long or too often. However, most batteries used at remote sites will only be serviced a few times and occasional limited overcharge will not seriously corrode grids but it will extend battery

life by reducing sulfation and electrolyte stratification.

Sealed VRLA Battery Charging. The 10 amp automotive charger is not designed for valve regulated lead-acid (VRLA) battery charging. There are special VRLA battery chargers of this size but they are expensive. Even though not designed for VRLA charging, inexpensive automotive chargers can be used to give both absorbed electrolyte and gelled electrolyte batteries a bulk charge. The finishing charge can then be supplied from another source.

To bulk charge a VRLA battery from a medium-power automotive charger, set the battery selector switch to charge a standard car battery. This setting of the automatic charging circuits should charge a VRLA battery to about 80% of full capacity. However, automatic charge circuits differ. The first time you use a charger make sure it switches off without overcharging VRLA batteries. Do not leave VRLA batteries on an automotive charger for more than one day.

Inexpensive DC power supplies can be used to provide a VRLA finishing charge. "Battery Eliminator" power supplies, sold to operate mobile equipment from line power, provide 13.8 volts. This is the upper float voltage for VRLA batteries. A 100 Ah VRLA battery that is 80% charged can draw 5 amps from a 13.8 volt supply. Make sure that the supply can provide this or that it has short circuit current protection or a series resistor to limit current. It takes over one day at this voltage to finish charging but the battery can be left connected to the supply indefinitely without excessive overcharge. If a 16 to 20 volt supply is available, then a series-switching solar charge controller such as the SunSaver can be used to regulate the finishing charge. Consult the manufacturer's data sheet about connection to DC supplies. Shunt-switching controllers will short circuit the DC supply and can not be used to produce a finishing charge from a voltage source.

Charging VRLA batteries at slightly higher than normal float voltages helps to equalize cells, remove sulfate crystals, and restore lost capacity. Charging at room temperature for 24 hours at 14.4 V will supply this small overcharge without much gassing. It is good practice to provide this overcharge to VRLA batteries before putting them in the field.

Battery Tests

The battery characteristic of greatest importance for small solar electric power systems is storage capacity. Unfortunately the equipment for directly measuring storage capacity is not as available as other test equipment, so the bulk of this discussion concentrates on other tests and what they show about the condition of a battery.

Charger Current. Simple observation of charging current can reveal the most serious battery problems. A discharged battery that shows no charging current when it is connected to a charger is either badly sulfated or very deeply discharged. Leave the battery connected to the charger for up to 48 hours. Charging may start when sulfate crystals break down or when the electrolyte becomes conductive enough to support measurable current. If there is no sign of recovery after

two days, the battery should be discarded.

If a battery draws very high current for more than an hour, it may have a shorted cell. Usually when a battery is bulk charging from a 10 amp charger, the current settles between 5 and 8 amps soon after the beginning of the charge period. Deeply discharged batteries will show a decrease from maximum charger current within the first 30 minutes. If prolonged high current indicates a shorted cell, switch off the charger at half-hour intervals and check the voltage. Increasing voltage shows the battery is charging. If the voltage fails to increase and the battery continues to draw high current, then the battery has a shorted cell and should be removed from service.

Some batteries will fail to finish charging and continue to draw about 2 amps. A 100 Ah battery should fully charge in less than one day from a 10 amp charger. The end of charge is detected by automatic chargers as a decrease in charging current below a preset level. Batteries with contaminated electrolytes, partial shorts, or antimony deposits on negative plates may have end of charge currents higher than this level. If a battery does not finish charging in a reasonable time, conduct the following float current test.

Float Current. To measure float current, connect a fully charged battery to a DC supply whose output voltage is set to the battery float voltage. Measure the current after allowing the battery to stabilize for one hour. Float voltages for some batteries are shown in *Table 9*. Float currents greater than C/300 (.33 A for a 100 Ah battery) may indicate a problem. Usually float currents taken at room temperature are about C/1000. If the float current seems high, make sure that the battery has finished charging by leaving the battery on the float supply and checking the current again several hours later. If the current is still high then the battery may be defective.

Float current increases by a factor of two for every 10 °C increase in temperature, which must be taken into account when interpreting float current measurements. Furthermore, wet deep-cycle batteries with antimony in the plate grids normally show an increase in float current as they age.

BATTERY TYPE	FLOAT VOLTAGE, 25°C
Vented Automotive	13.2 to 13.4 volts
Vented Wet Deep-cycle, RV24 and RV27	13.4 to 13.6 volts
Sealed Wet Stationary, S2000	13.5 volts
VRLA, gelled and AGM	13.6 to 13.8 volts

Table 9. Float voltages at 25 °C. Temperature compensate these voltages at -15 mV/°C.

An older battery with a high antimony content can have float currents in the C/100 range. High float current readings are not enough by themselves to condemn a battery. Continue testing with

the voltage checks below.

Voltage Checks. Loaded voltage checks and stable open-circuit voltage checks are important tests for determining the condition of a battery. The two tests provide different information about the condition of a battery. Load tests show a battery's ability to support a load and indicate its internal impedance. Open-circuit tests provide clues to the chemical state of a battery's cells. Both of these tests require a 3½ digit volt meter with at least 1% accuracy.

Loaded Voltage Test. Some manufacturers provide data for high-rate discharge tests. These tests are conducted with currents several times the rated capacity of the battery (e.g., 250 A for a 100 Ah battery). A lower current load test is described here for the following reasons. First, it takes special equipment to work with large currents. Second, defective batteries are more likely to explode when highly stressed. Finally, high-rate performance is not important for small solar electric power systems.

This load test is similar to the test described above in "Field Battery Checks". The advantage of shop load testing is that the battery can be fully charged and tested at near room temperature. This eliminates some of the unknown factors in field testing and makes the test more meaningful.

Connect a 1 ohm, 200 W load to a freshly charged battery while measuring its voltage with a digital volt meter. The voltage quickly drops because of IR losses. If the battery is good, changing polarization losses will cause the voltage to decrease over the first couple of minutes until a quasi- stable operating point is reached. As the discharge continues, the voltage may increase slightly as internal heating increases chemical activity. Test the battery under load for 5 minutes, which represents a discharge of about 1% of a 100 Ah battery's full-charge capacity.

As discussed previously in "Cell Characteristics", a cell discharging through a load has reduced terminal voltage from two sources. There is a loss from the resistance of the cell's internal impedance and a further loss from electrode polarization potentials. Both voltage losses increase with increasing current, see *Figure 7*.

The lead-acid batteries used in low-power PV systems have an internal resistance on the order of 10 mΩ when new. In the test conditions above, the current from the battery is 12 to 14 A and the IR loss expected is less than 0.2 volts. Electrode polarization losses vary with battery design and temperature. However, 0.1 V per cell is a good approximation for this test. Consequently, the total expected loss is about 0.8 volts. The full-charge open-circuit voltage of VRLA and wet deep-cycle batteries is about 12.8 volts (see next section), so the stable loaded voltage of a good, fully charged battery at room temperature should be about 12 volts when it is discharging into a 1 ohm load.

Grid corrosion is caused by aging or overcharging. It increases the internal resistance of a battery and is revealed in the test above by a lower than expected stable load voltage. Grid corrosion is expected in an older battery, and it is one way in which a battery wears out. For the relatively small loads of this application, a degree of grid corrosion is not harmful if the battery retains most of its rated capacity. However, batteries that produce less than 11 volts during a 1 ohm load

test are probably at the end of their useful lives.

Sulfated batteries have limited amounts of active materials available to sustain the chemical discharge reaction and tend to have large polarization losses. Badly sulfated batteries show a rapid decrease to less than 10 volts without reaching a stable discharge voltage. However, partially sulfated batteries may show no symptoms during a load test because enough active material is present to support the required discharge during the test.

Loaded voltage tests show whether a battery can support a load. They do not predict how long the battery can support the load. Badly damaged batteries will fail a load test while batteries with seriously reduced capacity can pass them.

Open-circuit Voltage Tests. Stabilized open-circuit voltage tests can provide information about battery capacity. As shown previously in *Figure 6,* the stable open-circuit voltage is proportional to the strength of the acid in the electrolyte. The electrolyte is most acidic and the open-circuit voltage is highest when the battery is fully charged. Given the fully charged open-circuit voltage and the fully discharged open-circuit voltage specified by the manufacturer; a battery's state of charge can be calculated from its stable open-circuit voltage. Where V_{CHG} is the fully charged open-circuit voltage, V_{DIS} is the fully discharged open-circuit voltage and V_{SOC} is the stable open-circuit voltage, then the state of charge (SOC) is

$$\mathbf{SOC = [(V_{soc} - V_{DIS})/(V_{CHG} - V_{DIS})] \times 100\%}.$$

To estimate the capacity of a battery from its stable open circuit voltage, the battery must be as fully charged as possible. Capacity is estimated by comparing the actual, fully charged, open-circuit voltage to the specification for the fully charged open-circuit voltage. Fully charged open-circuit voltages less than the design values indicate that battery plates have areas that have failed to recharge and return sulfate ions to the electrolyte. This makes the electrolyte less acid than it should be and lowers the open-circuit voltage of a fully charged battery. The error due to manufacturing tolerances is +/- 15% (Power Sonic, 1996, Figure 5). As stated previously in "Cell Characteristics", there is a small temperature dependance for the open-circuit voltage of +1.2 mV /°C for a six-cell battery.

Table 10 shows typical stable open-circuit voltages for the four main types of lead-acid battery used in small solar electric power systems. The left hand column can be read as state of charge but it indicates capacity, if the battery is fully charged when the open circuit voltage is read. These relationships are linear so values not on the table are easily calculated from the expression for state of charge given above.

State of Charge or Full-charge Capacity Estimate
from V_{soc} (6 cell) and Specific Gravity, 25°C

State of Charge or Capacity %	VRLA		Wet (flooded) Lead-acid			
	AGM	GEL	Small Deep-cycle		Automotive	
	V_{soc}	V_{soc}	V_{soc}	Specific Gravity	V_{soc}	Specific Gravity
100	12.84	12.72	12.72	1.280	12.63	1.265
75	12.54	12.42	12.51	1.245	12.41	1.229
50	12.24	12.12	12.30	1.210	12.20	1.193
25	11.94	11.82	12.09	1.175	11.98	1.156
0	11.64	11.52	11.88	1.140	11.76	1.120

Table 10. Open-circuit voltage (V_{SOC}), state of charge and capacity. Capacity can be estimated if the battery is as fully charged as possible. The temperature compensation for these voltages is 1.2 mV/°C for temperatures different than 25 °C.

Open-circuit voltage measurements are made when a battery's cells are in chemical equilibrium. Charging or discharging a battery upsets its chemical equilibrium, so several hours must pass after charging or discharging a battery before open-circuit voltage measurements can be made. Exact measurements are usually taken after 24 hours.

It would seem that a simple voltage check can give us a good estimate of battery capacity. However, the relationship between open-circuit voltage and capacity depends on any decrease in capacity appearing as a proportionate decrease in the number of sulfate ions in the electrolyte. This is true for capacity that is lost because sulfate ions are locked into lead sulfate crystals on the plates. It is not true if grid corrosion and sulfation work together to isolate active plate materials electrically and chemically. The storage capacity of these plate areas is lost without a proportionate decrease in the concentration of acid in the electrolyte. Consequently, open-circuit voltage measurements are indicators rather than decisive tests. A battery will never have more capacity than indicated by its stable open-circuit voltage. It usually has less.

Hydrometer Measurements. The electrolyte's specific gravity shows the same relation between state of charge and the concentration of acid in the electrolyte that the stable open-circuit voltage does. However hydrometer readings have the advantage of checking each cell individually and not the battery as a whole. Comparisons between cells show how well the charge is equalized and shows weak or damaged cells. *Table 10* shows the cell specific gravity and open-circuit battery voltage for two types of vented wet lead-acid battery.

Hydrometer readings should be taken after an overcharge mixes the electrolyte and before electrolyte levels are refilled. Read the scale value at the bottom of the dip (meniscus) between the hydrometer tube and its float. Interpreting the specific gravity reading involves knowing the hydrometer reference temperature and the electrolyte temperature when the measurement is made. The reading is corrected for temperature by adding 7 points (0.007) to the specific gravity measurement for each 10 °C above the reference or subtracting it for each 10 °C below it (BCI, 1995, p. 6-8). Neglecting a 10 °C temperature change results in an error of about 5% in estimating the cell state of charge from a hydrometer reading. Neglecting the same temperature change using the open-circuit voltage method produces an error of less than 2% for the whole battery.

It is convenient to use the stable open-circuit voltage method to estimate the state of charge of the battery and then check cell equalization with a hydrometer. An automotive battery hydrometer is good enough for comparative measurements and temperature dependancy can be ignored. Disregard the "Good, Fair, Poor" scale of such hydrometers and check to see that the cells have the same specific gravity within 50 points (0.050). Cell equalization is an important indicator if a fully charged battery shows a low open-circuit voltage. If the stabilized open-circuit voltage is nearly normal, a low cell specific gravity may indicate that the cell electrolyte is poorly mixed. Continue overcharge to mix and equalize the cells. Test again after a couple of hours.

Adding acid to cell electrolytes is sometimes advocated as a way of reviving dead batteries. Additional acid does replace sulfate ions that have become permanently crystallized on the plates but it does not restore active plate material. Consequently, the revived battery does not have restored storage capacity. It does have higher voltage and greater conductivity. This is useful when the battery supplies short high-rate discharges; for instance, starting a car. However, adding acid to cell electrolytes is not useful maintenance for low-power PV system batteries.

Direct Capacity Measurement. Despite the fact that battery capacity is the most important characteristic of low-power PV system batteries, it is seldom directly tested. Capacity is the area under the curve of discharge current versus time. All that is required is a current meter, a voltmeter, a load resistor, and a watch. The drawback is that someone has to take periodic readings and stop the test when the voltage indicates that the battery is fully discharged.

The block diagram of an automatic capacity tester is shown in *Figure 19.* The tester discharges the battery at a constant current, which makes battery capacity directly proportional to the discharge time. The adjustable reference is set so that the current through R1 is the desired discharge. C/20 is the usual discharge rate for measuring labeled capacity. End of discharge is detected by the 10.50 V comparator. The control, timing and display functions can be purchased or built from a microcontroller.

Direct capacity measurement is an accurate guide to battery quality. It is a conservative measure since the C/20 test current is many times higher than the load current required in a small PV power system application. Unlike capacity estimates based on open-circuit voltage measurements, direct measurement will never overstate the battery's capacity. Where resources permit, construction and use of a battery capacity checker is recommended.
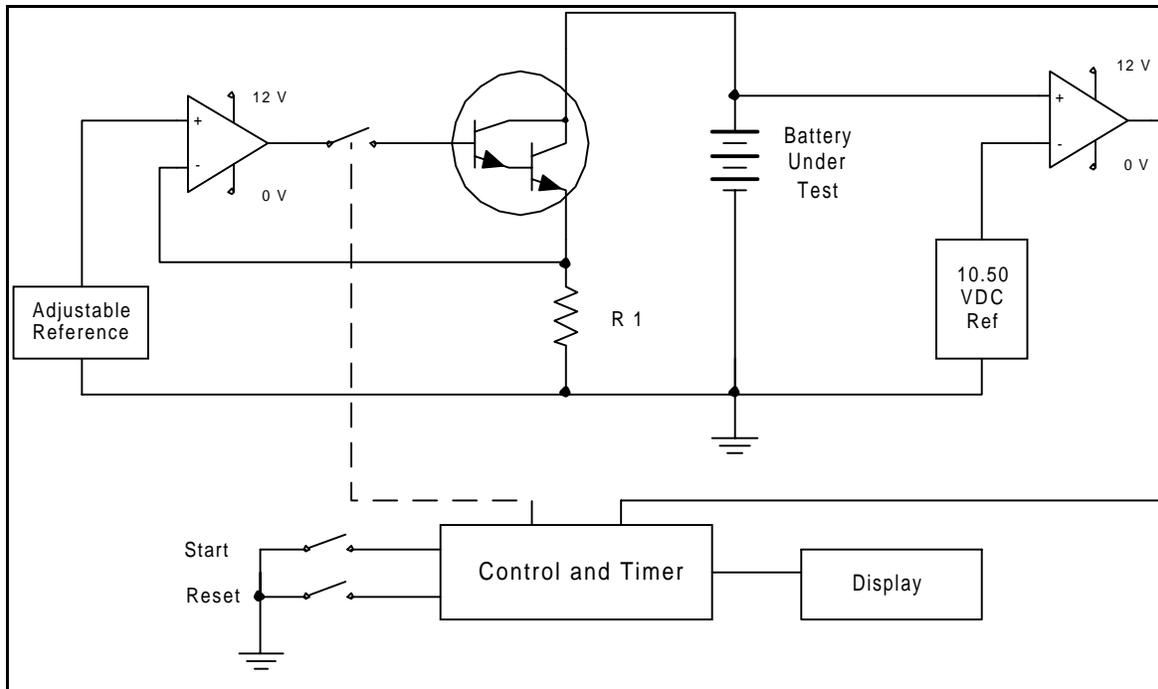
Figure 19. Block diagram of a battery capacity tester.

Diagnosing Problems

Table 11 lists the symptoms of overcharging and undercharging for the tests discussed above. These tests should be performed in the shop as part of the charging process in order to eliminate bad batteries and diagnose site charging system problems. Make an open-circuit voltage measurement before charging the battery. It shows the state of charge when the battery was removed from the field. A low state of charge despite good weather conditions indicates a charging system fault.

Begin charging the battery and observe the charge rate. The initial current acceptance by the battery is one of the best indicators of whether the battery has been undercharged or overcharged. Low initial charge current acceptance is a symptom of undercharging. On the other hand, if the initial charge current is high and remains high during the charging period, then damage due to overcharging is indicated. If the battery accepts no current over a 48 hour charge period, either extreme sulfation from undercharging or extreme electrolyte water loss from overcharging is indicated. Extreme sulfation or water loss are clear signs of site problems.

If the battery seems to charge correctly, continue charging and make a loaded voltage test when the battery is fully charged. A serious sulfation problem is shown by a discharge voltage that keeps falling without finding a stable operating point. A lower than expected stable discharge voltage indicates increased internal resistance from overcharging. If the battery has been in service for less than three years and load test results are poor, then site problems are indicated.

PROBLEM	UNDERCHARGING	OVERCHARGING
Fault	Plate Sulfation, low state of charge	Grid corrosion, electrolyte loss, plate shedding
Test	Indicator	Indicator
Charge behavior	Low initial charge current. Low charge acceptance.	Continuous high charge current from shorted cells. Battery does not finish charging, High float current.
Loaded Voltage Test	Rapid decrease to low voltage.	Low but stable discharge voltage.
Open-circuit Voltage Test	Reduced full-charge voltage from low electrolyte acidity.	Reduced full-charge voltage from damaged cells.
Hydrometer Reading	Low specific gravity.	Low specific gravity. Poor cell equalization.

Table 11. Battery diagnostic guide.

Allow the battery to rest for several hours and measure the stable open circuit voltage. Compare the measured open circuit voltage to the full charge open circuit voltage specified by the manufacturer or use *Table 10.* Both overcharging and undercharging can cause low open circuit voltages. However, without any other symptoms of overcharging, a low open circuit voltage is usually due to sulfation from undercharging. For example, if overcharging produces a shorted cell, the battery open circuit voltage will be less than 12 V, but the shorted cell should already be suspected because of high charging current.

If the battery under test is a vented wet battery, hydrometer tests can be used to measure the acidity of each cell individually. Low specific gravity across all cells is a sign of sulfation. A cell with a short-circuit will fail to charge and have very low specific gravity.

It is essential to know the age of a battery when interpreting test results. Sulfation and grid corrosion, in addition to being the symptoms of a poor charging system, are the normal mechanisms through which a battery wears out. Even in a good charging system a battery has a limited lifetime. In small PV power systems it is unrealistic to expect more than five years of service from a battery.

So when is a battery dead? Storage capacity is the crucial factor. Use direct capacity measurement or capacity estimates from open-circuit voltage tests to determine a battery's fitness to return to the field. Some manufacturers recommend that industrial users scrap batteries that have less than 80% of rated capacity (Johnson Controls, 1996, p.11). Another manufacturer recommends replacement at 60% (Power Sonic, 1996, p. 6).

Replacement when the fully charged battery capacity reaches 60% of nominal capacity is appropriate for batteries from low-power PV sites. Batteries in industrial installations receive regular charging and maintenance, so a capacity measurement of 80% is indicative of a high degree of general wear. At a small PV site, sulfation from a single bad winter may reduce capacity to less than 80% while in other ways the battery remains in good condition. A flexible standard, which takes into account a battery's history, should be used to evaluate batteries from remote PV sites. Putting a battery with seriously reduced capacity in a remote location is a bad idea while using it in a more accessible place makes sense.

Battery Storage

It is best to avoid storing lead-acid batteries because of self-discharge. The plates of discharged batteries sulfate and battery capacity can be permanently reduced. Batteries should never be stored unless they are fully charged.

Batteries may be stored on conductive surfaces like metal shelves or concrete floors. In the past, battery casings may have sweated electrolyte, and with the assistance of a conductive surface, batteries discharged; but modern plastic casings do not have this fault. This does emphasize the point that batteries should be clean when stored. At least the top of casings should be free from materials that might form a conductive path between the terminals.There are two ways to store batteries that minimize capacity loss. Float storage keeps batteries connected to a float voltage source so that self-discharge currents are immediately replaced. Alternatively, batteries can be periodically recharged.

A one ampere power supply can provide float current for up to five 100 Ah batteries. Set the supply to the appropriate float voltage (*Table 9)*. Connect fully charged batteries to the supply one at a time. Avoid overloading the supply by allowing time between each additional battery connection for the current to stabilize. If the float voltage is accurate, unattended storage for several months is possible. Temperature compensation may be required for long storage periods in fluctuating temperatures.

Lead sulfate crystals on battery plates can be removed by recharging the battery as long as recharge occurs before crystal structures form. The length of time a fully charged battery can sit in storage without sulfating depends on two factors, temperature and grid materials, because both control the rate of self-discharge. Cooler temperatures and non-antimony grids, such as the lead calcium grids found in VRLA batteries, allow longer storage times before recharge is required. However, all stored lead-acid batteries must be periodically recharged or they will permanently sulfate.

Either a regular recharging schedule or open-circuit voltage checks can be used to select batteries in need of recharge. At room temperatures, wet lead-acid batteries should be recharged on a monthly schedule, while VRLA batteries should be recharged every two to three months. If open-circuit voltage tests are used, recharge batteries when their state of charge falls to 80% as shown in *Table 10*.

Maintenance Records

It may take several years for a pattern of premature battery failure to show itself and it is not easy to remember all the details that can relate to a specific power system problem. Conditions at sites change. New instruments may be installed or adjustments are made that change load currents. The average irradiance may change because of changes to vegetation or weather patterns. The failed battery in question may be recently installed, or it may be an older battery that has come to the end of its normal service life. All these details can help assess a power system but it is not likely that they will be known unless maintenance records are kept. So let this discussion close with the thought that maintenance records are an essential diagnostic tool. Keep and use them.

GLOSSARY

Active material - The materials of the positive and negative electrodes which participate in the cell discharge and charge chemical reactions with the electrolyte. In a lead-acid battery the active material of the charged negative electrode is lead (Pb) and the active material of the charged positive electrode is lead dioxide (PbO_2). See Electrode.

AGM - Absorbed glass mat battery. This type of VRLA battery has its electrolyte immobilized in a micro glass fiber mat. See VRLA.

Ampere hour (Ah) - The unit of battery capacity measurement. It is the product of the discharge current in amperes and the discharge time in hours.

Aperture - The effective area of incident light passed to the active part of the solar panel. As the position of the sun changes so does the area of space intercepted by the solar panel.

Battery - A device that converts the chemical energy stored in its active materials to electrical energy. A battery is composed of one or more electrochemical cells. A primary battery can only discharge this energy. The chemical reaction in a secondary battery is reversible and the battery can be recharged. See Cell.

Bulk charge - The first period of battery recharge from a moderate or deep discharge when a battery can easily store all the current from a charging source.

Capacity (C) - The ability of the cell to store electrical energy. Capacity is measured in ampere hours. Lead-acid battery capacity is usually measured at a 20 hour discharge rate (C/20) to a cutoff voltage of 1.75 volts/cell. See Reserve capacity.

Cell- Electrochemical cells release electrical energy by means of chemical reactions with the cell electrolyte at the positive and negative electrodes. The reaction requires an external electrical connection between the electrodes to carry electrons from the negative electrode to the positive electrode. The electric current transfers chemically stored energy to an external load.

Charge - Cells store electrical energy as chemical energy. A charged cell is a cell that has energy that can be released from storage. To charge or recharge a secondary cell is to cause it to accept electric current for storage. The rate of charge is measured in amperes or as a fraction of the cell capacity, for example C/2 where C is 100 Ah is a current of 50 amps. See State of charge.

Corrosion - The result of a destructive chemical reaction. Grid corrosion in lead-acid batteries is caused by sulfuric acid attacking lead in the plate grids and changing it to lead dioxide.

Current source - An electric power source that attempts to maintain a constant current through its load. Ideally its output voltage will go to whatever value it must in order to force constant current through the load. Real current sources have a limit to their output voltage range called the compliance voltage. Solar panels are current sources with their constant current level set by the amount of sunlight on the surface of the panel and a compliance voltage of 18 to 20 volts. See Voltage source.

Deep-cycle - The discharge, from full charge, of at least 80% of a battery's stored energy; followed by immediate recharge. A battery designed for repeated deep discharges is called a deep-cycle battery. A deep-cycle battery's ability to endure deep discharge is measured by counting the number of times a battery can discharge 80% of its capacity and successfully recharge.

Discharge - The release of stored chemical energy as electric current. The rate of discharge is measured in amperes or as a fraction of the cell capacity, for example C/20 where C is 90 Ah is a current of 4.5 amps.

Electrode - The location where the active materials of the cell make contact with the electrolyte and the site of the chemical reactions of the cell. Often the electrode is a compound structure that mechanically supports the active materials and provides an electrical connection to the external circuit. See Active material, Plate, Grid.

Electrolyte - Provides the ionic current carriers that allow the transfer of electrons between electrodes within the cell. In a lead-acid battery the electrolyte is sulfuric acid (H_2SO_4) in a solvent of water.

Electrolyte-limited - A cell that can no longer discharge because its electrolyte has run out of ionic current carriers. In a lead-acid battery this happens when almost all the sulfate ions (SO_4^{-2}) have left the electrolyte to form lead sulfate ($PbSO_4$) on the plates. Also known as electrolyte starved. See Plate-limited.

Equalization - The process of charging all cells in a battery to an equal state of charge. Cell equalization occurs when the charging period is extended to allow all the cells to completely charge. The already charged cells will be in overcharge during this time.

Excess charge - The overcharge that occurs at the end of the charging period. See Overcharge.

Finishing charge - The period during charging when the battery is no longer able to store all the current that a voltage source can provide. The voltage source reaches its set point and charging current decreases.

Float current - The current from a float voltage source that counteracts the self-discharge current of the battery and keeps it fully charged.

Float voltage - The voltage that supplies the correct amount of current to the battery to replace self-discharge current.

Float service - Batteries in float service stand by until they are required to supply power to the load when other power sources fail. Float service batteries are connected to a float voltage source so that they do not self-discharge while they are waiting to supply power.

Flooded - A battery with a mobile liquid electrolytes is called a flooded or wet battery. Highly flooded batteries have large volumes of liquid electrolyte.

Gas recombination - VRLA batteries recombine the gases that form due to overcharge. This prevents the electrolyte from losing water.

Gassing - Electrical energy, which batteries are unable to store, decomposes electrolyte water. The break down of water forms hydrogen and oxygen gases that leave the battery and cause it to "dry out".

Gel cell - A type of VRLA battery whose electrolyte is immobilized by a gelling agent. See VRLA.

Grid - The part of the battery plate structure that mechanically supports the plate's active materials and conducts current from the plate. It is a mesh of lead alloy and its strength and ability to resist corrosion are very important in determining the service life of the battery, See Plate.

Internal impedance - The total opposition to current flow in a battery. Current is opposed by both the internal resistance of the battery and electrode polarization.

IR loss - The decrease in voltage caused by current moving through resistance. The loss of voltage in a discharging battery caused by current moving through the battery's internal conductors. Also known as the IR drop.

Irradiance - The amount of sunlight on the active surface of a solar panel. Its unit is W/m^2.

Nominal - The named or labeled value of a parameter and not necessarily the actual quantity in a particular situation.

Open circuit voltage - The voltage measured while the source is disconnected from any load other than the measuring device.

Orientation - The direction given by a compass. Solar panels are usually oriented to face south in the northern hemisphere and north in the southern hemisphere.

Overcharge - A battery that is forced to accept more current than it can store is in an overcharge condition. If a battery is recharged at high rate, the chemical reactions that store the energy may not be fast enough to keep up with the charger. A second form of overcharge occurs when a fully charged battery is forced to accept additional current. Large overcharges damage batteries. Occasional small overcharges of lead-acid batteries can be beneficial.

Plate - A flat electrode with a large surface area. The large surface increases the amount of active material which can simultaneously participate in chemical reactions and increases charge and discharge rates. Flat thin plates are strengthened with a supporting grid.

Plate-limited - A cell whose discharge is designed to stop when at least one of its electrodes has run out of active material. Also known as plate starved. See Electrolyte-limited.

Plate shedding - Plates shed active material when plate grids are damaged by corrosion. The material shed falls out of the plates and is the cause of short-circuits in cells.

Polarization loss - The loss of voltage at the cell electrodes because of the activation polarization overvoltage and the concentration polarization overvoltage. See text in "Cell Characteristics".

Prismatic - A style of cell construction based on a parallel array of rectangular plates and separators inside a box shaped casing.

Reserve capacity (RC) - SLI and some deep-cycle batteries label their capacity as reserve capacity rather than as a value in ampere hours. Reserve capacity is the number of minutes a battery can support a 25 amp discharge to a terminal voltage of 1.75 volts/cell. A rough conversion of reserve capacity to ampere hours is: Capacity (Ah) = 2/3 (RC in minutes).

Self-discharge - The release of a cell's chemically stored energy without current flow to an external circuit. Self-discharge is caused by local chemical action at the electrodes and is increased by temperature and contaminating materials, especially metal ions.

Separator - The porous insulator between plates designed to prevent short-circuits.

SLA - Sealed lead-acid battery. In particular, the small cylindrical high pressure type.

SLI - Starting, lighting and ignition batteries. Batteries designed to produce the short high currents required to start an engine. Automotive batteries are SLI batteries. Also called cranking batteries.

Specific gravity (SG) - The density of a substance in relation to water. The specific gravity of water is 1. Because the density of the electrolyte changes as the cell charges and discharges the measurement of the electrolyte specific gravity measures the state of charge of the cell. See State of charge.

Standard test conditions (STC) - Solar panel test condition at an irradiance of 1000 W/m^2, 25°C, and a spectrum defined by ASTM E 892.

Standby service - see Float service.

State of charge - The state of charge of a fully charged battery is 100%. A fully discharged battery, 0% state of charge, is defined by the conditions of its capacity measurement and not by a complete lack of charge. Capacity tests usually end when a C/20 discharge causes the loaded terminal voltage to reach 1.75 volts/cell. Discharge beyond this point is possible. A cell will discharge to its plate or electrolyte limit, however these very deep discharges are destructive. Normal operation of the battery occurs between 0 and 100% state of charge. Under the right conditions, both the open-circuit voltage and the electrolyte specific gravity can be used to measure the state of charge.

Stationary battery - A large wet battery designed for industrial float service.

Sulfation - When lead sulfate remains on battery plates for enough time, crystal structures form and sulfation occurs. It is difficult to change lead sulfate into active material and return sulfate ions to the electrolyte by recharging once lead sulfate crystallizes.

Surface charge - The polarization of a cell's electrodes causes charge storage at the electrode surfaces.

Tilt - The solar panel angle from horizontal.

Traction battery - Large wet deep-cycle batteries used for vehicles like forklifts and golf carts.

Undercharge - A battery that is not given enough charging current or time to fully recharge is undercharged. Lead sulfate remains on the plates of undercharged batteries. This crystallizes and the battery sulfates.

Vented - Wet batteries with cell openings that allow electrolytes to be serviced and overcharge gases to escape.

Voltage source - An electric power source that attempts to maintain a constant voltage across a load. Ideally a voltage source supplies all the current required by a load and maintains a constant voltage. In practice the ability of a voltage source to supply current is limited and the output voltage "loads down" when too much current is demanded.

VRLA - Valve regulated lead-acid battery. A class of sealed lead-acid batteries with immobilized electrolytes that recombine the gases formed by overcharge to prevent electrolyte dry out. There are two types of VRLA battery, gel cells and absorbed glass mat (AGM) batteries.

Wet - Batteries with mobile liquid electrolytes are called flooded or wet batteries.

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