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TEMPERATURE EFFECTS ON SEALED LEAD ACID BATTERIES AND CHARGING TECHNIQUES TO PROLONG CYCLE LIFE

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ABSTRACT

Sealed lead acid cells are used in many projects in Sandia National Laboratories Department 2660 Telemetry and Instrumentation systems. The importance of these cells in battery packs for powering electronics to remotely conduct tests is significant. Since many tests are carried out in flight or launched, temperature is a major factor. It is also important that the battery packs are properly charged so that the test is completed before the pack cannot supply sufficient power. Department 2665 conducted research and studies to determine the effects of temperature on cycle time as well as charging techniques to maximize cycle life and cycle times on sealed lead acid cells. The studies proved that both temperature and charging techniques are very important for battery life to support successful field testing and expensive flight and launched tests. This report demonstrates the effects of temperature on cycle time for SLA cells as well as proper charging techniques to get the most life and cycle time out of SLA cells in battery packs.

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I. BACKGROUND AND TERMINOLOGY

I.1 HISTORY

Lead-acid is the oldest rechargeable battery in existence. It has retained a market share in applications where newer battery chemistries would either be too expensive or the upkeep would be too demanding. During the mid 1970s, researchers developed a maintenance-free lead-acid battery that could operate in any position. The liquid electrolyte was transformed into moistened separators and the enclosure was sealed. Safety valves were added to allow venting of gas during charge and discharge. Driven by different market needs, two lead-acid systems emerged: the small sealed lead-acid (SLA), also known under the brand name of Gelcell, and the large valve-regulated-lead-acid (VRLA). Technically, both batteries are the same. Sealed lead acid batteries are a form of lead acid battery that uses a gel-type electrolyte rather than a liquid. During charging, the electrodes, which are made from lead alloys, never reach the stage where gas is generated. This allows it to be sealed and able to be used in any position. Since no water is used in the cells, no maintenance is required. Unlike the flooded lead acid battery, both SLA and VRLA are designed with a low over-voltage potential to prohibit the battery from reaching its gas-generating potential during charge. This low over voltage potential is because the VRLA cell is able to use the oxygen cycle during overcharge. The oxygen, evolved at the positive electrode when the cell is overcharged, is recombined at the negative electrode. A self–resealing valve is provided as a safety vent in case of misapplication or other abuse of the cell that would cause the internal cell pressure to increase. Because of the over voltage protection, these batteries can never be charged to their full potential. Since the sealed lead acid cell is never theoretically fully charged, it tends to have a relatively poor energy density (ratio of the battery's available energy to its size). This makes SLA's unsuitable for devices that demand compact size. However, SLA's have the lowest self-discharge rate of any of the rechargeables (~5% a month) and do not suffer from the memory effects displayed by NiCad's. SLA's prefer shallow cycling although they perform well with periodic heavy discharging. After a full recharge, they can be left on float charge indefinitely. The following are details of the SLA and outlines for charging techniques as well as graphs of different charging methods and effects of temperature on SLA's.

I.2 CELLS

Battery Cells are the most basic individual component of a battery. Each battery cell consists of a container in which the electrolyte and the lead plates can interact. While the nominal voltage of a SLA cell without a load is 2 volts, each cell fluctuates in voltage from about 2.15 volts fully charged to about 1.9 volts fully discharged. Note the small voltage difference between a full and an empty cell (another advantage of lead-acid batteries over rival chemistries).

I.3 C-RATE

Since batteries depend on a chemical reaction to produce electricity, their **Available Capacity** depends in part on how quickly you attempt to charge or discharge them relative to their **Total Capacity**. The **Total Capacity is frequently abbreviated to C** and is a measure of how much energy the battery can store. Available Capacity is always less than Total Capacity.

The charge and discharge current of a battery is measured in **C-rate**. Most portable batteries are rated at 1C. This means that a 1000mAh battery would provide 1000mA for one hour if discharged at 1C rate. The same battery discharged at 0.5C would provide 500mA for two hours. At 2C, the 1000mAh battery would deliver 2000mA for 30 minutes. 1C is often referred to as a one-hour discharge; a 0.5C would be a two-hour, and a 0.1C a 10-hour discharge.

Typically, the amp-hour capacity of a battery is measured at a rate of discharge that will leave it empty in 20 hours (a.k.a. the C/20 rate). The capacity of SLA batteries varies significantly depending on the actual rate of discharge, and is usually highest at the 20-hour rate i.e., when supplying a current of 0.05C. The nominal capacity rating is therefore usually given on the basis of this discharge rate. Longer discharge times produce higher capacity readings. If you attempt to discharge a battery faster than the C/20 rate, you will have less available capacity and vice-versa. The more extreme the deviation from the C/20 rate, the greater the available (as opposed to total) capacity difference. However, this effect is non-linear. The available capacity at the C/100 rate (i.e. 100 hours to discharge) is typically only 10% more than at the C/20 rate. Conversely, a 10% reduction in available capacity is achieved just by going to a C/8 rate (on average).

I.4 Depth of Discharge (DOD) and Cycle Life

The Depth of Discharge (DOD) is a measure of how deeply a battery is discharged. When a battery is 100% full, then the DOD is 0%. Conversely, when a battery is 100% empty, the DOD is 100%. The deeper batteries are discharged on average, the shorter their so-called cycle life. Unlike nickel-cadmium, the lead-acid does not like deep cycling. A full discharge causes extra strain and each cycle robs the battery of a small amount of capacity. This wear-down characteristic also applies to other battery chemistries in varying degrees. To prevent the battery from being stressed through repetitive deep discharge, a larger battery is recommended. However, companies such as Hawker have manufactured SLA cells (sold under the Cyclon name) that can maintain their cycle life even with continued deep discharging (DOD 50-100%).

NOTE: Lead-acid has a gradual voltage drop with a rapid drop towards the end of discharge. The general recommended end-of-discharge voltage for lead-acid is 1.75V/cell.

I.5 Discharge Level

The voltage point at which 100% of the usable capacity has been depleted is a function of the discharge rate. The recommended end of discharge voltage **(EODV)** is a function of the rate of discharge, and these numbers are given in the table below:

Anything up to 1.00C-10 are considered low discharge rates; anything over 1.00C-10 are considered high discharge rates.

Table 1: EODV According to C-Rate

Discharge rate in amps	Suggested minimum EODV per cell
$0.05C_{10}$ (C_{10}/20)	1.75V
$0.10C_{10}$ (C_{10}/10)	1.70V
$0.20C_{10}$ (C_{10}/5)	1.67V
$0.40C_{10}$ (C_{10}/2.5)	1.65V
$1.00C_{10}$	1.60V
$2.00C_{10}$	1.55V
$>5.00C_{10}$	1.50V

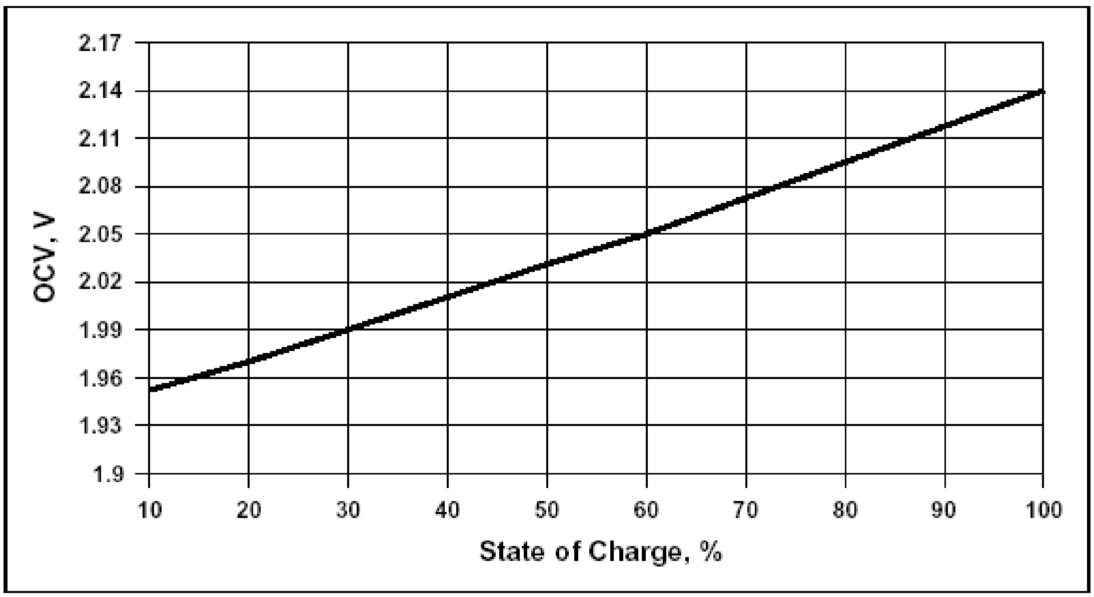
A high rate discharge equates to a low DOD while a low rate discharge is a high rate DOD event. Therefore, a higher EODV is recommended for a low DOD to prevent an over discharge.

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

150 - 200 cycles with 100% depth of discharge (full discharge)
400 - 500 cycles with 50% depth of discharge (partial discharge)
1000 and more cycles with 30% depth of discharge (shallow discharge).

SLA batteries typically achieve a working lifetime of about 300 - 500 cycles, depending on the depth of cycling and the operating temperature. This is significantly shorter than the lifetime of NiCad’s, and is due to a chemical reaction at the positive plates, which gradually causes them to expand and change in composition. So the charge capacity of an SLA slowly falls, as the battery is cycled. The primary reason for the relatively short cycle life after many full discharges is grid corrosion of the positive electrode, depletion of the active material and expansion of the positive plates. These changes are most prevalent at higher operating temperatures. Cycling does not prevent or reverse the trend. Under normal operating conditions, four or five years of dependable service life can be expected in stand-by applications (up to ten for the Hawker Cyclon line), or between 200 and 1000 charge/discharge cycles depending on the average depth of discharge. Below is a table that gives an approximation of the state of charge of a SLA cell.

Figure 1: State of Charge vs. Open Cell Voltage



The lead-acid battery should normally not be discharged beyond 1.75V per cell, nor should it be stored in a discharged state.

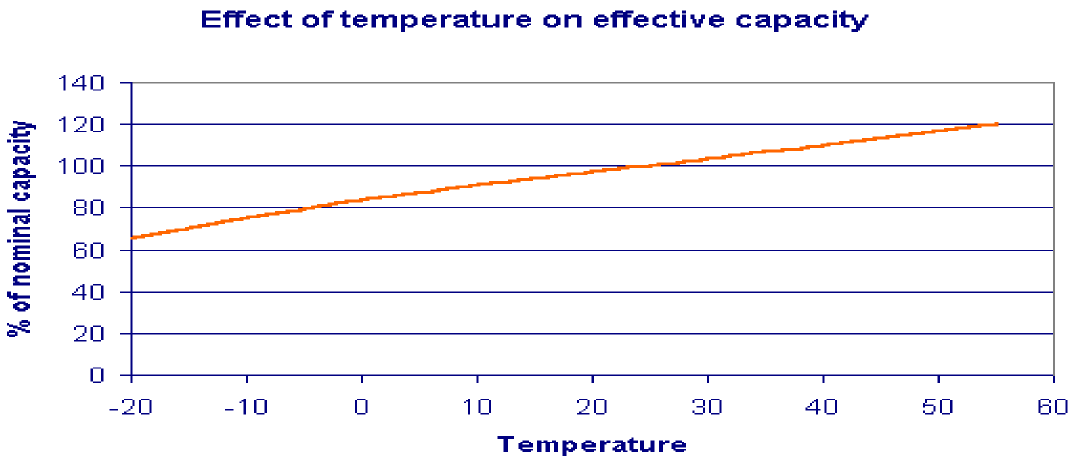
Always keep the open terminal voltage at 2.10V and higher. Leaving the battery in a discharged condition causes sulfation, a condition that makes the battery difficult, if not impossible, to recharge. At the end of this report is a method to reverse sulfation.

II. TEMPERATURE EFFECTS ON SLA CELLS

The optimum operating temperature for the lead-acid battery is 25°C (77°F). As a guideline, every 8°C (15°F) rise in temperature will cut the battery life in half. VRLA, which would last for 10 years at 25°C (77°F), will only be good for 5 years if operated at 33°C (95°F). Theoretically the same battery would endure a little more than one year at a desert temperature of 42°C (107°F).

The following graph was taken out of a Hawker Cyclon datasheet and is typical of most SLA cells.

Figure 2: Effect of Temperature on Effective Capacity



The following graph depicts studies conducted in a Sigma Systems C4 temperature chamber. The same electronic load was used each time. A Fluke189 multimeter with logging capability was attached to the positive and negative sides of the battery pack. Samples were logged every four minutes starting when the electronics were powered. When the battery pack dipped below 10 volts, the electronics were not sufficiently powered (DC to DC converters needed >10 volts) and the battery pack was considered 100% depleted.

Figure 3: Effects of Temperature on Cycle Time of SLA Cells

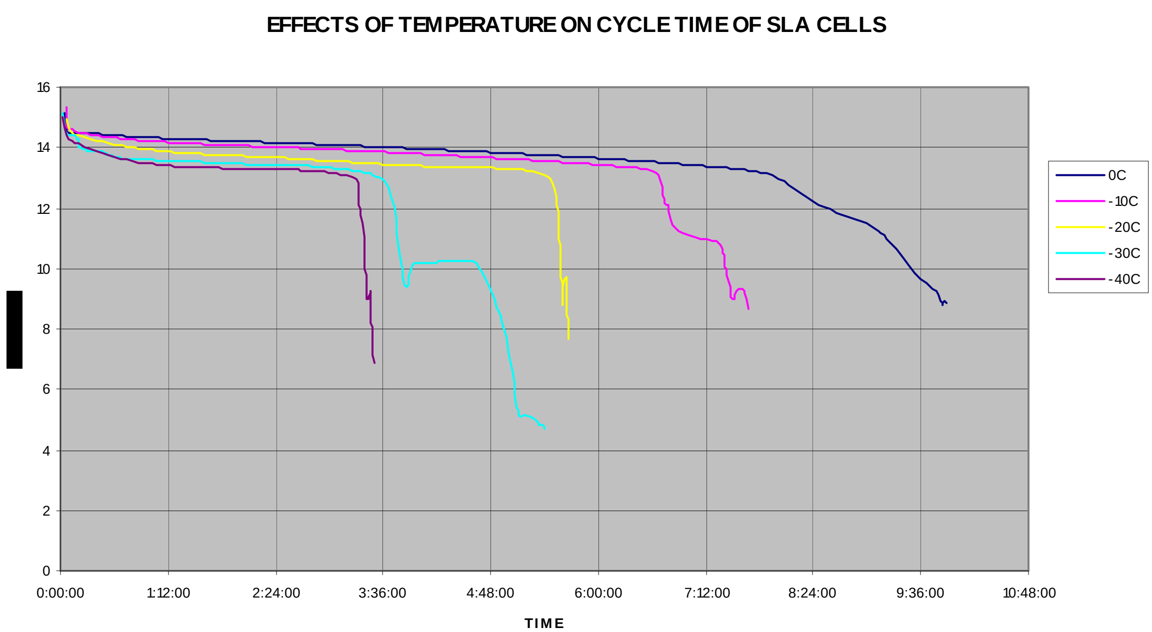


Table 2: Battery Depletion Time At Different Cold Temperatures

Temperatures	Duration
0C	9:32
-10C	7:25
-20C	5:35
-30C	4:39
-40C	3:24

III. CHARGING

III.1 Charging Characteristics

SLAs prefer to be kept fully charged at all times. Because of the high purity of the lead-tin grid (lead purity in excess of 99.99%), SLA's can be kept ***indefinitely*** on float charge. Lead-acid cannot be fully charged as quickly as nickel or lithium-based systems. Time must be allotted not only to recharge the battery, but also to let it rest in a fully charged state between deep, high rate discharges. If you need to replace 100 amp hours in 4 hours, then you need at least 25 amps. However, the truth is that you will need 30 to 40 amps or more and probably 6 to 8 hours because of the way that chargers and batteries behave after the battery is 80% recharged.

NOTE: It is more difficult, and it takes a lot longer to replenish the last 20% of the battery charge than it does to replenish the first 80% of the battery charge.

III.2. Charge Voltage Limits

Finding the ideal charge voltage limit is critical. Any voltage level is a compromise. A high voltage limit (above 2.40V/cell) produces good battery performance but shortens the service life due to grid corrosion on the positive plate. The corrosion is permanent. A low voltage (below 2.40V/cell) is safe if charged at a higher temperature but is subject to sulfation on the negative plate. The following chart depicts these limits.

Table 3: Characteristics of Charge Voltage Limits

Voltage Limit	2.30V to 2.35V/cell	2.40V to 2.45V/cell
Advantage	Maximum service life; battery remains cool during charge; ambient charge temperature may exceed 30°C (86°F).	Faster charge times; good, consistent capacity readings; less inclined to sulfation.
Disadvantage	Slow charge time; capacity readings may be inconsistent and declining with each cycle. Sulfation can occur if no topping charge is applied.	Not suitable for charging at high room temperatures. A hot battery may fail to reach the voltage limit, causing severe over charge. Subject to corrosion.

NOTE: IT IS IMPORTANT THAT FOR CYCLIC APPLICATIONS, IT IS IMPERATIVE THAT THE CHARGE VOLTAGE IS IN THE REQUIRED RANGE. IF THE VOLTAGE IS LOWER THAN REQUIRED, IT WILL LEAD TO A RAPID LOSS IN CAPACITY REGARDLESS OF THE MAGNITUDE OF THE INRUSH CURRENT.

The recombinant valve regulated lead acid (VRLA) design, such as the Hawker Cyclon series, is safe from overcharging. In case of misapplication or other abuse of the cell that would cause the internal cell pressure to increase, the self-resealing valve is a safety vent. Leaving the battery on float charge for a prolonged time does not cause damage. The self-discharge is about 40% per year, one of the best on rechargeable batteries. In comparison, nickel-cadmium self-discharges this amount in three months.

III.3 Quick Charging

Although lead-acids prefer long charging times, they can be charged fast in some applications. Quick charging can be done where power is needed for a shorter duration than usual. Below are some tables that give an approximation of quick charging at different rates.

Table 4: Quick Charging Rates and Returned Capacity

($1.5C_{10}$ inrush current)

Charge time at 2.45 vpc	Capacity returned
17 min.	50%
27 min.	80%
31 min.	90%
60 min.	100%

($2.5C_{10}$ inrush current)

Charge time at 2.45 vpc	Capacity returned
12 min.	50%
19 min.	80%
24 min.	90%
40 min.	100%

While the lead-acid cell can be charged quite fast, there does need to be some periods of extended charging time to maximize life of the cell.

Note: There are no limitations on the initial inrush current on the charger.

Constant current charging is the best method of recharging; constant voltage charging is not recommended.

III.4 MULTISTAGE CHARGING

Charging lead-acid batteries can be done manually with a commercial power supply. Calculate the charge voltage according to the number of cells. Charging a 12-volt battery (6 cells) at a cell voltage limit of 2.40V, for example, would require a

voltage setting of 14.40V. Hawker Cyclon SLA's have a range of 2.45-2.50 volts per cell.
First, set the charger (power supply) to 2.45V for each cell. *It is important to note that you must set the power supply while it is not attached to the battery pack, as the pack will discharge through the power supply.*

After setting the supply, attach it to the pack and apply power. The initial inrush current will be large (probably as much as power supply can handle) and then will gradually dwindle down to less that 100mA. Although this stage can be reached in less than an hour, it is best (especially if pack is 100% discharged) to leave it on this setting for 8-16 hours; 12 hours is sufficient. The battery pack is ~80% charged now.

Then, detach the power supply from the battery pack and set the supply to 2.27V per cell. Reattach the battery pack and leave it for an additional 8-16 hours with 12 hours again being sufficient. *This last setting is the "topping" or "float" charge and the battery pack can be left on this setting indefinitely, which compensates for the self-discharge.*

Note that Hawker Cyclon series have a large inrush current due to its low internal resistance and react very well to this large inrush current. Make sure to read the datasheet on the particular cell that is being used for information on what inrush current the cell can handle. In addition, the voltage limit shifts with temperature. A higher temperature requires slightly lower voltages and vice versa. Chargers that are exposed to large temperature fluctuations should be equipped with temperature sensors to assure optimum charge.

III.5 Float Charging

As the battery charges up, its terminal voltage increases, and the internal resistance decreases. Eventually, when it is fully charged, it will be taking a trickle current from the charge, which maintains its fully charged state. **At an ambient temperature of 25 degrees Celsius, the recommended charge voltage setting for float applications is 2.27 to 2.35 volts per cell.** This "float charge" means that the end user can just "plug in" a charger whenever he's not using the batteries in the field. The battery will be charged and kept at its maximum state of readiness until the next time it needs to be used. ***The battery can be left charging indefinitely***. The user always knows that the instrument is ready to go when it's needed. There's no need to wait until the battery is discharged before recharging. The sealed lead acid prefers to be float charged constantly, or recharged whenever it's not being used.

Aging affects each cell differently. If cells are connected in series, controlling the individual cell voltages during charge is virtually impossible. Even if the correct overall voltage is applied, a weak cell will generate its own voltage level and intensify the condition further. A weak cell may have to be replaced so as not to damage the other cells.

IV. STORAGE

SLA cells have long shelf life in that they can keep their charge for an extended time. However, for extended storage, open cell voltage should be audited every six months and the cells should be recharged when the open cell voltage approaches 2 volts per cell. If storage temperatures are significantly higher than 25 degrees Celsius, even for short durations, the frequency of the open cell voltage audit must be increased.

The cell voltages of a VRLA battery must be harmonized as close as possible. Applying an equalizing charge every 6 months brings all cells to similar voltage levels. This is done by increasing the cell voltage to 2.50V/cell for about 2 hours. During the service, the battery must be kept cool and careful observation is needed. Limit cell venting. Most VRLA vent at 5 psi. The Hawker Cyclon series can vent as high as 50 psi. Not only does escaping hydrogen deplete the electrolyte, it is highly flammable. Lead-acid must be stored in a charged state. A topping charge should be applied every six months to avoid the voltage from dropping below 2.10V/cell. Prolonged storage below the critical voltage also causes sulfation, a condition that is difficult to reverse.

Simple Guidelines

Always store lead acid in a charged condition. Never let the open cell voltage drop much below 2.10V. Apply a topping charge every six months or when recommended.

Avoid repeated deep discharges. Charge more often or use a larger battery.

Prevent sulfation and grid corrosion by choosing the correct charge and float voltages.

Avoid operating lead-acid at elevated ambient temperatures.

V. REVERSE SULFATION

In “over discharge” conditions, the sulfuric acid electrolyte can be depleted of the sulfate ion and become essentially water, which can create several problems. A lack of sulfate ions as charge conductors will cause the cell impedance to appear high and little charge current to flow. Longer charge time or alteration of charge voltage may be required before normal charging may resume. SLA batteries with mild sulfation can be restored but the work is time consuming and the results are mixed. Reasonably good results are achieved by applying a charge on top of a charge. This is done by fully charging an SLA battery, then removing it for a 24 to 48 hour rest period and applying a charge again The process is repeated several times and the capacity is checked with a final full discharge and recharge.

Another method of improving performance is by applying an equalizing charge, in which the charge voltage threshold is increased by about 100mV, typically from 2.40V to 2.50V. This procedure should last no longer than one to two hours and must be carried out at moderate room temperature. A careless equalize charge could cause the cells to heat up and induce venting due to excessive pressure. Observe the battery during the service.

The Hawker Cyclon requires slightly higher voltages to reverse sulfation. An adjustable power supply works best for the service. Set the current limit to the lowest practical setting and observe the battery voltage and temperature during charge. Initially, the cell voltage may rise to 5V, absorbing only a small amount of current. In about two hours, the small charging current converts the large sulfate crystals back into active material. The internal cell resistance decreases and the cell starts to clamp the voltage. At around 2.30V, the cell accepts charge. If the sulfation is advanced, this remedy does not work and the cell needs replacing.

VI. Charging POWER-SONIC batteries

Power-Sonic batteries are also used in some applications. The advantage to these batteries is that the company additionally sells chargers for specific cells. However, below are some guidelines for charging.
Cycle Applications: Limit initial current to 1200mA. Charge until battery voltage (under charge) reaches 2.40 to 2.50 volts at room temperature. Hold at 2.40 to 2.50 volts until current drops to approximately 60mA. Battery is fully charged under these conditions, and charger should either be disconnected or switched to “float” voltage.
“Float” or “Standby Service”: Hold battery across constant voltage source of 2.25 to 2.30 volts continuously. When held at this voltage, the battery will seek its own current level and maintain itself in a fully charged condition.

VII. CONCLUSION

Batteries are a principal means for remotely powering electronics. To maintain and maximize the potential of SLA cells, temperature and charging techniques play a crucial role. To maximize cycle duration and life of sealed lead acid cells, correct charging procedures should be followed. These cells have a lengthy charging cycle that should be taken into consideration although quick charging can be done for a short duration cycle. Temperature plays a major role in the cycle time and should be taken into consideration when implementing these cells. Below 0C, the cycle duration is greatly reduced.

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