



**VALVE-REGULATED LEAD-ACID BATTERIES
FOR STATIONARY APPLICATIONS**

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This pamphlet implements AFD 32-10, *Installations and Facilities*. It prescribes criteria for the application, selection, installation, and maintenance for valve-regulated lead-acid (VRLA) batteries on Air Force installations. Refer to AFJMAN 32-1280(I), *Facilities Engineering, Electrical Exterior Facilities*, and to AFJMAN 32-1281(I), *Facilities Engineering, Electrical Interior Facilities*, for general storage battery criteria. Users should send comments and suggested improvements on AF Form 847, *Recommendation for Change of Publication*, through major commands (MAJCOM) and HQ AFCESA/CESM, 139 Barnes Dr, Tyndall AFB FL 32403-5319 to HQ USAF/ILEO, 1260 Air Force Pentagon, Washington DC 20330-1260.

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Chapter 1

PURPOSE AND APPLICABILITY

1.1. Purpose. This AFMAN has been issued to provide users with application, selection, installation, and maintenance guidance for valve-regulated lead-acid (VRLA) batteries. The purpose of the requirements contained in this AFMAN is to assure the most reliable system possible with VRLA batteries. VRLA batteries are relatively new to the market and they have exhibited different aging and failure modes than traditional vented batteries. For this reason, this AFMAN provides a detailed explanation of VRLA battery design, degradation, and failure. Traditional vented lead-acid batteries are discussed only to the degree necessary to explain key differences between vented and VRLA batteries. The background information is educational in nature and is intended to provide insight into the purposes of the requirements for VRLA battery application, installation, and maintenance.

1.2. Need for Special Maintenance Procedures. VRLA batteries are more likely to fail before the end of their stated service life than are traditional vented lead-acid batteries, and their failure can be harder to detect by conventional methods. The maintenance requirements contained in this AFPAM are necessary to detect the onset of individual cell failures before the reliability of the entire battery is jeopardized. Detailed maintenance procedures are included to facilitate the required maintenance.

1.3. Material Covered. The complete life cycle of VRLA batteries is covered in this AFPAM, including selection, application, installation, periodic maintenance, testing, and eventual replacement.

1.4. Applicability:

1.4.1. Authority. This AFPAM complies with Air Force Instruction 32-1080, Electric Power Systems.

1.4.2. Type of Systems Covered. Compliance with the AFPAM is mandatory for VRLA stationary batteries in exterior and interior electrical systems that are the responsibility of the Base Civil Engineer at all facilities and bases. This AFMAN does not apply to motive power, air ground equipment (AGE), or aircraft batteries.

Chapter 2

LEAD-ACID BATTERY FUNDAMENTALS

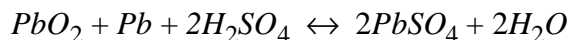
2.1. Electrochemical Process:

2.1.1. A battery provides electrical power by converting its stored chemical energy into electrical energy. This energy conversion is achieved by a chemical reaction in the battery that releases electrons. The process is reversible in a stationary battery. If a load is placed across the battery terminals, the chemical reaction produces electrical power. If electrical energy is directed into the battery (charging the battery), the chemical reaction reverses and restores the battery to a fully charged condition.

2.1.2. The generation of electrical current from a cell originates from a difference in electrochemical potential between two compounds inside the cell that are not in direct contact, but are connected by an electrically conducting medium. The two compounds are installed in the cell as positive and negative plates, and the connecting medium between the two plates is referred to as the electrolyte. As the plate materials chemically react with the electrolyte, a potential difference is created between the plates and the electrolyte. The positive plates have a positive potential in relation to the electrolyte; the negative plates have a negative potential in relation to the electrolyte. The electrochemical process between the plates and electrolyte creates a voltage between the positive and negative plates of the cell.

2.1.3. In a lead-acid battery, the positive plate material is lead dioxide (PbO_2) and the negative plate material is lead (Pb). The plate material is often referred to as the active material. The electrolyte is a sulfuric acid solution (H_2SO_4).

2.1.4. The overall chemical reaction within a lead-acid battery is described as the *full cell* reaction, and is given by:



2.1.5. Several observations can be made regarding the electrochemical process of a lead-acid battery:

2.1.5.1. When the battery terminals are connected to an external circuit, the current that flows from the battery is proportional to the potential difference of the plates and is limited mainly by the circuit resistance. The external connection provides a flow path for electrons, and thereby facilitates the conditions needed to sustain the chemical reaction. If the external circuit resistance is too small (short circuit), the current flow is limited mainly by the efficiency of the chemical reaction.

2.1.5.2. The sulfuric acid electrolyte is consumed in the discharge reaction and water is produced. Thus, the acid is continuously diluted during discharge. The decreasing concentration of acid in the electrolyte represents a decrease in the state of charge of the battery.

2.1.5.3. The active materials of both plates, lead and lead dioxide, are consumed during the discharge reaction and lead sulfate is produced. The lead sulfate is deposited onto both positive and negative plates as it is produced. Thus, the material composition of the plates changes during discharge.

2.1.5.4. The cell becomes less able to sustain the chemical reaction as the concentration of active material and acid decreases during discharge. Eventually, the quantity of active material or sulfuric acid (depending on which is limiting) is not sufficient to maintain the reaction at a rate that produces measurable current flow.

2.1.5.5. The injection of electrical energy into a battery during charging reverses the chemical reaction in the cell. To drive the chemical reaction in the charge direction, the battery must absorb energy. Thus, during charging, electrical energy is transformed to chemical energy.

2.1.5.6. Because the electrolyte is conductive, the chemical reaction can occur without an external circuit, and is referred to as self-discharge or local action. Self-discharge is usually a slow process; an open-circuit cell might take several months to over a year before it fully discharges.

2.2. Lead-Acid Battery Construction:

2.2.1. Basic Construction:

2.2.1.1. A lead-acid battery consists of individual cells connected together to provide the desired output voltage. A single cell consists of positive and negative plates assembled inside a container that is filled with a sulfuric acid electrolyte. The following basic components are assembled to make a cell:

- 2.2.1.1.1. Container
- 2.2.1.1.2. Lead dioxide positive plates
- 2.2.1.1.3. Lead negative plates
- 2.2.1.1.4. Separators and retainers
- 2.2.1.1.5. Sulfuric acid electrolyte

2.2.1.2. These components make up the basic building blocks of a lead-acid cell; their design and the method of construction vary according to the intended application. The following characteristics are commonly changed to tailor a battery to a specific application:

- 2.2.1.2.1. Plate and grid alloy material, alloy concentration, or geometry
- 2.2.1.2.2. Number of plates
- 2.2.1.2.3. Separator material type and thickness
- 2.2.1.2.4. Retainer design
- 2.2.1.2.5. Electrolyte specific gravity
- 2.2.1.2.6. Post seal design (copper inserts) or number of posts

2.2.2. Plate Design:

2.2.2.1. Lead-acid cells are defined by their plate construction and the alloys used in the plates. The *pasted flat plate* is the most common design for vented and VRLA cells. When a pasted flat plate is assembled, lead oxide (PbO) paste is applied to a lead alloy grid structure, and then allowed to dry in place. The lead oxide paste is called the active material. A grid structure containing the active material is a plate. Typical grids for a pasted flat plate are shown in [figure 2.1.](#) After the lead oxide paste has dried, the plates are immersed in a dilute sulfuric acid solution and

current is passed through them, with opposite polarities for the positive and negative plates. The lead oxide (PbO) is converted to lead dioxide (PbO_2) in the positive plates and to lead (Pb) in the negative plates. Figure 2.2. shows typical pasted flat plates with the active material in place.

Figure 2.1. Typical Positive and Negative Grids.

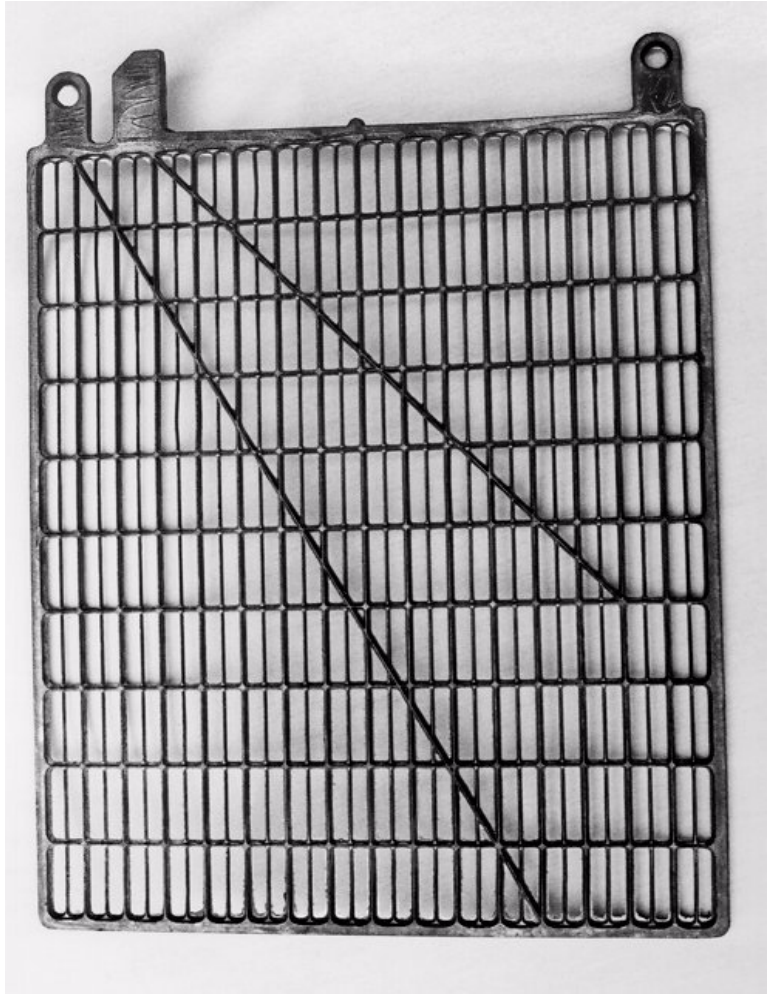


Figure 2.1. Continued.



Figure 2.2. Typical Positive and Negative Pasted Flat Plate.

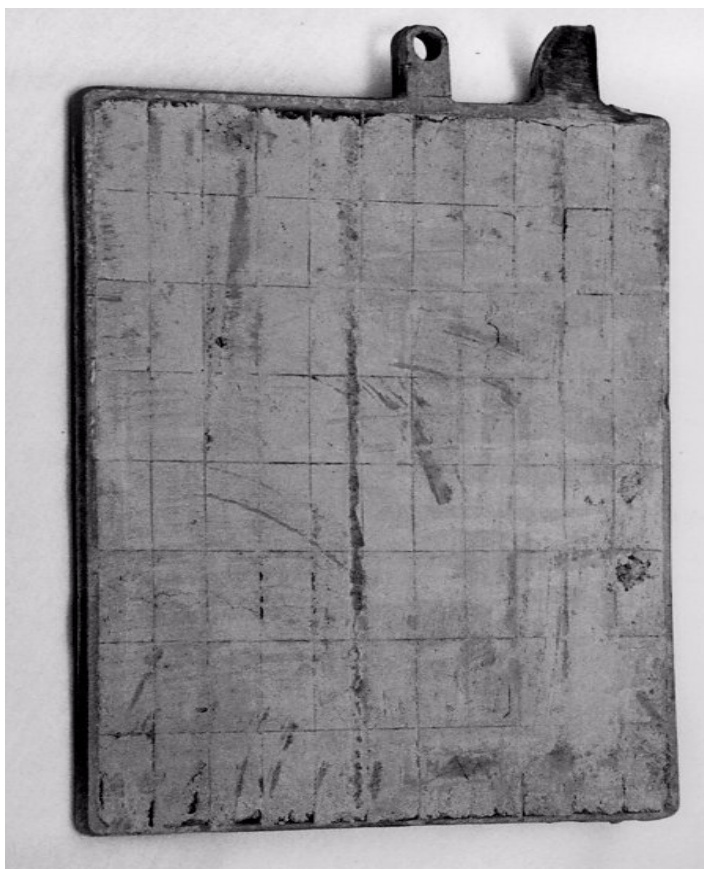
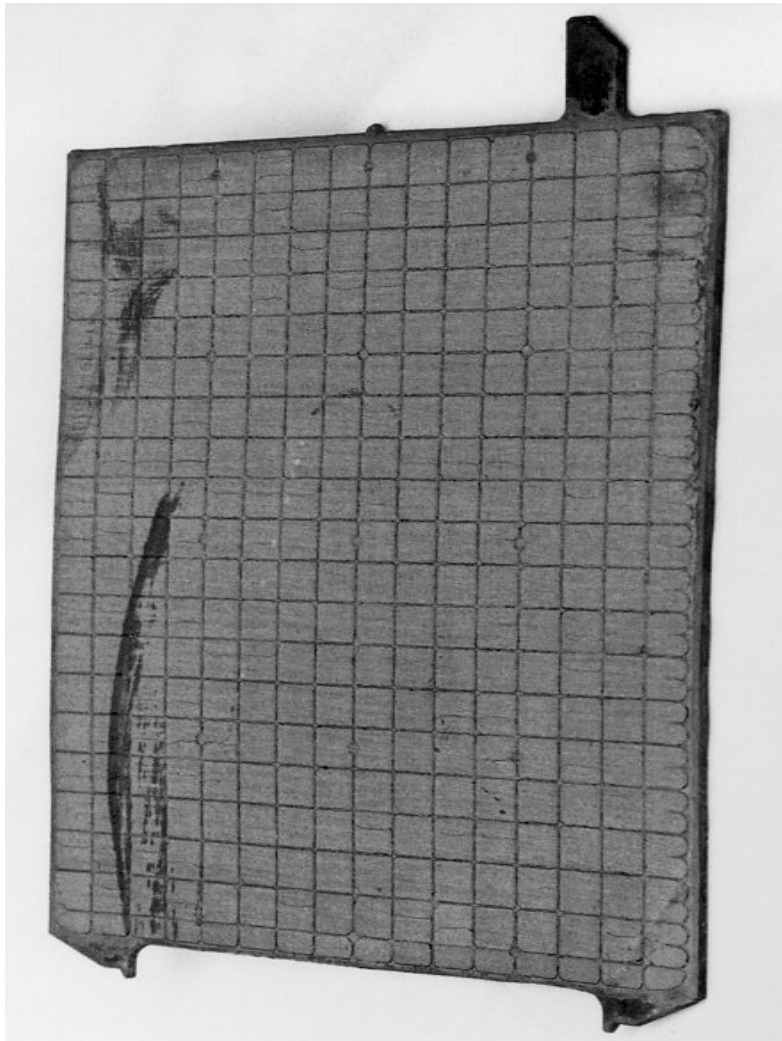
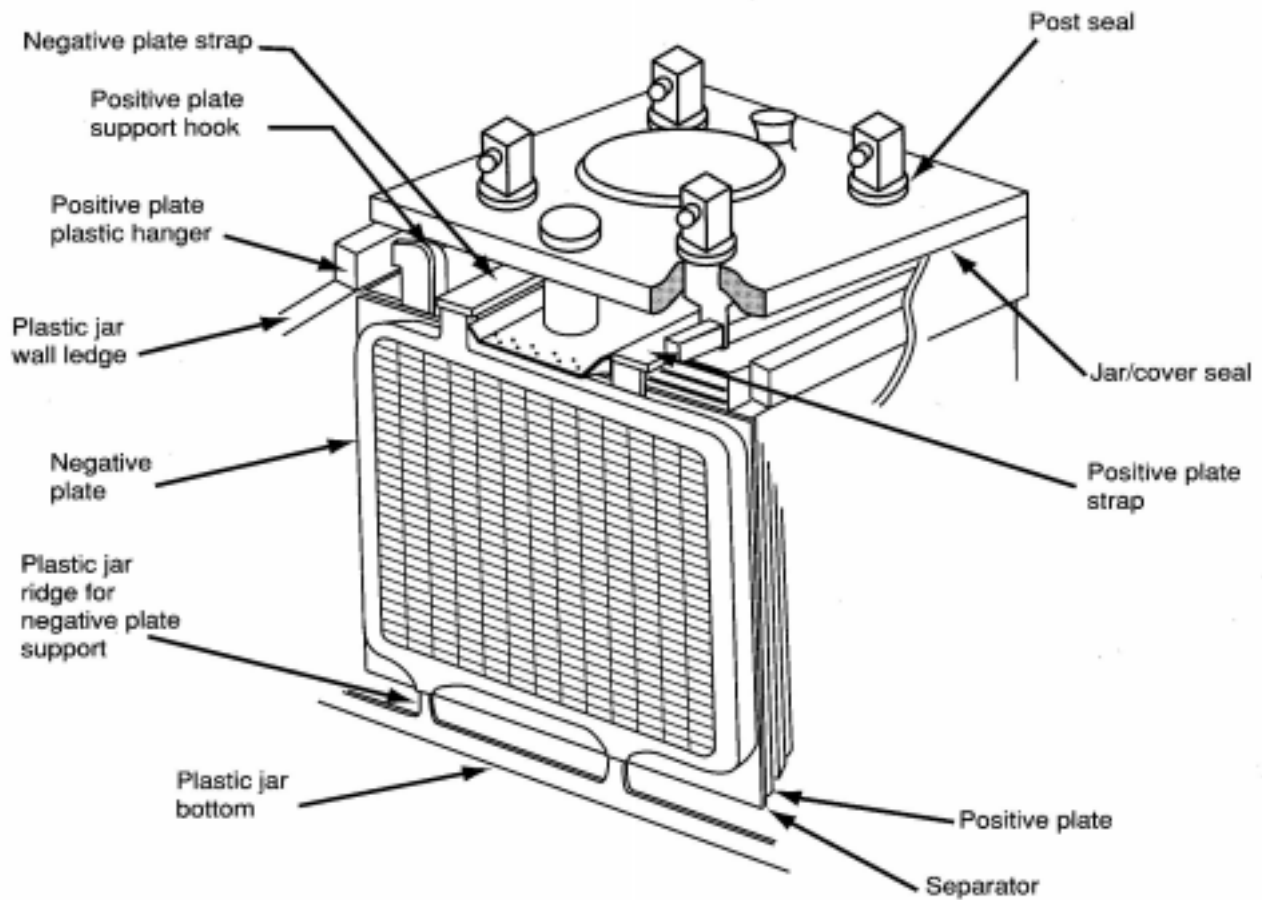


Figure 2.2. Continued.



2.2.2.2. Pasted flat plates are installed vertically in the cell. The plates are fused at the top of the cell to straps and posts, which conduct current from the plates to external cell connections. Positive plates might hang from the positive plate straps or container sidewalls, or might be cantilevered from the negative plates. The negative plates are usually supported by the negative plate straps and by feet that rest on the floor of the battery case. The plate support design is an important part of cell long-term battery reliability. Positive plates gradually grow larger during the service life. This plate growth must not place excessive internal stress or pressure on the container. A typical assembly of the plates into a cell container is shown in [figure 2.3](#).

Figure 2.3. Plate Assembly in Cell.



2.2.2.3. The grid structure of the cell has two functions:

2.2.2.3.1. To provide mechanical support for the active material, which does not by itself have the strength to be self-supporting.

2.2.2.3.2. To act as a conductor to transmit current from all parts of the active material to the plate terminal. The ideal grid design should maintain a uniform current distribution throughout the active material. An uneven current distribution could result in buckling of the plates during charge and discharge cycles.

2.2.2.4. The ideal grid has the following characteristics:

2.2.2.4.1. High conductivity

2.2.2.4.2. High strength

2.2.2.4.3. Corrosion resistance

2.2.2.4.4. Compatibility with the active materials

2.2.2.4.5. Manufacturability

2.2.2.5. Simultaneously achieving the above ideal grid characteristics is part of the art of battery construction. The grid is usually composed of a lead alloy in which the lead is hardened by the

alloy so that the grid can support the plate assembly. Lead calcium-based grids are commonly used for VRLA cell designs. Other materials might also be added to the basic lead calcium design to improve operational or manufacturing performance. For example, tin (0.3% to 0.6%) has been added to some lead calcium grids to:

2.2.2.5.1. Increase the grid alloy tensile strength.

2.2.2.5.2. Improve the ease of handling during manufacturing.

2.2.2.5.3. Inhibit passivation (a high resistance boundary) between the grid and active material on the positive plate.

2.2.2.6. Stationary batteries normally have n positive plates and $n+1$ negative plates. In this design, negative plates are on both sides of each positive plate to ensure that the positive plate chemical reaction is balanced. Otherwise, the more age-sensitive positive plate could expand abnormally or buckle because of an uneven chemical reaction rate.

2.2.3. Electrolyte:

2.2.3.1. The electrolyte in a lead-acid battery is a mixture of sulfuric acid and water. Specific gravity is a measure of the density of a liquid. The specific gravity of the electrolyte indicates the amount of sulfuric acid in the cell. Pure water has a specific gravity of 1.0 and the specific gravity of other liquids is usually expressed in relation to that of water. The lead-acid cell electrolyte specific gravity typically varies from 1.210 to 1.300, depending on the particular cell design. Most vented stationary cells have a specific gravity between 1.210 to 1.240. VRLA batteries commonly use electrolyte with a higher specific gravity (typically between 1.250 to 1.300) to compensate for a smaller quantity of electrolyte in the cell.

2.2.4. Separators:

2.2.4.1. Separators are installed between the plates to prevent the plates from touching and shorting. A separator is constructed of a porous, nonconductive, inert material that allows conduction of electrolyte ions between the plates.

2.2.5. Container Construction:

2.2.5.1. The battery components are enclosed in a plastic jar that functions as a leak proof container for the electrolyte. The top cover is bonded to the jar and a flame arrestor vent is installed on the cover to allow charge gases to escape.

2.2.5.2. The positive and negative cell terminals are usually designed for bolted connections and are often constructed of alloyed lead. Some batteries contain copper reinforcement inserts to improve conductivity and optimize high discharge rate performance. Copper inserts are typically used on the larger cells.

2.2.5.3. Jar-to-cover and terminal post seals are critical features of a cell design. A poor seal can contribute to the following problems:

2.2.5.3.1. Acid creepage up the post causing increased corrosion

2.2.5.3.2. Acid creepage up the post causing increased connection resistance, which can affect capacity or, in severe cases, result in post meltdown during discharge

2.2.5.3.3. Cell gases venting without the protection of a flame arrestor

2.2.5.3.4. Electrical faults which can lead to fire or electrical shocks

2.2.5.3.5. Air in-leakage to a VRLA cell that can lead to self-discharge

2.3. Electrical Characteristics:

2.3.1. Voltage:

2.3.1.1. A fully charged lead-acid cell has an open circuit voltage (OCV) of approximately 2.05 V to 2.15 V; the exact voltage varies with the electrolyte specific gravity and temperature. The OCV increases as the specific gravity increases, and decreases as the temperature decreases. The OCV varies with electrolyte specific gravity by the following relationship:

$$OCV = \text{Specific gravity} + 0.845$$

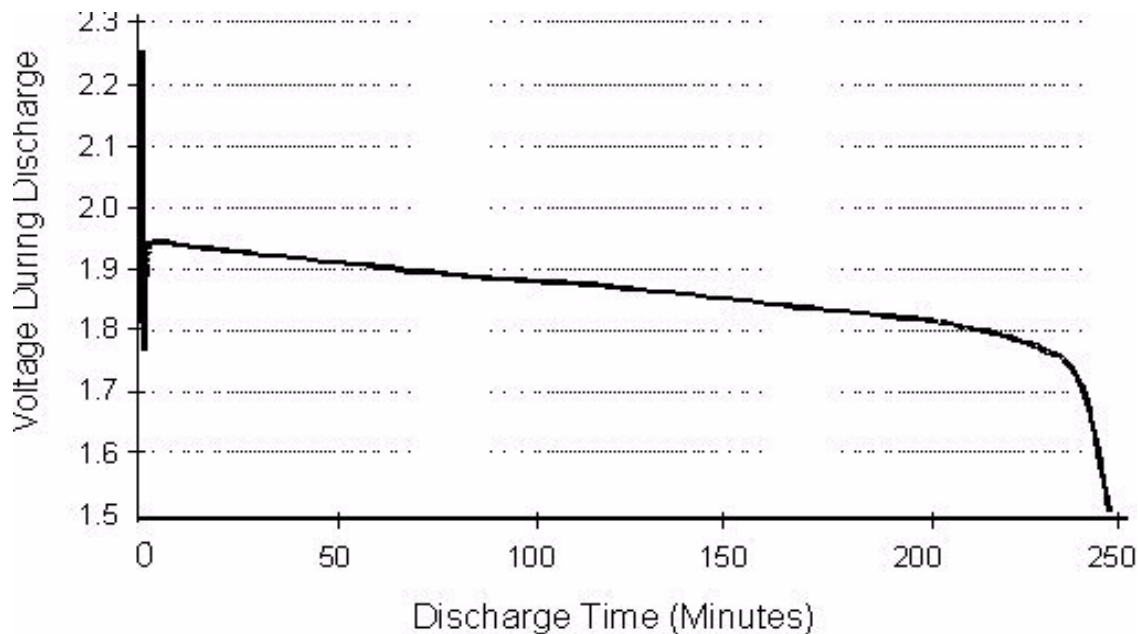
2.3.1.2. For example, the OCV of a cell with an electrolyte specific gravity of 1.215 is 2.06 V ($1.215 + 0.845 = 2.06$). The OCV of a cell with an electrolyte specific gravity of 1.300 is 2.15 V ($1.300 + 0.845 = 2.15$).

2.3.1.3. The charging float voltage must be greater than the cell OCV to overcome the cell's internal resistance and allow charging current to flow through the cell. The actual difference between the cell OCV and the desired charging float voltage is a function of the grid alloy type, specific gravity, and temperature, but is usually in the range of 0.10 to 0.20 V at 25°C (77°F).

2.3.1.4. When a lead-acid battery is at full capacity, receiving a trickle charge from the battery charger, it is said to be on a float charge. A float charge overcomes the battery's natural tendency to self-discharge, thereby keeping it fully charged. The float voltage for a lead-acid battery depends on the individual cell design and temperature. The optimal float voltage is determined by the manufacturer. An equalizing charge is intended to recharge the battery quickly and to completely restore the active materials in the plates. An equalizing charge is performed at a higher voltage than a float charge; the recommended equalize voltage value varies with the battery design and electrolyte specific gravity.

2.3.2. Discharge Characteristics:

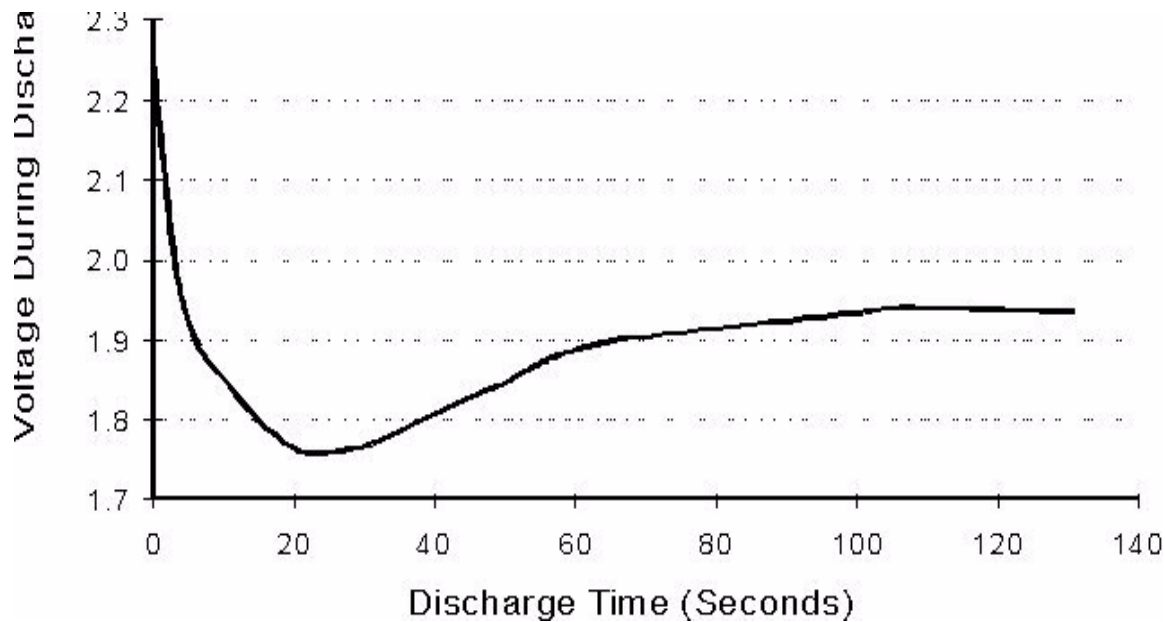
2.3.2.1. The expected voltage profile for a battery undergoing a constant current discharge is shown in [figure 2.4](#). The battery experiences an initial drop in voltage when it begins to discharge. After the voltage stabilizes from its initial drop, the voltage gradually decreases with time as the active materials and sulfuric acid are consumed in the chemical reaction. Toward the end of discharge, insufficient quantities of active material or sulfuric acid exist to sustain the chemical reaction and the voltage declines rapidly.

Figure 2.4. Typical Cell Voltage Profile During Constant Current Discharge.

2.3.2.2. A battery is often considered to be discharged when its voltage reaches 1.75 VPC during a discharge at its rated capacity. However, the system design could require a higher voltage (or allow a lower voltage) to meet the voltage requirements of all components. For some high-rate discharge applications, the battery manufacturer might provide discharge ratings for end voltages as low as 1.5 VPC. Manufacturers rarely provide discharge ratings below 1.5 VPC; once voltage has fallen this low, the rate of voltage decline is very rapid and little additional energy can be removed from the battery at that discharge rate.

2.3.2.3. Notice that [figure 2.4.](#) shows an initial voltage drop that quickly recovers, followed by a long slow discharge thereafter. Figure 2.5. shows in greater detail the discharge voltage characteristic at the beginning of the discharge. The initial voltage drop observed during discharge occurs because of two effects. First, the loss of the battery charger float voltage causes the battery voltage to fall to its open circuit voltage, or lower; the amount of voltage drop depends on the discharge rate. An additional temporary voltage dip might be also observed in which the battery voltage initially falls to some minimum level, followed by a slow recovery to a slightly higher voltage during the first few minutes of discharge. This initial voltage dip is referred to as the *coup-de-fouet* and its effect is primarily observed on stationary lead-acid batteries that have been maintained on a long-term float charge.

Figure 2.5. Typical Voltage Dip at Beginning of Discharge.



2.3.2.4. The coup-de-fouet primarily occurs with batteries on long term float for the following reason. The float charge process maintains the positive plates in a nearly fully charged condition, in which the active material is all lead dioxide, PbO_2 , with very little lead sulfate, $PbSO_4$, present under ideal conditions. During discharge, lead dioxide is converted to lead sulfate. However, the chemical reaction is better facilitated when a lead dioxide molecule is located adjacent to a lead sulfate molecule. In other words, the chemical reaction process improves in efficiency as lead sulfate sites are generated. During the initial moments of discharge, the chemical reaction is slightly less efficient, with the result that the voltage can dip to a lower than expected value and slowly recover from this voltage dip during the first few minutes of discharge as these lead sulfate sites are created.

2.3.2.5. The coup-de-fouet effect is described here because it can limit the high-rate discharge capability of a particular cell design. Some users have been caught by surprise during the first minute of a high-rate discharge. In the 1980s, some UPS users experienced a high rate discharge on their system in which battery voltage would fall below the low-voltage cutout of the UPS during the first minute of discharge. After resetting the low-voltage cutout, the UPS would perform normally without again actuating its low-voltage cutout. After further investigation, it was discovered that the coup-de-fouet dip during the first discharge had fallen low enough to trip the low-voltage cutout. But, in so doing, enough lead sulfate sites had been established that the subsequent battery discharge at the same rate would not experience as low of a dip. Some battery manufacturers were forced to derate their cell ratings to account for this effect.

2.3.2.6. In summary, the ideal long duration discharge has the following discharge characteristics:

2.3.2.6.1. An initial prompt voltage drop, followed by

2.3.2.6.2. A modest recovery in voltage during the first few minutes of discharge, followed by

2.3.2.6.3. A gradual and almost linear voltage drop during most of the discharge period, and

2.3.2.6.4. A rapid nonlinear voltage drop at the end of discharge

2.3.3. Capacity:

2.3.3.1. The rate (amperes or power) at which a lead-acid battery is discharged directly affects the ampere-hours that the battery can deliver—as the discharge rate increases, the ampere-hours that can be realized from the battery decreases. Decreased capacity at higher discharge rates is due to the following effects:

2.3.3.1.1. Less time is available for diffusion of electrolyte into the porous lead plates. The higher the discharge rate, the more the chemical reaction is limited to the surface of the plates.

2.3.3.1.2. The discharge chemical reaction process forms larger lead sulfate on the surface of the plates, which tends to close pores in the plates, thereby slowing electrolyte access to the remaining active material.

2.3.3.1.3. Voltage loss occurs more quickly because of increased cell internal resistance during discharge.

2.3.3.2. Battery capacity is normally described in terms of the number of ampere-hours or watts that the battery can supply for a specified time before voltage falls below a minimum value. A battery capacity rating for a typical battery is provided in [table 2.1](#). If the battery depicted in the table is discharging at 360 amperes, it is said to be discharging at the 5-hour rate. The table shows that total capacity is reduced at higher loads, as discussed previously. For example, a load of 250 amperes can be sustained for 8 hours (total capacity = 250 amperes x 8 hours = 2,000 ampere-hours). However, a load of 950 amperes can be maintained only for 1 hour (capacity = 950 ampere-hours).

Table 2.1. Typical Capacity Rating.

Discharge Time (hours to end voltage)	Capacity (ampere-hours)	Effective Discharge Rate (amperes)
8	2,000	250
5	1,800	360
3	1,500	500
1	950	950

2.3.3.3. The available battery capacity depends on the minimum allowed cell voltage during discharge. Manufacturers often provide capacity values referenced to 1.75 VPC end voltage at 25°C (77°F). If the user's application requires a higher minimum voltage, such as 1.81 VPC, the cell will not be able to provide the rated discharge for as long as it can to 1.75 VPC. Thus, the cell effectively has less available capacity as the minimum voltage requirement is increased.

2.3.4. Temperature Effects:

2.3.4.1. Temperature affects lead-acid battery performance. For the sake of standardization, battery performance ratings are normally specified at a temperature of 25°C (77°F). A lead-acid battery is an electrochemical device whose characteristics vary with temperature; heat accelerates chemical activity and cold slows it down. A change in the electrolyte temperature from the reference temperature has two significant effects on lead-acid battery performance:

2.3.4.1.1. The battery capacity decreases as the temperature drops below 25°C (77°F).

2.3.4.1.2. The battery life decreases as the temperature rises above 25°C (77°F).

2.3.4.2. At temperatures lower than 25°C (77°F), the battery cannot provide its rated capacity. In general, a lower temperature increases the viscosity of the electrolyte, and thus restricts its ability to circulate into the plates. Also, the efficiency of the chemical reaction decreases as temperature decreases.

2.3.4.3. Temperature variations have an opposite effect on battery life. The battery's positive plate corrosion rate increases exponentially as the electrolyte temperature rises above 25°C (77°F); sustained battery operation above 25°C (77°F) shortens battery life. For example, a common rule of thumb for lead-acid batteries is that an 8.3°C (15°F) average temperature rise decreases battery life by 50%.

2.3.4.4. The temperature characteristics of the battery must be evaluated at the design stage on the basis of the expected temperature environment. A battery located in a cold area might require derating to ensure that sufficient capacity is available to power the connected load for the specified duration. A battery in a high-temperature area will fail before reaching its advertised service life. Rated capacity and life are simultaneously obtained only when the battery is operated near 25°C (77°F).

2.4. Valve-Regulated Lead-Acid (VRLA) Battery Design:

2.4.1. Introduction to the VRLA Battery:

2.4.1.1. The previous sections provided technical information generally applicable to all lead-acid batteries, including both vented and VRLA types. This section provides design features unique to the VRLA battery.

2.4.1.2. The VRLA battery is an innovative design with many useful applications. It is effectively sealed such that the user can not gain access to the electrolyte. And, the electrolyte is immobilized so that it is not a free liquid as in a vented cell, with the result that a VRLA cell will leak little or no electrolyte if the container case is damaged.

2.4.1.3. Traditional vented lead-acid battery maintenance practices such as verifying electrolyte level and adding water cannot be performed on a VRLA battery because each cell is effectively sealed and the interior is inaccessible. VRLA batteries have been called *sealed* batteries because they are completely sealed except for a pressure relief valve that opens as needed to vent excess internal pressure. They have also been called *maintenance-free* batteries because periodic water addition is not allowed by the design. However, VRLA batteries are neither truly sealed nor maintenance free. The term *starved electrolyte* has also been used to describe VRLA batteries, referring to a lack of excess electrolyte. As the term starved electrolyte implies, the capacity of a VRLA battery can be limited by its electrolyte quantity. The term *valve-regulated* has become the standard name for this type of lead-acid battery. A typical VRLA cell is shown in [figure 2.6](#).

Figure 2.6. Typical VRLA Cell.

2.4.1.4. A bank of VRLA cells is often configured very differently than is a conventional vented battery bank. Vented cells must sit upright on racks to prevent electrolyte from spilling out of the flame arrestor or service ports. VRLA batteries have fewer limitations on cell orientation because the electrolyte has been immobilized. Manufacturers have capitalized on this feature to reduce the overall installed battery footprint. By installing the cells sideways in stackable modules, manufacturers have reduced the total required floor space for an installation. A horizontal installation of VRLA cell modules is shown in [figure 2.7](#).

Figure 2.7. VRLA Battery Installed Horizontally (Shown With and Without Protective Covers).

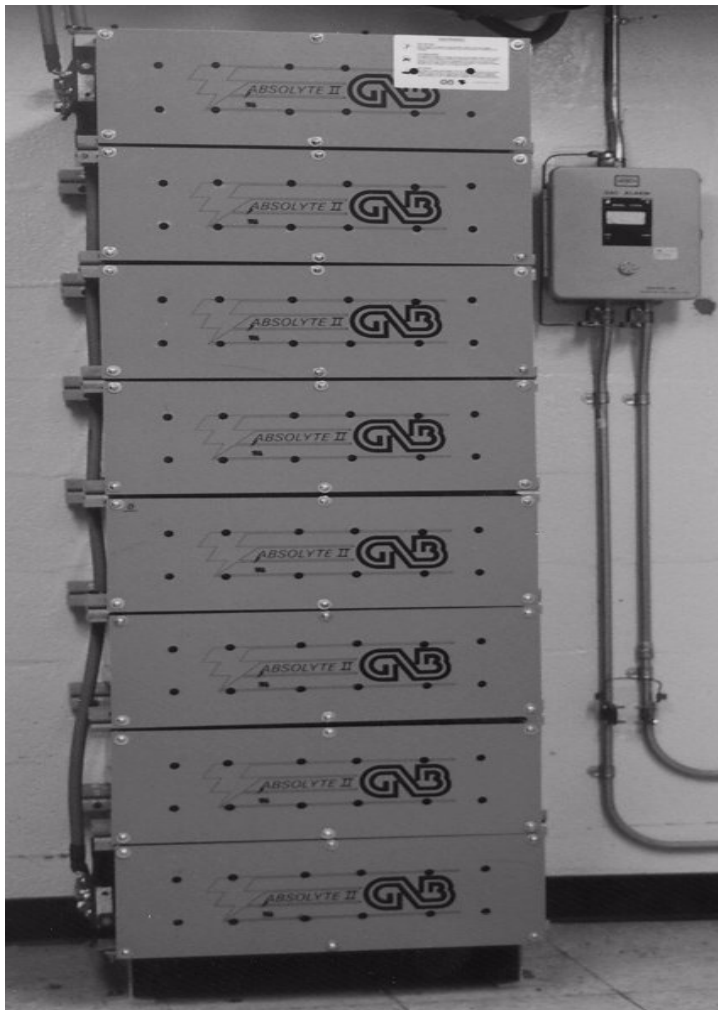
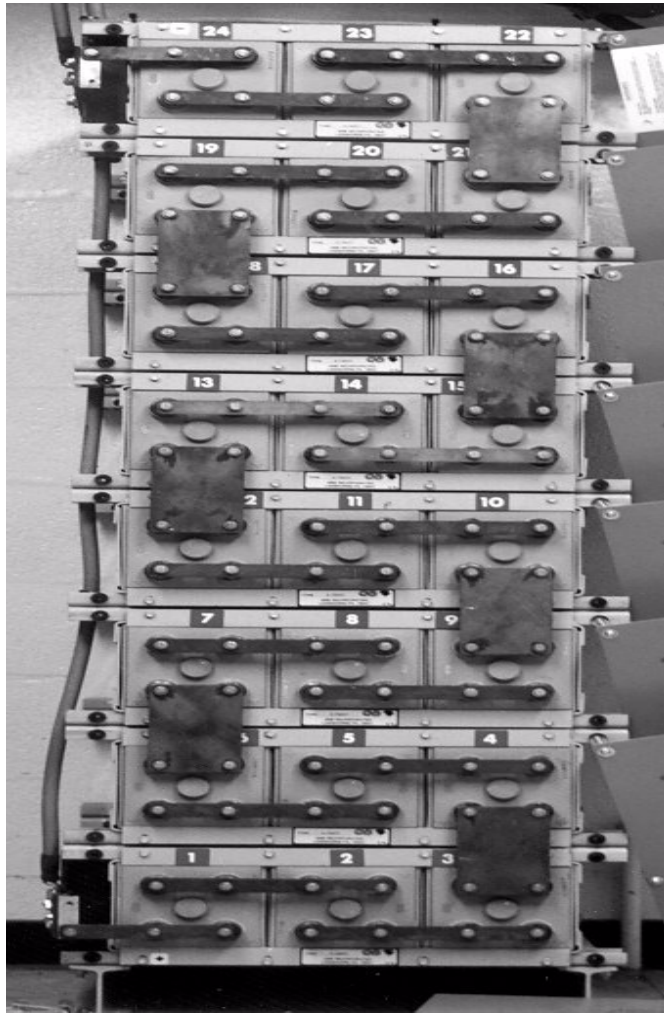
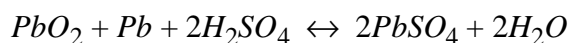


Figure 2.7. Continued.



2.4.2. Recombination Cycle:

2.4.2.1. The internal charge and discharge chemical reaction of a VRLA cell is the same as that in a vented cell. During discharge, lead on the negative plate and lead dioxide on the positive plate combine with sulfuric acid in the electrolyte to form lead sulfate on the plates and release electrons:



2.4.2.2. The above chemical reaction represents the net overall process; the actual chemical reaction on each plate is considerably more complex. The chemical reaction is also reversible so that the cell can be recharged. During standby float-charge operation, the applied charge is intended to maintain the cell in a fully charged condition. In either a vented or VRLA cell, charging current beyond that necessary to overcome the cell's tendency to self-discharge causes water to be dissociated into oxygen and hydrogen. In a vented cell, this lost water must periodically be replaced. VRLA batteries provide a means of recombining these charge gases, which reduces water loss.

Oxygen gas that evolves at the positive plate is allowed to migrate through the electrolyte to the negative plate, where the recombination reaction occurs. In a properly operating VRLA cell, oxygen is generated at the positive plate, but hydrogen generation at the negative plate is suppressed by the recombination process. The primary factor in a VRLA cell's ability to recombine charge gases is its efficiency in transporting the oxygen generated at the positive plates to the negative plates. When operating properly, a VRLA cell can recombine charge gases with an efficiency approaching 100%.

2.4.3. VRLA Cell Construction:

2.4.3.1. Absorbed Electrolyte Construction:

2.4.3.1.1. Two VRLA cell designs are available and they are completely different in their approach to immobilizing the electrolyte. The two types are the absorbed electrolyte and the gelled electrolyte.

2.4.3.1.2. An absorbed electrolyte design is constructed with the liquid electrolyte contained in highly absorbent glass mat separators positioned between the plates. This type of cell is called an absorbed glass mat (AGM) cell by some manufacturers. Absorbed electrolyte systems generally have a low internal resistance that allows the cell to provide a very high rate current.

2.4.3.1.3. The mat holds the electrolyte in place by capillary action, similar to the way a sponge holds water. The electrolyte is distributed throughout the mat and the mat is compressed between the plates to maintain the electrolyte in contact with the active material of the plates.

2.4.3.1.4. Achieving oxygen transport for an absorbed electrolyte cell involves creating voids, or gas channels, in the liquid-saturated mat through which the oxygen can migrate from the positive to the negative plates. Voids exist because the mats are filled to only 90% to 95% of their total capacity. With 5% to 10% of a mat's volume not filled, there are channels that allow oxygen migration.

2.4.3.1.5. One consequence of only partially filling the mat is that AGM cells can be limited in their capacity by the quantity of sulfuric acid in the electrolyte. A vented cell has a large electrolyte reserve, with the electrolyte level well above the top of the plates, and it is rarely capacity-limited by the electrolyte. At best, an AGM cell starts with the electrolyte level at the top of plates because the mat is wrapped around the plates and is not fully saturated with electrolyte. This makes the AGM cell particularly susceptible to a loss of capacity if any electrolyte is lost. The gradual loss of water from an AGM cell is referred to as *dryout* and is described in detail in paragraph 3.2.1.

2.4.3.2. Gelled Electrolyte Construction:

2.4.3.2.1. The gelled electrolyte cell design is similar to a vented cell except that the electrolyte has been *gelled* to immobilize it in place. The electrolyte is combined with a silica compound to create the gelled solution. In addition to gelling the electrolyte, the silica also facilitates oxygen transport from the positive to the negative plates.

2.4.3.2.2. The primary method of oxygen transport in a gelled electrolyte cell is through microscopic cracks created in the gel after a short period of operation. Initially, the gel has few cracks; therefore, oxygen transport is poor and the cell recombination efficiency is low when

the cell is first placed in service. This condition results in some water loss during the early stages of operation. The water loss causes the gel to contract, forming microscopic cracks in the gel structure. As the cracks are formed, oxygen transport is facilitated and the recombination efficiency increases to a steady-state level. Water loss is minimized after the cell enters the recombinant mode of operation. The silica added to the electrolyte also tends to increase the rate of oxygen transport by allowing oxygen to move over the surface of the silica chains, fibers, or filaments.

2.4.3.2.3. One consequence of the gelled electrolyte design is that it vents gases during the first several months of operation until it finally becomes recombinant. This means it vents hydrogen just like a vented cell during its early life. Manufacturers' literature might state that VRLA cells vent little or no hydrogen during normal operation, but the literature often does not address the potential for hydrogen emission when first placed in service.

2.4.3.2.4. The gelled electrolyte cell can have a higher internal resistance than the absorbed electrolyte cell, and might not be as effective for high rate/short duration discharges. In some respects, the gelled design can be thought of as a vented cell in which the liquid has been immobilized by gelling it. The gelled design has a greater electrolyte reserve than the AGM cell and is usually better suited for long duration applications. A gelled electrolyte cell is typically heavier and larger than an absorbed electrolyte cell for a given capacity.

2.4.3.2.5. The gelled electrolyte cell is not as widely used as the AGM cell. The AGM cell is easier to manufacture and recycle. Also, the AGM cell usually has a higher power density in a smaller footprint.

2.4.3.3. Pressure Relief Valve:

2.4.3.3.1. The VRLA cell is sealed such that the user can not add water to it. But, the VRLA is not completely sealed; its design includes a pressure relief valve to limit the maximum internal pressure of the cell, maintain a minimum internal pressure to promote recombination and minimize water loss, and prevent atmospheric oxygen from entering the cell and discharging the negative plates.

2.4.3.3.2. Depending on the design, VRLA cells typically operate with a positive internal pressure of 0.5 to 6 psig. The pressure relief valve vents any pressure exceeding the design limit.

2.4.3.3.3. The pressure relief valve must be able to open and reseal within a fairly narrow pressure band. Although the pressure relief valve must be capable of opening to prevent cell over-pressurization under abusive conditions, it is also critical that it recloses properly. Air (containing oxygen) entering through an open pressure relief valve will eventually discharge the negative plate by a chemical reaction with the oxygen in the air and cause a permanent loss of capacity. Proper pressure relief valve operation is vital to continued operation of the cell. Typical design constraints placed on the pressure relief valve by manufacturers include:

2.4.3.3.3.1. Vent pressure should be low to minimize pressure bulging of the container.

2.4.3.3.3.2. Vent pressure should change very little as the gassing rate increases.

2.4.3.3.3.3. Vent outlet should be as large as possible to insure rapid venting.

2.4.3.3.3.4. Valve elastomer material should be resistant to ozone cracking and acid.

2.4.3.3.3.5. Under static conditions, air must not be able to enter the cell.

2.4.4. Operational Characteristics:

2.4.4.1. Electrolyte Concentration:

2.4.4.1.1. A vented lead-acid cell has a substantial electrolyte reserve and its capacity is usually limited by the quantity of active material in its plates. The term *starved electrolyte* has been used to describe VRLA batteries, typically referring to the limited quantity of electrolyte in an AGM cell. Depending on the design, the capacity of a VRLA cell can be limited by its electrolyte quantity.

2.4.4.1.2. Manufacturers have attempted to improve VRLA battery capacity by increasing the electrolyte specific gravity of some AGM cells to as high as 1.300 (typical vented stationary batteries have a specific gravity of 1.210 to 1.240). A higher specific gravity means that more sulfuric acid is available to participate in the chemical reaction during discharge. Increasing the specific gravity also affects VRLA operating characteristics such as float voltage range and rated life. The gelled electrolyte design typically has a greater electrolyte reserve than the AGM design and generally does not require as high of a specific gravity to compensate for electrolyte-limited capacity.

2.4.4.2. Electrical Characteristics:

2.4.4.2.1. The electrical characteristics described in paragraph 2.3. apply to both vented and VRLA cells. The principal electrical difference between the two types is how the float voltage is distributed across the positive and negative plates. This section explains this key difference between vented and VRLA cells.

2.4.4.2.2. Float voltage is applied by the charger to maintain each cell fully charged. If the float voltage is too low, the cells can self-discharge and slowly lose capacity. If the float voltage is too high, the cells are overcharged, causing gassing and premature aging. Each battery type has a particular float voltage range within which optimal performance is expected—the battery remains fully charged without significant overcharging.

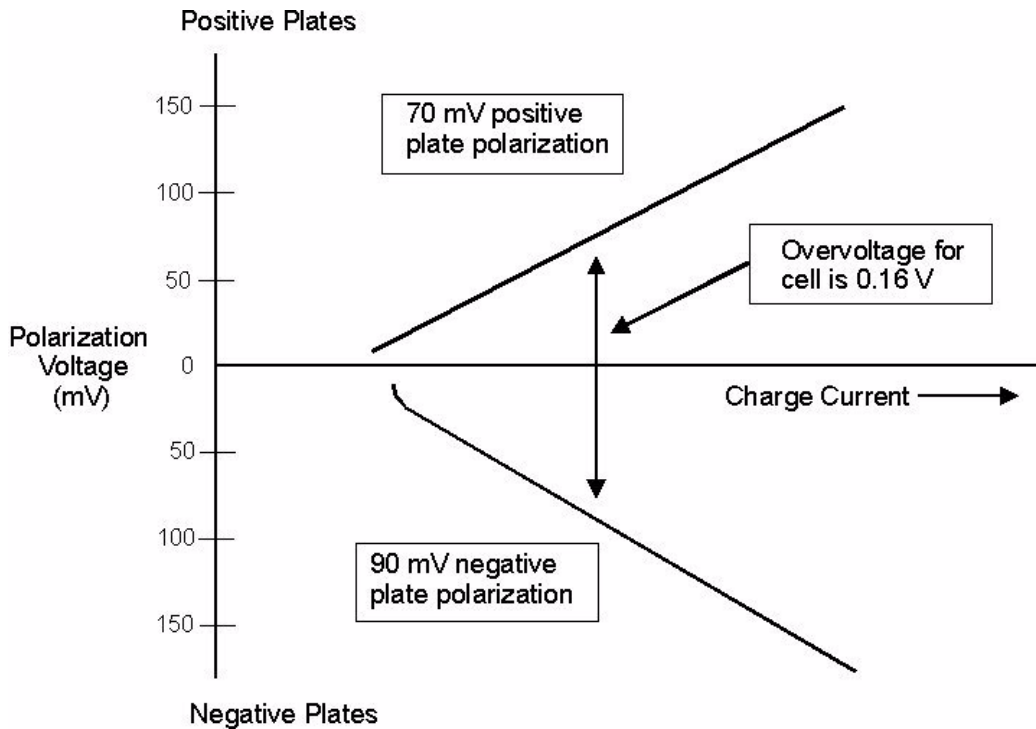
2.4.4.2.3. The open circuit voltage (OCV) is the voltage across the cell terminals when nothing is connected to it. Part of the OCV is made up by the positive plate positive potential with respect to the electrolyte. The remainder of the OCV is made up by the negative plate negative potential with respect to the electrolyte. The total OCV is the potential of the positive plate with respect to the negative plate.

2.4.4.2.4. If a cell is left on open circuit, it will slowly self-discharge and the OCV will drop as the cell discharges. When charging current is applied to the cell, the positive and negative plates polarize (develop an added potential) relative to their open circuit potential. The polarization does not occur immediately because some small amount of charging current is needed to offset the cell's tendency to self-discharge. As the charging current is increased, the cell's total voltage rises to be the sum of the OCV, the positive plate polarization, and the negative plate polarization. The total plate polarization is that potential on the plate in excess of its OCV potential.

2.4.4.2.5. Figure 2.8. shows a typical example of plate polarization as a function of charging current. Plate polarization is typically described with respect to the OCV plate potential. For the cell shown in [figure 2.8.](#), suppose that the cell OCV is 2.06 V. As shown for the specific

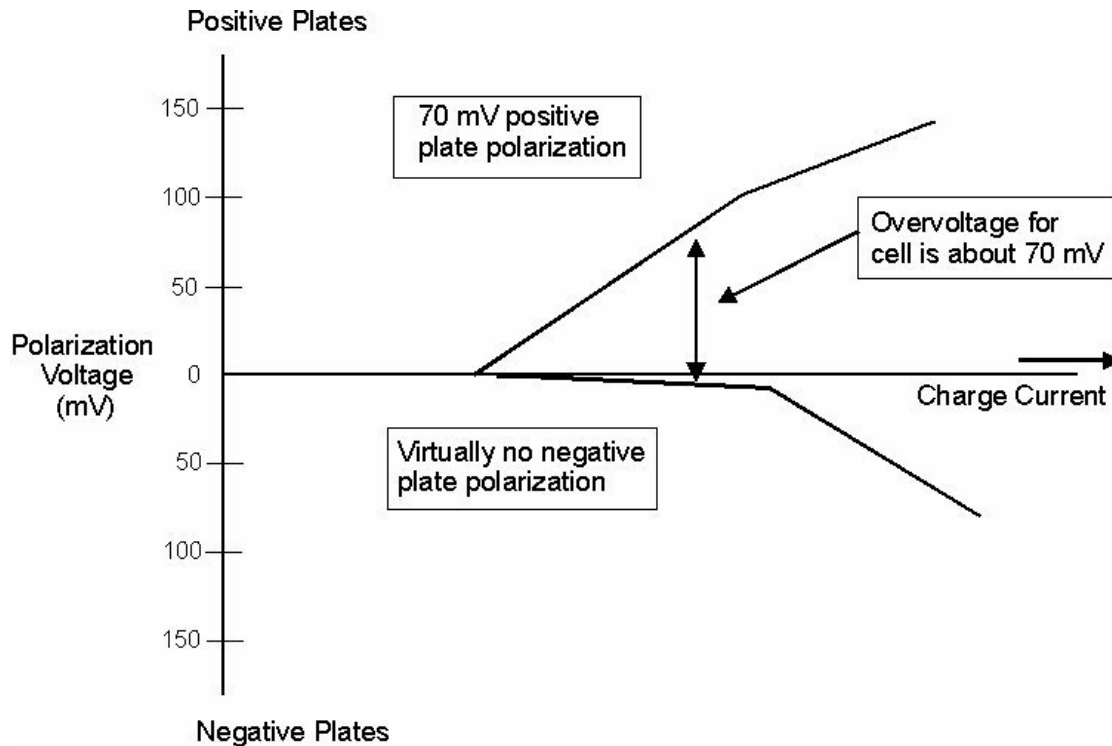
condition of float charging, the total cell voltage is 2.22 V with a polarization (overvoltage) of 0.16 V (or 160 mV). In this case, the polarization voltage is shared between the positive and negative plates, with 70 mV on the positive plate and 90 mV on the negative plate. This is a typical arrangement for a vented cell.

Figure 2.8. Vented Cell Plate Polarization.



2.4.4.2.6. The VRLA cell functions differently than the vented cell. During normal operation, oxygen is generated at the negative plate, the oxygen migrates to the negative plate, and suppresses hydrogen evolution at the negative plate. This recombination process effectively depolarizes the negative plate, meaning that the excess charging voltage is applied almost completely to the positive plate.

2.4.4.2.7. Figure 2.9. shows the typical polarization voltage of a VRLA cell. As can be seen, very little polarization voltage is applied to the negative plates under normal conditions. The charging current must be abnormally high before significant negative plate polarization is realized. Once the negative plate polarizes, the cell performs similar to a vented cell, with the negative plate also producing hydrogen. At this point, the rate of gas production exceeds the recombination ability of the cell and it will periodically vent gas through the pressure relief valve to relieve the internal pressure. A fine balance has to be maintained; the voltage has to be high enough to keep the negative plates from self-discharging, but not so high that the cell vents periodically. The proper float voltage is very important for VRLA cells. Paragraph 3.1. provides additional information regarding the detrimental effects of improper float voltages.

Figure 2.9. VRLA Cell Plate Polarization.

2.4.4.3. Gas Generation During Operation:

2.4.4.3.1. Hydrogen and oxygen gases can be released from a battery during operation. Oxygen evolves at the positive plate and hydrogen at the negative plate. Gases are generated primarily during battery charging; the rate of gas evolution depends on the charge voltage and the charge current that is not absorbed by the battery. The excess charge current causes electrolysis of the water in the electrolyte into hydrogen and oxygen.

2.4.4.3.2. *Overcharge* is the period after which the battery is fully charged when charging current mainly results in gas generation. The worst condition for hydrogen generation exists when maximum current is forced into a fully charged battery. Charging voltages at or above the equalizing charge level encourage gas evolution.

2.4.4.3.3. Some typical rules of thumb regarding hydrogen gas generation are provided below:

2.4.4.3.3.1. Gassing will double for each 0.05 V increase in float voltage for a fully charged cell.

2.4.4.3.3.2. Gassing will double for each 8.3°C (15°F) rise in temperature.

2.4.4.3.3.3. Gassing will increase by 10% for each 2,000-ft (610-meter) elevation change.

2.4.4.3.3.4. When all charging current is expended to liberate gases, each ampere-hour produces 25.51 cubic inches (0.418 liters) of hydrogen gas.

2.4.4.3.3.5. Per IEEE 1187, the maximum hydrogen generation rate is 0.000269-ft³/minute/ ampere/cell (0.0076 liters/minute/ ampere/cell).

2.4.4.3.4. Some battery manufacturers' literature markets "little or no hydrogen gas emission" as one more attractive design feature of the VRLA cell. Although it is true that a VRLA cell operating in the recombinant mode will vent very little gas, there are conditions under which the VRLA cell can vent as much hydrogen as a vented cell. For this reason, IEEE standards specify that VRLA battery installations should include adequate ventilation to avoid hydrogen buildup in the area.

2.4.4.3.5. Under the following conditions, a VRLA cell will vent hydrogen:

2.4.4.3.5.1. During an equalize charge or elevated float charge.

2.4.4.3.5.2. Whenever float voltage is set significantly higher than recommended by the manufacturer regardless of the reason—deliberately set, set in error, charger setpoint drift, or charger failure.

2.4.4.3.5.3. During the first few months of operation for a gelled electrolyte cell until it vents enough water to finally become recombinant. The same consideration applies to an AGM cell that was overfilled at the factory.

2.4.4.3.6. The system design must account for the possibility of hydrogen generation even for VRLA batteries. Not accounting for hydrogen gas emission from a VRLA cell is dangerous and can lead to personnel injury or equipment damage.

Chapter 3

VRLA BATTERY AGING, DEGRADATION, AND FAILURE

3.1. Introduction:

3.1.1. VRLA batteries exhibit the same aging and degradation characteristics as vented lead-acid batteries. But, they have additional failures modes that are a result of the new technology. Paragraph 3.2. provides an overview of traditional aging mechanisms for vented lead-acid and VRLA batteries. Paragraph 3.3. discusses additional aging and failure mechanisms specific to VRLA batteries.

3.2. Traditional Lead-Acid Battery Aging:

3.2.1. Service Life Considerations:

3.2.1.1. The lead-acid battery is a sacrificial design, destined to eventually wear out even in ideal conditions. And, when abused, it can fail even sooner. Under ideal conditions, both vented and VRLA batteries fail by natural aging due to the following causes:

3.2.1.1.1. Expansion and corrosion of the positive grid structure due to oxidation of the grid and plate materials. This degradation mechanism is unavoidable and is the most common natural failure mode for lead-acid batteries maintained on a float charge.

3.2.1.1.2. Loss of active material from the positive plate.

3.2.1.1.3. Loss of capacity due to physical changes in the active material of the positive plate.

3.2.1.2. Some vented batteries survive longer than 20 years with little loss of capability. Others fail within a few years of service. Several factors combine to affect battery life; examples are listed below.

3.2.1.2.1. Design life. Stationary batteries are typically available with a design life ranging from 5 to 20 years. Longer life batteries generally cost more.

3.2.1.2.2. Temperature. Elevated temperatures reduce battery life. An increase of 8.3°C (15°F) can reduce lead-acid battery life by 50% or more.

3.2.1.2.3. Cycle service. Excessive deep discharge cycles reduce life. Lead calcium batteries might be rated for as few as 50 deep discharge cycles.

3.2.1.2.4. Overcharging. Excessively high float voltages cause a higher positive plate corrosion rate. Overcharging also causes excessive gassing.

3.2.1.2.5. Undercharging. A low float voltage reduces capacity because of self-discharge. Undercharging can also result in sulfation, which can damage the plates.

3.2.1.2.6. DC ripple current. Excessive DC ripple current might contribute to battery aging. VRLA batteries are considered more susceptible to ripple current than vented lead-acid batteries.

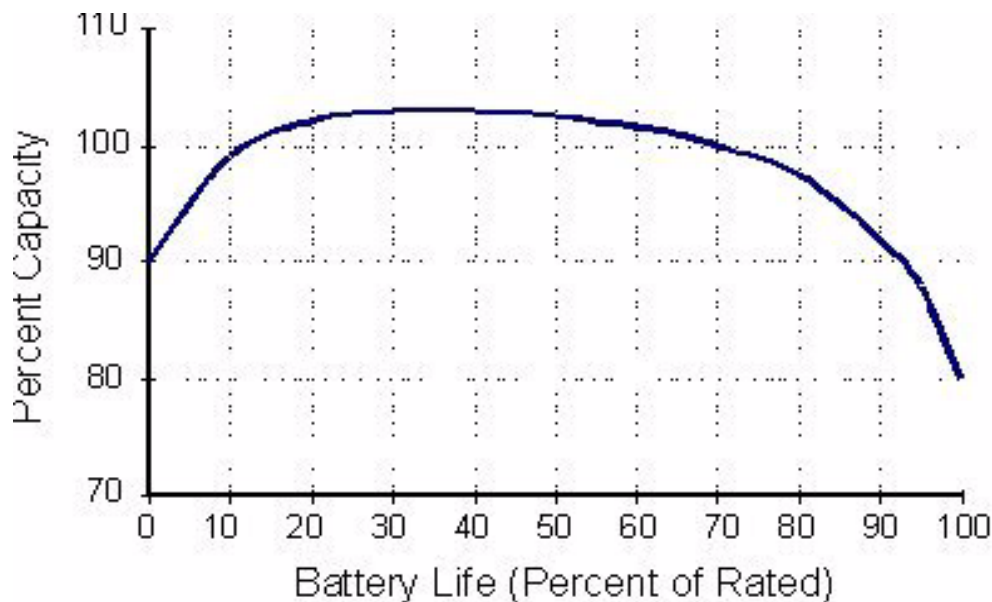
3.2.1.2.7. Manufacturing variations. Lot-to-lot processing variations can shorten battery life.

3.2.1.2.8. Improper storage. Storing wet cells beyond the manufacturer's recommended duration promotes sulfation, and decreases cell capacity and life.

3.2.1.2.9. Misapplications. Batteries are commonly designed for a specific use. If the battery is not designed for a given application, it might not meet its life or performance expectations.

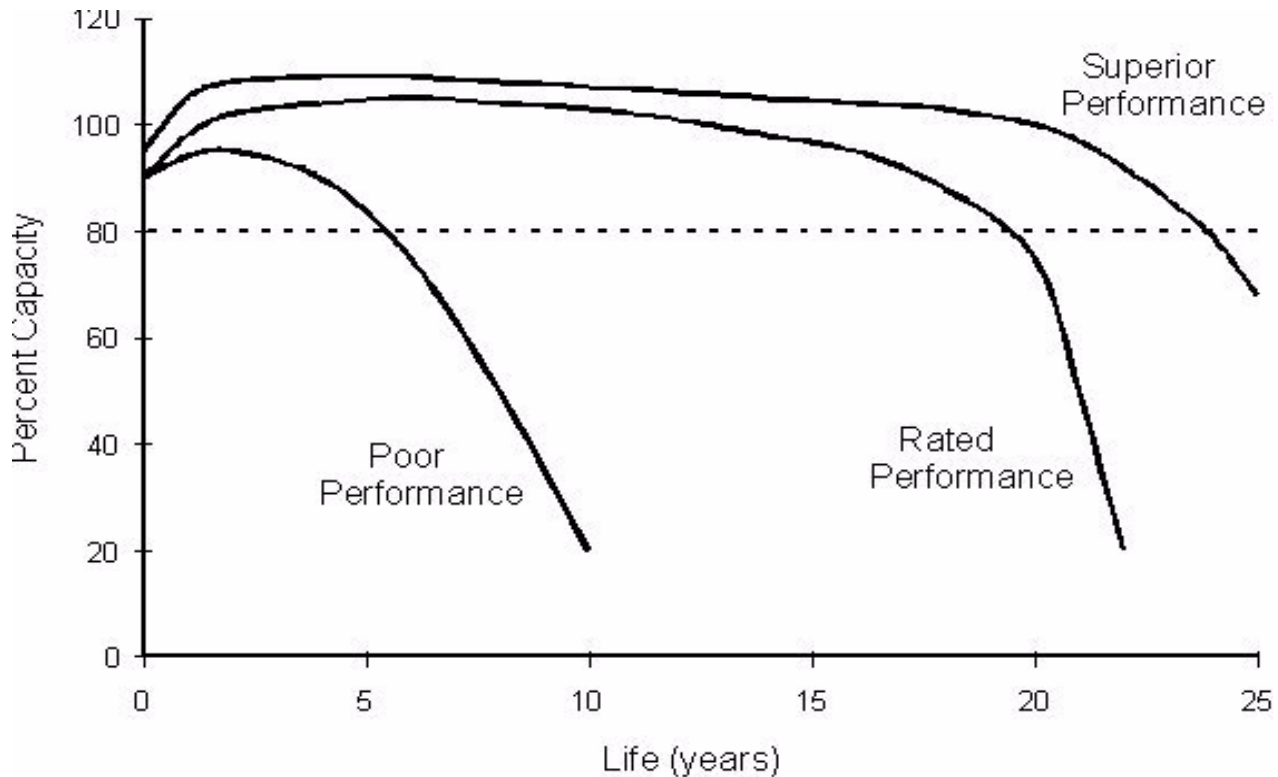
3.2.1.3. If properly designed, built, and maintained, a battery can provide several years of reliable service. The ideal profile of capacity during a lead-acid battery's operational life is shown in **figure 3.1**. A new battery might not initially provide 100% capacity. The capacity typically improves over the first few years of service, reaches a peak, and declines until the battery reaches its end of life. A reduction to 80% of the rated capacity is usually defined as the end of life for a lead-acid battery. Below 80%, the rate of battery deterioration accelerates, and it is more prone to sudden failure resulting from a mechanical shock (such as a seismic event) or a high discharge rate. Note that even under ideal conditions, a battery is expected to eventually wear out.

Figure 3.1. Ideal Battery Life Curve.



3.2.1.4. Figure 3.1. shows the ideal life curve for a lead-acid battery. The aging factors discussed above can combine so that the battery never attains 100% capacity. The effects can be dramatic; for example, a battery with an advertised life of 20 years can fail in less than 4 years in a harsh environment without proper maintenance. Figure 3.2. shows how the actual life can vary from the ideal case.

Figure 3.2. Possible Variations From the Ideal Battery Life Curve.



3.2.1.5. RLA battery technology has come a long way in the last 15 years; however, it is still developing and the degradation mechanisms are still not fully understood. What is known so far is that, in general, these batteries will fail before vented batteries if exposed to the same service conditions and environment. VRLA batteries usually have a much tighter operating window than their vented counterparts, making them more prone to degradation. VRLA batteries are also much less tolerant of the following conditions:

- 3.2.1.5.1. High temperature
- 3.2.1.5.2. Overcharge
- 3.2.1.5.3. Float voltage variations
- 3.2.1.5.4. Discharge

3.2.1.6. Section 3.3. provides information regarding VRLA failure modes.

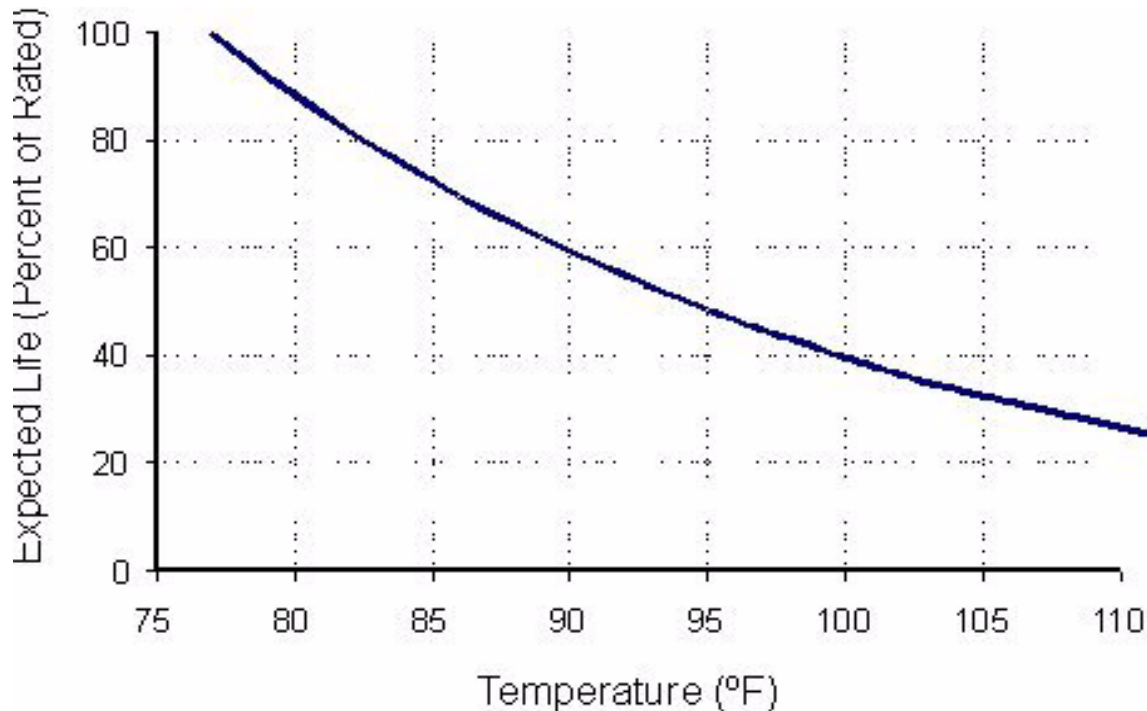
3.2.2. Temperature Effects:

3.2.2.1. Anticipated battery life is specified by the manufacturer for batteries installed in an environment at or near the reference temperature of 25°C (77°F). Above this temperature, battery life is reduced. The chief aging mechanism is accelerated corrosion of the positive plates, grid structure, and strap, which increases exponentially as a function of temperature.

3.2.2.2. A general rule of thumb for a vented lead-acid battery is that the battery life is halved for every 8.3°C (15°F) above 25°C (77°F). Thus, a battery rated for 20 years of operation under ideal

conditions at 25°C (77°F) might only last 10 years at 35°C (95°F). Figure 3.3. shows the typical expected reduction in service life as a function of temperature.

Figure 3.3. Temperature Effect on Lead-Acid Battery Life.



3.2.3. Discharge Cycle Service:

3.2.3.1. Battery failure rates, as defined by a loss of capacity and the corrosion of the positive plates, increase with the number of discharge cycles and the depth of discharge. Lead-acid batteries having lead calcium grid structures are particularly susceptible to aging due to repeated cycling.

3.2.3.2. A deep discharge cycle is defined as any discharge over 80% of the rated capacity. Some manufacturers provide warranties on lead calcium batteries based on the number of deep discharge cycles or the frequency of shallower discharge cycles.

3.2.4. Overcharging:

3.2.4.1. Overcharging accelerates corrosion of the positive plate grids and produces excessive gassing, which can loosen active material in the plates. Active material that becomes loose can cause mossing and excessive sediment buildup.

3.2.4.2. Occasional charging at higher voltages, such as an equalizing charge, can benefit the battery by removing plate sulfation and refreshing the plates. However, habitual overcharging damages the plates.

3.2.5. Undercharging:

3.2.5.1. Batteries lose capacity because of self-discharge if they are consistently undercharged. An undercharge condition is indicated by a low specific gravity, low cell voltage, or lighter color on the plates. An undercharged battery might not be at full capacity and can become permanently damaged from sulfation.

3.2.5.2. Chronic undercharging results in a harmful buildup of lead sulfate on the plates, called sulfation. Lead sulfate formed as a result of undercharging is inherently different in structure from lead sulfate formed during normal cell discharge. The lead sulfate formed during normal discharge has a very fine crystalline structure that is easily broken down by charging current. The lead sulfate crystals formed as a result of undercharging continue to grow and eventually reach a size that cannot be easily broken down by charge current. Additionally, the lead sulfate crystals physically occupy more space than the original active material. An excessive buildup of lead sulfate can make the plates warp or buckle.

3.2.6. Overdischarge:

3.2.6.1. Hydration occurs in a lead-acid battery that is overdischarged and not promptly recharged, or a battery that remains in a discharged condition for an extended time (such as might occur during long-term storage). Hydration results when the lead and lead compounds of the plates dissolve in the water of a discharged cell and form lead hydrate, which is deposited on the separators. When the cell is recharged, multiple internal short circuits occur between the positive and negative plates.

3.2.6.2. Once hydration is evident, the cell is permanently damaged. Hydration is visible in transparent vented cells as a white "bathtub ring" approximately halfway up the jar. Hydration is not visible in VRLA cells because the containers are opaque.

3.3. VRLA Battery Failure Modes:

3.3.1. Dryout:

3.3.1.1. Loss of water from a VRLA cell is irreversible in most designs. As a VRLA cell loses water, it can experience loss of capacity due to dryout. Water addition is not normally allowed by the VRLA design. These batteries have been referred to as *starved electrolyte*, meaning that the discharge capacity can be limited by the electrolyte. In this case, any loss of electrolyte can adversely affect capacity. A vented battery is expected to require periodic watering to restore lost water; however, any water loss from a VRLA battery is irreversible because water cannot normally be added to the cell. One study determined that a 10% water loss could correlate to a 20% loss of capacity. Any water loss from a VRLA cell is cause for concern.

3.3.1.2. The recombination process tends to be somewhat self-regulating in that recombination efficiency tends to improve as water is lost. In theory, a VRLA cell would lose water until it reached optimal recombination efficiency, with little water loss thereafter. However, other effects that occur during normal and abnormal operation also cause water loss:

3.3.1.2.1. Overcharging. This results in gassing that exceeds the recombination ability of the battery. Thus, gases are vented from the battery through the pressure relief valve and the volume of the electrolyte solution declines over time. Small amounts of gas are vented during normal float operation. Larger gas quantities are vented during higher charging rates, such as an equalize charge. Battery charger setpoint drift or failure can also cause increased gas venting.

3.3.1.2.2. Corrosion process. The grid corrosion process that occurs during normal aging of a lead-acid battery consumes part of the water in the electrolyte throughout the cell's operational life. One study showed that this normal aging process alone could consume enough of the electrolyte water to limit capacity.

3.3.1.2.3. High temperature. The gassing rate increases with temperature. At high temperature, some gases are vented rather than recombined inside the cell.

3.3.1.2.4. Failure of the pressure relief valve. A failure of the valve to fully shut causes the battery to operate like a vented cell; it continuously vents. Charge gases are then allowed to escape and the recombination process is ineffective.

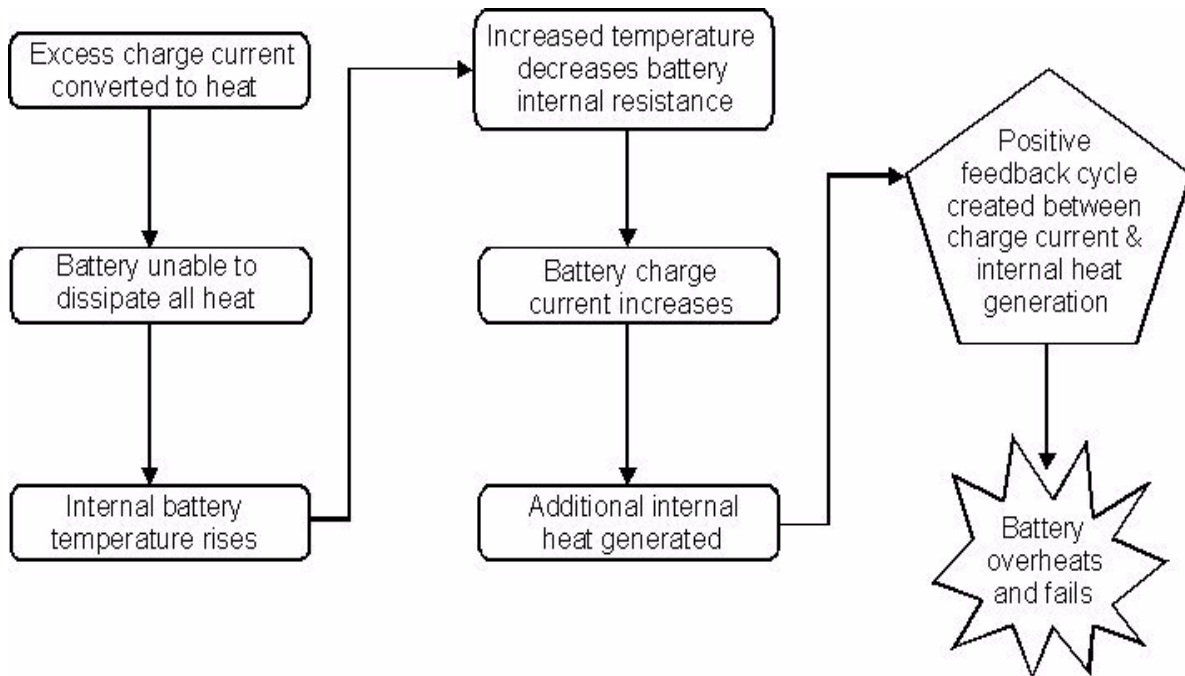
3.3.1.2.5. Water vapor diffusion through the container. As the temperature increases, the water vapor diffusion rate through the cell container also increases. The diffusion rate varies with the type and thickness of container materials, operating temperature, and relative humidity around the cell. Most manufacturers have selected container materials that minimize water vapor diffusion.

3.3.1.2.6. Leakage. A cracked battery case or failed terminal post seal is similar to failure of the pressure relief valve; the cell can continuously vent.

3.3.1.3. Two of the above causes of dryout—pressure relief valve failure and container leakage—actually represent another potential failure mode for a VRLA battery. The recombination process causes the negative plate to be maintained in an almost depolarized condition. Air in-leakage through a pressure relief valve, post seal leak, or container crack can cause eventual discharge of the negative plate. The cell will lose capacity as the negative plate discharges.

3.3.2. Thermal Runaway:

3.3.2.1. Thermal runaway is a failure mode in which a battery on a constant voltage charge at an elevated temperature destroys itself through internal heat generation due to high internal current. Under normal operating conditions, a VRLA battery on a float charge remains in a fully charged condition and most gases that are produced are recombined internally. Any overcharge energy results in heat generation. If the design of the battery in conjunction with its installed location is such that the generated heat can be dissipated without a rise in the battery temperature, thermal runaway is unlikely. However, if the battery temperature increases, higher current is required to keep the float voltage at the set level. The additional current results in more gas generation inside the cell, which generates more heat during recombination and further raises the battery temperature. If the situation is not corrected, the battery can overheat and destroy itself. The thermal runaway sequence is shown in [figure 3.4](#).

Figure 3.4. Thermal Runaway Sequence.

3.3.2.2. The design of VRLA batteries increases the probability of thermal runaway. Actually, thermal runaway can occur even in vented lead-acid batteries, but does so only rarely because of their better heat dissipation capability. In general, vented cells have the best heat dissipation characteristics, followed in order by gelled electrolyte cells and absorbed electrolyte cells. Inadequate heat dissipation is compounded by the installation design. Vented batteries are usually installed with some separation between cells, whereas VRLA batteries are often packed into the smallest possible footprint, and so have restricted airflow around the cells. In recent years, manufacturers have improved VRLA installations by including more air space around each cell.

3.3.2.3. Improper float voltage appears to be the greatest contributor to thermal runaway. A higher than recommended float voltage results in greater float current and thus battery overheating. The initial battery temperature influences the speed at which thermal runaway can occur; however, an improper float current and voltage alone can cause thermal runaway.

3.3.3. Complexity of the Recombination Process:

3.3.3.1. Although the principle of the recombination process might be conceptually simple for the user to understand, the actual implementation in a VRLA cell is quite complex. A delicate balance is maintained at the negative plates between oxygen recombination, hydrogen evolution, and plate sulfation. This complexity places stricter constraints on the design, manufacture, application, and use of these cells compared to an equivalent vented cell. VRLA batteries are more sensitive to float voltage variations. The proper float voltage is necessary to maintain each cell within the proper operating range. If the float voltage is too low, the negative plates might be undercharged, leading to capacity loss. If the float voltage is too high, the aging process will be accelerated and the rate of dryout will increase.

3.3.3.2. Figure 2.9. shows the typical polarization voltage of a VRLA cell. As can be seen, very little polarization voltage is applied to the negative plates under normal conditions. The charging current must be abnormally high before significant negative plate polarization is realized. This low level of polarization means that the negative plates can experience a loss of capacity over time by partially discharging if the level of polarization is inadequate to prevent self-discharge.

3.3.3.3. If the charging voltage is too high, the negative plate polarizes and the cell performs similar to a vented cell, with the negative plate also producing hydrogen. At this point, the rate of gas production exceeds the recombination ability of the cell and it will periodically vent gas through the pressure relief valve to relieve the internal pressure.

3.3.3.4. If the float voltage (and float current) is too high, the life of a VRLA cell will also be reduced, partly because of accelerated aging of the positive plate by the higher float current and partly because of the increased rate of internal dryout by more frequent gas venting. For this reason, the manufacturer typically specifies a maximum allowable float voltage and some manufacturers set limits on the frequency and duration of periodic equalizing charges. One manufacturer's operating manual predicts a 50% reduction in battery life if float voltage is continuously 2 mV above the specified range, and a 75% reduction in battery life if float voltage is continuously 6 mV above the specified range.

3.3.4. Temperature Effects:

3.3.4.1. VRLA batteries tend to be more susceptible to degradation and accelerated aging at higher temperatures than are vented lead-acid batteries. The recombination process that allows these batteries to operate without the need for water addition also releases heat. Older VRLA installations tend to have the cells tightly packed, further limiting heat dissipation capability. In UPS applications, these batteries are often enclosed inside a cabinet with little allowance provided for heat dissipation. All of these factors can combine to cause the battery to operate at a higher-than-ambient temperature, thereby decreasing its life. Higher temperatures also increase the rate of dryout and increase the susceptibility to thermal runaway. Abnormally high temperatures can cause a VRLA cell to fail completely.

3.3.5. Electrolyte Concentration:

3.3.5.1. The electrolyte in VRLA cells is a limited resource that can not normally be replenished. Any loss of electrolyte during normal and abnormal operating conditions can reduce capacity. In some cases, manufacturers have attempted to improve capacity by increasing the electrolyte specific gravity up to 1.300 (typical vented batteries have a specific gravity of 1.215 to 1.240). Increasing the specific gravity increases capacity at the expense of cell life. A higher specific gravity results in increased chemical activity, thereby causing an increased positive plate corrosion rate.

3.3.6. Absorbed Glass Mat Compression Effects:

3.3.6.1. VRLA batteries of the AGM design can experience changes in the mat position over time resulting in loss of compression between the mat and the plates. Compression between the absorbed glass mat and the plates is necessary to ensure that the plates are in constant contact with the electrolyte. Over time, small voids can develop between the mat and the plates, increasing the internal resistance and decreasing the available capacity. This effect is referred to as *loss of compression* and causes a permanent loss of capacity in an AGM cell. This loss of compression can be caused by manufacturing errors, improper design or design tolerances, and dryout. In particular,

the design and manufacturing process have been important contributors to loss of compression because battery manufacturers did not fully appreciate the importance of compression on the performance of a cell. Dryout is an inevitable aging effect that also changes the level of compression over a cell's service life.

3.3.7. Negative Strap Corrosion:

3.3.7.1. Some VRLA batteries have shown a tendency for the negative plate straps to corrode and fail prematurely. In an AGM VRLA cell, the negative strap is not immersed in the electrolyte; instead, it is exposed to a nearly pure hydrogen environment in the void space above the plates. With the negative strap exposed and the negative plates normally depolarized by the recombination process, the negative strap can experience sulfation that ultimately leads to its fracture and failure. Some manufacturers have redesigned their batteries to be more resistant to negative strap corrosion. Design changes have included wrapping the negative strap with absorbed glass mat material to help keep it wetted or more carefully matching the grip, strap, and post alloys.

3.3.8. VRLA Failure Characteristics:

3.3.8.1. Although it is a type of lead-acid battery, the VRLA battery is distinctly different from a vented lead-acid battery with regard to how it ages, degrades, and ultimately fails. The various failure modes described in the previous sections readily demonstrate these differences. Accordingly, VRLA cell failures tend to show up differently than do vented cell failures. A high-quality vented lead-acid battery tends to have its cells age at about the same rate. When periodic discharge tests are performed, it is not uncommon to find that all of the vented cells perform in a very similar manner during discharge. VRLA cells tend to exhibit a different behavior during discharge. Although many of the cells might perform quite well, some of the cells often randomly fail, with rapid voltage decline during discharge.

3.3.8.2. What this means for those users that perform periodic discharge tests is that a capacity test becomes more of a tool to find bad cells rather than a trending tool to determine overall battery capacity. Failed cells obviously require replacement; however, cell replacement can lead to other problems also. Refer to the previous discussion regarding the complexity of the recombination process; new replacement cells will usually have different float characteristics than the older cells already in service. Some battery manufacturers' literature attempts to address this inherent limitation of float charge behavior with the following recommendations:

3.3.8.2.1. Minimize the number of cells in series to reduce the likelihood that some cells are undercharged while other cells are overcharged.

3.3.8.2.2. Use cells of the same age and type in each string.

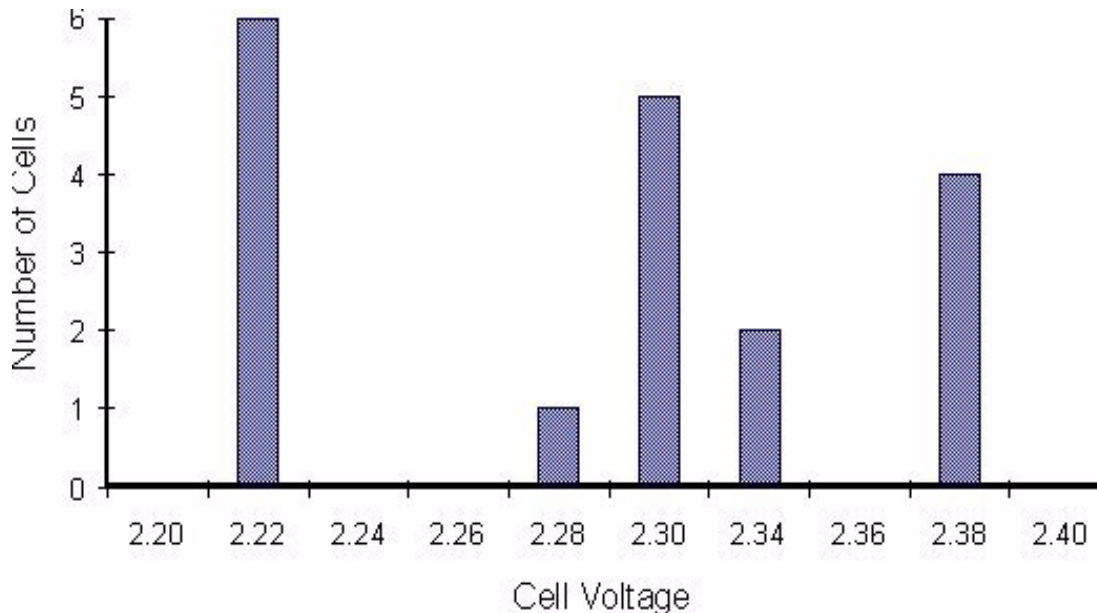
3.3.8.2.3. Avoid installing the battery near hot spots (or any location that can cause a temperature differential across the battery).

3.3.8.2.4. If necessary, break up the string into smaller charging groups (seldom done for stationary applications).

3.3.8.3. Although the above recommendations are well intended, they are not always achievable in the field. For example, replacement cells for failed cells will be of a different age than the remaining already installed cells. This will contribute to float voltage variations, but cannot be avoided because replacement cells are required. Usually, replacing the entire battery just because a few cells failed is not acceptable from a budget perspective. As more cells are replaced with

each year, the chances of having equal float characteristics across the battery become less and less probable. Figure 3.5. shows an extreme case of float voltage variations; notice that some cells are below the desired charging voltage while other cells are overcharged to the point of extreme gassing. Note that none of the cells are operated at the manufacturer's recommended float voltage of 2.25 V per cell.

Figure 3.5. Float Voltage Variation Observed at One Site.



3.3.8.4. Many VRLA batteries are installed throughout the world and the industry is beginning to acknowledge that a 20 year VRLA battery life is unlikely to realize. Recent industry experience indicates that a 4 to 7 year VRLA battery life is more likely, regardless of cell size or warranty claims.

3.3.8.5. In one study of almost 25,000 VRLA cells from 9 different manufacturers, the failure rates ranged from 27% to 86%, depending on the manufacturer. These cells were only 3 to 7 years old. The average failure rate was 64% for the entire tested population. This study concluded that the failures were generic and appeared to be independent of size or manufacturer over a range from 25 to 1,000 ampere-hours.

3.3.8.6. A European study of over 1,000 installations, of various system voltages and cell capacities, containing about 35,000 cells concluded that VRLA batteries require replacement after 5 to 8 years of operation. The shorter lifetime (5 years) was associated with batteries operating at 110 V or higher system voltages. The longer lifetime (up to 8 years) was applicable to better quality batteries and those of lower system voltages. AGM-type cells demonstrated a higher failure rate than did gel-type cells. No single or systematic factor was determined to cause this short lifetime.

3.3.8.7. Representatives of a major battery company recently provided an update regarding VRLA cells' expected life. Four different VRLA cells were tested, including three different AGM types and one gel-type. It was concluded that 20-year class AGM cells actually have an expected life of 5 years at 25°C (77°F), dropping to about 3 years at 32°C (90°F).

3.3.8.8. In summary, VRLA batteries can have a shorter-than-advertised life and some manufacturers have acknowledged this limitation. With each generation, VRLA batteries will likely continue to improve. However, their greatest strengths that make them so popular for use are also their greatest weaknesses in terms of the user's ability to identify cell failures.

Chapter 4 INDUSTRY STANDARDS APPLICABLE TO VRLA BATTERIES

4.1. Introduction:

4.1.1. The Institute of Electrical and Electronic Engineers (IEEE) provides comprehensive guidance for stationary batteries. IEEE has issued three standards to address the particular needs of VRLA batteries, including application, selection, installation, maintenance, and testing. Each standard is described in the following sections. The purpose of discussing these standards is to provide an overview of the type of inspection, testing, and maintenance that has been recommended by industry experts. The issues addressed by these IEEE standards have been considered in the development of this manual.

4.2. IEEE 1187-1996:

4.2.1. IEEE 1187-1996, *IEEE Recommended Practice for Installation Design and Installation of Valve-Regulated Lead Acid Storage Batteries for Stationary Applications*, provides recommendations for the design and initial installation of a VRLA battery. The following topics are addressed by this recommended practice:

- 4.2.1.1. Safety precautions and procedures
- 4.2.1.2. Battery location
- 4.2.1.3. Receiving and storage
- 4.2.1.4. Cell mounting and connections
- 4.2.1.5. Freshening/initial charge
- 4.2.1.6. Initial measurements and testing
- 4.2.1.7. Suggested records

4.2.2. As part of the installation process, IEEE 1187 sets the starting point for future maintenance by recommending that the following data be recorded at the time of installation:

- 4.2.2.1. Receiving inspection data and condition of charge
- 4.2.2.2. Initial resistance values of the intercell connections
- 4.2.2.3. Individual cell or unit voltage values at the completion of the initial charge
- 4.2.2.4. Acceptance test results
- 4.2.2.5. Initial ripple current
- 4.2.2.6. Individual cell or module internal ohmic values

4.3. IEEE 1188-1996:

4.3.1. IEEE 1188, *Recommended Practice for Maintenance, Testing, and Replacement of Valve Regulated Lead-Acid Batteries for Stationary Applications*, provides detailed periodic maintenance, inspection, and test recommendations for VRLA batteries. This recommended practice represents an important contribution to the industry by providing specific maintenance recommendations for VRLA batteries. The following topics are discussed in this recommended practice.

- 4.3.1.1. Safety precautions
- 4.3.1.2. Monthly general inspections:
 - 4.3.1.2.1. Overall float voltage check
 - 4.3.1.2.2. Charger output current and voltage check
 - 4.3.1.2.3. Ambient temperature and condition of the ventilation and monitoring equipment
 - 4.3.1.2.4. Visual inspection
- 4.3.1.3. Quarterly inspections:
 - 4.3.1.3.1. Monthly inspection as described above
 - 4.3.1.3.2. Internal ohmic value measurement
 - 4.3.1.3.3. Temperature measurement of each negative terminal
 - 4.3.1.3.4. Inter-cell connection resistance measurements for applications with a discharge rate of one hour or less
- 4.3.1.4. Semi-annual inspections:
 - 4.3.1.4.1. Quarterly inspection as described above
 - 4.3.1.4.2. Voltage of each cell or unit
- 4.3.1.5. Annual inspections:
 - 4.3.1.5.1. Semi-annual inspection as described above
 - 4.3.1.5.2. Inter-cell connection resistance measurement of all connections
 - 4.3.1.5.3. AC ripple current measurement
- 4.3.1.6. Corrective actions:
 - 4.3.1.6.1. High connection detail resistance measurement
 - 4.3.1.6.2. Significant changes in internal ohmic measurements
 - 4.3.1.6.3. Signs of electrolyte leakage
 - 4.3.1.6.4. Float voltage outside specified operating range
 - 4.3.1.6.5. Cell voltage below minimum specified voltage
 - 4.3.1.6.6. Cell temperature deviations by more than 3°C (5°F)
 - 4.3.1.6.7. Other abnormalities
- 4.3.1.7. Periodic tests:
 - 4.3.1.7.1. Acceptance test by the manufacturer or upon initial installation
 - 4.3.1.7.2. Continuity test on a semi-annual basis
 - 4.3.1.7.3. Performance test on an annual frequency until degradation is observed, at which time semi-annual performance tests should be performed
 - 4.3.1.7.4. Service test if desired to verify the battery's ability to fulfill the duty cycle

4.3.2. In several instances, the above recommendations represent a significant departure from traditional maintenance for vented batteries as well as from the recommended maintenance contained in some battery manufacturers' operating manuals. In particular, the scope and frequency of inspections and tests have been increased.

4.4. Other IEEE Standards:

4.4.1. IEEE 1189, *Guide for Selection of Valve Regulated Lead-Acid Storage Batteries for Stationary Applications*, provides information related to VRLA technology and should be considered a companion document to IEEE 1187 and IEEE 1188. Although maintenance information is not provided in this document, it does describe the technology in some detail.

4.4.2. IEEE 1184, *IEEE Guide for the Selection and Sizing of Batteries for Uninterruptible Power Systems*, also provides technical information related to selection and use of VRLA batteries.

Chapter 5

APPLICATION CONSIDERATIONS

5.1. VRLA Battery Desirable Features. The VRLA battery is an innovative design with many useful applications. It is effectively sealed such that the user can not gain access to the electrolyte. And, the electrolyte is immobilized so that it is not a free liquid as in a vented cell, with the result that a VRLA cell will usually leak little or no electrolyte if damaged. When they were first developed, VRLA batteries were intended for “install and forget” truly maintenance-free applications in which battery failure would be an inconvenience, not a catastrophe. Because of some of their desirable design features, VRLA batteries are becoming increasingly used in stationary battery systems to the point that they are now commonly found in critical applications. The VRLA battery market has grown to fill the demand for a battery with the following characteristics:

5.1.1. Immobilized electrolyte to prevent or minimize the potential for electrolyte leakage. This allows users to avoid the imposition of some environmental regulations regarding sulfuric acid spill contingencies in some states. This also allows users to install batteries in commercial buildings and other locations that would not normally have vented batteries installed.

5.1.2. Smaller installation footprints than vented equivalents. By immobilizing the electrolyte, the battery can be installed in different configurations. A typical installation has the VRLA cells oriented on their side rather than upright so that they can be stacked vertically. The result is that less floor space is required for the installation.

5.1.3. No maintenance. Because the battery is sealed and the electrolyte is inaccessible, water can not be added to a VRLA cell. This feature was referred to as *maintenance-free* in early literature; however, this term is less commonly used today because other types of maintenance are still necessary.

5.1.4. Higher power density for high-rate discharge UPS applications. Manufacturers have developed new designs and electrolyte concentrations to boost the high-rate capability.

5.2. Allowed Applications. VRLA batteries are allowed to be used in the following general types of applications:

5.2.1. Installations with small footprints such that a vented battery will not fit within the available space.

5.2.2. Locations in which the consequences of electrolyte leakage cannot be allowed. For example, commercial buildings cannot tolerate the consequences of electrolyte leakage into the internal wiring spaces between floors. A vented lead-acid cell can leak all of its electrolyte if the container fails; a VRLA battery will have little or no leakage upon container failure.

5.2.3. Installations in which the power density requirement exceeds the capability of a vented battery within the allowed footprint.

5.3. Excluded Applications. Just as VRLA batteries have applications in which they will be preferentially used, there are also applications in which their use should be avoided. Do not use VRLA batteries in the following general types of applications:

5.3.1. Unregulated environments that can experience abnormally high and low temperatures.

5.3.2. Unmonitored locations that seldom receive periodic maintenance checks.

5.3.3. Critical applications, unless the system design requires the features available only in a VRLA battery.

5.4. Vented Lead-Acid Batteries. As a general practice, do not use a VRLA battery if a vented lead-acid battery will satisfy the design requirements. VRLA batteries have exhibited a shorter service life than vented equivalents and have shown a tendency to fail without warning. A life-cycle analysis will usually select a vented lead-acid battery over a VRLA battery if actual expected lifetimes are used.

5.5. Monitoring and Maintenance. If the application requires the use of a VRLA battery, the periodic monitoring and maintenance requirements of this manual must be followed.

Chapter 6

PERSONNEL AND EQUIPMENT SAFETY

6.1. General Precautions:

6.1.1. Batteries and DC system components are different from AC electrical system equipment. Batteries contain acid, which is harmful to skin and eyes, and the electrical shock hazards associated with DC power can be more severe than those associated with AC power for equivalent voltages and currents.

6.1.2. Only authorized personnel who have been familiarized and trained on battery fundamentals and maintenance procedures are allowed to perform maintenance-related activities on a battery.

6.1.3. The following equipment shall be available for the safe handling of the battery and protection of personnel:

6.1.3.1. Safety glasses with side shields, goggles, and/or face shields

6.1.3.2. Acid-resistance gloves

6.1.3.3. Protective aprons and safety shoes

6.1.3.4. Portable or stationary water facilities for rinsing eyes and skin in case of contact with acid electrolyte

6.1.3.5. Class C fire extinguisher

6.1.3.6. Bicarbonate of soda to neutralize any acid spillage (0.1 kg/L or 1 lb/gal of water)

6.1.3.7. Adequately insulated tools

6.1.3.8. Lifting devices of adequate capacity, when required

6.2. Explosion Hazards:

6.2.1. Hydrogen and oxygen gases can be released from a battery during operation. Oxygen is generated at the positive plate and hydrogen is generated at the negative plate. Gases are created primarily during battery charging; the rate of gas evolution depends on the charge voltage and the charge current that is not absorbed by the battery. The excess charge current causes electrolysis of the water in the electrolyte into hydrogen and oxygen.

6.2.2. *Overcharge* is the period after which the battery is fully charged and charging current mainly results in gas generation. The worst condition for hydrogen generation exists when maximum current is forced into a fully charged battery. Charging voltages at or above the equalizing charge level encourage gas evolution.

6.2.3. VRLA batteries are a potential source of hydrogen gas. Under normal operating conditions with a VRLA cell recombining gases internally, very little hydrogen gas is generated. However, during equalize charge conditions, the rate of hydrogen gas generation can exceed the recombination ability of the cell, resulting in hydrogen venting through the pressure relief valve. Drift in the charger output voltage can also cause the battery voltage to be higher than normal. For these reasons, VRLA cells should be designed as if they will periodically vent hydrogen gas. The following summarizes the potential for hydrogen generation under different operating conditions:

6.2.3.1. Open circuit—Virtually no gas emission

6.2.3.2. Float charge—Minimal gas emission

6.2.3.3. Equalize charge and recharge—Potential for high gas emission

6.2.3.4. Discharge—Virtually no gas emission

6.2.4. Because of the electrochemical behavior of a VRLA cell, the space above the plates inside the cell contains almost entirely hydrogen gas. Any vented gas from a VRLA cell likely contains a high hydrogen percentage.

6.2.5. Cells are equipped with flame arresters designed to allow gases to escape the battery while preventing external sparks from igniting any gases inside the battery. A 4% hydrogen concentration is flammable. The ventilation system in a battery area should be designed to keep hydrogen concentration under 2%.

6.3. Short Circuit Hazards:

6.3.1. Personnel can become complacent when working around batteries. DC systems are often mistakenly considered to operate at innocent voltages. But, DC current represents a more severe shock hazard than an equivalent AC current because the current has no zero crossing, thus making it harder to break away from an electrical shock. Batteries can produce lethal currents. Also, the effects of a short circuit across battery terminals can create other personnel and equipment hazards, including damage from vaporized or molten metal fragments, and flash burn damage to the skin and eyes.

6.3.2. Because of the potential for personnel injury, the following safety precautions are required:

6.3.2.1. Wear proper safety clothing to prevent contact with acid or live electrical connections. Whenever working around batteries, wear a rubber apron and rubber gloves. Ensure goggles and face shields are available for personnel.

6.3.2.2. Use only insulated tools in the battery area to prevent accidental shorting across battery connections. Never lay tools or other metal objects on cells; shorting, explosion, or personal injury could result. As a general rule, the length of the exposed metal for any tool should be less than the distance between the positive and negative posts of each cell.

6.3.2.3. Wear only nonconductive hard hats near batteries. Metal hard hats can fall across the battery terminals or connections and create short circuits.

6.3.2.4. Remove all jewelry, wristwatches, or clothing with metal parts that could come into contact with the battery terminals.

6.3.2.5. Do not make or break series connections within an operating group of cells. Before proceeding, open the battery system circuit breaker to minimize the possibility of arcing.

6.3.2.6. Because batteries can generate hydrogen gas that, in sufficient concentrations, can be explosive if ignited, never bring burning materials such as lighted matches, cigarettes, or sparks of any kind near the battery. Avoid the use of spark-producing equipment near batteries. Residual gases can remain within cells during storage and shipment. Take these precautions at all times while handling batteries.

6.3.2.7. Ensure that the exit from the battery area is unobstructed.

6.3.2.8. Minimize access to the battery by personnel unaware of battery safety precautions.

Chapter 7

PERIODIC MAINTENANCE

7.1. VRLA Battery Inspections That Can and Cannot Be Performed:

7.1.1. All stationary batteries require periodic inspection and maintenance. Older literature from some battery manufacturers refers to VRLA batteries as *maintenance free*. Many users misinterpreted this terminology; the term maintenance free only meant that electrolyte checks could not be performed, other maintenance is still required. Because of their design, not all of the traditional inspections performed on vented lead-acid batteries can be performed on VRLA batteries. The following inspections and maintenance that would periodically be performed on a vented cell cannot be performed on a VRLA cell:

7.1.1.1. Electrolyte level checks. The electrolyte level can not be checked in a VRLA cell; the electrolyte is suspended in microporous mats or a gel surrounding the plates. Access to the electrolyte is not allowed.

7.1.1.2. Water addition. Water can not normally be added to a VRLA cell. The access port is sealed by a pressure relief valve. Furthermore, the cells are often installed on their side that would complicate water addition even if access was allowed.

7.1.1.3. Visual internal inspection. The opaque container of a VRLA cell does not allow for a check of the sediment space, or color and condition of the plates.

7.1.2. The electrolyte checks and visual inspection are valuable for vented lead-acid batteries. Just because these checks cannot be performed on a VRLA cell does not mean that the checks are not important. Other means of assessing the interior of a VRLA cell have been developed to compensate for the inability to perform electrolyte checks and the internal visual inspection.

7.1.3. The following general checks can still be performed on VRLA batteries:

7.1.3.1. External visual inspection

7.1.3.2. Float voltage checks

7.1.3.3. intercell connection integrity

7.1.4. In addition to the above checks, technology has been developed to monitor each cell's internal resistance. The quarterly inspections described in Section 7.3. provide additional information regarding this relatively new technology and its role in VRLA battery maintenance.

7.1.5. The following sections describe how the above checks are integrated into a periodic maintenance program.

7.2. Monthly Inspection:

7.2.1. Purpose of Inspection:

7.2.1.1. The purpose of the monthly inspection is to assess the general condition of the battery and battery area. This monthly inspection is intended to be a general quick check for the more conspicuous problems that can be encountered. The following types of battery degradation can be detected during the monthly inspection:

7.2.1.1.1. Abnormal battery area ambient temperature (high temperature can reduce battery life and contribute to dryout)

7.2.1.1.2. Improper operation of the battery area ventilation system

7.2.1.1.3. Improper float voltage

7.2.1.1.4. Electrolyte leakage from pressure relief valve, cracked container, or post seal

7.2.2. Inspection Procedure:

WARNING: Observe safety precautions for working with energized DC equipment and batteries.

NOTE: Whenever performing maintenance inspections, ensure that the manufacturers' instruction manuals for the battery and charger are available for review.

7.2.2.1. Verify that the battery area safety equipment is available and operational. This includes the eye wash station, shower, and fire extinguisher, as applicable.

7.2.2.2. Verify that personal safety equipment is available and in good condition. This includes goggles, face shields, plastic or rubber aprons, and gloves.

7.2.2.3. Verify that battery cleaning and acid neutralization supplies are available. Baking soda, water, a nonconductive container for mixing, and wiping cloths are recommended.

CAUTION: Use only clean water for cleaning battery components. Solvents and greases can damage the cell containers. Follow the manufacturer's instructions closely to avoid inadvertent harm to the battery.

7.2.2.4. Visually inspect the battery area for cleanliness. Assure that the area is dry and clear of debris.

7.2.2.5. Measure and record the battery area ambient temperature. The desired temperature should be in the range of 21°C (70°F) to 27°C (80°F).

NOTES:

If the battery is located in an enclosure, the ambient temperature should be measured inside the enclosure, not in the surrounding area.

Extended operation at a high temperature shortens battery life. In general, VRLA battery life is reduced by at least 50% for every 8.3°C (15°F) of continuous operation above 25°C (77°F). At very high temperatures, VRLA batteries are also more susceptible to other failure modes such as dryout or thermal runaway.

If a battery is normally maintained at a temperature significantly different than 25°C (77°F), verify that the float voltage is set in accordance with the manufacturer's recommendations.

7.2.2.6. Verify that the battery area ventilation system is operating by checking for airflow through the ventilation exhaust ducts. If the battery is enclosed in a cabinet, ensure that the cabinet ventilation is working properly (if so equipped) and that ventilation panels are not blocked.

WARNING: Inadequate ventilation can result in the dangerous buildup of hydrogen gas.

7.2.2.7. Visually inspect all cell jars or battery modules, and the battery rack for cleanliness and any signs of distortion or damage.

7.2.2.8. Verify that the cells have protective covers in place to minimize short circuit safety hazards. Figure 2.7. shows an example of a VRLA installation with and without the protective covers.

7.2.2.9. Visually check for cracks or signs of electrolyte leakage in each cell. Check for signs of electrolyte leakage from the pressure relief valve in each cell. Inspect the flooring below the cells for symptoms of past leakage. Figure 7.1. shows an example of floor corrosion caused by electrolyte leakage. If electrolyte leakage is observed, contact the manufacturer to determine if the cells require replacement. Electrolyte leakage can cause a loss of capacity and can lead to other VRLA failure modes.

Figure 7.1. Signs of Electrolyte Leakage From a VRLA Battery.



7.2.2.10. Visually inspect the cell posts for corrosion and damage. Wipe off any signs of corrosion from the posts. Regrease the post with anticorrosion grease, if necessary. Corrosion on the cell posts can indicate a loss of post seal integrity, which can result in rapid dryout and failure of a VRLA battery. Consult with the manufacturer if post seal failure is suspected.

7.2.2.11. Verify that the voltmeter calibration has not expired. Use a calibrated voltmeter with an accuracy of at least 0.5% of the measured voltage. Assure that the voltmeter test leads are well

insulated and securely attached to the meter to prevent their falling onto a cell and causing a short circuit.

CAUTION: Because float voltages are accurate cell indicators only when taken on a fully charged battery, be sure that at least 72 hours have elapsed since the system was discharged or equalized.

7.2.2.12. Record the charger output voltage and current. Verify that the output voltage is within the desired range.

CAUTION: Observe the proper polarity when taking voltage measurements to avoid positive and negative calibration differences in the voltmeter.

7.2.2.13. Measure and record the voltage at the battery terminals. Divide this measurement by the number of cells in the battery to confirm that the average individual cell voltage is within the range recommended by the manufacturer.

7.2.2.14. If float voltage is outside the recommended range, adjust the charger output to the recommended value in accordance with facility procedures.

7.3. Quarterly Inspection:

7.3.1. Purpose of Inspection:

7.3.1.1. The quarterly inspection provides confirmation that the battery and individual cells are being maintained within recommended operating limits. Also, the quarterly inspection for a VRLA battery is intended to confirm that excessive internal battery degradation has not occurred. The following checks are specified on a quarterly basis:

7.3.1.1.1. Monthly inspection as described in Section 7.2, except the float voltage checks are performed on all cells

7.3.1.1.2. Cell internal ohmic measurements

7.3.1.1.3. Temperature of the negative terminal of each cell

7.3.1.2. Cell internal ohmic measurements are intended to identify degraded or failed cells. Section 7.3.2. provides additional information regarding these measurements.

7.3.1.3. A check of cell temperature is prudent because a high cell temperature can indicate any of the following potential problems:

7.3.1.3.1. High temperatures reduce battery life by accelerating the internal corrosion rate. A common rule of thumb for vented lead-acid batteries is that a 8.3°C (15°F) rise in temperature decreases the expected life by 50%. For the same temperature rise, a VRLA battery experiences at least the same life reduction as a vented cell.

7.3.1.3.2. High battery temperatures can contribute to thermal runaway, a condition in which a battery on a constant voltage charge at an elevated temperature destroys itself through internal heat generation due to high internal current.

7.3.1.3.3. If the float voltage is too high for the actual cell temperature, the cell will be overcharged, leading to internal gassing and periodic venting of gases through the pressure relief

valve. A VRLA battery can suffer from thermal runaway due to overcharge at high temperatures.

7.3.1.3.4. A cell (or group of cells) with an abnormally high temperature in comparison to other cells can indicate that significant dryout has occurred or that a localized temperature dissipation problem exists.

7.3.2. Internal Ohmic Measurements Background Information:

7.3.2.1. Internal ohmic measurements are taken to determine the internal resistance of a battery. An internal ohmic measurement can be obtained in different forms—resistance, impedance, or conductance. Compared to the many decades that the lead-acid battery has been in use, the application of internal ohmic measurements is still a relatively new technology. The following explains why this technology has been specified for VRLA batteries:

7.3.2.1.1. VRLA batteries cannot be visually inspected internally; in vented batteries, the visual inspection often provides early visual indication of several possible battery problems.

7.3.2.1.2. Cell voltage measurements do not indicate internal problems until significant cell damage or degradation has occurred.

7.3.2.1.3. Dryout is a recognized failure mechanism for VRLA batteries. Traditional inspections are unable to detect this condition.

7.3.2.1.4. VRLA batteries have shown a tendency to be more susceptible to sudden death (an unexpected failure when a load is placed on the battery) than vented lead-acid batteries. Yet, the VRLA battery design precludes monitoring for this failure mode by conventional means.

7.3.2.1.5. VRLA batteries are more sensitive to high temperature, float voltage variations, overcharge, and over-discharge than vented lead-acid batteries. Therefore, some method of monitoring the internal rate of degradation has been needed.

7.3.2.1.6. Other conventional battery inspections do not necessarily provide a true indication of battery health. For example, specific gravity and cell voltage measurements do not indicate the available capacity. Either of these measurements offers general information regarding the quality of the electrolyte and the adequacy of the float voltage; however, neither provides information regarding the internal cell conduction paths or the actual cell capacity. In any event, specific gravity measurements are not possible for VRLA batteries.

7.3.2.1.7. Finally, there is no other measurement technique that offers the user any ability to “see” inside the cell. Some type of internal monitoring is needed. In some respects, an internal ohmic measurement of a VRLA battery is a limited substitute for the visual inspection of a vented lead-acid battery.

7.3.2.2. Three types of internal ohmic test equipment are available, capable of measuring conductance, impedance, or resistance, respectively. The following provides a brief description of each type. All three types are considered technically acceptable for use in stationary battery monitoring.

7.3.2.3. Conductance describes the ability of a circuit to facilitate current flow. In a typical conductance test, an AC voltage of known frequency and amplitude is applied across a cell or battery, and the AC current that flows in response to the applied voltage is observed. The measured conductance is the ratio of current to voltage, where the current is the component in-phase with the

AC voltage. The measured conductance value varies with battery manufacturer, type, and size. The Midtronics Celltron Plus is an example of a commercially available conductance tester (see [figure 7.2](#)).

Figure 7.2. Internal Conductance Tester.



7.3.2.4. A battery impedance tester capacitively couples a low-frequency current to the battery and measures the small AC voltage drop across the battery terminals. The voltage measurement is divided by the AC current passing through the battery to calculate the battery impedance. Consisting basically of a transmitter and receiver, an impedance tester applies an AC current to the battery under test. The AC test current is applied via a series capacitor (capacitive couple) to block the DC voltage of the battery. The receiver is clamped around a battery terminal and probes are used to measure the AC voltage across the battery. The instrument circuitry measures the rms current and voltage, then computes and displays these values as an impedance (milliohm). Figure 7.3. shows the Biddle Enhanced Battery Impedance Test Equipment (EBITE) test system.

Figure 7.3. Internal Impedance Tester.



7.3.2.5. A battery resistance measurement is taken by monitoring the instantaneous change in voltage when the battery is discharged by a specific amount. When a load is applied to a battery, an instantaneous voltage drop occurs and, when the load is removed, a voltage recovery subsequently occurs. By monitoring the current and cell voltage just prior to removal of the load and the recovered cell voltage, the internal cell resistance can be calculated by Ohm's Law. The Alber Cellcorder resistance tester is shown in [figure 7.4.](#) This tester provides a resistance measurement in terms of micro-ohms.

Figure 7.4. Internal Resistance Tester.



7.3.2.6. Each type of test equipment described above measures some form of the cell's internal resistance. The goal of an internal ohmic measurement is to measure changes in the internal resistance as the cell ages. As a VRLA cell ages from new to end-of-life, the internal resistance is expected to change significantly. It is important to understand that a cell's internal resistance can change by a number of factors in addition to the expected aging process. The following parameters affect the measured internal resistance:

7.3.2.6.1. Natural aging and degradation. Internal resistance increases with age. The goal of an internal ohmic measurement is to monitor the extent of this degradation.

7.3.2.6.2. State of charge. Internal resistance increases as a cell is discharged. To ensure consistency, internal ohmic measurements should only be taken on fully charged cells while on float charge.

7.3.2.6.3. Temperature. To the extent possible, measurements should be taken in the range of 18°C (65°F) to 29°C (85°F). Low temperatures cause increased resistance which could appear as a degrading performance trend by internal ohmic measurements.

7.3.2.6.4. Rated cell capacity. Internal resistance tends to decrease as the cell capacity is increased. In general, internal ohmic measurements taken on one size cell can not be compared to measurements taken from another cell size. The best method is to compare the measurements of all cells in a particular battery.

7.3.2.6.5. Cell-to-cell variations. Minor manufacturing and operating variations will contribute to minor differences in the measured internal resistance between cells.

7.3.2.6.6. Test equipment. Each type of test equipment performs its measurement by a different technique, and at a different test frequency and applied current. Thus, the various test instruments will provide different readings on the same cell. Although the different measurements can be correlated, they are not identical.

7.3.2.6.7. Measurement uncertainty. The test equipment calibration, rated accuracy, types of test probes, and quality of test connection all contribute to variations in the measurement.

7.3.2.7. Despite the above variations, internal ohmic measurements have demonstrated the ability to identify failed or low capacity cells. IEEE 1188 recommends investigating internal resistance changes of 20% or more. The following provides specific guidance regarding the interpretation of internal ohmic measurements:

7.3.2.7.1. Compare measurements to the reference value (internal ohmic value of the cell when new) for the particular cell size and type. The test equipment supplier or battery manufacturer can provide information regarding the expected reference value. Care must be taken that the selected reference value applies to the cell under test.

7.3.2.7.2. A conductance decrease >30% from the reference value likely indicates a low capacity cell. A conductance decrease >40% from the reference value likely indicates a failed cell.

7.3.2.7.3. An impedance or resistance increase >50% from the reference value likely indicates a low capacity cell. An impedance or resistance increase >80% from the reference value likely indicates a failed cell.

7.3.2.7.4. If the reference value for a particular cell type is not available, compare the internal ohmic measurements for all cells in the battery under evaluation. Even in degraded batteries, there are often good cells that still have an internal ohmic value near the reference value for that cell type. Estimate the reference internal ohmic value by selecting the average of the lowest impedance (or resistance) cells or the average of the highest conductance cells, depending on the test equipment used. Apply the guidelines described above using this estimated reference value.

7.3.3. Inspection Procedure:

WARNING: Observe safety precautions for working with energized DC equipment and batteries.

7.3.3.1. Perform the monthly inspection as specified in paragraph 7.2.

7.3.3.2. Use a temperature measurement device such as an electronic meter with attached temperature probe to measure the temperature of each cell. Verify that the calibration has not expired and that the calibrated measurement accuracy meets or exceeds $\pm 0.6^{\circ}\text{C}$ (1°F). Measure and record each cell temperature to the nearest whole degree by placing the temperature probe against the negative terminal of each cell.

WARNING: Be sure the uninsulated portion of the temperature probe is not long enough to simultaneously touch the positive and negative posts.

7.3.3.3. Investigate any higher than expected temperatures. If any cell temperature is more than 3°C (5°F) above the ambient temperature, investigate further.

NOTE: High cell temperatures can contribute to thermal runaway in a VRLA battery. Every effort should be made to keep the cell temperatures within the design limits.

7.3.3.4. Measure and record each cell float voltage. Compare the cell voltages to the range recommended by the manufacturer. Ensure that the voltage readings are within the tolerance specified by the manufacturer for the particular battery. If any individual cell measurement exceeds the manufacturer's recommended tolerance, investigate for abnormal conditions.

7.3.3.5. In accordance with the test equipment manufacturer's instructions, measure each cell's internal resistance, impedance, or conductance, as applicable. Take the internal ohmic measurement with the battery in a fully charged, steady state condition while on float charge. Readings taken on a discharged battery or a battery undergoing recharge are not indicative of the actual condition of the battery.

7.3.3.6. Evaluate the internal ohmic measurement taken on each cell and investigate any reading that varies from the cell's reference value by more than 25%. A conductance decrease $>30\%$ from the reference value likely indicates a low capacity cell. A conductance decrease $>40\%$ from the reference value likely indicates a failed cell. An impedance or resistance increase $>50\%$ from the reference value likely indicates a low capacity cell. An impedance or resistance increase $>80\%$ from the reference value likely indicates a failed cell.

7.3.3.7. If the cell internal ohmic measurements indicate possible low capacity cells, perform one of the following:

7.3.3.7.1. Replace the cells that have poor internal ohmic values.

7.3.3.7.2. Perform a capacity discharge test to confirm the low capacity cell(s); proceed further based on the capacity test results.

7.3.3.7.3. Contact the battery manufacturer for guidance.

7.4. Annual Inspection:

7.4.1. Purpose of Inspection:

7.4.1.1. The annual inspection includes the monthly and quarterly inspections. The additional inspections conducted annually allow a more detailed assessment of the battery condition. The following inspections are included in the annual inspections:

7.4.1.1.1. Monthly and quarterly inspections on all cells

7.4.1.1.2. Detailed cell and battery rack inspection

7.4.1.1.3. Connection resistance checks

7.4.1.2. Connection resistance checks are considered necessary for high-rate discharge applications. A high connection resistance can cause excessive heating or abnormal voltage drop during discharge, and can lead to severe damage during periods of high-rate discharge. The integrity of all battery electrical connections should be confirmed annually to ensure that all connections are acceptable; this inspection includes cell-to-cell (intercell) and external circuit terminations. The adequacy of electrical terminations is best determined by connection resistance measurements. Connections should be disassembled, cleaned, and reassembled only when resistance measurements indicate a high-resistance termination.

7.4.2. Inspection Procedure:

WARNING: Observe safety precautions for working with energized DC equipment and batteries.

7.4.2.1. Perform the monthly and quarterly inspections as specified in paragraph 7.2. and 7.3, respectively. Perform a detailed visual inspection of each cell to identify any signs of leakage, container cracking, or post seal failure.

7.4.2.2. Perform intercell connection resistance checks in accordance with paragraph 7.4.3. If a micro-ohmmeter is not available, check the torque of each connection in accordance with the manufacturer's instructions.

7.4.3. Intercell Connection Checks:

7.4.3.1. The procedure provided in this section assumes that a micro-ohmmeter is available to perform the specified checks. If this test equipment is not available, check the torque of each connection in accordance with the battery manufacturer's instruction manual.

7.4.3.2. Normal termination resistance varies with the battery size and termination technique. Normal resistance values can range from less than 10 micro-ohms for a large battery to well over 100 micro-ohms for a small battery. Review the battery manufacturer's instruction manual to determine acceptable values for a particular battery.

7.4.3.3. Intercell and termination resistance values are recorded as a baseline upon initial installation. Thereafter, annual measurements are trended against the baseline data to identify any degradation in the battery connections. Acceptance criteria should be established for resistance values; corrective action is required whenever the acceptance criteria are exceeded. The urgency of the corrective action should be based on the extent to which the measured resistance exceeds the acceptance criteria. For example, two levels can be established:

7.4.3.3.1. An absolute upper limit requiring immediate corrective action regardless of facility status

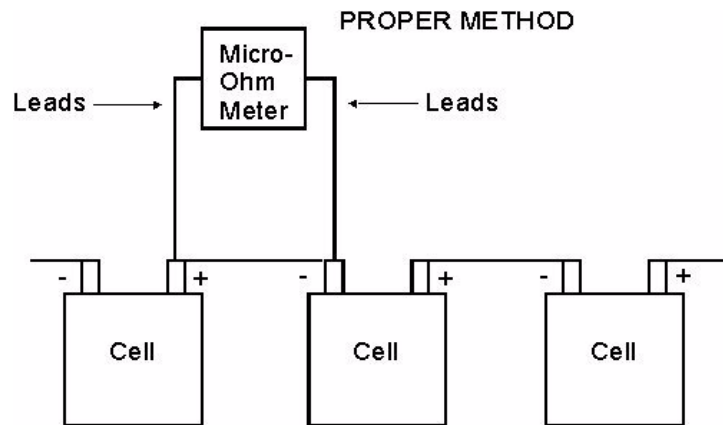
7.4.3.3.2. A lower limit requiring correction as a routine scheduled activity

7.4.3.4. Connection resistance measurements are normally taken with a micro-ohmmeter. Micro-ohmmeter measurements should be recorded to the nearest micro-ohm. Any digital readings in the milliohm range should be converted to micro-ohms. For example, a reading of 0.050 milliohm would be recorded as 50 micro-ohms. The micro-ohmmeter must be calibrated and should be accurate to within ± 2 micro-ohms.

7.4.3.5. Micro-ohmmeter measurements are normally limited to bolted connections. Some manufacturers use multicell jars in which the internal connections are welded in place. In this case, only the bolted connections on each end of the multicell jar are normally checked because the internal welded connections are inaccessible.

7.4.3.6. In principle, intercell measurements are always taken from the post of one cell to the post of the next cell. The cell is not included in the measurement; the resistance check is intended to determine the resistance of the bolted connection between the two posts. Micro-ohmmeters are capable of precise resistance measurements to a fraction of a micro-ohm (10^{-6} ohm). Care must be taken during micro-ohmmeter measurements; [figure 7.5](#) conceptually shows the proper test connection method for a micro-ohmmeter. It is important that the micro-ohmmeter probes touch only the posts, not the intercell connector hardware. The resistance of the connection between the post to the hardware is the concern, not the resistance of the connecting hardware.

Figure 7.5. Proper Micro-Ohmmeter Measurement.

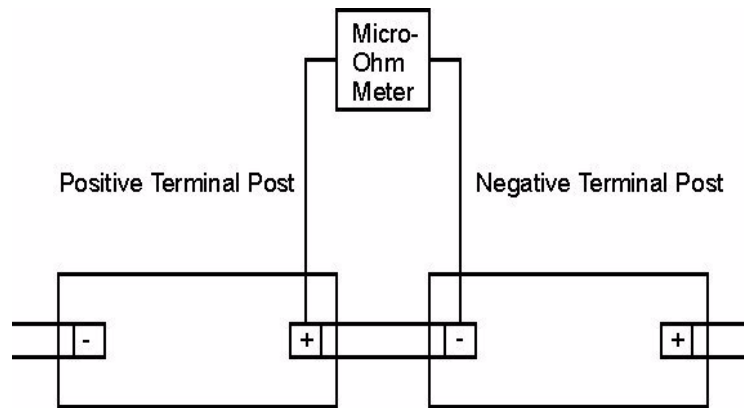


7.4.3.7. The micro-ohmmeter is very sensitive and can be permanently damaged if connected across a cell. Care must be taken to prevent the test leads from simultaneously touching the positive and negative posts of a single cell, or ends of a series of cells.

7.4.3.8. Because of the many cell designs and termination methods, it is not practical to cover all possible connection resistance configurations. Instead, a few common methods are presented as examples of how the measurement can be accomplished. Maintenance personnel should review the battery installations for their facility and determine the most suitable test method for each battery.

7.4.3.9. The intercell resistance measurement is simplest for cells containing one post each for the positive and negative terminal. The intercell connection resistance is determined by measuring the resistance from each cell's positive post to the next cell's negative post (see [figure 7.6](#)). The reading must be obtained with the probe actually on the post, not on the intercell connector.

Figure 7.6. Single Terminal Post Resistance Measurement.

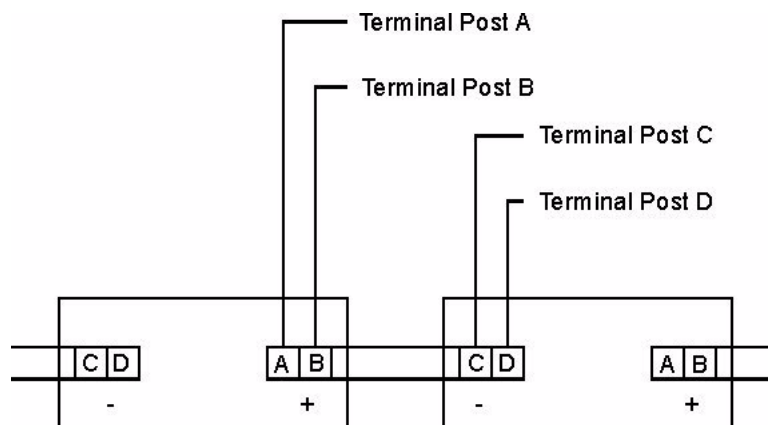


7.4.3.10. Another common design has two terminal posts on each end of the cell. The intercell connection bolts onto both posts as shown in [figure 7.7](#). Because there are four posts total, take two measurements as follows:

7.4.3.10.1. Terminal Post A to Terminal Post C

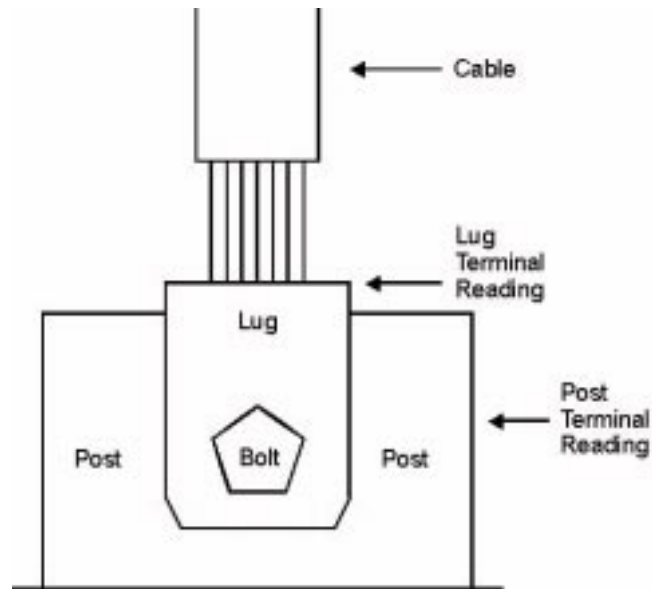
7.4.3.10.2. Terminal Post B to Terminal Post D

Figure 7.7. Two Terminal Post Resistance Measurement.



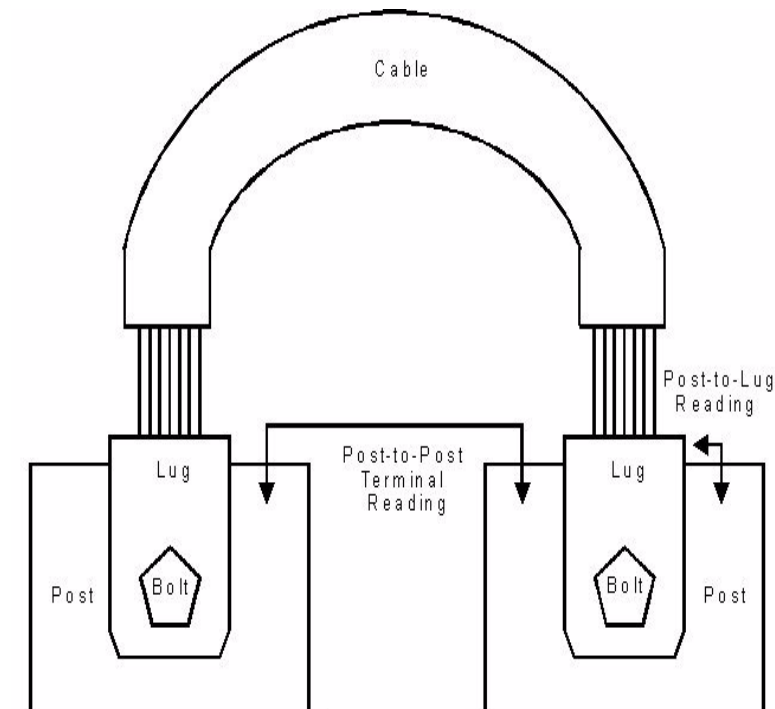
7.4.3.11. Inter-tier or inter-rack connections are sometimes made with cables because of the distance between cells. A lug is attached to each end of the cable and the lugs are bolted onto the appropriate cell posts. This post configuration is shown in [figure 7.8](#). In this case, a post-to-post measurement is still appropriate, but because the cable resistance is included in the measurement, termination problems can be masked by the cable resistance contribution to the measurement.

Figure 7.8. Cable Bolted to Terminal Post.



7.4.3.12. As a minimum, record the post-to-post resistance for a simple one post cell as shown in [figure 7.9](#). In addition, take post-to-lug measurements at each post to remove the cable resistance from the measurement. This measurement is also shown in Figure 7.9.

Figure 7.9. Inter-Tier or Inter-Rack Resistance Measurement.



7.4.3.13. A two post cell normally has a termination plate that bolts onto both posts. Cables connecting the two cells attach to the termination plate. The method of measurement in this case is

fundamentally the same as for the two-post cell method; post-to-post measurements are taken between the two cells. In addition, post-to-lug measurements can be recorded at each cell to obtain a more accurate measure of the actual termination resistance.

7.4.3.14. Some VRLA cell designs do not allow access to the post. Taking an intercell connection resistance measurement on the connecting hardware will be ineffective; the measurement will record only the resistance of the hardware, not the resistance of the connection. In these cases, check the torque of the connections in accordance with the battery manufacturer's instruction manual.

7.4.4. Correcting High Resistance Connections:

WARNING: Observe safety precautions for working with energized DC equipment and batteries.

7.4.4.1. If a resistance measurement exceeds the acceptance criteria, perform the following steps before resorting to disassembling the connection.

7.4.4.1.1. Inspect the connection for signs of corrosion.

7.4.4.1.2. Check the torque of the high-resistance bolted connection. If the connection hardware is a bolt and nut assembly, use two insulated wrenches to minimize stress on the connection. One of the two wrenches has to be a calibrated torque wrench. Do not exceed the manufacturer's recommended torque values. Recheck the resistance measurement after retorquing the connection.

7.4.4.2. If retorquing the connection provides acceptable results, take no further action. If there are signs of corrosion or if the resistance measurement still exceeds the acceptance criteria after retorquing, disassemble, clean, and repair the connection per the following steps.

7.4.4.3. Determine which connection is the source of the high resistance by taking additional resistance readings, as appropriate.

NOTE: By taking additional readings, the source of the high resistance can frequently be isolated to a single connection. This technique minimizes the number of connections that must be disassembled.

7.4.4.4. Establish proper conditions and remove the battery from service.

CAUTION: Do not break the connection between an operating group of cells.

7.4.4.5. Disassemble the connection to be repaired.

7.4.4.6. Clean the connector and cell posts using a soft plastic-bristle brush or other soft tool until no signs of corrosion or dirt remain. Small imperfections in the lead can be carefully removed with a fine file if the imperfection is preventing good contact between the mating surfaces.

CAUTION: Do not use a steel brush, brass brush, steel wool, emery cloth, sandpaper, metal file, or other abrasive device to clean connections; they will damage the lead plating on the connectors and posts.

NOTE: If the cleaning results in exposing copper underneath the lead plating, a new connector should be installed. Terminal posts must be cleaned carefully because the posts cannot be replaced.

7.4.4.7. Reapply anticorrosion grease onto the connectors and posts in accordance with the manufacturer's instructions.

WARNING: Apply anticorrosion grease strictly in accordance with the manufacturer's instructions. If the anticorrosion grease is overheated, it can exceed its flash point and start a fire.

7.4.4.8. Reinstall the connectors and torque the bolts to the manufacturer's required values.

7.4.4.9. Perform the connection resistance measurement again to confirm that the cleaning has corrected the problem.

7.5. Special Inspections:

7.5.1. The purpose of a special inspection is to ensure that the battery has not been damaged by an unusual condition or event. The annual inspection, including monthly and quarterly checks, should be performed whenever the battery has experienced an unusual condition. Examples of cases where a VRLA battery should receive a special inspection include:

7.5.1.1. Severe discharge

7.5.1.2. Severe overcharge

7.5.1.3. Exposure to extreme high temperature

7.5.1.4. Seismic event

7.5.1.5. Exposure to abnormal environments, such as storm leakage through the roof onto a battery

Chapter 8

PERIODIC TESTS

8.1. Capacity Discharge Test (Performance Test):

8.1.1. Background Information:

8.1.1.1. A capacity test determines the extent to which a battery is capable of supplying the manufacturer's rated discharge current for a given duration under a specific set of conditions. It is designed to allow trending of the battery's capacity by discharging the battery at a constant current or power to a predefined endpoint voltage and comparing the actual discharge time to the manufacturer's rated discharge time.

8.1.1.2. If the data has been properly obtained and recorded, the capacity test provides the most information about the battery's capacity and degree of internal deterioration. Even more important, the user has a means of estimating where the battery is along its life curve.

8.1.1.3. In general, the capacity test duration should correspond to the duty cycle duration as closely as possible. For example, if the battery was sized to provide a certain load for 2 hours, the capacity test should also be conducted at the manufacturer's 2-hour discharge rate. Because of the margins normally designed into the battery size, a capacity test duration corresponding to the duty cycle duration should provide reasonable assurance that the battery can meet its design requirements.

8.1.2. Test Frequency:

8.1.2.1. A capacity test should be performed as part of the acceptance testing of a new installation.

8.1.2.2. Perform a capacity test as necessary to resolve discrepancies in internal ohmic measurements (see paragraph 7.3.2). Depending on the warranty, the battery manufacturer might require capacity test data rather than internal ohmic measurement data before a warranty claim will be honored.

8.1.2.3. For critical installations, perform a capacity test every 2 years. The basis for this test frequency (longer than specified in IEEE 1188) is that quarterly internal ohmic measurements should also identify signs of degradation. As noted above, internal ohmic measurement test results can lead to the performance of a capacity test.

8.1.2.4. For non-critical applications, quarterly internal ohmic measurements are considered adequate; periodic capacity tests are not specified. However, a capacity test might still be required to resolve signs of degradation from the internal ohmic measurement data.

8.1.2.5. With regard to capacity testing, each facility is responsible for determining whether a particular installation is designated as critical or non-critical. A critical installation is one in which a loss of power can not be tolerated.

8.1.2.6. If a capacity test is specified and the test equipment is not available, perform a continuity test instead in accordance with paragraph 8.2.

8.1.2.7. A stationary battery used in an engine starting application does not require a capacity test if the battery periodically starts the engine. The monthly, quarterly, and annual inspections are

still required for stationary engine starting batteries. Note that this manual does not apply to motive power batteries.

8.1.3. Initial Conditions for Test:

8.1.3.1. Equalize the battery only if recommended by the manufacturer and return it to float charge for a minimum of 72 hours but less than 30 days before the start of the test.

NOTE: Some manufacturers do not recommend equalizing VRLA batteries to minimize gassing and water consumption. In general, an equalize charge should not be required specifically for a capacity test.

8.1.3.2. Check all battery connections and ensure that battery connection resistance measurements are within the expected tolerances. Correct any potential problems before starting the test.

8.1.3.3. Measure and record the float voltage of each cell just prior to the test.

8.1.3.4. Measure and record the cell temperature of 10% or more of the cells just prior to the test to establish an average temperature.

8.1.3.5. Measure and record the battery terminal float voltage.

8.1.3.6. Take adequate precautions (such as isolating the battery to be tested from the DC system) to ensure that a failure will not affect other equipment.

8.1.4. Capacity Test Procedure:

WARNING: Observe safety precautions for working with energized DC equipment and batteries.

8.1.4.1. Verify that the pretest requirements described in paragraph 8.1.3. have been completed.

8.1.4.2. Verify that the battery area ventilation is operating normally.

8.1.4.3. Determine the discharge rate by dividing the manufacturer's rated discharge (for the desired duration) by the appropriate temperature correction factor (based on the cell temperature readings). Consult the manufacturer for the proper discharge temperature correction factors for a specific battery.

8.1.4.4. Set up a test discharge load capable of maintaining the required constant current or constant power test discharge rate. The load bank typically generates a considerable amount of heat during the test; locate the load bank where it will not overheat other installed equipment.

8.1.4.5. Disconnect the battery charger from the battery and connect the load bank to the battery.

CAUTION: Be careful not to short-circuit the battery while making the connections to the load bank. One approach is to connect the cables first to the load bank, followed by the connection to the battery. The reason for this order of events is that the connection of the positive and negative leads at the load bank can be very close together with little room for error.

NOTES:

If the battery charger cannot be disconnected from the battery, the test discharge rate must be adjusted to compensate for the battery charger contribution.

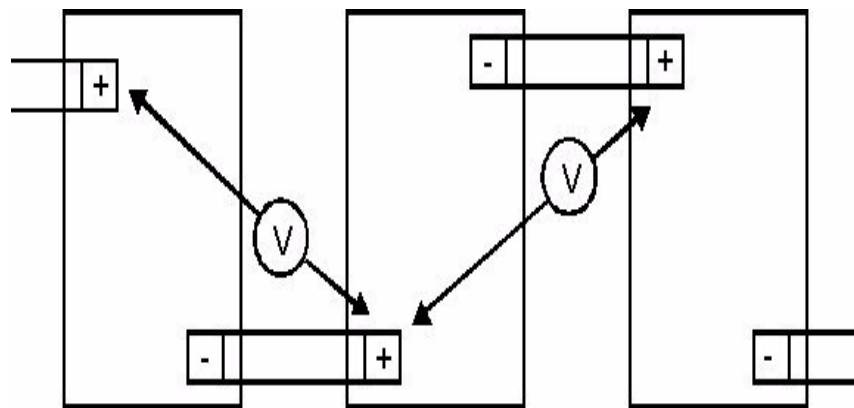
Cell jumpering equipment should be available and ready for use in case a cell(s) needs to be jumpered during the test.

8.1.4.6. Start the timer and begin the load test at the temperature-corrected test discharge rate.

8.1.4.7. Monitor the test current throughout the test and adjust the load bank as needed to maintain a constant test current.

8.1.4.8. Measure and record individual cell voltages and the battery terminal voltage. Take the readings just prior to starting the test, at the beginning of the test when load is first applied, at periodic intervals during the test, and at the completion of the test. At least three sets of readings under load should be taken. Measure individual cell voltages between respective posts of like polarity of adjacent cells, as shown in [figure 8.1.](#), to include the intercell connector voltage drop.

Figure 8.1. Typical Cell Voltage Measurement.



8.1.4.9. Maintain the test discharge rate until the battery terminal voltage decreases to the specified average end of discharge voltage per cell times the number of cells in the battery. Do not continue the test below the specified cutoff point; stop at the cutoff point to ensure that the battery capacity is always calculated with the same reference conditions from test to test, and to prevent overdischarge of some cells.

EXAMPLE: A test performed on a 60-cell battery with a specified end voltage of 1.75 V per cell would terminate at 105 V per the following equation:

$$V_{\text{end}} = (1.75 \text{ V}) \times (\text{Number of connected cells})$$

8.1.4.10. Use the following criteria to determine whether a test should be terminated because of a low-voltage cell(s).

8.1.4.10.1. If a cell is approaching cell reversal (1.0 V) and the test is >90% complete, continue the test until the specified battery terminal voltage is reached.

8.1.4.10.2. If the test is not near completion, an individual cell is approaching cell reversal (1.0 V), and the battery has not yet reached the specified terminal voltage, stop the test. Disconnect the low-voltage cell from the battery and bypass it by installing a jumper of adequate ampacity between the adjacent cells.

8.1.4.10.3. Calculate the new battery end terminal voltage limit due to removal of the cell and restart the test.

EXAMPLE: If the test termination voltage was 105 V for 60 cells based on 1.75 V per cell, the new test termination voltage would be 103.25 V if one cell is jumpered out.

NOTES:

Once a cell has reached 1.0 V, the cell voltage drops rapidly and the cell is nearing or has reached complete exhaustion. Continuing the test without jumpering the cell is acceptable only if the test is near completion.

The time required to jumper a cell and restart the test should be minimized. The downtime should be less than 10% of the intended test duration or 6 minutes, whichever is shorter. A longer downtime allows the battery to recover capacity. The downtime should not be included as part of the total duration of the capacity test.

Only one downtime is allowed per test. Additional downtimes allow the battery to recover and falsely indicate a higher battery capacity.

8.1.4.11. Observe the battery during the test for intercell connector heating.

8.1.4.12. Terminate the test when the battery terminal voltage decreases to the calculated end voltage. Record the total test time.

8.1.4.13. Disconnect the test equipment.

8.1.4.14. Recharge the battery in accordance with the manufacturer's instructions and restore it to normal standby service.

8.1.4.15. Calculate battery capacity using the following equation for discharge times greater than 1 hour:

$$\text{Percent capacity (77°F)} = (T_a/T_s) \times 100$$

where:

T_a = actual time of test to specified terminal voltage

T_s = manufacturer's rated time to specified terminal voltage

8.1.4.16. Compare the battery capacity to that obtained by previous capacity tests to determine the trend in battery capacity. A lead-acid battery typically requires replacement when its capacity has fallen to 80% of its rated capacity. Determine whether battery degradation is sufficient to warrant more frequent capacity testing. Evaluate the performance of individual cells to identify unacceptable cells.

8.2. Continuity Test:

8.2.1. Background Information:

8.2.1.1. A continuity test is a short duration test of the battery's capacity by having the battery carry the system load. A continuity test is normally initiated by turning off the associated battery charger.

8.2.1.2. A continuity test is to be performed instead of a capacity test (see paragraph 8.1) if capacity test equipment is not available.

8.2.1.3. A continuity test requires close monitoring of battery voltage throughout the test to ensure that a loss of power does not occur.

8.2.2. Procedure:

CAUTION:

Conduct a continuity test during stable system conditions (no thunderstorms or other events that might require battery backup power). Because the battery is partially discharged by the continuity test, stable system conditions are needed to ensure that the battery is recharged as soon as possible.

8.2.2.1. Before starting a continuity test, check the charger output current to determine the system load. Review the manufacturer's data sheet for the battery to predict how long the battery should be capable of carrying this load. Based on the total load and the battery's rated capability, determine how long to conduct the continuity test; it is not intended that a continuity test fully discharge the battery. The battery should have greater than 50% of its original capacity when the test is complete. Also, determine the minimum allowed DC voltage and establish test termination criteria above this minimum voltage.

8.2.2.2. Initiate the continuity test by turning off the battery charger.

CAUTION:

Monitor battery voltage closely at the beginning of the test. Immediately restore power to the charger if battery voltage is falling rapidly.

8.2.2.3. Constantly monitor battery voltage during the continuity test. Terminate the test by re-energizing the battery charger if the battery voltage falls to the low voltage limit established for the test. Otherwise, terminate the test when the battery has discharged for the planned duration.

8.2.2.4. Evaluate the test results by comparing the discharge rate and discharge time to the manufacturer's rating for the battery.

Chapter 9

INSTALLATION AND REPLACEMENT

9.1. Replacement Criteria:

9.1.1. Over the life of any backup power system, the installed battery eventually requires replacement. When the predicted end of life for a battery is less than 2 years away, the impending need for replacement should be identified and budgeted. Larger battery installations should be planned as far in advance as possible. Smaller batteries might not need as much lead-time for evaluation.

9.1.2. Any of the following conditions can require a battery replacement:

9.1.2.1. Capacity below, at, or approaching 80% (as determined by a capacity test)

9.1.2.2. Age approaching the manufacturer's predicted service life

9.1.2.3. Continuity test indicating low battery capacity

9.1.2.4. Excessive number of individual cell failures such that the entire battery should be replaced rather than individual cells

9.1.2.5. Load growth that prevents the battery from meeting its load requirements

9.1.2.6. New or revised design requirements

9.1.2.7. Severe battery degradation

9.1.3. Except for cases of sudden battery degradation, trending of battery performance should allow maintenance personnel to predict when replacement will be necessary.

9.1.4. Individual cells might require replacement when a capacity test or an internal ohmic measurement determines that they are degraded. Unless the battery is nearing the end of its service life or many cells in the battery are degraded, it is acceptable to replace individual cells within the battery. Based on industry experience to date, it is likely that some cells will require replacement in the first 4 years of service.

9.2. Battery Size Verification:

9.2.1. Some well-built and well-maintained batteries can last for many years. For a battery that was originally installed several years ago, it is possible that the design of other equipment in the facility or the design criteria for the facility has changed. Consider the following sizing guidelines for replacement batteries:

9.2.1.1. The facility might have more load on the battery than anticipated when it was originally sized. A load check should be performed as part of a battery replacement to confirm that the replacement battery is properly sized.

9.2.1.2. The original criteria for battery sizing might have assumed a shorter duty cycle than desirable for newer installations today. Replacement batteries could require a larger size just to meet the current criteria for the facility.

9.2.1.3. Verify the manufacturer's performance ratings for the battery. In the years since the last battery was installed, battery manufacturers might have changed the battery ratings.

9.2.1.4. Verify, if possible, that the original battery was properly sized, including allowances for aging, temperature, and design margin. It is possible that the battery was too small to fulfill its original design requirements with all factors considered.

9.3. Design Verification for a Replacement Battery Larger Than the Original:

9.3.1. If the decision is made to replace a battery with a larger battery, check the following system design features:

9.3.1.1. Verify that the larger battery, including the new battery rack will physically fit within the available footprint and that the allowable floor loading is not exceeded.

9.3.1.2. Check the new battery fault current and determine if protective devices and distribution equipment are still within their interrupting or withstand ratings.

9.3.1.3. Determine if the existing charger can recharge the battery in a reasonable time. A larger charger might be required as part of the battery replacement.

9.3.1.4. Verify that the battery cables are large enough to carry the larger battery output current.

9.4. Check of Other Equipment:

9.4.1. For a good battery installation, a battery replacement is a relatively rare event. The rest of the system should be inspected and upgraded, as needed, as part of the battery replacement. While the battery is out of service for replacement, perform the following:

9.4.1.1. Inspect DC system breakers.

9.4.1.2. Inspect cabling for aging or damage. Replace as necessary.

9.4.1.3. Inspect the battery rack for damage or corrosion. Replace as necessary.

9.4.1.4. Replace older fuses in the DC system as a precautionary measure.

9.4.2. The charger should receive special attention as part of a battery replacement. Complete the following:

9.4.2.1. If the new battery has a larger capacity, confirm that the charger size is still adequate.

9.4.2.2. Check the voltmeter calibration at the float and equalize voltages.

9.4.2.3. Check for loose connections and evidence of overheating.

9.4.2.4. Check the charger failure alarm by opening the AC breaker. Check the setting of other voltage relays.

9.4.2.5. Inspect contacts on relays for signs of pitting or burning.

9.4.2.6. Evaluate the output filter capacitors and replace if necessary.

9.4.3. As part of the battery replacement, make everything in the system as new as possible, not just the battery. The other equipment also ages. If it is not inspected and upgraded during the battery replacement, it might be many years before it is looked at closely again.

9.5. Maintenance Checks of a New Battery:

9.5.1. Review all manufacturer's recommendations for the installation and operation of the battery. The installed location and configuration must comply with the manufacturer's requirements.

9.5.2. Perform the following maintenance-related tasks as part of the installation:

9.5.2.1. Inspect all cells for damage before installation. Verify that the cells were stored in accordance with the manufacturer's recommendations.

9.5.2.2. Once the battery is installed, apply an initial charge in accordance with the manufacturer's recommendations.

9.5.2.3. Torque all intercell connections in accordance with the manufacturer's specifications. If a micro-ohmmeter is available, take a baseline set of intercell and termination resistance measurements. These resistance measurements will form the basis for future acceptance criteria.

9.5.2.4. Record baseline internal ohmic measurements for all cells.

9.5.2.5. A capacity test is recommended as part of the installation if the manufacturer did not perform an acceptance test before shipment. The purpose of this capacity test is to confirm adequate battery capacity and to identify any failed cells. If a capacity test is not performed, evaluate the internal ohmic measurements to ensure that all cells are consistent. Abnormal internal ohmic measurements might still require a capacity test to ensure that the battery is acceptable.

9.6. Warranty Considerations:

9.6.1. Most manufacturers offer a 1 or 2 year complete replacement warranty with a pro-rated warranty thereafter for larger stationary batteries. If the battery fails during the full-replacement period, the manufacturer will usually replace it at no charge. After the full-replacement period, the warranty is pro-rated based on the number of months in service, with the pro-rated amount based on the original battery cost. The pro-rated amount is normally applied as a credit to the current price of a replacement battery. Shipping and installation costs are usually excluded from the warranty.

9.6.2. The Power Conditioning and Continuation Interfacing Equipment (PCCIE) Special Maintenance Team (SMT) has negotiated a different warranty for certain uninterruptible power system (UPS) equipment. The contract was written with a full replacement of the battery within the first 3 years for any defects in materials and workmanship. After the first 3 years, the battery has a pro-rated warranty for an additional 3 years.

9.6.3. The manufacturer's warranty usually specifies required maintenance that must be performed and records that must be kept so as to document that the battery was properly maintained. There might also be restrictions on the average ambient temperature or the number of cycles placed on the battery.

9.6.4. The warranty, including full-replacement and pro-rated periods, is a commercial consideration established by the manufacturer. The warranty period might not have a direct relationship to the actual expected service life. For example, several studies have shown that VRLA cells often fail within 4 to 7 years, despite having a 20-year warranty.

9.7. Life Cycle Management:

9.7.1. A good system design balances the technical requirements with the cost and ongoing maintenance requirements. Consider the following factors when selecting the battery size and type:

9.7.1.1. Application and duty cycle requirements

9.7.1.2. System interface limitations

9.7.1.3. Service environment

9.7.1.4. Initial equipment cost

9.7.1.5. Installation cost

9.7.1.6. Ongoing maintenance cost

9.7.1.7. Periodic replacement cost

9.7.2. Some battery life cycle work sheets have shown a substantial savings for VRLA batteries (based on the assumption of a 20-year life and virtually no maintenance). An assessment of a battery's actual cost must be based on realistic life projections; consider the following costs:

9.7.2.1. Initial purchase of battery and rack, including freight.

9.7.2.2. Estimated installation cost, if different for the various battery types.

9.7.2.3. Periodic maintenance expense. The cost of monthly, quarterly, and annual maintenance should be assessed. Estimate maintenance costs for VRLA batteries based on the requirements of this AFMAN.

9.7.2.4. Periodic replacement.

9.7.3. Assume a service life of 8 years for life cycle calculations of VRLA batteries. This is typically shorter than the warranty life, but is based on the industry experience to date.

9.7.4. For life cycle planning, schedule replacement of long-life VRLA batteries every 8 years. The replacement schedule can be extended if maintenance records indicate acceptable performance.

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Attachment 1**GLOSSARY OF REFERENCES AND SUPPORTING INFORMATION*****References***

The most recent edition of referenced publications applies, unless otherwise specified.

IEEE 1187-1996, *IEEE Recommended Practice for Installation Design and Installation of Valve-Regulated Lead-Acid Storage Batteries for Stationary Applications*

IEEE 1188-1996, *IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve Regulated Lead-Acid Storage Batteries for Stationary Applications*

IEEE 1189-1996, *Guide for Selection of Valve Regulated Lead-Acid Storage Batteries for Stationary Applications*

IEEE 1184-1994, *IEEE Guide for the Selection and Sizing of Batteries for Uninterruptible Power Systems*

NFPA 70, *National Electrical Code*

NFPA 101, *The Life Safety Code*

AFJMAN 32-1280(I), *Facilities Engineering Electrical Exterior Facilities*

AFJMAN 32-1281(I), *Facilities Engineering Electrical Interior Facilities*

Terms

Acceptance Test—A constant current or power capacity test made on a new battery to determine whether it meets specifications or manufacturer's ratings.

Active Materials—The materials of the plates which react chemically to produce electrical energy when the cell discharges and which are restored to their original composition, in the charged condition, by a chemical reaction produced by the charging current.

Ampere-Hour Capacity—The number of ampere-hours that can be delivered under specified conditions, including temperature, rate of discharge, and final voltage.

Battery—Two or more cells connected to form one unit for producing electric energy at the required voltage and current levels.

Capacity—Ampere-hours available from a fully charged cell or battery.

Capacity Test—A discharge of a battery at a constant current or power to a designated terminal voltage.

Cell—An electrochemical device, composed of positive and negative plates, separator, and electrolyte, that is capable of storing electrical energy; when encased in a container and fitted with terminals, it is the basic component of a battery.

Charge—The conversion of electrical energy into chemical energy within the cell or battery. This restoration of the active materials is accomplished by maintaining a unidirectional current in the cell or battery in the opposite direction to that during discharge. A cell or battery that is said to be charged is understood to be fully charged.

Cycle—A battery discharge followed by a complete recharge. A deep, or full, cycle is described as the

removal and replacement of 80% or more of the cell's design capacity.

DC—Direct current.

Discharge Rate—The rate, usually expressed in amperes, at which electrical current is taken from the cell or battery.

Discharging—The withdrawing of electrical energy from a battery or cell.

Electrolyte—The conducting medium in which the flow of electric current takes place by the migration of ions. For example, the electrolyte for a lead-acid cell is an aqueous solution of sulfuric acid.

Equalize Charge—An extended charge to a measured end point that is given to a storage battery to insure the complete restoration of the active materials in all plates of the cells.

Float Charge—The method of maintaining a cell or battery in a charged condition by continuous, long-term constant-voltage charging at a level to balance self-discharge.

Float Voltage—The voltage applied to a battery to maintain the proper voltage for each cell of the battery during normal operation.

IEEE—Institute of Electrical and Electronics Engineers, Inc.

Internal Conductance—A measure of the ability of a cell or battery to facilitate current flow. Conductance is related to the inverse of impedance and resistance.

Internal Impedance—The opposition or resistance of a cell or battery to an alternating current of a particular frequency.

Internal Resistance—The opposition or resistance to electrical current flow within a cell or battery. Its value is dependent upon battery design, state of charge, temperature, and age.

Negative Plate—Consists of the grid and active material to which current flows from the external circuit when the battery is discharging.

Negative Terminal—The terminal toward which positive electric charge flows in the external circuit from the positive terminal when the cell discharges.

Nominal Gravity—The specific gravity of the electrolyte selected for the determination of the rated capacity of the storage battery when it is fully charged and correctly leveled.

Nominal Voltage—The characteristic operating voltage or rated voltage of a cell or battery.

Open Circuit Voltage—The voltage at a cell or battery terminals when no appreciable current is flowing.

Overcharging—Continuing charge after the battery has accepted its maximum amount of charge. In a vented cell, a result will be decomposition of water in the electrolyte into hydrogen and oxygen gases. In a VRLA cell, a result will be increased cell temperature and venting of gases through the pressure relief valve.

Oxygen Recombination—The electrochemical process in which oxygen generated at the positive plate during overcharge is reacted (reduced) with water at the negative plate at the same time, thereby producing heat.

Periodic Test—A test performed at scheduled intervals to detect failures and verify operability.

Polarization—The change in voltage at the terminals of the cell or battery when a specified current is

flowing; it is equal to the difference between the actual and the equilibrium (constant open-circuit condition) potentials of the plates, exclusive of the internal resistance drop.

Positive Plate—The grid and active material from which current flows to the external circuit when the battery is discharging.

Positive Terminal—The terminal from which the positive electric charge flows through the external circuit to the negative terminal when the cell discharges.

Rated Capacity—The ampere-hour capacity assigned to a storage cell by its manufacturer for a given discharge time, at a specified electrolyte temperature and specific gravity, to a given end-of-discharge voltage.

Recombinant Cell—A cell designed so that generated oxygen and hydrogen are recombined to form water rather than being vented from the cell (see Valve-Regulated Lead-Acid Cell).

Recombination—The chemical reaction of gases at the electrodes to form a nongaseous product.

Self-Discharge—The spontaneous decomposition of battery materials from a charged to a discharged state.

Stationary Battery—A storage battery designed for service in a permanent location.

Thermal Runaway—A condition whereby a battery on constant-potential charge at elevated temperature will destroy itself through internal heat generation due to high internal currents.

Undercharging—Applying less than the amount of current required to recharge a battery.

UPS—Uninterruptible Power System.

Valve-Regulated Lead-Acid (VRLA) Cell—A lead-acid cell that is sealed with the exception of a valve that opens to the atmosphere when the internal gas pressure in the cell exceeds the atmospheric pressure by a pre-selected amount. VRLA cells provide a means of recombination of internally generated oxygen and the suppression of hydrogen gas evolution to limit water consumption.

VRLA—Valve-regulated lead-acid.