

# IEEE Guide for Application and Management of Stationary Batteries Used in Cycling Service

IEEE Power and Energy Society

Sponsored by the  
Energy Storage and Stationary Battery Committee

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of the  
IEEE Power and Energy Society

Approved 27 September 2018

IEEE-SA Standards Board

**Abstract:** Information on the differences between stationary standby and stationary cycling applications and appropriate battery management strategies in cycling operations is covered in this guide. While the primary emphasis is on lead-acid batteries, information is also provided on alternative and emerging storage technologies. The management of battery systems in stationary standby service is covered in other IEEE documents and is beyond the scope of this guide.

**Keywords:** battery cycling, battery maintenance, battery operation, IEEE 1660™, standby battery, stationary battery

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## Participants

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Christopher Searles, Chair  
Jim McDowall, Vice Chair

Curtis Ashton  
Chris Belcher

Daniel Clark  
Jay Frankhouser  
Richard Hutchins

Larry Meisner  
James Midolo

The following members of the individual balloting committee voted on this guide. Balloters may have voted for approval, disapproval, or abstention.

Samuel Aguirre  
Ali Al Awazi  
Edward Amato  
Curtis Ashton  
Gary Balash  
Thomas Barnes  
William Bloethe  
Derek Brown  
Demetrio Bucaneg Jr.  
Paul Cardinal  
Troy Chatwin  
Randy Clelland  
Charles Cotton  
Matthew Davis  
Davide De Luca  
Peter Demar

Gary Donner  
Neal Dowling  
Donald Dunn  
Randall Groves  
Werner Hoelzl  
Alan Jensen  
Yuri Khersonsky  
Thomas Koshy  
Jim Kulchisky  
Mikhail Lagoda  
Chung-Yiu Lam  
Thomas La Rose  
Jon Loeliger  
William McBride  
James McDowall  
James Midolo  
Haissam Nasrat

Michael Newman  
Lorraine Padden  
Bansi Patel  
Christopher Petrola  
Art Salander  
Bartien Sayogo  
Cory Schaeffer  
Robert Schuerger  
Robert Seitz  
Wayne Stec  
Richard Tressler  
James Van De Ligt  
Gerald Vaughn  
Stephen Vechy  
John Vergis  
Jian Yu

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Christel Hunter  
Joseph Koepfinger\*  
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Hung Ling  
Dong Liu

Xiaohui Liu  
Kevin Lu  
Daleep Mohla  
Andrew Myles  
Paul Nikolich  
Ron Petersen  
Annette Reilly

Robby Robson  
Dorothy Stanley  
Mehmet Ulema  
Phil Wennblom  
Philip Winston  
Howard Wolfman  
Jingyi Zhou

\*Member Emeritus



## Introduction

This introduction is not part of IEEE Std 1660-2018, IEEE Guide for Application and Management of Stationary Batteries Used in Cycling Service.

The term “stationary battery” tends to conjure up many interpretations among power engineers, depending on one’s perspectives on battery energy storage. A stationary battery can be operated in two basic modes: 1) standby (or float) and 2) cycling applications including primary-power batteries (i.e., off-grid hybrid power sources), or distributed energy resources applications. Many standards developed for standby applications do not apply to cycling applications, and vice versa, but many users are unaware of the differences between standby and cycling battery operation and maintenance requirements. The purpose of this guide is to differentiate between these two applications and increase awareness of why and how to manage them differently. The guide is primarily informational and is not intended to provide specific recommendations for battery management in cycling applications. The targeted users are the owners, maintainers, and designers of battery systems used in stationary applications.

Some cycling applications, particularly those in grid-connected systems, are still emerging, and detailed operational and maintenance procedures are still being developed. The information on photovoltaic applications in this guide can be used as an example of a cycling application where this material has been formalized.

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# IEEE Guide for Application and Management of Stationary Batteries Used in Cycling Service

## 1. Overview

### 1.1 Scope

This guide provides information on the differences between stationary standby and stationary cycling applications and appropriate battery management strategies in cycling operations. While the primary emphasis is on lead-acid batteries, information is also provided on alternative and emerging storage technologies. The management of battery systems in stationary standby service is covered in other IEEE documents and is beyond the scope of this guide.

### 1.2 Purpose

This guide provides assistance to users of stationary battery systems in determining appropriate battery management strategies in cycling applications. Specifically, the guide addresses the primary similarities and differences in battery design and operation for standby versus cycling applications.

## 2. Normative references

This document does not require any normative references.

## 3. Definitions, acronyms, and abbreviations

### 3.1 Definitions

For the purposes of this document, the following terms and definitions apply. IEEE Std 1881, Standard Glossary of Stationary Battery Terminology [B14], should be consulted for the primary definition of terms not otherwise uniquely defined in this document.<sup>1</sup> The IEEE Standards Dictionary Online should be consulted for terms not defined in this clause.<sup>2</sup>

**coulombic efficiency (battery):** The ratio of the ampere-hour output from the battery to the ampere-hour input required to restore the initial state of charge.

<sup>1</sup>The numbers in brackets correspond to those of the bibliography in Annex A.

<sup>2</sup>IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>.

cycle life: The number of cycles (discharges and subsequent charges), under specified conditions, that a battery can undergo before failing to meet its specified end-of-life capacity.

cycle: A discharge and subsequent charge of a battery.

cycling: The repeated discharging and charging of a battery.

cycling service: DC system operation in which it is anticipated that the battery cycles frequently with minimum time on float charge.

energy efficiency: The ratio of the energy output on discharge to the energy input required to charge a cell or battery to the same state of charge at which the discharge began.

float service: See: standby service.

standby service: Operation of a dc system in which the battery spends the majority of the time on continuous float charge or in a high state of charge, in readiness for a discharge event. Syn: float service.

### 3.2 Acronyms and abbreviations

AGM	absorbed glass mat
CHP	combined heat and power
DER	distributed energy resources
DOD	depth of discharge
EDLC	electric double-layer capacitor
HEV	hybrid electric vehicle
MPPT	maximum power point tracking
PSOC	partial state of charge
PTC	PV USA test conditions
PV	photovoltaic
PWM	pulse-width modulation
SOC	state of charge
SOH	state of health
STC	standard test conditions
UPS	uninterruptible power supply
VRLA	valve-regulated lead-acid

## 4. Basic application concepts

### 4.1 Standby versus cycling batteries

There are two primary applications for stationary batteries:

- Standby [e.g., uninterruptible power supply (UPS)], also known as backup or float applications
- Cycling [primary-power source batteries, e.g., off-grid hybrid power sources and distributed energy resources (DER) applications]

Cycling service is divided between “shallow cycling” [typically 10% to 20% depth of discharge (DOD)] and “deep cycling” (typically 50% to 80% DOD).

Battery construction, operation, and maintenance are very different for each of these applications. While some batteries are capable of both standby and cycling service, using a battery specifically designed for standby service in a cycling application (or vice versa) may result in shorter life and poor performance. Therefore, the correct battery should be selected for each application and the correct maintenance standard(s) and recommendations followed for the application.

Typical applications in the standby category include telecommunications backup, emergency lighting, and UPS. Typical stationary cycling applications include off-grid renewable-energy applications, such as PV, and grid-connected applications, such as DER. See [Table 1](#).

Table 1—Typical battery requirements by application

Typical characteristic	Standby	Cycling (off-grid)	Cycling (grid-connected)
Discharge rate <sup>a</sup>	C/10 to 10C	C/200 to C/5	C/10 to 10C
Discharge frequency	< Once per month	Once per day	≥ Once per day
Cycle depth	< 10%	10% to 80%	20% to 80%
Recharge	Immediately	Daily or less frequently	Immediately
Recharge period	0.1 h to 24 h	1 d to 30 d	0.1 h to 20 h
Recharge source	Grid; constant	Renewable; variable	Grid; constant
Equalization required	Infrequent	Yes	Yes
Operating temperature	5 °C to +50 °C	−20 °C to +50 °C	5 °C to +50 °C

<sup>a</sup>By convention in the battery industry, the C rate used in this table is a current in amperes that is numerically equal to the rated ampere-hour (Ah) capacity.

Standby battery charge/discharge characteristics are well defined and straightforward. The batteries are in a float condition for indefinite periods and deliver power to the load infrequently. Sulfation of the plates and frequent equalization are typically not issues.

Cycling battery charge/discharge characteristics are very different from those of standby batteries, especially for renewable-energy applications such as PV. Because standards for PV applications already exist, this class of applications is used throughout the remainder of the guide as the primary example of a cycling application.

An example of a stand-alone remote PV home<sup>3</sup> will be used to describe a typical cycling application of a stationary battery. A block diagram of the system is shown in [Figure 1](#). Charge/discharge cycles for the month of December are shown in [Figure 2](#) and [Figure 3](#). Daily DOD is 15% to 25% (monthly average, 20.3%), but on days with minimal solar irradiance the DOD reaches 50%. In areas with significant seasonal variability, the daily cycles may be superimposed on a periodic or seasonal cycle that may be as deep as 80% DOD.

The charge controller was set to provide an equalization charge for three days prior to the capacity test and for seven days after the capacity test. Note that the amount of equalization charge was dependent on available charging current (available sunlight). Failure to equalize the battery in this application can degrade capacity by 50% in 12 months.

[Figure 3](#) shows battery voltage, PV current, and load current of the same system as [Figure 2](#). In order to differentiate PV array current from the 6.5 kW standby engine-alternator charging current, the charging current (A) is shown as a negative load current.

Battery loads vary constantly throughout each 24 h day as loads are turned on and off. Loads include, for example, lights, TV, washer/dryer, office equipment, hair dryer, and water pump. Average battery load current for the month was 10.1 A, and the maximum hourly average was 52.4 A.

<sup>3</sup>A 235 m<sup>2</sup> (2600 ft<sup>2</sup>) home: PV, 3.4 kW at STC, 2.8 kW at PTC; Batteries, (16) units rated 900 Ah at 24 V (dc), 6.2 kW standby engine-alternator.



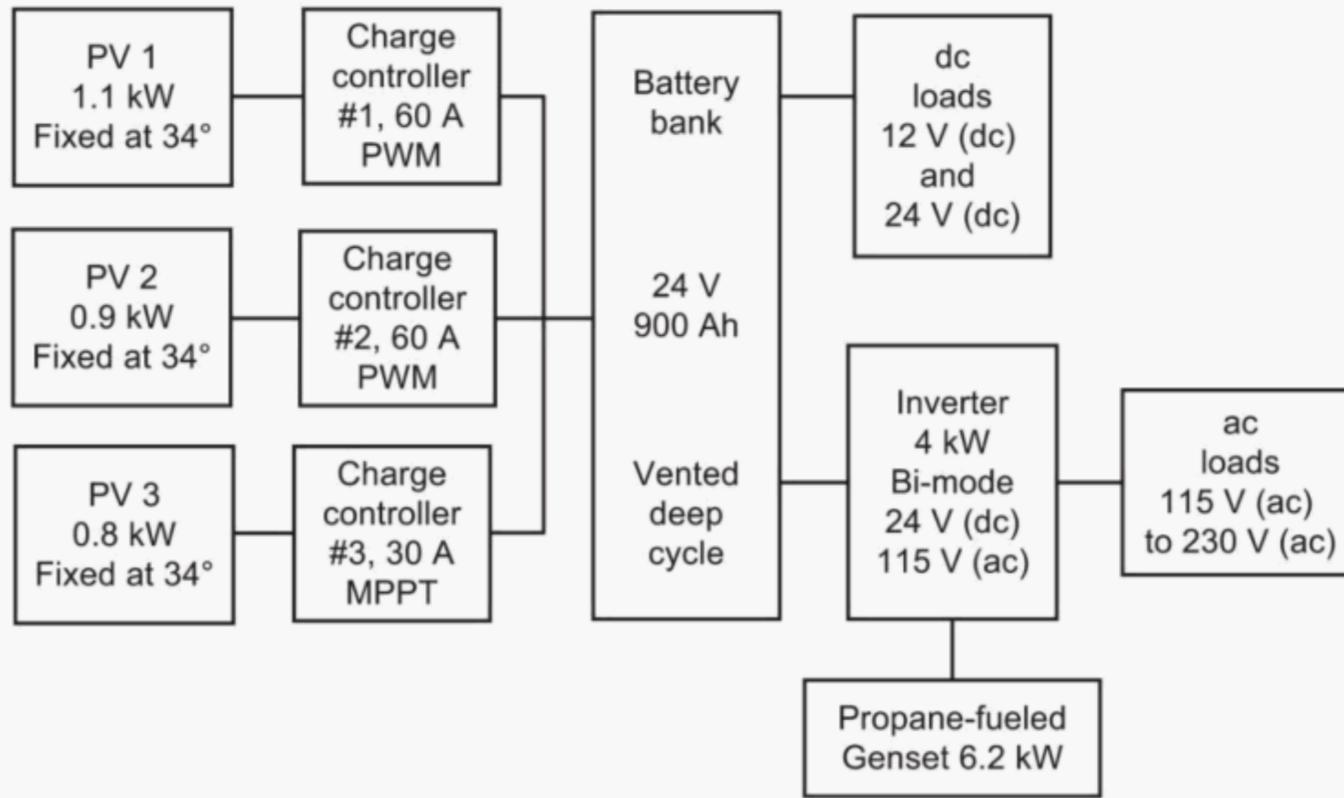


Figure 1—Block diagram of residential stand-alone PV system

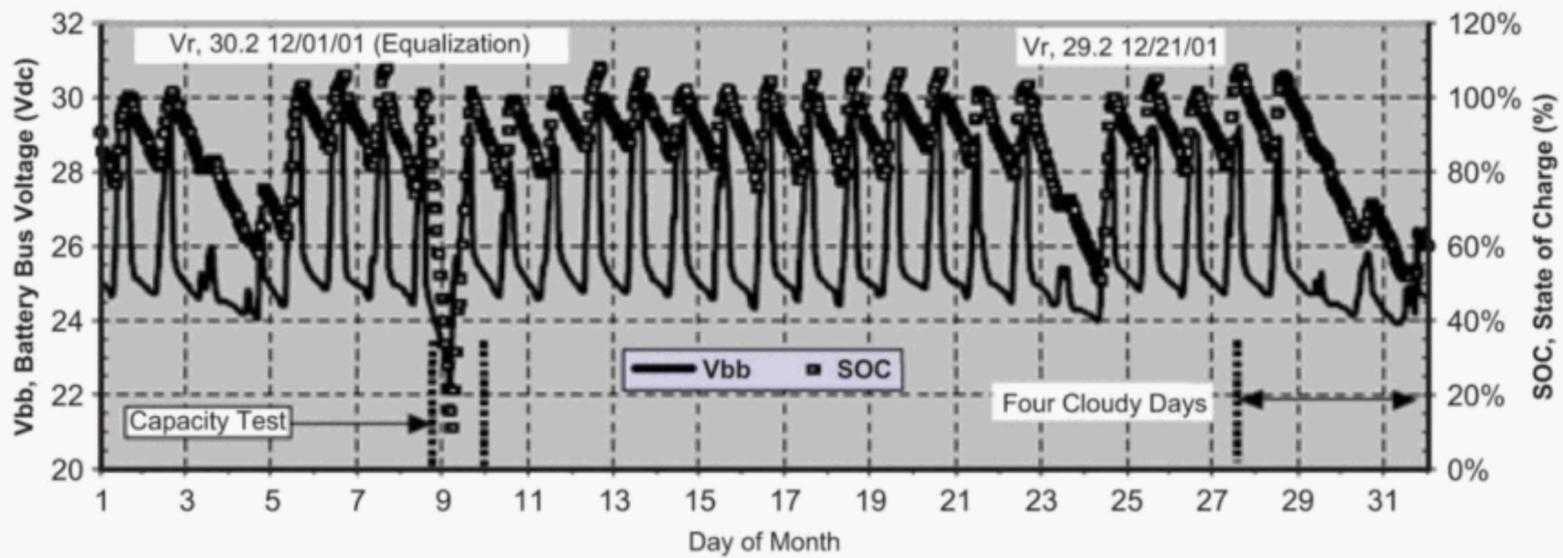


Figure 2—State of charge (SOC) and battery voltage

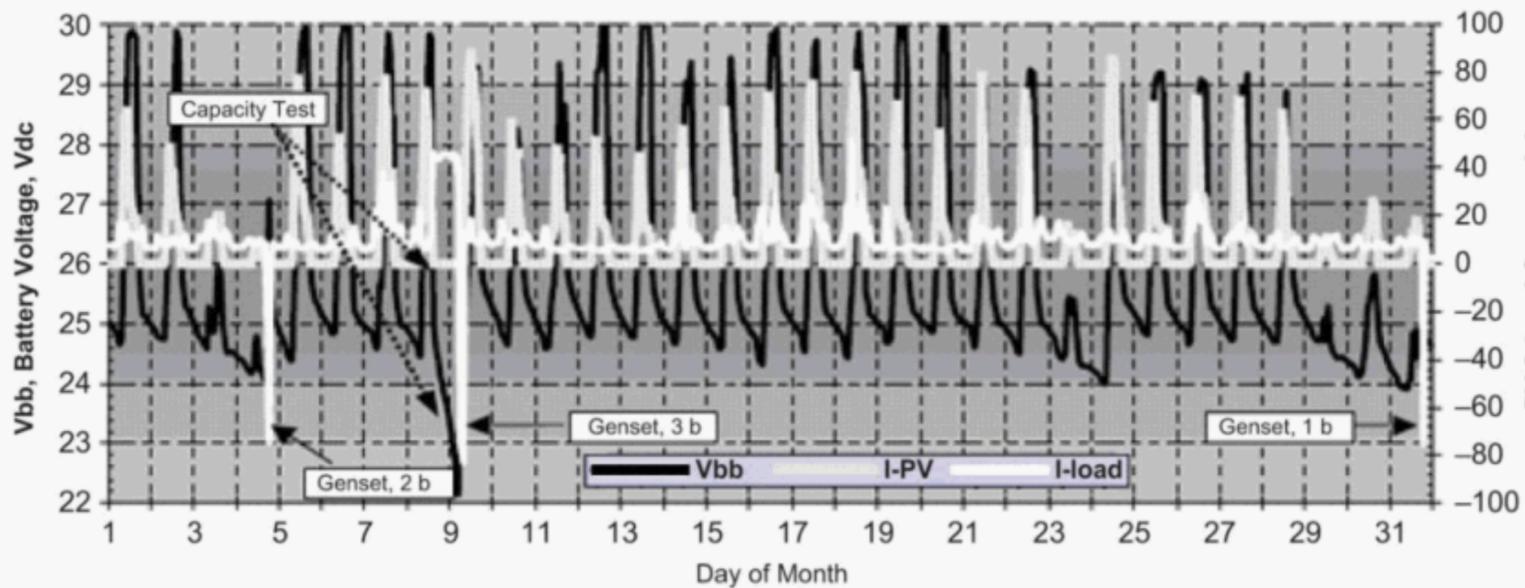


Figure 3—Battery voltage, PV current, and load current

## 4.2 Cycle life

Batteries in standby applications are typically not subjected to frequent charge/discharge cycles. The life of these batteries is generally a function of time and temperature.

The life of batteries designed for cycling applications, however, is more a function of cycle depth. For a first-order approximation for lead-acid batteries, the total number of ampere-hours that can be removed from a battery is finite. As the depth of discharge decreases, the ampere-hour throughput increases. A typical cycle life curve as a function of DOD is shown in Figure 4. Manufacturers can provide specific data for their products.

Tracking or recording the number and depth of discharges, particularly cumulative ampere-hours removed, can be useful in assessing the battery state of health (SOH) (see 8.4.6).

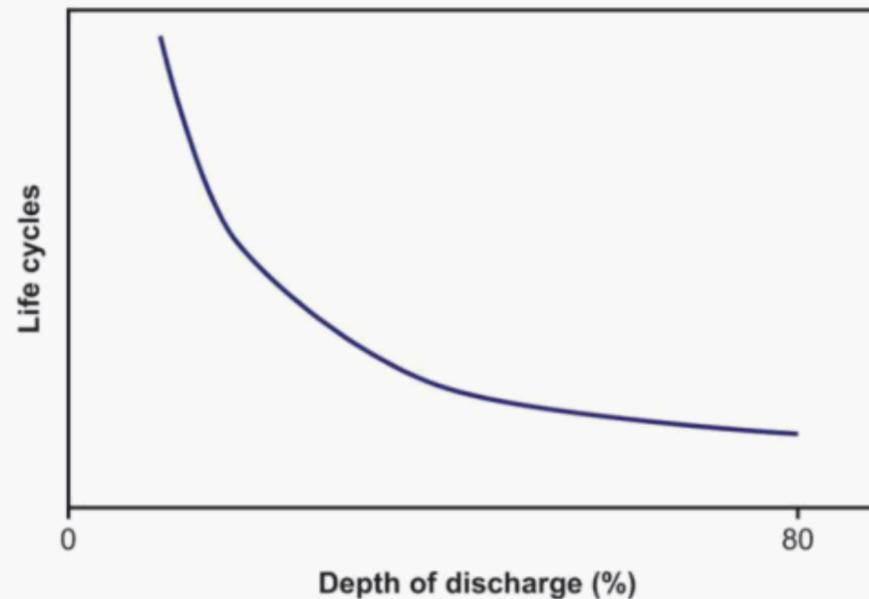


Figure 4—DOD versus life cycles

## 4.3 Charge efficiency

The energy efficiency of a battery is the energy in watt-hours (Wh) discharged divided by the energy in watt-hours for a complete recharge, and is usually around 70% to 85% for lead-acid batteries. Energy efficiency of a cycling battery is one factor in determining the recharge time. However, in many renewable-energy applications, including most PV systems, the coulombic (ampere-hour) efficiency is a more important value because the charging device is a current source, not a voltage source. It should also be noted that the recharge of batteries in such applications is impacted by the availability of the renewable resource (see 6.2).

The coulombic efficiency of a storage battery or cell is the electrochemical efficiency expressed as the ratio of ampere-hour output to the ampere-hour input required for a complete recharge. The incremental ampere-hour efficiency is called charge acceptance, which is the ability of a battery, when charging, to convert its active materials into a form that can subsequently be discharged. Charge acceptance is quantified as the ratio, expressed as a percentage, of the charge ampere-hours stored during an increment of time to the total ampere-hours supplied during that time. The charge acceptance for a vented lead-acid battery is nearly 100% until the battery reaches approximately 80% SOC, and decreases to 0% at 100% SOC.

# 5. Lead-acid technology

## 5.1 General

To understand the battery selection criteria, it is first necessary to understand the demands of the application and their impact on the typical lead-acid battery failure modes. In standby applications, the battery is on charge with



a float current flowing through the battery components continuously. Batteries in these applications typically spend over 99% of their service life on float charge and generally experience only shallow discharges of less than 10% when discharged. Their design considers the impact of continuous charging on the conductive structural components of the cell and may also consider the requirement for high-rate short-duration discharges.

In cycling applications, the battery is typically discharged to between 10% and 80% DOD and then recharged in as short a time as is practical. This type of application fully utilizes and stresses the active materials of the cell and, with repetitive cycles, can change the active materials' structures, resulting in a loss of capacity. Also, high-rate, high-temperature charging can potentially damage the plates and will result in significant gassing during the finishing phase of the recharge (see 7.4).

Design of lead-acid cells for cycling applications should consider the protection and preservation of the active materials during these deep discharges and high-rate recharges. The design should also consider that the batteries may operate at PSOC for prolonged periods. Advanced lead-acid designs have been developed to allow prolonged PSOC operation (see 9.2).

## 5.2 Lead-acid battery cell reactions

### 5.2.1 General

See B.1 for details of lead-acid electrochemistry.

### 5.2.2 Discharging

During the discharge process, the sulfuric acid ( $H_2SO_4$ ) in the electrolyte is consumed, resulting in the formation of lead sulfate in both the positive and negative plates. This leads to a progressive dilution of the acid. Under normal circumstances, this process is fully reversible. However, if a battery is over-discharged, the electrolyte may become so dilute that lead sulfate can dissolve. This situation can lead to "hydration shorts" through the separator when the lead sulfate precipitates out of solution upon recharging.

### 5.2.3 Recharging

During recharge, the lead sulfate from the plates is converted back to the charged form, and sulfuric acid is replenished. The active materials are normally returned to a fully charged condition once the charging source has restored approximately 102% to 120% of the ampere-hours previously removed, depending on the nature of the discharge and recharge regime.

### 5.2.4 VLA gassing

Charging energy that is not stored in the active materials is dissipated by various means. In the vented cell, most of the excess energy results in electrolysis of water to produce a stoichiometric mixture of hydrogen and oxygen, and these gases are released to the atmosphere. Distilled or deionized water should be supplied to make up for the water consumed. Depending on the positive-plate grid alloy, the charging voltage, and the float/finish current, the resulting water loss can be very small.

### 5.2.5 VRLA gas recombination

In the valve-regulated lead-acid (VRLA) cell, the electrolyte is immobilized either in a gelled form or absorbed in an absorbed glass mat (AGM) separator between the plates. This facilitates oxygen gas ( $O_2$ ) diffusion to the negative plate where the recombination reaction will occur (see B.1.4). Under perfect conditions, there is no net reaction. That is, there is no water loss or hydrogen gas evolved as a result of the electrolysis of the water at the positive plate. However, due to grid corrosion and other processes, recombination is not 100% efficient.

Therefore, some water loss and gassing will occur, although it will only be a fraction of that experienced in a

vented cell. Since VRLA cell designs typically do not allow electrolyte maintenance, overcharging should be minimized.

### 5.3 Lead-acid cell construction

#### 5.3.1 General

See [B.2](#) for details of lead-acid cell construction.

#### 5.3.2 Summary of component characteristics

As noted in the [Table 2](#) and [Table 3](#), standby and cycling batteries share a number of common physical characteristics, but they can differ significantly in grid geometry, grid alloy, active-material retention, and active-material density. In VRLA cells, there are also significant differences between those optimized for standby or cycling service. The trade-off is in high-rate performance versus retention of the active material with cycling.

Table 2—Typical vented lead-acid cell design characteristics

Vented cell component	Standby	Cycling
Lead grid alloy	Lead (Pb) Pb-Ca Pb-Ca-Sn Pb-Sb (1% to 2%)-Se	Shallow cycling Pb-Ca Pb-Ca-Sn Pb-Sb (1% to 2%)- Se Deep cycling Pb-Sb (3% to 8%) Pb-Sb (1% to 2%)- Se
Grid thickness		
Negative (mm)	1.5 to 2.3	2.5 to 3.0
Positive (mm)	3.0 to 8.0	5.0 to 8.0
Positive density (g/mm <sup>3</sup> )	0.0036 to 0.0040	0.0040 to 0.0048
Positive retention	Glass mat retainer	Glass mat retainer and/or wrapping
Separator	Polyethylene or rubber	Polyethylene or rubber
Separator thickness	Thin	Thick
Electrolyte specific gravity	Liquid 1.215 to 1.250	Liquid 1.240 to 1.330
Relative electrolyte quantity	Reserve	Reserve

Table 3—Typical VRLA cell design characteristics

VRLA cell component	Standby	Cycling
Lead grid alloy	Lead (Pb) Pb-Ca Pb-Ca-Sn Pb-Sn	
Grid thickness		
Negative (mm)	1.0 to 4.3	
Positive (mm)	1.0 to 7.0	
Positive density (g/mm <sup>3</sup> )	0.0036 to 0.0040	0.0040 to 0.0048
Positive retention	AGM: Wrap with moderate compression Gel: None or thin glass mat retainer	AGM: Wrap or multiple wrap with high compression Gel: Thin glass mat retainer
Separator	AGM Gel: Polyethylene or rubber	AGM Gel: Polyethylene or rubber
Separator thickness	Thin	Thick
Electrolyte specific gravity	AGM or Gel 1.240 to 1.330	AGM or Gel + H <sub>3</sub> PO <sub>4</sub> 1.240 to 1.325

Relative electrolyte quantity

AGM: Limited  
Gel: Reserve

AGM: Limited  
Gel: Reserve

Recent advances in lead-acid technology for cycling applications are grouped under the heading of 'advanced lead-acid' (see [9.2](#)).

### 5.3.3 Selection criteria for lead-acid batteries in cycling applications

The nature of the application should be analyzed to determine if a vented or VRLA battery is preferred.

The published characteristics of the relevant batteries should then be used to determine the most suitable model for a specific cycling application.

When specifying a battery for a cycling application, it is prudent to seek assurance that it was designed with consideration of the unique cycling requirements of that application. Consult the manufacturer for cycle-service test data, expressed as the number of cycles as a function of DOD.

## 6. Operating issues

### 6.1 Cycling applications

The following cycling applications are characterized by intermittent charging from a variety of sources:

- Renewables (wind, PV, etc.)
- Engine-driven generators (cyclic operation)
- Hybrid systems (e.g., a renewable source and an engine generator)
- Grid-connected chargers (where grid power may suffer frequent interruptions)

The loads in these applications can be highly varied, but are typically categorized as longer-duration energy loads, shorter-duration power loads, or a combination of both. Battery sizing and design issues for different load types are discussed in [6.3](#), [6.4](#), and [6.5](#).

An emerging class of applications is one in which the battery acts as a power buffer. The primary energy source in these applications is generally available but is frequently insufficient to supply the imposed loads. This may be because the loads exceed the rated output of the energy source, or because the rate of change in the loads exceeds the capability of the energy source to respond. When the load level falls below the rated output of the primary source, the battery is recharged.

The most prominent application in this class is distributed generation, in which relatively low-output generators are sited close to the loads they supply. Because these generators respond relatively slowly to load changes, batteries may be installed to improve the load response. Batteries are also required to supply starting power when the grid is not available.

This type of buffer operation may also require a battery to absorb power as generator output is ramped down after a load has been abruptly terminated. The most efficient way to accommodate this is to operate the battery in a less than fully charged state.

### 6.2 Charging energy limitations

One of the fundamental differences between standby operation and many cycling applications is the availability of energy for charging, particularly where this is from renewable sources. An implicit assumption in standby applications is that charging energy is essentially unlimited, and it is simply a question of how quickly the battery should be recharged. With renewables such as PV and wind, however, energy output can be highly variable on a diurnal and/or seasonal basis. Economic limitations also dictate that the output of PV panels be minimized to the extent practical. Batteries may therefore be subjected to cycles of varying depth, frequently with incomplete recharge between discharges. This can pose a challenge to both battery design and sizing.

This type of operation can lead to an apparent fading of capacity (also called “walk-down” or “ratcheting”). This is more correctly described as an SOC imbalance between the positive and negative plates, which occurs because the negatives of both lead-acid and nickel-cadmium cells tend to recharge more efficiently than the positives. Prolonged cycling operation with incomplete recharging is known as PSOC cycling. PSOC operation can be damaging for some battery types, and there is a general need for periodic equalizing and/or maintenance cycles to remove the imbalance. Some lead-acid cells can also suffer from a type of premature capacity loss, so it is important to use designs that are appropriate for this type of operation.

Charge input may also be limited by system voltage constraints. All batteries require a certain voltage window in which to operate. A higher-than-nominal voltage is used for charging, and the battery voltage falls on discharge. The extent to which the voltage is allowed to deviate from the nominal is frequently limited by the connected equipment (loads).

The most important requirement is that the charge voltage be high enough for the battery to be recharged effectively. If the voltage window is narrow, however, it may be necessary to compromise and lower the charge voltage so that the battery can be discharged to a minimum voltage that allows for reasonable capacity utilization. If this is the case, the battery will require a longer charging period to be completely recharged. An alternative may be to disconnect the battery from the load and perform offline recharging at higher voltage and controlled current. This can be achieved by adjusting the connected charging device parameters or by using an additional charger with or without a generator.

### 6.3 Discharge rate and depth of discharge

As discussed in 6.1, batteries may be required to supply longer-duration energy loads or shorter-duration power loads, depending on the application. Any battery type can be sized to supply short-duration power loads, but high-power battery designs supply them more efficiently than others.

The capacity of a battery is rated by the manufacturer, typically in ampere-hours, for a standard discharge duration. For example, high-quality lead-acid batteries for standby applications are typically rated for standard discharges of 8 h or 10 h, while batteries for PV are generally rated at the 20 h or 100 h rate. As the discharge time is reduced, the battery becomes less efficient and the available energy is reduced. This can be seen in the published discharge data for a typical, large vented lead-acid cell, rated 2320 Ah at the 8 h rate to 1.75 V/cell at 25 °C. Table 4 shows that, although the available current (power) increases as the discharge time is reduced, the capacity (energy) is severely reduced at shorter discharge times.

Table 4—Published discharge data for 2320 Ah cell to 1.75 V/cell at 25 °C

	8 h	6 h	4 h	3 h	2 h	90 min	60 min	30 min	25 min	15 min	1 min	
Rated current (A)	290	368	496	613	800	944	1168	1536	1616	1840	2240	
Available capacity (Ah)	2320	2208	1984	1839	1600	1416	1168	768	673	460	37	
RatedAh (%)	100	95	86	79	69	61	50	33	29	20	2	

The main design principle for high-power battery designs is that the battery can discharge a higher percentage of its stored energy over short durations than can lower-power “energy” designs. For a given power load, this enables a smaller battery capacity to be installed when a high-power battery is used.

Even though high-power batteries are more efficient for short discharges, the energy that is removed during a power discharge nevertheless represents a small percentage of the total. Hence, power-type cycling tends to be in the form of shallow discharges to a low DOD. Energy-type cycling, on the other hand, frequently results in deep discharges to a high DOD, which is more stressful for the battery.

## 6.4 Battery sizing issues

Based on the type of loads that are to be supported, the first step in sizing is to select the correct battery design—power, energy, or combination general purpose—for the load(s) to be supported. This is an important choice, because using the wrong design is less economical and may also result in premature failure.

The next step is to calculate the number of cells and the end-of-discharge voltage, based on the allowable voltage window. Generally, wider voltage windows provide for more economical batteries. Single cells provide more flexibility than multicell units in higher-voltage systems. For example, a 120 V (nominal) lead-acid battery may comprise 58 cells (rather than the usual 60 cells) to provide more effective charging. Reducing the number of cells results in a higher end-of-discharge voltage per cell, which should be considered when the battery size is calculated. Such flexibility may not be possible in lower-voltage systems or when the chosen design is supplied only in multicell units.

An inherent assumption in sizing batteries for standby applications is that the battery is in a fully charged state (100% SOC) at the beginning of the duty cycle. IEEE Std 485 includes a catch-all “design margin” that can, among other things, compensate for less than 100% SOC. However, this is not generally a suitable approach for cycling applications, in which a more rigorous approach to the SOC issue is required.

This point is particularly true for PV applications, in which the diurnal SOC variation is often superimposed on an annual cycle. The battery should be sized so that it can provide the necessary loads and reserves (autonomy) from the lowest expected SOC. IEEE Std 1013 provides a recommended practice for sizing lead-acid batteries for such situations. This practice is suitable for energy-type discharges; if the imposed loads include any of significant power levels, it is necessary to follow an approach that includes elements of both the PV and standby practices.

## 6.5 End of battery life

The criticality of system loads and the typical failure modes exhibited by a battery in cycling operation can influence the management of the overall system over its life. A gradual fading of capacity can generally be monitored and a replacement decision made before critical loads are compromised, whereas a sudden and unexpected failure is obviously something to be avoided.

The characteristic aging of lead-acid batteries in standby applications is for the capacity to increase gradually to around 105% to 110% of rated and to remain there until about two-thirds of the life has elapsed. The capacity then starts to decrease, with the rate of decline picking up as the capacity approaches 80% of rated. Beyond the 80% point, the capacity drops much faster and there is an increased likelihood of sudden failure. This effect is normally taken into account in battery sizing by the use of an aging factor, where the installed capacity is 125% of the base capacity required. Thus, the battery can still fulfill its requirements when the capacity is at the 80% end-of-life point.

Aging mechanisms in cycling applications may be different from the standby model. For example, prolonged undercharging may cause capacity loss due to sulfation. Although the 80% end-of-life capacity is often used in battery sizing for these applications, their designed autonomy period and typical charging environment also have an effect on the battery’s replacement. See IEEE Std 1013 for a discussion of replacement criteria for these applications.

Therefore, it is important to monitor the battery SOH to predict the end of life. In a cycling application, however, it can be difficult to separate SOC effects from the trend in SOH, and this can require additional sophistication in a monitoring system (see [8.4.6](#)) or extra intervention by the operator for battery testing.

Choosing a battery for a cycling application is not simply a matter of selecting one that is designed for frequent cycling. It is important to recognize the characteristics of the application—whether power loads or energy loads are to be supplied, at what intervals, and within what voltage window. Matching the battery type to the application and correctly sizing that battery are key factors in reliable operation.

## 7. Charge management

### 7.1 General

Proper charge management is very important in prolonging battery life in both standby and cycling applications. The chargers for standby battery systems are normally designed to provide for battery recharge to a useable condition in a relatively short period of time. In this way, the standby system can be available to provide electric power in the event of an outage shortly after the one that caused a discharge. Testing or monitoring is therefore often used to check the availability of a standby battery to provide an adequate discharge.

For batteries used in cycling applications, the charging is quite different. Discharges are, in general, sufficiently frequent that the operation itself can be used to verify proper charging. However, monitoring is still occasionally used to verify proper operation. Furthermore, in off-grid renewable-energy systems, the availability of charging power is much more limited. Cycling systems are designed to spend much more of the time with the batteries in discharge than standby systems, so charge management is more challenging.

### 7.2 Charging of lead-acid batteries

#### 7.2.1 General

Figure 5 shows a generalized schematic of the various phases of the charging of lead-acid batteries. It can be seen that there are four distinct types of charging that should be performed on lead-acid batteries if they are to provide satisfactory service for the life projected by their manufacturer:

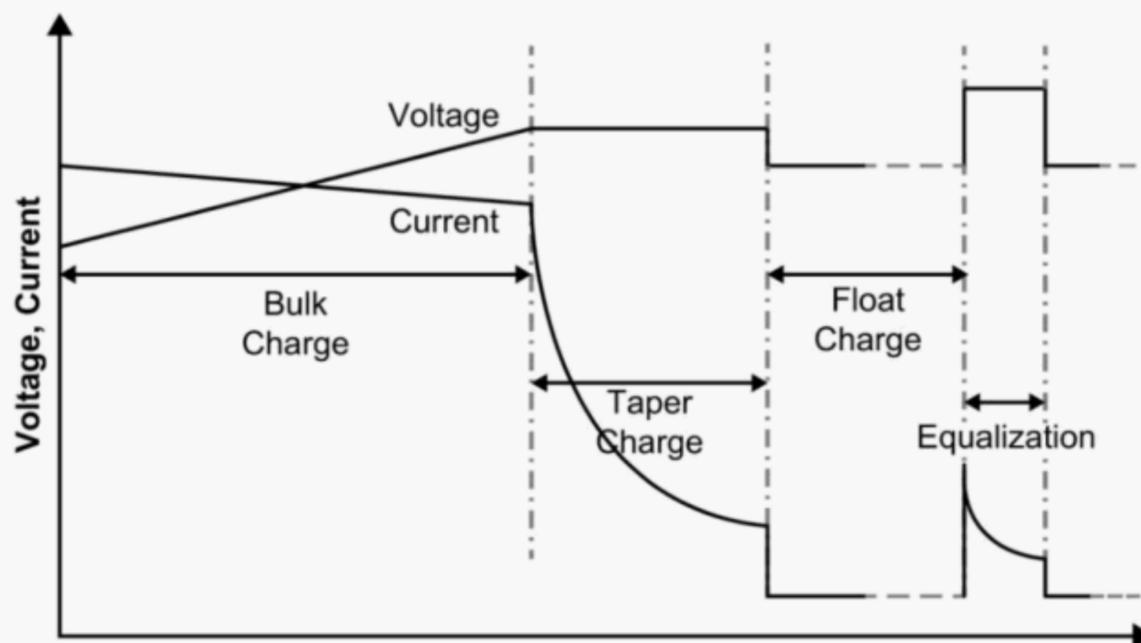


Figure 5—Generalized schematic of the charging of a lead-acid battery

#### 7.2.2 Bulk charge

The period during which time the charge current is provided by the charger with a magnitude that corresponds to the maximum charger power, or the power capability of the charger power source if this is less than the charger power capability. The bulk charge continues until the battery voltage reaches the regulation value recommended by the battery manufacturer. The charger may provide a constant power output to the battery or a constant current output, depending on the particular configuration.

#### 7.2.3 Taper charge

The period during which the battery is held at the manufacturer's recommended regulation voltage so that current tapers (decreases exponentially with time) according to changes in the effective internal resistance of

the battery being charged. The way in which the current tapers depends on the particular battery in use. For maximum life of the battery, the taper charge should be continued until the current has decreased to the level recommended by the battery manufacturer.

#### 7.2.4 Float charge

The period during which the battery is held at the manufacturer's recommended float voltage, and during which time the charge current is more or less constant. The voltage at which the battery is float-charged is generally the same or a little below the regulation voltage used for taper charging. The float charge in general is continued until the battery is required for discharge, or in some circumstances until an equalize charge is performed.

#### 7.2.5 Equalize charge

The period that allows all the cells to be charged to the same extent, and, for vented cells, provides a means of mixing stratified electrolyte. The equalize charge is performed at a specified voltage for a specified period of time or until the current tapers to a specified low value, as recommended by the battery manufacturer. For vented cells, the equalize charge can be considered complete when the lowest cell voltage stops rising for three consecutive readings that are 1 h apart.

### 7.3 Charging considerations for standby batteries

As stated in 7.1, bulk charges are generally infrequent in standby systems, and the batteries in these systems spend most of the time in the float-charge mode. During the bulk charge, the current can be as high as the limit specified by the manufacturer; however, the regulation voltage should not be exceeded at the full charge current for any extended period of time, particularly for VRLA batteries, so moderately good voltage regulation is desirable.

In some standby applications, particularly for the telecommunications industry, the regulation voltage and the float voltage are the same. Equalization charges are not performed because the equipment downstream of the battery is often powered directly from the same rectifiers used for battery charging. Changing the voltage of the rectifiers during operation adds further complexity to the system. In addition, the downstream equipment often has a limited voltage window, so the battery voltage cannot be raised to the normal regulation or equalization levels.

Both the float voltage and the float current should be monitored to provide assurance that there is not excessive water loss from vented cells, or that VRLA batteries are not dried out and possibly driven to a thermal runaway condition.

Neither float voltage ripple nor float current ripple from chargers should exceed the limits set by the manufacturer, although there are some who believe that imposing a varying current at specific frequencies can be beneficial. The battery manufacturer's recommendations on this matter should be followed.

### 7.4 Charging considerations for cycling batteries

In cycling applications, batteries rarely reach a full charge condition during normal operation. However, float or equalization charges can be implemented as part of the system setup and performed manually according to user requirements. As with float charging, special attention should be paid to the regulation voltage, the current during the equalization period (particularly for VRLA batteries), and ripple on the equalization or float current.

In cycling applications, the taper charge is sometimes called a finish charge, because it basically allows the charge to be properly finished. In vented cells that are deeply cycled on a frequent basis, adequately high regulation or equalization voltages, and consequently high finishing and regulation currents, are needed to de-stratify the electrolyte and minimize capacity loss. The window of operability of the downstream equipment

can sometimes limit the regulation or equalization voltage, particularly if there is a direct dc connection. In such cases the battery manufacturer should be consulted regarding an appropriate approach to attain the desired life.

If analysis of the particular cycling application indicates that there will be periods of several weeks or more when the battery is incompletely charged, the system designer should investigate special charging arrangements, such as incorporating another power source. Alternatively, consideration should be given to using batteries such as certain types of gel VRLA that appear to work better in these circumstances, or to utilizing a different battery chemistry altogether.

There are many variables in charging batteries most efficiently for cycling applications. This guide cannot prescribe all details of charging procedures in all situations. The details of charge management should be established in collaboration with the manufacturers of all system components (battery, charging source, and charge controller) for the specific application.

## 8. Maintenance and testing

### 8.1 General

The operational aspects of standby and cycling applications, particularly when coupled with other factors, have resulted in fundamentally different approaches to their respective maintenance and testing standards.

### 8.2 Types of battery system maintenance

Although they may be referred to differently in the various standards, there are three fundamental types of maintenance: preventive, corrective, and predictive. Preventive maintenance covers those aspects of maintenance that are routinely performed, such as watering vented batteries, to assure the effective operational performance of the battery system. Corrective maintenance resolves abnormal conditions found during other maintenance or testing. A combined visual and instrumented inspection of the battery system provides the information required for performing the appropriate type of maintenance. These inspections are conducted periodically, although the periodicity may vary for each parameter observed. For example, the electrolyte level may be checked monthly, whereas the resistance of cell connections may only be checked annually. Generally, a special inspection is also recommended whenever the battery system experiences an abnormal event, such as after a seismic event.

Preventive maintenance and corrective maintenance are commonly applied to both grid-tied and renewable-energy applications. There is also an emerging predictive type of maintenance. Predictive maintenance is used to correct potential problems, such as replacing a failing cell, before the actual associated problem is evident through its impact on the application's performance. Predictive maintenance is based on an analysis of data taken during both normal system operation and battery maintenance and testing. As will be evident from 8.5, predictive maintenance is more easily applied to applications in which the battery is in a fully charged state when the needed data is taken. Thus, predictive maintenance is more frequently applied to grid-tied than to off-grid renewable-energy applications. When predictive maintenance is applied to off-grid applications, it is generally for larger-sized systems or those having some form of automatic data acquisition and recording of the battery's operational data (see 8.4.6).

### 8.3 Types of battery system capacity tests

There are four basic types of battery system capacity testing: acceptance, performance, service, and modified performance. As apparent by its name, acceptance testing is generally a one-time test to verify that a delivered battery (or battery system) meets its procurement specifications. Acceptance testing generally measures the battery's capacity under a defined constant-current or constant-power load. Performance testing is basically the same type of test run at a subsequent time. The changes in battery capacity versus time are generally used to predict the need for battery replacement. However, the results of this test may also be an indicator that the

battery needs to be “equalized” if the battery had not been so conditioned before the tests were performed. Service testing is used to verify that the battery can meet its required load demands. Frequently, the capacity required to meet the load is less than the battery’s total capacity. However, the application’s load may require that this testing be conducted under varying current versus time demands (duty cycle). A modified performance test combines aspects of both the performance and service tests. Basically, a modified performance test is one in which normally two loads that envelop the application’s duty cycle are used. The application’s highest load is generally applied for a 1 min duration at the start of the test, and this is followed by a constant current or power load for the remainder of the test. Again, changes in the measured capacity are used as a battery replacement (or equalization) indicator. Performance, service, and modified performance tests are generally conducted on a periodic schedule; however, the periodicity of the testing schedule may be altered based on information obtained during the testing. Generally, the frequency of the testing increases as the tests indicate that the battery capacity is also decreasing significantly. Tests may also be recommended whenever the battery system experiences an abnormal event. Battery capacity testing is more often applied to grid-tied than off-grid renewable-energy applications.

## 8.4 Factors influencing battery maintenance and testing procedures

### 8.4.1 General

Several factors impact the development of battery maintenance and testing standards. This subclause provides a summary of the most influential of these factors and their effect on the development of the current battery maintenance and testing standards. It should be noted that the current maintenance and testing standards for off-grid battery systems were developed for PV energy applications. While these standards have general applicability to other renewable-energy sources, there could be some application-specific nuances that are not covered by them.

### 8.4.2 Basic purpose of the battery system in the application

Most existing battery systems are designed to provide the power when the application’s primary electrical system cannot meet its load requirements. In the standby case, the battery system generally provides power only when there is a failure in the application’s primary electrical power system. Thus, the fundamental maintenance and testing requirements for these systems are based upon assuring that the battery system is able to handle the entire system load requirements whenever this need arises. These battery systems often provide power either for an emergency system shutdown or until an alternative power source can take over the application’s load requirements. Generally, the load requirements can be established for these applications, and the battery system can be periodically tested to ensure that it has the capability to meet this load. Thus, the standards for these applications were tailored around both the maintenance and testing.

In the cycling applications, the battery system routinely supplements the primary electrical power system in meeting the application’s load requirements. The ability to define the supplemental battery power required varies significantly with the application. For example, the required supplemental power in a PV system depends on the solar resource (magnitude and duration of sunlight), which varies both daily and seasonally. As these applications often have no other source of power, the battery system may be designed to provide several days to sometimes several weeks (period of autonomy) of supplemental battery power with little or no battery charging. While a typical daily load could be established, testing to this requirement would provide little assurance as to the overall health of the battery. As will be discussed in [8.4.3](#), [8.4.4](#), and [8.4.5](#), there are other factors limiting the testing of the battery systems in these applications. Thus, the standards covering these battery systems were tailored around the maintenance requirements necessary to assure that they are in an operational condition capable of handling their typical daily as well as seasonal cycles.

### 8.4.3 Source of power for battery charging

The application’s primary source of electrical power for charging the battery has a profound effect on the maintenance and testing approaches for these battery power systems. The readily available electrical power of grid-tied power systems provides a reliable means not only for charging the battery after any desired performance

testing, but also for maintaining the battery in a fully charged state. Knowing that the battery is fully charged permits the taking and interpretation of data, such as cell voltages, that are important to battery maintenance. For example, logging the history of such cell data provides important information for predictive maintenance.

The testing of an off-grid renewable-energy application's battery capacity requires either an alternative source of power or an extended favorable period of the application's renewable-energy resource (sunshine in the case of PV) to charge the battery before and after any such test. For the most meaningful tests, the battery should not only be fully charged, but also equalized, before the testing. Obviously, this requires additional pre-test battery charging time. These requirements limit the flexibility of conducting these tests. While there are a significant number of PV applications where the batteries are being tested, performance testing of off-grid battery systems is not as frequently undertaken as desirable. However, since these systems are essentially being "tested" with each cycle, the impact of not testing is not as detrimental as would first appear. Another significant factor impacting the maintenance and testing of these systems is that their battery may not be fully charged during any period of maintenance. Not knowing the SOC of the battery means that the interpretation of some data, such as cell voltages, is more difficult. Thus, cell data may not be as meaningful a predictor of impending battery problems for these battery systems as it would be for those associated with grid-tied applications.

#### 8.4.4 System economics

A maintenance and testing protocol could be developed for each application that would assure the optimal life and performance of the battery power system. Such an optimal protocol may belie the overall economics of both the system and the maintenance and testing protocol itself. Thus, an important aspect influencing the adoption of these battery maintenance and testing standards is the cost of the recommended procedures versus their overall system value. For example, a greater expense can be justified for the maintenance and testing of high-value power applications such as those providing high revenue or for those supporting critical safety systems. In some cases, additional regulatory requirements may apply to critical safety systems that could transcend an application's strict economics.

The cost of testing and maintenance should not be compared to the cost of the battery, but the value of the load that is being supported by the battery. If the result of a failed battery is simply inconvenience, then it makes economic sense to perform just enough maintenance to minimize a catastrophic battery event such as a fire or meltdown. On the other hand, if the battery supports a critical load (revenue, safety, or quality of service), extensive maintenance and testing may be justified regardless of the cost of the battery. Scheduling periodic battery replacements may be more economical than performing maintenance, but it may not ensure a reliable system.

It should be noted that some cycling applications do not support critical or high-value loads. Since standards are written to cover a multitude of applications, the recommended maintenance and testing procedures that have been developed are generally more applicable to moderate- to high-value applications. Also, they generally provide maintenance and testing requirements that would provide a reasonable level of battery system life and performance for moderate- to large-capacity systems.

#### 8.4.5 Maintenance and testing personnel

Battery power systems can pose significant hazards to those individuals performing maintenance and testing. Without exception, these standards specify that those individuals doing the required work be both knowledgeable of these hazards and experienced with working with battery systems. The standards convey information on the necessary safety requirements. The maintenance and testing procedures should also be designed within the capabilities of the personnel likely to be associated with the application.

Another important aspect relating to these personnel is whether or not they are on-site. Having a readily available staff generally permits a more frequent maintenance schedule than when the staff must travel to remote sites. Locations without on-site individuals may take advantage of remote battery-monitoring systems (see [8.4.6](#)).

#### 8.4.6 Automated monitoring

It is helpful for the user to understand the cycle life design parameters of the battery and this may be used in decisions regarding battery replacement. Various battery monitoring systems are available to track the number of discharges, DOD, and cumulative ampere-hours removed.

Monitoring the voltage, current and temperature during discharge may also be used to estimate battery SOC. This information may be used as a battery management tool; for example, in a hybrid off-grid power system, a predetermined SOC may trigger the starting of the generator to recharge the battery. Likewise, the monitoring system can determine when the battery has reached a full SOC and can signal the generator to shut down.

More feature-rich monitors are available to monitor additional parameters such as ohmic measurements. In standby applications, ohmic measurements are used as an aid in trending battery SOH. In a cycling application, however, it can be difficult to track SOH using ohmic measurements because the battery is rarely at a full SOC.

Automated battery monitoring systems have the advantage of providing continuous monitoring for alarm conditions. Further discussion of monitoring systems is provided in IEEE Std 1491™ [B11].

#### 8.5 The existing battery maintenance and testing standards

For stationary standby applications, IEEE Std 450 [B1], IEEE Std 1188 [B9] and IEEE Std 1106 [B6] cover maintenance and testing for vented lead-acid, VRLA, and nickel-cadmium, respectively. A single standard, IEEE Std 937 [B4], covers both vented lead-acid and VRLA for PV systems. IEEE Std 1145 [B8] covered nickel-cadmium batteries in PV applications but was allowed to lapse since these batteries are infrequently used in PV applications. IEEE Std 1361 [B10] includes a laboratory test procedure for PV batteries, while IEEE Std 1661 [B12] provides a field-test procedure for batteries in PV-hybrid systems that include a dispatchable power source for bringing the battery to a full state of charge.

#### 8.6 Features of these battery standards

In all cases, these standards provide information on periodic inspection procedures for the battery and its associated system and environment. These standards provide a listing of the battery system items to be inspected and the periodicity of these inspections. The items inspected typically vary with each specific period. For example, inspections might be scheduled on a quarterly, semiannual, and annual basis, with each of the subsequent inspections including the items of the preceding period in addition to its own items. Both visual and instrumented inspections are part of these periodic inspections. Visual inspections deal mostly with the maintenance of items that can be so identified, such as corroded cell connectors or electrolyte leakage. The measurement of the various parameters associated with the battery, its individual cells, and its charger or charger controller is an important aspect of these inspections. In general, measurements of cell voltages and temperatures, battery and charger voltages, and cell and battery connection resistances are made. Ohmic cell measurements are presented as an alternative inspection technique for monitoring the health of standby lead-acid batteries. Specific gravity measurements for vented batteries are currently recommended on a quarterly basis only in PV applications. The inspection of physical environment is also part of these inspections with attention given to items such as overall and connector cleanliness, battery rack condition, and enclosure temperature and ventilation. Based on the visual and measurement results of these inspections, the appropriate preventive and corrective actions are defined. Any unsafe condition, such as a voltage leakage to ground, receives special attention.

For standby applications, acceptance, performance, modified performance, and service tests along with their recommended schedules are defined (see 8.3). Information on the interpretation of the results of these tests is also provided along with recommendations as to modification of their schedules based on test results that the battery is beginning to fail. While there are no battery capacity tests currently defined for PV applications without a dispatchable power source, the PV-hybrid and grid-tied maintenance and testing standards provide information that can be beneficial for defining tests for those PV systems for which testing is conducted. The

PV maintenance standard does contain a series of recommended pre-operational cell and battery measurements defined for the lead-acid PV applications. IEEE Std 1361 [B10] includes a laboratory battery cycle test that exposes a battery to operation under both deficit and excess array power. While this test is primarily designed to test the voltage set points for the system's charge controller, its application also provides some measure of the appropriateness of a particular battery to its simulated solar conditions.

## 8.7 Misapplication of maintenance and testing standards

The primary reason for having battery maintenance and testing standards is to help assure that the battery systems meet their intended design requirements, service life, and performance expectations. It is therefore important to understand how the application or misapplication of specific maintenance practices can affect system operation. Capacity testing of a battery system is a predictor of future system failure and the need for battery replacement. However, applying the wrong test might not provide the right information. For example, if the application's duty cycle has short but significant current demands and if the battery is only tested through a performance test based on its average load, the test results may not accurately indicate whether the load requirements can be met.

For those PV battery systems that are not being tested, the degradation of their battery's capacity with time is generally unknown. Since the charging of these batteries depends on the amount of the sunlight incident on the PV array, many of these batteries may experience extended periods when they may not be fully charged. This condition can be aggravated in systems that may have marginally sized PV arrays or may not have a routinely actuated battery "equalization" feature. As the indication of battery failure for these systems is often determined by their inability to meet the load, there is a possibility of replacing batteries that have not failed but are merely not fully charged. On the other hand, PV applications typically use batteries having capacities that can bridge extended periods (days to weeks) of less than normal solar resources, so battery degradation may go undetected if the solar resource is sufficient to routinely charge the battery. To circumvent this confusion requires some form of capacity testing of a fully charged battery—a task that requires the pre- and post-test battery charging requirements (i.e., alternative power source or an extended period of sunshine) discussed in 8.4.3.

There are inherent problems associated with the inappropriate application of maintenance procedures as well. Generally, these are associated with the lack of maintenance on a schedule appropriate to the battery's requirements in the particular application. Not replacing lost electrolyte in vented batteries before the cell's plates are exposed is one example, and this particular maintenance requirement is sometimes ignored in remote unmanned PV applications. In the same vein, specific gravity measurements are performed annually for vented lead-acid batteries in float applications, but more frequent measurements are valuable in cycling applications. For example, specific gravity measurements can indicate when the cells are at differing states of charge and thus in need of an equalization charge. One difficulty with specific gravity measurements is that the frequent discharging in PV applications may result in stratification of the electrolyte. Where allowed by the cell design, it can be useful to take specific gravity readings at different levels within a cell. Significant differences also indicate a need for equalization. Excessive cell connection resistance is another example of a problem that may go undetected if the maintenance is not performed on an appropriate schedule. Visual inspection of connections may not provide sufficient information as to a connection's integrity. Corrective maintenance based on the resistance measurements is required, with the measurement interval being tailored to the application. Applications having abusive environments, for example, significant vibrations or thermal extremes, may require more frequent inspections. Virtually all aspects of battery system maintenance have some associated danger if the appropriate inspections and corrective actions are either not made or are not made on a schedule appropriate to the application operational environment.

The costs associated with the battery's maintenance and testing should be considered against both the cost of the battery and its value to the application. There is an increasing movement to reduce and/or eliminate battery maintenance and testing in some applications where the associated costs are not justified. This may result in the battery being replaced either too early or too late in its life. In the former case, the associated system lifetime battery replacement costs will be greater than necessary, and in the latter case, the battery could fail to meet the application's requirements.

## 9. Alternative electricity storage technologies

### 9.1 General

Demands for higher energy density and better cycling capability have led to the investigation and development of different battery technologies, such as nickel-cadmium, nickel-metal hydride, lithium-ion, and sodium- $\beta$  technologies such as sodium-sulfur and sodium-nickel chloride, as well as advances in lead-acid technology. Flow battery technologies, differing significantly from conventional batteries, are also deployed. In addition, new, non-battery storage devices such as flywheels and electric double-layer capacitors (EDLCs, also known as supercapacitors or ultracapacitors) are being deployed.

### 9.2 Advanced lead-acid

Most advanced lead acid batteries use a form of carbon, e.g., black carbon, to aid in reducing irreversible sulfation on the negative plate in PSOC operation (see 6.2). One approach is to add the carbon to the negative active material. Another approach is to replace a portion of the negative electrode with a carbon component that has the characteristics of an electric double-layer capacitor.

### 9.3 Nickel-cadmium

Nickel-cadmium is a mature battery technology that is widely used for short-duration and long-duration discharges, depending on battery design. Applications that involve environmentally hostile sites typically use nickel cadmium technology because of its superior performance in both cold and hot environments. The transportation industries, mainly railroads and mass transit systems, use nickel-cadmium batteries for both engine starting and energy applications.

Cells range from tiny rechargeable AAA cells to large cells used in multi-megawatt stationary batteries. A completed project in Alaska uses a 26 MW, 15-min nickel-cadmium battery, capable of discharging up to 46 MW. This site is the largest known nickel-cadmium installation in the world.

A myth that seems to continue to plague the nickel-cadmium technology is the notion that the battery has a memory effect that requires special handling in order to maintain the capacity of a battery. Most of these ideas are related to user experience with sealed cylindrical nickel-cadmium cells typically used in portable household appliances. Memory can be an issue with these types of cells; however, the memory problem does not exist in large stationary nickel cadmium batteries.

### 9.4 Nickel-metal hydride

Nickel-metal hydride technology is typically used in small applications such as digital cameras and portable two-way radios. The larger applications are primarily motive power for HEVs. The robustness and cycle life expectancy for this technology is the primary driver for its use. However, this technology becomes rather expensive when batteries are assembled to operate in a megawatt, megawatt-hour environment, and consequently there is little potential use in large, utility-scale applications at the present time.

### 9.5 Lithium-ion

Lithium-ion technology has been widely deployed in cycling applications. Most lithium-ion batteries provide thousands of deep discharge cycles, and many are suitable for continuous partial-state-of-charge (PSOC) cycling operation. A major benefit of this technology is its energy density, which can be more than three times the energy density of lead-acid technologies. Consequently, more energy can be made available in a much smaller space than that required by lead-acid.

Lithium-ion cells have been developed for both long-duration and short-duration applications. The technology encompasses a range of electrochemical systems with a variety of positive and negative active materials to

optimize parameters such as energy density, recharge rate, operating life, and safety. Standard lithium-ion cells are produced in prismatic (rectangular) or cylindrical format with membrane-type separators and liquid electrolyte. Lithium-ion polymer technology incorporates similar electrodes but with those electrodes bonded together with a polymer matrix. Liquid electrolyte is infused into the polymer and is effectively immobilized as a gel. The structural support provided by the polymer allows these cells to be housed in foil pouches rather than metallic containers, thus providing flexibility of cell geometry and improved energy density compared to typical cylindrical cells.

To optimize performance and to operate the battery safely, lithium-ion batteries include battery management systems. These controls maintain proper charging voltages and protect the battery from overcharge or over discharge. A fuller evaluation of lithium-ion and other lithium-based technologies and their management systems is included in IEEE Std 1679.1 [B13].

## 9.6 Sodium- $\beta$

Sodium- $\beta$  technologies include sodium-sulfur and sodium-nickel chloride, and are markedly different from conventional systems. Most currently deployed systems operate at close to 300 °C, and have molten electrodes and a solid ceramic electrolyte. These technologies incorporate heating systems to maintain operating temperature. Regular cycling also contributes to system heating.

These technologies have an energy density three times that of lead-acid and provide thousands of deep cycles, making them well suited to deep daily discharges.

The sodium-sulfur battery, better known as the NaS Battery, is widely deployed in Japan and elsewhere. Sodium-nickel chloride batteries have been used for both cycling and standby operation.

## 9.7 Flow technologies

### 9.7.1 General

There are several flow battery chemistries that have been developed, the predominant types being vanadium redox and zinc-bromine. Flow batteries have been deployed in multi-megawatt-hour systems. One characteristic of flow technology is that the power and energy functions are decoupled. Energy is stored external to the cells in the form of charged electrolytes, the larger the storage tanks, the more energy that is available. Power output is determined by the cell stacks through which the electrolytes are pumped. Typically, flow batteries are configured for multiple hours of discharge, but have versatility to address a broad range of applications. Flow-battery cycle life is theoretically unlimited, although in practice the membrane that separates the electrolytes is typically a limiting factor. One of the challenges in designing flow batteries is in overcoming shunt losses as the conductive electrolytes are pumped through multiple cells simultaneously.

## 9.8 Non-battery storage technologies

### 9.8.1 General

Because lead-acid batteries have a poor track record in utility-scale cycling applications, the development of alternative energy-storage devices was undertaken. Two major developments in non-battery energy storage are the flywheel and the EDLC. A major advantage of non-battery energy storage is that the number of cycles expected from these technologies is substantially higher than that expected in chemistry-based storage technologies.

### 9.8.2 Electric double-layer capacitors

EDLCs store energy electrostatically in the double layer at the surface of a pair of electrodes immersed in a suitable electrolyte. Lacking the faradic reactions of electrochemical systems, the stored energy in EDLCs



is typically an order of magnitude less than that of batteries, but the power density is much higher. There are two types of EDLCs that are being deployed: symmetric devices that have identical carbon electrodes immersed in aqueous or organic electrolytes and asymmetric devices in which the positive electrode is replaced by an electrochemical electrode. Examples of positive electrodes in asymmetric devices include a nickel-oxyhydroxide electrode in an alkaline electrolyte and a lead-dioxide electrode in an acidic electrolyte (see 9.2). The addition of a battery-like positive electrode provides a flatter discharge curve and thus provides a higher energy content for the asymmetric devices.

EDLCs are used in numerous cycling applications, including pitch control systems for large wind turbines and regenerative braking systems for tramways. EDLCs are also used in conjunction with batteries, both with primary batteries where pulse power is required and with secondary batteries, for example, in vehicle starting systems.

### 9.8.3 Flywheels

Conventional flywheels with large steel rotors have long been commercialized, and newer flywheels with high-speed carbon-fiber rotors are now entering industrial production. There are several versions that range in the tens of kilowatts to several hundreds of kilowatts. Although the flywheel is primarily thought of as a power device, there are some that can deliver energy levels in the tens of kilowatt-hours. Such flywheels have been proposed for use in frequency regulation and are expected to be in service in this application by the time this guide is published.

## 9.9 Future emerging technologies

Lead-acid batteries have been the most widely used energy devices for more than 100 years, but they have limitations for large-scale cycling applications. Other battery chemistries and energy-storage devices are being increasingly considered for utility-scale energy-storage applications. Lithium technology batteries are fast becoming cost-effective, and their safety issues are being resolved. Sodium-sulfur batteries and flow batteries will deliver the high energy levels needed to support utility applications. New energy storage components such as flywheels and supercapacitors are fast becoming cost-effective, reliable power sources. Lead-acid battery use will continue to flourish in applications with lower energy and power requirements, but the new technologies are rapidly achieving acceptance in utility-scale applications.

## Annex A

(informative)

### Bibliography

Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

[B1] IEEE Std 450™, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications.<sup>4,5</sup>

[B2] IEEE Std 484™, IEEE Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications.

[B3] IEEE Std 485™, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications.

[B4] IEEE Std 937™, IEEE Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for Photovoltaic (PV) Systems.

[B5] IEEE Std 1013™, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stand-Alone Photovoltaic (PV) Systems.

[B6] IEEE Std 1106™, IEEE Recommended Practice for Installation, Maintenance, Testing, and Replacement of Vented Nickel-Cadmium Batteries for Stationary Applications.

[B7] IEEE Std 1115™, IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Applications.

[B8] IEEE Std 1145™-1999, IEEE Recommended Practice for Installation and Maintenance of Nickel-Cadmium Batteries for Photovoltaic (PV) Systems.

[B9] IEEE Std 1188™, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead-Acid (VRLA) Batteries for Stationary Applications.

[B10] IEEE Std 1361™, IEEE Guide for Selection, Charging, Test, and Evaluation of Lead-Acid Batteries Used in Stand-Alone Photovoltaic (PV) Systems.

[B11] IEEE Std 1491™, IEEE Guide for Selection and Use of Battery Monitoring Equipment in Stationary Applications.

[B12] IEEE Std 1661™, IEEE Guide for Test and Evaluation of Lead-Acid Batteries Used in Photovoltaic (PV) Hybrid Power Systems.

[B13] IEEE Std 1679.1™, IEEE Guide for the Characterization and Evaluation of Lithium-Based Batteries in Stationary Applications.

[B14] IEEE Std 1881™, IEEE Standard Glossary of Stationary Battery Terminology.

[B15] Rand, D. A. J., R. Woods, and R. M. Dell, Batteries for Electric Vehicles. New York: John Wiley & Sons, Inc., 1998.

<sup>4</sup>IEEE publications are available from the Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>). [Annex A](#).

<sup>5</sup>The IEEE standards or products referred to in [Annex A](#) are trademarks owned by the Institute of Electrical and Electronics Engineers.

## Annex B

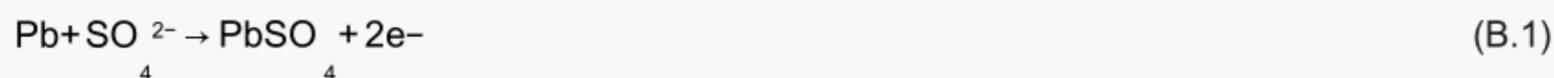
(informative)

### Lead-acid cell theory and construction

#### B.1 Lead-acid electrochemistry

##### B.1.1 Discharge reactions

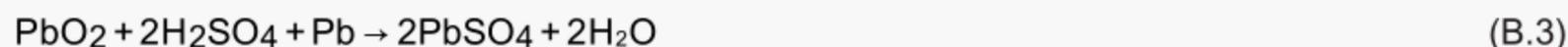
The reaction at the lead (Pb) negative plate, which generates the electron current source, follows in [Equation \(B.1\)](#):



The reaction at the lead dioxide (PbO<sub>2</sub>) positive plate, which accepts the electrons from the negative plate, follows in [Equation \(B.2\)](#):



The net discharge reaction follows in [Equation \(B.3\)](#):

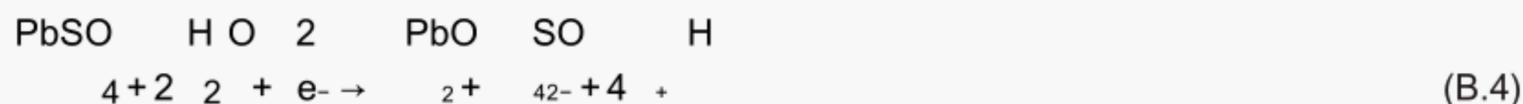


Notice that the reaction results in the sulfation of both plates and the consumption of the acid from the electrolyte.

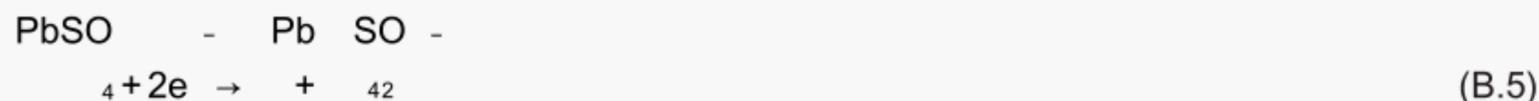
Since the lead sulfate (PbSO<sub>4</sub>) crystals are larger than the pores of the positive active material (PbO<sub>2</sub>) in which they form, they create stress in active material, which results in shedding of material at the surface of the plate.

##### B.1.2 Recharge reactions

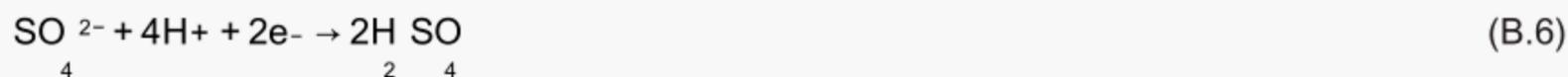
The discharge reaction of [Equation \(B.3\)](#) is fully reversible. The recharge reaction at the positive plate follows in [Equation \(B.4\)](#):



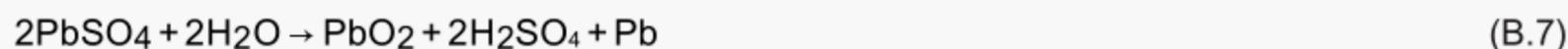
The recharge reaction at the negative plate follows in [Equation \(B.5\)](#):



During recharge, the sulfate ions and hydrogen ions combine to reform the sulfuric acid of the electrolyte, as given in [Equation \(B.6\)](#).



The net recharge reaction follows in [Equation \(B.7\)](#):



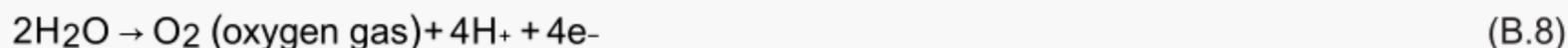
The active materials should be fully recharged once the charger has provided a minimum of between 102% and 110%, depending on the nature of the discharge and recharging regime, of the Ah previously removed.



### B.1.3 Vented cell gassing reactions

If the charger is not disconnected from the vented cell once charged, but is allowed to float-charge the battery, water from the electrolyte will be electrolyzed and gases will be given off per [Equation \(B.8\)](#) and [Equation \(B.9\)](#).

At the positive plate, the reaction follows in [Equation \(B.8\)](#):



The reaction at the negative plate follows in [Equation \(B.9\)](#):



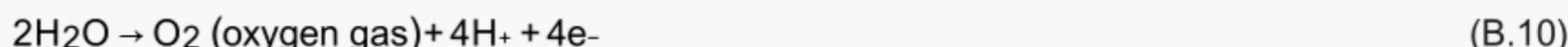
In the vented cell, these gasses are released into the atmosphere. Depending on the positive plate grid alloy and the charging voltage, the float/finish current and water loss can be very small. The rate of water loss due to overcharging will be  $3.36 \times 10^{-7} \text{ m}^3$  per ampere-hour per cell. In a vented cell, distilled or deionized water is supplied to make up for that which is gassed off.

The hydrogen gas generated resulting from overcharge of the “vented” cell will be at a rate of approximately  $1.27 \times 10^{-7} \text{ m}^3$  per second per ampere-hour per cell. A 4% level of hydrogen gas in air is a potentially flammable mixture, therefore positive ventilation is normally required.

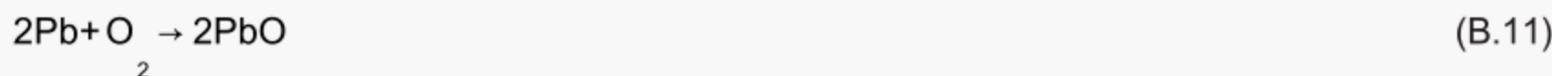
### B.1.4 VRLA gas recombination

In the valve regulated lead-acid (VRLA) cell, the electrolyte is immobilized by either being in a gelled form or being completely absorbed in an absorbent glass mat (AGM) separator between the plates. This immobilization facilitates oxygen gas diffusion to the negative plate where the reactions per [Equation \(B.10\)](#), [Equation \(B.11\)](#), and [Equation \(B.12\)](#) will occur.

At the positive plate, the reaction is the same as with the vented cell, as given in [Equation \(B.10\)](#).



The oxygen gas generated at the positive plate is channeled through the gel or AGM to the negative lead (Pb) plate where the following series of reactions will occur, as given in [Equation \(B.11\)](#).



The oxygen gas oxidizes the contacting areas of the negative plate, as given in [Equation \(B.12\)](#).



The oxidized areas react with the sulfuric acid to discharge the areas and regenerate the water lost at the positive plate. This is an exothermic reaction (generates heat) and is given in [Equation \(B.13\)](#).



The discharged areas of the negative plate are recharged.

Under perfect conditions, there is no net reaction. That is, there is no water loss or hydrogen gas evolved as a result of the electrolysis of the water at the positive plate. However, the cycle is not 100% efficient and

so there will be some water loss and gassing for this and other reasons, although it will only be a fraction of that experienced in a vented cell. Since VRLA cells are sealed in terms of electrolyte maintenance, any overcharging should be minimized so as not to exceed the cells gas diffusion rate and recombination capability. Any water lost cannot normally be resupplied. That is one of the features of the typical VRLA cell—no electrolyte maintenance under normal conditions.

This oxygen recombination capability and the sealed nature of the cell add two new potential failure modes to the list of possibilities: thermal runaway and dryout. Both failure modes are related to overcharging.

## B.2 Lead-acid cell construction

This subclause will review how the lead-acid battery electrochemical reactions are implemented in both “float” service and cycle service designs, and how the application requirements determine the physical properties of the respective components.

The lead-acid cell is a nominal 2 V, as determined by the type of active materials utilized, and it has the following seven basic components:

- Positive plate containing lead-dioxide ( $\text{PbO}_2$ )
- Negative plate of porous lead (Pb)
- Separator to prevent touching and electrical shorting between the two plates
- Electrolyte of  $\text{H}_2\text{SO}_4$  and  $\text{H}_2\text{O}$
- Cell “top lead” and intercell conductive path
- Vent system
- Container

For the purposes of differentiating float-service and cycle-service lead-acid batteries, this subclause will focus on the different characteristics of the positive and negative plates and separators and the third active material, the electrolyte.

While solid lead Planté plates are available, this discussion will be limited to the more prevalent pasted plate and tubular plate technologies.

### B.2.1 Pasted plates

The grid of the positive plate provides the mechanical structure to which the paste of active material is applied and also provides for the conduction of the current to the reacting sites of the lead dioxide ( $\text{PbO}_2$ ). The lead alloy used in the grid and its geometry can have a profound effect on the rate at which it will normally corrode and disintegrate and the float and cycle service life attained.

### B.2.2 Tubular plates

The tubular-plate design places the active material in nonconductive porous tubes. An alloyed lead rod is positioned in the center of each tube to act as a current conductor. Due to the material-retention properties of the tube, this design is capable of many charge/discharge cycles.



## B.2.3 Positive plate alloys

### B.2.3.1 Lead-antimony (Pb-Sb) alloys

Today's forklift and golf-car battery grids typically contain 3% to 6% antimony. The high cycle life attained seems to be due to the antimony diffusing into the positive active material with the result being that smaller lead sulfate ( $\text{PbSO}_4$ ) crystals are formed during discharge. As a result, less stress is created in the pasted material and this reduces material shedding. The antimony seems to improve not only the cohesion of the active material but also its bond to the grid.

However, the downside is that antimony is released into the electrolyte as the grid corrodes and discharges the negative plate. This results in faster self-discharge, shorter shelf life, higher floating and finish currents, higher gassing rates, and higher water-consumption rates.

In addition to the high electrolyte-maintenance requirements, the lead-antimony grid has a rather high corrosion rate. In some cases, good cycling capability has been retained with significant reduction in the gassing rates and required maintenance with the antimony content being reduced to as low as 1.5%, provided there is also the addition of either selenium (Se) or cadmium (Cd) to the alloy. However, the addition of cadmium, it being a heavy metal, may also introduce special considerations related to recycling.

Therefore, while the lead antimonial grid provides higher cycle life, it is typically accompanied by greater maintenance requirements when used in float-service applications. Consequently, in vented cells, the lead-antimony grid system is typically used in applications requiring high cycle life and where the high gassing rates and frequent water additions are acceptable.

### B.2.3.2 Lead-calcium (Pb-Ca) grid alloys

An alternative grid alloy is that of lead-calcium (Pb-Ca). The level of calcium is small and typically below 0.08%. The addition of this small amount of calcium improves the strength of the grid but does not affect the negative plate. When calcium is used as the alloying agent, the float and finishing currents, gassing rates, and water consumption rates may be one-tenth that experienced with lead-antimony grids.

However, on the downside, lead-calcium alloy grids exhibit inter-granular corrosion, which can result in excessive dimensional growth and grid-wire loss of contact with the active material with frequent deep cycling. Also, cells with lead-calcium grids can exhibit development of an insulating passivation barrier between the grid wire and active material. To minimize these negative characteristics, the lead-calcium grid alloy may be adjusted to include tin (Sn), selenium (Se), and/or silver (Ag).

In vented cells, lead-calcium alloy grids are the choice for applications requiring low maintenance and infrequent deep cycles while being on continuous float charge.

For optimum utilization of materials, a high-rate battery, such as those used in engine-starting or 15 min uninterruptible power supply (UPS) applications, will typically maximize the active material surface area exposed to the electrolyte. This means more but thinner plates and grids. Since grid corrosion is the normal failure mode for float-service batteries on continuous charge, use of thinner grids may mean improved high-rate performance but also results in reduced number of cycles as well as reduced float-service life measured in years.

Very thick, more robust plate grids may be used in cycling batteries because, at the lower discharge rates, maximum surface area is not of special benefit because time is available for the slow diffusion of electrolyte acid into the plate where it reacts with the bulk of the active material. Consequently, batteries with superior cycle-service life typically have thicker, more robust grids and plates.



### B.2.4 Active material

The active material paste composition and density has a great impact on the high-rate performance and cycling capability of the lead-acid battery.

For superior high rates, positive active material surface area exposed to the electrolyte for reaction is maximized. This requires a paste of low density that is very porous when cured and formed. While this low-density paste presents a high surface area active material resulting in high-discharge-rate capability, it is also very weak and will crumble and shed with frequent deep cycles.

The typical failure mode of a battery in cycle service is shedding of the positive active material rather than grid corrosion as in float-service applications.

The density of the paste can vary from perhaps 3.5 g/cm<sup>3</sup> for engine-starting float-service batteries to as much as 4.8 g/cm<sup>3</sup> for batteries with reduced high-rate performance but extended cycle-service life.

The negative plate active material is a special case in terms of cycle life. The fine metallic lead crystals of the active material initially present a large surface area for reaction but grow in size with successive cycles with a resulting loss of active material surface area. This effect is retarded through the use of various additives to the negative paste called “expanders.” These include barium sulfate (BaSO<sub>4</sub>), carbon black (soot), and lignin and its derivatives such as ligno-sulphonate. Some manufacturers will use different expanders depending on the intended use being a float or cycle service application. Judicious use of expanders in the negative-plate pasted material is essential to achieving an acceptable cycle-service life.

Recent advances in negative electrode materials for cycling applications are grouped under the heading of ‘advanced lead-acid’ (see 9.2).

### B.2.5 Separators

The separator completes the mechanical construction of the element. With vented cells, the standard was a rubber separator with ribs and a thin glass mat “retainer” that faced and supported the positive-plate active material. In float service, this thin sheet of glass mat was more than sufficient to retain the minor amount of positive active material that would normally be shed due to the occasional minor cycling and any erosion due to gas bubbles during charging. In some high-rate vented cells, a retainer was not even used due to the shallow cycles (less than 50% DOD) encountered in the application. This prevented gas bubbles from being entrained between the plates and blocking access of the electrolyte to the active material. The rubber separator has since been replaced in most products with a microporous polyethylene plastic.

The normal failure mode for lead-acid cells in cycle service is deterioration of the positive plate active material. This occurs as the pasted material is stressed by lead-sulfate crystals formed in the pores of the active mass and as the surface is eroded by the gas bubbles during aggressive high-rate charging.

In vented cells intended for cycling service, retention of the positive plate active material is a significant issue. In these designs, the positive plate is typically wrapped with several layers of fibrous glass mat material to retain the positive active material in place and minimize any erosion due to vigorous bubbling during recharging.

To achieve high cycle life in a VRLA battery, the typical approach is to use a higher-density paste in the positive plate, wrap the positive plate with multiple layers of the AGM material, and maintain very high compression of the element to secure the active material of the pasted plate. This technique can result in a cycle life of two times to four times that achieved with conventional AGM and gelled electrolyte designs.



### B.2.6 Electrolyte

The electrolyte is the third active material utilized in the lead-acid battery. It is a solution of sulfuric acid and water with a resulting specific gravity of between 1.210 and 1.300 depending on the battery design.

The typical vented battery used in float service for switchgear and telecommunications applications has a specific gravity of about 1.215, meaning it is a solution of 20% acid and 80% water by volume. The lower gravity is used to accommodate lower float-voltage requirements and a lower grid-corrosion rate.

Vented cells in high-rate UPS applications typically use an electrolyte specific gravity of 1.250 to 1.260 with the result of increased current capability during short-duration discharges and greater total capacity in longer-duration discharge. However, higher charging voltage is required with the elevated specific gravity.

Cells that are frequently cycled are more subject to electrolyte stratification. That is, the heavier acid tends to stratify and sink to the lower portion of the container. If not corrected, this can result in a temporary loss of capacity and premature failure of the positive active material at the lower portion of the plate. A solution to this issue in vented cells is to occasionally equalize charge the system at elevated voltage to generate significant gassing, and the gas bubbles mix the electrolyte thus restoring the temporarily lost capacity and full utilization of the plate.

While electrolyte stratification can occur in taller (greater than 300 mm) VRLAAGM cells, the taller cells are usually mounted in the horizontal configuration to minimize this phenomenon.



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