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IEEE Guide for Selection, Charging, Test, and Evaluation of Lead-Acid Batteries Used in Stand-Alone Photovoltaic (PV) Systems

IEEE Standards Coordinating Committee 21

Sponsored by the
IEEE Standards Coordinating Committee 21 on
Fuel Cell Photovoltaics, Dispersed Generation, and Energy Storage



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IEEE Guide for Selection, Charging, Test, and Evaluation of Lead-Acid Batteries Used in Stand-Alone Photovoltaic (PV) Systems

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IEEE Standards Coordinating Committee 21
on
Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage

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Abstract: This guide is applicable to all stand-alone photovoltaic (PV) systems where PV is the only charging source. Stand-alone photovoltaic (PV) system parameters and operating conditions are discussed in relation to battery characteristics and expected system performance. Charging parameters for PV systems are suggested to help in the selection of a battery for a specific application. Finally, a performance test to verify the battery selection and system parameters is provided, including discussions on how to interpret test results. Test results only provide information on initial battery performance. No cycle-life predictions are made.
Keywords: lead-acid battery test procedure, lead-acid battery tutorial, photovoltaic (PV) battery characteristics, PV battery selection, PV systems, PV battery test procedure

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Introduction

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The PV system designer depends on the capacity of a storage battery for reliable extended operation of the system load during hours of darkness and below-average solar resource. Photovoltaic systems can subject batteries to harsh operational environments with minimal control of recharge profiles. The economics of photovoltaic modules limit the ability to charge the battery at more traditional motive power deep-cycle charge rates and times. Typical charge rates for small stand-alone PV systems are less than 6.5 amperes and may be less than 2.0 amperes per 100 amphere-hours of battery capacity. Relatively low rates, coupled with the unpredictability of the solar resource, results in limited recharge capabilities.

Stand-alone PV systems are typically used in remote locations with minimal power resources, which limits the amount of initial battery boost charging possible. In daily operation, the limited available PV charging source combined with relatively low-charge regulation voltages may be insufficient to provide a full charge to the battery. In an effort to identify appropriate stand-alone PV system parameters together with appropriate battery technology, a repeatable test procedure is provided to verify PV system parameters based on laboratory battery performance testing. This test procedure is designed to be characteristic of the low-charge/discharge rates, shallow cycle operation, and various charging methods used in PV systems.

This guide contains relevant information on PV system design considerations as related to lead-acid batteries and a recommended test plan for evaluating battery performance in a particular system design. Specific lead-acid battery topics include the following:

— PV battery selection

— PV battery characteristics

— PV battery testing and evaluation

The recommended test plan for evaluating PV batteries includes the following:

— Limitations and expectations

— System parameter selection

— PV battery cycle test

— Interpretation of test results

This guide may be used separately, or in combination with IEEE Std 937™-2000, IEEE Recommended Practice for the Installation and Maintenance of Lead-acid Batteries for Photovoltaic (PV) Systems, and IEEE Std 1013™-2000, IEEE Recommended Practice for Sizing Lead-acid Batteries for Photovoltaic (PV) Systems. Together, these documents will provide the user with a general guide to sizing, designing, placing in service, maintaining, and testing lead-acid storage batteries for PV systems.

Interpretations and errata

Interpretations and errata associated with this amendment may be found at one of the following Internet locations:

— http://standards.ieee.org/reading/ieee/interp/

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IEEE Guide for Selection, Charging, Test, and Evaluation of Lead-Acid Batteries Used in Stand-Alone Photovoltaic (PV) Systems

1. Overview

This guide was written to provide a relevant photovoltaic (PV) battery test procedure that can be used to evaluate battery performance and identify appropriate PV battery charging requirements. Use of this document by funding organizations, battery manufacturers, PV system integrators, and consumers should provide the means for improved battery selection and its subsequent charging specifications. It is intended that this document provide a means to identify more cost-effective and reliable PV batteries.

1.1 Scope

This guide contains a tutorial on lead-acid battery technology, battery charging characteristics, and a laboratory test procedure to evaluate charge parameters and battery performance. The information on lead-acid battery designs and environmental characteristics is provided to help the PV system designer make appropriate battery decisions. PV system parameters and operating conditions are discussed. Charging parameters related to PV systems are also suggested to help in the selection of appropriate test setpoints. Finally, a performance test to verify the battery's operating setpoints and performance is provided, including discussions on how to interpret test results.

This guide is applicable to all stand-alone PV systems where PV is the only charging source. This guide does not include PV hybrid systems.

1.2 Purpose

This document provides guidance in understanding lead-acid battery charging requirements in relation to the operational parameters that affect overall PV system design and battery performance. This document will aid in battery selection, evaluation, and PV system design, and it does provide a test plan for evaluating the selected battery.

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2. References

This guide shall be used in conjunction with the following publications. When the following specifications are superseded by an approved revision, the revision shall apply.

IEEE Std 937™-2000, IEEE Recommended Practice for the Installation and Maintenance of Lead-acid Batteries for Photovoltaic (PV) Systems.[1, 2]

IEEE Std 1013™-2000, IEEE Recommended Practice for Sizing Lead-acid Batteries for Photovoltaic (PV) Systems.

3. Definitions

For the purposes of this guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition [B4] should be referenced for terms not defined in this clause.[3]

3.1 amphere-hours (Ah) charge efficiency: This is calculated by dividing the Ah discharged by the required Ah charged to maintain battery capacity under specific cycle and charging conditions.

3.2 autonomy: The length of time that a photovoltaic (PV) system can provide energy to the load without energy from the PV array.

3.3 battery conditioning: It charges a battery to its full capacity after performing multiple cycles. Battery conditioning is designed specifically for obtaining maximum new battery capacity.

3.4 calculated photovoltaic (PV) array amphere-hours (Ah) to load Ah ratio (A:L): The monthly daily average PV ampere-hours available divided by the monthly daily average load ampere-hours. Average daily PV ampere-hours are calculated by taking the daily average solar resource for each month in kWh/m^2 times the PV array current at its maximum power point (Imp) at standard test conditions (STC). Array to load ratios can also be calculated in terms of their respective Watt-hour parameters.

3.5 charge amphere-hours (Ah) to load Ah ratio (C:L): The total available charge ampere-hours (Ah) divided by the load Ah. Charge Ah are calculated by integrating the set charge current over the total charge time. The actual charge Ah is not necessarily the calculated charge Ah because of charge current tapering at regulation voltage.

3.6 charge controller: An electrical control device that regulates battery charging by voltage control and/or other means. It may also incorporate one or more of the following functions: discharge termination, regulation voltage temperature compensation, load control, and status indication.

3.7 c/x charge/discharge rate: The manufacturer's rated battery capacity in ampere-hours usually at the 20 h rate divided by the discharge time in hours. A 100 Ah battery discharged/charged at the 35 h rate would result in a discharge/charge current of 2.86 amphere (100/35 = 2.86 amphere).

3.8 deficit charge: Charging a battery with less amphere-hours (Ah) than is required to return the battery to its initial state-of-charge. This results in a reduction in the battery state-of-charge.

3.9 end-of-discharge voltage (EODV): The battery voltage just prior to load termination. It will be the minimum voltage for the given discharge cycle.

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3.10 low-voltage disconnect (LVD): The battery voltage at which the load is disconnected to prevent over-discharge. This is the determining factor for the actual maximum allowable depth of discharge and available battery capacity in a photovoltaic (PV) system.

3.11 low-voltage reconnect (LVR): The battery voltage at which the load is reconnected after a low-voltage disconnect.

3.12 opportunity charging: Partial or complete charging of the battery whenever the opportunity arises.

3.13 overcharge: The number of ampere-hours (Ah) charged divided by the number of Ah discharged times 100. Typical overcharge values are between 105% and 130%.

3.14 premature capacity loss: Significant lead-acid battery capacity loss, usually greater than 10%, that occurs during cycling even though the battery receives adequate charge to recover the discharged capacity. The decline in capacity occurs early in the projected cycle-life of the battery without any of the traditional capacity loss or wearout mechanisms.

3.15 regulation reconnect voltage (V_{rr}): The battery voltage at which the charge controller reconnects the charging source to the battery.

3.16 solar insolation: The total daily solar irradiance in kWh/m^2. Most data for a geographic location are reported for each month as the average daily irradiance for a specific array tilt angle. Typical daily values are between 2 and 7 kWh/m^2.

3.17 standard test conditions (STC): The accepted conditions under which photovoltaic (PV) devices are commonly rated: 1000 W/m^2 irradiance at a spectral distribution of airmass (AM) 1.5 and a 25 °C PV cell temperature.

3.18 sulfation, excessive or "hard": The growth of lead sulfate ($PbSO_4$) crystals on the positive and negative plates of a lead-acid battery after an extended time in a discharged condition. "Hard" can be identified by an abnormal drop in electrolyte specific gravity after an equalization charge and by a gritty texture on the plates.

3.19 sustaining charge: The battery will be restored to the same state-of-charge it was prior to the discharge.

3.20 termination voltage: The battery voltage at which discharge is terminated.

4. Safety

CAUTION

Whenever batteries are used, certain safety concerns need to be considered. Installation of batteries under test should be in accordance with procedures outlined in IEEE Std 937-2000.[4] Goggles for eye protection, acid-resistant gloves, eyewash stations (portable or stationary), electrolyte neutralizing solutions, protective clothing, and a class C fire extinguisher should be considered mandatory for personnel safety.

Select a solution (or powder) that will neutralize the 20% to 30% sulfuric-acid solution (standard electrolyte). Sodium bicarbonate (baking soda) works well to neutralize electrolyte spills. Neutralizing electrolyte spills may subject the users to hazardous waste regulations. Contact the local hazardous waste office for guidance.

[4]For information on references, see Clause 2.

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4.1 Arc hazard

Batteries used in low-voltage small stand-alone PV systems can be a source of considerable electric arc hazards. Care must be taken to prevent accidentally shorting the positive and negative terminals of a cell or battery when using metallic tools or other metallic objects, such as jewelry. In most cases, battery short circuit currents can exceed 1000 amphere. Special electrically insulated tools are used to enhance safety. In addition, it is prudent to fuse and properly size all conductors in the system to prevent damage to wiring and test equipment in the event of a short circuit or equipment malfunction.

4.2 Hydrogen venting

Vented lead-acid batteries release significant quantities of hydrogen and oxygen gas as a result of the electrolysis of water. The electrolysis of water is a consequence of the battery charging process and begins to occur at voltages over 2.25 volts (V) per cell. As the charge voltage increases, the electrolysis also increases accordingly. To protect against igniting the potentially flammable and/or explosive hydrogen and oxygen mixture inside the vented battery, the National Electrical Code, Section 480.10 [B1] requires that battery installations use flame-arrester vent caps. Flame-arrester vent caps for vented batteries typically consist of a microporous ceramic or plastic foam to prevent a flame or other external ignition source from igniting the hydrogen inside the cell.

Valve-regulated lead-acid (VRLA) batteries under normal operation only vent very small quantities of hydrogen; thus, room ventilation is more than adequate for hydrogen protection as long as charge voltage is controlled. If VRLA battery charge voltage is uncontrolled and reaches excessive levels, then the quantity of hydrogen released can approach that of vented batteries. In applications where VRLA batteries are placed in enclosures restricting air circulation, additional ventilation may be required.

The maximum hydrogen evolution rate, as found in IEEE Std 484™-1997 [B6], occurs when the battery is fully charged at the maximum charge current. To calculate maximum hydrogen production and thus required room air ventilation, the following equation is suggested:

$$P_H = 1.27 \times 10^{-7} \times N \times I(m^3/s) \quad (1)$$

where

P_H is the production of hydrogen,

N is the total number of cells in the battery,

I is the maximum charge in amperes per cell at 25 °C.

Once the volume of hydrogen production is known, the percent of hydrogen buildup in the battery room can be calculated by using the room air volume and the room air exchange rate. The battery room should be free of areas that might collect pockets of hydrogen gas. Most system designers require hydrogen levels below 1% or 2%, because the lower flammable limit is 4%. A battery room that meets the above requirements for ventilation should not be considered a classified (hazardous) location; thus, special electrical equipment enclosures to prevent fire or explosions should not be necessary.

4.3 Secondary containment

Secondary containment to prevent uncontrolled electrolyte spills from vented batteries is a requirement in the Uniform Fire Code, Article 64 [B7] and may be required in certain jurisdictions.

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5. Lead-acid battery selection and use

It is important to understand the advantages and limitations of the different lead-acid battery designs available and their performance characteristics. Battery performance is highly dependent on matching the appropriate battery design to the battery application. Lead-acid batteries are designed for engine starting, lighting, and ignition (SLI), deep-cycle (motive power), stationary float service (uninterruptible power supplies or UPS), and energy storage systems. Usually the deep-cycle batteries provide the best performance in PV systems because they have a high cycle-life and are more resistant to the deleterious effects of deficit-charge cycling (see Annex A).

5.1 Battery characteristics

There are a number of basic battery characteristics that can have a significant impact on PV system performance. Among the more important characteristics are temperature effects, recharge efficiency, sulfation, stratification, and charge voltage. Annex B contains a brief description of battery characteristics and possible PV system design solutions for optimum battery health.

5.2 PV system parameters

PV system parameters need to be defined with the battery in mind. Small system modifications can have a dramatic impact on battery performance. It is important to clearly define battery charging requirements and then meet those charging requirements with proper charge control voltage and array sizing (see Annex C). Many of the parameters selected are dependent on the system load profile, site weather conditions, system hardware, and battery requirements. Because of the high life-cycle costs associated with the battery, the charging requirements of the battery should be identified first, and then the PV system should be designed to provide those battery charging requirements. For example, if a battery needs to be charged to 2.35 V per cell and only discharged to 1.95 V per cell, then a PV charge controller that will charge to the appropriate regulation voltage and limit discharge to the specified LVD should be used. The same process can also be used to evaluate a range of charge to load ratios and charge rates. For example, if the PV battery needs more time at regulation voltage and/or requires a weekly finish-charge, then a larger PV array to load ratio will be required to provide the longer finish-charge time necessary to maintain a higher state-of-charge.

6. Recommended test plan

The PV Battery Cycle Test operates the battery in a scenario that attempts to simulate the daily charge/discharge cycles of a PV system in high and low solar resource periods. During high solar resource periods, the battery will shallow-cycle to a high state of charge everyday. This use profile is simulated by the initial 25 shallow cycles in the test procedure. During low solar resource periods, the battery can discharge down to the LVD. This use profile is simulated by the six deficit charge cycles to LVD. Recovery from LVD requires consistent and substantial charge from the PV array. This use profile is simulated by approximately 20 recovery charge cycles. When the test is complete, relative battery performance can be gauged by comparing the initial and final capacity test results. To help identify the cause of any capacity loss, the battery charge regulation voltage, specific gravity, and overcharge are used to evaluate if the battery was undercharged or suffering from premature capacity loss.

6.1 Limitations and expectations

The value of the test results is dependent on how well the test duplicates the PV system parameters. After the test procedure is complete, a decision can be made using battery capacity and other performance indicators to determine the acceptability of the battery and the associated system charging parameters.

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6.2 Objectives

This test is designed to simulate battery use in a stand-alone PV system. Three specific objectives are as follows:

— Evaluate the PV battery and PV battery charging performance in a test that simulates sustaining, deficit, and recovery charge conditions

— Identify and test the PV battery charging parameters

— Characterize possible PV system designs with the goal of extending PV battery cycle-life

6.3 Parameter selection

The test procedure uses regulation voltage (V_r), available charge Ah to load Ah (C:L) ratio, and "typical" PV charge rates (C/X). The C:L ratio is used to reproduce the calculated available PV array Ah to load Ah (A:L) ratio that would normally be used in array sizing. This test does not take into account the battery charging effects from the ramp up and down in charge current by the PV array. Actual PV array charging would tend to be more efficient because of the inherent taper charge characteristic of the PV array. The "typical" PV charge rate should be an average of the daily PV array current.

In addition to the test parameters, the deficit-charge recovery time period is also an important variable in this test procedure. As the C:L ratio increases from 1.1 to over 1.5, the number of deficit-charge cycles decreases dramatically and, consequently, the time that the battery spends in a discharged condition. Reducing the number of deficit-charge cycles is an important factor in minimizing the formation of "hard" sulfates in the battery and thus is critical in maintaining battery capacity.

6.4 PV battery test procedure

The PV battery test consists of five major elements, the Initial Battery Charge, Initial Capacity Test, Cycle Test, Final Capacity Test, and Evaluation of Results, as shown in Figure 1. After the Evaluation of Results, the testing may be complete if battery performance is acceptable. If the performance is not acceptable, new test parameters may be selected and the test may be repeated to improve battery performance or identify other acceptable system battery charging parameters.

6.4.1 Test equipment and data acquisition

The PV battery cycle test requires an adjustable current charging power supply capable of constant-current charging to an adjustable regulation voltage, which is then automatically switched to a constant-voltage power supply at regulation voltage. Once the battery has finished charging, an electronic or resistive load is required to discharge the battery at the appropriate current. Both the power supply and the load will require a control system to charge and discharge the battery for the required time. If a resistive load is used, then the load resistor should be adjusted to provide the average required discharge current. The resistor setting will depend on the voltage characteristics of the battery and the discharge termination voltage. System control and data acquisition are usually accomplished using a computer-based system.

The 25 sustaining-charge cycles in this test are controlled by the charge and discharge time. Although the discharged Ah will be constant, the charged Ah may vary when the battery reaches regulation voltage. Accurately determining the Ah data requires sampling the current at regular intervals and integrating this current data over time. The data sampling and integration interval needs to be frequent enough to account for charge current changes that occur as a result of the power supply or charge taper when the battery reaches regulation voltage.

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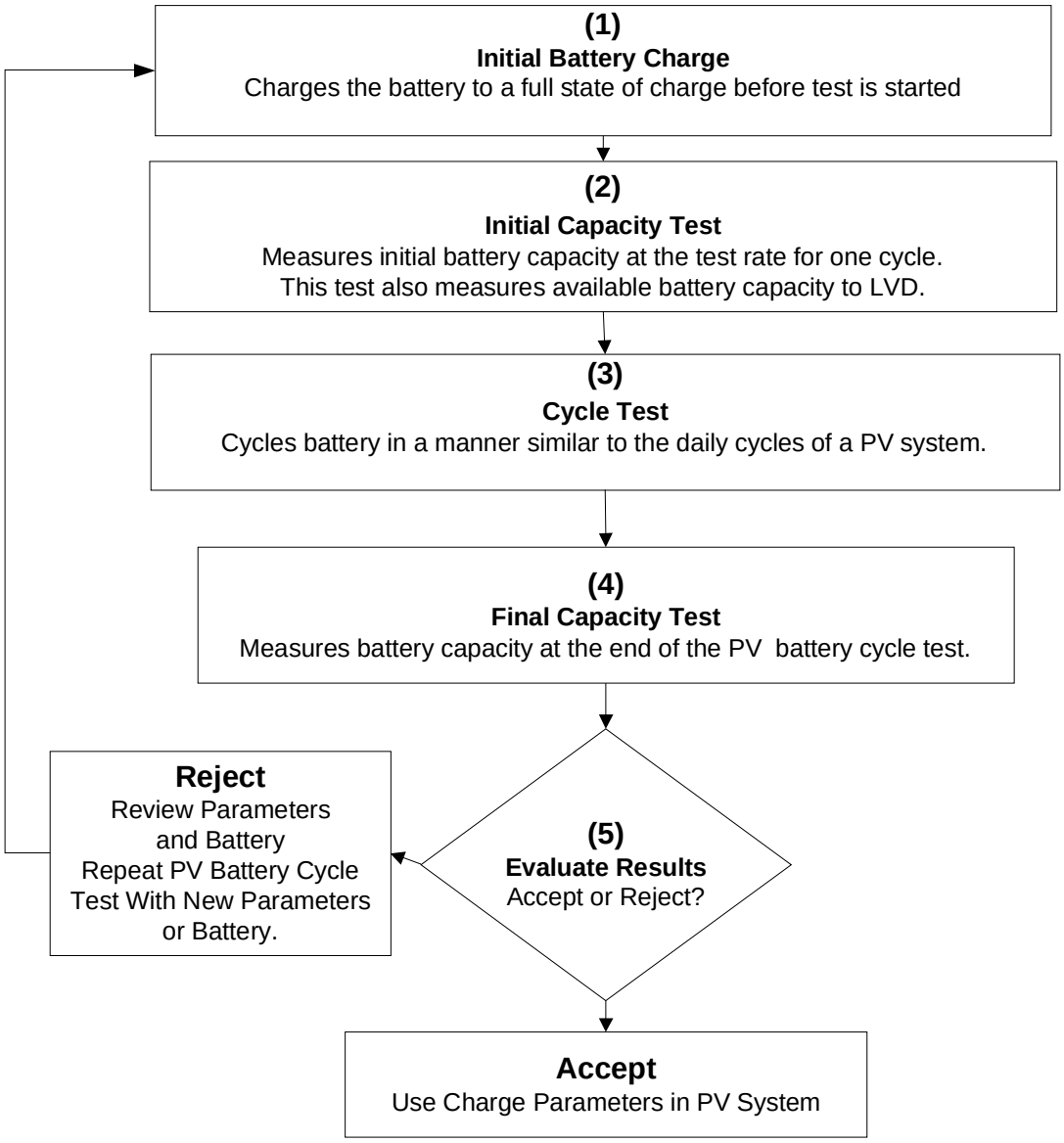

Figure 1—PV battery cycle test procedure

To measure Ah overcharge during the 25 sustaining-charge cycles will require zeroing the Ah count at the start of each discharge cycle. To measure the available Ah capacity to the LVD for the deficit-charge cycles, the Ah count should not be zeroed at the beginning of each discharge cycle. This running Ah count is necessary to provide the available Ah capacity to LVD. The recovery charge cycles also do not zero the Ah count on discharge. This running Ah count provides information on the adequacy of the recovery charge. The test data should be recorded at intervals not to exceed 30 minutes. Test data are also recorded at the beginning and end of each discharge and charge cycle. Battery voltage and current readings for end of charge and discharge should be absolute readings and not averages over the measurement interval.

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The battery temperature should be held to within ±3 °C of the value specified for the test. The standard test temperature is 25 °C, but other temperatures can be used. Stabilized temperature baths or standard room temperature control is required. Battery temperature should be recorded at the same frequency as the other test data.

6.4.2 Initial battery charge

Prior to performing the Initial Capacity Test, an Initial Battery Charge needs to be performed. The battery manufacturer should be consulted for battery charging instructions for an Initial Charge. The investigator should use the charging specifications provide by battery manufacturer or from the battery installation and operation manual. If this information is unavailable, Table 1 provides suggested values. A current-limited, constant voltage method should be used for the charging. This procedure may be referred to as the Initial Charge, boost charge, or freshening charge. When requesting this information, it should be communicated that this will be a charge sequence intended to get the battery to 100% SOC or ready for installation.

Table 1—Default initial charging parameters (constant voltage/PWM)

Cell Type	Voltage Limit (V per cell)[a]	Voltage Limit (V, nominal 6/12 V battery)[a]	Minimum Duration of Constant-Voltage Regulation at Specific Voltage Limit (h)
Vented, lead-antimony	2.55	7.65/15.3	3
Vented, lead-calcium	2.66	7.98/16.0	3
VRLA, AGM (see manufacturer's specifications)	2.35	7.05/14.1	12
VRLA, gel (see manufacturer's specifications)	2.35 to 2.40	7.20/14.4	12

[a]This value has to be within the system's operating voltage limits.

NOTE—Voltages specified for battery temperature at 25 °C + or – 3 °C.

V per cell = volts per cell, AGM = Absorbed Glass Mat, Gel = gelled electrolyte.

The Initial Capacity Test should be performed at no less than 12 h and no more than 72 h after this Initial Battery Charge. Record the charge in ampere-hours and electrolyte specific gravity for vented batteries to identify any damage or unusual battery characteristics from handling and storage.

6.4.3 Initial capacity test

After the Initial Battery Charge, the battery will be discharged to the termination voltage (minimum discharge voltage) specified by the battery manufacturer. This voltage is usually 1.75 V per cell for deep-cycle lead-acid batteries. The capacity test will be conducted at the discharge and charge rate desired in the Cycle Test. During discharge, the battery voltage and Ah removed should be recorded at the LVD voltage and termination voltage. The battery manufacturer should be contacted to determine the acceptable range in initial capacity. If initial capacity is well below the rated capacity, then the battery may not be acceptable for testing.

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6.4.4 Procedure for initial capacity test

a) Determine the nominal or manufacturer's capacity rating for the discharge rate desired. Use the average current from the PV system design. See Table 2 for recommended discharge/charge rate if the actual PV system rate is unknown.

b) Set the discharge rate for constant current for an electronic load. For a resistive load, use rated current at 2.0 V per cell for the current and voltage determined in Step a) of this subclause.

c) Begin discharge, record battery or cell voltage and current, and record the Ah discharged to LVD and Ah discharged to termination voltage (usually 1.75 V per cell or other specified).

d) Charge the battery in accordance with the Initial Battery Charge procedure.

e) Record total charge Ah.

f) Determine the percent overcharge for the recharge by dividing the charged Ah by the discharged Ah and then multiplying the results by 100.

g) Use capacity to LVD and termination voltage for the initial capacity measurement and in the Cycle Test parameter calculations.

6.4.5 Procedure for PV battery cycle test

Table 2 is provided as a baseline for cycle parameter determination. The values identified in Table 2 are reasonable starting parameters for PV battery systems based on typical stand-alone PV system designs. Other V_r setpoints, charging rates, C:L ratios, depths of discharge (DODs), and temperatures may be used based on stand-alone PV system designer and user requirements. Battery preparation for cycle testing should only include the Initial Battery Charge and one Initial Capacity Test. Batteries that have been in storage without regular freshening charges per manufacturer's specifications or used batteries should not be used. An example test profile is presented in Figure 2 for a 90 Ah VRLA battery.

Table 2—Default PV battery cycle test parameters

Variable	Vented, Lead-Antimony[a]	Vented, Lead-Calcium[a]	VRLA, AGM[a]	VRLA, Gel[a]
V_r setpoint, V per cell (constant voltage, PWM)	2.40 to 2.50	2.45 to 2.55	2.35	2.35 to 2.40
V_r setpoint, V per cell (on/off disconnect)	2.45 to 2.50	2.45 to 2.55	2.40 to 2.42	2.40 to 2.42
V_{rr} setpoint, V per cell (on/off reconnect)	2.25 to 2.28	2.25 to 2.28	2.25 to 2.28	2.25 to 2.28
Charge rate, C/h	C/35	C/35	C/35	C/35
Discharge rate, C/h	C/35	C/35	C/35	C/35
LVD, V per cell	1.90 to 2.00	1.90 to 2.00	1.90 to 1.95	1.90 to 1.95
LVR, V per cell	2.17 to 2.25	2.18 to 2.25	2.18 to 2.25	2.18 to 2.25
C:L ratio	1.3	1.3	1.3	1.3
DOD,%	20	20	20	20
Temperature, °C	25	25	25	25

[a]This value has to be within the system's operating voltage limits.

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Example Cycle Test for Figure 2 (Actual Figure 2 values in parentheses):

a) Identify: rated battery capacity (90 Ah), V_r setpoint (2.35 V per cell), discharge/charge rate (C/35, 2.57 A), LVD (1.9 V per cell), C:L Ratio (1.3), DOD (20%), and Temperature (25 °C).

b) Conduct Initial Charge (use manufacturer's recommended LVD and termination voltage values if possible) (see 6.4.2) and Initial Capacity Test at the above regulation voltage and discharge/charge rate (see 6.4.4). Record battery capacity to LVD (1.90 V per cell, 80 Ah) and termination voltage (1.75 V per cell, 92 Ah).

c) Calculate 20% DOD Ah (0.2 x 92 = 18.4 Ah), deficit-charge Ah required to discharge battery to LVD in six cycles (80 Ah/6 cycles = 13.3 Ah/cycle), and calculate charge and discharge time with a C:L ratio of 1.3 (discharge time = 18.4/2.57 = 7.16 h , charge time = (18.4 x 1.3)/2.57 = 9.31 h).

d) Calculate the number of recovery cycles plus five cycles required to recover from LVD.
[80 Ah/((18.4 Ah x 1.3 C:L) –18.4 Ah discharged) + 5 cycles] = 20 cycles.

e) Begin 25 sustaining cycles at specified V_r, rate, C:L ratio, LVD, DOD, and temperature.

f) Begin six cycles at deficit C:L ratio designed to discharge to LVD (–13.3 Ah/cycle).

g) Begin 20 recovery cycles using sustaining-charge cycle parameters from Step e) of this subclause.

h) Conduct two Final Capacity Tests at specified rate (see 6.4.6). Recharge the battery same as the Initial Charge in Step b) of this subclause.

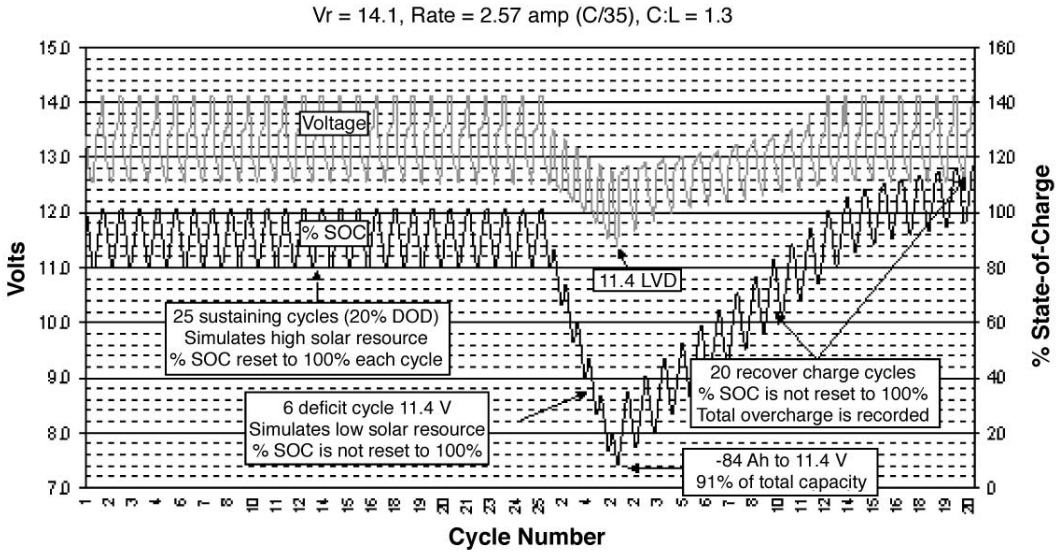

Figure 2—Example PV battery cycle test profile

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6.4.6 Procedure for final capacity tests

a) Set the discharge and charge rates to those used for the Initial Capacity test.
b) Begin discharge, record battery or cell voltage and current, and record the Ah removed at LVD and the Ah removed at 100% discharge or at termination voltage as used in the initial capacity test.
c) Recharge the battery in accordance with the Initial Battery Charge procedure.
d) Record total recharge Ah.
e) Begin second discharge, record battery or cell voltage and current, and record the Ah removed at LVD and the Ah removed at 100% discharge or at termination voltage as used in the previous capacity test.
f) Recharge the battery in accordance with Step c) of this subclause.
g) Record total recharge Ah.
h) Determine the overcharge for the recharge by dividing the charged Ah by the discharged Ah.

6.4.7 Test results to record

a) Charge and discharge parameters.
b) Initial battery capacity.
c) Vented battery electrolyte specific gravity before PV battery cycle test (charge indicator).
d) Percent of overcharge in Ah for the first and last of the 25 sustaining-charge cycles (charge indicator).
e) The difference between first and last end-of-discharge-voltage for the first and last of the 25 sustaining-charge cycles (charge indicator).
f) Total Ah discharged to LVD (available capacity).
g) Specific gravity for vented batteries after recovery charge (charge indicator).
h) First final capacity (charge indicator).
i) Second final capacity (identifies if capacity loss is recoverable).
j) Percentage change between initial and first final capacity (ideally, this second capacity should be no more than 10% below initial capacity, but this is dependent on the battery and charge parameters).
k) Test temperature.

6.5 Evaluation of test results

The acceptability of the battery and charging parameters for PV applications will need to be determined based on individual requirements. This test is designed only to provide relative performance information. Each PV system will have different requirements and available components. Tests that most closely represent the actual system design will provide the most accurate battery performance data. Battery test parameters that result in no or minimal capacity loss are the most desirable for maximum PV system and battery performance.

Previous experience with fielded stand-alone PV systems and laboratory testing has shown that an initial capacity loss of up to 10% is not uncommon (see Woodworth et al. [B9], Vinal [B8], and Hund [B2], [B3]). If final battery capacity is less than 90% of initial capacity, then the test parameters, system design, or battery design may be improved. If battery capacity is less than 80%, then there are problems with the charging parameters or battery (see Annex A through Annex C). In these cases, the percent of overcharge during the sustaining cycles, specific gravity after cycling, and EODV can be used to determine if the battery was being charged adequately or if the battery is experiencing premature capacity loss. Significant capacity loss is an indicator of a reduction in cycle-life.

The percent of overcharge per cycle is a good indicator of adequate recharge. The battery manufacturer should be contacted for recommended overcharge values, but in general, batteries used in PV systems will

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require between 105% and112% overcharge for VRLA batteries and 110% and 130% for vented batteries. If the percent overcharge is low for vented batteries, then a higher regulation voltage or greater C:L ratio may be needed. If overcharge is low using VRLA batteries, then the manufacturer's recommended regulation voltage should still be used, leaving only the C:L ratio as a means to increase charge.

Specific gravity measurements that are within manufacturer’s specifications after cycling are an indicator of adequate charge for vented batteries. Most deep-cycle lead-antimony batteries will have a fully charged specific gravity of about 1.280. This value can vary between batteries, so it is always a good idea to contact the battery manufacturer to get the proper specific gravity for the battery under test. If the temperature-corrected specific gravity is more than 0.010 points below the initially measured fully charged value after cycling, then the battery may not be receiving adequate charge.

End-of-discharge voltage during sustaining cycles may fall by a few millivolts. This drop is usually less than 3.3 mV/cell. If this value is greater, then the battery may be under charged or degrading during the sustaining charge cycles.

In summary, if capacity loss is low (<10%), then the battery charging parameters are acceptable. If capacity loss is significant (>10%), then it is best to review battery selection and battery charging parameters to identify a possible cause for the capacity loss. Performance verification of the new PV system parameters or battery can be accomplished with a repeat of the entire PV Battery Cycle Test.

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Annex A

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Lead-acid battery technologies

A.1 Battery applications

Lead-acid batteries are almost universally used in PV systems because of their low cost and availability. A few special application PV systems use nickel-cadmium batteries or advanced technologies to improve reliability and/or to reduce maintenance. This is a very small percentage of the applications, and as a result, this document will only address the lead-acid battery technology. At present, the dominant lead-acid battery technologies used in PV systems are divided into two major groups, vented (flooded) lead-acid batteries and valve-regulated lead-acid batteries that have their electrolyte contained in a medium of either glass fibers or gel. Batteries from both subgroups are designed for starting, lighting, and ignition (SLI), deep-cycle marine/recreational vehicle (RV), deep-cycle golf cart, deep-cycle industrial motive power, small float service stationary uninterruptible power supply (UPS), and large stationary float service applications. Each of the above battery applications will also have a number of options available for the six major battery markets indicated above. Generally stand-alone PV systems use batteries designed for the SLI automotive, deep-cycle marine/RV, or deep-cycle motive power golf cart markets. The most relevant to PV systems are the vented and VRLA deep-cycle batteries. Even though automotive SLI batteries are not designed for deep-cycling and have a significantly shorter cycle-life, they are universally available and are the lowest initial cost short-term option. The common deep-cycle marine/RV batteries are designed to be more tolerant to deep-cycling. Motive power golf cart batteries are designed for deep-cycle service with cycle-life ratings significantly greater than the deep-cycle marine/RV batteries. Motive power and/or golf cart batteries are not commonly available in auto parts stores and may not be available in developing countries. If they are used in these applications, they may require special shipping or other arrangements.

A.2 Vented lead-acid batteries

When used and maintained properly, the vented lead-acid battery has a long and successful track record for providing power in SLI, deep-cycle motive power, and standby stationary float service applications. Each of these major categories uses batteries specifically designed for that application. The key for successful battery operation is to use the appropriate battery for the application, provide the required maintenance, and provide a cycle profile consistent with the battery design.

If SLI batteries are used in PV systems, it is important to understand their use, design, and limitations. Most vented SLI batteries now used in developed countries are of the lead-calcium open vent design. SLI batteries are designed to be used for short high-rate discharges in engine starting and to provide brief lighting loads. The battery grids are specially designed for this application by making them thin for more surface area and alloying them with lead-calcium to reduce water consumption and maintenance. The thin grids are susceptible to cracking and grid corrosion from the mechanical stresses of cycling and the normal electrochemical wearout processes.

Another group of SLI batteries used in PV systems in developing countries have a similar design to the above SLI batteries except that they use a low percentage of antimony (~2% to 3%) in the lead grids and they have slightly thicker grids. These batteries are similar to SLI batteries used in developed countries up until the 1960s, but they are still common in developing countries and are similar to deep-cycle marine/RV batteries presently in use in developed countries. In these batteries, the grids are slightly thicker and the

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antimony grid alloy is more resistant to cracking, stratification, and premature capacity loss. Cycle-life is greater than the lead-calcium batteries but is much less than the motive power and golf-cart batteries. In many countries, this may be the only battery available, and with proper care, they can have an average life of 1.5 years.

The marine/RV batteries are a deep-cycling battery that is very popular with the PV industry. The construction is similar to the lead-antimony SLI batteries except that the grids are thicker, more antimony is used as an alloying element in the grids, the positive paste active material is formulated for cycling applications, and more space is provided for plate sediment. The combination of these design improvements results in a significant improvement in cycling ability without a significant increase in cost.

The deep-cycle golf cart batteries are medium-duty cycling batteries that are also very popular with the PV industry. The construction of these batteries includes grids with a medium thickness of 3 to 4 mm, a grid alloy with a relatively high antimony content in the 4% to 6% range, a positive plate active material designed for deep-cycling, and more space for plate sediment. The grid thickness provides extra strength and excess metal to delay the normal wearout mechanisms of grid corrosion and active material shedding. The additional antimony provides more resistance to grid corrosion and minimizes capacity loss over the life of the battery. A more robust positive active material is more tolerant to cycling stresses and maintains capacity over the life of the battery. Typically, the deep-cycle battery designs require more watering and maintenance. The cost of deep-cycle golf-cart batteries is somewhat more than marine/RV batteries, but the cycle-life can be much greater. Due to volume production, the deep-cycle golf cart batteries may provide the lowest life-cycle cost option in properly designed small stand-alone PV systems.

Industrial motive power forklift batteries represent the most robust battery designs for deep-cycle battery applications. The major differences between golf cart batteries and motive power forklift batteries are the plate thickness and the rating process. Industrial motive power truck battery plate thickness is usually in the 5 to 6 mm range, and the capacity rating is usually at the 6 h rate. Golf cart batteries, on the other hand, are rated in minutes at a 75 amphere discharge rate or at the 20 h rate. This rating difference results in industrial motive power forklift batteries that are more conservatively sized. The cycle-life of these batteries is generally more than twice that of golf cart batteries, but their cost is also higher.

Industrial stationary batteries are also available for PV systems. These batteries can be used in deep-cycling and shallow-cycling applications with good results, but they can be more costly than motive power batteries. Some cycling stationary batteries are designed to have a much lower water consumption rate compared with deep-cycle motive power batteries. This can be an important consideration in PV system design.

A.3 VRLA batteries

VRLA batteries first became available in the early 1980s and have enjoyed a steady growth in production since then. VRLA batteries now represent a significant portion of the PV battery market. The VRLA technology is one of the most important lead-acid battery developments in the twentieth century. The early marketing strategies promoted this battery as a “sealed” or “maintenance free” battery, which it is not. The VRLA battery uses the oxygen recombination cycle to return most of the gas produced from electrolysis back into water. Small quantities of water may be lost from venting of excess gas and from internal grid corrosion. VRLA batteries cost more, degrade faster at high temperatures, require more stringent charge control, and may have a lower cycle-life than the vented alternative. The impetus for using VRLA batteries is due primarily to the fact that no watering is required, minimal electrolyte residue is left on the battery terminals, no special provisions for venting hydrogen gas other than room ventilation is usually required, installation requires less floor space, and the electrolyte is held immobilized in a glass mat or gel, which makes transportation safer and easier.

VRLA batteries have three design features that are unique with respect to their vented counterparts. These unique features are the captive electrolyte, a cell pressure valve, and the oxygen recombination cycle. The

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captive electrolyte is suspended in either glass fibers called the absorbed glass mat (AGM) or in the silica gel. In AGM and gel batteries, the hydrogen ions produced at the negative plate and oxygen gas produced at the positive plate recombine electrochemically at the negative plates to conserve water. The VRLA battery technology does occasionally vent a very small amount of hydrogen and oxygen gas when it is under charge; consequently, the VRLA battery should be installed in a ventilated enclosure. The venting occurs when a low-pressure gas relief valve allows excess gas to vent when the battery reaches its maximum internal pressure. The valve also prevents air from entering back into the battery and causing negative plate discharge from atmospheric oxygen. The valve is a critical part of the oxygen recombination cycle because it prevents atmospheric oxygen from entering the battery. The oxygen recombination cycle in Equation (A.1) includes the following chemical reactions:

Positive plate releases O_2 on charge

$$H_2O \Leftrightarrow 2H + 1/2O_2 + 2e \quad \text{(A.1)}$$

O_2 passes through AGM or gel to the negative plate

$$Pb + 1/2O_2 \Leftrightarrow PbO$$

$$PbO + H_2SO_4 \Leftrightarrow PbSO_4 + H_2O$$

$$PbSO_4 + 2H^+ + 2e \Leftrightarrow Pb + H_2SO_4$$

The required maintenance on VRLA batteries in stand-alone PV systems as compared with stationary float service applications is less than on deep-cycle vented lead-acid batteries. VRLA stand-alone PV system maintenance usually involves retorquing electrical interconnections, removing corrosion, measuring cell or monoblock voltages, and ensuring that the battery charger is working properly and meeting manufacturer's charge requirements.

A.4 Battery selection

Battery selection is dependent on battery availability, application, performance, cost, and system size. Because lead-acid batteries are heavy and contain sulfuric acid, shipping them can be difficult and result in damaged batteries. In many remote or developing country locations, it may be more practical to use local batteries, because replacement batteries may be needed in the future. When vented deep-cycle lead-antimony batteries are available, they may be the lowest life-cycle cost option. In applications where battery watering is not possible, or very expensive, or where shipping of liquid electrolyte is difficult, the VRLA battery can be a cost-effective option. With larger PV systems, the batteries will also need to be larger. Generally, the maximum number of parallel strings is four. With four strings, the 6 V golf cart battery systems are limited to about 880 Ah and the larger deep-cycle L-16 floor scrubber batteries are limited to about 1400 Ah. Above this size, larger batteries should be used. The larger batteries are typically the deep-cycle industrial forklift batteries or large stationary batteries. These batteries can be used in battery banks with capacities well over 10 000 Ah.

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Annex B

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Lead-acid battery characteristics

B.1 Self-discharge

All lead-acid batteries are subject to self-discharge or “local action” at all times. The effect of self-discharge only becomes a problem when batteries are left in storage without freshening charges. The self-discharge rate is a function of temperature, grid alloy, battery age, acid-specific gravity, and battery design. Self-discharge is a result of ongoing internal electrochemical reactions that essentially act as a continuous battery load. The most effective method to minimize self-discharge is to lower battery temperature. Lead-calcium grid alloys also greatly reduce self-discharge. Damage to batteries in storage due to self-discharge is only prevented by providing freshening charges on a regular basis.

The self-discharge rate for new vented deep-cycle high-antimony batteries is about 2.5% per week at 25 °C. The self-discharge rate increases dramatically at 40 °C to over 5% per week and decreases to less than 1% per week at 0 °C. The self-discharge rate also increases significantly as the battery ages. Generally battery manufacturers will recommend a freshening charge every month or two for most vented deep-cycle batteries.

The self-discharge rate for a deep-cycle vented low-antimony grid alloy battery is about 1% per week, whereas the lead-calcium alloy grids and VRLA batteries are typically less than 1% per week at 25 °C. For VRLA batteries at 40 °C, the self-discharge rate is about 2.5% per week, and at 0 °C, the self-discharge is near zero. The vented lead-calcium battery usually has only a slightly higher self-discharge rate compared with the VRLA battery. Battery manufacturers recommend a freshening charge about every six to seven months for vented lead-calcium and VRLA batteries.

B.2 Temperature effects

Battery temperature has a significant impact on cycle-life, capacity, charge voltage, electrolyte-specific gravity, and water consumption. Most lead-acid batteries are rated for operation at 25 °C; therefore, most battery specifications will be for operation at 25 °C. If the battery is used at other temperatures, then the specifications for cycle-life, capacity, charge voltage, electrolyte specific gravity, and water consumption will need to be adjusted accordingly.

The useful life of vented stationary float-service batteries will decrease by about 50% if the battery temperature increases 10 °C (35 °C battery temperature). If the battery operating temperature drops 10 °C to 15 °C, then the life will increase by about 10%. Although the exact temperature/life relationship for deep-cycle batteries is not known, a similar relationship should hold because the degradation mechanism is the same as for float-service batteries.

Cycle-life of VRLA batteries is much more dependent on temperature, but the exact value of reduction in cycle-life is not known. However, it is known that the VRLA cycle-life reduction is greater than that of deep-cycle batteries for every 10 °C increase in battery temperature over 25 °C.

The capacity of all lead-acid batteries is affected by temperature. The capacity temperature relationship is not linear, but for most operating temperatures, a 1%/°C temperature/capacity relationship is acceptable. As the rated capacity is at 25 °C, the capacity increases above 25 °C and decreases below 25 °C by the specified

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amount. A capacity and temperature coefficient value is provided in IEEE Std 450™-1995 [B5] for stationary batteries.

Battery charge or regulation voltage needs to be adjusted by about –0.005 V/°C/cell as the battery temperature changes. The battery temperature compensation value for a specific battery is normally provided by the battery manufacturer. Above 25 °C, the regulation voltage needs to be reduced, and below 25 °C, the regulation voltage needs to be increased. Equation (B.1) is the formula for cell temperature-compensated regulation voltage:

$$V_r\text{/cell (Temp Comp)} = ((\text{Bat Temp} - 25\ ^\circ\text{C}) \times -0.005) + V_r\text{/cell @ 25 °C} \quad \text{(B.1)}$$

The need for temperature-compensated regulation voltage in PV systems occurs when battery temperatures deviate from 25 °C. Without temperature compensation, the lead-acid battery will not be fully charged at low temperatures and will be excessively charged at high temperatures.

B.3 Electrolyte management

Vented deep-cycle lead-acid batteries require addition of pure water to the electrolyte. Usually, water additions are required every one to six months depending on battery design and how old the battery is. Older batteries require more water. Only very rarely will vented batteries require more electrolyte. Electrolyte additions would only be needed if a cell leaks electrolyte. VRLA batteries generally cannot be watered and thus do not require any water additions.

Water consumption increases at higher battery temperatures and decreases at lower temperatures, and thus, maintenance should be increased or decreased accordingly. Most of the increased water loss is due to the lower electrolysis voltage at higher temperatures and the venting gas that carries with it the products of electrolysis and water vapor.

Electrolyte specific gravity is also affected by temperature and needs to be adjusted accordingly depending on both specific gravity and temperature. Because a temperature-compensated specific gravity measurement requires a specific gravity and temperature measurement, the coefficient for that specific gravity is usually obtained from a table. For example, at a measured specific gravity of 1.300 at 0 °C, the specific gravity needs to be adjusted downward by 0.000738/°C to 1.282 to obtain a reading at 25 °C. At 40 °C, the same temperature-compensated specific gravity would read 1.271. Specific gravity tables can be obtained from the manufacturer's installation and operation manual or battery textbooks (see Vinal [B8]).

Electrolyte stratification is caused when the heavier acid formed by the decomposition of sulfates on recharge migrates to the bottom of the battery and the lighter water/electrolyte mixture moves to the top of the battery. The nonuniformity in acid distribution causes unequal electrode utilization, reduced capacity, and premature electrode failure. If the gassing on recharge in vented batteries is limited by a low-regulation voltage or is cut short, then the required mixing of the electrolyte will not occur. Recovery requires extended heavy gassing of the battery for hours at voltages at or above 2.40 V per cell. Undersized PV arrays and/or low-regulation voltages are the major causes of battery stratification in PV systems.

In addition to the temperature effects, there are a number of other factors that need to be considered when measuring electrolyte-specific gravity. These factors include the state of charge of the battery, electrolyte water level, electrolyte stratification, and the cycle history of the battery. The most useful specific gravity data for a PV system are obtained just after a normal charge cycle when there has been a high solar resource period where the battery has recovered from any previous discharges. This measurement will provide an operational specific gravity, which should be near the manufacturers specified value for that battery. In cases where the electrolyte level is low, the measured value will be significantly higher than the specific gravity measured at a full electrolyte level. Manufacturers specify specific gravity at a full electrolyte level. All specific gravity

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measurements should be at the same water level to reduce measurement error. If specific gravity measurements are obtained at other than a high state of charge, then significant error can also be introduced as a result of stratification and sulfation.

B.4 Cycle-life

Lead-acid batteries designed for cycling applications usually have a manufacturer's rated cycle-life. The published cycle-life values are usually given at several different depths of discharge. The shallower the depth of discharge, the greater the cycle-life. It is important to understand that the rated cycle-life is usually measured under optimum conditions. If battery use is under less than optimum conditions, then the expected cycle-life may be less due to other battery degradation mechanisms. Cycle-life ratings for vented deep-cycle lead-antimony batteries range from less than 200 deep-cycles for light-duty batteries to over 1500 deep-cycles at 80% DOD for heavy-duty industrial motive power batteries. The wearout mechanism is generally positive plate grid corrosion. The biggest difference between batteries with low and high cycle-life ratings is the positive plate grid thickness. Battery cost is usually proportional to grid thickness, cycle-life, and capacity.

The cycle-life of properly maintained and installed VRLA batteries is generally less than 300 deep-cycles for light-duty batteries and less than 1200 deep-cycles at 80% DOD for heavy duty industrial VRLA batteries. VRLA battery cycle-life is usually limited by water loss and grid corrosion, but other degradation mechanisms may also limit cycle-life.

B.5 Battery coulombic or ah recharge efficiency

Battery coulombic efficiency is usually measured using the discharged Ah divided by the charged Ah. Lead-acid battery charge efficiency is affected by battery state of charge (SOC), battery design, battery grid alloy, charge rate, battery history, battery age, and cycle DOD. The charge efficiency for a discharged vented battery is initially about 99%, and as the battery approaches higher states-of-charge, the efficiency will drop off and approach zero near 100% SOC. There are significant efficiency differences between vented lead-antimony and VRLA batteries. This is due to VRLA battery design and grid alloy. As a rough comparison, vented lead-antimony batteries will be about 80% efficient and VRLA batteries will be about 90% to 95% efficient for 100% DOD cycles. This means that to recharge VRLA batteries requires about 105% to 110% more Ah and to recharge vented lead-antimony batteries requires about 120% more Ah. Most of the efficiency improvement in VRLA batteries is due to the grid alloy and the immobilized electrolyte in conjunction with the valve-regulated vent caps, which facilitate the oxygen recombination process and eliminates the need to mix electrolyte.

Efficiency is lower for vented batteries because of the electrolyte stratification and the required electrolysis on charge. In addition to stratification and electrolysis, the battery history can make recharge considerably less efficient. If the battery is left in a discharged condition, then other battery degradation mechanisms such as "hard" sulfation and degradation of the positive active mass will result in a slower capacity recovery. To recover the lost capacity requires considerably more overcharge than the normal recharge and therefore lowers charge efficiency. The exact efficiency value for a specific SOC will vary considerably depending on the above factors. Therefore, PV array sizing needs to be increased to accommodate these efficiency losses so that the battery can recover from extended periods in a discharged condition.

B.6 Charge acceptance

Charge acceptance is a term used to describe the rate at which the battery can be recharged. Charge acceptance is also related to the "ampere-hour law" (see Vinal [B8]), where the charging rate in amperes is

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kept below a value equal to the number of ampere-hours to be charged into the battery. Using the "ampere-hour law" for recharge, the battery should not gas excessively or overheat. Charging vented batteries in excess of the charge acceptance limit will tend to result in secondary reactions such as electrolysis and will not reduce the time required to return the battery to 100% SOC.

In PV systems, the charge rate is low, but the limited charge acceptance is still a factor when the battery reaches about 80% to 90% SOC. At this point, the charge current will usually be limited by the regulation voltage. Any excess current will only be used in electrolysis to gas the battery, which is needed for destratification of vented batteries. The charging current will continue to drop until the battery reaches 100% SOC, and then only the electrolysis or gassing current will be left. The time required to achieve 100% SOC would be an indication of charge acceptance and may be many hours. Another measure of charge acceptance is the number of Ah returned back to the battery within a fixed time period under a fixed voltage at a constant temperature. It is important to understand that in PV systems, it is necessary to ensure that there is an adequate PV array size to provide the battery with sufficient charge to recover from the previous discharge cycle.

B.7 Sulfation

Sulfation is the normal result of battery discharge when lead-sulfate forms on the surface and in the pores of the active plate material [see Equation (B.2)].

Positive Plate

$$PbO_2 + 4H^+ + 2e \Leftrightarrow Pb^{2+} + 2H_2O \quad \text{(B.2)}$$

$$Pb^{2+} + SO_4^{2-} \Leftrightarrow PbSO_4$$

Negative Plate

$$Pb \Leftrightarrow Pb^{2+} + 2e$$

$$Pb^{2+} + SO_4^{2-} \Leftrightarrow PbSO_4$$

Sulfation becomes a problem when large crystals of lead sulfate form on the active material as a result of inadequate charging and battery neglect or misuse. It is difficult, by charging, to decompose these large lead sulfate crystals in order to return their sulfate ions back to the electrolyte. This effectively reduces battery capacity and life. Large sulfate crystals may be detectable by a hard rough surface on the active plate material or a low specific gravity after an equalization charge. This is called excessive sulfation or "hard" sulfation.

"Hard" sulfation is caused by some of the following form of abuse:

— Allowing the battery to stand in a discharged condition for an extended period of time.

— Adding additional electrolyte to the battery cells instead of water.

— Operating the battery while consistently undercharging it.

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Temperature fluctuations while the battery is standing idle also play an important part in the growth of large sulfate crystals. When the temperature increases, the smaller sulfate crystals dissolve in the electrolyte, and when the temperature decreases, the sulfate solubility is lower and the crystals slowly grow larger again. The temperature swings promote the slow growth of large sulfate crystals that would otherwise be small and more easily dissolved into the electrolyte. An undersized PV array and/or low-regulation voltage will result in consistently undercharged batteries and "hard" sulfation in addition to other battery degradation processes.

B.8 Hydration

Hydration occurs when a lead-acid battery is overdischarged and left in the discharged condition for an extended period of time. Hydration is formed when lead is dissolved into solution with the water in the electrolyte that results from overdischarge. A hydrated battery will have a white film around and between the plates. This lead-hydrate film will inhibit charge, making the battery unrecoverable.

B.9 Mossing

Mossing can occur in vented cells where sloughed active positive material will circulate in the electrolyte and reform as negative material as it touches and adheres to the negative plate. A shorted cell may result when mossing occurs at the top of the cell and bridges its separators. This process is also referred to as treeing.

B.10 Battery mounting orientation

All vented batteries are required to be in the upright position, but VRLA batteries will operate in any position except upside down. The manufacturers of large industrial AGM VRLA batteries with plates over 0.4 m tall recommend that the battery be installed on its side. This reduces the height that electrolyte is required to wick up in the AGM and improves performance. Gel VRLA technology is unaffected by the mounting orientation.

B.11 Life-cycle considerations

To achieve the best cycle-life for a given application and battery requires the user to understand the battery design limitations, charge requirements, and maintenance requirements. Premature battery failures can generally be avoided by proper charge and/or installation and maintenance.

B.12 Battery thermal runaway

Under abnormal circumstances, battery thermal runaway can occur as a result of excessive charging at elevated temperatures. As the battery temperature increases, the electrolysis voltage drops, and this can result in excessive charge currents, which also increase the rate at which the internal battery heating occurs. As temperature control is an important consideration, any external heating such as that from direct sunlight should be avoided. Without proper charge control, which includes temperature-compensated regulation voltage, this process continues uncontrolled until the heat generated causes the plastic battery case to melt and vent, resulting in battery failure. Vented (flooded) batteries can dissipate heat much more effectively due to their excess liquid electrolyte, so the thermal runaway problem is predominately associated with VRLA batteries because of their limited ability to dissipate heat.

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Annex C

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PV system operational parameters

C.1 Battery charging

To prevent batteries in stand-alone PV systems from being undercharged, the charge regulation voltage must be set at the appropriate level, the PV array to load ratio must be sufficient, and/or the solar resource must be sufficient for the system design. Charging batteries is not simple and can be accomplished with many different charge profiles. As a rule of thumb, charging at a higher regulation voltage requires less time at regulation voltage and charging at a lower regulation voltage requires more time at regulation voltage. The time spent on charge below the regulation voltage is called the bulk-charge phase, and the time at regulation voltage is usually called the finish-charge or taper-charge or absorption phase of battery charging. PV systems operating during full sun periods may provide 2.5 h or less at regulation voltage every day, so most of the finish charge and, consequently, electrolyte mixing has to be done in that time period. The variations in the seasonal solar resource where the sun may be obscured during winter months or rainy seasons also need to be anticipated. In these low resource periods, the battery may not reach regulation voltage for weeks. This can seriously degrade the battery capacity even after an equalization charge.

The goal of battery charging is to return the battery to a high SOC each cycle to minimize the capacity degradation resulting from deficit-charge cycling. In addition to standard battery recharge, some battery applications will require an equalization or complete finish-charge at regular intervals to return the battery to 100% SOC. Battery recharge is dependent on battery technology and the cycle profile. These two factors will determine how the battery should be charged. The battery charging parameters include regulation voltage, charge rate, time at regulation voltage, battery temperature, temperature-compensated regulation voltage, and equalization or finish-charge voltages and times. The charge algorithm is a critical element in the performance of the battery; therefore, every effort should be made to use an acceptable charge algorithm for the battery and application. The important consideration for PV systems is whether the system is capable of recovering lost battery capacity from low solar resource periods during average solar resource periods. If the time that the battery spends recovering from a discharge is excessive, then permanent capacity loss will result. The maximum safe recovery time is very dependent on the battery design.

C.2 Battery equalization

An equalizing charge is intended to correct any capacity, cell voltage, and/or specific gravity inequalities that may occur during service. It is a prolonged charge usually at an elevated voltage. The frequency of equalizing charge is dependent on the battery, charge algorithm, and cycle profile. Many manufacturers recommend an equalization charge every one to two weeks for daily use deep-cycle motive power industrial batteries. VRLA batteries may also require equalization charges and may or may not require an increase charge voltage. Equalizing VRLA batteries is recommended by the battery manufacturer when cell voltages become unbalanced or when the battery is left discharged for an extended time. A typical equalization charge for a VRLA battery may require 24 hours at the standard or slightly elevated regulation voltage (2.35 or 2.40 V per cell). Therefore, VRLA battery equalization in PV systems may not be practical.

Some PV charge controllers have a preset equalization-charge function that is triggered based on lapsed time or battery voltage. Others have a manually triggered equalization-charge function. When these functions are engaged, they generally boost the battery charging voltage for one day. The charge controller needs to reach the equalization voltage to complete the equalization charge. In most cases, the PV charge

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controller equalization voltage is not as high, the time at equalization voltage is not as long, and the frequency of equalization charging is not as often as is recommended by the battery manufacturer. This is because of the limited charge current available with PV and the difficulty in using one equalization function for all PV systems and vented battery designs. Many PV systems may not be able to reach the normally high equalization voltage and spend the required time at voltage for a complete equalization charge, but even if equalization is not complete, the additional charge can be beneficial.

C.3 PV array to load ratio

The PV array to load ratio (A:L) is the average daily PV ampere-hours or watt-hours available divided by the average daily load ampere-hours or watt-hours. The A:L ratio is a very important PV system design parameter because it determines if there are sufficient charge Ah or Wh to recharge the battery during average solar resource periods. In low resource periods, the A:L ratio can be insufficient to charge the battery, and in high resource periods, it can result in excessive battery charging. An average daily A:L ratio of 1.3 for Ah or 1.4 for Wh can maintain the PV battery regulation voltage for about two to three hours every day. Some batteries may suffer permanent capacity loss as a result of the low A:L ratio during low resource periods. If battery performance problems arise after extended low resource periods, then battery recovery can be improved by increasing the A:L ratio.

C.4 Charge contollers

PV charge controllers are designed to prevent excessive battery charging. In addition to charge control, PV charge controllers may include equalization charge control functions, a LVD, a load control relay, a battery status indicator, a backup engine generator charge control relay, a PV power diverter to auxiliary load, and a wiring center. PV charge controllers will use one of three basic charge control methods, which are on/off, pulse width modulated (PWM), and constant voltage. All the above charge control methods will work well with vented batteries, but it's important to use the right regulation voltage for the battery and system design. Typically, VRLA batteries are more easily charged with PWM and constant voltage charge control. This is because of the difficulty in obtaining the correct time interval between the high-voltage disconnect and reconnect for on/off controllers. Rapid on/off cycling can cause the charge controller to malfunction if the reconnect voltage is too high or undercharge the battery if the reconnect voltage is too low. Usually, battery manufacturers do not provide recommended on/off setpoints, so determining the right setpoints can require some testing if the PV system has higher or lower than normal charge rates or has loads that operate while the PV is charging the battery. Generally, battery manufacturers do provide recommended constant voltage setpoints, which are also the same as PWM setpoints.

C.5 V_r setpoint

The V_r setpoint is the maximum voltage that a charge controller will allow the battery to reach under charging conditions. At this point, the charge controller will either discontinue charging or begin to taper the charging current to the battery. Most battery manufacturers will recommend constant voltage setpoints for charging their batteries in cycling applications. With vented lead-antimony batteries, there is considerable flexibility with respect to V_r setpoint. V_r setpoint values for constant voltage charging from 2.40 V per cell to 2.45 V per cell are common and in special cases can be set up to 2.55 V per cell depending on system and battery design. Higher regulation voltages will increase available capacity but increase water loss. VRLA battery designs require very precise voltage regulation at the battery manufacturer's recommended V_r setpoint. VRLA setpoints of 2.35 V per cell or 2.40 V per cell for cycle charging applications are most common. Increasing the regulation voltage above the manufacturer's recommended value may shorten the cycle-life of VRLA batteries due to an increased likelihood for venting and water loss.

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On/off controllers require two setpoint voltages, the array disconnect (V_r) and the reconnect voltage (V_{rr}). In most stand-alone PV systems using vented lead-antimony batteries, the array disconnect voltage should be between 2.45 and 2.50 V per cell and the array reconnect should be about 2.28 V per cell. The choice of the array reconnect voltage is dependent on the load profile and the switching speed of the PV charge controller. If there is a load current when the PV array reaches the disconnect voltage, then the reconnect voltage may be lowered to accommodate the rapid drop in battery voltage under load.

Most battery manufacturers do not recommend on/off charging for VRLA batteries, but many PV systems have successfully used on/off controllers if setpoints are appropriate. The key to successful implementation of an on/off VRLA charge controller is to set the array disconnect to about 0.02 to 0.05 V per cell higher than the recommended constant voltage regulation voltage and set the reconnect voltage to about 2.28 V per cell. For larger systems, on/off staged PV array shedding is quite effective in providing a taper charge for VRLA batteries. Table C.1 provides possible PV charge controller setpoints for VRLA, vented lead-calcium, and vented lead-antimony batteries (Woodworth et al. [B9] and Hund [B2])]

Table C.1—Default PV battery charge controller regulation voltages at 25 °C

Variable	Vented, Lead-Antimony[a]	Vented, Lead-Calcium[a]	VRLA, AGM[a]	VRLA, Gel[a]
V_r setpoint, V per cell (constant voltage or PWM)	2.40 to 2.50	2.45 to 2.55	2.35	2.35 to 2.40
V_r setpoint, V per cell (on/off disconnect)	2.45 to 2.50	2.50 to 2.55	2.40 to 2.42	2.40 to 2.42
V_{rr} setpoint, V per cell (on/off reconnect)	2.25 to 2.28	2.25 to 2.28	2.25 to 2.28	2.25 to 2.28
LVD, V per cell	1.90 to 2.00	1.90 to 2.00	1.90 to 2.00	1.90 to 2.00
LVR, V per cell	2.17 to 2.25	2.18 to 2.25	2.18 to 2.25	2.18 to 2.25

* This value has to be within the system's operating voltage limits.

C.6 Maximum system voltage

Many PV battery systems are nominally 48 V or less. Higher voltage battery banks are routinely installed and used successfully, but special care must be taken with these higher voltage battery systems to prevent cell imbalances, ground faults, and ensure electrical safety.

As the number of series cells in a battery increases (e.g. battery strings over 48 V), it becomes increasingly easier for individual cells to become charge imbalanced. As a consequence, the battery's cells can be at various states of charge, which will be reflected by cells having various voltages and available capacities. If not corrected, any imbalanced condition will continue to degrade with subsequent cycles, resulting in increasingly greater variation in cell voltages and, more importantly, cell available capacities. In any case, the battery manufacturer should be consulted for corrective action. One bad cell can damage the entire battery bank. To prevent this requires cell voltage monitoring at regular intervals and appropriate action when a bad cell is identified. There are a number of probable causes for battery string cell imbalances that could include a weak cell, high-resistance connection, and consistent undercharging. If repair of the connection and/or an equalization charge does not recover the cell, then cell replacement is possible in some cases where the battery string is relatively new.

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Electrical safety at higher battery voltages requires electrically shielding all exposed battery terminals and using electrical disconnects, fuses, and circuit breakers rated for the maximum DC battery voltage (NFPA-70 [B1]).

C.7 Ground faults

The higher the battery voltage, the more impact existing battery string ground faults have on the system. Ground faults can result in battery fires and explosions due to the electrical heating of a current path to ground. Preventing ground faults requires good battery installation and maintenance practices. Battery maintenance includes the following:

— Removing corrosion and electrolyte vapor deposits on the top surface of the battery
— Ensuring that there are no conductive surfaces to ground near the terminals
— Using nonconductive battery trays or cases, particularly for systems over 48 V
— Using appropriate battery vent caps with flame arresters to minimize the possibility of fire and/or explosions

Ensuring adequate standoff or separation between battery terminals and grounded support structures is critical. Electrolyte mist will deposit on battery surfaces, reducing the electrical resistance to ground. If electrically conductive and grounded battery trays are used with vented cells, then the possibility of ground faults is greatly increased. Section 690.71(D) of the National Electric Code® NEC® prohibits the use of conductive cases for vented lead-acid battery systems operating above a nominal 48 V (24, 2 V cells) (NFPA-70 [B1]).[5] Conductive racks may be used for these systems provided no rack material is within 150 mm of the tops of the cells.

For VRLA batteries, the conductive electrolyte is well contained within the battery and usually does not form on the battery surface. The improved electrolyte containment allows VRLA batteries to be used in conductive trays or racks over 48 V. VRLA batteries do leak electrolyte on occasion, so every effort should be made to keep these batteries clean and minimize electrically conductive support structures near the battery terminals. In many higher voltage battery banks, ground fault detection equipment is an important safety feature that can warn personnel when excessive leakage currents are occurring and a ground fault is pending.

C.8 Depth of discharge

Depth of discharge (DOD) is the percentage of discharged Ah per cycle relative to rated battery capacity. Most applications only cycle the battery to a maximum of 80% DOD or less. PV systems will usually cycle the batteries daily between 10% and 20%, but in low solar resource periods, the battery may cycle to the LVD. LVD is usually set between 1.9 V per cell and 2.0 V per cell for discharge rates higher than the 35 h rate. The above LVD setpoints will discharge the battery between 50% and 95% DOD. It is also important to adjust the LVD voltage upward to prevent overdischarge if discharge rates are much lower.

C.9 Temperature effects

PV systems are installed all around the world in hot and cold climates, and as a result of these climate variations, batteries in these systems need to be cared for appropriately. It is unlikely that PV batteries will be installed in systems where there is extra power for heating and air conditioning, so some battery temperature extremes are unavoidable. If the battery temperature deviates from 25 °C significantly,

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temperature-compensated regulation voltage is a recommended feature of the PV charge controller. Additional cost-effective measures for battery temperature management include insulating the battery enclosure, partially or completely burying the battery enclosure, and ensuring that the battery or enclosure is not exposed to direct sunlight or cold drafts. It is also important to understand that VRLA batteries are much more sensitive to temperatures over 25 °C. Many times just using a more heat-tolerant battery such as a vented lead-antimony battery is a good solution to the potential cycle-life limiting effects of higher operating temperatures on VRLA batteries. Vented lead-acid batteries can be operated at temperatures between -10 °C and 40 °C, but every effort should be made to maintain battery temperature near 25 °C when possible. This prevents freezing of the electrolyte, excessive grid corrosion and improves performance. VRLA batteries, on the other hand, are much more tolerant to cold temperatures because if the electrolyte freezes, it is unlikely to crack the battery case, but at temperatures near 35 °C, VRLA batteries are near their recommended high-temperature limit.

C.10 Autonomy

Autonomy is the number of days a PV battery will carry the load without energy from the PV array. The number of days of autonomy is a function of the acceptable loss of load probability and the weather patterns. Although many stand-alone PV systems are designed with five days of autonomy, some critical load systems (e.g., telecommunication) feature batteries with ten or more days of autonomy. Typical autonomies range from 5 to 25 days. Several factors go into this design guideline, including the length of typical cloudy periods and the practical limits for system component sizing. Low insolation days in locations where PV is used will usually last less than five days. Excessive autonomy can make it difficult to charge the battery and can increase system cost with an oversized battery.

C.11 Geographical site location

Geographical site location issues generally include weather patterns, minimum and maximum temperatures, and earthquake zones. If the weather patterns are such that there are seasonal patterns of low solar resource, then the load may have to be disconnected or greatly reduced during that time period. In very cold or very hot climates, the batteries should be insulated or installed underground to protect them from extreme temperatures. In earthquake zones, the batteries need adequate support as required by the local building codes.

C.12 PV battery end-of-life

In stationary float service applications, battery end-of-life is generally defined when battery capacity drops to less than 80% of its rated value. If this requirement was applied to stand-alone PV systems, many batteries would be at end-of-life shortly after installation. End-of-life for PV batteries is not well defined. In most stand-alone PV applications, the battery end-of-life is defined when the battery fails to meet the daily loads of the system during good solar resource periods. Battery failure can be due to undercharging, excessive loads, system component failures, or normal battery wearout. Excessive loads and/or system component failures will usually result in undercharged batteries with associated capacity loss. If the battery is continually undercharged, then “hard” sulfation, stratification, negative plate grid loss, and other degradation mechanisms in the positive active mass will result in permanent premature capacity losses. Battery recovery after continued under charging may or may not be possible by equalization. Normal wearout also results in capacity loss from the traditional mechanisms of positive grid corrosion and positive active material shedding. When this occurs, the battery can experience excessive positive plate growth or bulging and cell shorting.

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