IEEE Guide for the Selection and Sizing of Batteries for Uninterruptible Power Systems

Sponsor

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IEEE Power Engineering Society

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Abstract: The characteristics of the various battery energy systems available are described so that users can select the system best suited to their requirements. This guide also describes how the rectifier and the inverter components of the uninterruptible power system (UPS) can relate to the selection of the battery system.
Keywords: flooded cell, hydrogen evolution, lead-acid battery, nickel-cadmium battery, Planté plate, uninterruptible power system (UPS), valve-regulated lead-acid (VRLA) cell, vented cell

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Introduction

(This introduction is not a part of IEEE Std 1184-1994, IEEE Guide for the Selection and Sizing of Batteries for Uninterruptible Power Systems.)

Our society's increasing dependence on computerized information has resulted in the expanded use of uninterruptible power systems (UPS) to ensure the integrity of essential power systems. These systems require that stored energy be available to maintain operation. Although rotating inertia has at times been used to store this energy, batteries remain the preferred method of energy storage for this purpose.

An array of battery designs and extensive technologies are available to the user. This guide is intended to inform the user of the various battery technologies available and some of the design points to be considered when selecting a battery for UPS applications. Some of the battery design options that result in volumetric efficiency may also result in reduced life. This guide can help the user to become aware of which designs and operating procedures can result in optimum battery life.

This guide is intended to be used along with IEEE Std 485-1983, IEEE Recommended Practice for Sizing Large Lead Storage Batteries for Generating Stations and Substations; IEEE Std 484-1987, IEEE Recommended Practice for Installation Design and Installation of Large Lead Storage Batteries for Generating Stations and Substations; IEEE Std 450-1995, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications; and IEEE Std 1106-1987, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Nickel-Cadmium Storage Batteries for Generating Stations and Substations.

This guide was prepared by the Task Force on Battery/UPS Interface, a sub-organization of the Station Batteries Working Group, Station Design Subcommittee of the Energy Development and Power Generation Committee of the IEEE Power Engineering Society. At the time this guide was approved, the Task Force had the following membership:

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Contents

CLAUSE PAGE

1. Scope ... 1

2. References ... 1

3. Definitions ... 2

4. Lead-acid battery technology ... 3

   4.1 Cell construction ... 4
   4.2 Vented lead-acid batteries ... 10
   4.3 Valve-regulated (sealed) lead-acid batteries ... 11

5. Nickel-cadmium battery technology ... 12

   5.1 Cell construction ... 13
   5.2 Plate construction ... 14
   5.3 Vented nickel-cadmium batteries ... 15
   5.4 Sealed nickel-cadmium batteries ... 15

6. Service life considerations ... 15

   6.1 Lead-acid cells ... 15
   6.2 Nickel-cadmium cells ... 17

7. Selection and sizing of UPS batteries ... 19

   7.1 Operating considerations ... 19
   7.2 Specific considerations—Lead acid ... 20
   7.3 Specific considerations—Nickel cadmium ... 21
   7.4 Warranty considerations ... 22

8. Sizing examples ... 23

   8.1 Sample application: Three-phase UPS ... 23
   8.2 Operating conditions ... 23
   8.3 Voltage drop/cable sizing ... 23
   8.4 Lead-acid calculations ... 24
   8.5 Nickel-cadmium calculations ... 26

ANNEX

Annex A (informative) Effects of elevated electrolyte temperatures on commercial, vented lead-acid batteries applied to uninterruptible power system service ... 28

Annex B (informative) Effects of annual temperature variations for vented lead-acid cells on total battery life ... 29

Annex C (informative) Seismic requirements ... 30

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IEEE Guide for the Selection and Sizing of Batteries for Uninterruptible Power Systems

1. Scope

This guide is intended to assist users who select battery systems for uninterruptible power systems (UPS). The guide informs users of the characteristics of the various battery energy systems available so they can select the system best suited to their requirements. This guide does not place any restrictions on the rectifier or inverter components of the UPS. It does, however, describe how those components can relate to the selection of the battery system.

This guide divides the available technologies into the following two main categories:

a) Lead-acid batteries, which include both vented (flooded) and valve-regulated (sealed) constructions
b) Nickel-cadmium batteries

For each category, both the technology and the design of the battery are described in order to facilitate user selection. The specific advantages for particular applications are also listed.

Several battery designs are available to the UPS user. Each design has advantages and disadvantages, all of which should be considered when selecting a battery.

2. References

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

ANSI/NFPA 70-1993, National Electrical Code® (NEC®).[1]

IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).[2]

IEEE Std 450-1995, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications.

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[1]NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA.

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IEEE Std 1106-1987, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Nickel-Cadmium Storage Batteries for Generating Stations and Substations (ANSI).

IEEE Std 1115-1992, IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Applications (ANSI).

UL 94-1991, Tests for Flammability of Plastic Materials for Parts in Devices and Appliances.[3]

UL 924-1990, Emergency Lighting and Power Equipment.

UL 1778-1992, Uninterruptible Power Supply Equipment.

Uniform Building Code™, 1991 ed., International Conference of Building Officials (ICBO).[4]

3. Definitions

The following definitions apply specifically to the subject matter of this guide. For other definitions, refer to the standards listed in clause 2.

3.1 crazing: The small internal cracking around a point of mechanical stress that sometimes occurs in plastics.

3.2 cycle: A battery discharge followed by a complete recharge. A deep (or full) cycle is described as the removal and replacement of 80% or more of the cell's design capacity.

3.3 cycling: The repeated charge/discharge cycle of a storage battery. Some batteries are rated by their ability to withstand repeated, deep discharge cycles.

3.4 float service applications: Storage batteries applied for reserve use and maintained at a continuous "float" voltage point selected to just exceed the batteries' internal (self-discharge) losses.

3.5 flooded cell: A liquid electrolyte filled vented cell.

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

3.7 thermal runaway: A condition that is caused by a battery charging current that produces more internal heat than the battery can dissipate. This condition ultimately causes cell venting and premature failure.

3.8 valve-regulated lead-acid (VRLA) cell: A lead-acid cell that is sealed with the exception of a valve that opens to the atmosphere when the internal gas pressure in the cell exceeds the atmospheric pressure by a pre-

[3]UL publications are available from Underwriters Laboratories, Inc., 333 Pfingsten Road, Northbrook, IL 60062-2096, USA.

[4]ICBO publications are available from the International Conference of Building Officials, 5360 S. Workman Mill Road, Whittier, CA 90601, USA.

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selected amount. VRLA cells, sometimes called recombinant cells, provide a means of recombination of internally generated oxygen and suppression of hydrogen gas evolution to limit water consumption.

3.9 vented cell: A cell in which the gaseous products of electrolysis and evaporation are allowed to escape into the atmosphere as they are generated.

4. Lead-acid battery technology

The lead-acid battery is one of the oldest rechargeable (secondary) battery technologies in existence. A number of designs have evolved to meet specific design objectives and applications.

a) *Components*. Lead-acid batteries have an acidic electrolyte solution of sulfuric acid (H_2SO_4). The active plate materials are lead dioxide (PbO_2) for the positive electrode and sponge lead (Pb) for the negative. The active materials for both the positive and negative electrodes are incorporated in a plate structure composed of lead or a lead alloy.

   The electrolyte, a solution of sulfuric acid and water, is an active component in the overall cell reaction. Its concentration depends on the battery design. On discharge, lead sulfate ($PbSO_4$) is formed at both the positive and the negative plates, and the concentration of sulfuric acid in the electrolyte is reduced as sulfate ions are consumed and water is generated.

   During recharge, the lead sulfate is converted back into lead dioxide at the positive plate and sponge lead at the negative. Towards the end of recharge and during float operations, oxygen and hydrogen are generated at the positive and negative plates, respectively.

b) *Voltage*. The fully charged lead-acid cell has an open circuit voltage of approximately 2.10 V, which varies as a function of cell specific gravity and temperature. Open circuit voltage increases with specific gravity and decreases with temperature, and may range from 2.06 to 2.15 V/cell. Float voltages range from 2.15 to 2.40 V/cell, depending on their individual cell designs, temperature, and manufacturer recommendations.

c) *Design*. Lead-acid battery designs are available for the following three standby applications:

   1) Long duration (i.e., telecommunications or low rate) batteries are designed for applications in which the standby loads are relatively small and the battery is required to supply these loads for a minimum of 3 h. Long duration batteries are characterized by thicker plates and lower specific gravity electrolytes. The typical discharge duration is 8 h.

   2) General purpose (i.e., switchgear and control) batteries are similar to the long duration battery, but have additional design features to improve conductivity. In UPS applications, this design is best suited for discharge times of 1–3 h.

   3) Short duration (i.e., UPS or high rate) batteries are designed to supply large amounts of power for a relatively short period of time. Short duration batteries are typically characterized by thinner plates and higher specific gravity electrolytes. These batteries are best suited for applications requiring reserve times of 1 h or less. The typical discharge time is 15 min.

In addition to these designs that typically serve standby or float service applications, there are batteries available for a variety of other applications. For example, motive power batteries (used in fork lifts, golf carts, etc.) have a unique construction designed to withstand the physical abuse of constant movement and vibration, and to withstand hundreds if not thousands of discharge/recharge cycles. Motive power batteries are rarely used for UPS applications.

Another design is the starting-lighting-ignition (SLI) battery for automotive application. There are also designs that have been adapted to special applications [e.g., those that must be performed under extreme

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temperatures, those that require a specific charge/discharge capability, or those involving a limited space with seismic requirements (see annex C)].

Note—All batteries should be recycled.

4.1 Cell construction

The smallest unit of a lead-acid battery is the cell. In its simplest form, a cell consists of a physically separated positive and negative plate assembled in a container with a sulfuric-acid electrolyte.

The lead-acid cell has the following five basic components:

a) Container
b) Positive plate(s) of lead dioxide
c) Separator/retainer
d) Negative plate(s) of sponge lead
e) Electrolyte of sulfuric acid

These components may be designed and implemented in various ways to optimize performance for specific applications.

The performance of a cell is typically optimized through variations in grid alloy and geometry, separator material type and thickness, retainer existence and design, terminal design, and electrolyte specific gravity.

4.1.1 Plate constructions

Lead-acid batteries are described by their plate construction and the metal alloys (if any) that are used to strengthen the plate grid structures. Several designs have been created to improve performance characteristics, including cycling and life expectancy. Each design, however, places its own constraints on cell operation.

4.1.1.1 Flat plate

Of the lead-acid designs, the pasted flat plate (see figure 1) is the most common. The active material is formulated into a paste mixture, which is applied to a lead alloy grid. This grid structure provides many interconnecting current paths to the plate terminal. The plates are installed vertically in the cell.

The typical pasted flat plate is mostly used in full float applications. Cycling can be improved by the addition of plate material retention devices (see 4.1.3).

Pasted flat plates are manufactured with grids of varying thickness (see 4.1.1.7).

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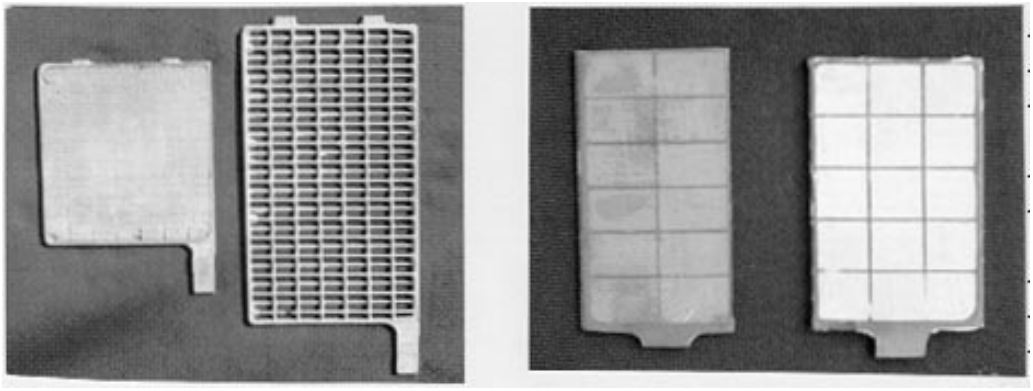


Figure 1—Examples of pasted flat plates

4.1.1.2 Planté plate

The Planté positive plate (see figure 2) uses a thick, pure lead casting that is attached to an antimony alloy lead connecting strap. The surface of the plate becomes the active material, and both sides of the plate are configured to increase the surface area.

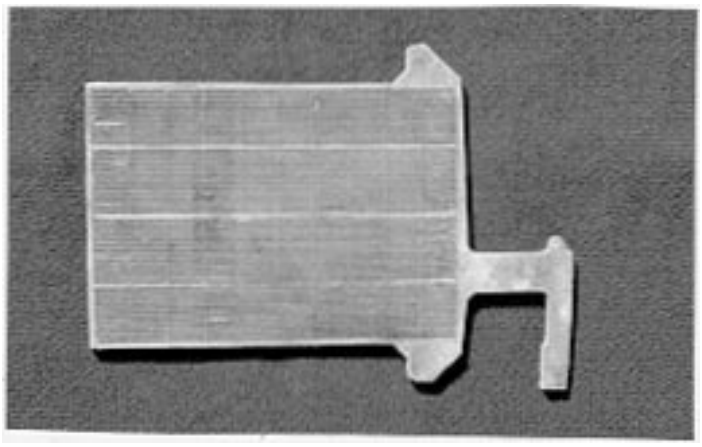


Figure 2—Planté plate

4.1.1.3 Modified Planté plate

The modified Planté positive plate design (see figure 3) uses a thick antimony alloyed lead grid with cast holes into which coiled, corrugated pure lead strips have been pressed. Like the Planté design, the surfaces of the lead strips become the active material.

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Both Planté designs provide a very long float service life and are capable of many charge/discharge cycles. They can be used for high-rate, short-discharge applications, but may require more floor space than other designs.

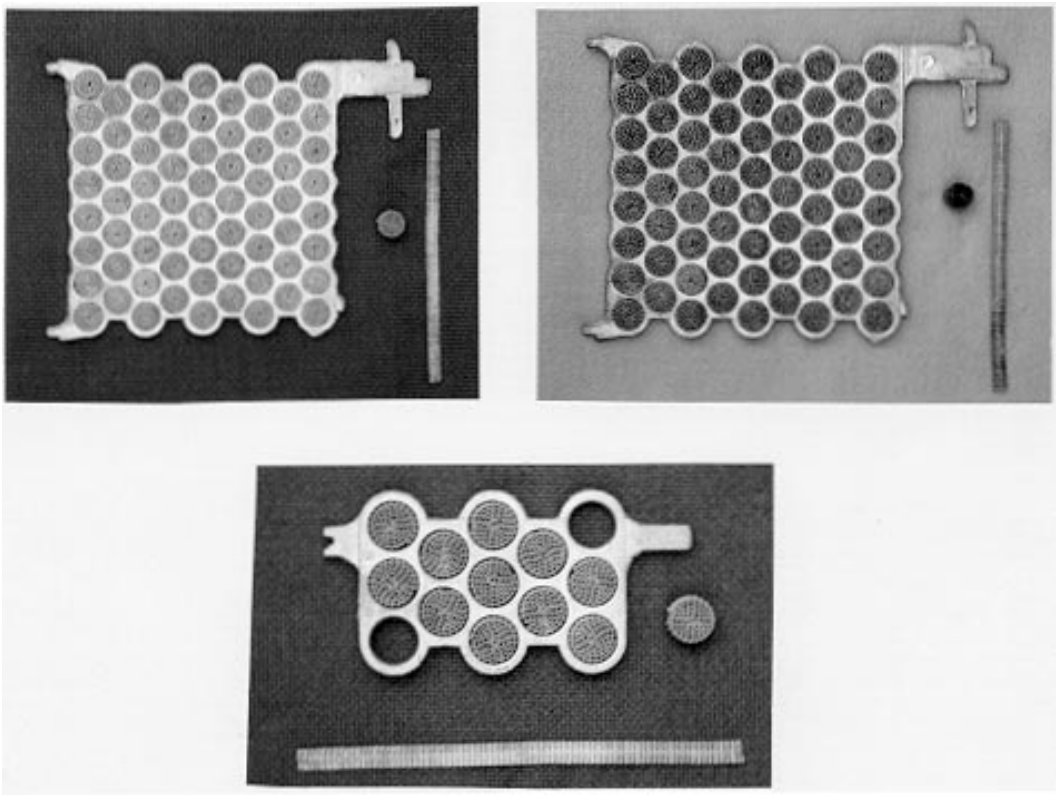


Figure 3—Examples of modified Planté plates

4.1.1.4 Round plate

Round plate construction (see figure 4) is a variation of the pasted flat plate design. In the round plate design, the active material paste is applied to a pure lead grid structure that is horizontal, round, and slightly conical. Like the pasted flat plate, the round plate is designed for float service applications and will exhibit similar charge/discharge cycling capabilities. However, its high-rate, short-duration discharge performance is less than that of most flat plate designs.

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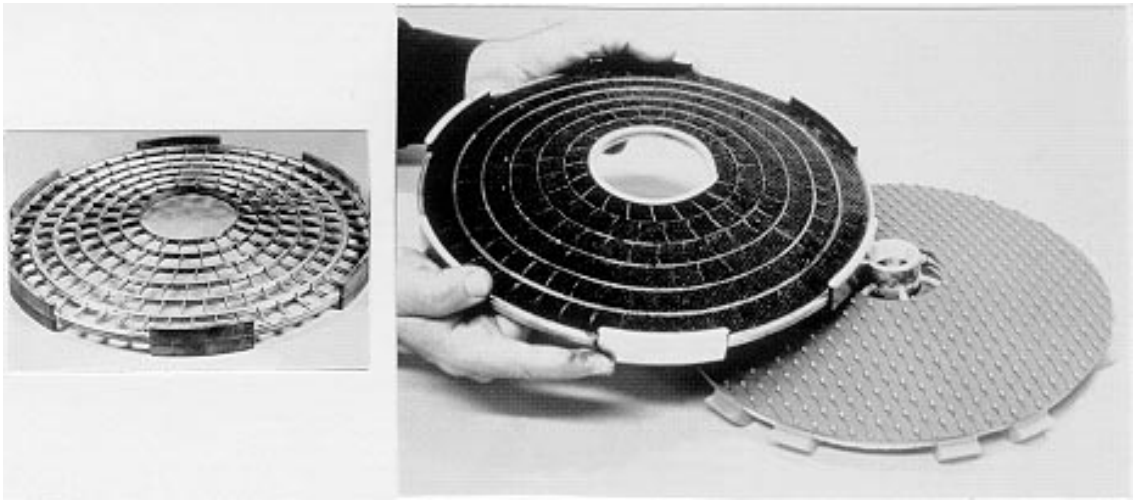


Figure 4—Examples of round plates

4.1.1.5 Tubular plate

The tubular plate design (see figure 5) involves a positive plate arrangement that 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. Flooded cells with tubular positive plates can be used for high-rate, short-discharge applications, but their rather poor high-rate performance will require a larger capacity to be used.

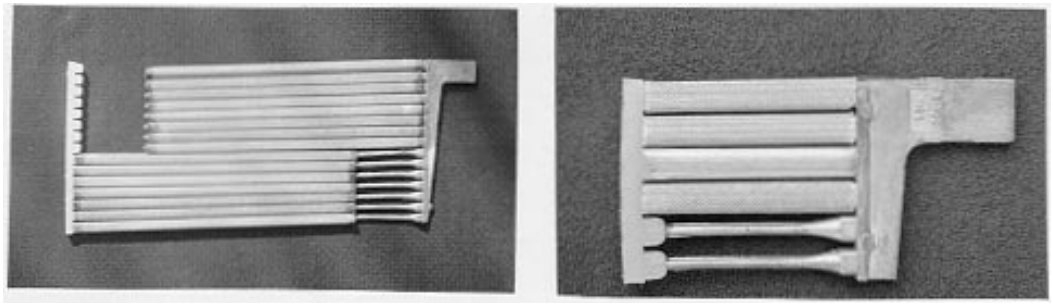


Figure 5—Examples of tubular plates

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4.1.1.6 Negative plate construction

With the exception of the round plate, flooded lead-acid batteries (using the positive plate designs described previously) use a negative electrode that is a pasted flat plate. Batteries with round positive plates employ pasted round negative plates.

4.1.1.7 Plate thickness

As a lead-acid battery discharges, the active material on both the positive and negative plates is converted to lead sulfate. In pasted plate designs, this conversion process occurs slowly, first converting the active material on both flat surfaces of the plate, and then converting the material behind those surfaces, gradually reaching the interior of the plate from both sides. Batteries designed for 8 h, low-rate discharges usually have thick plates since the slow discharge allows full advantage to be taken of the active material near the center of the plate.

In order to meet the UPS demand for high-rate, short-term energy, the battery manufacturers expose the maximum plate surface area to the electrolyte by providing many thinner plates per cell, rather than the fewer thick plates that would be found in a battery designed for a longer (8 h) discharge rate. The disadvantage of the thinner plate construction is that the positive plates tend to fail from positive plate corrosion sooner than the heavier thick plates.

4.1.2 Grid types

Lead is the primary component of battery grids. However, since lead is a soft metal, the grids are generally alloyed with a hardening metal so that they can support the plate element in the cell jar. The most common grid alloys are

a) Lead calcium grids
b) Lead antimony grids
c) Selenium/cadmium grids
d) Pure lead grids
e) Hybrid grids

4.1.2.1 Lead calcium grids

Cells with calcium alloy grids require very low float currents to keep them at full charge, which results in very low gassing rates and water consumption. These cells usually require a higher float voltage than those with other grid designs.

Calcium cells function well under float conditions, but might be less suitable when frequent deep discharge service is required. When used in UPS service, excessive testing of the system (resulting in frequent battery discharges) should be avoided.

Lead calcium grid cells are typically recommended where shallow moderate cycling is expected (see 6.1.2).

4.1.2.2 Lead antimony grids

Grids alloyed with antimony are used in applications where frequent cycling and/or deep discharge service is required. Antimony content varies among manufacturers from 1–8%. High antimony grids (above 9%) are rarely used.

Float charge current, gas evolution, and watering frequency are proportional to the antimony content of the grids. Furthermore, as antimony grid cells age, releasing increasing amounts of antimony to the electrolyte,

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float current, water consumption, and hydrogen evolution increase due to interaction of the dissolved antimony with the negative plate.

4.1.2.3 Selenium/cadmium grids

Lead grids alloyed with selenium or cadmium and a very low level of antimony (about 1%) yield a grid that has good cycling service but virtually eliminates the antimony migration that can raise the float current and water consumption as the cell ages (see 4.1.2.2).

4.1.2.4 Pure lead grids

Positive grids made from pure lead can avoid some of the life-degradation properties associated with hardening agents in other alloy systems. Float, cycling, and water additions are comparable to calcium systems. Pasted plate cells with pure lead grids should not be confused with Planté type cells (see 4.1.1.2 and 4.1.1.3).

4.1.2.5 Hybrid grid designs

Generally, battery cells employ positive and negative grids of the same alloy (except for the Planté cell, which normally uses lead antimony negative plates). In so-called “hybrid” designs, the positive and negative grids are fabricated from different alloys. Antimony-based alloys are generally used for the positive grids and calcium-based alloys are generally used for the negative grids.

4.1.3 Separators and retainers

A separator is a porous nonconductive inert material designed to prevent the positive and negative plates from physically coming into contact with each other. The separator also prevents conductive bridges (dendrites) of active material from forming between the plates and short-circuiting the battery.

A retainer is a porous mat of inert material (typically fiberglass) that is either pressed between the plates or wrapped around the positive plate, depending on the anticipated use of the battery. A retainer helps to minimize the tendency of the positive active material to shed or slough off the plate during discharge and recharge. Many UPS batteries have no retainers to permit closer plate spacing, lower impedance, and higher short-term discharge rates.

4.1.4 Electrolyte

The electrolyte is a mixture of sulfuric acid and water. Pure sulfuric acid has a specific gravity of 1.835, while the diluted solution used for electrolyte is typically in the range of 1.210 to 1.300.

The acid reacts with the active materials of the plate during discharge, forming lead sulfate ($PbSO_4$) and producing power.

4.1.5 Plate element support

The method used to support the plate element is an important aspect of cell design. Because the positive plates in the lead-acid system tend to physically grow larger during their service life, their support must be designed to preclude either undue internal stress or excessive pressure on the container itself, which would result in crazing or breakage. Often this is accomplished by allowing the positive plate to be constrained only at the point where it attaches to the internal positive strap.

The plate element should also be constrained to prevent undue stress on the container caused by external movement during shipment or if the battery is to be applied in an area of seismic activity (see annex C).

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4.1.6 Jars and covers

The battery components are enclosed in a jar that provides a durable, leakproof container for the electrolyte. A cover is bonded or welded to the jar, completing the enclosure.

Although covers are normally opaque, jars are often transparent to allow visual inspection of the cell element. Transparent jar materials include polystyrene (PS), styrene-acrylonitrile (SAN), polycarbonate (PC), and polyvinyl-chloride (PVC). However, not all flooded lead-acid designs utilize transparent jars. Some designs employ translucent polypropylene, and other designs use materials that are completely opaque (e.g., ABS plastic).

Whatever material is used, the primary requirement for vented cells is that the design enables the user to visually determine the electrolyte level of the cell. Valve-regulated cells do not normally use transparent containers since the electrolyte level is not variable and the internal cell components (e.g., the plates) are not visible for inspection. Otherwise, the jars and/or containers are similar to those used for flooded cells.

As an additional precaution, many jars and covers are also manufactured using flame-retardant materials, such as PC and PVC.

4.1.7 Jar-to-cover and post seals

Post seals are one of the most critical aspects of cell design. The integrity of the post seal has a direct bearing on the float life and performance of the UPS battery, and its construction should be carefully considered in relation to its intended application.

Poor seals can cause a number of serious problems such as electrical faults that result in fires and electrical shocks.

If the seals allow acid to creep up the post, oxidation will occur, which can lead to increased resistance at the connection or to corrosion of the post. This degraded conductivity will cause a drop in available capacity or, in severe cases, may lead to post meltdown. Violation of either the jar-to-cover or post seals may also result in venting cell gases without the precaution of the flame arrestor. In valve-regulated cells, this will lead to cell dry-out and premature failure.

4.1.8 Cell terminal posts

Typically the positive and negative terminals of all flooded lead-acid cells/modules are designed for bolted connections and are generally constructed of alloyed lead. To improve conductivity and optimize high-rate performance, some designs are provided with copper reinforcement.

Terminal posts with copper reinforcement provide tighter intercell connections, but if the copper is exposed to electrolyte it may result in additional post maintenance, and, in extreme cases, may contaminate the battery cell.

4.2 Vented lead-acid batteries

4.2.1 Electrolyte systems

Vented (flooded) lead-acid cells are constructed with the liquid electrolyte completely covering (flooding) the closely spaced plates. The electrolyte maintains uniform contact with the plates. Depending on plate thickness (among other factors) cells of this design can provide a very high, short-duration current due to their low internal resistance.

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4.2.2 Flame arrestor vents

Flame arrestor vents must be provided and installed for all flooded lead-acid cells. As vented lead-acid batteries reach full charge, an explosive mixture of hydrogen and oxygen is emitted through the vent. If the vent is not functioning as designed, a spark could explode the concentration of gas within the cell.

4.2.3 Hydrogen evolution

Since hydrogen could accumulate to an explosive mixture, the battery enclosure and/or room must be appropriately ventilated. The volume of the evolved hydrogen may be obtained from the manufacturer or calculated from the following formula (from IEEE Std 484-1987)[5]:

Maximum hydrogen evolution in ft^3/min = no. cells × 0.000269 × charge current

The worst condition exists when forcing maximum current into a fully charged battery. The amount of charging current required to maintain proper float/equalizing voltage is dependent on the grid alloy, cell capacity, and electrolyte temperature.

4.3 Valve-regulated (sealed) lead-acid batteries

Valve-regulated cells are sealed with the exception of a valve that opens periodically to relieve excessive internal pressure. These cells provide a means for recombination of charge gas to limit water consumption. This is accomplished by allowing oxygen evolved from the positive plate to pass across to the negative, where the recombination reaction occurs. The valve regulates the internal pressure to optimize recombination efficiency, hence the term “valve regulated.”

In a flooded electrolyte system, excess charging energy causes water to be broken down into hydrogen and oxygen, which are vented out of the cell; this lost water must eventually be replaced. In a valve-regulated system, hydrogen evolution is suppressed in normal operation. Charging above recommended manufacturer’s ratings or at elevated temperatures will result in venting of hydrogen and oxygen from the cell; prolonged over-charging will result in premature failure.

4.3.1 Absorbed electrolyte systems

Valve-regulated lead-acid (VRLA) cells of this design are constructed with a controlled volume of liquid electrolyte contained in a highly absorbent blotter-like separator positioned between closely spaced plates. This nonwoven separator distributes the electrolyte uniformly and maintains it in contact with the plate active material, while permitting the passage of oxygen evolved during charging. Due to their low internal resistance, cells of this design are able to provide a very-high-rate, short-duration current.

4.3.2 Gelled electrolyte systems

VRLA cells of this design are similar to flooded designs, except that the electrolyte has been “gelled” to immobilize it. Cells of this design can provide a high-rate, short-duration current, but because of the higher internal resistance they are not as effective as the absorbed electrolyte design. On the other hand, the additional electrolyte reserve found in gelled designs make them better suited for long duration applications than equivalent absorbed electrolyte cells. A gelled electrolyte cell is typically heavier and larger than an absorbed electrolyte cell for a given capacity.

[5]Information on references can be found in clause 2.

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4.3.3 Valve and flame arrestors

Whichever electrolyte immobilization technique is selected, this cell design will employ a pressure relief valve. This valve is designed to:

a) Limit the maximum pressure within the cell (0.5 to approximately 50 PSIG, depending on the design)
b) Prevent the oxygen of the atmosphere from entering the cell and discharging the negative plates

If this valve or other seals should fail, the cell would start to perform as a wet flooded cell, gas, and eventually dry out.

There are conditions of cell operation where explosive mixtures of hydrogen and oxygen may be present; therefore, flame arrestor vents should be provided.

4.3.4 Cell ventilation

Valve-regulated cells should be placed in a well-ventilated environment, and should not be placed in the heat flow of electronic equipment within the same enclosure.

Proper cell ventilation around the cell casing is recommended to reduce the possibility of thermal runaway.

Under normal recombination operation, valve-regulated cells periodically vent small amounts of hydrogen, and some hydrogen may also diffuse through the plastic case. Larger amounts of gas are emitted when the battery is overcharged. Under these conditions, use the same formula as specified in 4.2.3 to calculate the worst-case hydrogen evolution. Users should consult the manufacturers' specifications to determine whether additional ventilation is required for a particular application.

5. Nickel-cadmium battery technology

Nickel-cadmium batteries use an alkaline electrolyte (potassium hydroxide). The active materials are nickel hydroxide in the positive plate and cadmium hydroxide in the negative plate.

The electrolyte in the nickel-cadmium battery does not take part in the overall cell reaction, so the specific gravity does not change during charge and discharge. The electrolyte retains its ability to transfer ions between the cell plates, irrespective of the charge level, and also acts as a preservative of steel components in the cell mechanical structure.

The batteries are resistant to mechanical and electrical abuse, operate well over a wide temperature range, and can tolerate frequent shallow or deep discharging (see 6.2.8). These features may offer advantages for some UPS applications.

a) *Voltage*. The nickel-cadmium cell has an open circuit voltage of approximately 1.30 V and a nominal discharge voltage of 1.20 V. The manufacturers' recommendations indicate a range of float voltages of 1.38–1.47 V/cell and equalizing voltages of 1.47–1.65 V/cell, depending on their individual designs. Nickel-cadmium cells can tolerate very high charge rates without damage, and may be left off charge for years with no life loss.
b) *Capacity.* The cell can tolerate complete discharge with almost no permanent deterioration of capacity or life. Depending on the number of cells used, the typical end-of-discharge voltage in this application may vary from 1.00–1.10 V/cell. It is advisable to use the lowest end-of-discharge voltage and the largest possible number of cells that will satisfy the manufacturer's charging recommendations, since this will result in the most economic battery for the application (see clause 7).

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5.1 Cell construction

As with other battery types, nickel-cadmium batteries consist of a number of individual cells connected together in series (and sometimes in parallel). For most UPS applications, cell capacities range from as little as 5 to over 1500 Ah (see 5.4). In addition to consisting of individual cells, nickel-cadmium batteries are often available using multicell units with 2–10 or more cells per container.

Several designs of vented nickel-cadmium batteries are available, depending on plate construction. The most commonly used designs are the pocket plate, the fiber plate, the sintered plate, and the plastic bonded plate (see 5.2).

Although most nickel-cadmium batteries for the UPS application are vented, sealed cells and other special designs are also available (see 5.4). The type of cell chosen depends on the application load current, voltage window, and discharge time required.

5.1.1 Separators and retainers

Separators in nickel-cadmium cells provide physical and electrical isolation of the positive and negative plates. In many cases, the separators have an open construction, using plastic rods or grids, or corrugated plastic sheets with large perforations. Some newer plate designs, in which the active material is on the exposed plate surface, use microporous plastic separators to prevent conductive crystal bridges (dendrites) from forming between the plates.

Because the active materials in nickel-cadmium cells are not normally prone to shedding, retainer mats are not used.

5.1.2 Jars and covers

Nickel-cadmium cells generally have jars and covers made of plastic. For especially harsh conditions, cells with stainless steel cases are also available. Most containers are made of translucent polypropylene, which allows the user to monitor electrolyte levels. The cover is welded to the jar, ensuring an impermeable, secure joint.

Other container materials include high impact PS, SAN, and butadiene-reinforced styrene. For installations where low flammability is required, flame-retardant plastic materials or stainless steel are available.

5.1.3 Cell covers and post seals

Terminal posts are usually sealed with a gasket and O-ring. It is essential to have an effective seal, particularly for the negative terminal; otherwise, potassium carbonate, a gray-white powder, tends to form around the terminal.

Excessive buildup of potassium carbonate around the posts may cause grounding problems. Although post seal leakage does not cause terminal post corrosion or degradation of electrical connections, it is important to keep the post exterior clean.

5.1.4 Cell connections

The intercell connectors are made of nickel-plated copper. The nickel plating on the copper should be impermeable. Nickel-plated or stainless steel nuts or bolts are generally used for the connections.

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5.1.5 Plate thickness

Nickel-cadmium cells are designed with varying plate thickness. For long-duration, low-discharge rates, thick plates (3–4 mm) are used. Medium rate cells, used in applications where a combination of high and low discharge currents are required, have thinner plates (2–3 mm). For short-duration, high-rate performance, which depends more on the active plate surface available rather than the total amount of active material, thin plates (0.8–1.5 mm) are used.

5.2 Plate construction

Nickel-cadmium battery types are normally characterized by their plate constructions. Differences between the various types can be seen in high-rate performance, cycling capability, and physical size and weight.

5.2.1 Pocket plate

Pocket plates consist of interlocking pockets of perforated, nickel-plated steel strips, which are pressed around the active materials to provide a current path and to reduce shedding. The plate is sealed in a steel frame and welded or bolted to the current collectors and terminal posts. All mechanical parts and connections in the cell are made of steel.

To improve the battery's performance, additives are combined with the active materials. Graphite is added to the positive plate for improved conductivity, while an expander (typically iron oxide) is added to the negative plate to stabilize capacity and enhance cycle life (see 6.2.2).

The separators are constructed of plastic, in the form of either rods or grids, or of perforated corrugated sheets.

5.2.2 Fiber plate

Fiber plates are formed from a mat of nickel-plated fibers impregnated with the active materials. The plated fibers are welded to nickel-plated steel tabs connected to the steel terminal posts. The separators are usually made of perforated, corrugated plastic sheets, or microporous plastic.

In the fiber plate cell, no graphite or iron oxide is added to the active materials, which is an advantage if the battery is operated at very high temperatures and with repeated deep discharge cycles. Fiber plate cells may also offer advantages of increased capacity for a given size and weight.

5.2.3 Sintered plate

In the sintered plate, carbonyl nickel powder is sintered at high temperature to a current collector of pure nickel or nickel-plated steel. The resultant porous structure is then impregnated with the active materials. The plate pieces are welded to tabs, and connected to the steel terminal posts.

The sintered plate has excellent conductivity and high power density. Sintered plate designs are often used in small sealed cells, usually for portable consumer electronics, and in specialized batteries for aircraft applications. Sintered plates are also used in hybrid designs for industrial uses, including UPS (see 6.2.8).

5.2.4 Plastic bonded plate

In a plastic bonded plate, the active materials are combined with a plastic powder and a solvent to form a thick paste, which is extruded onto a strip of pure nickel or nickel-plated steel. The plate pieces are welded to tabs, and connected to the steel terminal posts.

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Positive plates with this construction have added graphite to improve conductivity (see 6.2.2), but unlike other designs, the plate element must be clamped to inhibit expansion of the positive plate during the charge/discharge cycle. Consequently, this design is used only for negative plates in hybrid cells.

The plastic bonded negative plates do not use iron oxide in the active material.

5.2.5 Hybrid designs

A combination of different plate types is sometimes used to optimize cell design, performance, and life for a particular application. One example uses a sintered positive plate with a plastic bonded negative to give good high temperature and cycling characteristics, and low weight and volume.

5.3 Vented nickel-cadmium batteries

5.3.1 Electrolyte systems

The specific gravity of the alkaline electrolyte ranges from 1.160 to 1.250. Lower specific gravities are used in cells with large electrolyte reserves, while higher specific gravities are used for low-temperature applications.

Since the electrolyte concentration does not vary with state of charge, frequent specific gravity readings are unnecessary.

5.3.2 Vents and flame arrestors

Cells are frequently equipped with flip-top vents to facilitate water addition. Alternative designs are threaded or bayonet-type vents. Flame arrestor vents are provided for all vented nickel-cadmium cells. Some manufacturers offer catalytic recombination vent caps to reduce maintenance. These should be correctly sized for the individual application and cell type.

5.4 Sealed nickel-cadmium batteries

Sealed nickel-cadmium cells are normally used in electronics and consumer equipment, such as cordless power tools. They are limited in capacity and are therefore used mainly in small UPS applications.

The cells are typically constructed from sintered or pasted electrodes that are wound together with a separator to form a cylindrical plate group. The cell container is completely sealed and no gas is released under normal operating conditions. Valve-regulated designs are also available for larger capacities. In construction they resemble vented cells, but also incorporate a special separator which allows charge gases to recombine.

6. Service life considerations

6.1 Lead-acid cells

Lead-acid cells are the predominant energy storage choice for UPS applications. Clause 6 alerts the user to the several factors that may affect the service life of lead-acid cells. As indicated below, many of these factors may be controlled through proper application, installation, maintenance, operation, and environmental control.

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6.1.1 Temperature

The battery charging current and corrosion rate of the positive grid advances exponentially with increased electrolyte temperature. Prolonged operation at elevated temperatures will shorten the life of the battery. Colder temperatures ensure longevity, but the slowed electrochemical reaction will reduce the available capacity.

For maximum efficiency, the battery should be maintained at its optimum temperature. Battery life and electrical performance are rated at a standard temperature of 25 °C (77 °F). During operation, the maximum spread of individual cell temperatures should not exceed 2 °C (5 °F) (per IEEE Std 484-1987). When charging at a fixed float voltage, the float current will increase with increasing temperature and decrease with decreasing temperature.

The VRLA cell is affected to a greater extent by temperature extremes than are vented (flooded) cells. To minimize the temperature effects and possible thermal runaway, the float charging voltage should be adjusted according to the temperature of operation. At elevated temperature, the float charging voltage should be decreased from that recommended at 25 °C (77 °F) by 0.005 V/cell per degree Celsius (0.003 V/°F) above 25 °C (77 °F).

At reduced temperature the float charging voltage may be increased 0.005 V/cell per degree Celsius (0.003 V/°F) below 25 °C (77 °F) from the voltage recommended at 25 °C (77 °F).

(Annex A shows the life reductions that may be expected from elevated temperatures and annex B shows how to calculate the effects of temperature variations on service life.)

6.1.2 Cycle service

A stationary lead-acid battery can survive more short-duration, shallow cycles than long-duration, deep discharge cycles. The user should understand that the very high, short-term discharge rates in the UPS application may result in discharge cycles of significant depth, and regulate maintenance testing schedules accordingly.

Various grid alloys and paste formulations affect the sensitivity of the cell to cycled service. Consider that short, nearly undetectable power dropouts, can, depending on UPS design, place the UPS load on the battery for a considerable period.

The cycle life of a grid design may be extended by either placing retaining mats against the positive plates or by enveloping the positives in a perforated container. This partial electrical isolation increases internal resistance, and will limit the rate at which power is withdrawn from the battery. It may also increase the required size of the battery.

The user should specify the extent of the cycle service that will be required.

6.1.3 Elevated float voltages

Float voltages in excess of that required to overcome the self-discharge rate of the cell will cause higher float currents and higher corrosion rates at the positive plates. The best float voltage is the value at which the battery remains in a fully charged state and that causes the least amount of corrosion and gassing.

Telecommunications cells with 1.215 nominal specific gravity electrolyte can float as low as 2.17 V/cell. However, this is accomplished by a rather expensive cell matching procedure, which assures that each cell in the series battery string will maintain its charge at this minimal point.

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Manufacturers generally recommend a 2.20–2.30 V/cell float for UPS applications, depending mainly on electrolyte specific gravity. The excess energy of float voltages above 2.30 V/cell increases the electrolysis of the water in the electrolyte, which not only requires more frequent water additions but also causes cell gassing. The free oxygen generated at the positive plates accelerates corrosion and will diminish the life of the cell.

6.1.4 Ripple currents

UPS applications can place unusual load conditions on a battery. Typically, UPS battery design seeks excellent short-term, high-rate current characteristics which in turn require the lowest possible internal cell resistance. This low resistance allows a lower impedance path for the ripple current coming out of the rectifier stage of the UPS than the filter capacitors in the output of the rectifier.

In addition, the inverter stage of the UPS requires large instantaneous dc currents as it builds ac power from the parallel rectifier/battery combination.

With a high impedance ac power source, short-term, instantaneous load current changes will be drawn from the lower impedance battery. These factors may result in a relatively high ac component in the battery. At present, manufacturers place no warranty penalties on vented cells operated in a high ripple current environment. However, ripple is an important consideration in effecting design life and it is advisable to maintain the rectifier filters as prescribed by the manufacturer.

Note—Ripple currents can cause overheating in VRLA batteries.

6.2 Nickel-cadmium cells

In nickel-cadmium cells there is no deterioration of the mechanical structure of the plates (as with lead-acid batteries). Consequently, there is no sudden loss of battery capacity or performance. Instead, cell aging relates to changes in the active materials, and capacity degradation is continuous over time.

6.2.1 Temperature

All batteries are affected by high temperatures. However, nickel-cadmium cells can sustain high temperatures more easily than most other systems because the chemistry in the active materials is relatively stable. For example, at 32 °C (90 °F) the normal life of a nickel-cadmium cell is diminished by about 20%, compared with a reduction of approximately 50% for a lead-acid cell.

Moreover, a nickel-cadmium battery will not be destroyed by low temperatures or freezing. With a normal electrolyte, the battery will operate at temperatures as low as –30 °C (–22 °F) to –40 °C (–40 °F); with a higher specific gravity electrolyte, it will operate at even lower temperatures. The available capacity is reduced at low temperatures, but at –40 °C (–40 °F) a nickel-cadmium battery can deliver 60% or more of rated capacity.

6.2.2 Carbonation

Potassium carbonate is formed in alkaline electrolyte when it is exposed to air, and also as a result of the oxidation of graphite when it is used as a conductive material in positive plates. Potassium carbonate buildup is rarely a problem in float service applications, unless the battery is operated at extremely high temperatures, or is deeply discharged on a frequent basis

The amount of carbonate should not be allowed to increase over the limits specified by the manufacturers. Carbonation may have an adverse effect on cell life and high-rate performance, particularly at low temperatures. A standard test method exists for determining the carbonate content of the electrolyte.

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6.2.3 Cycle life

Nickel-cadmium cells provide long-term cycle service for deep discharge applications. The gradual aging of the active materials, mainly due to recrystallization, influences the cycle life of the cell. There is no plate corrosion, shedding, or growth, as in lead-acid cells, so there is always some available capacity, even if it has been reduced.

To enhance cycle life and to reduce the adverse effect of high temperatures, various amounts of lithium hydroxide may be added to the potassium hydroxide electrolyte. The manufacturers specify the exact amount to be added.

6.2.4 Float charge

The float voltages recommended for nickel-cadmium cells are generally in the range of 1.38–1.47 V/cell. The manufacturer's recommended voltage will maintain a cell in a fully charged condition and minimize water consumption. Higher float voltages will result in increased water loss.

After extended float charging of a nickel-cadmium battery, it is normal to see a lowering of the average discharge voltage, compared with that of a battery that has been fully charged at constant current. This may affect the available capacity to a specified end-of-discharge voltage.

The data used in nickel-cadmium battery sizing calculations should be based on prolonged constant potential charging.

6.2.5 Equalizing charge

Recommended equalizing voltages range from 1.47–1.65 V/cell. To achieve reasonable end-of-discharge voltages, the equalizing voltage attainable in a specific application is normally restricted by system voltage limitations to about 1.55 V/cell.

Generally, equalizing is used for a fast recharge after a discharge, and to assist in electrolyte mixing after water addition (two rate chargers are generally recommended by the manufacturers). Depending on the float voltage chosen, routine periodic equalizing may be unnecessary.

6.2.6 Ripple currents

Nickel-cadmium cells are not adversely affected by significant amounts of ripple currents from rectifiers/inverters. The impedance of the cell is nearly constant from a fully charged state to an almost completely discharged state. Nickel-cadmium cells possess good filtering capability.

6.2.7 Gassing

After a vented nickel-cadmium cell has been brought to a full state of charge, additional charging results in the electrolysis of water to produce hydrogen and oxygen gas. As with other vented cells, the gas is vented from the cell in an explosive mixture that must be efficiently exhausted from the room. However, this gas is free from corrosive vapor, and it is usually unnecessary to provide a separate room for the battery.

6.2.8 Memory effect

In a limited number of applications, repeated shallow cycling to approximately the same depth of discharge may be associated with continual low-rate charging. This in turn may result in a premature voltage drop, if the discharge is continued past its normal termination point. The memory effect involves a loss of surface area in the negative active material due to the growth of large crystals. It may be avoided with proper charging techniques.

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The memory effect occurs mainly in cells with sintered negative plates charged at very low rates. These conditions are inapplicable in virtually all industrial applications.

A cell may have its memory erased by a complete discharge, followed by a full charge with constant current.

7. Selection and sizing of UPS batteries

The following subclauses provide an overview of the techniques and application considerations used to determine a battery size. IEEE Std 485-1983 and IEEE Std 1115-1992 offer more detailed information and procedures on the methods used for sizing batteries.

7.1 Operating considerations

An uninterruptible power system places a constant power load on the batteries, rather than the constant current load that is typical of other applications. Since the UPS maintains a constant ac output voltage into a constant load, the required power (in kilowatts) is constant. When the battery is supplying the system, the dc input voltage to the inverter stage of the UPS decreases slowly as the active materials in the battery are converted to the discharged state. To maintain a constant power output, the discharge current increases accordingly.

Long-duration, low-discharge rate batteries are rated in ampere hours, typically for an 8 h or a 20 h rate. For example, an 800 AH lead-acid, 8 h battery that can supply 100 A continuously for 8 h may supply 160 A continuously for 4 h (640 AH), or 350 A continuously for 1 h (350 AH). Discharging any battery at a higher rate reduces the available energy from the battery. High-rate, short-duration batteries sometimes do not have ampere hour rating specified. During a high-rate battery discharge, the battery current changes occur often enough to render constant current sizing charts unreliable. Many manufacturers now provide UPS battery sizing charts with kilowatt/discharge time parameters.

7.1.1 Design and aging margins

Although it is possible to size the battery for a smaller connected load, the UPS battery is generally sized to accommodate the full load capacity of the UPS.

The installed battery capacity should be adjusted so that the battery is capable of supporting the full UPS load at the end of the battery life. For example, a lead-acid battery has reached the end of its life when the available capacity drops to 80% of rated. Therefore, to ensure that the battery will support the fully loaded UPS for the entire battery life interval, battery size should be increased by a 25% margin.

7.1.2 Voltage window design

The UPS voltage window determines the voltage range over which the battery is allowed to operate. The number of cells in the battery should be chosen so that the battery may be adequately charged, while allowing an end-of-discharge voltage that results in efficient utilization of the battery's capacity (see 7.1.3).

When significant end-of-battery discharge currents must serve distant UPS loads, the planned battery end-of-discharge voltage should be increased to compensate for the voltage drop in the load cabling. These factors will be demonstrated in the example shown in clause 8.

The maximum allowable voltage of the UPS and other connected loads is the maximum voltage that may be applied to the battery. This voltage is generally used for high-rate charging (also called equalizing or boost charging). This allows for more rapid recharge after a discharge, and is able to correct deviations in

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individual cell voltages. For the latter purpose, a high-rate charge may be applied to the entire battery or to an individual cell.

The minimum allowable system voltage determines the final voltage to which the battery may be discharged. In general, it is more economical to select the number of cells in the battery that gives the lowest possible end-of-discharge voltage, provided that the battery may be charged in accordance with the manufacturer's recommendations within the maximum voltage limit for the system.

7.1.3 UPS charging limitations

When calculating the relation of battery size to the rectifier and inverter subsystems of the UPS, the user should consider the battery charging capability of the rectifier and the charge acceptance of the battery. The UPS system should minimize the discharge cycles imposed on the battery, caused by load changes exceeding the rectifier output or response capability.

In addition, the rectifier should be sized to meet the full system load, system loss, and transient requirements while providing battery recharge current, in order to minimize the period during which the load is not protected by a fully charged battery. Battery recharge is a function of charge acceptance, which is related to the battery technology selected and the importance of the load being fully protected following restoration of the normal ac supply to the rectifier.

7.1.4 Equalizing charge

An equalizing or freshening charge is given at a voltage higher than the float voltage for a selected length of time necessary to correct deviations from the manufacturer's specified voltage or gravity, or if one or more cells fall below the minimum voltage defined by the manufacturer (corrected for temperature). The equalizing charge should not exceed the voltage limits of the connected equipment and should not exceed the battery manufacturer's specifications. The equalizing charge can be applied to the entire battery or to an individual cell. Since excessive equalizing charge will have an adverse effect on battery life, equalizing should be minimized.

Given this consideration, the user will want to evaluate the use of any equipment that automatically equalizes after a discharge, particularly if that equipment automatically equalizes for a long period of time after short discharges. Recharging will occur at normal float voltages; however, recharging can be expedited using an equalizing voltage charge.

Note—Most manufacturers do not recommend equalizing charge for VRLA cells.

7.1.5 UPS operating limitations

The following variables affect recharge time:

a) The battery size, discharge rate, and time
b) The capability of the UPS to recharge the battery when connected to its load
c) The battery electrolyte temperature

7.2 Specific considerations—Lead acid

7.2.1 Initial capacity

Batteries may have less than rated capacity when delivered. Unless 100% capacity upon delivery is specified, initial capacity can be as low as 90% of rated capacity. This will rise to rated capacity in normal service after several discharge cycles or after several years of float operation.

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7.2.2 Specific gravity

Specific gravity is an indicator of the ratio of sulfuric acid and water in the electrolyte of a lead-acid cell. Specific gravity varies slightly with temperature and is normally specified at 25 °C (77 °F). Usually, flooded lead-acid cells operate in the specific gravity range of 1.215–1.300.

Battery performance and resistance to freezing increase with the specific gravity of the electrolyte. Cells designed with lower specific gravity electrolyte would have the least performance capability, but have the longest design life and require the lowest float voltage, whereas identical cells designed with higher specific gravity electrolyte would have the greatest performance capability, but exhibit shorter design life and require a higher float voltage. The user should determine which of these factors is most critical to the required application.

7.2.3 Temperature

Operating batteries at temperatures below 25 °C (77 °F) decreases performance. Note that temperature derating factors (see IEEE Std 485-1983) apply to the discharge rate and not the discharge time. For example, a temperature derating factor of 1.11 for a certain cell type at 15.6 °C (60 °F) indicates that battery performance is approximately 10% less than at 25 °C (77 °F). If this battery can supply, say, 100 kW for 15 min at 25 °C (77 °F), it will be capable of delivering 90 kW for 15 min at 15.6 °C (60 °F). Conversely, the battery may be able to supply the same 100 kW load for only 10 min at 15.6 °C (60 °F), because of the decrease in battery efficiency at higher discharge rates. The extent of this effect varies with cell construction.

7.3 Specific considerations—Nickel cadmium

7.3.1 Initial capacity and aging considerations

Nickel-cadmium batteries display 100% of their published capacity upon delivery (see 6.2). The capacity then decreases gradually during the life of the battery, with no sudden capacity loss being encountered. The rate of capacity loss is dependent upon such factors as operating temperature, electrolyte specific gravity, and depth and frequency of discharge. For UPS applications involving short-duration, high-rate discharges, the rate of falloff in high-rate performance occurs more slowly than the rate of long-rate capacity loss (approximately 1% per year). The designer should therefore consider battery aging in light of the battery duty cycle, the expected operating conditions, and the planned life of the UPS system. Aging effects may be taken into account by the use of a separate factor, or, more commonly, by inclusion in the system design margins. Consult the battery manufacturer for additional information on aging factors.

7.3.2 Specific gravity

The electrolyte concentration of nickel-cadmium cells does not vary with state of charge, as with lead-acid cells, so the specific gravity remains essentially unaltered. Performance at room temperature in UPS applications is not markedly affected by variations in electrolyte specific gravity, so this aspect is not generally a factor in nickel-cadmium battery selection.

7.3.3 Temperature

While most UPS batteries operate in climate-controlled environments, it is not unusual for nickel-cadmium UPS batteries to be subjected to a wider range of temperatures. If the lowest expected electrolyte temperature is below the standard temperature used to establish performance ratings [normally 25 °C (77 °F)], then the battery size should be increased. The value of the temperature derating factor is dependent upon battery design, discharge time, and electrolyte temperature at the beginning of the discharge. There is generally no noticeable increase in the available capacity at temperatures above 25 °C (77 °F). Consult the battery manufacturer for temperature derating factors for various discharge times and temperatures.

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7.4 Warranty considerations

Since the warranties vary widely among manufacturers, the warranty deserves careful consideration when selecting a battery.

7.4.1 Full warranty replacement

If the battery becomes defective within the initial interval of service life, it will usually be replaced by the battery manufacturer at no charge.

7.4.2 Pro-rated adjustment

If a battery fails prematurely after the full warranty replacement interval, the cost of the replacement battery is pro-rated based on the months of in-service use. This credit is applied to the current price of the battery.

7.4.3 Miscellaneous charges

Shipping and installation of the new battery may or may not be covered as a part of the warranty adjustment.

7.4.4 Warranty evaluation

In evaluating a warranty the following items should be considered:

— Full replacement period
— Pro-rated adjustment period
— Shipping charges
— Installation costs
— Use conditions
— Temperature
— Load profile
— Cycling
— Ripple currents
— Charging
— Maintenance practices/records
— Warranty start date
— Defective battery disposal
— Claim
— Verification costs
— Installation testing requirements and restrictions

7.4.5 Battery monitor systems

If a special warranty is negotiated, the user might consider providing a monitor system to document a proper environment and maintenance program. The features of a monitor system should be discussed with the battery manufacturer as a part of the special warranty negotiations. The following points are worthy of consideration.

a) The total number and depth of discharges taken from the battery
b) The total cumulative kilowatt hours removed from the battery
c) The float voltage variations vs. time
d) The electrolyte temperature variations vs. time
e) The total cumulative time at equalizing charge

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This record can assure the user that the battery is being properly maintained and provide proof to the manufacturer that all warranty conditions have been met. It is desirable in warranty claims to have an irrefutable record of the battery cycles. In some cases, even an imperceptible input power dropout can result in a battery discharge until the UPS rectifier ramps up to normal voltage and the UPS resynchronizes with the commercial power line.

8. Sizing examples

8.1 Sample application: Three-phase UPS

System size: 500 kVA at 0.80 PF, 400 kW
System output voltage: 3 ph, 120/208 Vac (not required for calculation)
Inverter efficiency: 0.92 efficiency at full load (dc input to ac output)

Battery load (kW_b):

$$\frac{400\ kW}{0.92\ eff} = 435\ kW_b$$

8.2 Operating conditions

UPS dc operating range
432 Vdc maximum rectifier equalizing voltage
405/420 Vdc normal float voltage range
290 Vdc minimum inverter low voltage cutoff battery
Reserve time: 20 min
Battery temperature range: 15.6 °C (60 °F) minimum, 40 °C (104 °F) maximum

8.3 Voltage drop/cable sizing

During operation from the battery plant, the current drawn by the UPS will increase as the voltage decreases at the battery. Maximum current will occur as the battery approaches its final voltage. The user should identify the required minimum voltage at the inverter, and the voltage drop between the battery and the inverter, and adjust the minimum battery voltage accordingly.

In this example, the heavy batteries must be located in the basement of a relatively “light load design” commercial office building. The UPS must be located 160 cable feet away in available space on the second floor. The 1500 A can be handled by 4-750, RHW, MCM cables each on the positive and negative battery feeders [the National Electrical Code® (NEC®) (ANSI/NFPA 70-1993) ampacity chart 310-16 allows a 1900 A load for this combination]. Using the resistance values found in NEC table 8, the IR drop is calculated at 1.03 V in each of the two load feeders. The sum of the individual cell voltages at the low UPS operating point is not then 290 V but 292.06 V, including the dc voltage losses.

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Example:

Maximum discharge current:

$$\frac{435\ \text{kW} \times 1000}{290(\text{min load Vdc})} = 1500\ \text{A}$$

Cable run	is 160 ft (one way)
Cable size	is (4) 750 MCM
Cable voltage drop	is 1.03 V (one way)

The battery terminal voltage is then 2.06 V greater than the minimum load voltage. A minimum calculated battery voltage of 292 V is practical.

8.4 Lead-acid calculations

8.4.1 Initial assumptions and limiting factors

Battery discharge voltage range: 1.67–2.10 V/cell
Battery equalizing charge range: 2.30–2.50 V/cell

Sample calculation. Since the battery capacity does not remain at its nameplate rating throughout its life, a 25% margin will be included as an aging factor for the 435 kW_b determined in 8.1.

Then:

$$435\ \text{kW} \times 1.25 = 544\ \text{kW}_b$$

Also, since it is expected that the operating temperature will drop to a low of 15.6 °C (60 °F), the battery capacity should be increased by another 11% (per IEEE Std 485-1983) to ensure that it will provide rated load at reduced temperature.

The corrected battery load then becomes:

$$544\ \text{kW}_b \times 1.11 = 604\ \text{kW}_b$$

8.4.2 Selection of number of cells and end voltage

In order to take full advantage of the battery's usable capacity, the lowest possible end-of-discharge cell voltage should be used. This is subject to the limits imposed by the minimum allowable system voltage and the battery manufacturer's stated minimum cell voltage for the discharge time in question.

More important, the battery must first be capable of being charged in accordance with the manufacturer's recommendations and within the maximum system voltage limit.

For this example, it is assumed that the manufacturer recommends an equalizing voltage of 2.40/cell. The maximum number of cells is therefore:

$$\frac{\text{Maximum system voltage}}{\text{Recommended equalizing V/cell}} = \frac{432}{2.40} = 180\ \text{cells}$$

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(Note that in this case no adjustment is made for the voltage losses in the cables and cell connectors. In the final stages of battery recharge the current drops to a point where the voltage drops are insignificant on the large cables that have been sized for the final discharge currents.)

Allowing for the planned 2 V loss in the cables, the minimum battery voltage of 292 V is then used to calculate the final voltage per cell:

$$\frac{\text{Minimum UPS voltage}}{\text{Number of cells}} = \frac{292}{180} = 1.62 \text{ V/cell}$$

In most cases, the calculated number of cells and minimum voltage per cell would be used directly in the remainder of the battery sizing exercise. However, in this example, it is assumed that the battery manufacturer states a minimum discharge voltage of 1.67 V/cell for a 20 min discharge. Since the calculated minimum voltage is 1.62 V/cell and the manufacturer's minimum voltage is 1.67 V/cell, it is necessary to adjust the number of cells to reflect the higher value of the minimum discharge voltage.

$$\frac{\text{Minimum battery voltage}}{\text{Minimum discharge V/cell}} = \frac{292}{1.67} = 175 \text{ cells}$$

8.4.3 Cell selection

At this point it has been determined that the battery required is one with 175 cells that can deliver 604 kW for 20 min and not drop below 1.67 V/cell. Each cell shall then deliver:

$$\frac{604 \text{ kW}}{175 \text{ cells}} = 3.45 \text{ kW/cell}$$

Now there is complete information with which to consult the manufacturer's performance charts and select the proper cell for the application (20 min, 1.67 V/cell, and 3.45 kW/cell).

It may be beneficial to repeat the calculation to optimize the number of cells for a particular cell type. For example, if there is a cell that can provide 3.40 kW/cell, it would probably be more economical to increase the number of cells, rather than using 175 of the next larger cell size. In this case, the new number of cells would be:

$$\frac{604 \text{ kW}}{3.40} = 178 \text{ cells}$$

Note that changing the number of cells will affect both the equalizing and the end-of-discharge voltages. Increasing the number of cells allows a lower end-of-discharge voltage per cell (more usable capacity) within the lower system limit, but may result in a required equalizing voltage that is higher than the upper system limit. Decreasing the number of cells will not impose any constraints on the maximum voltage limit, but will result in a higher end-of-discharge voltage per cell (less available capacity). In this particular example, it is already known that 180 cells can be accommodated within the upper system voltage limit. At the lower voltage limit, the use of 178 cells would allow discharging to 1.64 V/cell, but would fail to meet the battery manufacturer's stated minimum of 1.67 V/cell.

Battery selection, then, is a process of finding the best fit between the maximum charge voltage and the minimum operating point of the UPS that will allow the maximum use of the available battery capacity.

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8.5 Nickel-cadmium calculations

8.5.1 Initial assumptions and limiting factors

Battery equalizing voltage 1.52 V/cell
Battery discharge voltage 1.00–1.10 V/cell

Sample calculation. Since the design life (assumed to be 15 years) is well within the life expectancy of vented nickel-cadmium batteries, a 10% margin will be included as an aging factor for the 435 kW_b determined in 8.1. Typically, temperature factors are used in nickel-cadmium battery sizing only when there is a considerable deviation from room temperature. In this example, the 15.6 °C (60 °F) minimum temperature typically would give rise to a capacity reduction of only 3% or so. This figure would generally be incorporated into the overall battery sizing margins (see 7.1.1) to give a combined figure for both aging and low temperature operation.

$$435\ kW_b \times 1.10 = 479\ kW_b$$

8.5.2 Selection of number of cells (cell type) and end voltage point

The most economical battery choice results from using the lowest end-of-discharge voltage and the largest possible number of cells that will satisfy the manufacturer's recommendations. The first step in the battery calculation is to ensure that the battery can be properly charged.

For this example, it is assumed that the manufacturer recommends a minimum equalizing voltage of 1.52 V/cell. The maximum number of cells is therefore:

$$\frac{\text{Maximum system voltage}}{\text{Minimum equalize V/cell}} = \frac{432}{152} = 84\ \text{cells}$$

(Note that in this case no adjustment is made for voltage losses in the battery cables and cell connectors. In the final stages of battery recharge the current drops to a point where the voltage drops are insignificant on the large cables that have been sized for the final discharge currents.)

Allowing for the planned 2 V loss in the cables, the minimum battery voltage of 292 V is then used to calculate the final voltage per cell:

$$\frac{\text{Minimum battery voltage}}{\text{Number of cells}} = \frac{292}{284} = 1.03\ \text{V/cell}$$

8.5.3 Cell selection

At this point it has been determined that the battery required is one with 284 cells that can deliver 479 kW for 20 min and not drop below 1.03 V/cell.

$$\frac{479}{284} = 169\ \text{kW/cell}$$

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Now there is complete information with which to consult the manufacturer's performance charts and select the proper cell for the application. When using tabular data, it may be necessary to interpolate between published values. For instance, in the example the cell type required is one that will supply 1.69 kW/cell for 20 min to a final voltage of 1.03 V/cell. In this case it would probably be necessary to interpolate between values given for a final voltage of 1.05 V/cell and 1.00 V/cell. Since most manufacturers offer high, medium, and low rate cell ranges, it may be advisable to determine cell sizes for two or more of the ranges. The most economical option meeting the above parameters can then be chosen. Battery selection then, is a process of finding the best fit between the maximum charge voltage and the minimum operating point of the UPS that will allow the maximum use of the available battery capacity.

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Annex A
Effects of elevated electrolyte temperatures on commercial, vented lead-acid batteries applied to uninterruptible power system service

(informative)

Figure A.1 shows the effects of temperature on battery life.

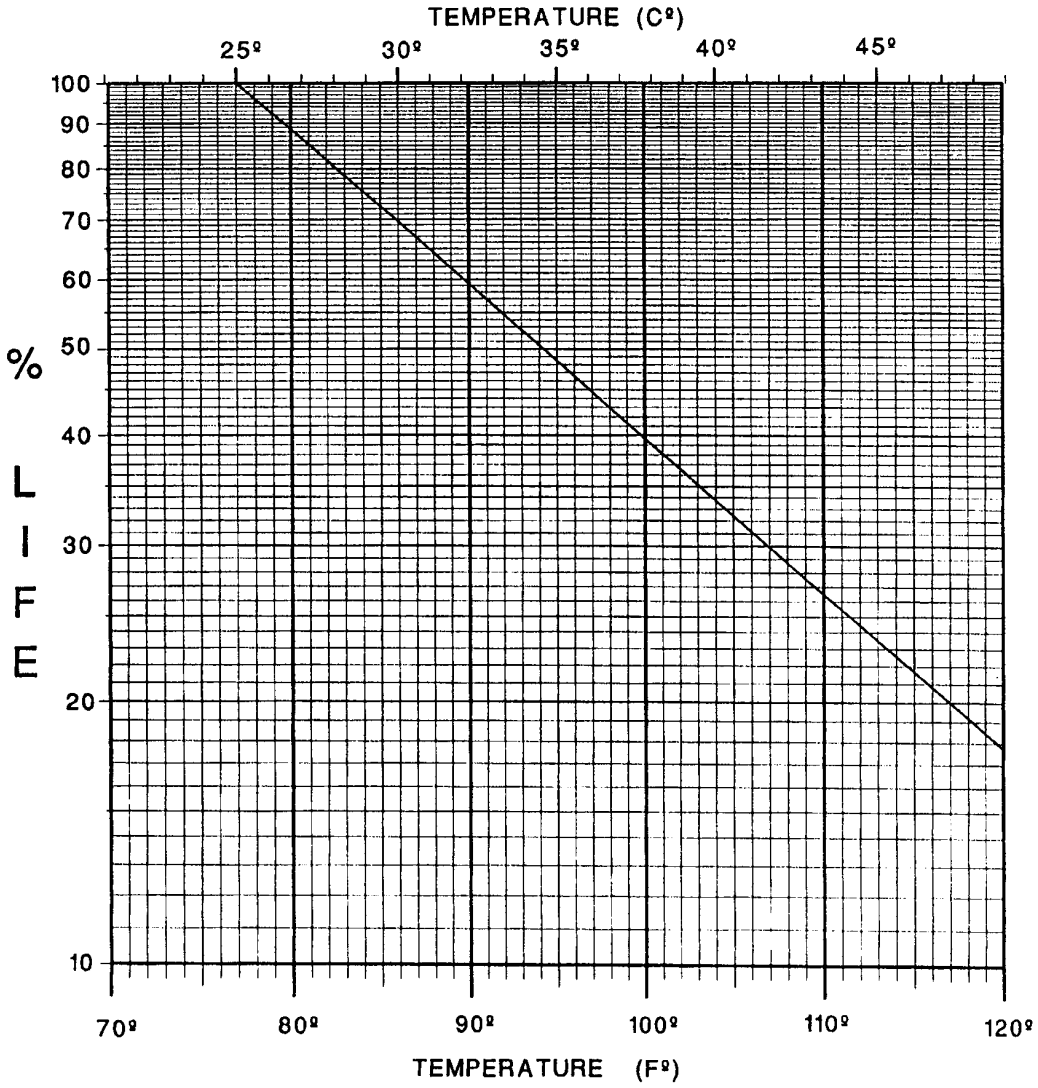


Figure A.1—Effects of temperature on battery life

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Annex B
Effects of annual temperature variations for vented lead-acid cells on total battery life

(informative)

Seldom does a battery remain at the same temperature throughout the entire year. This formula integrates annual variations by calculating the months of aging at elevated temperatures vs. months of life at normal [25 °C (77 °F)] temperature.

$$Lt_c = \left[\frac{240}{\left(\frac{1}{L} \times \text{mos @ } T_1\right) + \left(\frac{1}{L} \times \text{mos @ } T_2\right) + \left(\frac{1}{L} \times \text{mos @ } T_3\right) + \left(\frac{1}{L} \times \text{mos @ } T_n\right)} \right]$$

where

Lt_c = The temperature corrected years of battery life
L = % life from annex A divided by 100
Months @ T_1 = Number of months at temperature T_1
B_L = Normal expected battery life in months (240 for this example)

NOTE—$T_1 = T_2 + T_3 ... + T_n$ must equal 12 (one year)

Example: The electrolyte temperature at installation "Y" is 32.8 °C (91 °F) for four months, 30 °C (86 °F) for four months, and 25 °C (77 °F) for four months during a year.

$$Lt_c = \left[\frac{240}{\left(\frac{1 \times 4}{0.52}\right) + \left(\frac{1 \times 4}{0.65}\right) + \left(\frac{1 \times 4}{1}\right)} \right] = \frac{240}{7.69 + 6.15 + 4.00} = \frac{240}{17.84} = 13.45 \text{ years}$$

The installation "Y" battery ages 7.69 months during its four months at 32.8 °C (91 °F), it ages 6.15 months during its four months at 30 °C (86 °F), and it ages 4 months during its four months at 25 °C (77 °F). It then ages an equivalent of 17.84 months per calendar year.

If the user chooses to operate the battery at the elevated temperatures described in this example, the design life can be expected to drop from 20 years to 13.45 years.

NOTE—It is accepted that VRLA batteries are more sensitive to temperature effect than vented cells, but quantitative factors have not yet been identified.

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Annex C
Seismic requirements

(informative)

This annex applies only to those applications that must withstand earthquake activity.

In the U.S. and Canada, the Uniform Building Code™ divides the country up into five regions, based on probability and severity of earthquake activity. Higher zone numbers require more substantial rack construction and cell retention.

Zone 0–1: Negligible seismic activity (Great Plains, deep south)

Zone 2: Infrequent and minor seismic activity (Rocky Mountain states, parts of New England, and Appalachian chain)

Zone 3: Significant seismic activity (parts of Midwest, parts of Rocky and Sierra Mountain ranges)

Zone 4: Areas of intense seismic activity (most of California, Pacific plate faults)

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