

IEEE/ASHRAE Guide for the Ventilation and Thermal Management of Batteries for Stationary Applications

Co-Sponsors

IEEE Power and Energy Society
Stationary Batteries Committee



and

ASHRAE
Guideline Project Committee 21 (GPC 21)



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IEEE/ASHRAE Guide for the Ventilation and Thermal Management of Batteries for Stationary Applications

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**Energy Storage and Stationary Battery Committee
of the
IEEE Power and Energy Society**

and

**ASHRAE
Guideline Project Committee 21 (GPC 21)**

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Abstract: Vented lead-acid (VLA), valve-regulated lead-acid (VRLA), and nickel-cadmium (Ni-Cd) stationary battery installations are discussed in this guide, written to serve as a bridge between the electrical designer and the heating, ventilation, and air-conditioning (HVAC) designer. Ventilation of stationary battery installations is critical to improving battery life while reducing the hazards associated with hydrogen production. This guide describes battery operating modes and the hazards associated with each. It provides the HVAC designer with the information to provide a cost effective ventilation solution.

Keywords: ASHRAE Guideline 21, battery, battery cabinets, battery gassing, battery room, battery vaults, forced ventilation, hydrogen, IEEE 1635™, natural ventilation, stationary battery, thermal management, ventilation, ventilation system maintenance

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Introduction

This introduction is not part of IEEE Std 1635-2018/ASHRAE Guideline 21, IEEE/ASHRAE Guide for the Ventilation and Thermal Management of Batteries for Stationary Applications.

The primary purpose of this guide is to assist users involved in the design and management of new stationary lead-acid, valve-regulated lead-acid, and nickel-cadmium battery installations. The focus is the environmental design and management of the installation, to improve create a safe workplace and to maximize battery reliability as well as the safety of personnel and equipment. This guide is a joint effort by the IEEE and ASHRAE.

IEEE Std 1635/ASHRAE Guideline 21-2012 was first published in 2012. Per IEEE bylaws, a Sponsor and Working Group can conduct the revision of a standard at any time. A revision prior to year 10 will keep the standard continuously active for another 10-year period after the approval of the revision by the IEEE-SASB. The joint IEEE and ASHRAE working groups identified technical errors and omissions in the first edition that they felt could not wait until the next cycle. These included the following:

- Revised some formulae in A.2. Increased gassing equations for vented high-rate lead-acid batteries by as much as three times due to an oversight in the reference document
- Revised Table 1, Table 2, and Table 5. Gassing rates for vented high-rate lead-acid batteries were revised higher (by as much as three times) and added variations in design of nickel-cadmium cells
- Added new text for battery ratings in 7.2.2.4 for “high rate” batteries
- Reformatted and revised 7.2.4 for clarity and incorporated 7.2.7
- Deleted 7.2.7 and incorporated it into 7.2.4
- Subclause 7.2.6 was revised for clarity
- Revised Table 4 and Table 6 to add variations in design of nickel-cadmium cells
- Updated Equation (8) and Equation (9)
- Added text to A.6.1 regarding nickel-cadmium cells
- Added A.6.2, A.6.3, and A.6.4 for nickel-cadmium cells
- Revised B.2.3.1.2, to B.2.3.3, to B.2.3.4, and to B.2.3.1.5 to address variations in design of nickel-cadmium cells
- Annex C added several updates to reflect changing requirements in codes related to battery room ventilation
- Annex F was folded into Annex D
- Annex G was added to instruct in how to read battery data sheets, with examples of various battery types
- Bibliography was moved to Annex H
- Editorial changes are incorporated (most were paragraph numbering changes, reference changes, or grammatical changes)

Contents

1. Overview	11
1.1 Scope	11
1.2 Purpose	11
1.3 Exclusions.....	12
1.4 Document organization.....	12
2. Normative references.....	13
3. Definitions, acronyms, and abbreviations	13
3.1 Definitions	13
3.2 Acronyms and abbreviations	14
4. Battery safety hazards and considerations.....	15
5. Fundamentals.....	15
5.1 Battery types.....	15
5.2 Battery application.....	19
5.3 Installation enclosure applications.....	19
6. Heating, ventilation, and air conditioning	20
6.1 General	20
6.2 HVAC design for performance.....	21
6.3 HVAC design for safety	22
7. Environmental design.....	24
7.1 General	24
7.2 Operating modes.....	24
7.3 Heating, ventilating, and air-conditioning system design requirements	36
7.4 HVAC system design for ventilation.....	38
7.5 Integrated battery areas.....	40
7.6 Controls and alarms	40
7.7 Battery room hazard classification	41
7.8 Battery enclosure design.....	42
8. Economics	42
8.1 General	42
8.2 Battery replacement factors	43
8.3 Relative importance of the installation	43
8.4 Reliability of the HVAC system.....	43
8.5 Availability of maintenance resources.....	43
8.6 Cost and availability of battery replacement	43
8.7 HVAC System control based on battery operating mode	43
9. Environmental management (operation and maintenance).....	44
9.1 Battery system operation and maintenance.....	44
9.2 HVAC system operation and maintenance	44
Annex A (informative) Hydrogen generation in lead-acid and nickel-cadmium batteries	46
A.1 Purpose	46
A.2 Gassing equations for lead-acid batteries.....	46
A.3 Sample gassing calculations for vented lead-calcium batteries	58
A.4 Sample gassing calculations for lead-calcium-tin VRLA batteries.....	60
A.5 Sample gassing calculations for vented lead-antimony batteries.....	61

A.6 Battery gassing calculations for Ni-Cd batteries.....	64
A.7 Sample gassing calculations for Ni-Cd batteries	67
Annex B (informative) Heat generation in lead-acid batteries	70
B.1 Purpose.....	70
B.2 Basics of battery heat generation	70
B.3 Sample battery heat generation calculations for vented lead-acid batteries	92
B.4 Sample heat generation calculations for lead-calcium tin VRLA batteries.....	94
B.5 Sample heat generation calculations for Ni-Cd batteries	96
Annex C (informative) Existing U.S. codes and standards	98
Annex D (informative) Explosive and toxic gas allowance considerations	100
D.1 Permissible hydrogen concentrations	100
D.2 Permissible hydrogen sulfide concentrations and responsive actions.....	100
D.3 Permissible arsine and stibine concentrations.....	101
Annex E (informative) Thermal runaway.....	102
E.1 Lead-Acid battery thermal runaway.....	102
E.2 Thermal runaway in Ni-Cd batteries	103
Annex F (informative) Sample HVAC calculations.....	104
F.1 Heat and hydrogen generation sample calculations.....	104
F.2 Cooling	105
F.3 Ventilation/Exhaust	105
Annex G (informative) Example battery data sheets.....	106
G.1 General.....	106
G.2 Long or medium duration lead-acid battery data sheet examples	106
G.3 High rate lead-acid battery data sheet examples	106
G.4 Ni-Cd battery data sheet example	111
Annex H (informative) Bibliography	112

IEEE/ASHRAE Guide for the Ventilation and Thermal Management of Batteries for Stationary Applications

1. Overview

1.1 Scope

This guide discusses the ventilation and thermal management of stationary battery systems as applied to the following:

- Vented (flooded) lead-acid (VLA)
- Valve-regulated lead-acid (VRLA)
- Nickel-cadmium (Ni-Cd)
- Partially recombinant nickel-cadmium

For each category, both the technology and the design of the battery are described in order to facilitate user understanding of the environmental issues associated with each type of technology.

The scope of this document includes only stationary batteries under conditions of expected use. Multiple operating modes are identified.

The ventilation practices described in this guide represent the “best practice” based on the information available at the time this document was developed. The user should evaluate these practices against their operating experience, operating conditions, number and size of battery systems, manufacturer’s recommendations, resources, and needs in developing an environment that is conducive to safety and optimum operation of the equipment. These recommendations were developed without consideration of economics, availability of equipment and personnel, or relative importance of the application. Design of a ventilation system for a specific battery installation requires consideration of all issues, not just the technical issues considered in this document.

1.2 Purpose

The purpose of this document is to provide heating, ventilation, and air conditioning (HVAC) and battery system designers and users with information and recommendations concerning the ventilation and thermal management of stationary battery installations.

1.3 Exclusions

Specifically not included in this document are the following:

- Ventilation for spilled electrolyte, as a spill is considered an accident condition. Ventilation for fumes associated with spills due to handling of batteries is addressed in IEEE Std 1578™ [B39].¹
- Recharging stations for motive power or automotive batteries. These stations use different charging regimes from stationary float applications, although the charging gases produced can be managed in accordance with the guidelines in this document.
- Batteries that are embedded in small equipment such as desk-top uninterruptible power supply (UPS) systems and emergency lighting systems.
- Battery installations in classified (hazardous) environments.
- Ventilation for gases or other byproducts given off by battery installations involved in fires. The latter are not considered conditions of expected use, and in such circumstances ventilation could be disabled. For example, Li-ion batteries do not vent Hydrogen under normal or extreme conditions, and thus are not covered in this document; however, they do give off byproducts of combustion in cases of thermal runaway. For installation requirements (other than ventilation, which is covered in this document) for all stationary battery types in areas where the model Fire Codes are applicable, see NFPA 1 [B44] and the IFC [B28].
- Ventilation of the charger, UPS, or other equipment associated with the battery system.
- Design for fire or smoke events.
- Ventilation and management of gases, such as, arsine, stibene, hydrogen sulfide, ozone, sulfur dioxide, sulfur trioxide, or chlorine, produced during extreme over charge conditions (e.g., charger malfunction, multiple shorted cells).
- General design criteria for HVAC systems and/or design alternatives and schemes.

1.4 Document organization

This recommended practice is divided into nine clauses. Clause 1 provides the scope of this guide. Clause 2 lists references to other standards that are useful in applying this guide. Clause 3 provides definitions, acronyms, and abbreviations that are either not found in other standards, or have been modified for use with this guide. Clause 4 discusses battery safety hazard considerations. Clause 5 provides information on battery fundamentals. Clause 6 provides information on heating, ventilation, and air conditioning. Clause 7 provides information on environmental design. Clause 8 discusses the economics of battery ventilation system design. Clause 9 provides information on environmental management.

This guide has nine annexes. Annex A provides the gassing calculations. Annex B provides heat generation calculations. Annex C provides information on codes and standards. Annex D provides information on explosive and toxic gas allowance considerations. Annex E provides information on thermal runaway. Annex F provides sample HVAC calculations. Annex G contains example battery data sheets. Annex H provides bibliographic references.

¹The numbers in brackets correspond to those of the bibliography in Annex H.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

NFPA 90A, Standard for the Installation of Air-Conditioning and Ventilation Systems.²

3. Definitions, acronyms, and abbreviations

For the purposes of this document, the following terms and definitions apply. IEEE Std 1881 [B41] should be consulted for the primary definition of battery-related terms not otherwise uniquely defined in this document. The *IEEE Standards Dictionary Online* and *ASHRAE Terminology of Heating, Ventilation, Air Conditioning, & Refrigeration* [B9] should be consulted for terms not defined in this clause.^{3, 4}

3.1 Definitions

confined space: A space that (1) is large enough and so configured that an employee can bodily enter and perform assigned work; (2) has limited or restricted means for entry or exit (for example, tanks, vessels, silos, storage bins, hoppers, vaults, and pits); and (3) is not designed for continuous employee occupancy.

NOTE—See Code of Federal Regulations (29CFR1926 [B17]).⁵

controlled environment vault (CEV): A remote and partially or fully buried structure to house electronic and telecommunications equipment that includes backup power.

flammable: Subject to easy ignition and rapid flaming combustion. A flammable liquid is a liquid with a flashpoint of not more than 93 °C. A flammable solid is one that is readily combustible or may cause or contribute to fire through friction. A flammable gas is a gas having a flammable range with air at 20 °C and a standard pressure of 101.3 kPa.

NOTE—See UNECE GHS [B58].

flammable-air-vapor mixture: Mixture of a flammable vapor in air between the lower flammability limit (LFL) and upper flammability limit (UFL).

hydrogen pocket: A volume of air in which hydrogen accumulates to a concentration approaching or exceeding the lower flammability limit (LFL).

hydrogen trap: A spatial feature that prevents diffusion of hydrogen, thereby leading to the creation of a hydrogen pocket.

string: A grouping of interconnected cells that has the same nominal voltage as the dc system.

thermal management: The use of various temperature monitoring devices, heating and cooling methods to control temperature within a defined space.

thermal runaway: A condition that is caused by a battery charging current or other process that produces more internal heat than the battery can dissipate.

² NFPA publications are published by the National Fire Protection Association (<http://www.nfpa.org/>).

³ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>.

⁴ *ASHRAE Terminology of Heating, Ventilation, Air Conditioning, & Refrigeration* is available at www.ashrae.org/resources--publications/free-resources/ashrae-terminology

⁵ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

3.2 Acronyms and abbreviations

ac	alternating current
Ah	Ampere-hours
AGM	absorbed glass mat
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.
BTUH	BTUs (British Thermal Units) per hour
CEV	controlled environment vault
cfm	cubic feet per minute
CFR	Code of Federal Regulations
dc	direct current
EEC	European Economic Community
EU	European Union
EVPC	end voltage per cell
FV	final voltage
GHS	Globally Harmonized System of classification and labeling of chemicals
HSE	Health and Safety Executive (UK Health and Safety agency)
HVSD	high-voltage shutdown
HVAC	heating, ventilation, and air conditioning
ICBO	International Conference of Building Officials
ICC®	International Code Council® ⁶
IFC®	International Fire Code® [B28] ⁷
IU	current-limited constant potential charging
LEL	lower explosive limit
LFL	lower flammability limit
LOI	limiting oxygen index
MERV	minimum efficiency reporting values
NCBI	National Center for Biotechnology Information
NEC®	National Electrical Code® [B45] ⁸
NESC®	National Electrical Safety Code® [B30] ⁹
Ni-Cd	nickel-cadmium battery
NIH	National Institutes of Health
OSHA	Occupational Safety and Health Administration
Pa	Pascals (international unit of pressure)

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PBE	Plastic Bonded Electrode
ppb	parts per billion
ppm	parts per million
PSOC	partial state of charge
PV	photovoltaic
s.g.	specific gravity
SCBA	self-contained breathing apparatus
UEL	upper explosive limit
UFL	upper flammability limit
UNECE	United Nations Economic Commission for Europe
UPS	uninterruptible power supply
VLA	vented lead-acid battery
VPC	volts per cell
VRLA	valve-regulated lead-acid battery

4. Battery safety hazards and considerations

There are two primary safety considerations associated with the ventilation and thermal management of stationary battery installations. The first is personnel safety; the second is the reliability of the battery and the equipment located in the same or adjacent spaces. This document focuses primarily on personnel safety hazards that can be mitigated through ventilation and thermal management, although where equipment reliability is affected, it will be noted. Safety hazards associated with gas evolution from stationary battery installations include the following:

- Explosive gases
- Toxic gases
- Corrosive gases
- Acid vapor and or mist

The causes, risks, and mitigation of these safety hazards are discussed in detail in Clause 6 and Clause 7 following a discussion of battery types and typical applications for each type.

5. Fundamentals

5.1 Battery types

Rechargeable batteries store and release electrical energy through reversible chemical reactions. As the batteries release or discharge their stored electrical energy, the principal inefficiency involves electrical resistance to the current flow, causing thermal energy to be released. The process of storing electrical energy is also accompanied by inefficiencies, resulting in the release of thermal energy and evolution of gases. The release of thermal energy is due to electrical resistance or exothermic chemical reactions. The evolution of gases is due to incidental chemical reactions. Some of these incidental chemical reactions result in the release of oxygen and hydrogen gas.

5.1.1 Lead-acid batteries

5.1.1.1 Cell reactions

Lead-acid is the most common battery type used in stationary applications. In the charged condition, the active material in the positive plate is lead dioxide; in the negative, it is sponge lead. The sulfuric acid electrolyte solution is an active component in the cell charge/discharge reaction. The plate structure is typically grids or spines of pure lead or lead alloys with various hardening and grain refining agents added such as calcium, tin, antimony, selenium, etc. The alloy composition affects the gassing characteristics of the battery (see 7.2).

The ideal, reversible discharge/recharge reaction is as follows [see Equation (1)]:



where

Pb is metallic lead
 PbO_2 is lead dioxide
 H_2SO_4 is sulfuric acid
 $PbSO_4$ is lead sulfate
 H_2O is water

The ideal recharging reactions are as follows:

Positive plate [see Equation (2)]



where

SO_4^{2-} is the sulfate ion
 H^+ is the hydrogen ion
 e^- is an electron

Negative plate [see Equation (3)]



When a cell is subjected to an overcharge it will electrolyze water in the electrolyte. The electrolysis will produce oxygen gas at the positive plate as noted in Equation (4). As long as the oxygen gas production does not exceed the achievable oxygen gas diffusion rate of the cell, the principal reaction at the negative plate will be recombination as noted in Equation (5). The recombination reaction is exothermic, producing heat at the negative plate. To the extent the overcharge current leads to oxygen production exceeding the achievable oxygen diffusion rate of the cell, the negative plate reaction will proportionately shift to hydrogen gas production as noted in Equation (6), leading to the release of both hydrogen and oxygen gas from the cell.

Overcharge reactions are as follows:

Positive plate



where

O_2 is oxygen gas

Negative plate reactions are as follows:

Recombination



Gas production:



where

H_2 is hydrogen gas

During normal charging of lead-acid batteries a small portion of the charge current results in corrosion of their lead positive plate grid structure. This process is represented by Equation (7) [with the corresponding reaction at the negative shown in Equation (6)].

Positive plate grid corrosion reaction:



5.1.1.2 Vented lead-acid (VLA) batteries

The VLA battery is simply a lead-acid battery with a free-flowing liquid electrolyte that allows any gases generated during charging to be vented directly to the atmosphere. That volume below the cover and above the electrolyte level can be up to 67% hydrogen and 33% oxygen by volume, which is an explosive mixture. Typically, these gases are vented via a flame arresting (safety) vent to prevent ignition from a spark or flame outside the cell from entering the cell container and igniting the contained gases.

For VLA batteries being overcharged, the principal reaction at the negative plate involves gas production as in Equation (6). Recombination as in Equation (5) does occur, but at such a low rate that it can be disregarded. The reason is that oxygen gas diffuses at a very slow rate through liquid electrolyte. During a recharge, the rate of gas production is dependent on a number of factors involving characteristics of both the batteries and the charger. In general, peak gas production occurs at the end of the recharge as the batteries near their full state of charge. At this point, most of the charge energy results in electrolysis of water.

VLA batteries use pure lead as well as a variety of lead alloys, which impact the generation rate and types of gases produced during an overcharge condition. The alloys discussed in the tables in Clause 7 are lead-calcium, lead-antimony, and lead-selenium. Lead-calcium batteries have low float currents. Lead-antimony and lead-selenium have higher float currents, which increase over the life of the battery. Pure lead cells have the lowest float current. All lead-acid batteries are capable of producing hydrogen sulfide gas (toxic and

corrosive) and acid mist under extreme overcharge conditions, but such failure modes are beyond the scope of this document. See Annex D for additional information.

5.1.1.3 Valve-regulated lead-acid (VRLA) batteries

VRLA batteries are designed to take advantage of the naturally occurring recombination cycle where internally generated oxygen gas molecules are recombined with hydrogen ions to form water molecules. Key construction elements of these batteries are pressure relief valves and immobilized electrolyte construction to permit oxygen gas migration to the negative plate.

To reduce electrolysis of the electrolyte and the resulting water loss, VRLA batteries are designed to have low float current. Today's VRLA battery technologies are based on lead-calcium, lead-tin, or pure-lead grid alloys. The electrolyte is immobilized in either a glass mat [absorbed glass mat (AGM)] or a silica gel (gelled-electrolyte cell). These construction methods achieve rates of oxygen gas migration sufficient to allow recombination at a level to substantially reduce or eliminate the need for watering for the life of the battery.

Recombination occurs when oxygen gas generated at the positive plates migrates to the negative plates for recombination with hydrogen ions to form water molecules. The principal limiting factor to recombination is the sustainable rate of migration of oxygen gas molecules to the negative plate.

The pressure relief valve allows excess internal pressure from generated gases to be relieved while preventing atmospheric air from entering the battery. When the valves do function to relieve internal pressure, the gases that escape directly equate to a loss of water from the battery that generally cannot be replaced.

The recombination reaction is exothermic releasing heat at the negative plate. The greater the overcharge current, the greater the oxygen generated at the positive plate. This will result in greater heating at the negative plate and that heat must be dissipated. If thermal equilibrium cannot be reached, thermal runaway may occur (see Annex E). Regardless of whether or not thermal runaway occurs with increasing overcharge current, at some point the oxygen generation rate will exceed the diffusion rate to the negative plate and oxygen and hydrogen gas will be expelled as with a vented cell. The vented gas will remove some of the excess heat, but this is at the expense of water loss from the cell.

During normal charging of VRLA batteries, a small portion of the charge current results in corrosion of their lead positive plate grid structure [Equation (7)]. The oxygen consumed by this reaction is not available for recombination at the negative plate, so the only possible reaction at the negative plate is hydrogen gas evolution, in accordance with Equation (6). This low rate but continuous release of hydrogen results in a gradual increase in pressure in the head space of the cell; when the pressure reaches a predefined level the valve opens, some hydrogen is released, and then the valve reseals. The rate of hydrogen release from this process is significantly lower than from vented cells. See 7.2 for gassing rate information.

5.1.2 Nickel-cadmium (Ni-Cd) batteries

Vented Ni-Cd batteries behave in a similar way to VLA batteries on overcharge, releasing hydrogen and oxygen gases in a 2-to-1 ratio. See 7.2 for gassing rate information. There are also partially recombinant designs, which may or may not be fitted with pressure valves. Consult the manufacturer for specific information regarding gassing rates under the expected operating conditions. In the absence of such information these products may be conservatively treated in the same way as vented designs.

Fully sealed Ni-Cd cells, such as those used in portable appliances, are not suitable for use in stationary float applications.

5.2 Battery application

5.2.1 General

Batteries can be categorized either by the type of service or by the type of installation enclosure. Battery applications by service application and by enclosure application are discussed as follows.

5.2.2 Service applications

5.2.2.1 Standby or float service

In standby or float, a battery is maintained by a charger at or near full charge to maximize the energy available to the application. Common application types are as follows:

- Telecommunication (low rate, long duration)
- UPS (high rate, short duration)
- Switchgear (general purpose, medium duration)
- Starting batteries (high rate, short duration)

5.2.2.2 Cycling service

These applications are characterized by frequent discharge/charge cycles. The increase in discharge/recharge cycles typically increases the amount of gas and heat generated by the installation. However, this is not always true, particularly in photovoltaic (PV) and other applications designed to operate at a partial state of charge (PSOC).

5.3 Installation enclosure applications

5.3.1 General

Personnel safety and proximity to critical equipment are important considerations when deciding whether or not a dedicated battery room is necessary. Batteries should be enclosed to prevent unauthorized access because of safety considerations. The necessary enclosure may consist of a battery cabinet, a cage, enclosing partitions or walls, or a vault. When enclosure is not feasible, personnel should be appropriately notified of any battery-related hazards present. In some cases, local building codes will require batteries to be installed in a dedicated battery room. As the nature of the facility in which the batteries are installed becomes more critical, it is common to see the batteries isolated from other equipment.

5.3.2 Dedicated battery rooms

A dedicated battery room is a specially constructed and equipped area typically used primarily for installation of the battery and other components of the dc system. Batteries are typically installed on open racks. The room is physically separated from other areas, avoiding localized heat sources, with controlled access and doors and partitions determined to meet the required fire resistance rating for the application. For purposes of this guide, a battery room may include the charging or UPS equipment to which the batteries are connected.

5.3.3 Indoor cabinets

Indoor cabinets are enclosures housing batteries and/or monitoring equipment. The purpose of the cabinet is to house the batteries in a compact space while limiting unauthorized access to live electrical components. The batteries in indoor cabinets are almost exclusively of the VRLA type. For small systems, the batteries and charging system or UPS might be located in a common cabinet. While acid mist or vapor is not normally

an issue during normal charge modes, if the batteries are vented type, it is preferred that the cabinet ventilation system provide for isolation of the battery exhaust from the electronics.

5.3.4 Outdoor cabinets

The most common (but not the only) applications for outdoor battery cabinets are for telecommunications electronic equipment, signal cabinets, and utility substations. Most of these cabinets are equipped with VRLA or Ni-Cd batteries for backup. Some outdoor cabinets may have an HVAC system, but many others do not. Those that do not have HVAC may use passive heat exchangers to reduce the interior cabinet temperature rise to no more than 10 °C above outdoor ambient temperatures. Usually, the electronics in the cabinet are in a sealed chamber, so the batteries are usually kept in a separate chamber with some sort of ventilation. Outdoor ambient temperature extremes, radiant heating, and cabinet positioning can all affect the performance and health of the batteries.

5.3.5 Controlled environment vault (CEV)

The most common application for CEVs is to house telecommunication equipment. CEVs are remote, partially or fully buried structures to house equipment including backup power. CEVs are locked and unoccupied except when maintenance or installation is taking place so they must be remotely monitored. The batteries are normally installed in relay racks and co-located with other electrical and electronic equipment. As the name implies, ventilation and temperature control is always present in order to keep the electronic equipment operating within its recommended range. Temperature tolerance of the batteries may be lower than for the electronics (see 7.8.4).

5.3.6 Integrated battery and equipment areas

Sometimes batteries are integrated into equipment areas. For example:

- Telecommunication and UPS system battery plants often share the same space as the equipment they support. Many battery systems in these environments use VRLA batteries. In smaller telecommunications installations, batteries are often mounted on trays in open relay racks below the rectifiers. UPS equipment is more often enclosed in cabinets. The batteries can be integrated into the UPS equipment, or they can be in cabinets.
- Batteries used in larger utility substations are most often VLA. These systems are generally located in the substation control house along with control equipment. In smaller substations where the control house consists of a single cabinet, the batteries are typically VRLA and enclosed in the substation cabinet.

6. Heating, ventilation, and air conditioning

6.1 General

A well-designed HVAC system for environments in which stationary batteries are installed should simultaneously achieve the following objectives:

- Optimize *performance* of the battery system within the budgetary constraints of the project (see Clause 8)
- Provide maximum *safety* for personnel and infrastructure

6.2 HVAC design for performance

6.2.1 Temperature

6.2.1.1 Battery life

The stated operating life of a stationary battery is typically based on an electrolyte temperature of 25 °C (77 °F) in North America and 20 °C (68 °F) in other parts of the world. Ni-Cd batteries are less affected than lead-acid batteries by temperature extremes. Continuous operation at elevated temperature will reduce the life of a lead-acid battery by approximately 50%% for every increase of 8.3 °C (15 °F) in electrolyte temperature above 25 °C (77 °F). For Ni-Cd batteries life is reduced by 50% for every 30 °C (54 °F) above 25 °C (77 °F). Operation at reduced temperatures results in some gain in battery life, but the gain is significantly less than the loss of life above the design temperature.

6.2.1.2 Battery capacity

The ability to provide power on demand decreases as electrolyte temperature is reduced. The extent of this decrease depends on battery chemistry, cell design, and discharge rate. The minimum design temperature is established during battery sizing and requires coordination between the battery system and HVAC design engineers.

6.2.1.3 Ambient temperature

Changes in electrolyte temperature lag behind changes in ambient air temperature. Parameters that can affect electrolyte temperature as a function of ambient temperature include the following:

- Battery mass
- Spacing/airflow between batteries
- Duration of temperature deviation
- Charging current

The optimal operating range for a battery (VLA, VRLA, or Ni-Cd) is an electrolyte temperature between 20 °C and 25 °C. Operation in this temperature range provides the best balance between capacity and battery life. When a battery is float charged, the heating due to the charge current and, in the case of VRLA, the recombination reaction results in the internal battery temperature being approximately 1 °C (2 °F) higher than the ambient temperature. Because of this heating effect, the optimal ambient temperature range is 19 °C to 24 °C (66 °F to 75 °F). The optimal temperature range for a specific application depends on the balance between battery life and capacity, the capital and operating costs of the HVAC system, and the requirements of other equipment located in the same area. Achieving this balance requires dialogue between the battery system specifier and HVAC system designer.

Gassing increases with increasing temperature. In lead-antimony batteries, gassing also increases with age. See Clause 7 for methods to calculate the gassing rates.

Maintaining the battery installation within the optimal temperature range reduces the possibility of thermal runaway.

6.2.1.4 Temperature gradients

Installation design should allow for radiant and convective heat dissipation around the battery. Heat sources and airflow should be managed so as to limit electrolyte differential temperature within a series battery string to a maximum of 3 °C for lead-acid and 5 °C for Ni-Cd batteries.

6.2.2 Air humidity

Batteries can function across a very wide range of humidity. High humidity is generally not a problem unless it condenses and causes oxidation of exposed metal parts, such as intercell connections. Low humidity conditions are a long-term issue for VRLA batteries due to increased water loss that results in reduced battery life. Low humidity presents no problem for VLA batteries, but it does increase the potential for electrostatic discharge (ESD). Personnel working in close proximity to a battery vent, regardless of humidity level, should take precautions to avoid generating an ESD as it can ignite the hydrogen and oxygen in the head space of a battery, thereby creating the possibility of an explosion even when the battery is fitted with flame arrestors. Relative humidity should be maintained above 20%, ideally between 35% and 65%. No special humidity control features are normally necessary.

6.2.3 Air contaminants

6.2.3.1 Dust

Water soluble salts found in dust particulate buildup, especially when it has metallic (conductive) elements and/or is combined with humidity levels above 40%, can lead to accelerated corrosion levels, tracking, and electrical shorting or arcing problems on batteries. It is recommended that medium efficiency filters be used to filter outside air supplied to an indoor battery installation. Filters with ASHRAE 52.2 minimum efficiency reporting values (MERVs) between 7 and 11 should be used to filter the outside air source (ASHRAE Standard 52.2-2007 [B8]).

6.2.3.2 Other contaminants

A comprehensive HVAC design should take into account not only any vapors or gases produced by the battery, but other vapors or gases present in the facility that could potentially damage the batteries or associated equipment. Chemical process industry facilities are an example of facilities likely to contain other vapors or gases of concern. Electrical contacts and connections are particularly susceptible to damage from corrosive chemicals. In more extreme environmental conditions, battery racks may also be vulnerable to corrosive attack.

6.3 HVAC design for safety

6.3.1 Flammable/explosive gases

The potentially explosive gas emitted by all vented lead-acid and Ni-Cd stationary batteries is hydrogen. The hydrogen gas is released in a two-thirds/one-third mixture with oxygen gas. The evolution of this gas mixture depends highly upon the charging current flowing through the battery. The relationship of current to operating mode, temperature, and other factors are covered in more depth in Clause 7.

Flammable and explosive limits apply generally to vapors and are defined as the concentration range in which a flammable substance can produce a fire or explosion when an ignition source (such as a spark or open flame) is present. The concentration is generally expressed as percent fuel by volume (Interactive Learning Paradigms [B42]).

Above the UFL, the mixture of substance and air is too rich in fuel (deficient in oxygen) to burn (Interactive Learning Paradigms [B42]). The upper explosive limit (UEL) is the mixture of substance and air that is too rich in fuel to explode.

Below the LFL the mixture of substance and air lacks sufficient fuel (substance) to burn. The lower explosive limit (LEL) is the mixture of substance and air that is too lean in fuel to explode.

WARNING

Any concentration between the LFL and UFL limits can either ignite or explode. While hydrogen and air mixtures above the UFL and UEL cannot burn or explode respectively, the introduction of air would cause the mixture to become diluted and the concentration could drop into the hazardous range (Interactive Learning Paradigms [B42]).

The LEL of hydrogen is approximately 17% and the LFL is approximately 4% (NFPA 497 [B50]). The UEL is about 56% and the UFL is approximately 75% (NFPA 497 [B50]). While technically incorrect, it is common for the flammability limits to be referred to as the explosive limits. In stationary battery installations, the UFL for hydrogen is not exceeded because the gas released from the batteries is not pure. It is a mixture that is one third oxygen gas, two thirds hydrogen gas, and accompanied by small amounts of other elements.

6.3.2 Hydrogen traps

Hydrogen molecules are the smallest and lightest of all naturally occurring molecules. Accordingly, hydrogen is very easily dispersed with a minimum amount of air movement. Hydrogen also mixes with air by diffusion. Usually, unrestricted natural air movement in the vicinity of the battery is sufficient to disperse released hydrogen. If there is insufficient airflow to disperse hydrogen vented from a battery, concentrated hydrogen pockets may form near the battery vents on the lower tiers of a battery rack. Ensuring good air movement through the battery racks will prevent hydrogen concentration.

6.3.3 Confined spaces

Ventilation of confined spaces is of particular importance because of the increased possibility of hydrogen traps forming flammable or explosive hydrogen concentrations. One example of such a space, where batteries are installed, is a CEV in a remote telecommunications site (see 7.8.4).

6.3.4 Thermal runaway

Thermal runaway can occur in any aqueous battery type, but is most likely to occur in a VRLA battery due to its limited water content. HVAC designs that fail to provide adequate ventilation and temperature control, or electrical designs with oversized chargers or excessively high charger voltage settings contribute to the phenomenon. Operational issues such as ventilation or temperature control malfunctions, individual cell failure(s), or charger malfunctions may aggravate the situation. During thermal runaway, hydrogen gas evolution greatly increases. The event may continue without abatement, causing other gases and particulates to become airborne.

For VRLA batteries, thermal runaway is a significant safety concern, but it can be detected and controlled with appropriate safeguards in the electrical system design. See Annex E for more information on thermal runaway.

Thermal runaway in vented lead-acid batteries is rare and most commonly occurs in lead-antimony designs towards the end of life when charging current is at its maximum.

Thermal runaway in Ni-Cd batteries is normally associated with separator breakdown resulting in recombination heating (see Annex E for additional information).

6.3.5 Toxic gases

Toxic gases from lead-acid batteries such as hydrogen sulfide, arsine, and stibine (see Annex D) are normally only present during thermal runaway or at very high voltages (around 2.65 V/cell) and are not included in the scope of this document. See 6.3.4, 7.2.9.2, and Annex E for further discussion of thermal runaway.

6.3.6 Corrosive gases and acid vapor

During operational modes such as boost or equalize charge, small quantities of corrosive gases such as hydrogen sulfide and acid vapor in lead-acid batteries and potassium hydroxide (KOH) vapors in NiCd batteries can be generated. The quantities generated are normally too small to be detected. The amount of corrosive gas or acid vapor generated is so small (even in these modes) that this is primarily a long-term concern for equipment reliability. Examples of equipment subject to potential long-term equipment reliability issues when exposed to corrosive gases include cell terminations, inter-tier and inter-rack lug-to-cable connections, and electronic equipment (e.g., chargers, UPS) installed in close proximity to the battery.

Since release of corrosive gases and acid vapor during boost or equalize charge is rare and the quantities are small when it does occur, they generally pose little personnel risk. Normal building ventilation is usually sufficient to disperse the corrosive gases and acid vapor. No special ventilation fan or duct construction material will generally be required. Exhaust pickup locations near the floor are generally not needed. It should be noted that the corrosive effect of gases is magnified by humidity.

Corrosive gas and acid vapor generation during thermal runaway can be significant. See Annex E for a discussion on thermal runaway and Annex D for a discussion on hydrogen sulfide gas.

7. Environmental design

7.1 General

The following subclauses describe the common battery operating modes and the relevant environmental design parameters for each mode. The HVAC system should be designed to address the site-specific features. Safety, performance, and the reliability of the HVAC system can be achieved by keeping the system design simple, but with sufficient redundancy.

7.2 Operating modes

7.2.1 General

The most accurate values for current, hydrogen release, and heat generation should be obtained from the manufacturer. However, if such values cannot be obtained, the equations in Table 1 through Table 5 will give reasonable upper bound estimations for a given operating mode. By necessity, the equations in the tables are based on assumptions to be applicable to the broadest ranges of battery types (meaning that some individual batteries from some manufacturers may have somewhat different gassing characteristics). Annex A and Annex B describe the assumptions used in the development of the equations along with the applicable references. In addition, the tables do not account for excessive abnormalities in individual batteries or in operating conditions. All of this means that while the calculations of the tables will give reasonable upper bound estimates of hydrogen gassing and heat generation for the great majority of applications, there may be individual cases where the hydrogen release or heat generation is higher.

The typical mode(s) of operation will help determine which table to use for gassing and heat generation calculations.

Gassing calculations under float conditions should generally not be used as the basis for ventilation design. Due to failure modes, human error, and code requirements, it is probably safest to use gas generation calculations for boost charging in Table 2 to determine normal ventilation requirements (it will be noted that even assuming these conditions, gas generation is relatively low). Additional ventilation may be needed for initial charging (particularly for vented cells) based on the calculations in Table 5 for that mode.

When determining HVAC design to maintain space temperature, the heat generation calculations from Table 1 are normally the most appropriate to use for float applications. For cycling applications, the heat generation calculations from Table 3 for discharge and Table 4 for bulk recharge are normally most appropriate.

7.2.2 Assumptions for the tables

7.2.2.1 Units

The equations produce results in SI units, including that for the generation rate of the hydrogen gas. For inch-pound units, appropriate conversion factors should be applied [e.g., $\text{m}^3/\text{s} \times 2119 \approx$ cubic feet per minute (cfm)].

7.2.2.2 Standard temperature and atmospheric pressure

Table 1 through Table 7 are based on an operating temperature of 25 °C (77 °F) at sea level. Hydrogen gassing and heat release are directly related to current flow into the battery. Increases in temperature will increase current, and therefore increase gassing and heat release. Lower temperatures will have the opposite effect. If the battery will be operated in an elevated temperature environment, the battery manufacturer should be contacted to determine the exact effect on gassing and heat release. Gassing and the heat release rate double for approximately every 8 °C to 10 °C (15 °F to 18 °F) above 25 °C (77 °F) for lead-acid batteries due to a rise in current. For elevated temperatures, up to 33 °C (92 °F), or operation at elevations up to 300 m (approximately 1000 ft), a battery on float, without an adjustment for temperature, will react similarly to a battery on equalize, and Table 2 may be used. For higher temperatures, the battery manufacturer should be contacted. For elevations above 300 m, the normal atmospheric pressure at the battery location should be used to adjust the hydrogen evolution rate.

7.2.2.3 Upper bounds

Conservative assumptions are made in the tables to simplify both the gassing and heating calculations. For example, a review of the literature from multiple manufacturers was performed, and the combination of recommended voltage and specific gravities that would give the highest gassing and heat release for a given operating mode for the majority of the manufacturers was used. The conservative estimates are such that the gassing and heat generation would not be likely to exceed the results given by the tables in over 95% of actual cases; however, for the most accurate calculations, refer to Annex A and Annex B.

7.2.2.4 Battery ratings

Note that although some lead-acid batteries will have ratings for both the 8 h (C_8) rate and the 15 min (P_{15}) rate, most batteries are designed for either a long duration, or a short-duration discharge. For long and medium duration discharge batteries, use the C_8 rate. For batteries designed for rapid discharge (such as in a UPS), use the P_{15} rate. It will make a difference with some calculations, especially those for internal resistance and intercell connector resistance, used in the charge and discharge heat generation rate equations; and in vented lead-acid batteries.

European lead-acid batteries may be rated at the 10 h (C_{10}) rate to 1.8 V/cell at 20 °C or at the 15-minute rate to 1.65 V/cell at 20 °C. These ratings are essentially equivalent to the C_8 rating or the P_{15} rating at 25 °C, respectively. For non-standard Ah ratings (such as 20 h or 100 h), ask the manufacturer for the C_8 rating.

Note that the C_8 rating is in Ampere-hours and not Amperes. Figure G.1 (in Annex G) gives an example of a data sheet for a long duration design VRLA battery and points out which of the many numbers is the C_8 rating to 1.75 V/cell at 25 °C.

Batteries used in high rate (such as UPS) applications have standard ratings in either kW/cell or W/cell for 15 min. For lead-acid batteries, end voltage per cell (EVPC) at the end of discharge is typically 1.67 V at

25 °C (North America) or 1.65 V at 20 °C (Europe). The same battery at longer durations (such as up to 3 h in telecommunications) is typically discharged to an EVPC of 1.75 V, and is usually rated in Ah/cell. Tables in Figure G.2 (in Annex G) provide both ampere rate and kW rate for a VRLA unit. Tables in Figure G.3 (in Annex G) provide comparable rates for a VLA (“flooded”) unit.

Ni-Cd batteries are generally rated at the 5 h (C_5) rate to 1.0 V/cell at 20 °C regardless of whether they are a high rate, medium, or long duration battery design. Figure G.4 gives an example Ni-Cd datasheet, showing how to find the appropriate C_5 rating.

7.2.2.5 Current

Due to subtle differences in cell chemistry between differing manufacturers and models, the most accurate current in amperes at a specified voltage can be obtained from the manufacturer. However, if such a value cannot be obtained, the equations in the following tables will give a reasonable upper bound estimation of the current for a given operating mode (see Annex A and Annex B for how these equations were determined).

Note that not all the current is included in the VRLA battery hydrogen gassing calculations. This is because almost all of the current drives the recombination process and there is very little generation of hydrogen gas. Due to recombination, very little gas escapes the cell. If the battery manufacturer gives the actual gas release numbers for the different operating modes, then these numbers are generally more accurate than the values produced by the equations.

7.2.2.6 Oxygen evolution

While vented batteries evolve both hydrogen and oxygen into the surrounding atmosphere, only the hydrogen gassing equations are given. The oxygen produced does not contribute any more to the flammability of hydrogen because there is already oxygen in the atmosphere into which the hydrogen is being released.

7.2.2.7 Counting the cells in a module

The number of cells can be misleading from a visual perspective. Smaller batteries typically come in multi-cell units. A lead-acid battery with a nominal rating of 12 V actually has 6 cells and should be counted as 6. A nominal 12 V Ni-Cd battery typically has 9 to 10 cells.

7.2.2.8 Estimates of resistance

For the internal resistance of the cells and intercell connector resistances for heat generation calculations, the best data comes from the manufacturer. The equations in the tables are to be used if data cannot be obtained from the manufacturer or from direct readings. The resistance equations in the tables represent generic numbers obtained by averaging the data from multiple manufacturers.

7.2.2.9 Differing battery models in the same site

In facilities with multiple batteries, using multiple battery types or batteries located in areas with varying environmental conditions, each battery should be individually evaluated based on its type and the expected environmental conditions, and the results added together.

7.2.3 Standby/float operation

The float, also known as standby, operating mode occurs when a constant voltage is applied to the battery terminals sufficient to maintain an approximately constant state of full charge. The float operating mode can be detected by observing the float/equalize mode of the chargers. Most batteries in stationary applications (with the exception of cycling batteries, such as PV/solar applications; or constant-current charging schemes) spend more than 99% of the time on float.

For applications where infrequent cycling of batteries is expected, the heat generation calculations of Table 1 (see Annex F for an example) should be used in HVAC system sizing. The calculations in Annex B should be used for the following applications:

- a) Where frequent cycling occurs
- b) Where frequent boost/equalize or finishing charges occur
- c) Where the dc system does not give the HVAC system a continuous indication of the dc system operating mode

Even though heat generation during discharge/recharge is higher than float charge, heat dissipation remains low due to the large thermal mass of batteries. Most discharges and recharges are short (except in cycling applications) so although the rate of heat generation on discharge or bulk recharge may be calculated to be a significant number and may result in some elevation of room temperature, this effect is temporary and should not be used for HVAC sizing calculations. See 7.2.8 for further information on the calculation of heat generation for cycling applications.

Table 1—Standby/float operating mode

Battery type	Design parameter		
	Flammable gases	Toxic and corrosive gases	Heat generation
Vented lead-acid			
Lead-calcium	$H_{2\text{-rate}} = 1.27 \times 10^{-7} \times I \times n_c$ where $I = C_8 \times 9.76 \times 10^{-5}$ a or $I = P_{15} \times 0.075$ b	None	$q_W = 0.264 \times I \times n_c$
Pure lead	$H_{2\text{-rate}} = 1.27 \times 10^{-7} \times I \times n_c$ where $I = C_8 \times 6.62 \times 10^{-5}$		
Lead-selenium	$H_{2\text{-rate}} = 1.27 \times 10^{-7} \times I \times n_c$ where $I = C_8 \times 3.27 \times 10^{-4}$ or $I = P_{15} \times 0.0835$		
Lead-antimony	$H_{2\text{-rate}} = 1.27 \times 10^{-7} \times I \times n_c$ where $I = C_8 \times 8.97 \times 10^{-4}$ or $I = P_{15} \times 0.230$		
Valve-regulated lead acid			
Lead-tin or lead-calcium AGM	$H_{2\text{-rate}} = n_c \times C_8 \times 2.69 \times 10^{-12}$ $H_{2\text{-rate}} = n_c \times P_{15} \times 6.73 \times 10^{-10}$	None	$q_W = 0.34 \times I \times n_c$ where $I = C_8 \times 0.00121$ or $I = P_{15} \times 0.326$
Low-antimony AGM	$H_{2\text{-rate}} = n_c \times C_8 \times 1.39 \times 10^{-11}$ $H_{2\text{-rate}} = n_c \times P_{15} \times 3.48 \times 10^{-9}$		$q_W = 0.34 \times I \times n_c$ where $I = C_8 \times 0.00626$ or $I = P_{15} \times 1.69$
Lead-calcium gel	$H_{2\text{-rate}} = n_c \times C_8 \times 6.72 \times 10^{-12}$		$q_W = 0.34 \times I \times n_c$ where $I = C_8 \times 6.1 \times 10^{-4}$
Nickel-cadmium ^c			
Foamed/PBE	$H_{2\text{-rate}} = 1.78 \times 10^{-11} \times C_5 \times n_c$	None	$q_W = 1.43 \times 10^{-5} \times C_5 \times n_c$
Partially-Recombinant Fiber or Pocket plate	$H_{2\text{-rate}} = 6.35 \times 10^{-12} \times C_5 \times n_c$		$q_W = 1.22 \times 10^{-4} \times C_5 \times n_c$
Sintered/PBE	$H_{2\text{-rate}} = 1.27 \times 10^{-10} \times C_5 \times n_c$		
Non-recombinant Fiber or Pocket plate			
where			
I	is the current through each string in amperes (A)		
C_8	is the 8 h ampere-hour rating of a lead-acid cell to 1.75 V at 25 °C		
P_{15}	is the 15-min kW/cell rating of a lead-acid cell to 1.67 V at 25 °C		
C_5	is the 5 h ampere-hour rating of a Ni-Cd cell to 1.0 V at 20 °C		
$H_{2\text{-rate}}$	is the hydrogen gas release rate in m ³ /s at standard sea level atmospheric pressure and 25 °C		
q_W	is the total heat produced in watts		
n_c	is the number of cells in the plant		

^aThis formula is the best estimate from available data of gassing current when floating at an approximate average upper bound of 0.19 V/cell over open circuit. This covers the majority of the installed base applications, but there may be a few where the float voltage is even higher. In such cases, the formula from A.2.3.2 should be used.

^bNote that the gassing values for high-rate (such as those used with UPS systems) vented lead-calcium batteries in this table (as well as the corresponding formulas in Table 2 and Table 5) are 3 times what they were in the initial edition (2012) of this document due to an oversight in the reference document.

^cNote that the formulas for Ni-Cd batteries in this table (as well as values in Table 2, Table 4, Table 5, and Table 7) are divided up by differing plate technologies, whereas in the original version of this document, all Ni-Cd batteries were treated the same.

7.2.4 Accelerated recharge, boost, and equalize charge modes

Accelerated recharge, boost, and equalize charge modes raise the charger output voltage above float.

7.2.4.1 Accelerated recharge mode (fast charge)

Accelerated recharging is usually done by setting the charger to the equalize voltage level for a few minutes to a few days, to more quickly replace energy following a discharge. This is not done for all applications, but is common in cycling applications. It is least common in non-cycling applications using VRLA batteries.

Accelerated recharge can be recognized by the charger being in the equalize mode, or by a bus voltage higher than the normal float voltage and battery current above the float level. See Table 2.

The primary difference between accelerated recharge and equalize charge is that during the initial stages of an accelerated recharge, nearly all the charge current is going into bulk recharge with minimal gassing. For this period of the accelerated recharge, the bulk charge calculations in Table 4 can be used. As the recharge progresses, the cells begin gassing. This is the end of the bulk charge portion of the accelerated recharge. The recharge then progresses to the equalize charge mode described in 7.2.4.3.

7.2.4.2 Boost charge mode (finish charge/absorptive charge)

A boost charge is a battery charge at a higher than usual voltage to recover capacity from an extended period of non-use or cycling. Boost charges are common in photovoltaic and other off-grid applications where battery capacity may slowly degrade due to inefficiencies associated with repeated cycling or charge-current unavailability for extended periods. For carbon-enhanced lead-acid batteries designed specifically for PSOC operation, boost charging is not always used.

Boost charges are similar to accelerated recharge, in that they are characterized by a period of bulk recharge followed by a period of equalize. They can be recognized in the same manner as an accelerated recharge. Some solar charge controllers may have more than one “boost” charge voltage setting. In those cases, the highest setting should be used in calculating gassing and heat.

7.2.4.3 Equalize charge mode

Equalize charging may be used to correct variations in state-of-charge among cells in a charged battery. It is rarely entered into automatically. Usually it is a reaction to a low voltage or voltage imbalance problem detected by maintenance or monitoring. Vented lead-acid users sometimes equalize individual cells with a single-cell charger. When individual cell equalization is used, compute gassing only for cells being equalized.

Generally, high-discharge-rate VRLA batteries are not equalize or boost (high-recharge-rate) charged. However, some UPS, PV, and engine starting chargers are set up to do this automatically and the function must be turned off if it is not desired.

The equalize mode can be recognized by the charger being visibly switched to the equalize mode or by a higher bus voltage than float. Refer to Table 2 for the calculations for this mode. Battery current will be above the float level but, due to instrument accuracy and resolution, this may not be observable using the installed instrumentation. System limits (due to maximum equipment operating voltages) may dictate equalize voltages at the low end or below manufacturer recommended values.

If calculation simplicity is desired and/or the dc system does not give the HVAC system indications of the present operating mode, the gassing calculations from Table 2 can be used as a default (in fact, some jurisdictions require that this mode be used for the gassing calculations). Not only does this calculate gassing at equalize voltage levels, but takes into account the possibility of high charger voltage (malfunction or human error), or some partially- or fully-short-circuited cells in the string. The gassing will be higher than that computed on float, but will still be small enough that an increase in ventilation airflow should not be needed.

Table 2—Accelerated recharge, boost and equalize charge modes

Battery type	Design parameter		
	Flammable gases	Toxic and corrosive gases	Heat generation
Vented lead-acid			
Lead-calcium and pure lead	$H_{2-\text{rate}} = 1.27 \times 10^{-7} \times I \times n_c$ where $I = C_8 \times 4.88 \times 10^{-4}$ a or $I = P_{15} \times 0.375$	None	$q_{\text{Wh}} = 0.369 \times I \times n_c \times t$
Lead-selenium	$H_{2-\text{rate}} = 1.27 \times 10^{-7} \times I \times n_c$ where $I = C_8 \times 0.00175$ or $I = P_{15} \times 0.448$		
Lead-antimony	$H_{2-\text{rate}} = 1.27 \times 10^{-7} \times I \times n_c$ where $I = C_8 \times 0.00492$ or $I = P_{15} \times 1.26$		
Valve-regulated lead acid			
Lead-tin or lead-calcium AGM	$H_{2-\text{rate}} = n_c \times C_8 \times 1.04 \times 10^{-11}$ $H_{2-\text{rate}} = n_c \times P_{15} \times 2.60 \times 10^{-9}$	None	$q_{\text{Wh}} = 0.449 \times I \times n_c \times t$ where $I = C_8 \times 0.00252$ or $I = P_{15} \times 0.659$
Low antimony AGM	$H_{2-\text{rate}} = n_c \times C_8 \times 5.36 \times 10^{-11}$ $H_{2-\text{rate}} = n_c \times P_{15} \times 1.34 \times 10^{-8}$		$q_{\text{Wh}} = 0.449 \times I \times n_c \times t$ where $I = C_8 \times 0.0130$ or $I = P_{15} \times 3.41$
Lead-calcium gel	$H_{2-\text{rate}} = n_c \times C_8 \times 2.60 \times 10^{-11}$		$q_{\text{Wh}} = 0.449 \times I \times n_c \times t$ where $I = C_8 \times 0.00126$
Nickel-cadmium ^b			
Sintered/PBE	$H_{2-\text{rate}} = 5.73 \times 10^{-10} \times C_5 \times n_c$	None	$q_{\text{Wh}} = 0.001 \times C_5 \times n_c \times t$
Non-recombinant Fiber or Pocket plates			
Partially-recombinant Fiber or Pocket plates			
Foamed/PBE	$H_{2-\text{rate}} = 1.08 \times 10^{-10} \times C_5 \times n_c$		$q_{\text{Wh}} = 1.90 \times 10^{-4} \times C_5 \times n_c \times t$
where			
q_{Wh}	is the heat generated, in watthours (Wh)		
t	is the time, in hours (h)		

^aThis formula represents the best estimate from available data of gassing when the boost/equalize voltage is at an approximate upper bound of 0.33 V/cell over open circuit. This covers 95% of the installed base, but there are some applications where the boost/equalize voltage may be even higher. In those cases, the formula from A.2.3.2 should be used to calculate the higher gassing current.

^bNi-Cd boost/equalize/finish charge gassing and heat release are highly dependent on the constant voltage or constant current chosen for the boost charge regime. The numbers in this table represent maximum constant-voltage equalize/boost charge voltages recommended by the manufacturer, but more accurate numbers are obtained by using the actual equalize/boost charge voltages or constant currents (see A.6.3 for further information on calculating more exact estimates).

7.2.5 Discharge

Discharge occurs whenever the batteries are called upon to deliver power to the loads, typically when ac power or other primary sources of power fail. Depending on the duration of the outage, and the design of the backup system, discharge can last from seconds to days. This mode is typically distinguished by a “battery on discharge” or “low-voltage” alarm for float applications (this is not true of cycling applications).

Lead-acid batteries on discharge have a slightly endothermic chemical reaction, so the only heating is due to current through internal and intercell resistance. In a long duration discharge, the currents are relatively low, and therefore the endothermic nature of the chemical reaction outweighs the Joule heating from the I^2R losses. Thus, the formulas in Table 3 are not provided for C_8 rates, but only for high-rate batteries. Note that the internal resistance is not calculated for Ni-Cd batteries, because the heating effects provided by that resistance are minimal, and are taken into account by the general equation provided.

Table 3—Discharge mode

Battery type	Design parameter		
	Flammable gases	Toxic and corrosive gases	Heat generation
Lead-acid high rate applications (typically rated at P_{15})	None or miniscule	None	$q_{wh} = (I \times t \times n_c) \times ((0.727 \times (s.g.)) + 0.0718 - \frac{V_{c-eod}}{2})$ where $I = \frac{I_L}{N_s}$
Lead acid long duration discharge			typically neutral or slightly endothermic; hence no formula are provided
Ni-Cd			$q_{wh} = 0.285 \times I \times t \times n_c$ where $I = \frac{I_L}{N_s}$
where N_s is the number of parallel strings feeding the load I_L is the load current in amperes (A) $s.g.$ is the nominal specific gravity (s.g.) of a fully charged cell V_{c-eod} is the average expected end-of-discharge voltage per cell at the battery plant			

7.2.6 Bulk recharge

During bulk recharge, nearly all the charge current is being used to recharge the plates and minimal to no gassing occurs. It can be identified by the charger being at current limit. Depending on the duration of the depth of discharge, the size of the batteries being recharged, and the charging current available, bulk recharge can last from seconds to days. During most of the recharge, the system voltage will slowly rise from its initial value until the charger set point is reached. Once the charger comes out of current limit, the bulk recharge period ends. As the charge current tapers off, gassing slowly begins. When the charge current reaches the normal float current, gassing rates can be calculated using Table 1, or when the normal equalize current is reached gassing rates can be calculated using Table 2).

Table 4—Bulk recharge mode

Battery type	Design parameter		
	Flammable gases	Toxic and corrosive gases	Heat generation
Vented lead-acid	None or miniscule	None	$q_{Wh} = C_{r-s} \times n_c \times 0.14$
VRLA			$q_{Wh} = C_{r-s} \times n_c \times 0.138$
Ni-Cd			$q_{Wh} = C_{r-s} \times n_c \times -8.82 \times 10^{-3}$
where C_{r-s} is the ampere-hours (Ah) removed from the string during discharge that must be replaced (see B.2.3.1.4 for further information on how to determine this factor)			

7.2.7 Initial and freshening charge modes

An initial charge (also known as a *commissioning charge*) is only applied when the battery is first placed into service. It is normally performed at equalize or higher voltage potentials (Table 5, assumes the higher voltage in order to provide the worst-case gassing and heat generation rates), but normally runs for at least double the equalize time. Due to the extended time, temperatures tend to rise higher than during an equalize charge, so that total gassing at the end of the charging period is higher. If cells have been in extended storage for greater than or equal to the manufacturer's recommended interval, the manufacturer typically recommends a freshening charge, which can be similar to an initial charge in terms of voltage, but is usually for a shorter period of time.

NOTE—Maximum storage intervals are temperature and chemistry dependent. Contact the manufacturer for storage interval recommendations based on the actual storage conditions.

An initial charge for VLA batteries typically runs between 100 h to 250 h (it can be more than that—consult the battery engineer or installer) and is manually initiated. Initial charging of VRLA batteries should only be done if recommended by the manufacturer and should be limited to the time specified by the manufacturer (it is almost never done for high rate VRLA batteries, so no equations are included for VRLA batteries with those ratings in Table 5). Ni-Cd commissioning charging is not as rare as a VRLA initial charge, and also does not last more than 48 h (note that Ni-Cd manufacturers typically recommend an initial charge at constant current and Table 5 reflects this practice).

The initial charge is a once-in-a-lifetime event for any given battery type, and so the ventilation system should not be designed to compensate for this mode of operation. Instead, the ventilation system should be designed for the other modes, and temporary ventilation may be needed during the initial charge mode. The requirement for additional ventilation should be evaluated as the existing ventilation may have the additional capacity, and temporary ventilation may not be necessary.

Table 5—Initial/Commissioning, or freshening charge mode

Battery type	Design parameter		
	Flammable gases	Toxic and corrosive gases	Heat generation
Vented lead-acid			
Lead-calcium or pure lead	$H_{2-\text{rate}} = 1.27 \times 10^{-7} \times I \times n_c$ where $I = C_8 \times 0.00157$ or $I = P_{15} \times 1.20$	None	$q_{\text{Wh}} = 0.539 \times I \times n_c \times t$
Lead-selenium	$H_{2-\text{rate}} = 1.27 \times 10^{-7} \times I \times n_c$ where $I = C_8 \times 0.00269$ or $I = P_{15} \times 0.689$		
Lead-antimony	$H_{2-\text{rate}} = 1.27 \times 10^{-7} \times I \times n_c$ where $I = C_8 \times 0.00893$ or $I = P_{15} \times 2.29$		
Valve-regulated lead acid			
Lead-tin or lead-calcium AGM	$H_{2-\text{rate}} = n_c \times C_8 \times 1.04 \times 10^{-11}$ $H_{2-\text{rate}} = n_c \times P_{15} \times 2.60 \times 10^{-9}$	None	$q_{\text{Wh}} = 0.449 \times I \times n_c \times t$ where $I = C_8 \times 0.00252$ or $I = P_{15} \times 0.659$
Low antimony AGM	$H_{2-\text{rate}} = n_c \times C_8 \times 2.68 \times 10^{-11}$ $H_{2-\text{rate}} = n_c \times P_{15} \times 6.71 \times 10^{-9}$		$q_{\text{Wh}} = 0.449 \times I \times n_c \times t$ where $I = C_8 \times 0.00650$ or $I = P_{15} \times 1.70$
Lead-calcium gel	$H_{2-\text{rate}} = n_c \times C_8 \times 2.60 \times 10^{-11}$		$q_{\text{Wh}} = 0.449 \times I \times n_c \times t$ where $I = C_8 \times 0.00126$
Nickel-cadmium			
Non-recombinant Fiber or Pocket plates	$H_{2-\text{rate}} = 2.54 \times 10^{-8} \times C_5 \times n_c$	None	$q_{\text{Wh}} = 0.0704 \times C_5 \times n_c \times t$
Sintered/PBE			
Partially-recombinant Fiber or Pocket plates	$H_{2-\text{rate}} = 1.27 \times 10^{-9} \times C_5 \times n_c$		$q_{\text{Wh}} = 0.0438 \times C_5 \times n_c \times t$
Foamed/PBE	$H_{2-\text{rate}} = 1.27 \times 10^{-8} \times C_5 \times n_c$		

7.2.8 Cycling operating mode

The cycling mode occurs when batteries are repeatedly discharged and recharged. During recharge in cyclical applications, an accelerated recharge voltage level is usually applied during the early stages of the recharge cycle, but then decreased towards a float level to reduce gassing. In many cycling applications (e.g., PV), the battery may rarely get fully recharged.

Batteries in cycling applications are usually in a discharge or recharge mode, and if the primary source is there for extended periods of time, they may be in a finish charge or float charge mode. The charging system should provide indications of the current mode of operation.

The cycling mode is determined by the design of the installation. Refer to Table 2, Table 3, and Table 4 for the calculations for the various modes during cycling operation.

7.2.9 Failure modes (abnormal operation)

7.2.9.1 General

The normal HVAC system does not need to accommodate the heat or gases generated during abnormal operation of the batteries. NFPA 1 (Fire Code) [B44], NFPA 90A [B49], the International Fire Code [B28], and other regulatory documents provide guidance for battery fires and extreme failure modes such as thermal runaway.

7.2.9.2 Thermal runaway

Thermal runaway is described in 6.3.4. As noted there, thermal runaway should be a rare event. It is more commonly associated with VRLA cells, older lead-antimony vented cells, and high-temperature environments, but can occur in almost any cell. During thermal runaway, higher currents are drawn through the battery in float or equalize mode, thereby increasing gassing.

Thermal runaway can be detected by higher than normal float currents, and/or by battery temperatures significantly higher than ambient. See Table 6.

Table 6—Thermal runaway

Battery type	Design parameter		
	Flammable gases	Toxic and corrosive gases	Heat generation
Vented lead-acid			
Pure lead or lead-calcium or lead-selenium	These cells rarely go into thermal runaway without a manufacturing defect or multiple cell failures (the design criteria of Table 2 adequately cover this slight possibility).		
Lead-antimony	$H_{2-\text{rate}} = 1.27 \times 10^{-7} \times I \times n_c$ where $I = C_8 \times 0.0217$ or $I = P_{15} \times 5.54$	Hydrogen sulfide arsine stibine	$q_w = 0.499 \times I \times n_c$
Valve-regulated lead acid			
Lead-tin or lead-calcium AGM	$H_{2-\text{rate}} = n_c \times C_8 \times 1.33 \times 10^{-10}$ $H_{2-\text{rate}} = n_c \times P_{15} \times 3.33 \times 10^{-8}$	Hydrogen sulfide	$q_w = 0.455 \times I \times n_c$ where $I = C_8 \times 0.00498$ or $I = P_{15} \times 1.29$
Low antimony AGM	$H_{2-\text{rate}} = n_c \times C_8 \times 6.82 \times 10^{-10}$ $H_{2-\text{rate}} = n_c \times P_{15} \times 1.72 \times 10^{-7}$		$q_w = 0.455 \times I \times n_c$ where $I = C_8 \times 0.0257$ or $I = P_{15} \times 6.67$
Lead-calcium gel	$H_{2-\text{rate}} = n_c \times C_8 \times 3.32 \times 10^{-10}$		$q_w = 0.455 \times I \times n_c$ where $I = C_8 \times 0.0025$
Nickel-cadmium			
Ni-Cd	It is not normally possible to drive these batteries into thermal runaway unless maintenance (water additions) is neglected and the battery is severely overcharged.		

7.2.9.3 Shorted cells

With fewer than 10% shorted (or partially shorted) cells in the string (IEC 62485-2 [B29]), gassing response is similar to equalize mode. With a higher percentage of shorted cells per string, the battery can be driven into thermal runaway.