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IEEE Guide for the Characterization and Evaluation of Sodium-Beta Batteries in Stationary Applications

IEEE Power and Energy Society

Sponsored by the
Stationary Battery Committee

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IEEE Guide for the Characterization and Evaluation of Sodium-Beta Batteries in Stationary Applications

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Stationary Battery Committee of
the
IEEE Power and Energy Society

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Abstract: This document provides guidance for evaluation of the characteristics and performance of Sodium-Beta batteries by a potential user for stationary applications. Information regarding technology description, safety, aging and failure modes, evaluation techniques, and regulatory issues is included in this guide. This document is to be used in conjunction with IEEE Std 1679™, IEEE Recommended Practice for the Characterization and Evaluation of Emerging Energy Storage Technologies in Stationary Applications. Sodium-Beta batteries include those secondary (rechargeable) electro-chemistries with sodium as the active species exchanged between the electrodes during charging and discharging, and operating above the melting point of sodium. These batteries use a solid β″-alumina electrolyte, typically written as β″-alumina. Examples of secondary Sodium-Beta batteries are sodium-metal chloride and sodium-sulfur batteries.

Keywords: battery, β″-alumina ceramic, energy storage, high-temperature battery, IEEE 1679.2™, molten salt, secondary, sodium-beta, sodium-metal halide, sodium-nickel chloride, sodium-sulfur, standby service, stationary application

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Introduction

This introduction is not part of IEEE Std 1679.2-2018, IEEE Guide for the Characterization and Evaluation of Sodium-Beta Batteries in StationaryApplications.

Sodium-Beta batteries have seen a tremendous growth in interest and application, in particular where battery size and weight and operation in wide ambient temperature ranges are of paramount interest. The use of these batteries are now being evaluated and used in stationary applications. Because of the differences between Sodium-Beta batteries and conventional industrial batteries, such as lead-acid and nickel-cadmium, there is a need for objective information and suitable evaluation techniques. This document provides a technology description, information on aging and failure modes, a discussion on safety issues, evaluation techniques and regulatory issues for the major types of Sodium-Beta batteries for use in stationary applications.

Contents

IEEE Guide for the Characterization and Evaluation of Sodium-Beta Batteries in Stationary Applications

1. Overview

1.1 Scope

This document provides guidance for an objective evaluation of Sodium-Beta energy storage technology by a potential user for any stationary application. This document is to be used in conjunction with IEEE Std 1679™ IEEE Recommended Practice for the Characterization and Evaluation of Emerging Energy Storage Technologies in SecondaryApplications.[1]

For the purposes of this document, Sodium-Beta batteries include those secondary (rechargeable) electro-chemistries with sodium as the active species exchanged between the electrodes during charging and discharging, and operating above the melting point of sodium. These batteries use a solid β″-alumina electrolyte, typically written as β″-alumina. Examples of secondary Sodium-Beta batteries are sodium-metal chloride and sodium-sulfur batteries. Non-rechargeable batteries are beyond the scope of this document.

The outline of IEEE Std 1679 is followed in this document, with tutorial information specific to Sodium-Beta batteries provided as appropriate. Examples of tutorial information include technology descriptions, operating parameters, failure modes, safety information, battery architecture, and qualification and application considerations.

This document does not cover sizing, installation, or routine maintenance and testing requirements, except insofar as they may influence the evaluation of a Sodium-Beta battery for its intended application.

1.2 Purpose

Sodium-Beta batteries have been used in various stationary and non-stationary applications for many years. With the growing availability of Sodium-Beta batteries, there is a need to provide appropriate information on safety and operating conditions related to these applications. End-users would benefit from having a guide to assist in evaluation of this technology for stationary applications.

Used with IEEE Std 1679-2010, this guide describes a format for the characterization of Sodium-Beta battery technologies in terms of performance, service life, and safety attributes. This format will provide a framework for developers and manufacturers to describe their products. The resulting information will assist

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[1] Information on references can be found in Clause 2.

users, integrators, and servicing organizations in evaluating the possible use of these batteries in stationary applications and to provide objective criteria for comparative evaluation.

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.

IEEE Std 1679™-2010, IEEE Recommended Practice for the Characterization and Evaluation of Emerging Energy Storage Technologies in StationaryApplications.[2,3]

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The IEEE Standards Dictionary Online[4] and IEEE 1881 Standard Glossary of Stationary Battery Terminology[B7][5] should be consulted for terms not defined in this clause.

molten-salt battery: a class of batteries that use molten salts as an electrolyte. See also: Sodium-Beta cell

Sodium-Beta cell: a cell containing molten or semi-molten sodium and another material, which act as the negative and positive electrodes respectively.

Sodium β″-alumina: An impermeable white ceramic, consisting of β″-alumina (β″-Al2O3) complexed with sodium ions, used in Sodium-Beta batteries as a separator and electrolyte.

sodium-nickel chloride: A Sodium-Beta cell using nickel chloride as the main material in the positive electrode.

NOTE—Most designs also include iron chloride in the positive so they are technically sodium-nickel-iron chloride cells[6]

sodium-metal chloride: A generic name for a family of sodium-based cells using one or more chlorinated metal compounds as the positive electrode material.

sodium-metal halide cell: See: sodium-metal chloride.

sodium-sulfur cell: A Sodium-Beta cell using sulfur as the positive electrode material.

3.2 Acronyms and abbreviations

BMS	battery management system
GHS	Globally Harmonized System

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[3]The IEEE standards or products referred to in this clause are trademarks of The Institute of Electrical and Electronics Engineers, Inc. [4]IEEE Standards Dictionary Online is available at: http://dictionary.ieee.org. [5]The numbers in brackets correspond to those of the bibliography inAnnexA
[6]Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

NRTL	Nationally Recognized Testing Laboratory
PPE	personal protection equipment
PSOC	partial state of charge
SDS	safety data sheets

4. Document structure

Clause 5 through Clause 9 of this document follow the clauses of IEEE Std 1679-2010. Information specific to sodium batteries is included where appropriate. Additional subclauses have been added to this document where further guidance is required.

5. Technology descriptions

5.1 General

Refer to Clause 5 of IEEE Std 1679-2010. This clause describes the main sodium batteries that are either used or are being considered for stationary battery applications. These include sodium-metal halide and sodium-sulfur. The information provided in this clause relates primarily to the energy storage system components of these technologies and does not address power conversion and grid interconnections.

5.2 Storage medium

5.2.1 General

In general, Sodium-Beta batteries utilize a hermetically sealed case to contain sodium and another material, which act as the positive and negative electrodes of an electrochemical energy storage system. These materials must operate at an elevated temperature as to be in a molten or semi-molten state (260 °C to 350 °C). A solid electrolyte that is commonly made from a β″-alumina ceramic provides the physical and electrical separation between the two molten materials.

During the charging process, an external voltage is imposed on the battery, which oxidizes the active material in the positive electrode, liberating sodium ions. The sodium ions diffuse through the ceramic and are reduced to metallic sodium, resulting in a charged battery. When a load is connected between the electrodes, a flow of the electrons is then able to pass from the positive electrode to the negative electrode resulting in the reduction of sodium ions that diffuse back through the ceramic. This diffusion allows the component remaining on the positive electrode to be oxidized.

5.2.2 Sodium-metal halide

The term “sodium-metal halide” describes a class of electro-chemistries, of which sodium-nickel chloride is the most common. Sodium-metal halide batteries consist of a nickel chloride and sodium-aluminum chloride as the positive electrode, sodium as the negative electrode, and utilize a solid electrolyte of β″-alumina ceramic that separates both electrodes. The chemistry of the sodium-nickel chloride battery becomes active when the temperature reaches about 260 °C. The open-circuit voltage of sodium-nickel chloride cell chemistry is about 2.5 V, while operating at an internal temperature in a range of approximately 250 °C to approximately 350 °C. Depending on the application, a sodium-nickel chloride battery may discharge as low as about 1.7 V per cell. The nominal recharge voltage is about 2.7 V per cell (see Figure 1).

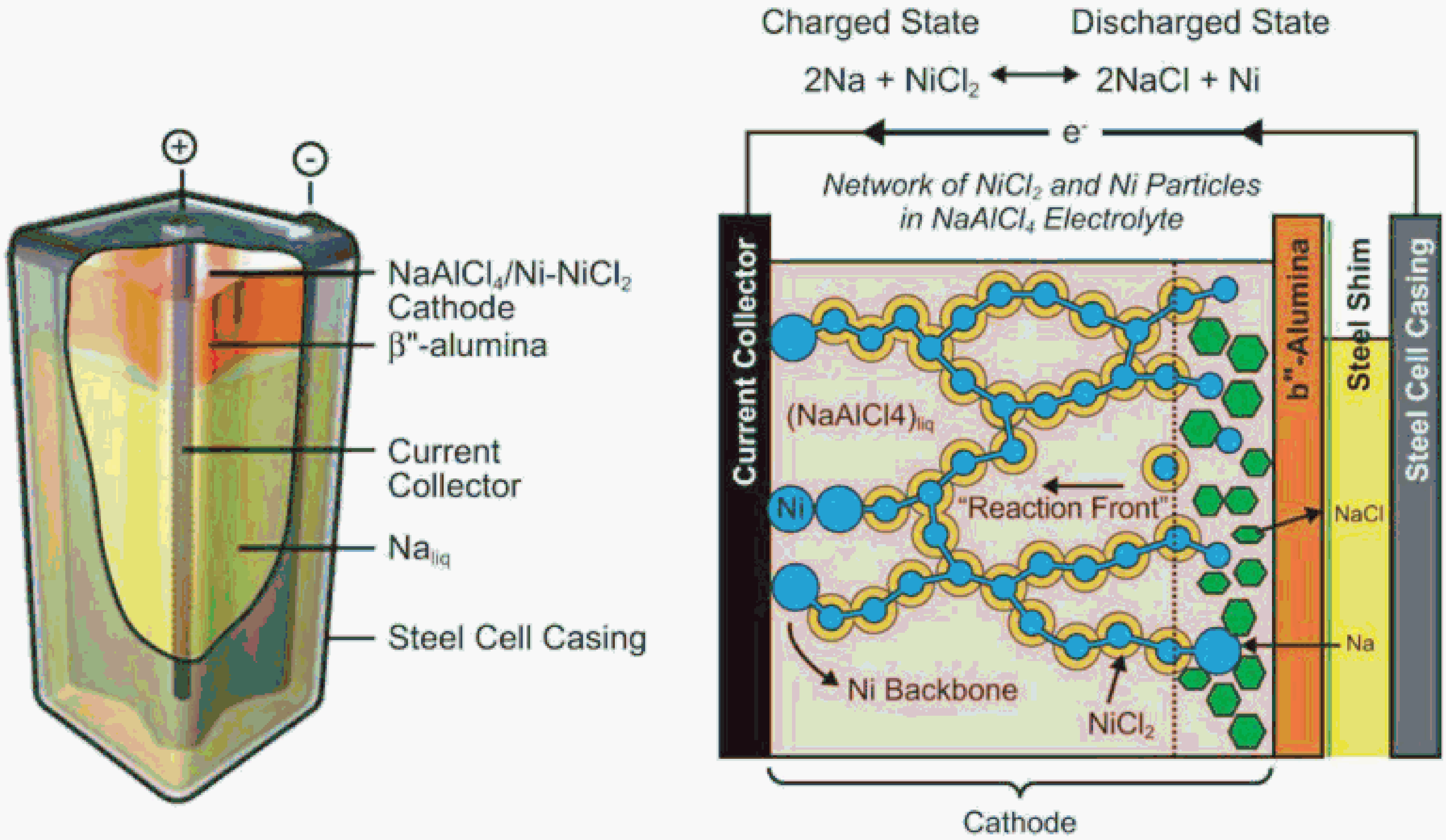

Figure 1—Sodium-nickel chloride principle

5.2.3 Sodium-sulfur

Sodium-sulfur batteries consist of sulfur as the positive electrode, sodium as the negative electrode, and utilize a solid electrolyte of β″-alumina ceramic, which separates both electrodes. The open-circuit voltage of sodium-sulfur cell chemistry is about 2.0 V. Depending on the application a sodium-sulfur battery may discharge in the range of 1.78 V to 1.90 V per cell. The chemistry of the sodium-sulfur battery becomes active when the temperature reaches about 300 °C to 350 °C (see Figure 2).

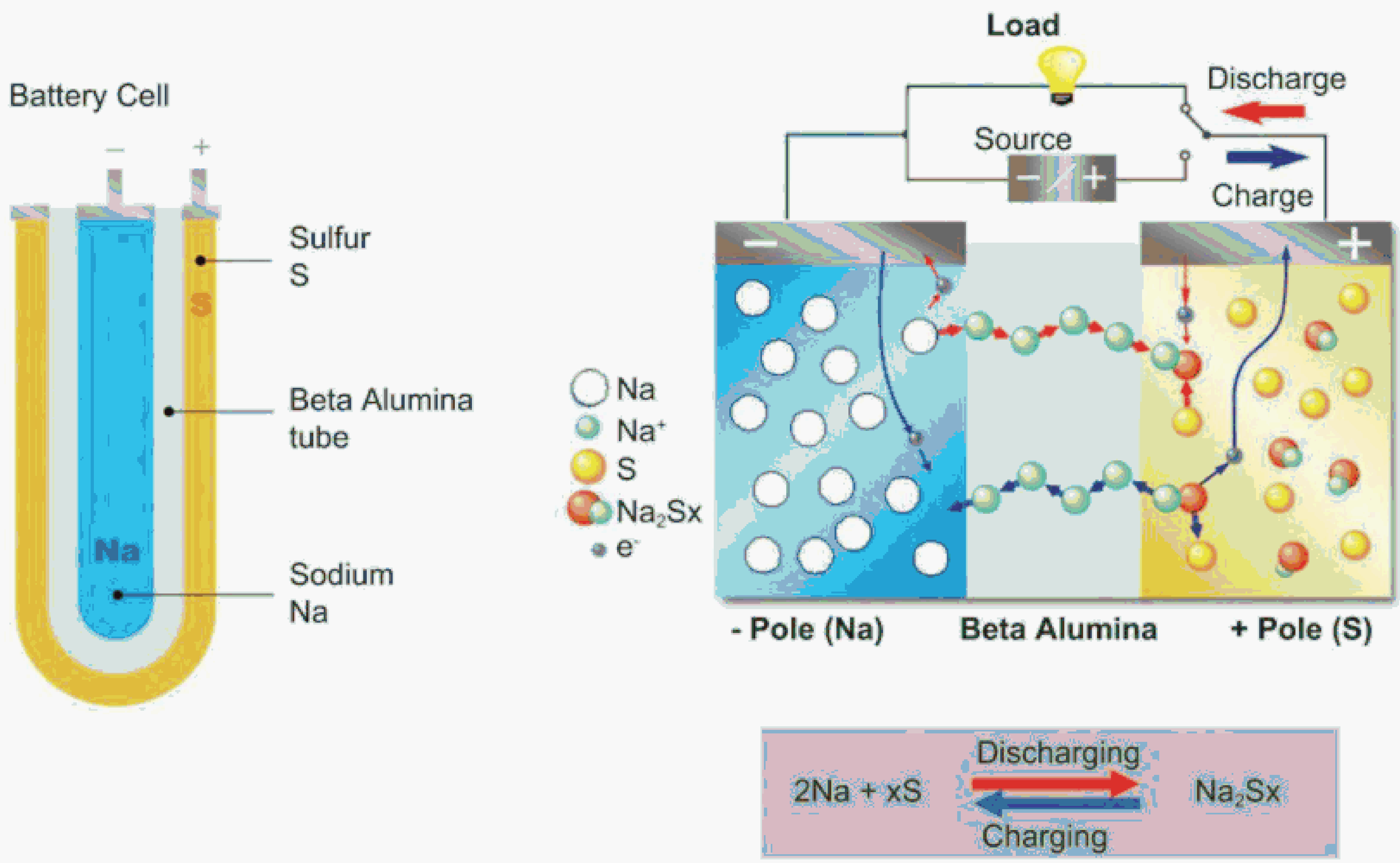

Figure 2—Sodium sulfur principle

5.3 Intended applications

Sodium-Beta battery systems are suitable for most stationary battery applications. Existing designs are optimized for longer-duration discharges (see 5.6). Theoretically, they can also be optimized for high power, making them suitable for stationary applications such as uninterruptible power supplies. They are small and lightweight compared to similar capacity lead-acid configurations, making sodium batteries attractive as replacements for applications that have limited space and increasing energy requirements.

As a result of operating at relatively high temperatures and self-regulating the operating temperature using internal heating and cooling techniques, Sodium-Beta batteries are well suited to being installed in environments with extremely wide temperature ranges. Certain Sodium-Beta technologies are offered for continuous cycling applications (e.g., grid-connected energy storage), such as frequency regulation, peak shaving, and valley fill.

5.3.1 Sodium-metal halide

Sodium-metal halide batteries are used for applications requiring energy storage with a moderate power/energy ratio. Existing designs of sodium-metal halide batteries work best for discharges of 2 h to 4 h, making them well suited for both central-office and outside-plant telecom duties, as well as other standby applications. Utility-scale installations providing 2 h to 6 h of capacity in the 100 kWh to multi-MWh range are typical, providing services such as load-leveling/peak-shaving operations and smoothing /shifting of renewable energy systems.

5.3.2 Sodium-sulfur

Sodium-sulfur batteries are applied where lower power/energy ratio is required, typically with a 4 h to 6 h discharge. They are a good fit for high-energy-density applications requiring storage for long discharges, particularly with regular cycling (see 5.6). Typical applications include utility load-leveling and peak-shaving operations, as well as use for smoothing/shifting renewable energy systems.

5.4 Components and construction

5.4.1 General

Although there are multiple chemistries and physical formats available, the following generic description applies to many commercially available sodium designs.

5.4.2 Sodium-metal halide battery components

The fundamental building block of a sodium-metal halide battery is the cell, which is sealed and contains the electrochemical reaction. The cells of sodium-metal halide batteries are generally much smaller than those of sodium-sulfur batteries. Cells are assembled into strings for the required voltage, which are then built into modules containing a single string or multiple strings in parallel. Each module is controlled by a battery management system (BMS). These assemblies are described in 5.4.2.1 through 5.4.2.3.

5.4.2.1 Cells and strings

Each cell consists of the following:

— Mechanical structure: a sealed metallic case and an electrical insulator that holds the electrodes apart. The orientation of sodium-metal halide cells is generally in the vertical position.

— Positive current collector: generally a nickel (or nickel plated) current collector with a relatively small terminal on the top center of the cell that extends deep into the active materials.

- Negative current collector: generally the outer metallic case that defines the form factor and provides much of the physical strength of the cell.
- Positive electrode: generally a mixture of common salt (NaCl) and metal (nickel, or nickel and iron, and small quantities of aluminum) in the form of granulated powder, distributed around a nickel or copper-nickel collector. The initial charge oxidizes the nickel (or metal mix) and decomposes the NaCl to sodium and chloride ions, with the chloride ions combining with the oxidized metal to form a porous metal or nickel chloride electrode.
- Negative electrode: liquid sodium.
- Electrolyte: a β″-alumina ceramic that permits the transfer of sodium ions while blocking other elements of the electrodes and liquid sodium terachloroaluminate ($NaAlCl_4$) that permits the sodium ions to be transferred during charge and discharge cycles.

Strings of cells are assembled by electrically isolating each cell in a string from the others and welding a bridging strap between the positive current collector and an adjacent negative current collector. The number of cells in a string (that are connected in series) determines the string voltage, while the number of strings in a module (that are connected in parallel) determines the capacity of the module. Bridging straps are welded in place and not bolted as thermal cycles and the inability to access these later for servicing makes this a critical component for reliability.

5.4.2.2 Module

The module provides the mechanical strength of the entire assembly, determines the footprint, while providing thermal insulation and electrical insulation between the cells and the outside environment. Construction of the module should provide for a spill containment means in the event a cell breach occurs while the materials are molten. Additionally, the thermal insulation should limit the skin temperature of the battery to a level that is safe for service personnel to routinely touch.

5.4.2.3 Battery management system

The battery management system provides the following functions:

- Manages the heating and cooling (if applicable) of the internal cells
- Protects the battery from being operated outside its allowable parameters
- Protects the load in the case a battery module malfunctions
- Provides overcurrent protection for personnel and equipment safety

Battery management systems may also provide data regarding the battery temperature, voltage, state of charge and other metrics to the operator and/or service personnel. In addition, the BMS may provide an interface to legacy charging systems (see 5.7).

5.4.3 Sodium sulfur battery components

5.4.3.1 General

The fundamental building block of a sodium-sulfur battery is the hermetically sealed cell that contains the electrochemical components. The cells of sodium-sulfur batteries are generally much larger than those of sodium-metal halide batteries. Strings are assembled by connecting the positive and negative electrode current collectors of adjacent cells (i.e., series connected) until the required voltage is achieved. Multiple strings are connected in parallel to create modules to achieve the required energy and reliability. One or more modules are housed within metallic enclosures equipped with resistance heaters to create stand-alone battery assembly. A BMS maintains the internal operating temperature of the assembly within the range of 300 °C to 350 °C during normal operation. The BMS also limits the state of charge and discharge and monitors block voltage. The stand-alone assemblies and BMS are housed within an enclosure engineered to provide heat rejection by natural circulation over the ambient temperature range of –20 °C to +40 °C. These assemblies are described in 5.4.3.2 through 5.4.3.4.

5.4.3.2 Cells and module Strings

The sodium-sulfur cell is configured as a cylinder with a rounded bottom. Each cell is composed of:

- An outer metallic cell case, which serves as the cathode current collector during discharge cycles.
- A ring-shaped sulfur impregnated graphite felt in contact with the cell case, which serves as the cathode.
- An ion-conductive electrolyte that also serves as an electron insulator (i.e., the β″-alumina solid electrolyte tube), which separates the anode and cathode.
- A central chamber containing sodium, which serves as the anode during discharge cycles. The current collectors, electrodes, and electrolyte for this cell configuration are as follows:
  - The negative current collector is a relatively small metallic terminal on the top, center of the cell and in contact with the sodium active material in the central chamber.
  - The positive current collector is the outer metallic cell case that defines the form factor and provides much of the physical strength of the cell.
  - The positive electrode is the elemental sulfur within the annular space outside of the β″-alumina tube. During discharge cycles, sulfur reacts with sodium ions to form sodium polysulfide in that space. This reaction is reversed during charge cycles.
  - The negative electrode is the metallic sodium in the central chamber.
  - The electrolyte is an ion-conductive β″ alumina ceramic tube, which permits the transfer of sodium ions while blocking electron flow between electrodes.

Strings of cells are assembled by welding a conductor strap between the positive and negative terminals of adjacent cells. The number of cells placed in series string determines the string voltage, while the number of strings placed in a parallel determines the energy capacity of the module. Adjacent modules are connected by a bus bar, and the number of modules placed in series within a module determines the module voltage and energy capacity.

5.4.3.3 Module

Asodium-sulfur battery module consists of:

- The required number and arrangement of cells
- Insulated, double-walled stainless steel container
- Resistance heaters located inside the insulated container
- Temperature and voltage sensors

The stainless steel module container provides the mechanical strength of the entire assembly, while providing thermal and electrical insulation between the cells and the outside environment. The space between cylindrical cells and the inside of the container is filled with sand for added thermal capacitance and packing stability, as well as to limit the potential for oxidation. The module container provides for spill containment in the event of a cell breach while the materials are molten.Additionally, the thermal insulation limits the skin temperature of the battery module to a level that is safe for service personnel.

5.4.3.4 Battery management system

The battery management system provides the following functions:

- Thermal management to maintain the normal internal temperature
- State of charge management to prevent over charge and over discharge
- Collection of cumulative data for cycle-life management
- Control interface between the battery and power conversion system
- Communications interface for remote monitoring
- Safety features for protection of personnel, service load and proximate equipment

5.5 Operating conditions

The operating conditions of the technology should be fully defined.

For sodium-metal halide technology, operating conditions include the following:

- Operating temperature (external): Whether ambient temperature or heated/cooled.
- Sodium-metal halide batteries are designed to operate at high temperature with an internal operating temperature of between 260 °C and 270 °C. Therefore, at colder ambient temperatures greater thermal loss will occur.
- Ambient temperature range: −40 °C to 65 °C.
- Relative humidity range: 5% to 95% RH non-condensing typical range.
- Ventilation: The required ventilation is based on the heat rejection of the individual model and desired ambient operating temperature. There are no hazardous gasses emitted from the battery that would require ventilation during either normal operation or abuse.
- Shock and vibration: Sodium-metal halide batteries are robust and designed to operate properly in a variety of vibration and seismic conditions. Products should be tested and rated for mechanical shock (drops), transportation vibration, seismic, and normal operational environment vibration. The user should ensure the battery has been tested to operate properly in the intended seismic zone, facility conditions, and intended transportation methods.
- Environmental (IP or NEMA) Ratings: Users should verify the environmental rating of the battery and/or its enclosure. These ratings can include moisture, dust ingress, mechanical protection, vermin, and other outside environmental conditions.

For sodium-sulfur technology, operating conditions include the following:

- Sodium-sulfur batteries are designed to operate at high temperature with an internal operating temperature of between 300 °C and 360 °C. Therefore, at colder ambient temperatures greater thermal loss will occur. Loss of heating power may result in damage if the active material temperature reaches the freezing point.
- Ambient temperature range: −20 °C to 65 °C.
- Relative humidity range: 5% to 95% RH non-condensing typical range.
- Ventilation: The required ventilation is based on the heat rejection of the individual model and desired ambient operating temperature. There are no hazardous gasses emitted from the battery that would require ventilation during either normal operation or abuse.

— Shock and vibration: Sodium-sulfur batteries are robust and designed to operate properly in a variety of vibration and seismic conditions. Products should be tested and rated for mechanical shock (drops), transportation vibration, seismic, and normal operational environment vibration. The user should ensure the battery has been tested to operate properly in the intended seismic zone, facility conditions, and intended transportation methods.

— Environmental (IP or NEMA) Ratings: Users should verify the environmental rating of the battery and/or its enclosure. These ratings can include moisture, dust ingress, mechanical protection, vermin, and other outside environmental conditions.

5.6 Power and energy characteristics

Each application dictates both the instantaneous power and energy necessary to support the load for the duration needed. Sodium-Beta batteries are commercially available to address a variety of load profiles, typically by providing a system solution that is pre-configured for certain applications. Traditionally, other chemistries provide individual cells or batteries that are engineered into final configurations by the user or consulting engineer. Most Sodium-Beta batteries are factory configured to address unique markets. Existing designs of sodium-metal chloride batteries typically have a power to energy ratio of between 1:2 or 1:4, resulting in a 10 kWh battery being capable of providing 5 kW for 2 h or 2.5 kW for 4 h, respectively.

Most sodium-sulfur batteries are very large (e.g., in the megawatt range) and rated for long duration (e.g., in hours) discharge.

Users should consult the manufacturer for the specific power and energy ratings before selecting batteries for their application.

While Sodium-Beta batteries may be paralleled for additional capacity, modules are generally not allowed to be configured in series to increase the voltage. Users should ensure the application voltage range and the operating voltage range of Sodium-Beta battery systems are mutually compatible when specifying batteries.

5.7 Charging characteristics

Two charging characteristics of Sodium-Beta batteries should be understood.

— As Sodium-Beta batteries are charged, the internal impedance increases until the charging current approaches 0 A at the fully charged condition. At that point a switch may be opened to discontinue charging.

— Sodium-Beta cells charge with 100% coulombic efficiency, and once they are charged, they do not self-discharge. The chemistry does not exhibit secondary reactions and materials and active materials are not consumed during storage, float, or stand-by operation. Sodium-Beta cells do, however, require occasional operation of the heater to maintain proper operating temperature. This energy could come from the charging system or the cells themselves.

As with all other battery systems, Sodium-Beta battery systems should be connected to charging sources that provide the proper voltage and sufficient charging current to support the required charge time. The battery itself will limit the charging current to the appropriate level. Some configurations of batteries may disconnect when only a small percentage (3% to 5%) of the total charging current remains. The maximum charging current will be drawn from the charger for approximately 10% to 20% of the total charging time. When interfaced with legacy charging systems, special controls or electronics (such as a dc-dc converter) may be needed in the BMS to provide the appropriate voltage and current to the battery module.

While other battery chemistries may require “trickle charging” or “float charging” to keep the batteries fully charged, Sodium-Beta batteries do not. Once charge has been terminated, the batteries remain charged until

the energy is removed through discharge. However, even when at full charge, the internal battery heaters occasionally draw power from the charging system to maintain optimal internal temperature. Although fundamentally different from float charging, the relatively small current necessary to operate the internal heaters and the BMS must be considered in the design of the charging system. Individual manufacturers may present the heating and BMS quiescent current as system current, heater current, or charging current. The heating timing and duration varies depending on the thermal insulation design. The user should verify that the time to service or warm-up time plus charge time is acceptable for the application. On standby, the ambient temperature is a factor in heater operation, while in active operation the charge-discharge profile of the application predominates.

It is acceptable to operate Sodium-Beta batteries in partial state of charge (PSOC) conditions/applications and it will not affect their calendar or cyclic life.

5.8 Active management requirements

All sodium batteries require active self-management generally accomplished by a battery management system. The user can typically access the data collected by the BMS. However, the battery management functions are autonomous. The management system provides a disconnect means and overcurrent protection.

Typically, a Sodium-Beta battery BMS will provide alarms when conditions are outside of set threshold values or safe operating parameters. Some alarm conditions may cause the battery to disconnect. The user should evaluate that these conditions are acceptable for their intended application.

5.9 Application interface

Sodium-metal halide and sodium-sulfur batteries are available in several configurations depending on the specific application. Most Sodium-Beta batteries BMS provide a user interface; however, there is not an absolute requirement for this interface. If interfacing electronics are provided, they should be evaluated for suitability of supporting the application from electrical, environmental, and mechanical perspectives. Software interfaces should likewise be evaluated for proper physical connection, protocol, and desired management functions.

Users are advised to check the protocols provided for specific applications.Sodium-Beta battery configurations may offer a variety of protocols for each application type. Typically, an RS-485, CAN-Bus, or ModBus are provided. Ethernet and other IP-based protocols may be optionally available. Refer to manufacturer information or typical schematic diagrams.

5.10 Maintenance requirements

5.10.1 Periodic maintenance

Sodium-metal halide batteries typically have low maintenance requirements. Users should perform thermal scanning of power connections during discharge (giving adequate time for temperature rise in the connections) where applicable, or verification of proper torque of power connections. Verify remote alarming continuity; proper settings of alarm thresholds in the event they were changed by an operator; and remote intelligent communications, preferably on an annual basis. If remote communication is not provided, periodic visual inspection is recommended. Discharge testing may also be used to verify correct BMS prediction of capacity.

Sodium-sulfur batteries typically have low maintenance requirements. Users may need to maintain enclosure filters, sulfur dioxide sensors and monitors, wind indication apparatus, and fire suppression systems.

5.10.2 Component replacement

Sodium-Beta batteries typically have no user-replaceable components. See manufacturer recommendations for repair or service.

5.10.3 Personnel qualification and training

There are no unique personnel qualification and training requirements specific to the use of sodium batteries. The user should always refer to the manufacturer's documentation for specific details regarding Sodium-Beta batteries.

5.10.4 Safety equipment

5.10.4.1 Sodium-metal halide

Therearenospecialpersonalprotectionequipment(PPE)requirementswhenhandling,installing,maintaining, or testing sodium batteries other than what is required for any battery. Electrical PPE is required based on the voltage at the module and battery terminals that are exposed. Because there are interrupting devices internal to the modules, any arc-flash calculations need to consider the interrupting time of these devices. There are no chemical hazards associated with sodium batteries and no chemical PPE is required. When batteries are charged and in service, electrical protection gear approved for the voltage and available current of the system is required. Refer to NFPA 70E [B10].

Fire-extinguishing agents should be determined by the manufacturer safety data sheets (SDS) and may include Class D fire extinguishers, clean agent gasses, or copious amounts of water. Only in the event of severe mechanical damage to the batteries is there a potential for active materials to be exposed.

Signage shall indicate the room contains sodium batteries and the following fire-fighting considerations:

- Flammability—materials will not burn in air when exposed to a temperature of 816 °C (1500 °F) under typical fire conditions
- Reactivity—normally stable
- Health—poses no health hazard
- Special Considerations—reacts with water in an unusual or dangerous manner

When removing a battery follow manufacturer's directions, which may recommend discharge.

5.10.4.2 Sodium-sulfur

For normal handling in storage condition, there is no special gear necessary beyond typical PPE for the weight handled and environment worked in. When batteries are charged and in service, electrical protection gear approved for the voltage and available current of the system is required. Refer to NFPA 70E [B10].

Fire-extinguishing agents should be determined by the manufacturer and reported on the SDS. Agents to be used on sodium-sulfur battery fires include dry-chemical, carbon dioxide, foam, and dry sand. Personnel fighting the fire may be required to use self-contained breathing apparatus (SCBA). Fire-fighting measures may include containment activities and water spray of nearby structures to limit spread.

5.10.5 Special tools and equipment

The user should always refer to the manufacturer's documentation for specific details regarding Sodium-Beta batteries. Sodium-sulfur batteries may require a sand sprayer and gas tanks for calibrating sodium dioxide sensors.

6. Characterization information

The information provided in Clause 3 of IEEE Std 1679-2010 applies equally to all technologies including Sodium-Beta batteries.

6.1 Submittal conventions

It is important to note that most manufacturers have a proprietary formulation for the cells used in their Sodium-Beta battery. Because of this, cell performance can vary between different chemistries and the optimal conditions can vary as well. For this reason, the specification of the conditions is particularly important for all characterization information. It is important that a user ask the manufacturer for relevant safety and performance criteria specific to the intended application and conditions when selecting a Sodium-Beta battery.

6.2 Aging mechanisms and failure modes

The aging of Sodium-Beta batteries results primarily from cycling. The BMS will exhibit calendar aging based on the thermal environment in which the product is operated. In general, higher temperatures will accelerate aging. The manufacturer should specify the cycle-life curves based on operating temperature and discharge rate. In general, deeper discharges will result in a reduction of cycle-life. The user should consult the manufacture cycle-life data to determine if the product's aging characteristics meet the requirements of the application.

Sodium-Beta batteries are designed to operate at elevated temperatures above the melting point of the metallic sodium. In the event the battery temperature falls below its operating range, the cell resistance increases due to reduced ion mobility. The BMS is designed to notify the user and prevent permanent damage to the battery, although this condition will result in loss of ability to provide energy.

In the event of a mechanical failure of the solid electrolyte (β″-alumina), the active materials can come into contact resulting in the conversion of the materials into stable solids while releasing its stored energy as heat. In sodium-metal halide this type of failure results in a short circuit, while in sodium-sulfur it results in an open circuit. Insulation systems are generally designed to contain the heat caused by a solid electrolyte failure.There may be a limitation to the number of freeze-thaw cycles that a Sodium-Beta battery can sustain before failure. Consult manufacturer data. There is a potential for terminal seal failures or other cell breaches resulting in the release of molten materials and possible short circuits. Such failures can be mitigated by the addition of fuses between cells and/or mechanical containment.

For sodium-sulfur batteries, a loss of heating in a discharged condition and subsequent freezing of the active materials will result in battery failure.

Sodium-Beta battery sub-system failures should not result in serious damage to the battery, but may cause accelerated aging.

6.3 Safety

Under standard operating conditions or single-mode failures, Sodium-Beta batteries typically do not out-gas or produce hazardous substances. See 7.3 for information on operating in non-standard or abuse conditions.

Battery Management Systems provide short-circuit, overcurrent, and under/over-voltage protections in addition to its charge and thermal management functions. The BMS can mitigate failures or unsafe conditions (see 6.2) and notify the operator of these conditions. In case of a failure of the BMS, it is unlikely that hazardous energy or material will be released. See 5.4 for a detailed description of the BMS.

There are specific chemistry-related safety issues that should be provided by the manufacturer and considered as part of the evaluation.

There are potential electrical hazards that can be mitigated with the use of proper PPE and insulated tools. See NFPA 70E [B10], IEEE Std 1657 [B5], and IEEE Std 1657a [B6] for further information.

7. Qualification testing

7.1 General

Refer to Clause 4 of IEEE Std 1679-2010.

7.2 Functional testing

7.2.1 General

These tests are typically performed once to represent serial production units.

7.2.2 Sodium based battery system and safety devices

A Sodium-Beta battery requires an electronic control management system to help ensure the battery is operated within ranges that are safe to the operator, service personnel, the environment, and the battery itself. Functional testing of Sodium-Beta batteries should be performed on a system level, including the electronic management system, to help ensure proper and safe operation. These systems provide control of the critical aspects of a Sodium-Beta battery system, examples of which are listed below.

— Proper operating temperature of the battery pack (both heating and cooling as necessary)
— Capability to deliver required energy for the specified duration
— Maximum current limitation
— Measurement of internal operating parameters (see 5.8)
— Isolation from the charging source and/or load in the case of a failure
— Any serial production testing necessary per the contract or regulatory requirements

Sodium-Beta batteries also have various safety devices to maximize safety in the event of a cell or electronic failure (see 7.4). It is important that all safety devices be in place prior to any functional testing.

7.2.3 Environmental conditions

Functional testing of Sodium-Beta batteries should be done within the expected range of environmental conditions of the final application. Important environmental factors include but are not limited to:

— Expected temperature range
— Altitude
— Humidity
— Seismic exposure
— Low-level vibration (e.g., traffic vibration)
— Airborne contaminants

7.3 Abuse tolerance

7.3.1 General

Sodium-Beta battery systems should be abuse tested to determine their safety response under various conditions. All electronic controls and all safety devices must be in place for abuse testing. Where possible, it is desirable for sodium batteries to remain functional following abuse. In the event of failure, sodium batteries are expected to fail safely (see 6.3 and 7.4). Abuse testing includes three distinct areas as listed below:

— Electrical abuse

— Environmental abuse

— Mechanical abuse

7.3.2 Electrical abuse

Electrical abuse may include the items in the list below. The abuse range tested should be selected to ensure it always encompasses the operating range. Other tests should be considered based on the potential of occurrence in the application. Testing should be appropriate for the battery chemistry and construction, including the following:

— Charger failure

— External short-circuit

— Improper setting or failure of low-voltage disconnect

— Thermal cycling due to external power failure

— Module reverse wiring connection (improper installation)

— Surge withstand

— Electrostatic discharge (ESD) withstand

— Dielectric voltage withstand

— Radiated immunity

— Conducted immunity

7.3.3 Environmental abuse

Environmental abuse may include the items in the list below. Tests may be considered based on the potential of occurrence in the application such as humidity, altitude, and airborne contaminants. Testing should be appropriate for the battery chemistry and construction, including the following:

— High temperature (operational)

— Low temperature

— Start-up at low temperature

— Temperature cycling

— Freeze-thaw cycling

— Salt-fog test

— Polymeric flame resistance test

— Needle flame test

— Flame spread criteria
— Partial/complete immersion in salt water

7.3.4 Mechanical abuse

Mechanical abuse may include the items in the list below. Other tests may be considered based on the potential of occurrence in the application. Testing should be appropriate for the battery chemistry and construction:

— Mechanical shock (drop)
— Transportation vibration
— Installed and facility vibration
— Seismic
— Crush
— Puncture/penetration
— Installation orientation

7.4 Fault tolerance

Sodium-Beta batteries have several layers of control and safety devices. These devices typically disable or prevent the sodium battery system from being operated when unsafe external or internal conditions exist. Fault tolerance is designed to test the battery system operation upon the failure of these devices, one at a time. To demonstrate maximum level of fault tolerance, such testing should be carried out under the abuse conditions listed in 7.3. Having a primary safety device disabled during these tests constitutes a double-fault event. There is not a requirement for batteries to remain functional during or after these tests. The results should document any cell-to-cell propagation failures resulting from the testing.

7.5 Field testing

Once functional and abuse testing has been completed, field-testing is typically performed in accordance with the recommendations in IEEE Std 1679-2010.

7.6 Standards compliance testing

7.6.1 General

Safety standards applicable to Sodium-Beta batteries fall into two categories:

— Universal safety standards
— Application-specific standards

Universal safety standards, as their name implies, are applied to cells, modules or batteries regardless of the intended application. Application-specific standards are intended to cover abuse conditions that the product may be subjected in specific operating scenarios.

Depending on the industry in which they are being used, Sodium-Beta batteries may be required to pass one or more standards. Some users may allow the manufacturer to perform their own testing, while others will require that the testing be performed or witnessed by a Nationally Recognized Test Laboratory (NRTL).

7.6.2 Universal safety standards

Examples of universal standards applicable to Sodium-Beta products are:

- EN 61000-6-1, applicable to individual cells and battery packs [B3]
- UL 1973, applicable to modules, packs and complete battery systems [B14]
- IEC 62477-1, applicable to battery systems with power conversion devices (see 5.7) [B2]

7.6.3 Application-specific standards

At the time of preparing this document, the only application-specific standard for Sodium-Beta batteries in stationary applications is Telcordia GR-3176 [B4], applicable to the telecommunications industry.

8. Regulatory issues

8.1 General

Refer to Clause 7.4 of IEEE Std 1679-2010.

8.2 Transportation

Sodium battery assemblies are considered hazardous materials while being transported. All sodium battery packaging should be placarded as:

- Batteries containing sodium
- Dangerous when wet
- Cargo aircraft only
- UN 3292 (special provisions 239 and 295) [B15]
- 49CFR173.189 Batteries containing sodium or cells containing sodium [B1]

Additional signage may be required to comply with individual state, county, or municipal regulations.

8.3 Safety documentation

To aid in safe installation, operation, maintenance and eventual removal, as well as provide emergency first responders with guidance, safety documentation should be provided by the manufacturer.

GHS Harmonized SDS or battery information sheets may be provided to satisfy these criteria. This safety documentation may provide additional details on appropriate signage that may be required by local authorities (such as NFPA 704 signage (US) or international as required) [B12].

8.4 Permitting issues

The manufacturer should identify any hazardous materials or conditions required for state, county, or municipal code compliance and installation/operational permits. Refer to Clause 6.4 of IEEE Std 1679-2010.

8.5 Certification

It is important for the end-user to confirm that the appropriate regulations were properly met and that documentation is available if necessary for verification.

Certification of electromagnetic compatibility (immunity from electromagnetic fields and limiting emissions of electromagnetic fields) is important for the BMS electronics of Sodium-Beta batteries.

8.6 Disposal and recycling

Sodium-Beta batteries are generally not disposed of as standard household waste, and disposal or recycling should follow manufacturer instructions.

Sodium-metal halide batteries should be returned to the manufacturer for disposal and/or recycling. Batteries should be in a discharged state and shipped per manufacturer's instructions (see 8.2). An alternative to disposal is having the battery repaired by the manufacturer.

9. Evaluation techniques

9.1 General

The end user should consider the operational characteristics as well as the intended installation environment when evaluating Sodium-Beta batteries.

9.2 Application considerations

9.2.1 General

In addition to general applications considerations detailed in 7.2.1 of IEEE Std 1679-2010, the end user should consider the following aspects associated with Sodium-Beta batteries:

— Heat dissipation and current consumption (current consumption is generally greater than other technologies)

— Service duty (freeze-thaw cycle of active materials)

— Ambient temperature range (heating system efficiency increases with higher ambient temperature)

— Time to service (warm up prior to recharge)

— System size and weight

— Cycle life (frequency and depth of discharging)

— System reliability

— End-of-life disposition

9.2.2 Balance of system components

Part of the evaluation of a Sodium-Beta system should include thermal regulation system, BMS electronics, and any included interfaces. The system designer should verify that these components are suitable for the expected site conditions and should evaluate overall system reliability accordingly.

9.2.3 Safety

The user should evaluate the safety characteristics of Sodium-Beta battery systems to determine comparative risks with other technologies under consideration. For example, the availability of appropriate fire suppression methods, required mechanical safety or segregation, ventilation criteria, and PPE should be considered. See 6.3.

9.2.4 Code compliance

The end user is responsible for compliance to all relevant codes and should consider how a Sodium-Beta battery will be regulated by the authority having jurisdiction (AHJ). Both the IFC and NFPA 1 [B9] have specific requirements for Sodium-Beta batteries. These codes include specific criteria including maximum allowable quantities, maximum string size, physical location limitations, signage, fire suppression and detection, hazard mitigation analysis, spill control, and seismic requirements.

NFPA 111 [B11] provides additional criteria for battery systems and a new energy storage document NFPA 855 [B13] also may apply to some Sodium-Beta battery installations. Some municipalities impose additional codes that exceed these model codes with additional limitations and certification criteria for battery rooms and personnel.

9.3 Life-cycle costing

9.3.1 General

It will generally be necessary to evaluate the costs associated with anticipated life and disposal of Sodium-Beta batteries. The manufacturer should provide the user detailed life data (predictive or actual) for new Sodium-Beta battery systems based on the intended application. Typical failure modes and conditions affecting these occurrences should be provided. See 6.2.

The user may be able to obtain life-cycle data from the battery management system. Consult the manufacturer for information on the product.

Annex A

(informative)

Bibliography

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

[B1] 49 CFR 173.189, Batteries Containing Sodium Cells or Containing Sodium.[7]

[B2] EN 62477-1, Safety requirements for power electronic converter systems and equipment—Part 1: General.[8]

[B3] EN 61000-6-1, Electromagnetic compatibility (EMC). Generic standards. Immunity for residential, commercial and light-industrial environments.

[B4] GR-3176, Generic Requirements for Sodium Nickel Chloride (Molten Salt) Batteries For TelecommunicationsApplications.[9]

[B5] IEEE Std 1657™-2009, IEEE Recommended Practice for Personnel Qualifications for Installation and Maintenance of Stationary Batteries.

[B6] IEEE Std 1657a™-2015, IEEE Recommended Practice for Personnel Qualifications for Installation and Maintenance of Stationary Batteries—Amendment 1: Updated Safety Sections.

[B7] IEEE Std 1881™-2016, IEEE Standard Glossary of Stationary Battery Terminology.

[B8] International Fire Code, Section 608, Stationary Storage Battery Systems.[10]

[B9] NFPA 1, Fire Code Chapter 52: Energy Storage Systems.[11]

[B10] NFPA 70E®, Standard for Electrical Safety in the Workplace, 2015.

[B11] NFPA 111, Standard on Stored Electrical Energy Emergency and Standby Power Systems.

[B12] NFPA 704: Standard System for the Identification of the Hazards of Materials for Emergency Response.

[B13] NFPA 855, Standard for the Installation of Stationary Energy Storage Systems.

[B14] UL 1973, Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER)Applications.[12]

[B15] UN 3292, Batteries, containing sodium.[13]

[7] CFR publications are available from the U.S. Government Printing Office (http://www.gpo.gov/).
[8] EN publications are available from the European Committee for Standardization (CEN) (http://www.cen.eu/).
[9] Available at: https://telecom-info.telcordia.com/site-cgi/ido/docs.cgi?ID=SEARCH&DOCUMENT=GR-3176&#ORD
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