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Aging Management Guideline for Commercial Nuclear Power Plants – Stationary Batteries

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AGING MANAGEMENT GUIDELINE FOR COMMERCIAL NUCLEAR POWER PLANTS- STATIONARY BATTERIES

FINAL REPORT

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Abstract

This Aging Management Guideline (AMG) describes recommended methods for effective detection and mitigation of age-related degradation mechanisms in BWR and PWR commercial nuclear power plant stationary batteries important to license renewal. The intent of this AMG is to assist plant maintenance and operations personnel in maximizing the safe, useful life of these components. It also supports the documentation of effective aging management programs required under the License Renewal Rule 10 CFR Part 54. This AMG is presented in a manner that allows personnel responsible for performance analysis and maintenance to compare their plant-specific aging mechanisms (expected or already experienced) and aging management program activities to the more generic results and recommendations presented herein.

MASTER

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1. EXECUTIVE SUMMARY

1.1 Purpose and Objectives

Continued operation of nuclear power plants for periods that extend beyond their original 40-year license period is a desirable option for many U.S. utilities. Effective aging management of plant components is important to reliability and safety, regardless of current plant age or extended life expectations. Before granting approval for operation beyond 40 years, the U.S. Nuclear Regulatory Commission (NRC) requires that aging evaluations be performed for components considered important to license renewal which could have age-related degradation unique to license renewal. The existence of appropriate aging management programs, or the justification that an effective aging management program is not needed, must be demonstrated for such components. Both the NRC and the utility want assurance that high reliability for plant components which support safety functions is maintained, during both the current license term and throughout the extended life operating period.

The purpose of this Aging Management Guideline (AMG) is to describe recommended methods for effective detection and mitigation of aging mechanisms in nuclear plant stationary batteries important to license renewal and important to safe, reliable power production. The intent of this AMG is to assist plant maintenance and operations personnel in maximizing the safe, useful life of these batteries. This AMG also supports the documentation of effective aging management programs required under the License Renewal Rule 10 CFR 54.[1.1]

This AMG has the following objectives.

- Provide practical guidance to plant technical and maintenance staff for managing aging mechanisms for stationary batteries, which are critical components to safe plant operation and are also important to license renewal.
- Define this guidance in a step-by-step, "if-then" approach, with observable and measurable criteria and corrective steps. This guidance is based on industry and vendor research, plant experience, and results of the U.S. NRC's Nuclear Plant Aging Research (NPAR) Program.[1.2]
- Cover the majority of stationary battery types, manufacturers, applications, and environments, as confirmed by a survey of components in current use in nuclear plants.
- Define the reasoning for components not covered, or those considered not subject to a long-term aging management program.

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- Provide sufficient reasoning for the use of this AMG as a reference document for a license renewal application under 10 CFR 54.

1.2 Scope

This AMG defines aging mechanisms and effective life cycle management techniques for commercial nuclear power plant stationary batteries. These batteries are important to plant safety and operability, under the current licensing basis and per 10 CFR 54.[1.1] The components discussed herein are found in both boiling water reactor (BWR) and pressurized water reactor (PWR) facilities. The primary target audience for this guideline are plant engineering, operations, and maintenance personnel, although it will also be of interest to those involved with nuclear plant extended life programs. The AMG is presented in a manner which allows personnel responsible for performance analysis and maintenance to compare their plant-specific aging mechanisms (expected or already experienced) and aging management program activities to the more generic results and recommendations presented in this AMG.

The strategy for preparing this guideline includes 1) identifying battery types, major subcomponents, and typical operating conditions, and 2) collecting and evaluating operating/maintenance history information, identifying the stressors acting on these batteries, and determining the significance of the battery aging mechanisms. After completing these tasks and reviewing currently utilized aging management practices, guidelines are presented for effective management of these batteries.

The input for development of this AMG includes design data, operating/maintenance history (including degradation findings and failure incidents), and current inspection, testing, and maintenance program activities. The information is obtained from a variety of sources including NRC publications, computerized industry databases, manufacturer literature, individual nuclear plant records, and aging management reports and papers prepared by Electric Power Research Institute (EPRI), U.S. Department of Energy (DOE), and engineering consultants.

Stationary batteries provide an emergency DC power source in the event of a loss of normal system AC/DC power, a loss of all AC power, or a station blackout (SBO) event. The batteries provide power directly to critical DC loads or, via DC-to-AC inverters, to critical AC loads such as diesel generator starter motors, circuit breakers, control relays, annunciators, and safety-related instrumentation.

Stationary batteries are composed of individual storage cells, which are connected together to provide the required voltage and current. A typical cell consists of two active materials, electrolyte, terminals, a vent cap, separators, racks, a container/cover assembly, and intercell connectors with associated hardware.

Table 1-1 lists the manufacturers of stationary batteries for commercial nuclear power plants, as determined from a review of data reported to the Institute for Nuclear Power Operations (INPO) Nuclear Plant Reliability Data System (NPRDS).

Table 1-1. Battery Manufacturers Used in Commercial Nuclear Power Plants

Manufacturer	% in Use (NPRDS)*	Battery Type	Plant Type
C&D Charter Power Systems	38.1%	Lead-acid, nickel-cadmium	BWR, PWR
GNB Batteries (formerly Gould Ind. Battery Div.)	27.5%	Lead-acid, nickel-cadmium	BWR, PWR
Exide Corp.	27.1%	Lead-acid, nickel-cadmium	BWR, PWR
SAFT Nife Inc. (formerly SAB Nife Inc.)	2.4%	Nickel-cadmium	PWR
BBC Brown Inc.	1.6%	Lead-acid	PWR
Electro-Motive	1.6%	Lead-acid	BWR
Power Battery	1.6%	Lead-acid	BWR

* As reflected from data in the INPO Nuclear Plant Reliability Data System.

1.3 Conclusions

This AMG evaluates all known aging mechanisms for nuclear power plant stationary batteries. Section 4 examines these aging mechanisms first for relevancy, and then the relevant mechanisms are examined to determine which are significant, and which are non-significant. No distinction was made as to whether or not the aging mechanism was "unique to license renewal." Section 5 examines aging management programs/techniques to determine which are effective for detecting and/or mitigating the significant aging mechanisms.

In general, the stationary batteries employed in different plants are constructed from the same materials and subcomponents, and are subject to similar operating conditions. Additionally, the subcomponent parts of these batteries are made of the same materials, and are subject to similar operating conditions. It was therefore possible to prepare this AMG on a generic basis by examining the stressors and aging mechanisms that affect the subcomponent parts that make up the batteries.

1.3.1 Aging Mechanism Conclusions

The aging mechanisms considered in this AMG are described in Section 4.2.1 and are:

- Material Chemical Changes
- Corrosion
- Fatigue
- Wear
- Thermal Aging
- Contamination
- Gassing and Electrolyte Evaporation
- Fouling

Wear was generally determined to be a non-relevant aging mechanism, since stationary batteries have no moving components and periodic maintenance activities do not create significant wear stresses (Section 4.2.1.4).

The remaining aging mechanisms were found to be relevant and were evaluated for significance in Section 4.3 on a subcomponent basis. Each of these mechanisms was found to be significant for at least one subcomponent part used in the batteries. Tables 4-7, 4-8, and 4-9 summarize the significance of these aging mechanisms for each subcomponent part.

The aging management programs/techniques that effectively manage the significant aging mechanism/subcomponent combinations are discussed in Section 5.

1.3.2 Aging Management Program Conclusions

The aging management programs/techniques presented in this AMG were divided into two groups: commonly used programs/techniques and less commonly used programs/techniques. These are listed below.

Commonly Used Aging Management Programs/Techniques

- Preventive Maintenance (Routine Inspections and Operability Checks)
- Surveillance Program
- "Good Housekeeping" Practices - Operation Logs and Checklists
- On-Line Monitoring and Annunciator Response Procedures
- Corrective Maintenance Procedures
- Class 1E Battery Seismic Qualification
- Operational Experience Reviews and Trending

Less Commonly Used Aging Management Programs/Techniques

- Continuous Environmental Monitoring and Environment Mitigation
- Sample Cell Analysis
- Battery Charger Output Waveform Monitoring
- Battery Impedance Testing
- Battery Conductance Testing
- Infrared Thermographic Inspection
- Periodic Battery Replacement
- Potential Surveillance Tests for Detecting Seismic Vulnerability

The commonly used programs/techniques are currently implemented at most nuclear facilities. The less commonly used programs/techniques may be implemented at some nuclear plants, but in general are not in wide use and may not be formalized with written procedures. Effective aging management programs must (see [1.1]):

1. Identify and mitigate age-related degradation unique to license renewal,

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2. Contain acceptance criteria against which the need for corrective action can be evaluated and assure timely corrective action when the acceptance criteria are not met, and
3. Be implemented by the facility operating procedures and reviewed by the onsite review committee.

The aging management programs/techniques and typical inspection frequencies are described generically in Section 5.2 (Common Programs) and Section 5.3 (Less Common Programs), and the relationship between these aging management programs/techniques and the significant aging mechanisms determined in Section 4 is examined. The results of this examination are shown in Tables 5-4 and 5-5 (Common Programs) and 5-14 (Less Common Programs). These tables relate the aging management programs/techniques to the significant aging mechanisms for the individual battery subcomponents.

Section 5.4 provides qualitative and quantitative "if-then" criteria with decision branches, for use by inspectors, surveillance testers, and/or system engineers, to compare plant-specific program coverage against programs/techniques determined to be effective at detecting and mitigating the significant aging mechanisms. Recommendations are made regarding minimum recommended programs/techniques, highly recommended programs/techniques, and less used but highly proactive programs/techniques. These criteria and recommendations are summarized in Tables 5-15 through 5-21. The minimum recommended programs from Tables 5-15, 5-16, and 5-19 are repeated at the end of Section 1 in Tables 1-2 through 1-4.

These tables indicate that currently available programs are generally effective at detecting and mitigating aging mechanisms in stationary batteries. **No broad, new industry programs are required.**

The uncertainty of seismic vulnerability of the aged Class 1E lead-acid batteries which are not qualified per IEEE 535-1986 remains an issue for battery aging management. Current inspections and surveillance tests will detect degradation in a battery's ability to deliver its rated power capacity, but not the internal structural strength of the battery that may make it vulnerable to a design basis event. Because the qualified electrical life of a battery is probably longer than its seismic-qualified life, aged batteries not seismically qualified at end-of-life conditions may fail during a seismic event, even though the batteries are capable of delivering required capacity before the event. Practical methods for detecting or mitigating the corrosion condition of relevant battery internal parts which is the cause of the potential problem are under development. Three options for monitoring and estimating the battery degradation condition related to seismic vulnerability include disassembly inspection of artificially aged sample cells, seismic testing of artificially aged sample cells, and periodic disassembly inspection of sample cells. Further research and development work is needed to find improved surveillance and monitoring techniques for identifying incipient seismic vulnerabilities of aged batteries.

New "round-cell" battery designs developed by AT&T for telephone system applications minimize or eliminate many of the common aging mechanisms inherent in the traditional rectangular multi-cell design currently used in nuclear plants. Application of round-cell

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technology is beginning in U.S. plants. This technology also offers the potential for reduced surveillance and maintenance frequency.

Section 6 provides further discussion on these issues which may affect plant-specific aging management program planning.

Table 1-2. Minimum Recommended Aging Management Programs and Activities for Large Lead-Acid Stationary Batteries

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Preventive Maintenance or Surveillance	Inspect for General Cleanliness of the Battery, Battery Rack, and Battery Area	At Least Monthly	Material Chemical Changes Corrosion Fatigue Fouling	
	Measure and Record the Float Voltage at the Battery Terminals	At Least Monthly	Material Chemical Changes Corrosion Thermal Aging Gassing and Electrolyte Evaporation Fouling Dryout (Valve-Regulated Design) Thermal Runaway (Valve-Regulated Design)	
	Measure and Record the Charger Output Current and Voltage	At Least Monthly	Material Chemical Changes Corrosion Thermal Aging Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design) Thermal Runaway (Valve-Regulated Design)	
	Check and Record Electrolyte Levels	At Least Monthly	Gassing and Electrolyte Evaporation	Vented Design Only
	Inspect for Cracks in Cells or Leakage of Electrolyte	At Least Monthly	Material Chemical Changes Fatigue	

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Table 1-2. Minimum Recommended Aging Management Programs and Activities for Large Lead-Acid Stationary Batteries (continued)

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Preventive Maintenance or Surveillance (continued)	Inspect for Corrosion at Terminals, Connectors, and Racks	At Least Monthly	Corrosion Fouling	
	Record Ambient Temperature and Condition of Ventilation Equipment	At Least Monthly	Thermal Aging Corrosion Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design) Thermal Runaway (Valve-Regulated Design)	
	Record Pilot Cell Voltage, Specific Gravity, and Electrolyte Temperature	At Least Monthly	Material Chemical Changes Corrosion Thermal Aging Gassing and Electrolyte Evaporation	Vented Design Only
	Record the Specific Gravity of Each Cell	3 Months	Material Chemical Changes Gassing and Electrolyte Evaporation	Vented Design Only
	Record the Voltage of Each Cell and the Battery Terminal Voltage	3 Months	Material Chemical Changes Corrosion Thermal Aging Wear (Valve-Regulated Design Only)	
	Record the Temperature of the Electrolyte in Representative Cells	3 Months	Thermal Aging Gassing and Electrolyte Evaporation	Vented Design Only
	Visually Inspect and Record the Condition of Each Cell	Annually	Material Chemical Changes Corrosion Fatigue Fouling	

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Table 1-2. Minimum Recommended Aging Management Programs and Activities for Large Lead-Acid Stationary Batteries (continued)

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Preventive Maintenance or Surveillance (continued)	Measure and Record the Cell-to-Cell and Terminal Connection Detail Resistance	Annually	Corrosion Fatigue Fouling	
	Check and Record the Integrity of the Battery Rack	Annually	Corrosion Fatigue	
Surveillance	Perform a Battery Service Test	Annually or Once/Cycle	Material Chemical Changes Gassing and Electrolyte Evaporation Corrosion Thermal Aging	Safety-Related Vented Batteries Only
	Perform a Battery Performance Test Under As Found Conditions (Vented Batteries)	5 Years	Material Chemical Changes Gassing and Electrolyte Evaporation Corrosion Thermal Aging	If battery shows signs of degradation or has reached 85% of its expected service life, then increase frequency to annually or once/cycle.
	Perform a Battery Performance Test Under As Found Conditions (Valve-Regulated Batteries)	Annually or Once/Cycle	Material Chemical Changes Dryout Corrosion Thermal Aging	If battery shows signs of degradation or has reached 85% of its expected service life, then increase frequency to semi-annually.
Class 1E Seismic Qualification	Seismically Qualify the Batteries and Racks in Accordance with Reg. Guide 1.158 and IEEE STD 535-1986	Once	Fatigue	

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Table 1-2. Minimum Recommended Aging Management Programs and Activities for Large Lead-Acid Stationary Batteries (continued)

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
"Good Housekeeping" Practices - Operation Logs and Checklists	Log Float Voltage and Current	Once/Shift	Material Chemical Changes Corrosion Thermal Aging Thermal Runaway (Valve-Regulated Design)	
	Log Ambient Temperature	Once/Shift	Corrosion Thermal Aging Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design) Thermal Runaway (Valve-Regulated Design)	
	Electrolyte Level Check	Once/Shift	Gassing and Electrolyte Evaporation	
	Visual Observation	Once/Shift	Material Chemical Changes Corrosion Fatigue Fouling	
On-Line Monitoring and Annunciator Response Procedures	Alarm for Low Battery Voltage	Continuous	Material Chemical Changes Corrosion Thermal Aging	
	Alarm for High Battery Voltage	Continuous	Thermal Runaway (Valve-Regulated Design)	
Corrective Maintenance	Perform an Equalize Charge	As Indicated by Low Cell Voltages or Following a Battery Discharge	Material Chemical Changes Thermal Aging	

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Table 1-2. Minimum Recommended Aging Management Programs and Activities for Large Lead-Acid Stationary Batteries (continued)

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Corrective Maintenance (continued)	Clean and Tighten Terminations and Intercell Connectors	As Indicated by High Resistance Readings or Visible Corrosion or Fouling	Corrosion Fatigue Fouling	
	Properly Remove and Restore Cells During Battery Maintenance or Replacement	Whenever Battery Cells are Removed or Installed	Material Chemical Changes Fatigue	

Table 1-3. Minimum Recommended Aging Management Programs and Activities for Large Nickel-Cadmium Stationary Batteries

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Preventive Maintenance or Surveillance	Inspect for General Cleanliness of the Battery, Battery Rack, and Battery Area	At Least Monthly	Material Chemical Changes Corrosion Fatigue Fouling	
	Measure and Record the Float Voltage at the Battery Terminals	At Least Monthly	Thermal Aging Gassing and Electrolyte Evaporation Fouling Dryout (Valve-Regulated Design)	
	Measure and Record the Charger Output Current and Voltage	At Least Monthly	Thermal Aging Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design)	
	Check and Record Electrolyte Levels	At Least Monthly	Gassing and Electrolyte Evaporation	Vented Design Only

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Table 1-3. Minimum Recommended Aging Management Programs and Activities for Large Nickel-Cadmium Stationary Batteries (continued)

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Preventive Maintenance or Surveillance (continued)	Inspect for Cracks in Cells or Leakage of Electrolyte	At Least Monthly	Material Chemical Changes Fatigue	
	Inspect for Corrosion at Terminals, Connectors, and Racks	At Least Monthly	Corrosion Fouling	
	Check and Record the Operability of the Ventilation Equipment	At Least Monthly	Thermal Aging Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design)	
	Record Pilot Cell Electrolyte Temperature	At Least Monthly	Thermal Aging Gassing and Electrolyte Evaporation	Vented Design Only
	Record the Voltage of Each Cell	3 Months	Material Chemical Changes Thermal Aging Wear (Valve-Regulated Design Only)	
	Measure and Record the Cell-to-Cell and Terminal Connection Detail Resistance	Annually	Corrosion Fatigue Fouling	
	Check and Record the Integrity of the Battery Rack	Annually	Corrosion Fatigue	
Surveillance	Perform a Battery Service Test	Annually or Once/Cycle	Material Chemical Changes Gassing and Electrolyte Evaporation Thermal Aging	Safety-Related Vented Batteries Only

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Table 1-3. Minimum Recommended Aging Management Programs and Activities for Large Nickel-Cadmium Stationary Batteries (continued)

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Surveillance (continued)	Perform a Battery Performance Test Under As Found Conditions (Vented Batteries)	5 Years	Material Chemical Changes Gassing and Electrolyte Evaporation Thermal Aging	If battery shows signs of degradation or has reached 85% of its expected service life, then increase frequency to annually or once/cycle.
	Perform a Battery Performance Test Under As Found Conditions (Valve-Regulated Batteries)	Annually or Once/Cycle	Material Chemical Changes Dryout Thermal Aging	If battery shows signs of degradation or has reached 85% of its expected service life, then increase frequency to semi-annually.
"Good Housekeeping" Practices - Operation Logs and Checklists	Log Float Voltage and Current	Once/Shift	Material Chemical Changes Thermal Aging	
	Log Ambient Temperature	Once/Shift	Corrosion Thermal Aging Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design)	
	Electrolyte Level Check	Once/Shift	Gassing and Electrolyte Evaporation	
	Visual Observation	Once/Shift	Material Chemical Changes Corrosion Fatigue Fouling	
On-Line Monitoring and Annunciator Response Procedures	Alarm for Low Battery Voltage	Continuous	Material Chemical Changes Thermal Aging	

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Table 1-3. Minimum Recommended Aging Management Programs and Activities for Large Nickel-Cadmium Stationary Batteries (continued)

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Corrective Maintenance	Clean and Tighten Terminations and Intercell Connectors	As Indicated by High Resistance Readings or Visible Corrosion or Fouling	Corrosion Fatigue Fouling	
	Properly Remove and Restore Cells During Battery Maintenance or Replacement	Whenever Battery Cells are Removed or Installed	Material Chemical Changes Fatigue	

Table 1-4. Recommended Programs/Techniques for Small Stationary Batteries

Programs/Techniques	Vented Lead-Acid Type	Vented Nickel Cadmium Type	Valve-Regulated Batteries	Comments
Routine Inspections				
<u>Monthly</u>				
• General appearance and cleanliness of battery and battery surrounding area	X	X	X	• Frequencies of inspection may vary, depending on the requirements of plant Technical Specifications, related regulatory requirements or operating experience.
• Battery electrolyte level	X	X		
• Signs of physical damage and electrolyte leakage	X	X	X	• Annual inspection can be performed in conjunction with capacity test.
• Verification of float voltage (use existing meter if available)	X	X	X	

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Table 1-4. Recommended Programs/Techniques for Small Stationary Batteries (continued)

Programs/Techniques	Vented Lead-Acid Type	Vented Nickel Cadmium Type	Valve-Regulated Batteries	Comments
Routine Inspections (continued)				
<u>Annual (or refueling)</u>				
• Ensuring clean and tight terminal connections	X	X	X	
• If applicable, using a calibrated meter to verify the existing meter	X	X	X	
Capacity Tests				
• Performance or service test on an annual or a refueling outage basis	X	X	X	• Test frequency may be determined by plant Technical Specifications, related regulatory requirements or operating experience.
• Acceptance test at initial installation (as necessary)	X	X	X	
Periodic Battery Replacement	X	X	X	<ul style="list-style-type: none"> • Replacement intervals are to be established based on manufacturer's information and operating experience. • Adequate replacement intervals may allow measures to relax capacity test frequencies, or even to eliminate capacity tests for non-safety-related batteries.

1.4 References

- 1.1 Title 10, U.S. Code of Federal Regulations, 10 CFR Part 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants," December 13, 1991.
- 1.2 NUREG-1144, "Nuclear Plant Aging Research (NPAR) Program Plan - Status and Accomplishments," U.S. Nuclear Regulatory Commission, Revision 2, June 1991.

2. INTRODUCTION

2.1 Background

The DOE-sponsored Plant Lifetime Improvement (PLIM) Program, in cooperation with the Electric Power Research Institute (EPRI) Life Cycle Management (LCM) Program, is establishing and demonstrating a predictable license renewal process for existing light water reactors (LWRs) in the United States. An important element of this program was the development of Nuclear Management and Resources Council (NUMARC) License Renewal Industry Reports (IRs), which cover critical classes of equipment such as reactor pressure vessels, reactor coolant pressure boundary piping, containment structures, and low-voltage environmentally qualified cables. To support continued demonstration of PLIM and LCM concepts, there is a need for further industry development of guidelines that describe and evaluate acceptable aging management approaches for several groupings of equipment not evaluated in the IRs. This Aging Management Guideline (AMG) evaluates stationary batteries determined to be important to license renewal.[2.1]

Continued operation of nuclear power plants for periods that extend beyond the original 40-year license period may be desirable for many U.S. nuclear plant operators. To allow operation of the plant during a license renewal period, utilities must show that the aging unique to license renewal of components important to license renewal has been managed such that these components will not degrade to the extent that they are incapable of supporting required functions. Therefore, to control the aging of components important to license renewal during the license renewal period, operators of nuclear power plants must identify and perform activities necessary to manage the aging of components so that proper function is assured.

For components to retain function during the license renewal period, activities such as preventive maintenance and refurbishment may be necessary during the current license period even though some of these activities may not have been necessary to guarantee function during the current license period. These activities would be necessary to assure that there is no loss of required functions, no unacceptable reduction in safety margins, and that higher rates of challenge to plant safety systems do not occur during the license renewal period.

2.2 Purpose and Objectives

The purpose of this AMG is to provide cost-effective, practical methods to plant technical staff for the management of aging in batteries, and to provide generic technical support for the license renewal integrated plant assessment under 10 CFR 54.

The objective of this AMG is to provide an analysis of the potential degradation modes for stationary batteries and to provide acceptable guidelines for developing effective aging management programs for controlling significant degradation mechanisms.

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The step-by-step evaluation approach is:

- Define which batteries in the plant are important for power production or important to license renewal, and therefore require evaluation. Document bases for methodology used to select these batteries.
- Define which battery components/subcomponents are classified as "consumables" or "renewables," and not subject to a formal aging management program.
- Specify battery boundaries (inputs, outputs, bounded subcomponents).
- Identify the predominant types of batteries (manufacturer, type, rating, class, service, etc.), and design similarities and differences relevant to aging management guidelines.
- Identify types of battery components which are excluded and why (i.e., low number in service, unique to one plant, etc.).
- Identify relevant plant design requirements, NRC regulatory and licensing requirements, and relevant codes and standards (only as they relate to aging management).
- Identify relevant license renewal requirements.
- Examine and review industry operating history for these batteries, and by trending or other analysis reach conclusions on relevant aging mechanisms.
- Define applicable stressors and associated aging mechanisms.
- Determine relevance and significance of aging mechanisms to batteries or their subcomponents.
- Define generic elements of an "effective" aging management program for significant aging mechanisms.
- Identify and review common maintenance, surveillance testing, inspection, refurbishment and replacement techniques and programs used for batteries, for their effectiveness in aging management (including trending).
- Identify and review "new" or "plant-unique" methods used for aging management.
- Correlate effective programs with component/aging mechanism combinations.
- Prepare guidelines to detect and mitigate significant aging mechanisms for the battery type.
 - Measurement and verification criteria
 - "If-then" acceptance criteria

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— "If-then" criteria for mitigative or refurbishment activities

- Identify potentially significant aging mechanism/component combinations not addressed by an effective plant program.
- Recommend options for new programs, and enhancements of existing practices, to deal with mechanism/component combinations not covered by a current effective program.
- Address other issues relevant to developing a plant-unique program.

This AMG is intended for use by nuclear plant personnel performing stationary battery aging evaluations and to provide additional information and guidance in the formulation of their aging management programs. This AMG also provides additional value to nuclear plant operators as follows.

1. The AMG is a well-researched technical document that can be used by maintenance and system engineering personnel for the identification, characterization, and management of age-related degradation in stationary batteries. It can also be used as a base document for plants developing a license renewal application.
2. The results in this AMG are based on an extensive literature search. Therefore, nuclear plant personnel can use this AMG as an exhaustive compilation reference document for relevant information about stationary batteries. Some of the references used include:
 - EPRI Reports
 - EPRI Nuclear Maintenance Application Center (NMAC) Reports and Maintenance Guides
 - NRC Bulletins, Information Notices, Circulars, Generic Letters and Reports
 - Code of Federal Regulations
 - Vendor Manuals
 - Institute of Electrical and Electronics Engineers (IEEE) and other Standards
 - Foreign References and Technical Papers
3. This AMG consolidates historical maintenance and industry operating information into one source. The plant maintenance/system engineer will find this useful for both the identification of age-related degradation (including root causes) and the verification of appropriate corrective action. Issues discussed in the guideline include:
 - Equipment design differences relevant to aging considerations

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- Equipment obsolescence as it affects aging management
 - Service environments
 - Operating and maintenance history from the INPO NPRDS and NRC License Event Report (LER) databases
 - Historical overhaul data from refurbishment facilities
 - Additional operating and maintenance history from responses to plant surveys
4. Stationary battery aging phenomena are described in detail. This will be useful for maintenance interval and reliability evaluations. The following topics are discussed.
- Stressors acting on battery components
 - Aging mechanism identification
 - Significance of aging mechanisms using "if-then" criteria
 - Age-related degradation of stationary batteries components
 - Potential failure modes
5. The AMG can be an effective tool for stationary battery aging management and personnel training. That is, it:
- Identifies the need for aging management and compliance with maintenance rule requirements
 - Contains a correlation between the scope and frequency of maintenance practices and stationary battery performance and rate of degradation
 - Presents information that can be used in the construction of meaningful life-cycle management charts and to improve the accuracy of cost/benefit determinations
 - Discusses both conventional and non-conventional maintenance techniques, and considers how these practices can be utilized to effectively manage equipment aging
 - Characterizes initiation and progression of equipment aging for use in training personnel responsible for maintenance and inspection activities
 - Identifies concepts, principles, and methods for evaluating stationary batteries not in the scope of this guideline.

2.3 Contents of Aging Management Guideline

This AMG covers nuclear plant stationary batteries, which provide emergency DC power to critical plant AC and DC loads during loss of battery charger(s), loss of normal (offsite) AC power, or station blackout (SBO) events. This includes stationary batteries which supply loads important to license renewal under 10 CFR 54.

Section 3 of the guideline describes the stationary batteries by surveying the equipment used, identifying the materials of construction, and discussing the different types of designs. Section 3 also includes a breakdown of the subcomponents (or subassemblies) that need to be examined. The subcomponents which are classified as renewable are identified. Industry operating, maintenance, and aging management experience for the components is provided and evaluated. This information provides data to support and substantiate the conclusions of this aging management evaluation.

Section 4 of this guideline provides a discussion of the various stressors acting on the batteries. Stressors manifest over time into aging mechanisms, which ultimately cause component degradation if not detected and mitigative actions implemented. The relative influence of these stressors to cause degradation of battery subcomponents is summarized in tabular form. The results of aging studies are used to describe aging mechanisms known to cause degradation. An aging mechanism is potentially significant when, if allowed to continue without detection or mitigation measures, its aging effects could cause the component to function outside of acceptance criteria. Aging mechanisms for the subcomponents are identified and evaluated. Operational demands, environmental conditions, failure data, and industry operations and maintenance history are considered, and the significance of the aging mechanisms determined. The approach addresses the theoretical basis for aging degradation and the operating experience.

Section 5 discusses effective aging management techniques for the aging mechanisms determined in Section 4 to be significant. Common maintenance, inspection, testing, and surveillance techniques/programs are described. A brief discussion of less common activities and techniques is also included. The effectiveness of these techniques/programs for managing the significant aging mechanisms is evaluated. Variations in plant aging management programs/techniques are considered. The minimum set of requirements for an effective program/technique is presented in the form of "if-then" criteria.

Section 6 discusses the unique issue of seismic vulnerability in aged stationary batteries not qualified per IEEE 535-1986. Short-term management options which provide marginal assurance of stationary battery reliability with respect to a seismic event are discussed. Section 6 also discusses the option of "round-cell" technology for battery replacements, yielding improved resistance to aging mechanisms.

2.4 Generic License Renewal Requirements

10 CFR 54.21 [2.1] describes the requirements for the content of technical information in the license renewal application. Section 54.21 states that a supplement to the Final Safety Analysis Report (FSAR) must be prepared that contains an Integrated Plant Assessment (IPA) that must:

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1. Identify and list all systems, structures, and components (SSCs) important to license renewal,
2. Identify those structures and components (SCs) that contribute to the performance of a required function or could, if they fail, prevent an SSC important to license renewal from performing its required function, and
3. For the identified SCs, determine those that could have age-related degradation that is unique to license renewal.

To identify the age-related degradation* that is unique to license renewal (in item (a)(3) of Section 54.21), the definition of age-related degradation unique to license renewal must be applied. Age-related degradation unique to the license renewal period[2.1] is degradation:

1. That occurs during the term of the current operating license, but whose effects are different in character or magnitude after the term of the current operating license (the period of extended operation); or
2. Whose effects were not explicitly identified and evaluated by the licensee for the period of extended operation and the evaluation found acceptable by the NRC; or
3. That occurs only during the period of extended operation.

The criteria for determining SSCs important to license renewal, the criteria for evaluating whether an SC is necessary for the performance of a required function, and the technical criteria used to determine whether an SC is subject to age-related degradation unique to license renewal must be defined.

For each of the SCs having age-related degradation that is unique to license renewal, the age-related degradation must be addressed by an effective program or shown not to need to be addressed by an effective program. An effective program is a documented program to manage age-related degradation unique to the license renewal period that ensures that an SSC important to license renewal will continue to perform its required function or will not prevent the performance of a required function during the period of extended operation.

The effective program must:

1. Identify and mitigate age-related degradation unique to license renewal,
2. Contain acceptance criteria against which the need for corrective action can be evaluated and assure timely corrective action when the acceptance criteria are not met, and

* See definitions for the aging terminology used in this AMG.

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3. Be implemented by the facility operating procedures and reviewed by the onsite review committee.

10 CFR 54.21 continues with a discussion of changes to the current licensing basis and plant modifications, which are outside the scope of this report.

Additionally, this AMG supports the determination that existing aging management practices are satisfactory for fulfilling license renewal requirements and meeting review conditions stated in the draft version of NUREG-1299, "Standard Review Plan for the Review of License Renewal Applications for Nuclear Power Plants." [2.2] Components included in the classification of "important to license renewal" are identified, and stressors, aging mechanisms, and failure modes for these components are defined. Furthermore, this guideline states the type of existing practices that are acceptable for the management of aging as well as areas requiring further plant-specific evaluation. Exemptions and requests for relief (pursuant to 10 CFR 50.12 and 10 CFR 50.55a, respectively) were not considered under this guideline in that these areas are plant-specific in nature and therefore must be considered on a plant-by-plant basis.

This report will evaluate stationary batteries with respect to the requirements of 10 CFR 54.21 and will provide a discussion of the types of stationary batteries important to license renewal and the age-related degradation affecting components and subcomponents of the stationary batteries. The following sections detail the analysis leading to the determination of age-related degradation and the means necessary to address it.

2.5 Method Used to Define Scope of Components Important to License Renewal

The review and evaluation of plant equipment for license renewal differs from the initial licensing of the plant. A substantial operating history of plant stationary batteries has been established, and the current licensing basis of the plant has evolved since the original license was issued. Therefore, the basis for license renewal is to continue safe and reliable plant operation in accordance with the current licensing basis taking into consideration the maintenance and operating history. A structured approach is used to identify the plant components which are required for safe and reliable plant operation and important to license renewal.

The License Renewal Rule [2.1] requires an IPA to complete a license renewal application. The IPA identifies SSCs important to license renewal, identifies significant age-related degradation which may affect SSC functioning, and evaluates effective programs credited for detecting and managing this aging during the license renewal term. The requirements of the integrated plant assessment are further defined in the NRC's draft Regulatory Guide [2.3] and the NRC's draft Standard Review Plan. [2.2] The integrated plant assessment is reviewed by the NRC during processing of the license renewal application.

To determine the stationary battery covered by license renewal requirements, the definition of SSCs important to license renewal [2.1] must be evaluated. The current definition of SSCs important to license renewal includes:

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1. Safety-related SSCs, which are those relied upon to remain functional during and following design basis events to ensure:
 - (i) The integrity of the reactor coolant pressure boundary;
 - (ii) The capability to shut down the reactor and maintain it in a safe shutdown condition; or
 - (iii) The capability to prevent the consequences of accidents that could result in potential offsite exposure comparable to the 10 CFR Part 100 guidelines.
2. All non-safety-related SSCs whose failure could directly prevent satisfactory accomplishment of any of the required functions identified in paragraphs (1) (i), (ii), or (iii) of this definition.
3. All SSCs relied on in safety analyses or plant evaluations to demonstrate compliance with the Commission's regulations for fire protection (10 CFR 50.48), environmental qualification (10 CFR 50.49), pressurized thermal shock (10 CFR 50.61), anticipated transients without scram (10 CFR 50.62), and station blackout (10 CFR 50.63).
4. All SSCs subject to operability requirements contained in the facility's Technical Specifications' Limiting Conditions for Operation.

Reference 2.2 identifies stationary batteries in plant DC power systems and instrument AC power systems as important to license renewal. These components supply motive and control power to equipment that is safety-related or important to safety. Sections B.4.3.1 and B.4.3.2 of Reference 2.2 provide the regulatory basis for inclusion of these batteries in effective aging management programs.

In addition, the battery/battery charger systems associated with control power to breakers and switchgear in the switchyard are identified in Reference 2.2, Section B.4.7.1 as important to license renewal and subject to the requirements of effective aging management. Control of offsite power sources is a Technical Specification Limiting Condition of Operation.

Plant-specific design of emergency (or essential) lighting systems may include self-contained lighting packs with an integrated battery/battery charger. Operation of the emergency lighting system may be credited in the design basis response to fire or loss of offsite power events. If so credited, then the emergency lighting pack battery/battery charger unit is important to license renewal, and subject to an effective aging management program. This is covered by Section B.4.5 of Reference 2.2.

Plant-specific design of computer systems may include portions or all of a computer system which is used in Class 1E safety-related systems for monitoring or control purposes. Post-accident monitoring, safety-grade signal processing, and safety-grade digital control subsystems may meet the definition of 10 CFR 54.3 as important to license renewal. In addition, "information systems" such as the Safety Parameter Display System, and displays associated with Regulatory Guide 1.97 compliance, may be credited in the current licensing basis, and be

important to license renewal under 10 CFR 54. Such computer systems may have local batteries associated with their reliable performance. These batteries would then be subject to effective aging management programs. Sections B.4.6 and B.4.8 of Reference 2.2 address these systems.

The plant-specific selection of stationary batteries for effective aging management must first consider the requirements of 10 CFR 54.3. Further guidance on the plant screening process for selecting the components is provided in the draft NRC Regulatory Guide DG-1009.[2.3] Additional guidance may also be available from the Monticello License Renewal Application, when docketed. At the time of this guideline preparation, the NUMARC had established draft guidance through a Screening Methodology Ad Hoc Advisory Committee document,[2.4] but the industry had not formally adopted this guidance document.

Beyond the requirements of license renewal, selection of stationary batteries for effective aging management should also consider the plant-unique current licensing basis. Commitments made during resolution of the Station Blackout issue, or in response to individual plant examinations and probabilistic risk analyses, or in response to electrical distribution system functional inspections, may influence the selection of additional batteries to be covered under the effective aging management guidelines of this document. The recent adoption of the Maintenance Rule, 10 CFR 50.65,[2.5] creates interrelated requirements for evaluating maintenance performance and root cause analysis of age-related degradation.

The Monticello and Yankee Rowe Lead Plant License Renewal Programs represented the first application of the License Renewal Rule methodology. These programs determined that **all stationary batteries currently installed in the plant are important to license renewal**. This suggests that the effective aging management guidance presented in this document should be applied to all stationary batteries in a plant. This universal application of effective aging management programs is confirmed by the extent to which NPAR program research has focussed on these components, as detailed in Section 3.

2.6 Method Used to Define Aging Mechanisms Assessed in This Study

This guideline document researches two broad sources of information for determining effective aging management practices, including the identification of aging stressors and mechanisms, and the review of programs which detect and mitigate this aging. These two sources include the following.

1. Industry Research Results

- a. EPRI, and its Nuclear Safety Analysis Center and Nuclear Maintenance Applications Center, have completed several research programs and maintenance guidelines related to batteries in nuclear and fossil plant applications.
- b. The IEEE, through its Nuclear Power Engineering Committee, has developed several standards related to design, operation, and maintenance of stationary batteries. Subcommittee 3, Working Groups 3.3 and 3.4, of IEEE directs this effort. The IEEE draft standard for assessing, monitoring, and mitigating aging effects on Class 1E equipment[2.6] is of particular importance.

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The IEEE standards have subsequently been referenced in NRC Regulatory Guides and the Standard Review Plan for License Renewal.

- c. The NRC's NPAR Program, as defined in Reference 2.7, has researched aging stressors and mechanisms for stationary batteries, including significant compilation of historical performance data. These are documented in a series of NUREG technical reports as detailed in Sections 3 and 4.
- d. NUREG-0304,[2.8] periodically issued by the U.S. NRC, provides abstracts of research and data collection activities performed under NRC sponsorship.
- e. A search was made of relevant industry research papers through the DIALOG database, which accesses a variety of government, academic, and private industry abstract sources.

2. Industry Experience Records

- a. A host utility provided detailed information on stationary battery design performance and aging management techniques, and served to benchmark this guideline document.
- b. Questionnaires were sent to all operating U.S. commercial nuclear power plants, requesting design, operating, and performance/aging data for their stationary batteries. In addition, utilities were asked to submit copies of their procedures and programs for maintenance, testing, and inspection. A 15% return was achieved and contributed significant information to this report.
- c. NRC Inspection and Enforcement bulletins, notices, circulars, and letters were reviewed for relevant age-related events, root cause analyses, and mitigative actions for stationary batteries.
- d. The INPO NPRDS was accessed for reported failure events related to aging issues. INPO Significant Event Reports and Significant Operating Event Reports were also reviewed for relevant events.
- e. The NRC Licensee Event Report database, which documents component failures, causes, and corrective actions, was accessed via Oak Ridge National Laboratory for the batteries in review.
- f. The vendors who supplied the majority of stationary batteries in use in U.S. nuclear power plants were contacted for information on age-related failures and mitigative techniques which may have been developed.
- g. The Pilot Plant Life Extension reports for Monticello and Surry, as available, and the Monticello and Yankee Lead Plant License Renewal Program Reports, as available, were reviewed as a confirmation of the relevant aging mechanisms and effective aging management programs utilized.

An analysis of these industry documents and databases is provided in Section 3.

Article 54.21 of Reference 2.1 requires that age-related degradation unique to license renewal must be effectively managed. This guideline evaluates all age-related degradation and associated aging mechanisms. **No attempt was made to identify the stressors, aging mechanisms, or the corresponding age-related degradation that may be unique to the license renewal period.** Because the unique to license renewal period screen was not used in the evaluation process, the scope of components important to license renewal may be significantly larger in this AMG.

2.7 References

- 2.1 Title 10, U.S. Code of Federal Regulations, 10 CFR Part 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants," December 13, 1991.
- 2.2 NUREG-1299, "Standard Review Plan for the Review of License Renewal Applications for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, Draft for Comment, November 1990.
- 2.3 Regulatory Guide DG-1009, "Standard Format and Content of Technical Information for Applications to Renew Nuclear Power Plant Operating License," U.S. Nuclear Regulatory Commission, Draft, December 1990.
- 2.4 NUMARC Report Number 90-11, "Methodology to Evaluate Plant Systems, Structures, and Components for License Renewal," Nuclear Management and Resources Council, December 1990.
- 2.5 Title 10, U.S. Code of Federal Regulations, 10 CFR Part 50.65, "Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants," July 10, 1991.
- 2.6 IEEE Standard P-1205, "IEEE Guide for Assessing, Monitoring, and Mitigating Aging Effects on Class 1E Equipment Used in Nuclear Power Generating Stations," Institute of Electrical and Electronics Engineers, Unapproved Draft, October 26, 1992.
- 2.7 NUREG-1144, "Nuclear Plant Aging Research (NPAR) Program Plan — Status and Accomplishments," U.S. Nuclear Regulatory Commission, Revision 2, June 1991.
- 2.8 NUREG-0304, "Regulatory and Technical Reports (Abstract Index Journal), Annual Compilation for 1992," U.S. Nuclear Regulatory Commission, Volume 16, No. 4, March 1992.

3. EQUIPMENT AND COMPONENTS EVALUATED

This section identifies the light water reactor (LWR) stationary batteries to be evaluated for life cycle management. Sections 3.1 through 3.4 describe the selection methodology, the equipment in the evaluation scope, and the groupings of subcomponents established for evaluation. The key design codes and standards, operating history, and the associated aging implications are discussed in Sections 3.5 and 3.6, respectively.

3.1 Selection Methodology

Identifying the stationary batteries to be evaluated for life cycle management involved the review of industry documents, plant documents for typical boiling water reactors (BWRs) and pressurized water reactors (PWRs), and a survey of utility engineers. The review of industry documents included the following.

1. Review of 10 CFR 54, Definitions of Systems, Structures and Components Important to License Renewal,[3.1] and the draft Standard Review Plan for License Renewal.[3.2]
2. Review of BWR Lead Plant Project Technical Reports.[3.3]
3. Review of PWR Technical Demonstration Project (EPRI) Technical Findings.[3.4]
4. Review of 10 CFR 50.65 Maintenance Rule.[3.5]

These documents provide current industry and NRC thinking with respect to selecting the stationary batteries that are important to a life cycle management program, and the aging and performance issues that need to be evaluated. The License Renewal Rule[3.1] and Maintenance Rule[3.5] use similar criteria for selecting systems, structures, and components that need to be addressed by the requirements of these rules. The License Renewal Rule focuses on the detection and mitigation of age-related degradation, while the Maintenance Rule focuses on maintaining performance. Equipment meeting the selection criteria of these two rules is also important to life cycle management. The methodology used to select the equipment evaluated in this guideline was provided in Section 2.5.

A survey/questionnaire was sent to every operating U.S. commercial nuclear power plant. Seventeen (17) plants provided plant-specific data on batteries. This data was used for comparison of equipment selection, and for comparison to industry document summaries of maintenance and operation histories. Utility data compared favorably with the equipment selection and historical data. No previously unknown degradation mechanism was identified.

3.2 Evaluation Scope

The selection methodology described in Section 3.1 was applied to the stationary batteries to be evaluated.

3.2.1 Stationary Batteries

Batteries are used in a variety of systems in a nuclear power plant. Based on their application, batteries are categorized as primary batteries or secondary batteries. A primary battery is defined as a multicell battery that has a nonreversible chemical process and is the normal source of power in the application. A secondary battery is defined as a battery which has a reversible chemical action (i.e., is rechargeable) and typically provides backup power. In a nuclear power plant, secondary battery applications account for almost all of the stationary battery installations. The batteries evaluated in this report are secondary batteries.

The typical applications of stationary batteries in nuclear power plants include the following.

1. Plant-wide DC power distribution systems (Class 1E and non-Class 1E) that power various plant DC and AC (via inverters) auxiliary loads.
2. Plant offsite switchyard DC control power sources.
3. Dedicated DC distribution systems that power some specific loads.
4. Uninterruptible power supply (UPS) equipment for computer systems or communication systems.
5. Dedicated single loads, such as an engine cranking source or an emergency lighting unit.

Based on Reference 3.1 and 3.2 criteria, the stationary batteries included in this guideline are:

1. 250 Vdc, 125 Vdc, and 48/24 Vdc station batteries used in the DC power distribution systems.
2. 12 Vdc and 6 Vdc stationary batteries used in emergency lighting units.
3. Stationary batteries that support fire protection, anticipated transients without scram, station blackout requirements, or other requirements credited in the plant current licensing basis.
4. Stationary batteries serving relay/control systems in the switchyard.
5. Stationary batteries serving equipment which is subject to operability requirements in the plant Technical Specification Limiting Conditions for Operation.

The lower voltage batteries (24 Vdc and 48 Vdc) are usually associated with specific loads, such as special control and instrumentation circuits, a stand-alone UPS system, or engine cranking power. The 125 Vdc and 250 Vdc batteries are more often used in applications

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Figure 3-1. Typical 125 Vdc Distribution System.

involving plant-wide DC power distribution, including powering DC motors and serving as part of a UPS system. A typical 125 Vdc distribution system is shown in Figure 3-1.

3.2.2 Subcomponents

Stationary batteries consist of a number of subcomponents. These subcomponents and their basic functions are listed in Table 3-1. The particular subcomponents included in stationary batteries varies among types. Section 3.4 describes the differences among various battery designs.

It is regarded as standard maintenance practice to replace certain components or component parts during normal maintenance activities. These components and parts are designated as "renewable" for the purpose of aging management evaluation. Plant programs which call out "renewables" are stipulated to be inherently effective in managing age-related degradation for the renewables.

The criteria that must be met by the renewable components are:

- The component is a low cost item.
- A large number of functionally identical components are represented in the plant.
- An adequate inventory of replacement components exists.
- The component can be replaced in a time frame that would not require a plant shutdown.
- The renewable components are widely used in other industrial applications.

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Table 3-1. Stationary Battery Subcomponents

Subcomponent	Function	Material	Required for Successful Operation	Renewable	Further Evaluation Required
Grid	Support structure for active material, conductor of current from active material to plate terminal.	lead/lead-calcium/lead-antimony (lead-acid battery); nickel/nickel plated steel/nickel plated fibers (nickel-cadmium battery)	Yes	No	Yes
Active Material	Compound that undergoes a chemical reaction to produce an electrical current.	lead-negative plate lead dioxide - positive plate (lead-acid battery), nickel hydroxide - positive plate cadmium hydroxide - negative plate (nickel-cadmium battery)	Yes	No	Yes
Electrolyte	Electrically conductive solution/gel surrounding the plates which reacts with the active materials to produce an electric current.	Sulfuric acid (lead-acid battery), potassium hydroxide (nickel-cadmium battery)	Yes	No	Yes
Separator	Porous, nonconductive material installed between the plates to prevent the plates from touching and shorting.	Rubber/glass mat or microporous polyethylene	Yes	No	Yes
Retainer	Porous mat wrapped around the positive plate edges (and sometimes between plates) in lead-acid batteries to prevent shedding of active material from the plate.	Fiberglass	Yes	No	Yes
Case/Cover/Gasket	Plastic leak-proof enclosure housing battery components and electrolyte.	Polycarbonate, styrene acrylonitrile, butadiene styrene	Yes	No	Yes
Top Conductor/Straps	Metal conductor located at the top of the cell which serves to support the plates and connects electrically the positive (and negative) plates of a cell together.	Lead alloy, sometimes with copper (lead-acid battery), nickel/steel (nickel-cadmium battery)	Yes	No	Yes
Terminal Posts	Metal conductors which electrically connect the top conductors for the negative and positive plates to the cabling outside the cell. Usually designed for bolted connections.	Lead alloy, sometimes with copper inserts (lead-acid batteries), nickel/steel (nickel-cadmium battery)	Yes	No	Yes
Flame Arrestor	Device installed on the cover of vented batteries to allow gasses, evolved during charging, to escape while preventing spark or flame from entering the cell. Also prevents excess electrolyte evaporation.	Fused aluminum	Yes	Yes	No

Table 3-1. Stationary Battery Subcomponents (continued)

Subcomponent	Function	Material	Required for Successful Operation	Renewable	Further Evaluation Required
Pressure Relief Valve	The pressure control device (valve-regulated batteries only) used to maintain a specific internal cell pressure to optimize the recombination efficiency of the cell.	Miscellaneous	Yes	No	Yes
Racks	Free standing structure providing support and protection to cells during normal operation and seismic events.	Steel	Yes	No	Yes
		Fiberglass (AT&T Round Cell)			
Terminal Post Seals	Seal/gasket between terminal post and cell cover to maintain leak-tight barrier and prevent gasses and electrolyte from escaping.	Rubber, plastic	Yes	Yes	Yes (in combination with post)
Intercell Connectors and Associated Hardware	Provide electrical connection to adjacent cells.	Lead Plated Copper (Lead-Acid)	Yes	No	Yes
		Nickel Plated Copper (Nickel-Cadmium)			

- The renewable component is typically replaced on a periodic or corrective basis, and not refurbished.

Table 3-1 identifies the standard renewable subcomponents for stationary batteries. Evaluations and additional actions to detect and mitigate age-related degradation for renewables are not required.

The remaining stationary battery subcomponents included in this evaluation are identified in Table 3-1.

3.3 Component Boundaries

This section defines the boundaries of component evaluation for this guideline.

Stationary batteries of relatively large sizes are usually supported off the floor using battery rack structures (see Figure 3-2), while smaller batteries are usually supported by the equipment they serve. The component evaluation boundaries for large batteries include the battery cells, installation racks, and termination connections at which the battery is tied to a DC bus/charger through bus-bars/cables. The bus-bars or power cables connected to the battery are not included in the evaluation scope.

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For batteries installed on the equipment they serve, evaluation boundaries only include the battery cells and cell interconnections or cell unit. The associated battery supports are equipment dependent and are considered part of the equipment, and are not addressed in this AMG.

Figure 3-2. Typical Vented Lead-Acid Battery (with Rack).[3.6]

3.4 Description of Components Evaluated

Batteries store energy in a chemical form. Charging and discharging of batteries are basically chemical reaction processes. The essential parts of a rechargeable battery cell are two dissimilar electrodes immersed in or in contact with an electrolyte in a container. The active materials on the electrodes (plates) react with the electrolyte and provide current during discharge to convert the battery's stored chemical energy into electrical energy. The electrochemical process can also be reversed when an externally applied electrical power source directs the energy into the battery cell, resulting in a reverse reaction. While the design function of a secondary battery is always the same (storing energy and providing DC power when needed), the specific design and performance requirements vary based on the application. For instance, some applications require a battery capable of delivering a high power output rate over a relatively short period of time. Other batteries are expected to power loads continuously for a considerable period of time. Variations in application call for significantly different discharge characteristics of batteries, and contribute to design variations in battery type and configuration.

Most batteries consist of multiple cells or multi-cell units interconnected to achieve the required voltage and capacity levels. Single unit multi-cell batteries may be found in some low voltage, low capacity applications, such as emergency lighting units.

3.4.1 Predominant Types of Components

The types of stationary batteries currently used in a nuclear power plant may include lead-acid, nickel-cadmium, silver-cadmium, and other types. Among them, the lead-acid and nickel-cadmium batteries account for well over 90% of the total battery installations in the U.S. nuclear power plants. Stationary batteries are also commonly divided into vented and valve-regulated designs. Because of similarity in design, the lead-acid and nickel-cadmium valve-regulated battery types are discussed together. Table 3-2 lists the characteristics of various battery types.

3.4.1.1 Vented Lead-Acid Battery

The vented lead-acid battery is the most commonly used battery in nuclear power plants. Figure 3-2 shows a line of vented lead-acid cells.

Basic Cell Construction

The following basic components constitute a single vented lead-acid cell.

- Container
- Lead Dioxide Positive Plates
- Lead Negative Plates
- Post, Strap, and Seal Assembly
- Separators and Retainers
- Sulfuric Acid Electrolyte
- Intercell Connectors and Associated Hardware

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Table 3-2. Comparison of Battery Characteristics

Characteristic	Lead-Acid		Nickel-Cadmium	Vented Construction	Valve-Regulated Construction
	Antimony	Calcium			
Long Expected Service Life		X	X	X	
Good Ability to Cycle	X		X	X	
Wide Operating Temperature Range		X	X	X	
Low Gas Generation		X	X	N/A	N/A
Good Gas Recombination Capability	N/A	N/A	N/A		X
Low Watering Frequency		X	X		X (Not Required)
Short Recharge Time	X	X		N/A	N/A
Ability to Tolerate Wide Charger Output Deviations		X	X	X	
Ruggedness			X		X
Low Cost	X	X		X	
N/A = Not Applicable					

For different applications, these components may be made of different materials or have different construction to achieve the desired performance characteristics of the battery. A battery cell intended for reliable, long-life service in one application may fail well short of expectation in another application. Figure 3-3 shows a typical lead-acid cell.

Figure 3-3. Typical Vented Lead-Acid Cell.[3.7]

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A plate of a battery cell is made of a grid and active material attached to the grid. Figure 3-4 shows a typical grid assembly. The grid serves both as a support for the active material and as a conductor to transmit current generated from the active material attached all over the grid to the plate terminal. The plates are welded to conductive straps and posts at the top of the cell. The posts provide electrical connections to the cell (see Figure 3-5).

There are mainly two methods for constructing plates, Plante' (or formed) and pasted designs. The Plante' type can be seen mostly in older batteries, in which an electrochemical process is utilized to form a thin layer of active material from the metallic lead of the grid. This type is no longer common among the U.S. manufacturers. The pasted design is assembled by applying lead oxide (PbO) as a paste to a lead alloy grid, and then drying the paste in a controlled manner. This type of plate is further formed by immersing it in a dilute sulfuric acid solution and passing current through it, with opposite polarities for the positive and negative plates. The lead oxide (PbO) is converted to lead dioxide (PbO_2) in the positive plates and to lead (Pb) in the negative plates.

A typical plate installation into a cell container is shown in Figure 3-6. Positive plates may hang from the positive plate straps or container side walls, or may be cantilevered from the negative plates to allow for positive plate growth. The negative plates are usually supported by the negative plate straps and by feet that rest on the plate support of the cell case. Normally, there is one more negative plate than the number of positive plates in a battery cell, which means that on both sides of each positive plate, there is a negative plate. This can ensure a balanced chemical reaction rate on both sides of a positive plate, avoiding abnormal positive plate expansion.

Separators are placed between the positive and negative plates to provide a physical separation and, at the same time, allow conduction of ions through the electrolyte between the plates of opposite polarity. A separator is made of a porous, non-conductive, inert material such as rubber/glass mat or microporous polyethylene sheets.

A retainer is a porous mat of inert material such as fiberglass which is either pressed between the plates or wrapped around the positive plate. As the cell ages, repeated cycling of charge and discharge tends to cause shedding of active material from the positive plate surface. The use of retainers helps maintain the active material in place on the plates. It is also important to note that the subsequent compound of the chemical reaction is insoluble in the electrolyte. Thus, under normal operating conditions, the active materials remain in their respective positions, or need to be maintained in position.

The cell terminals are usually designed for bolted connections and are constructed of lead alloy. Copper inserts may be used in some of the terminal designs to improve conductivity and optimize high discharge performance. However, the copper inserts could also pose the potential of cell electrolyte copper contamination.

Terminal post seals are one of the critical features of a cell design. A degraded or defective seal will introduce electrolyte leakage and undesirable gas venting.

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Figure 3-4. Typical Vented Lead-Acid Grid Assembly.[3.8]

Figure 3-5. Post, Strap, and Seal Assembly.[3.8]

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Figure 3-6. Typical Plate Installation.[3.8]

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The battery components are enclosed in a plastic container or cell case (or "jar"). The top cover is bonded in some manner to the jar. The jar and cover are usually made of materials such as polycarbonate, styrene acrylonitrile, or butadiene styrene. A seal is also provided between the jar and cover. The cell case is typically clear, which makes possible the inspection of cell electrolyte level. For cells with an opaque container, the electrolyte level is typically determined by viewing the cell interior through the vent.

Cell venting is accomplished through a flame arrester installed on the top of each cell. This prevents overpressure in the cell container due to gas generation resulting from battery charging, but the vented cell design also introduces normal loss of water in the electrolyte and makes maintaining electrolyte level a necessary regular activity.

The cells are electrically connected with intercell connectors and associated hardware (nuts, bolts, washers) attached to the cell terminals. The intercell connectors are typically lead plated copper bars and the hardware is usually stainless steel. Cable lugs are used to provide inter-rack and inter-tier cable connections to end cell terminals.

Battery racks are free standing, metal structures that provide support and protection to individual battery cells during normal operation and seismic events. The racks allow for visual inspection of the cell container exterior and electrical connections, and provide room for servicing and, if necessary, replacing individual or groups of cells. The racks are normally constructed of steel, and are painted with a protective coating to limit damage from chemical spills. Typical designs include two rows of cells one-above another (tiered design), and two rows one in front of the other with the back row at a higher elevation (step design). Cell spacers and insulated rails are used to prevent motion of the cells against each other or the rack. The racks are grounded using copper cabling. In general, the racks used for lead-acid, nickel-cadmium, and valve-regulated batteries are similar in design.

Vented Lead-Acid Battery Types

The vented lead-acid batteries evaluated in this guide can be grouped into the following types based on the selection of plate material.

- Lead Antimony Plate Design
- Lead Calcium Plate Design
- Pure Lead Plate Design

Each of the types has its own advantages and disadvantages with regard to the various applications and maintenance.

The two most common plate grid materials used by U.S. utilities are lead calcium and lead antimony. The difference in grid material properties introduces the following characteristics.

Batteries with lead calcium grids require relatively low float current to maintain their full charge state, which means low gassing rates and low water loss. However, lead calcium cells have a limited capability (on the order of about 50) to withstand repeated cycle operations of deep discharge. Therefore, lead calcium batteries are usually used for emergency standby service

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applications, which are normally in the float charge condition, and subject to few deep discharges.

Batteries with lead antimony grids are close to the opposite of lead calcium batteries. They are better suited for frequent cycling and/or deep discharge applications. The battery float current is relatively high and proportional to the antimony content in the grids, which results in increased gas evolution and water loss. Also, as the cells age, antimony is released into the electrolyte and interacts with the negative plates. The result is that float current, gas evolution, and water loss tend to increase with cell age. Lead antimony batteries are not widely used among the standby battery installations in nuclear power plants.

The design discharge rate and capacity of a cell is also affected by the thickness of plate and number of plates. In general, the capacity of a cell increases with the thickness of its plates because of the resultant increase of the amount of active material, while the peak discharge rate decreases with the reduction of cell total effective active material surface area. Other plate designs are also available, though so far not widely used in the stationary batteries, including round plate and tubular plate. Section 6.2 discusses alternative plate designs relative to aging management issues.

Operation Characteristics

In a vented lead-acid battery cell, the active material on a positive plate is lead dioxide (PbO_2) and that on a negative plate is lead (Pb). The electrolyte is sulfuric acid solution (H_2SO_4). The double-sulfate reaction in the cell can be described in terms of the following reactions.

Positive Plate

Negative Plate

Combined Equation

The equations should be read from left to right for the process of battery discharge and from right to left for charge. Gases are evolved primarily during battery charging, oxygen at the positive plates and hydrogen at the negative plates. These equations only represent the chemical processes in an ideal battery (i.e., no impurities).

The battery functional parameters include ratings of voltage, current, and capacity. Charging and discharging processes directly affect a battery's capacity and service reliability. Ambient temperature also has a significant impact on the performance and service life of a lead-acid battery.

A lead-acid cell typically has an open circuit voltage of approximately 2.06 Vdc when at a fully charged stage. Two charging modes are used for charging a battery, a float charge state and an equalizing charge state. A float charge maintains the battery's fully charged condition during standby operation by delivering a small current from the battery charger to cancel the effect of battery natural self-discharge. An equalizing charge is the method used to recharge a battery's capacity through recovering all useable active materials in the cell plates. The proper float and equalizing voltages of a battery depend on the individual cell design, and are usually specified by the manufacturer for optimal operation. An equalizing charge operation requires a voltage higher than a float charge.

When a battery begins to discharge, an instant voltage drop will occur because of the presence of the battery's internal resistance. From then on, the decrease of voltage is slow and steady as the discharge progresses. A battery is normally considered as being fully discharged when its voltage reaches 1.75 Vdc per cell during a discharge. Thereafter, further discharge will soon cause rapid decline of the battery voltage, or even reverse some individual cells' polarity, resulting in permanent damage.

The capacity of a battery is rated in relation to the discharge rate. The available capacity of the battery decreases as the discharge rate rises. The relation between the two is non-linear. The capacity change is due to the factors of reduced time available for chemical reaction, limited amount of active materials accessible to electrolyte, and increased cell internal resistance. For a given cell, the contact surface area between the plate active materials and electrolyte is limited at any instant. A high discharge rate introduces intensive sulfation on the plate surface, reducing the access pores in the plates. Thereby, less active materials are used in the discharge process.

Lead-acid batteries are very sensitive to their ambient temperatures. The batteries are specified at 25°C [77°F] for their rating. Above that temperature, the battery is capable of carrying greater than its reference capacity, but its service life will be reduced. An increase of 8°C [15°F] can cause a reduction of 50% or more of the expected life. With a temperature lower than 25°C [77°F], the available capacity of the battery will decrease and it may not be able to perform its required functions. Therefore, selection of battery float temperature is important to prevent a battery from both overcharging and undercharging.

3.4.1.2 The Vented Nickel-Cadmium Battery

Nickel-cadmium batteries are not as widely used as the lead-acid batteries in nuclear power plants, especially in applications requiring large capacities. Although nickel-cadmium batteries have a reputation for being reliable and long lasting, their high cost limits widespread use. Unlike a lead-acid battery where cost to capacity ratio decreases as the size increases, the cost of a nickel-cadmium battery is almost proportional to its size. The large nickel-cadmium batteries used in regular UPS and DC distribution systems are usually of the vented construction. Figure 3-7 shows a typical vented nickel-cadmium battery. Nickel-cadmium batteries are particularly well suited in applications of continuous operation, and have a great tolerance to temperature variations.

Figure 3-7. Typical Vented Nickel-Cadmium Cell.[3.9]

Basic Cell Construction

Similar to a lead-acid battery, a nickel-cadmium battery consists of interconnected individual cells. The essential subcomponents of a nickel-cadmium cell include:

- Container
- Nickel Hydroxide Positive Plates
- Cadmium Hydroxide Negative Plates
- Post, Strap, and Seal Assembly
- Separators
- Potassium Hydroxide Electrolyte
- Intercell Connectors and Associated Hardware

The containers of vented nickel-cadmium batteries are mostly made of translucent polypropylene material which allows visual inspection of the electrolyte level. A flame arrestor vent is provided for the release of gases. Terminal posts are sealed with a gasket and O-ring to prevent electrolyte leakage. The intercell connectors are typically nickel-plated copper bars with stainless steel hardware.

Separators in a nickel-cadmium cell are used to establish electrical and physical isolation between the positive and negative plates. Separator designs vary widely, from plastic rods or grids to perforated plastic sheets.

Vented Nickel-Cadmium Battery Types

The vented nickel-cadmium batteries evaluated in this guide can be grouped into the following types based on the plate construction.

- Pocket Plate Design
- Sintered Plate Design

Each of the types has its own advantages and disadvantages with regard to applications and maintenance.

Nickel-cadmium batteries are generally distinguished by their variations in plate construction. The different types of plate designs affect the performance and physical size or weight of a cell. The available types include pocket plate, sintered plate, fiber plate, and other designs. The pocket plate type is generally used for vented cells and accounts for over 90% of nickel-cadmium batteries used by the utilities. Sintered plate construction is more expensive and typically used for small sealed cells.

The pocket plates are built of flat pockets of perforated, nickel-plated steel strips that are pressed around the active materials. The thin steel strips are perforated with a total hole area of 15% to 30%. The plate is sealed in a steel frame and then welded or bolted to the plate bus that is attached to the terminal posts. In this design, the active materials are totally enclosed in the steel pockets. The electrolyte has access to the active materials through the perforated holes in the steel strips, but the holes are too small for active particles to escape. The perforated steel enclosure also applies physical pressure against the active materials, and thus promotes conductivity and minimizes plate swelling. Figure 3-8 illustrates the pocket plate construction for a nickel-cadmium battery.

Figure 3-8. Nickel-Cadmium Battery Pocket Plate Construction.

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For sintered plates, a nickel powder is sintered at high temperature to pure nickel or nickel-plated steel to create a porous structure, which is then impregnated with the active materials. The plates are welded to tabs that are attached to the steel terminal posts. The sintered plate design has high conductivity and its power density is greater than the pocket plate. However, this type of construction is more prone to memory effect limitations and thermal runaway, which are discussed in Sections 4.3.3.3 and 4.3.3.4.

In addition to differences in plate type, variations in plate thickness are also used to design batteries for different applications. Thick plates mean high volume of plate active materials, and fit into the discharge performance requirement of long duration with low discharge rates. On the contrary, the discharge characteristic of high rates and short duration requires the plates to be thin in order to increase the total plate surface area through increasing the number of plates.

Racks used for nickel-cadmium batteries are similar to those used for lead-acid batteries discussed in Section 3.4.1.1.

Operation Characteristics

A nickel-cadmium battery also depends on a chemical reaction process for storing or releasing energy. The active material on the cell positive plates is nickel hydrate ($\text{Ni}(\text{OH})_3$), and that on the negative plates is cadmium (Cd). Potassium hydroxide (KOH) serves as the electrolyte. The chemical reactions are described in the following equations:

At Positive Plates

At Negative Plates

Combined Cell Reaction

The equations should be read from left to right for discharge and from right to left for charge. It is demonstrated in the equations that the electrolyte only serves as a medium supporting the reactions at the positive and negative plates. There is no chemical change in the electrolyte. Therefore, the specific gravity of a nickel-cadmium battery cannot be used as an indicator of the battery charge state.

The operation modes of a vented nickel-cadmium battery are similar to those of a vented lead-acid battery, including discharge, equalizing charge, float charge, and standby. The nominal voltage of an individual cell is typically 1.2 Vdc. With a cell being fully charged, the cell's open

circuit voltage can reach around 1.3 Vdc. Normally, the battery is considered fully discharged when the average voltage per cell drops to the range of 1.0 to 1.1 Vdc. In the same way as a lead-acid battery, the capacity rating of a nickel-cadmium battery is based on the discharge rate, and its capacity decreases as the discharge rate increases. Ambient temperature has less effect on nickel-cadmium batteries than on lead-acid batteries. The optimal temperature for nickel-cadmium batteries is also set at 25°C [77°F]. For every increase of 8°C [15°F] in temperature, the battery service life will only be reduced by about 20% in comparison to the 50% reduction for lead-acid batteries. Good temperature tolerance performance is also exhibited at temperature ranges lower than 25°C [77°F]. The capacity loss of nickel-cadmium batteries due to low operation temperature is far less than that of lead-acid batteries. Overall, nickel-cadmium batteries are better suited for applications subject to substantial environmental temperature variations.

Nickel-cadmium batteries are considered more reliable also because the cell electrolyte is non-corrosive, and problems of plate growth are not as severe as with lead-acid batteries. However, it should be noted that "voltage depression," a normal phenomenon of reduced battery average discharge voltage due to extended float operation, must be taken into consideration in the process of sizing a nickel-cadmium battery. The voltage depression effect can lower the available capacity of a battery, which may affect the battery's performance of required functions. Often, this potential problem is addressed by battery manufacturers in their battery rating systems.

3.4.1.3 Valve Regulated Battery Designs

The valve-regulated cells (see Figure 3-9), also called "sealed" cells, are designed to substantially reduce the amount of water loss by providing a means for recombining the charge gases hydrogen and oxygen. A pressure regulating valve controls the cell internal pressure to increase the recombination efficiency and limit the maximum internal pressure. When operating in an ideal condition, a valve-regulated cell can recombine charge gases with an efficiency close to 100%. For this reason, these cells have no provision for water addition. However, the cells are neither completely sealed nor maintenance free.

The construction of valve-regulated batteries varies considerably. However, the plates, grids, terminal posts, cases, covers, and top conductors/straps are similar in design to the vented lead-acid or nickel-cadmium cells discussed earlier. The three main types are flooded type, absorbed electrolyte type, and gelled electrolyte type. The absorbed or gelled electrolyte design does not have the cell installation restriction requiring upright orientation as does the vented cell design.

A flooded sealed cell, similar to a vented cell, has a liquid electrolyte covering the plates. The main difference is that a pressure control valve replaces the vent cap of a vented cell, for the purpose of regulating the internal pressure to optimize recombination of the gases generating during charging, and to limit the maximum internal cell pressure. Although the achieved recombination efficiency is much better than that of a vented cell through the valve addition, the flooded sealed cell design still trails the absorbed and gelled types in recombination ability. The flooded cell design allows for storing an excess of electrolyte to account for expected water losses.

Figure 3-9. Typical Valve-Regulated Lead-Acid Cell.[3.10]

The absorbed electrolyte design relies on highly absorbent silica glass mat separators to hold the electrolyte. The separators are tightly placed between the cell plates. The mats are not filled to their saturation limits, in order to leave room for oxygen passage from the positive to the negative plates for recombination. Absorbed electrolyte cells have a relatively low internal resistance, and are capable of providing a very high rate of output current for a short duration.

A gelled electrolyte cell has the electrolyte held in place against the plates by combining the electrolyte with a silica compound. The oxygen migration is facilitated by the microscopic cracks created in the gel after a short period of operation. Because of few existing cracks when the battery is initially installed, the recombination efficiency is poor and there is some water loss in the early stages of operation. The water loss causes the gel to contract, which cracks the gel structure. The gas recombining process becomes more efficient as the cracks develop, and water loss becomes minimal. The high internal resistance characteristic of the cell implies that it is not suited for applications demanding a high discharge rate. Nevertheless, the design gives the cell a great electrolyte reserve, and the gelled electrolyte cell has good long duration discharge performance.

Because the electrolyte is held by silica glass mats or silica gel, the electrolyte level does not actually exist in valve-regulated batteries, except for the flooded type. Access to the electrolyte is not allowed for all three valve-regulated battery types. Due to their design features, the batteries are more sensitive to their ambient temperature and operating conditions. High temperature and overcharge will significantly reduce the service life. Valve-regulated batteries are also vulnerable to the "thermal runaway" phenomenon. In this case, a battery under a constant voltage charge condition at an elevated temperature may damage itself through internal

heat generation due to high internal current. When operated under similar operational conditions and environment, valve-regulated batteries are generally more likely to fail before their vented counterparts.

The sealed nickel-cadmium batteries recombine oxygen and hydrogen gases in a method similar to the sealed lead-acid batteries.

3.4.2 Manufacturers' Design Differences

Based upon a review of design and vendor data, battery designs among the manufacturers are basically similar. There are variations in size, shape, and cell internal supporting structure, however, the basic elements constituting a cell are generally the same for each battery type. The existing differences may affect, to some degree, the reliability and service life of the various batteries, but they are not of such fundamental deviations as to require separate, distinctive evaluations with regard to aging mechanisms and associated detection and mitigation techniques.

There have been failure reports in NPRDS data which attributed the failure cause to inherent battery design defects, and the batteries were subsequently replaced. Design problems of such nature are not in the scope of this guideline. Therefore, it is concluded that the differences among manufacturers' designs are not enough to warrant different aging management guidelines, or to necessitate discussion of differences in aging mechanisms. Table 3-3 lists the manufacturers of stationary batteries that are supplied to nuclear plants according to data from the NPRDS.

Table 3-3. Battery Manufacturers

Manufacturer	% in Use (NPRDS)	Battery Type	Plant Type
C&D Charter Power Systems	38.1%	Lead-acid, nickel-cadmium	BWR, PWR
GNB Batteries (formerly Gould Ind. Battery Div.)	27.5%	Lead-acid, nickel-cadmium	BWR, PWR
Exide Corp.	27.1%	Lead-acid, nickel-cadmium	BWR, PWR
SAFT Nife Inc. (formerly SAB Nife Inc.)	2.4%	Nickel-cadmium	PWR
BBC Brown Inc.	1.6%	Lead-acid	PWR
Electro-Motive	1.6%	Lead-acid	BWR
Power Battery	1.6%	Lead-acid	BWR

3.5 Design Requirements and Applicable Codes and Regulations

The design, inspection, and testing requirements for electric power systems for nuclear power plants are given by General Design Criteria 17 and 18 in Appendix A to 10 CFR 50. The Standard Review Plan[3.2, 3.11] identifies guidelines which amplify these requirements.

NRC Regulatory Guides provide methods acceptable to the NRC staff of complying with the General Design Criteria, with respect to the design, qualification, installation, operation, maintenance, testing, and replacement of system equipment.

Regulatory Guides 1.32, 1.100, 1.128, 1.129, and 1.158 are directly applicable to the batteries evaluated in this report and are presented in Table 3-4.

Regulatory Guide 1.32[3.12] pertains to the design, operation, and testing of safety-related electric power systems for nuclear power plants and endorses (with some exceptions) IEEE STD 308-1974. Regulatory Guide 1.100[3.13] pertains to seismic qualification of electric and mechanical equipment and endorses (with some exceptions) IEEE STD 344-1987. Regulatory Guide 1.128[3.14] pertains to installation and installation design of large lead storage batteries and endorses (with some exceptions) IEEE STD 484-1975. Regulatory Guide 1.129 [3.15] pertains to performing maintenance, testing, and replacement of large lead storage batteries and endorses (with some exceptions) IEEE STD 450-1975. Regulatory Guide 1.158 [3.16] pertains to qualification of safety-related lead storage batteries and endorses (with some exceptions) IEEE STD 535-1986.

Table 3-5 lists the IEEE standards and recommended practices that are relevant to aging, aging detection, and aging mitigation of stationary batteries. Many of the standards are only applicable to the Class 1E (safety-related) batteries, while the rest of them provide generic requirements for storage batteries or systems containing batteries. Among the listed IEEE

Table 3-4. Regulatory Guides Relevant to Batteries

Guide Number	Title	Endorsed IEEE Standard
RG 1.32	Criteria for Safety-Related Electric Power Systems for Nuclear Power Plants	IEEE STD 308-1974 (Latest Version IEEE STD 308-1980)
RG 1.100	Seismic Qualification of Electric and Mechanical Equipment for Nuclear Power Plants	IEEE STD 344-1987
RG 1.128	Installation Design and Installation of Large Lead Storage Batteries for Nuclear Power Plants	IEEE STD 484-1975 (Latest Version IEEE STD 484-1987)
RG 1.129	Maintenance, Testing, and Replacement of Large Lead Storage Batteries for Nuclear Power Plants	IEEE STD 450-1975 (Latest Version IEEE STD 450-1987)
RG 1.158	Qualification of Safety-Related Lead Storage Batteries for Nuclear Power Plants	IEEE STD 535-1986

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standards, six are currently in unapproved draft version which may undergo minor or substantial changes prior to issuance.

Table 3-5. IEEE Standards Related to Stationary Batteries

Standard Number	Title	Relevant Requirements	Relevant Recommendations
308-1980	IEEE Standard Criteria for Class 1E Power Systems for Nuclear Power Generating Stations	Providing criteria for: <ul style="list-style-type: none"> • System capability, availability, and independence • Periodic equipment tests to detect equipment deterioration and to demonstrate standby equipment operability • Periodic system tests to demonstrate that equipment meets design requirements 	
344-1987	IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations		Providing recommendations of seismic qualification methods for Class 1E equipment
446-1987	IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications		Providing guidance on battery system design, sizing, and maintenance
450-1987	IEEE Recommended Practice for Maintenance, Testing, and Replacement of Large Lead Storage Batteries for Generating Stations and Substations		Recommending practice for: <ul style="list-style-type: none"> • Periodic inspections and special inspections • Corrective actions • Capacity tests • Replacement criteria
484-1987	IEEE Recommended Practice for Installation Design and Installation of Large Lead Storage Batteries for Generating Stations and Substations		Recommending practices for installation design with regard to location, mounting, ventilation, and instrumentation
484-1983	IEEE Recommended Practice for Sizing Large Lead Storage Batteries for Generating Stations and Substations		Providing guidance for: <ul style="list-style-type: none"> • Defining duty cycles • Cell selection • Battery sizing
535-1986	IEEE Standard for Qualification of Class 1E Lead Storage Batteries for Nuclear Power Generating Stations	Providing information on: <ul style="list-style-type: none"> • Principles and methods of qualification • Procedure and documentation requirements 	

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Table 3-5. IEEE Standards Related to Stationary Batteries (continued)

Standard Number	Title	Relevant Requirements	Relevant Recommendations
946-1992	IEEE Recommended Practice for the Design of Safety-Related DC Auxiliary Power Systems for Nuclear Power Generating Stations		Providing general design guidance for DC power systems, including some battery-related topics such as charger ratings and short-circuit characteristics.
1106-1987	IEEE Recommended Practice for Maintenance, Testing, and Replacement of Nickel-Cadmium Storage Batteries for Generating Stations and Substations		Recommended practice for: <ul style="list-style-type: none"> • Periodic inspection and special inspection • Corrective actions • Capacity test and test procedure • Replacement criteria
1115-1992	IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Application		Providing guidance for: <ul style="list-style-type: none"> • Defining duty cycles • Cell selection • Battery sizing
PAR-1184 (Unapproved Draft)	IEEE Guide for the Selection and Sizing of Batteries for Uninterruptible Power Systems	Providing an overview of battery design and construction, including lead-acid and nickel-cadmium batteries	
PAR-1187 (Unapproved Draft)	IEEE Guide for Installation Design and Installation of Valve-Regulated Lead-Acid Storage Batteries	Providing guidance for installation design with regard to location, mounting, ventilation, and instrumentation	
PAR-1188 (Unapproved Draft)	IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead-Acid Batteries for Stationary Applications		Recommending practice for: <ul style="list-style-type: none"> • Periodic inspections • Corrective actions • Capacity tests • Replacement criteria
PAR-1189 (Unapproved Draft)	IEEE Guide for Selection of Valve-Regulated Lead-Acid Storage Batteries	Providing guidance for battery selection and addressing design considerations, failure modes, and reliability issues	
P-1205 (Unapproved Draft)	IEEE Guide for Assessing, Monitoring, and Mitigating Aging Effects on Class 1E Equipment Used in Nuclear Power Generating Stations		Providing guidance for: <ul style="list-style-type: none"> • Identification of stressors and aging mechanisms • Aging assessment approaches • Methods for monitoring and mitigating aging degradation

The following subsections discuss compliance with the Standard Review Plan, and the specific applicability of these codes, guidelines, standards, and recommended practices to stationary battery aging management.

3.5.1 Compliance With Standard Review Plan

NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants,"[3.11] establishes the format and content requirements of the safety analysis reports prepared for nuclear plants during design and construction. This plan was developed from many years of experience by the NRC staff in establishing and using regulatory requirements in evaluating the safety of nuclear power plants and in reviewing safety analysis reports. As with its predecessor documents, NUREG-0800 does not require the licensee to specifically address the provisions for detection and mitigation of aging.

NUREG-1299, "Standard Review Plan for the Review of License Renewal Applications for Nuclear Power Plants,"[3.2] focuses on the license renewal requirements contained in 10 CFR 54.[3.1] The format and content of the integrated plant assessment, to be prepared in support of the license renewal application, is described. The primary objective of the assessment is to provide assurance of safe operation during the license renewal period, by determining the effectiveness of plant programs to detect and mitigate age-related degradation of systems, structures, and components (SSCs).

NUREG-1299[3.2] is a draft document only and was written before the concept of age-related degradation unique to license renewal was introduced into the license renewal rule. The NRC is expected to issue a new draft version of the document for public comment in 1994. This document identifies each system which may be important to license renewal, and is intended to be used by the NRC staff during performance of safety reviews of applications. It provides the framework to ensure that (among other things) the application identifies systems, structures, and components which are important to license renewal, significant age-related degradation has been identified and evaluated, and programs to manage aging are or will be implemented. This Standard Review Plan (SRP) discusses aging for the typical SSCs important to license renewal. Typical age-related degradation mechanisms that could affect the operation and safety of stationary batteries are identified.

Standard Review Plan-License Renewal (SRP-LR) sections were reviewed to ensure that this aging management guideline considers the identified battery aging mechanisms and programs for management of stationary battery aging. Sections 4 and 5 of this guideline include the evaluations and conclusions of battery aging and aging management. Where applicable, additional aging mechanisms and aging management programs identified in industry documents and lead plant license renewal studies are discussed.

3.5.2 General Standards

IEEE STD 308-1980[3.17] provides criteria for capability, availability, and independence for Class 1E power systems. The standard requires periodic system and equipment tests to detect deterioration toward an unacceptable condition, and to demonstrate operability of standby systems and equipment not exercised during normal plant operation.

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IEEE STD 344-1987[3.18] provides recommendations on the seismic qualification methods for Class 1E equipment. The standard does not require equipment to be brought to its end-of-life condition prior to seismic testing. This is a relevant point further discussed in Section 6.1 along with the corresponding IEEE STD 535-1986 (below).

IEEE STD 446-1987[3.19] provides guidance on the design, construction, and maintenance of stored energy systems for emergency and standby use. Battery system design, sizing, and maintenance are generally described.

IEEE STD 450-1987[3.20] recommends detailed maintenance activities for large lead storage batteries, including periodic inspections and capacity tests. Corrective actions and battery replacement criteria are also provided. The standard is applicable to vented lead-acid batteries and is a key reference for establishing effective maintenance programs.

IEEE STD 484-1987[3.21] establishes the recommended methods for installing lead-acid stationary batteries. It offers a guidance for an initial battery installation, a battery replacement, or a review of an existing battery installation.

IEEE STD 485-1983[3.22] is applicable to lead-acid batteries, and provides detailed guidance for determining a battery duty cycle and selecting a proper battery size capable of meeting the duty cycle load requirements.

IEEE STD 535-1986[3.23] establishes the seismic qualification methods for Class 1E lead storage batteries. The standard requires the batteries to be aged to the expected service life prior to seismic testing. Qualification principles and methods are described in detail. Section 6.1 contains additional discussion.

IEEE STD 946-1992[3.24] provides useful guidance for the design of DC power systems, including battery-related topics of charger rating and battery short circuit characteristics.

IEEE STD 1106-1987[3.25] provides recommendations regarding the maintenance of nickel-cadmium storage batteries, similar to that of IEEE Standard 450 for lead-acid storage batteries. The standard is only applicable to vented battery types, and serves as a principal reference source for the aging management evaluation of the nickel-cadmium batteries.

IEEE P-115[3.26] is to be used for sizing nickel-cadmium stationary batteries, and provides detailed information regarding how to determine a battery duty cycle and how to select a battery size capable of meeting the duty cycle load requirements.

The following five IEEE standards are currently in their draft versions. They may undergo minor or substantial changes prior to their issuance. However, the draft documents do provide useful information and the direction with regard to recommended practices for battery selection, sizing, installation, and maintenance.

IEEE PAR-1184, Draft[3.27] is intended to give guidance on the selection of batteries used for uninterruptible power systems. An overview of lead-acid and nickel-cadmium batteries, both vented and valve-regulated, is provided.

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IEEE PAR-1187, Draft,[3.28] IEEE PAR-1188, Draft,[3.29] and IEEE PAR-1189, Draft[3.30] apply to valve-regulated lead-acid batteries. These three standards will establish methods for the installation design of batteries, recommend battery inspection, test, and other maintenance practices, and address design and selection considerations for batteries. Failure modes and reliability issues related to valve-regulated lead-acid batteries are discussed.

IEEE P-1205, Draft 8[3.31] contains guidelines for assessing, monitoring, and mitigating aging effects on Class 1E equipment. Aging effects tables are provided which list stressors, aging mechanisms, and aging effects for polymers, lubricants, and metals used in a wide variety of Class 1E equipment. General methods for monitoring and mitigating aging degradation are presented along with recommendations on utilizing equipment data in aging evaluations.

Regulatory Guide 1.32[3.12] endorses IEEE STD 308-1974 with certain exceptions. The only exception that relates specifically to batteries concerns battery performance discharge tests. It states that the test interval should be as specified in IEEE STD 450-1975 (which is basically every five years, reduced to one year after the battery shows signs of aging) instead of the 3 years specified in IEEE STD 308-1974. Also, the exception states that in addition to the performance test, the battery service test described in IEEE STD 450-1975 should be performed during refueling operations or at some other outage, with intervals between tests not to exceed 18 months. The 1980 version of IEEE STD 308 removed the three year interval test requirement.

Regulatory Guide 1.100[3.13] endorses IEEE STD 344-1987 with some provisions related only to mechanical equipment such as pumps and valves. IEEE STD 344-1987 provides guidance for seismic qualification of Class 1E equipment without specific consideration of aging degradation. Because of that, the qualification methods have limited effectiveness on the stationary batteries. The seismic vulnerability issue has been confirmed in laboratory test results.

Regulatory Guide 1.128[3.14] endorses IEEE STD 484-1975 with provisions, some of which relate to ventilation, location, and mounting considerations. In addition, the guide requires that certain recommendations contained in the standard be treated the same as the requirements of the standard.

Regulatory Guide 1.129[3.15] endorses IEEE STD 450-1975 with an exception regarding the battery service test. It has the same test interval requirement as Regulatory Guide 1.32 and additionally, if the system design is changed so that the previous service is no longer a valid test of the capability of the battery to meet the changed design requirements of the system, the user should conduct the service test for the new system design.

Regulatory Guide 1.158[3.16] endorses IEEE STD 535-1986 with one exception. The NRC will allow for the use of previously qualified batteries, in lieu of qualification of upgraded replacement batteries in accordance with IEEE STD 535-1986, for replacement batteries bought under a purchase order issued prior to February 28, 1989, or if batteries qualified in accordance with IEEE STD 535-1986 are unavailable to meet installation or operational schedules.

3.6 Operating and Service History

A review of industry data and documents was conducted to determine the industry-wide operating experience with the batteries evaluated in this guideline. Operating history information was obtained from a host utility, responses to plant questionnaires, Nuclear Plant Reliability Data System (NPRDS) and Licensee Event Report (LER) searches, industry literature, and NRC IE notices, bulletins, circulars, and generic letters.

3.6.1 Nuclear Plant Reliability Data System

The NPRDS was developed in 1973 for collecting data on safety-related equipment. Since then, the data system scope has been expanded to include other systems and components that provide critical safety functions and whose loss of function can initiate a significant transient. Component failure records are to be submitted whenever an NPRDS-reportable component fails to perform one or more of its intended functions. Reporting of failures is a voluntary industry effort and, therefore, there are many variations in interpretation of reportability requirements and contents and consistency of reports. For example, potential failures that were prevented by testing and corrective action may not have been reported. If that is the case, mean-time-between-failure data calculated from reported failure data would not be accurate. Per INPO89-014, [3.32] United States nuclear utilities have demonstrated their support of NPRDS by dedicating resources to report all reportable failures that have occurred since January 1, 1984, or when the plant begins commercial operation. Prior to 1984, the LER was widely used for reporting failures.

A search of the Nuclear Plant Reliability Data System yielded 247 reported battery failures for 165 batteries at 79 nuclear power plants. Failure causes were not always given, or were sometimes given in ambiguous terms such as "aging" or "end of life." Figure 3-10 depicts the distribution of causes for all reported battery failures. Causes were not given or could not be determined for many of the battery failures (20.6%). The largest identifiable failure cause was "aging" (32.8%), followed by design problems (8.5%), human error (8.1%), corrosion (7.7%), and manufacturing defects (5.7%). The remaining failure causes each contributed less than 5% to the total reported failures.

NPRDS battery failures that appeared to be age-related were identified. Age-related failures include causes such as "aging," corrosion, dirt, "end of life," high temperature, and plate expansion. There were 131 age-related failures identified for 96 batteries at 51 plants. These failures account for 53.0% of the 247 reported battery failures. Figure 3-11 depicts the distribution of the age-related failure causes. The majority of the age-related failures (70.2%) were attributed to the ambiguous causes of "aging" (61.8%) and "end of life" (8.4%). The largest definitive age-related failure cause was corrosion (14.5%), followed by dirt (8.4%). The remaining age-related failure causes each contribute less than 5% of the total age-related reported failures.

The NPRDS data was also analyzed to determine which subcomponent part failures contributed the most to battery failures. Figure 3-12 depicts the distribution of failed parts for all reported battery failures. Specific part failures were not identified for a majority (54.7%) of the battery failures. The specific parts identified that contribute the most to battery failures are

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Figure 3-10. Failure Causes for All NPRDS Battery Failures.

Figure 3-11. Failure Causes for Age-Related NPRDS Battery Failures.

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Figure 3-12. Failed Parts for All NPRDS Battery Failures.

cell cases (15.8%), intercell connections (14.2%), and the posts/terminals (6.5%). All other part failures each contribute less than 5% to the total reported battery failures.

Figure 3-13 depicts the distribution of failed parts for the 131 age-related battery failures. Specific part failures were not identified for a majority (61.8%) of the age-related battery failures. The specific parts identified that contribute the most to age-related battery failures are intercell connections (15.3%), cell cases (7.6%), and the posts/terminals (6.1%). All other part failures each contribute less than 5% to the total identified age-related battery failures.

To further understand the susceptibility of batteries to age-related degradation, the NPRDS data was analyzed to determine the significant aging mechanisms for each subcomponent part. The distribution of causes for age-related failures of each subcomponent part were determined. The following paragraphs describe the results of this effort for the most significant failed parts.

The most significant aging cause identified for the intercell connections was corrosion (62.5%), followed by dirt (31.3%) and "aging" (6.3%).

The aging mechanisms identified for the cell cases were aging (50.0%), plate expansion (40.0%), and "end of life" (10.0%).

The aging causes identified for the posts/terminals were corrosion (75.0%), dirt (12.5%), and "aging" (12.5%).

The reporting of component failure data involves the reporter's interpretation of reporting guidelines, component reportability, and available information about failures. Despite these drawbacks, the NPRDS is still the most comprehensive failure data base available to the nuclear industry. If it is recognized that any failure rate data extracted from the NPRDS database will

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Figure 3-13. Failed Parts for Age-Related NPRDS Battery Failures.

be a bounding value, then it can prove quite useful to determine the mean time between failures, and hence a failure rate, for batteries.

Figures 3-14 and 3-15 show the total and age-related number of NPRDS-reported battery failures per plant per year, respectively. The trend in both figures shows a significant increase in 1983-88. This increase in failures is consistent with the higher priority reporting was given by utilities, and the greater emphasis the data system was given in the industry. Since 1989, the total and age-related number of failures reported has decreased. This may be due to an increased emphasis on preventive maintenance practices, improved monitoring methods, or improvements in manufacturer quality and design.

Figures 3-16 and 3-17 show the total and age-related number of reported NPRDS battery failures plotted by equipment service time for the last 20 years (i.e., 1972 to 1992). The data have been normalized to show failures per plant year, by dividing the total number of failures occurring for a given equipment service time by the number of plants that have been in service for the given service time, or longer. This normalization prevents skewing of the data due to more plants being in service at the shorter service times, and contributing to higher total battery failures at these shorter service times.

Each figure also shows a best fit linear curve of the form $Y=ax+b$. The slope of the curve and the distribution of the data points in Figure 3-16 suggest that batteries under a significant "burn-in" period where the failure rate is initially high, but falls off as time progresses. This behavior is supported by the fact that of the 247 reported failures, 116 (47%) occurred at service times of five years or less. Additionally, there were 116 components that had only one reported failure, 59 of which (51%) occurred at service times of five years or less.

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Figure 3-14. All NPRDS Battery Failures by Year.

Figure 3-15. Age-Related NPRDS Battery Failures by Year.

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Figure 3-16. All NPRDS Battery Failures by Service Time.

Figure 3-17. Age-Related NPRDS Battery Failures by Service Time.

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The slope of the curve and the distribution of the data points in Figure 3-17 suggest a fairly constant failure rate with a pronounced "wear out" peak at a service time of nine years. Since the batteries are designed for a 20-year life, a wear out peak at nine years suggests that battery aging is not being effectively managed. Further analysis of the data showed that almost all of the failures in this "wear out" peak occurred in 1986 or earlier, prior to the issuance of the IEEE recommended maintenance practices.[3.20, 3.25] Since this document will show that current maintenance practices based on these IEEE standards are effective, we can only conclude that maintenance practices prior to 1986 and prior to the issuance of these standards did not effectively manage aging.

The time between failures for the 247 battery failures reported in the NPRDS ranged from 1 day to 6,513 days (156,312 hours). The mean time between failure (MTBF) for the batteries was calculated to be 1,700 days (40,800 hours) with a standard deviation of 1,511 days (36,264 hours). This implies a wide variation in the time between failures. The failure rate corresponding to the mean time between failures is 2.45×10^{-5} failures per hour. Because of this wide variation in failure rates, MTBF data should be used with caution.

If we consider age-related failures only, then the time between age-related failures identified in the NPRDS ranged from 17 days to 5,875 days (141,000 hours). The mean time between age-related failures was calculated to be 1,977 days (47,448 hours) with a standard deviation of 1,694 days (40,656 hours). Again, this implies a wide variation in the time between age-related failures. The failure rate corresponding to the mean time between age-related failures is 2.10×10^{-5} age-related failures per hour. Because of this wide variation in failure rates, MTBF data should be used with caution.

In summary, the NPRDS data indicates the following.

- At least 53.0% of the reported battery failures are considered age-related failures.
- The failed parts that contribute the most to age-related battery failures are intercell connections (15.3%), cell cases (7.6%), and posts/terminals (6.1%).
- The most significant identifiable aging mechanisms are corrosion (14.5%) and dirt (8.4%).
- Failure rate trends suggest that current maintenance practices are effective at detecting and mitigating aging of batteries.
- The mean time between age-related battery failures is 1,977 days, which corresponds to a failure rate of 2.10×10^{-5} age-related failures per hour.

3.6.2 Licensee Event Report Data

Licensee Event Reports are submitted to the NRC by nuclear power plants for a number of reasons. Some of the reasons which are applicable to the stationary batteries evaluated in this guideline include:

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- Any operation or condition prohibited by the plant's Technical Specifications.
- Any event or condition that results in the condition of the nuclear power plant, including its principal safety barrier, being seriously degraded.
- Any event where a single cause or condition caused at least one independent train to become inoperable in multiple systems, or two independent trains to become inoperable in a single system.

A search of the Sequence Coding and Search System (SCSS) database for LERs reporting age-related failures of stationary batteries from 1980 through June 1992 was obtained from Oak Ridge National Laboratory. Because the report entries do not contain the information about battery initial installation date or service time, the age of the batteries at the date of failure recorded in the LER system was neither available nor easily determined. The data does not include the failure events which were caused by other equipment connected to the batteries or battery systems, such as chargers or power feeders.

This data search identified 29 age-related LERs for the given dates. Analysis of the data indicates that the age-related failure causes are not well defined in the event descriptions. For example, container cracks may be due to aging/embrittlement of the container material, or due to expansion of the cell plates. Because of this ambiguity in report descriptions, general cell failures due to unknown causes were the most significant contributor to age-related battery failures (37.9%), followed by electrolyte low specific gravity (34.5%), plate expansion (10.3%), corrosion (10.3%), internal shorts (3.5%), and loose connections (3.5%). Figure 3-18 depicts this distribution of failure causes. Figure 3-19 depicts the distribution of age-related failed parts for the battery LER failure data. Again, it was not always clear from the LER description which subcomponent part had failed. Therefore, the most common part failure was simply identified as the cell (37.9%) followed by the electrolyte (34.5%) terminals (10.3%), case/jar (10.3%), and the plates (7.0%). Three of these age-related events (10.3%) resulted in a controlled plant shutdown. Nine of these age-related events (31.0%) resulted in loss of one train of redundant safety systems but did not result in a plant shutdown. The remaining 17 age-related events (58.7%) had no effect on the plant due to system or battery redundancy.

In summary, the LER data indicates the following.

- The most common identifiable failure modes were electrolyte related failures (34.5%), corrosion (10.3%), and plate expansion (10.3%).
- The most common identifiable failed parts were electrolyte (34.5%), terminals (10.3%), and cases (10.3%).
- Due to system or battery redundancy, only 10.3% of the age-related failures resulted in a plant shut down.

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Figure 3-18. Failure Modes for Age-Related LER Battery Failures.

Figure 3-19. Failed Parts for Age-Related LER Battery Failures.

3.6.3 Questionnaire Responses

Questionnaire responses related to batteries were obtained from 6 utilities covering 17 plants, including a host utility. Table 3-6 summarizes the questionnaire responses pertaining to stationary battery system applications. Responses covered the 250/125 Vdc, 24/48 Vdc, and 250/125 Vdc switchyard applications. Other common battery uses include computer systems, security systems, diesel engine starting, diesel fire pump starting, and emergency DC lighting systems.

Based on the questionnaire responses, original batteries are still in use at 35% of the plants. Where battery replacement has occurred, the primary reason was installation of an improved design. Thirty-five percent of the respondents have replaced lead-antimony batteries with improved lead-calcium batteries. Other battery replacements have occurred due to cell end of life and failure of the electrolyte. The aging mechanisms most often experienced by the various plants include corrosion of the cell terminals and interconnecting cabling/bus work, cracks and/or leaks in the cell container, electrolyte carbonization of nickel-cadmium batteries, and high resistance/loose connections.

The results of the survey, although part of a small sample number, generally reflect the results of the NPRDS and LER database searches. No new degradation mechanisms were revealed from the questionnaire results.

Table 3-6. Battery Applications (from Plant Questionnaires)

System	Number of Plants	Total Number of Batteries	Range of Batteries Used in System	Average Number of Batteries Used in System	Median Number of Batteries Used in System
Plant 250/125 Vdc	14	18	1 to 2	1.29	1.0
Plant 125 Vdc	17	57	1 to 8	3.35	2.0
Plant 48/24 Vdc	7	32	2 to 8	4.57	4.0
Plant Other	15	62	1 to 18	4.13	3.5
Emergency Lighting Packs	1	280	280 to 280	280.0	280.0
Switchyard 250 Vdc	0	0	0 to 0	0.0	0.0
Switchyard 125 Vdc	10	16	1 to 2	1.60	1.5
Switchyard Other	6	4	0.5 to 1	0.67	0.5

Note: A half battery indicates one battery shared between the units of a two-unit station.

3.6.4 Industry Literature

NUREG/CR-4098[3.33] focuses on the seismic-fragility tests of new and accelerated-aged battery cells. The cells which experienced accelerated aging and seismic testing were disassembled and thoroughly inspected, in order to determine failures causes and the role age degradation plays in reduced cell capacity and eventual cell failure. The degradation experienced after accelerated aging, and which frequently lead to seismically induced failure, included:

- brittleness in positive bus and grid material
- excessive sulfation leading to plate hardening and expansion
- case embrittlement
- corrosion of positive buses and grids

NUREG/CR-4099[3.34] focuses on the seismic fragility tests of naturally aged battery cells. Extensive evaluation of internal cell components was conducted to determine significant aging degradation mechanisms, and the effects of seismic events on cell capacity and survivability. The significant age-related degradation that was observed in these naturally aged cells were:

- brittle and corroded positive bus material
- excessive sulfation of positive plate, leading to plate hardening and expansion

NUREG/CR-4457[3.8] reviewed the battery operating histories from four databases: LER data from 1976 to 1986, NPRDS data from 1973 through 1985, Oak Ridge National Laboratory's In-Plant Reliability Data System (IPRDS) data, and S. M. Stoller Corporation's Nuclear Power Experience (NPE) database from 1960 through 1985.

The LERs showed that low specific gravity (27%), human error (28%), insufficient charge/weak cells (20%), high/low electrolyte (9%), faulty connections (5%), charger malfunction (4%), and design/fabrication/construction (3%) were the most common causes of LER events.

The NPRDS data showed that "wearout" (36%), unknown (31%), manufacturing/design defect (14%), and human error (16%) were the most common causes of battery failure. A possible reason for the large number of "wearout" and "unknown failures" is that the NPRDS does not have specific categories for failures.

The NPE data showed that unknown (21%), human error (20%), low performance (20%), battery charger malfunction (10%), cracked case (7%), and poor connections (6%) were the most common causes of battery failure.

The IPRDS data indicated that grounds (31%), faulty indication (21%), low voltage/will not hold charge (18%), corrosion (14%), and leakage (6%) were the most common causes of battery failure. The high number of grounds causing battery failure may be due in part to the small plant population represented by the IPRDS.

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NUREG/CR-4457 also reviewed current IEEE Standards and Regulatory Guides for their recommended maintenance, testing, and monitoring programs and frequencies, and compared them against battery conditions and stressors. The report also identified and reviewed improved surveillance testing methods for batteries.

NUREG/CR-4533[3.35] investigated aging mechanisms which lead to failure in lead-acid batteries. The report identifies plate expansion, loss of active material from the positive plate, and loss of capacity due to chemical changes in the positive plate active material as the primary age-related degradation mechanisms.

NUREG/CR-5448[3.36] presents results of a seismic testing program on naturally aged Class 1E batteries obtained from a nuclear plant. The program used 12 batteries naturally aged to 13.5 years in a nuclear facility and tested them at four different seismic levels representative of the levels of possible earthquakes specified for nuclear plants in the United States. The report concluded that when batteries are operated and maintained in accordance with IEEE STD 450 and Regulatory Guide 1.129, some internal damage to the plate separators may occur at the most severe seismic levels, but adequate electrical capacity and seismic ruggedness will be retained by the battery and battery rack. However, these conclusions are only applicable to 13.5 year old lead-calcium batteries.

EPRI TR-100248[3.37] provides guidelines and recommended maintenance practices for vented lead-acid and nickel-cadmium, and valve-regulated lead-acid, stationary batteries. The guideline discusses operations, aging processes, and failure modes.

The EPRI report finds that both vented and valve-regulated lead-acid batteries fail by natural aging due to:

- expansion and corrosion of the positive plate grid structure due to oxidation
- loss of active material from the positive plate
- loss of capacity due to physical changes in active material

Other aging mechanisms which may be important in cell failure are thermal aging, corrosion of terminals, and cracked/leaking containers and seals.

For nickel-cadmium batteries, the predominant age degradation mechanisms include:

- aging of active materials
- cracked/leaking containers and seals
- corroded/loose connections
- carbonization of electrolyte

EPRI TR-100249[3.9] provides guidelines and recommended maintenance practices for emergency battery lighting units (EBLs). It includes an evaluation of aging mechanisms, failure data, and life expectancy for EBLs. This EPRI report focuses on root cause determination and preventive measures for limiting failure.

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According to the review of NPRDS and LER data in EPRI TR-100249, the predominant EBL failures are due to battery leaks (29%), low capacity (21%), lamp burned out (22%), electronic failure (16%), and battery low level (6%). A majority (75%) of these failures are due to maintenance activities or program controls. The predominant aging mechanisms which lead to lead-acid battery failure include:

- expansion and corrosion of positive grid plate
- loss of active material from the positive plate
- loss of capacity due to physical changes in the active material of the positive plate

The predominant aging mechanism for nickel-cadmium batteries is aging of the nickel hydroxide in the positive plates. This is a gradual degradation, so that the life expectancy of the nickel-cadmium battery is substantially longer than its lead-acid counterpart.

3.6.5 NRC IE Publications

The NRC IE Circulars, Notices, Bulletins, and Generic Letters pertaining to stationary batteries are listed and summarized in Table 3-7. There are eight notices and one generic letter pertaining to stationary battery design, operation, and maintenance. The problems addressed in these INs were encountered at a few nuclear power plants and are considered typical among all the plants. The INs and Generic Letter reviewed for this report include the following:

IN No. 83-11: Possible Seismic Vulnerability of Old Lead Storage Batteries

IN No. 84-83: Various Battery Problems

IN No. 85-74: Station Battery Problems

IN No. 86-37: Degradation of Station Batteries

IN No. 89-16: Excessive Voltage Drop in DC Systems

IN No. 89-17: Contamination and Degradation of Safety-Related Battery Cells

IN No. 91-64, Supplement 1: Site Area Emergency Resulting From A Loss of Non-Class 1E Uninterruptible Power Supplies

IN No. 92-48: Failure of Exide Batteries

Generic Letter 91-06: Resolution of Generic Issue A-30, "Adequacy of Safety-Related DC Power Supplies," Pursuant to 10 CFR 50.54(f)

Each of these are discussed in the following paragraphs.

Table 3-7. NRC IE Circulars, Notices, Bulletins, and Generic Letters Related to Stationary Batteries

Document	Title	Summary
Information Notice 83-11 March 14, 1983	Possible Seismic Vulnerability of Old Lead Storage Batteries	<ul style="list-style-type: none"> Alerted licensees to the possibility of common mode failure of the DC System due to seismic vulnerability of plates and cases in aged lead-acid batteries. Seismically qualified batteries could also be vulnerable if they were not qualified in accordance with IEEE STD 535-1986.
Information Notice 84-83 November 19, 1984	Various Battery Problems	<ul style="list-style-type: none"> Discussed the problem of battery case cracking caused by the use of trichloroethylene to clean the anti-corrosion grease from battery posts. Discussed the degradation of the vinyl straps on battery racks caused by the use of hydrocarbon based grease.
Information Notice 85-74 August 29, 1985	Station Battery Problems	<ul style="list-style-type: none"> Discussed problems with battery maintenance ranging from a lack of records and written procedures to common errors and procedures that did not comply with Regulatory Guides, IEEE Standards, or vendor manuals.
Information Notice 86-37 May 16, 1986	Degradation of Station Batteries	<ul style="list-style-type: none"> Severe flaking of plates and hook area where the plates connect to the cell posts can increase seismic vulnerability. Discussed improper seismic installation.
Information Notice 89-16 February 16, 1989	Excessive Voltage Drop in DC Systems	<ul style="list-style-type: none"> Improperly sized cable caused excessive voltage drop in supply to circuit breakers. Not applicable to batteries.
Information Notice 89-17 February 22, 1989	Contamination and Degradation of Safety-Related Battery Cells	<ul style="list-style-type: none"> Copper contamination can lead to loss of capacity. Galvanic reactions due to impurities in the plate weld material caused crumbling of plates and a reduction in the plate-to-bus bar junction area.

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Table 3-7. NRC IE Circulars, Notices, Bulletins, and Generic Letters Related to Stationary Batteries (continued)

Document	Title	Summary
Information Notice 91-64, Supplement 1 October 7, 1992	Site Area Emergency Resulting From a Loss of Non-Class 1E Uninterruptible Power Supplies	<ul style="list-style-type: none"> Discussed replacement interval for control logic backup power battery packs in an Exide UPS unit. High float voltage and/or excessively high temperatures substantially decrease battery life. Maintenance should be based on actual in-service conditions.
Information Notice 92-48	Failure of Exide Batteries	<ul style="list-style-type: none"> Inadequate post seal design and corrosion of the posts led to cracking of the case and electrolyte leakage, causing battery failure.
Generic Letter 91-06 April 29, 1991	Resolution of Generic Issue A-30, "Adequacy of Safety- Related DC Power Supplies," Pursuant to 10 CFR 50.54(f)	<ul style="list-style-type: none"> Addresses adequacy of DC power systems with regard to multiple and common-cause failures. Recommendations for design, operation, surveillance, and maintenance were discussed.

Information Notice No. 83-11[3.38] raised the vulnerability question of aged lead-acid storage batteries to seismically induced failure. There had been a series of events involving spontaneous battery failure or degradation which, though not related to seismic events, caused concern regarding the potential vulnerability of old batteries to a seismic event. These spontaneous failure or degradation was attributed to swollen positive plates and/or cracked cases. Even for the seismically qualified batteries, the batteries were rarely qualified by prototype testing of aged cells. This suggests that a seismic event could cause a common-mode failure of the plant DC systems. However, the notice stated that battery cells qualified in accordance with IEEE STD 535-1986 would have a qualified life reflecting the increased seismic vulnerability of old batteries.

Information Notice No. 84-83[3.39] identified instances of battery case cracking resulting from the use of a solvent, trichloroethylene, used to clean the anti-corrosion grease on the battery posts, or from the application of hydrocarbon-based grease to the vinyl straps on the battery racks for facilitating cell installation. Warning against use of solvents or solvent-containing substances near battery cases or covers are provided by the battery manufacturer in their procedures.

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Information Notice No. 85-74[3.40] described the maintenance practice problems associated with station batteries. These problems include the lack of maintenance records, no written procedures for conducting equalizing charges of the station batteries, mistakes in maintenance activities, maintenance procedures not complying with the Regulatory Guides, IEEE standards, or vendor's manuals, insufficient maintenance programs, and others. The notice also provided several reference materials for guidance.

Information Notice No. 86-37[3.41] presented a case of substantial degradation of all station batteries at the Rancho Seco Nuclear Power Plant. The batteries, which were 15 years old and expected to last about 20 years, exhibited severe flaking of the cell plates and flaking of the plates' hook area where the plates connect to the cell posts. The batteries were also found not installed in accordance with the battery vendor's seismic qualification recommendations. Although the batteries were able to pass a duty cycle discharge test, they were replaced due to the vulnerability to a seismic event. The notice emphasized the importance of examining the internal connection between the plates, the bus-bar, and post.

Information Notice No. 89-16[3.42] discussed a DC voltage supply problem associated with the operation of battery charger or motor generator (MG) set circuit breakers. This problem was due to the use of undersized cable and was determined to be design related. Consequently, this notice is not applicable to stationary batteries.

Information Notice No. 89-17[3.43] identified a number of cases of contamination and degradation of safety-related battery cells. The batteries showed signs of discoloration and copper contamination. This condition can lead to loss of battery capacity and serious system deterioration. The notice also described a case of battery degradation which consisted of crumbling or eating away of positive plates. It was believed to have been caused by a galvanic reaction from impurities in the plate weld materials. The crumbling reduced the plate-to-bus bar junction area. The high environment temperature may have accelerated the degradation. The notice addressed the important role of battery vendors in providing appropriate recommendations, and in determining the root cause of a problem once the contamination and degradation occur.

Information Notice No. 91-64[3.44] addressed an issue related to the replacement intervals for the control logic backup power battery packs associated with an Exide UPS unit. In addition to providing the information of unit design modification, the notice discussed the review results regarding the Gate's Energy Products rechargeable batteries used in that Exide UPS unit. The battery performance data from the manufacturer indicates that battery life expectancy is a function of float voltage and temperature values, with charge and discharge cycle life being a function of the depth of discharge. High float voltage values and/or excessively high operating temperature values substantially decrease battery life. Adequate maintenance for the battery packs based upon actual in-service conditions is required.

Information Notice No. 92-48[3.45] identified a condition of cracking on the face of battery jars, which caused leakage of electrolyte and subsequent inoperability of the battery. The root cause was attributed to inadequately designed battery terminal post seals. Corrosion builds up over time in the seal area and stresses the seal area, and, ultimately, the cell cover cracks. In one case, a repair was performed to prevent further post seal leakage. However, the repair

tends to mask any further cracking until catastrophic failure occurs. Replacement of the battery may be required to address the problem.

Generic Letter 91-06[3.46] addressed the resolution of Generic Issue A-30, "Adequacy of Safety-Related DC Power Supplies." The specific area of concern was the adequacy of the minimum design requirements for DC power systems, particularly with regard to multiple and common-cause failures. Recommendations were discussed for the DC power system on the aspects of system design, operation, surveillance, and maintenance. The issues related to the batteries are included in the discussion of the recommendations.

3.7 References

- 3.1 Title 10, U.S. Code of Federal Regulations, 10 CFR Part 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants," December 13, 1991.
- 3.2 NUREG-1299, "Standard Review Plan for the Review of License Renewal Applications for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, Draft for Comment, November 1990.
- 3.3 Monticello Lead Plant Task 2 Summary Report, "Identification of Systems, Structures, and Components Important to License Renewal," Electric Power Research Institute, to be published in late 1994.
- 3.4 Yankee Atomic Electric Company License Renewal Project Summary Report, Electric Power Research Institute, to be published in 1994.
- 3.5 Title 10, U.S. Code of Federal Regulations, 10 CFR Part 50.65, "Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants," July 10, 1991.
- 3.6 C & D Charter Power Systems Sales Brochure 12-560, "Selection Guide for Earthquake-Protected Battery Racks for the United States," 1990.
- 3.7 C & D Charter Power Systems Sales Brochure 12-311, "DCU Lead-Calcium, DU Lead-Antimony Standby Batteries, 25 to 200 Ampere-hours," 1992.
- 3.8 NUREG/CR-4457, "Aging of Class 1E Batteries in Safety Systems of Nuclear Power Plants," Idaho National Engineering Laboratory, EG&G Idaho, Inc., July 1987.
- 3.9 EPRI NMAC TR-100249, "Emergency Battery Lighting Unit Maintenance Guide and Application, Final Report," Electric Power Research Institute, October 1992.
- 3.10 C & D Charter Power Systems Sales Brochure 12-360, "Liberty Series Valve-Regulated (Sealed), Lead-Calcium Battery," 1991.
- 3.11 NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, June 1987.

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- 3.12 Regulatory Guide 1.32, "Criteria for Safety-Related Electric Power Systems for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, Revision 2, February 1977.
- 3.13 Regulatory Guide 1.100, "Seismic Qualification of Electric and Mechanical Equipment for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, Revision 2, June 1988.
- 3.14 Regulatory Guide 1.128, "Installation Design and Installation of Large Lead Storage Batteries for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, Revision 1, October 1978.
- 3.15 Regulatory Guide 1.129, "Maintenance, Testing, and Replacement of Large Lead Storage Batteries for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, Revision 1, February 1978.
- 3.16 Regulatory Guide 1.158, "Qualification of Safety-Related Lead Storage Batteries for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, February 1989.
- 3.17 ANSI/IEEE STD 308-1980, "IEEE Standard Criteria for Class 1E Power Systems for Nuclear Power Generating Stations," Institute of Electrical and Electronics Engineers, 1980.
- 3.18 ANSI/IEEE STD 344-1987, "IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations," Institute of Electrical and Electronics Engineers, August 3, 1987.
- 3.19 ANSI/IEEE STD 446-1987, "IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications," Institute of Electrical and Electronics Engineers, 1987.
- 3.20 ANSI/IEEE STD 450-1987, "IEEE Recommended Practice for Maintenance, Testing, and Replacement of Large Lead Storage Batteries for Generating Stations and Substations," Institute of Electrical and Electronics Engineers, 1987.
- 3.21 ANSI/IEEE STD 484-1987, "IEEE Recommended Practice for Installation Design and Installation of Large Lead Storage Batteries for Generating Stations and Substations," Institute of Electrical and Electronics Engineers, 1987.
- 3.22 ANSI/IEEE STD 485-1983, "IEEE Recommended Practice for Sizing Large Lead Storage Batteries for Generating Stations and Substations," Institute of Electrical and Electronics Engineers, 1983.
- 3.23 ANSI/IEEE STD 535-1986, "IEEE Standard for Qualification of Class 1E Lead Storage Batteries for Nuclear Power Generating Stations," Institute of Electrical and Electronics Engineers, June 25, 1986.

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- 3.24 ANSI/IEEE STD 946-1992, "IEEE Recommended Practice for the Design of Safety-Related DC Auxiliary Power Systems for Nuclear Power Generating Stations," Institute of Electrical and Electronics Engineers, 1992.
- 3.25 ANSI/IEEE STD 1106-1987, "IEEE Recommended Practice for Maintenance, Testing, and Replacement of Nickel-Cadmium Storage Batteries for Generating Stations and Substations," Institute of Electrical and Electronics Engineers, April 4, 1988.
- 3.26 ANSI/IEEE STD 1115-1992, "IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Applications," Institute of Electrical and Electronics Engineers, September 1992.
- 3.27 IEEE PAR-1184, "IEEE Guide for the Selection and Sizing of Batteries for Uninterruptible Power Systems," Institute of Electrical and Electronics Engineers, Unapproved Draft, January 14, 1992.
- 3.28 IEEE PAR-1187, "IEEE Guide for Installation Design and Installation of Valve-Regulated Lead-Acid Storage Batteries," Institute of Electrical and Electronics Engineers, Unapproved Draft, September 1993.
- 3.29 IEEE PAR-1188, "IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead-Acid Batteries for Stationary Applications," Institute of Electrical and Electronics Engineers, Unapproved Draft, March 1992.
- 3.30 IEEE PAR-1189, "IEEE Guide for Selection and Sizing of Valve-Regulated Lead-Acid Batteries for Stationary Applications," Institute of Electrical and Electronics Engineers, Unapproved Draft, December 12, 1991.
- 3.31 IEEE STD P-1205, "IEEE Guide for Assessing, Monitoring, and Mitigating Aging Effects on Class 1E Equipment Used in Nuclear Power Generating Stations," Institute of Electrical and Electronics Engineers, Unapproved Draft, October 26, 1992.
- 3.32 INPO 89-014, "The Nuclear Plant Reliability Data System Objectives and Uses," Institute of Nuclear Power Operations, Revision 01, March 1991.
- 3.33 NUREG/CR-4098, "Seismic-Fragility Tests of New and Accelerated-Aged Class 1E Battery Cells," Sandia National Laboratories, January 1987.
- 3.34 NUREG/CR-4099, "Age-Related Degradation of Naturally-Aged Class 1E Battery Cells," Sandia National Laboratories, April 1986.
- 3.35 NUREG/CR-4533, "Program to Analyze the Failure Mode of Lead-Acid Batteries," Sandia National Laboratories, April 1986.
- 3.36 NUREG/CR-5448, "Aging Evaluation of Class 1E Batteries: Seismic Testing," Idaho National Engineering Laboratory, EG&G Idaho, Inc., August 1990.

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- 3.37 EPRI NMAC TR-100248, "Stationary Battery Maintenance Guide, Final Report," Electric Power Research Institute, December 1992.
- 3.38 NRC Information Notice No. 83-11, "Possible Seismic Vulnerability of Old Lead Storage Batteries," U.S. Nuclear Regulatory Commission, March 14, 1983.
- 3.39 NRC Information Notice No. 84-83, "Various Battery Problems," U.S. Nuclear Regulatory Commission, November 19, 1984.
- 3.40 NRC Information Notice No. 85-74, "Station Battery Problems," U.S. Nuclear Regulatory Commission, August 29, 1985.
- 3.41 NRC Information Notice No. 86-37, "Degradation of Station Batteries," U.S. Nuclear Regulatory Commission, May 16, 1986.
- 3.42 NRC Information Notice No. 89-16, "Excessive Voltage Drop in DC Systems," U.S. Nuclear Regulatory Commission, February 16, 1989.
- 3.43 NRC Information Notice No. 89-17, "Contamination and Degradation of Safety-Related Battery Cells," U.S. Nuclear Regulatory Commission, February 22, 1989.
- 3.44 NRC Information Notice 91-64, Supplement 1, "Site Area Emergency Resulting from a Loss of Non-Class 1E Uninterruptible Power Supplies," U.S. Nuclear Regulatory Commission, October 7, 1992.
- 3.45 NRC Information Notice 92-48, "Failure of Exide Batteries," U.S. Nuclear Regulatory Commission, July 2, 1992.
- 3.46 NRC Generic Letter 91-06, Resolution of Generic Issue A-30, "Adequacy of Safety-Related DC Power Supplies," U.S. Nuclear Regulatory Commission, April 29, 1991.

4. STRESSORS AND AGING MECHANISMS

This section describes applicable stressors and aging mechanisms, and assesses the potential significance of these mechanisms for lead-acid and nickel-cadmium batteries and their subcomponents. These stressors (identified in Section 4.1) and aging mechanisms (Section 4.2) were determined by considering the design of the batteries, including battery racks, their specific service and operating experience, and relevant industry information and reports.

4.1 Determination of Stressors Acting on Batteries

A stressor is an agent or stimulus that stems from pre-service and service conditions and can produce immediate or aging degradation of a system, structure, or component. Materials used during component manufacture, assembly, and installation are subject to some level of degradation due to residual and/or applied stressors. Also, stressors caused by normal operation and environmental conditions have a direct effect on the manifestation of aging mechanisms. It is therefore important to understand the behavior of materials, when subject to these various stressors, in order to satisfactorily design and operate the component and to develop methods for detecting and mitigating component degradation.

The stressors which may be relevant to stationary batteries and battery racks, singly, or in combination are:

- Electrical
- Mechanical
- Thermal
- Chemical
- Electrochemical
- Contaminants
- Humidity
- Radiation

The following sections discuss the applicability of each stressor to stationary batteries and battery racks. Tables 4-1, 4-2, and 4-3 summarize the results of these evaluations for vented lead-acid, vented nickel-cadmium, and valve-regulated batteries, respectively.

4.1.1 Electrical

Electrical stressors result from normal battery operation such as float charging, discharging, and equalize charging. Electrical stressors also result from abnormal operation such as overcharging or undercharging caused by improper operation of the battery charger, battery terminal tracking, or flashover. Susceptible parts include the active material, plate grids, straps, terminals, and electrolyte.

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Table 4-1. Summary of Applicable Stressors, Aging Mechanisms, Degradation Type, and Operational Effects for Vented Lead-Acid Batteries

Applicable Stressors	Aging Mechanisms	Degradation	Operational Effects
ELECTRICAL			
Overcharging	Gassing/Electrolyte Evaporation Thermal Aging Corrosion	Loosening of Plate Active Material Accelerated Corrosion of Positive Grids, Straps, and Terminals Excessive Heating of Electrolyte	Reduced Capacity
Undercharging	Material/Chemical Changes	Sulfation of Plates Buckling of Plates	Reduced Capacity Battery Failure
AC Ripple	Gassing/Electrolyte Evaporation Thermal Aging Corrosion	Loosening of Plate Active Material Accelerated Corrosion of Positive Grids, Straps, and Terminals Excessive Heating of Electrolyte	Reduced Capacity
Over-Discharging	Material/Chemical Changes	Hydration of Lead Components Internal Short Circuits	Reduced Capacity
MECHANICAL			
Mishandling During Maintenance/Installation	Fatigue	Cracked Case Seal Damage Broken Terminals/Connectors	Reduced Capacity Battery Failure
Seismic Events	Fatigue	Connector Failure Cracked Case	Battery Failure
Plate Growth	Fatigue	Cracked Case/Electrolyte Leakage Loosening of Active Material Grid Damage Cell Internal Support Damage	Reduced Capacity

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Table 4-1. Summary of Applicable Stressors, Aging Mechanisms, Degradation Type, and Operational Effects for Vented Lead-Acid Batteries (continued)

Applicable Stressors	Aging Mechanisms	Degradation	Operational Effects
THERMAL			
High Temperature	Gassing/Electrolyte Evaporation Material Chemical Changes Thermal Aging Corrosion	Loosening of Plate Active Material Increased Oxidation/ Corrosion	Reduced Capacity
Low Temperature	Material Chemical Changes	Increased Electrolyte Viscosity	Reduced Capacity
CHEMICAL			
Electrolyte Impurities	Material Chemical Changes	Rapid Grid Oxidation Shedding of Active Material Excessive Gassing Separator Deterioration	Reduced Capacity
Copper Contamination	Material Chemical Changes	Copper Sulfate Deposits on Negative Plate	Reduced Capacity Battery Failure
Use of Improper Grease or Cleaning Solvents	Material Chemical Changes	Cracking of Case Cracking of Vinyl Straps on Racks	Reduced Capacity Battery Failure
ELECTROCHEMICAL			
External Oxidation Environment	Corrosion	Corrosion of Terminals, Intercell Connectors	Reduced Voltage Output
Normal Electrochemical Reactions	Material Chemical Changes	Loss of Active Material Dilution of Electrolyte	Reduced Capacity
Internal Oxidation Environment	Corrosion	Corrosion of Grid, Straps, Posts	Reduced Capacity Battery Failure
Electrolyte Impurities	Material Chemical Changes	Battery Self-Discharge	Reduced Capacity
CONTAMINANTS			
Dust/Dirt Buildup	Corrosion Fouling	Accelerated Oxidation/ Corrosion of Terminals Low Resistance Between Terminals Low Resistance to Ground	Reduced Capacity Battery Failure Cell Discharge Ground Shorts

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Table 4-1. Summary of Applicable Stressors, Aging Mechanisms, Degradation Type, and Operational Effects for Vented Lead-Acid Batteries (continued)

Applicable Stressors	Aging Mechanisms	Degradation	Operational Effects
CONTAMINANTS (continued)			
Electrolyte Leakage/Spills	Corrosion Fouling	Accelerated Oxidation/ Corrosion of Terminals, Connectors, Racks Low Resistance Between Terminals Low Resistance to Ground	Cell Discharge Ground Shorts Reduced Capacity Battery Failure
HUMIDITY			
Moisture	Corrosion	Oxidation/Corrosion of Terminals, Connectors, and Racks	Reduced Capacity Battery Failure

Table 4-2. Summary of Applicable Stressors, Aging Mechanisms, Degradation Type, and Operational Effects for Vented Nickel-Cadmium Batteries

Applicable Stressors	Aging Mechanisms	Degradation	Operational Effects
ELECTRICAL			
Long-Term Float Operation	Voltage Depression	Reduced Battery Average Discharge Voltage	Reduced Capacity
Overcharging	Gassing	Loss of Electrolyte/ Uncovering of Plates	Reduced Capacity
MECHANICAL			
Mishandling During Maintenance/Installation	Fatigue	Cracked Case Seal Damage Broken Terminals/Connectors	Battery Failure Reduced Capacity
Seismic Events	Fatigue	Connector Failure	Battery Failure

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Table 4-2. Summary of Applicable Stressors, Aging Mechanisms, Degradation Type, and Operational Effects for Vented Nickel-Cadmium Batteries (continued)

Applicable Stressors	Aging Mechanisms	Degradation	Operational Effects
THERMAL			
High Temperature	Gassing/Electrolyte Evaporation Material Chemical Changes Thermal Aging	Carbonation of Electrolyte	Reduced Capacity
Low Temperature	Material Chemical Changes	Increased Electrolyte Viscosity	Reduced Capacity
CHEMICAL			
Electrolyte Carbonation	Material Chemical Changes	Decreased Electrolyte Conductivity Increased Cell Resistance	Reduced Capacity
ELECTROCHEMICAL			
External Oxidation Environment	Corrosion	Corrosion of Terminals, Intercell Connectors, Racks	Reduced Voltage Output
Normal Operation	Material Chemical Changes	Loss of Active Material	Reduced Capacity
CONTAMINANTS			
Dust/Dirt Buildup	Corrosion Fouling	Accelerated Oxidation of Terminals Low Resistance Between Terminals Low Resistance to Ground	Cell Discharge Ground Shorts Reduced Capacity Battery Failure
Electrolyte Leakage/Spills	Fouling	Low Resistance Between Terminals Low Resistance to Ground	Reduced Capacity Battery Failure Cell Discharge Ground Shorts
HUMIDITY			
Moisture	Corrosion	Oxidation/Corrosion of Connectors and Racks	Reduced Capacity Battery Failure

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Table 4-3. Summary of Applicable Stressors, Aging Mechanisms, Degradation Type, and Operational Effects for Valve-Regulated Batteries^{(1),(2)}

Applicable Stressors	Aging Mechanisms	Degradation	Operational Effects
ELECTRICAL			
Overcharging	Gassing/Electrolyte Evaporation	Dryout	Battery Failure
AC Ripple (Lead-Acid Only)	Thermal Aging	Excessive Heating Dryout	Battery Failure
Low Discharge Cycling (Ni-Cd Only)	Material Chemical Changes	Memory Effect	Reduced Capacity
THERMAL			
High Temperature	Material Chemical Changes Gassing/Electrolyte Evaporation	Cell Dryout Thermal Runaway (Lead-Acid Only)	Battery Failure
MECHANICAL			
Normal Operation of the Relief Valve	Wear	Failure of Valve to Seat Dryout	Battery Failure
<p>(1) Includes both lead-acid and nickel-cadmium battery designs.</p> <p>(2) Stressors and aging mechanisms which are applicable to the two vented designs are also applicable to their respective valve-regulated design (see Tables 4-1 and 4-2).</p>			

Overcharging usually occurs when a battery is close to fully charged or at a fully charged state under a float charge condition. During that period, if the charge rate exceeds the rate by which the remaining uncharged active material can be charged, or exceeds the charge rate needed to compensate the effect of battery "self-discharge," the amount of charging current in excess of what can be used will decompose the water in the electrolyte, and produce oxygen at the positive plates and hydrogen at the negative plates. This phenomenon, known as gassing, considerably increases the rate of heat generation beyond that due to resistance losses (I^2R). Therefore, overcharging will generally result in excessive gassing and an increase of electrolyte temperature.

Undercharging is usually caused by improper operation of the battery charger, but may also be caused by battery terminal tracking or flashover. Undercharging can lead to excessive sulfation which can impair the battery's ability to perform its required function.

Overcurrent conditions can occur due to short circuits either internal or external to the cells. Overcurrent conditions can cause reduced output voltage, reduced capacity, and excessive internal heating.

The following paragraphs discuss issues specific to each battery category.

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Vented Lead-Acid Batteries

Overcharging can cause extensive gassing, which can loosen the active materials in the plates of a lead-acid battery and thereby reduce the battery capacity. Gassing also creates an oxidizing environment which accelerates corrosion of the positive plate grids, straps, and terminals.

Undercharging is mainly caused by an inadequate float voltage and can result in permanent damage of the lead-acid battery from sulfation. Chronic undercharge causes a buildup of lead sulfate on the plates, which differs in structure from the lead sulfate buildup that occurs during normal battery discharge. During prolonged undercharging, the lead sulfate crystals grow in such a way that they can not be easily broken down by charge current, making that portion of the active material no longer recoverable. Additionally, the lead sulfate occupies more space than the original material, and excessive amounts can make the plates buckle.

Ripple voltage on a charger's output can also stress lead-acid batteries. Excessive AC ripple seems to have similar effects on the plates as overcharging. Studies to date indicate a possible correlation between ripple and accelerated corrosion at the surface between the grid and active material.[4.1]

Lead-acid batteries may also experience a phenomenon known as "hydration" if the battery is over-discharged and left in a discharged condition without immediate recharge. In this case, the electrolyte specific gravity has been reduced to such a low level that the lead components dissolve into the electrolyte. The reaction of dissolution forms many compounds and salts. These substances clog separator pores and, upon recharge, react to form metallic lead. In the process, thousands of short circuit paths are created. Initially, the effect of these short circuits is only reflected as a slight increase in charge current and may not be noticeable. Over time, short circuits become so extensive that maintaining the cells in a charged state is almost impossible, resulting in reduced battery capacity. A low-voltage cut-out control mechanism can be used to avoid over-discharge or hydration.

Therefore, electrical stressors may result in aging mechanisms that cause age-related degradation of vented lead-acid batteries.

Vented Nickel-Cadmium Batteries

Nickel-cadmium batteries are not affected as much by overcharging or undercharging as lead-acid batteries. Overcharging can cause excessive gassing which will require more frequent watering, but will not directly cause any degradation of battery internal components due to the installation design of the active material. However, if the plates become uncovered due to electrolyte loss from gassing, the battery capacity will be reduced. Voltage depression may occur for a nickel-cadmium battery under long-term float operation. Although this is a normal phenomenon, voltage depression can also reduce the battery's capacity. Some manufacturers account for the problem in their battery rating systems through the use of a compensating factor.

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Ripple current, even of significant magnitude, has little impact on nickel-cadmium batteries. The batteries' characteristic of low internal impedance provides an effective AC ripple filtering capability.[4.2]

Therefore, electrical stressors may result in aging mechanisms that cause age-related degradation of vented nickel-cadmium batteries.

Valve-Regulated Batteries

Valve-regulated batteries include both lead-acid and nickel-cadmium types. In addition to the above discussions pertaining to each of the two types, valve-regulated batteries are subjected to some additional aging due to electrical stressors.

Overcharging to the extent of gassing which exceeds the recombination ability of the battery will lead to accelerated water loss because of excess gases being vented through the pressure relief valve. Since there is only a limited amount of electrolyte reserve, but no means for water addition, valve-regulated batteries are very vulnerable to dryout failure which is a dominant failure for this type of battery.

Repetitive low discharge cycling coupled with low charging rates can cause a memory effect in sealed, sintered plate nickel-cadmium batteries, in which the battery assumes the lower capacity normally demanded of it. The memory effect can be erased from a cell by complete discharge of the cell followed by a full recharge at constant current, although several cycles may be required to completely erase the memory effect. Pocket plate nickel-cadmium batteries do not develop a memory effect.[4.2]

Therefore, electrical stressors may result in aging mechanisms that cause age-related degradation of valve-regulated batteries.

4.1.2 Mechanical

Mechanical stresses can be caused by battery handling, seismic bracing, seismic events, or excessive growth of the positive plates, which is only associated with lead-acid batteries. Susceptible parts include the active material, plate grids, cell internal supports, cases, post seals, terminals, connectors, and battery racks.

Handling, either during installation or during maintenance, can harm or disable the battery. Mishandling during installation can result in cracked cases and leakage of the electrolyte which, if undetected, could result in low electrolyte level with decreased battery capacity and corrosion of the battery racks. Mishandling during maintenance and installation can result in damaged or broken terminals and connectors. If excessive force is used to tighten post connections, the post seals may be damaged, resulting in increased corrosion of posts due to acid creepage up the post. A broken seal will also cause venting of gases without the protection of a flame arrestor.[4.1, 4.2]

Improper seismic bracing (either design or installation caused) can cause stresses to the battery cases resulting in cracks and leaks. Additionally, improper seismic bracing can cause the

battery to experience larger-than-expected stresses during a seismic event, and then possibly fail and not be available to provide needed power after the event.[4.1]

All of these mechanical stressors may result in aging mechanisms that cause age-related degradation of all three battery categories: vented lead-acid, vented nickel-cadmium, and valve-regulated batteries. Problems specific to lead-acid batteries and valve-regulated batteries are discussed in the following paragraphs.

Lead-Acid Batteries

Both types of lead-acid batteries (vented and valve-regulated) experience oxidation of the positive plate grid structure. Under float conditions, the lead or lead-alloy grid is oxidized along with the active material to form lead dioxide. Lead peroxide and lead sulfate also accumulate over time. These lead compounds have a larger volume than the original material, causing the plates to grow and stress the grid structure. Such stresses can crack the active material which can lead to shedding of the active material, resulting in reduced battery capacity. Plate growth also places stress on the battery internal components and container, which can lead to cracking of the case and rupture of the cover and post seals, resulting in electrolyte leakage and venting of gases without the protection of a flame arrestor.

Valve-Regulated Batteries

The pressure relief valve in both types of valve-regulated batteries (lead-acid and nickel-cadmium) experiences mechanical stress every time it operates to relieve battery internal pressure. These stresses can cause wear or malfunction of the valve. Failure of the valve to properly seat allows gases to escape, resulting in electrolyte loss, that can lead to dryout and battery failure.

Therefore, mechanical stressors may result in aging mechanisms that cause age-related degradation of vented lead-acid batteries, vented nickel-cadmium batteries, and valve-regulated batteries.

4.1.3 Thermal

Thermal stressors result from battery internal heating or abnormal ambient temperature. Susceptible parts include the active material, plate grids, straps, separators, terminals, and electrolyte. Nickel-cadmium batteries are capable of operating in a much wider range of temperature than lead-acid batteries, while valve-regulated batteries are usually restricted to a much tighter operating temperature window than their vented counterparts. The following paragraphs discuss the issues specific to each type of battery.

Vented Lead-Acid Batteries

Battery ratings and service lives are normally given for operation at 25°C [77°F]. Operation at higher temperatures accelerates the chemical activity within the cells which has the effect of increased capacity. However, the battery self-discharge rate also increases significantly with increasing temperature, causing an increase in charge current, which can lead to an overcharging condition at the positive plates. Overcharging can cause excessive gassing, which

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can loosen active material and increase corrosion of the plate grids, straps, and terminals (see Section 4.1.1). Additionally, elevated temperatures in and of themselves promote oxidation, with the corrosion rate increasing exponentially with temperature. The overall effect of elevated temperature operation of lead-acid batteries is that the service life is usually halved for every 8°C [15°F] increase above 25°C [77°F].[4.2]

Operation at temperatures below 25°C [77°F] will prolong the life of a lead-acid battery. However, the battery capacity will be substantially decreased due to an increase in electrolyte viscosity, which restricts the ability of the electrolyte to circulate between the plates. Additionally, during discharge the specific gravity of the electrolyte decreases which raises the electrolyte freezing temperature, making lead-acid batteries unsuitable for low temperature (i.e., less than -3.9°C [25°F]) applications.

Therefore, thermal stressors may result in aging mechanisms that cause age-related degradation of vented lead-acid batteries.

Vented Nickel-Cadmium Batteries

Nickel-cadmium batteries have a greater temperature tolerance than lead-acid batteries. High temperature can cause overcharging of a nickel-cadmium battery which can result in gassing and water loss, but does not result in accelerated corrosion of internal components (see Section 4.1.1). High temperature increases the buildup of potassium carbonate in the electrolyte from the reaction of the potassium hydroxide electrolyte with carbon dioxide in the atmosphere. Electrolyte carbonation reduces the electrolyte conductivity, which increases the internal resistance, resulting in a loss of capacity. Nickel-cadmium battery life is reduced by 20% for each 8°C [15°F] increase over 25°C [77°F], much less than the 50% reduction for lead-acid batteries under similar conditions. However, unlike lead-acid batteries, operating at temperatures above 25°C [77°F] will not result in an increased battery capacity.

Operation at temperatures below 25°C [77°F] will reduce the capacity of a nickel-cadmium battery, but the capacity decrease rate is much lower than that for a lead-acid battery. The electrolyte specific gravity of a nickel-cadmium battery does not change during charge or discharge, which means the electrolyte freezing temperature does not change. However, a significant drop of temperature below 25°C [77°F] does pose the potential of compromising the battery's required function.

Therefore, thermal stressors may result in aging mechanisms that cause age-related degradation of vented nickel-cadmium batteries.

Valve-Regulated Batteries

In addition to what has been stated for vented lead-acid and vented nickel-cadmium batteries, the valve-regulated design introduces additional aging caused by thermal stressors. Valve-regulated batteries are usually restricted to a much tighter operating temperature window than their vented counterparts.

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High temperatures can cause overcharging which can lead to dryout, a predominant failure mode for valve-regulated batteries (see Section 4.1.1). High temperature can also cause thermal runaway in valve-regulated lead-acid batteries. During this phenomenon, as the battery temperature increases, higher charging current is required to maintain the required float voltage. The additional current results in extra gas generation inside the cell. Both the higher current and increased gas recombination cause increased heat generation and further raise the cell temperature. Thermal runaway occurs in valve-regulated lead-acid batteries when this condition becomes self-sustaining. Under such conditions the battery will destroy itself through self-overheating. Although thermal runaway can occur in vented lead-acid batteries, the heat dissipation capability and typical installation design of vented lead-acid batteries make it a rare occurrence.

Therefore, thermal stressors may result in aging mechanisms that cause age-related degradation of valve-regulated batteries.

4.1.4 Chemical

Chemical stressors result from electrolyte impurities, copper contamination, the atmosphere, grease, and/or cleaning chemical solvent. Susceptible parts include the active material, plate grids, separators, cases, and racks.

The use of the wrong type of grease or chemical cleaning solvent during maintenance can cause potential problems to battery cases and racks for all types of batteries. NRC Information Notice 84-83 identified such failures where cracking of battery cases or vinyl straps on the battery racks were attributed to the cleaning solvent and grease induced chemical stress, respectively.

The following paragraphs discuss the issues specific to each type of battery.

Lead-Acid Batteries

Electrolyte impurities and copper contamination are the main sources of chemical stress for both types of lead-acid batteries (vented and valve regulated). Impurities that reach the electrolyte through water addition (vented type only) or some other means will introduce many problems. Chemical reactions between electrolyte or lead compounds and impurities (organic matter and metals) can result in rapid grid oxidation, shedding of active material, excessive gassing, and separator deterioration. One way to avoid the problem during water addition in vented type batteries is to use distilled water.

Batteries susceptible to copper contamination have copper inserts in the terminal posts, which have a lead coating to isolate the copper from the electrolyte. Although the main cause of copper contamination is related to design/manufacturing defects, normal wear can also cause copper contamination. The copper reacts with the electrolyte to form copper sulfate, which is then deposited on the negative plates reducing the available surface area of the active material. Ultimately, the battery voltage cannot be sustained at the required level and the battery has to be replaced.

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Therefore, chemical stressors may result in aging mechanisms that cause age-related degradation of vented and valve-regulated lead-acid batteries.

Nickel-Cadmium Batteries

As discussed in Subsection 4.1.3, nickel-cadmium batteries are susceptible to electrolyte carbonation. The potassium carbonate formed from the reaction between the potassium hydroxide electrolyte and carbon dioxide in the atmosphere decreases the electrolyte conductivity and increases the cell internal resistance. The electrolyte can also react with graphite additives in the nickel hydroxide positive plate to form carbonate, but this effect is negligible in comparison to that of the reaction with the atmosphere. Carbonation is mainly a problem for vented nickel-cadmium batteries. Valve-regulated batteries are less vulnerable to the problem because of their design feature.

Therefore, chemical stressors may result in aging mechanisms that cause age-related degradation of vented and valve-regulated nickel-cadmium batteries.

4.1.5 Electrochemical

Electrochemical stressors result from the normal electrochemical reactions that occur inside batteries during charging and discharging. Electrochemical stressors can also result from an oxidation environment external to the batteries. Reactions between the plates and electrolyte, as well as impurities in the electrolyte, cause electrochemical stresses in lead-acid batteries. Susceptible parts include the active material, positive plate grids, straps, terminals, and intercell connectors.

All types of batteries are subject to external oxidation or corrosion at the terminals and intercell connectors, which can cause excessive voltage drops and overheating which will lead to additional corrosion, voltage drops, and overheating. Although this is true for all batteries, lead-acid batteries are more vulnerable to such problems due to the acid electrolyte.

The paragraphs below discuss the remaining electrochemical stressors specific to each type of battery.

Lead-Acid Batteries

The normal electrochemical reactions that occur inside vented and valve-regulated lead-acid batteries during charging and discharging result in gradual aging of the active material and electrolyte. During discharging, lead sulfate is formed on the positive and negative plates, the sulfuric acid electrolyte is consumed, and water is produced. During charging, the lead sulfate formed on the plates is converted back into active material (lead at the negative plate and lead dioxide at the positive plate), and the water is converted back into sulfuric acid. However, during repeated discharge/charge cycles, there may be a gradual buildup of lead sulfate on the plates that does not get converted back into active material. Such buildup reduces the amount of available active material and leaves the electrolyte in a slightly diluted condition. This results in reduced battery capacity, and if left unchecked over many years can result in a significant reduction in capacity.

Corrosive electrochemical reactions between the electrolyte and the plate grids, straps, and posts occur in the oxidizing environment that exists at the positive plates. These oxidation reactions begin at the material grain boundaries and cause the materials to become brittle. These reactions and the resultant corrosion are both accelerated by battery internal and external heat (see Section 4.1.3).[4.1]

Impurities in the electrolyte can cause an electrochemical phenomenon known as "local action," which has the effect of battery self-discharge. The impurities in the electrolyte can react chemically with the active material or can be deposited on a plate. This will create a difference in the electromotive force developed at different points of the plate sufficient to produce local currents between those points through the electrolyte. The most important form of local action is that due to the deposit of a metallic impurity on the negative plates, causing the discharge of the active material by local currents. In this state, the specific gravity will be lowered, due to the chemical reactions, and the battery will appear to need charging. However, the positive plates are still fully charged and subsequent charging will result in overcharging the positive plates, along with gassing and increased temperatures, as previously discussed in Section 4.1.1. Local action increases with increased temperature and specific gravity of the electrolyte.[4.1]

Therefore, electrochemical stressors may result in aging mechanisms that cause age-related degradation of vented and valve-regulated lead-acid batteries.

Nickel-Cadmium Batteries

The normal electrochemical reactions that occur inside the batteries during charging and discharging are the only applicable electrochemical stressors for nickel-cadmium batteries. These reactions result in gradual aging of the active material primarily due to recrystallization of the nickel hydroxide in the positive plates. The aging is linear over time under steady-state conditions.[4.2]

Therefore, electrochemical stressors may result in aging mechanisms that cause age-related degradation of vented and valve-regulated nickel-cadmium batteries.

4.1.6 Contaminants

Contaminant stressors result from dust and dirt in the environment as well as electrolyte leaks and spills. Susceptible parts include intercell connectors, terminals, and racks. Dust and dirt in the environment may be present and can accumulate on the top of batteries and connections. Buildup of deposits can create battery grounds and short circuits across the terminals. Deposit induced corrosion will also increase connection resistance.

Electrolyte leaks and spills are harmful to the batteries. The electrolyte of lead-acid batteries is corrosive and can corrode the battery terminals, connectors, and racks. Leaked electrolyte can also develop low resistance paths to ground or between the positive and negative posts. Although the electrolyte of nickel-cadmium batteries is non-corrosive, it can still act as a conductive path between the positive and negative terminals if leaked onto the battery top.

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Therefore, contaminant stressors may result in aging mechanisms that cause age-related degradation of vented lead-acid batteries, vented nickel-cadmium batteries, and valve-regulated batteries.

4.1.7 Humidity

Stationary batteries are normally located in a mild and controlled environment where water spray or steam are not expected. Additionally, during design basis events, the conditions would not vary much from normal. However, moderate humidity, sufficient to cause condensation, does add to the effect of corrosion on battery electrical connections and racks. Other battery subcomponents are not affected by the applicable humidity levels.

Therefore, humidity may result in aging mechanisms that cause age-related degradation of vented lead-acid batteries, vented nickel-cadmium batteries, and valve-regulated batteries.

4.1.8 Radiation

Stationary batteries are not subject to high or sustained radiation exposure during normal operation or during postulated design basis events. The normally expected background radiation levels are far below the radiation damage threshold for the batteries.

Therefore, radiation is not a relevant stressor for vented lead-acid batteries, vented nickel-cadmium batteries, and valve-regulated batteries.

4.2 Description of Applicable Aging Mechanisms

This section defines the aging mechanisms resulting from applicable stressors identified in Section 4.1. Precursors and manifestations, rate of aging, consequences, and mitigating aspects are covered. Once relevant aging mechanisms are defined, an assessment of significance is performed. This utilizes the data compiled and assessed in Sections 3.4 through 3.6, with emphasis on industry historical data and research compiled in Section 3.6. Aging mechanisms are then categorized as "significant" or "non-significant." Many aging mechanisms only act at preferred locations, or in specific combinations/synergies. Significant mechanisms are examined in Section 5 against maintenance/testing/refurbishment/replacement programs used to detect and mitigate aging.

Age-related degradation means a change in a structure's or component's characteristics (e.g., physical or chemical properties, or performance), that occurs with time due to one or more aging mechanisms. Aging can affect all structures and components to some degree. The rate, magnitude, or character of age-related degradation can change over time as a result of environmental conditions, service duty, or specific material performance. Existing regulatory and industry programs, and the consensus established by industry codes and standards, continue to address parameters of aging mechanisms and the means of mitigating age-related degradation.

As defined in 10 CFR 54.3, age-related degradation is unique to license renewal when 1) its effects are different in character or magnitude after the term of the current operating license, or 2) its effects were not explicitly identified and evaluated for the period of extended operation

and the evaluation found acceptable by the NRC, or 3) it occurs only during the period of extended operation. The provisions of 10 CFR 54.21(a)(5) require that it be demonstrated that age-related degradation unique to license renewal is addressed, or need not be addressed, in an effective program.

This AMG goes beyond this strict interpretation of 10 CFR 54.3 to evaluate all aging degradation mechanisms for the entire plant operating period (current and renewal license). This provides suitable guidance for safe and efficient power production. This AMG is essentially structured to satisfy 10 CFR 54.21(a)(5)(i) by creating and implementing effective plant programs. It makes no distinction of whether an age-related degradation mechanism is, or is not, unique to license renewal.

The aging stressors considered in the evaluations have been described in Section 4.1. The structure or component design, constituent materials, and both the normal and abnormal stressors and environments, are considered when establishing the set of relevant mechanisms that could degrade the structure or component. The selection of the relevant mechanisms is also influenced by the review of industry experience (see Section 3.6). Any mechanisms which are not known to contribute to the age-related degradation of the structure or component are not listed in the set of relevant mechanisms, nor is the supporting justification for their exclusion provided in the evaluation. These same principles are applied when determining the set of relevant mechanism for battery subcomponents.

Determining the significance of an age-related degradation mechanism for a structure or component is an integrated evaluation process. The relevant material considerations affecting the degradation processes are evaluated with the design and operational information to understand the aging mechanisms, rate of degradation, and the consequences of degradation. The term "potentially significant" is applied because these evaluations typically do not result in closed-form solutions or determinations. Age-related degradation is potentially significant when, if allowed to continue without the detection and mitigative measures of a plant program(s), the component or structure cannot be shown to be capable of performing its required function during its service term. The effectiveness of the credited plant program(s) then requires further evaluation.

The significance of the relevant degradation mechanisms is determined by quantitative and/or qualitative methods if a plant-unique evaluation is applied. Where practical, potentially significant degradation mechanisms are expressed in terms of the degradation sites, susceptible constituent components or parts, root cause and physical manifestation of the degradation, and projected effects of degradation on the structure or component functions.

For some aging mechanism/component combinations, the evaluation demonstrates that age-related degradation does not lead to a significant reduction in capability of the component to perform the functions defined as important to license renewal. It is verified that the design provisions and/or operating requirements adequately accommodate the degradation. These aging mechanism/component combinations are excluded from further consideration of age-related degradation, and the justification for this determination is documented in this report.

4.2.1 Relevant Aging Mechanisms Identified for Evaluation

This section describes aging degradation mechanisms, and assesses the potential relevance of these mechanisms, to battery components. The aging mechanisms are determined by considering the design of the batteries, their service and operating experience, and relevant industry information and reports. The degradation mechanisms to be evaluated are:

- Material Chemical Changes
- Corrosion
- Fatigue
- Wear
- Thermal Aging
- Gassing and Electrolyte Evaporation
- Fouling

Tables 4-4 through 4-6 summarize the relevancy of these mechanisms to vented lead-acid, vented nickel-cadmium, and valve-regulated battery subcomponents respectively. General definitions of these aging mechanisms follow in this section. Section 4.3 then evaluates the significance of these mechanisms for the subcomponent types.

4.2.1.1 Material Chemical Changes

Chemical reactions cause material changes, which can be part of either normal battery operation or the undesirable degradation process. Contaminants can also cause chemical reactions that result in undesirable material changes. The chemical changes resulting in battery aging can be irreversible, and the accumulated effects could be severe self-discharge, gradual loss of material, the creation of barriers to the chemical processes during battery charge and discharge, or physical damage of subcomponents. Corrosion is discussed separately. Contributing factors may include battery undercharge, active material impurities, electrolyte contamination, improper use of greases and cleaning solvents, operating and ambient temperatures, and/or normal active material aging caused by the buildup of lead sulfate due to repeated discharge/charge cycles (see Section 4.1.5). In lead-acid batteries, material chemical changes can occur in the electrolyte, plates, separators, and container. For nickel-cadmium batteries, material chemical changes can occur in the electrolyte, plates, and container. Material chemical change is not a relevant aging mechanism for the separators in nickel-cadmium batteries because hydration is a phenomenon specific to lead-acid batteries (see Section 4.1.1).

4.2.1.2 Corrosion

Corrosion is the long-term oxidation of the battery subcomponents, resulting in high connection resistance or material loss. Corrosion includes chemical changes in metal and organic materials exposed to the oxidation environment inside a battery cell, or to the general environment. The corrosion rates can be affected by contaminants, humidity, excessive gassing, and high temperature. For lead-acid batteries, corrosion may occur in plates, straps, terminal posts, intercell connectors, and racks. For nickel-cadmium batteries, corrosion can occur in the terminal posts, intercell connectors, and racks. Corrosion is not a relevant aging mechanism for

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the plates and straps in nickel-cadmium batteries because the electrolyte, unlike the electrolyte in lead-acid batteries, is not corrosive.

Table 4-4. Summary of Vented Lead-Acid Battery Subcomponent Stressors, Aging Mechanisms, and Operational Effects

Subcomponent	Applicable Stressors	Aging Mechanisms	Operational Effects
Container	Improper Cleaning Solvents Plate Growth Handling Elevated Temperature	Material Chemical Changes Fatigue Thermal Aging	Cracked Container Electrolyte Leakage Reduced Capacity
Electrolyte	Undercharging Overcharging Impurities Elevated Temperature	Material Chemical Changes Gassing and Electrolyte Evaporation	Reduced Capacity
Plates	Normal Charging Overcharging Undercharging Impurities Charge/Discharge Cycles Seismic Events	Material Chemical Changes Corrosion Fatigue Gassing	Loss of Active Material Reduced Capacity Battery Failure
Cell Top Straps	Normal Charging Overcharging Elevated Temperature Charge/Discharge Cycles Seismic Events	Corrosion Fatigue	Reduced Capacity Battery Failure
Separators	Overdischarging Overcharging Excessive AC Ripple Elevated Temperature	Material Chemical Changes Thermal Aging	Internal Short Circuits Reduced Capacity Battery Failure
Terminal Posts	Humidity Dust and Dirt Electrolyte Leaks/Spills Improper Handling	Corrosion Fatigue Fouling	High Connection Resistance Short Circuits Reduced Output Battery Failure
Intercell Connectors	Humidity Dust and Dirt Electrolyte Leaks/Spills Improper Handling	Corrosion Fatigue Fouling	High Connection Resistance Reduced Output
Terminal Post Seals	Plate Growth Terminal Post Corrosion Elevated Temperature	Fatigue Thermal Aging	Loss of Electrolyte Reduced Capacity Battery Failure
Battery Racks	Electrolyte Leaks/Spills Humidity Seismic Events	Corrosion Fatigue	Rack Failure Loss of Battery

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Table 4-5. Summary of Vented Nickel-Cadmium Battery Subcomponent Stressors, Aging Mechanisms, and Operational Effects

Subcomponent	Applicable Stressors	Aging Mechanisms	Operational Effects
Container	Improper Cleaning Solvents Elevated Temperature Handling	Material Chemical Changes Fatigue Thermal Aging	Cracked Container Electrolyte Leakage Reduced Capacity
Electrolyte	Exposure to Carbon Dioxide Overcharging Elevated Temperature	Material Chemical Changes Gassing and Electrolyte Evaporation	Decreased Electrolyte Conductivity Loss of Electrolyte Reduced Capacity
Plates	Normal Charging/ Discharging	Material Chemical Changes	Reduced Capacity
Separators	Overcharging Excessive AC Ripple Elevated Temperature	Thermal Aging	Reduced Capacity Battery Failure
Terminal Posts	Humidity Dust and Dirt Electrolyte Leaks/Spills Improper Handling	Corrosion Fatigue Fouling	High Connection Resistance Short Circuits Reduced Output Battery Failure
Intercell Connectors	Humidity Dust and Dirt Electrolyte Leaks/Spills Improper Handling	Corrosion Fatigue Fouling	High Connection Resistance Reduced Output
Terminal Post Seals	Terminal Post Corrosion Elevated Temperature	Fatigue Thermal Aging	Loss of Electrolyte Reduced Capacity
Battery Racks	Humidity Dust and Dirt Seismic Events	Corrosion Fatigue	Rack Failure Loss of Battery

Table 4-6. Summary of Valve-Regulated Battery Subcomponent Stressors, Aging Mechanisms, Phenomena, and Operational Effects^{(1),(2)}

Subcomponent	Applicable Stressors	Aging Mechanisms/ Phenomena	Operational Effects
Pressure Relief Valve	Normal Operation	Wear	Loss of Electrolyte (Dryout) Battery Failure
Electrolyte	Overcharging Elevated Temperature Failed Pressure Relief Valve Cracked Container or Seal	Dryout	Reduced Capacity Battery Failure
Lead-Acid Battery	Elevated Temperature Improper (High) Float Voltage Excessive AC Ripple	Thermal Runaway	Battery Failure
Sintered Plate Nickel-Cadmium Battery	Successive Small Discharge Cycles	Memory Effect	Reduced Capacity

(1) Includes both lead-acid and nickel-cadmium battery designs.

(2) Stressors and aging mechanisms which are applicable to the two vented designs are also applicable to their respective valve-regulated design (see Tables 4-4 and 4-5).

4.2.1.3 Fatigue

Fatigue is defined as structural deterioration of material that occurs due to repeated stress/strain cycles of sufficient magnitude, caused by fluctuating loads or temperatures. Repeated cyclic loading causes crack initiation at the most highly affected locations. Subsequent cyclic loading and/or thermal stress will likely result in crack growth. Contributors to fatigue cracking consist of material, structural, and environmental factors, such as residual or internally developed stresses, surface roughness, surface oxidation, and chemical attack. The time between localized fatigue crack initiation and eventual detection of the growing crack may represent a large portion of component life. In addition, a design basis seismic event will induce significant mechanical stresses on the battery subcomponents, which may result in fatigue and cause battery failures. For lead-acid batteries, fatigue may be found in the internal straps, plates, terminal posts, intercell connectors, post seals, containers, and racks. For nickel-cadmium batteries, fatigue may occur in the terminal posts, intercell connectors, post seals, containers, and racks. Fatigue is not a relevant aging mechanism for plates and straps in nickel-cadmium batteries because, unlike lead-acid batteries, there are no stresses due to plate growth or corrosion.

4.2.1.4 Wear

Wear is the process of material loss due to relative movement between contacting parts of a component. Degradation from wear is time-dependant in nature. Wear can occur in the pressure relief valves of lead-acid and nickel-cadmium valve-regulated batteries.

Wear is not relevant to the batteries of vented construction since there is no relative movement between parts during operation. Therefore, further evaluation is not required for wear of vented lead-acid or vented nickel-cadmium batteries.

4.2.1.5 Thermal Aging

Long-term high temperatures can cause embrittlement of non-metallics and loss of dielectric strength of insulating materials. Degradation from thermal aging is time-dependent in nature. Thermal aging can occur in the separators, containers, and post seals of lead-acid and nickel-cadmium batteries.

4.2.1.6 Gassing and Electrolyte Evaporation

Gassing is the result of battery overcharging as described in Section 4.1.1. Gassing creates or worsens the oxidation environment inside battery cells, has the tendency to dislodge the active material from the plates of lead-acid batteries, and can cause water loss when gasses escape. Contributing factors include overcharging and high temperature. Gassing affects the plates and the electrolyte in lead-acid batteries. For nickel-cadmium batteries, gassing affects the electrolyte, but not the plates due to the installation design of the active material.

Electrolyte evaporation is another source of water loss. Contributing factors include high temperatures. Electrolyte evaporation affects the electrolyte of lead-acid and nickel-cadmium batteries, but the effect is normally minor when compared to that of gassing.

4.2.1.7 Fouling

Fouling, as it is used for electrical equipment, is defined as the accumulation of foreign material, such as dust or dirt, from the environment. Such accumulation could reduce the function of the component over time. For lead-acid and nickel-cadmium batteries, fouling can affect terminal posts and intercell connectors, and may promote high electrical connection resistance, short circuits, or grounds.

4.3 Significance of Relevant Aging Mechanisms

The following subsections assess the potential significance of the aging mechanisms that were determined in Section 4.2.1 to be relevant for vented lead-acid, vented nickel-cadmium, and valve-regulated batteries. The potential significance is determined based on the ability of the battery to perform its required function, assuming the degradation mechanism is allowed to continue unmitigated.

4.3.1 Significance of Relevant Aging Mechanisms for Vented Lead-Acid Batteries

The aging mechanisms from Section 4.2.1 that were determined to be relevant for vented lead-acid batteries are:

- Material Chemical Changes

- Corrosion
- Fatigue
- Thermal Aging
- Gassing and Electrolyte Evaporation
- Fouling

The following subsections assess the potential significance of each of these mechanisms with respect to the battery subcomponents.

4.3.1.1 Material Chemical Changes

The subcomponents susceptible to material chemical changes are the electrolyte, plates, separators, and containers. The material chemical changes that occur during normal battery discharge are reversed during normal battery charging. Therefore, the material chemical changes discussed here are those that are irreversible and result in a degraded battery.

Electrolyte - Material chemical changes can occur in the electrolyte due to sulfation caused by undercharging or impurities in the electrolyte. Sulfation will consume the electrolyte, reducing its specific gravity (see Section 4.1.1). Impurities in the electrolyte can also cause chemical reactions that consume the electrolyte, reducing its specific gravity. Such chemical changes result in reduced battery capacity, and the eventual inability to maintain the terminal voltage. Therefore, material chemical change is a potentially significant degradation mechanism for the electrolyte in lead-acid batteries.

Plates - Material chemical changes can occur in the plates due to oxidation caused by float charging, sulfation caused by undercharging, or electrochemical reactions caused by electrolyte impurities. Oxidation and sulfation of the positive plates form lead dioxide, lead peroxide, and lead sulfate which occupy more space than the original material, causing expansion of the positive grid, embrittlement of the grid, increased internal resistance, and separation of the active material from the grid. The result is increased mechanical stress on the plates and jar, and decreased battery capacity. Electrochemical reactions due to impurities in the electrolyte cause local action at the plates (see Section 4.1.5) resulting in decreased battery capacity, and potential overcharging of the positive plates. Therefore, material chemical change is a potentially significant degradation mechanism for the plates in lead-acid batteries.

Separators - Material chemical changes can occur in separators due to hydration (see Section 4.1.1). The formation of metallic lead on the surface of the separators builds numerous short circuit paths between the positive and negative plates. This results in the inability to maintain the battery in a charged state. Therefore, material chemical change is a potentially significant degradation mechanism for separators in lead-acid batteries.

Containers - Improper use of greases and cleaning solvents during maintenance can cause material chemical changes to the container. The chemical reactions can dissolve the material or weaken the container structure, inducing cracks in the container. Therefore, material chemical change is a potentially significant degradation mechanism for the containers of lead-acid batteries.

4.3.1.2 Corrosion

The subcomponents susceptible to corrosion are the plates, internal straps, terminal posts, intercell connectors, and racks.

Plates and Internal Straps - Corrosion occurs in plate grids and straps due to the oxidizing environment that exists at the positive plates. The resulting lead compounds are more brittle than the original material, and the available cross-sectional area in the grids or straps for carrying current is reduced, causing an increase in battery internal resistance. The structural weakness introduced by corrosion can make a battery seismically vulnerable. Also, the increased internal resistance due to corrosion can cause decreased battery capacity. High temperatures and excessive gassing accelerate the corrosion at the positive plates and straps. Therefore, corrosion is a potentially significant degradation mechanism for the plates and straps in lead-acid batteries.

Terminal Posts and Intercell Connectors - Corrosion of the posts and connectors can occur due to excessive ambient humidity, external dust and dirt, and electrolyte leaks and spills. Corrosion can cause high connection resistance and embrittlement of the material, resulting in decreased battery output and overheating of the posts and connectors. Corrosion of terminal posts may also stress the post seals and cover. Therefore, corrosion is a potentially significant degradation mechanism for terminal posts and connectors in lead-acid batteries.

Racks - Electrolyte leaks or spills are the main cause of battery rack corrosion. Humidity and high temperature also contribute to corrosion. The rack structure can be substantially weakened over time due to corrosion, resulting in structural failure of the rack and loss of the supported battery. Therefore, corrosion is a potentially significant degradation mechanism for the supporting racks of lead-acid batteries.

4.3.1.3 Fatigue

The subcomponents susceptible to fatigue are plates, internal straps, terminal posts, intercell connectors, post seals, containers, and racks.

Plates and Internal Straps - Fatigue failure can occur in plates and straps due to the repeated thermal and mechanical stresses that accompany battery charge/discharge cycles. Seismic events may also cause fatigue failures of these subcomponents if they are not properly qualified. Contributing factors include corrosion of the plates and straps, which reduces the mechanical strength of the parts. Fatigue failures of plates or straps can cause loss of active material or loss of electrical continuity, resulting in reduced battery capacity or total loss of battery output. Therefore, fatigue is a potentially significant degradation mechanism for the plates and straps in lead-acid batteries.

Terminal Posts and Intercell Connectors - Repeated or improper torquing of connections during installation or maintenance can result in cracked or broken terminal posts or intercell connectors. This results in increased connection resistance or loss of electrical continuity, and also increases the seismic vulnerability of these parts. The result is reduced battery capacity or a total loss of battery output. Therefore, fatigue is a potentially significant degradation mechanism for the terminal posts and intercell connectors in lead-acid batteries.

Post Seals and Containers - Fatigue failures can occur in post seals and containers due to improper handling, plate growth, and excessive corrosion of the terminal posts which stresses the seals and covers. Cracking of the post seals and containers can cause loss of electrolyte and venting of gases, resulting in reduced battery capacity or total loss of battery output. Therefore, fatigue is a potentially significant degradation mechanism for the post seals and containers of lead-acid batteries.

Racks - Fatigue failure of the rack can occur during a seismic event if the racks are degraded by corrosion, resulting in structural failure of the rack and loss of the supported battery. Therefore, fatigue is a potentially significant degradation mechanism for the racks supporting lead-acid batteries.

4.3.1.4 Thermal Aging

The subcomponents susceptible to thermal aging are post seals, separators, and containers.

Post Seals and Containers - Thermal aging can occur in post seals and containers which are exposed to excessively high temperatures relative to their constituent materials. Typically, the battery seals and containers are exposed to temperatures of 16-40°C [60-104°F], which do not cause significant thermal aging of plastic and rubber materials. This is also indicated in the past operating experience. Therefore, thermal aging is not considered significant for the post seals and containers.

Separators - Thermal aging of the separators can occur due to excessive electrolyte temperatures caused by overcharging or excessive AC ripple on the charger output. Elevated temperature reduces the dielectric strength of separator material and causes structural deterioration in the separators, resulting in battery internal short circuits. Such short circuits result in reduced battery capacity or the inability to maintain the battery in a charged state. Therefore, thermal aging is a potentially significant degradation mechanism for the separators in lead-acid batteries.

4.3.1.5 Gassing and Electrolyte Evaporation

Electrolyte and Plates - Gassing and electrolyte evaporation can occur in the electrolyte due to overcharging and excessive temperatures, respectively. Gassing is the main cause of water loss from the electrolyte, and is also a contributor to active material shedding from the plates which results in sediment buildup at the bottom of the cell. Electrolyte evaporation also contributes to water loss. Water loss and active material shedding result in reduced battery capacity. Sediment buildup can cause short circuits between the positive and negative plates, resulting in reduced battery capacity and eventually the inability to maintain the battery in a charged condition. Gassing also increases the oxidizing environment at the positive plates and at the electrolyte-air interface at the top of the cell. Therefore, gassing and electrolyte evaporation is a potentially significant degradation mechanism for the electrolyte and plates in lead-acid batteries.

4.3.1.6 Fouling

Terminal Posts and Intercell Connectors - Fouling of the terminal posts and intercell connectors can occur due to the accumulation of dirt, dust, and leaked electrolyte. Such fouling can cause corrosion at the electrical connections, short circuits between the positive and negative posts, and battery grounding, resulting in degraded battery output, battery discharge, or overheating of the connections. Therefore, fouling is a potentially significant degradation mechanism for the terminal posts and intercell connectors of lead-acid batteries.

4.3.2 Significance of Relevant Aging Mechanisms for Vented Nickel-Cadmium Batteries

Aging degradation processes are very different for nickel-cadmium batteries and lead-acid batteries. One distinct difference lies in the non-corrosive electrolyte of nickel-cadmium batteries in contrast to the highly corrosive electrolyte of lead-acid batteries. The aging mechanisms from Section 4.2.1 that were determined to be relevant for vented nickel-cadmium batteries are:

- Material Chemical Changes
- Corrosion
- Fatigue
- Thermal Aging
- Gassing and Electrolyte Evaporation
- Fouling

The following subsections assess the potential significance of each of these mechanisms with respect to the battery subcomponents.

4.3.2.1 Material Chemical Changes

The subcomponents susceptible to material chemical changes are the electrolyte, plates, and containers.

Electrolyte - Material chemical changes can occur due to carbonation of the potassium hydroxide electrolyte when it is exposed to carbon dioxide in the air (see Section 4.1.4). The formed potassium carbonate decreases the conductivity of the electrolyte, and has the effect of increased battery internal resistance and a loss of capacity. High temperature or frequent cycling can accelerate the carbonation process. Therefore, material chemical change is a potentially significant degradation mechanism for the electrolyte in nickel-cadmium batteries.

Plates - Since the electrolyte is non-corrosive and does not react with the battery cell internal steel components, the internal supporting structure stays intact over the period of battery service life. The only change in the plates is the gradual aging of the active material. Degradation of nickel-cadmium batteries is primarily due to the recrystallization of the nickel hydroxide in the positive plates. This aging process is gradual and linear with time under steady-state conditions.[4.2] Therefore, material chemical change is a potentially significant degradation mechanism for the plates in nickel-cadmium batteries.

Containers - Similar to the situation for lead-acid batteries, improper use of greases and cleaning solvents during maintenance work may cause damage to the container of the nickel-cadmium battery. Chemical reactions between the grease or solvent and the container can dissolve the container material or weaken the structure, causing cracking of the container. Therefore, material chemical change is a potentially significant degradation mechanism for the containers of nickel-cadmium batteries.

4.3.2.2 Corrosion

The subcomponents susceptible to corrosion are terminal posts, intercell connectors, and racks.

Terminal Posts, Intercell Connectors, and Racks - Corrosion can occur in these subcomponents primarily due to the environmental conditions, since the battery electrolyte is non-corrosive. Humidity, dust accumulation, and temperature are thus the main factors. The battery installation environment, in general, is considered mild, and the corrosion rate is likely to be relatively low compared with the conditions for lead-acid batteries. However, unchecked corrosion could cause failure of these subcomponents. Therefore, corrosion is a potentially significant degradation mechanism for the terminal posts, intercell connectors, and racks of nickel-cadmium batteries.

4.3.2.3 Fatigue

The subcomponents susceptible to fatigue are terminal posts, intercell connectors, post seals, containers, and racks.

Terminal Posts and Intercell Connectors - Repeated or improper torquing of connections during installation or maintenance can result in cracked or broken terminal posts or intercell connectors. This results in increased connection resistance or loss of electrical continuity, and also increases the seismic vulnerability of these parts. The result is reduced battery capacity or a total loss of battery output. Therefore, fatigue is a potentially significant degradation mechanism for the terminal posts and intercell connectors in nickel-cadmium batteries.

Post Seals and Containers - The differential in material thermal expansion, corrosion of the terminal posts, and improper handling can introduce stresses to the post seals and container cover. Excessive stresses can cause fatigue cracking of the seals and cover, which leads to undesirable gas release, possible air intrusion, and loss of electrolyte. Though the leaked electrolyte will not create a corrosive environment, it is capable of forming conductive paths between the posts or to ground. Therefore, fatigue is a potentially significant degradation mechanism for the post seals and containers of nickel-cadmium batteries.

Racks - Fatigue failure of the battery rack can occur during a seismic event if the racks are degraded by corrosion, resulting in structural failure of the rack and loss of the supported battery. Normally, the racks are located in a mild environment and not likely to suffer much corrosion. However, if the battery installation has to meet the requirements of seismic qualification, rack corrosion over the battery service life may constitute a potential problem for

the installation to withstand a design basis seismic event. Therefore, fatigue is a potentially significant degradation mechanism for the racks supporting nickel-cadmium batteries.

4.3.2.4 Thermal Aging

The subcomponents susceptible to thermal aging are post seals, separators, and containers.

Post Seals and Containers - Thermal aging can occur in post seals and containers which are exposed to excessively high temperatures relative to their material thermal characteristics. Typically, the battery seals and containers are not exposed to such temperatures and do not fail due to thermal aging. Operating experience and research studies also support the conclusion. Therefore, thermal aging is not considered significant for the post seals and containers.

Separators - Thermal aging of the separators can occur due to excessive electrolyte temperatures caused by overcharging or excessive AC ripple on the charger output. Elevated temperature gradually reduces the dielectric strength of separator material, and deteriorates the mechanical strength of the separators, resulting in current leaks or short circuits between positive and negative plates. Such short circuits result in reduced battery capacity and the eventual inability to maintain the battery in a charged state. Therefore, thermal aging is a potentially significant degradation mechanism for the separators in nickel-cadmium batteries.

4.3.2.5 Gassing and Electrolyte Evaporation

Electrolyte - Gassing and electrolyte evaporation can occur in nickel-cadmium batteries due to overcharging and elevated temperature, respectively. Gassing is the main cause of electrolyte water loss, which will reduce the battery capacity if the electrolyte level drops below the top of the plates. Normal evaporation also contributes to the water loss. Therefore, gassing and electrolyte evaporation is a potentially significant degradation mechanism for the electrolyte in nickel-cadmium batteries.

4.3.2.6 Fouling

Terminal Posts and Intercell Connectors - Dirt, dust, and leaked electrolyte are the typical elements contributing to fouling of the terminal posts and intercell connectors. Accumulation of dirt and dust, coupling with moisture condensation, can cause corrosion at the electrical terminations, and introduce undesirable current paths to ground or between the positive and negative terminal posts. Although the electrolyte of nickel-cadmium batteries is non-corrosive, leaked electrolyte is capable of creating short circuits and battery grounding due to its conductive properties. Fouling can result in degraded battery output, battery discharge, or overheating of connections. Therefore, fouling is a potentially significant degradation mechanism for the terminal posts and intercell connectors of nickel-cadmium batteries.

4.3.3 Significance of Relevant Aging Mechanisms for Valve-Regulated Batteries

As mentioned previously, the valve-regulated batteries evaluated here include both lead-acid and nickel-cadmium types. The degradation mechanisms described in Sections 4.3.1 and 4.3.2 for the vented batteries are also applicable to their valve-regulated counterparts. The

evaluation here will not repeat the evaluations of Sections 4.3.1 and 4.3.2, but will only address the issues specific for the valve-regulated or sealed design configuration.

The aging mechanism from Section 4.2.1 that was determined to be relevant for valve-regulated batteries is:

- Wear of the Pressure Relief Valve

In addition to this aging mechanism, there are three additional failure phenomena that can occur in valve-regulated batteries:

- Dryout
- Thermal Runaway of Valve-Regulated Lead-Acid Batteries
- Memory Effect in Valve-Regulated Nickel-Cadmium Batteries

The following subsections assess the potential significance of each of these mechanisms/phenomena with respect to the battery subcomponents.

4.3.3.1 Wear of the Pressure Relief Valve

Wear occurs in the pressure relief valve due to the relative movement between contacting internal parts. Over time, wear may cause a malfunction of the valve. A failure of the valve to fully shut or regulate allows gases and vapors to escape, resulting in lowered gas recombination efficiency. Because water replenishment is not possible, valve failure can lead to dryout (see Section 4.3.3.2). Therefore, wear is a potentially significant aging mechanism for pressure relief valves in valve-regulated batteries.

4.3.3.2 Dryout

Excessive electrolyte/water loss from a cell is one of the main failure phenomenon for the valve-regulated batteries. Unlike vented batteries, there is no provision for water addition to valve-regulated batteries. The limited amount of electrolyte reserve in the batteries makes them vulnerable to the adverse effect of any significant loss of electrolyte.

Electrolyte loss may occur by the following four means:

- Venting of gasses that exceed the battery's recombination capability, that were produced by overcharging.
- Abnormal venting of gases during operation due to failure of the pressure relief valve.
- Water vapor diffusion through the container due to increased temperature.
- Electrolyte leakage or unregulated gas ventilation caused by a cracked container or failed terminal seal.

Once electrolyte loss reaches a certain point, the battery will no longer be able to perform its required function due to the reduction of available capacity. Dryout is a dominant failure mode for both lead-acid and nickel-cadmium valve-regulated batteries.

4.3.3.3 Thermal Runaway of Valve-Regulated Lead-Acid Batteries

Thermal runaway is a failure phenomenon in which a battery on a constant voltage charge at an elevated temperature can be damaged through internal heat generation due to high internal current. Under normal operating conditions, a valve-regulated lead-acid battery on a float charge remains in a fully charged condition and the gases that are produced are recombined internally. Any overcharge energy results in heat generation. If the design of the battery in conjunction with its installed location are such that the generated heat can be dissipated without a rise in the battery temperature, thermal runaway is unlikely. However, if the battery temperature increases, higher current is required to keep the float voltage at the set level. The additional current results in more gas generation inside the cell, which generates more heat during recombination and further raises the battery temperature. If the situation is not corrected, the battery can overheat and damage itself. Improper float voltage appears to be the greatest contributor to thermal runaway. A higher than recommended float voltage results in greater float current and thus battery overheating. Excessive ripple from the charger can also contribute to higher battery temperatures.[4.2] Therefore, thermal runaway is a potentially significant failure phenomenon for valve-regulated lead-acid batteries.

4.3.3.4 Memory Effect of Valve-Regulated Nickel-Cadmium Batteries

Memory effect is the tendency of a battery to assume the capacity normally demanded of it when operated in successive cycles of an identical, but less than full, depth of discharge. This phenomenon has been a problem with sealed nickel-cadmium batteries in some applications. Memory effect occurs primarily in sealed, sintered plate nickel-cadmium batteries, and is a result of very low charging rates coupled with repetitive cycling. Pocket plate nickel-cadmium batteries do not develop a memory effect. A cell can have its memory effect erased by complete discharge of the cell, followed by a full recharge at constant current (several cycles may be needed to completely eliminate the memory effect).[4.2] Therefore, memory effect is a potentially significant failure phenomenon for sintered plate valve-regulated nickel-cadmium batteries.

4.3.4 Aging Mechanism Synergies and Dependencies

Aging mechanisms were generally evaluated in Sections 4.3.1 through 4.3.3 as if they manifested individually on a component. Where a direct cause/effect link existed between two mechanisms, this was also discussed. Both theoretical considerations and field history indicate that the effects of two or more aging mechanisms acting simultaneously on a component may change the course of degradation and modify the failure mode. The time duration for significant degradation to occur under these conditions may be less than the duration for each individually acting aging mechanism.

Gassing and fouling are both significant synergistic contributors to the severity and rate of corrosion. Corrosion, on the other hand, has influence on the mechanical strength of

components and can be a synergistic cause of fatigue failure during a design basis seismic event. The failure history data presented in Section 3.6 generally does not indicate the impact of synergistic effects on specific failures, so it is not possible to quantitatively determine from available data at what rate synergistic effects are occurring.

4.4 Summary

Tables 4-7 through 4-9 summarize the significant aging mechanisms by subcomponent for vented lead-acid, vented nickel-cadmium, and valve-regulated stationary batteries, respectively. These tables also summarize the conclusions presented in Section 3.6 on industry operability data, which consists of NRC IE documents, responses to various utility questionnaires, NPRDS and LER data. Degradation mechanisms of material chemical change, corrosion, fatigue, thermal aging, electrolyte gassing and evaporation, and fouling are potentially significant for all the batteries evaluated in this guideline. Wear is a potentially significant aging mechanism for the valve-regulated batteries only because of the presence of the pressure relief valve.

The significant aging mechanism/component combinations identified in this section are further evaluated in Section 5 to determine the effective programs to detect and mitigate the aging degradation of the stationary batteries.

Table 4-7. Summary of Significance of Aging Mechanisms for Vented Lead-Acid Battery Subcomponents

Subcomponent	Aging Mechanism					
	Material Chemical Changes	Corrosion	Fatigue	Thermal Aging	Gassing and Electrolyte Evaporation	Fouling
Container	PS	NR	PS	NS	NR	NR
Electrolyte	PS	NR	NR	NR	PS	NR
Plates	PS	PS	PS	NR	PS	NR
Straps	NR	PS	PS	NR	NR	NR
Separators	PS	NR	NR	PS	NR	NR
Terminal Posts	NR	PS	PS	NR	NR	PS
Intercell Connectors	NR	PS	PS	NR	NR	PS
Terminal Post Seals	NR	NR	PS	NS	NR	NR
Battery Racks	NR	PS	PS	NR	NR	NR

PS = Aging mechanism is Potentially Significant for subcomponent.
 NS = Aging mechanism is Not Significant for subcomponent.
 NR = Aging mechanism is Not Relevant for subcomponent.

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Table 4-8. Summary of Significance of Aging Mechanisms for Vented Nickel-Cadmium Battery Subcomponents

Subcomponent	Aging Mechanism					
	Material Chemical Changes	Corrosion	Fatigue	Thermal Aging	Gassing and Electrolyte Evaporation	Fouling
Container	PS	NR	PS	NS	NR	NR
Electrolyte	PS	NR	NR	NR	PS	NR
Plates	PS	NS	NR	NR	NR	NR
Separators	NR	NR	NR	PS	NR	NR
Terminal Posts	NR	PS	PS	NR	NR	PS
Intercell Connectors	NR	PS	PS	NR	NR	PS
Terminal Post Seals	NR	NR	PS	NS	NR	NR
Battery Racks	NR	PS	PS	NR	NR	NR

PS = Aging mechanism is Potentially Significant for subcomponent.

NS = Aging mechanism is Not Significant for subcomponent.

NR = Aging mechanism is Not Relevant for subcomponent.

Table 4-9. Summary of Significance of Aging Mechanisms/Phenomena for Valve-Regulated Battery Subcomponents^{(1),(2)}

Subcomponent	Aging Mechanism/Phenomenon			
	Wear	Dryout	Thermal Runaway	Memory Effect
Pressure Relief Valve	PS	NR	NR	NR
Electrolyte	NR	PS	NR	NR
Lead-Acid Battery	PS Pressure Relief Valve	PS Electrolyte	PS	NR
Sintered Plate Nickel-Cadmium Battery	PS Pressure Relief Valve	PS Electrolyte	NR	PS

PS = Aging mechanism is Potentially Significant for subcomponent

NS = Aging mechanism is Not Significant for subcomponent

NR = Aging mechanism is Not Relevant for subcomponent

(1) Includes both lead-acid and nickel-cadmium battery designs.

(2) Aging mechanisms which are significant for the two vented designs are also significant for their respective valve-regulated designs (see Tables 4-7 and 4-8).

4.5 References

- 4.1 NUREG/CR-4457, "Aging of Class 1E Batteries in Safety Systems of Nuclear Power Plants," Idaho National Engineering Laboratory, EG&G Idaho, Inc., July 1987.
- 4.2 EPRI NMAC TR-100248, "Stationary Battery Maintenance Guide, Final Report," Electric Power Research Institute, December 1992.

5. EFFECTIVE MANAGEMENT OF AGING MECHANISMS

An effective program for addressing battery degradation will provide for both understanding and managing the aging mechanisms. Key elements of an effective program reflect the technical aging issues and potential consequences of the aging process being mitigated.

Aging mechanisms and their effects must be understood with sufficient accuracy and detail to provide the basis for developing and implementing aging management strategies that address actual or potential root causes of equipment failures. The requisite understanding may be either empirical or mechanistic, depending on the nature and potential consequences of a particular aging mechanism. An understanding of degradation requires a detailed awareness of equipment design, fabrication, installation, testing, inservice operation, and maintenance cycles. Degradation of batteries is a time dependent phenomenon that depends on the interactions of materials with environmental and operational stressors.

The programs discussed in this section are suggestions. They are meant to be guidelines that provide alternative methods that can be used to establish an effective program. Different combinations of maintenance techniques can be used to create plant-specific effective programs.

5.1 Generic Elements of an Effective Aging Management Program

The stationary batteries evaluated in this guideline must continue to safely and reliably function throughout their service life. Degradation of a battery is a regulatory concern when the equipment normally functions to ensure plant safety, and the degradation progresses to the point of impaired safety performance.

The License Renewal Rule,[5.1] paragraph 54.21, requires that certain nuclear plant components, including the batteries, be subject to programs that effectively manage component degradation and their associated aging mechanisms. Guidance is also provided in the draft Standard Review Plan for license renewal.[5.2] The Maintenance Rule[5.3] requires that nuclear plant components, including batteries, meet specified performance parameters. In addition, quality assurance criteria[5.4] require development and implementation of programs to ensure that conditions adverse to quality, including degraded battery performance, are promptly identified and corrected.

Criteria have been established for determining if a plant program is effective for detecting and mitigating the effects of aging. These criteria are provided in Reference 5.1 and state that a program is effective if:

- The program is documented, its implementing procedures are approved by on-site review committees, and it is implemented in accordance with plant administrative procedures, and
- The program procedures ensure that the component's required functions are properly addressed considering the effects of age-related degradation, as appropriate, and

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- The program establishes specific acceptance criteria against which the need for corrective action is to be evaluated, and requires timely corrective actions to be taken when the acceptance criteria are not met.

Reference 5.3 states in part under paragraph [A] [1] "Each holder of an operating license . . . shall monitor the performance or condition of SSCs . . . in a manner sufficient to provide reasonable assurance that SSCs . . . are capable of fulfilling their intended functions."

Paragraph [A] [2] states in part "Monitoring . . . is not required where it has been demonstrated that the performance or condition of a SSC is being effectively controlled through the performance of appropriate preventive maintenance, such that the SSC remains capable of performing its intended function."

The three criteria for determining program effectiveness are broken down into distinct categories. The following provides further guidance for each category to determine if a program satisfies the criteria.

5.1.1 Program Is Documented

The criterion for a program to be documented satisfies 10 CFR 50 Appendix B - Quality Assurance Criteria, which states in part "Every applicant for an operating license is required to include, in its final safety analysis report, information pertaining to the managerial and administrative controls to be used to assure safe operation." Therefore, a program being documented means that specific managerial and administrative control commitments have been made and are included on the respective plant docket via the updated final safety analysis report. Programs and activities not documented in the updated final safety analysis report may be documented in specific docketed commitments. Docketed commitments can result from responses to generic letters, I.E. bulletins, orders, 10 CFR 50.59 evaluations, notices of violations, etc., and other programmatic or procedural commitment made to ensure compliance with the Code of Federal Regulations.

5.1.2 Program Implementing Procedures Approved by On-Site Review Committee and Program Implemented Via Administrative Procedures

These two criteria for procedural approvals and administration of the program also satisfy 10 CFR 50 Appendix B. Item I. - *Organization of this Appendix* states in part "the authority and duties of persons and organizations performing activities affecting the safety-related functions of structures, systems, and components shall be clearly established and delineated in writing." This Appendix further states in Item II - *Quality Assurance Program*, that "This program shall be documented by written policies, procedures, or instructions and shall be carried out throughout plant life in accordance with those policies, procedures, or instructions."

Each program must be documented with written policies (i.e., administrative procedures), and the program implementing procedures must be reviewed and approved by on-site review committees to ensure that activities affecting the required function of the batteries are correctly performed.

5.1.3 Component's Required Functions Properly Addressed

Each battery evaluated in this guideline provides a support function to prevent or mitigate the consequences of postulated accidents that could cause undue risks to the health and safety of the public. Methods by which each component accomplishes this action is termed its required function. A battery may have only one or several required functions.

The required function for a battery is typically stated in terms of the battery's ability to power a certain load at a given voltage and current for a specified period of time. The scope and content of all program implementing procedures credited for effective management of aging are reviewed to ensure that aging mechanisms and degradation, affecting the capability of the equipment to satisfy its required function(s), are adequately detected and mitigated.

5.1.4 Age-Related Degradation Effects Properly Addressed

All aging mechanisms occurring to the batteries will manifest and progress at different rates, and are affected by many variables such as material composition, operating service conditions, environmental parameters, geometric configuration, etc. As such, program implementing procedures must be performed at a frequency commensurate with the rate of aging, to ensure detection and mitigation of degradation. Detection and mitigation of degradation provides assurance that the equipment's required function will not be compromised during its service life. Inspection, test, replacement, and refurbishment procedures are performed at frequencies which are based on equipment qualification requirements, regulatory specifications, vendor recommendations, industry experience, observations by knowledgeable plant personnel, etc. and can be adjusted as experience dictates.

5.1.5 Acceptance Criteria Established to Determine Need for Corrective Action, Corrective Actions Specified, and Timely Action Taken

These three criteria for determining program effectiveness also satisfy 10 CFR 50 Appendix B. Item V states in part that "Instructions, procedures, or drawings shall include appropriate qualitative and quantitative acceptance criteria for determining that important activities have been satisfactorily accomplished." Item XVI, *Corrective Action*, states that "Measures shall be established to assure that conditions adverse to quality are promptly identified and corrected."

All program implementing procedures shall contain acceptance criteria in the form of recorded data, documented observances, procedural step signoffs, etc. to demonstrate that activities performed on the batteries for detecting and mitigating degradation have been either satisfactorily accomplished, or corrective actions identified to ensure required function capability. This may include recording of measured process or state variables to provide for trending of slow-acting aging mechanisms.

The corrective actions required may encompass a wide range of activities which cannot be clearly identified in the program implementing procedure. Provisions shall be made, however, to document what corrective actions were taken. These corrective actions may be in the form of references to work requests, additional diagnosis, retesting, non-destructive examinations, etc.

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Program administrative procedures and/or specific implementing procedures shall provide guidance relative to the timeliness of corrective actions taken. This guidance shall be considered with respect to the aggressiveness of the aging mechanism (i.e., rate of degraded performance or function) and the frequency of program activities to detect and mitigate degradation. Performing timely corrective action ensures that equipment required functions are not compromised throughout the equipment's service life.

5.1.6 Program Effectiveness Matrix

Table 5-1 entitled, "Effective Program Criteria and Assessment Matrix," can be used to document the evaluation of a program and corresponding implementing procedures to effectively detect and mitigate battery age-related degradation.

Table 5-1. Effective Program Criteria and Assessment Matrix										
I.D. of Equipment Being Evaluated	Effective Program(s) Name									
Program Criteria										
Program Is Documented (See Note 1)										
Implementing Procedure(s) Approved by O.R.C										
Implemented Via Administrative Procedures										
Component Safety Functions Properly Addressed										
Age Related Degradation Effects Properly Addressed (Mechanism(s) and Rate of Degradation)										
Acceptance Criteria Established to Determine Need for Corrective Action										
Corrective Action Specified										
Timely Action Taken (See Note 2)										
Notes: F = Full compliance P = Partial compliance, subject to program enhancement N = Not in compliance, subject to program enhancement NA = Not applicable 1 = Documented means specific commitments are included on the docket (i.e., updated SAR, responses to GL, IEB, IEN, NUREGs, Orders, 10 CFR 50.59, etc.) 2 = "Timely" is considered with respect to the aggressiveness of the degradation and frequency of the program activities to ensure that required functions are not compromised.										

Author:	Date:
Reviewer(s):	Date:

5.2 Effective Programs Commonly Used in the Industry

Demonstrating the adequacy of plant procedures to detect and mitigate degradation is accomplished by 1) substantiating that established programs and procedures effectively ensure the capability of the associated components to perform their required function(s) throughout their entire service life, or 2) taking actions in the form of program and/or procedural enhancements necessary to manage the aging mechanism(s) which are not adequately addressed by current established programs and/or procedures. Adequacy of programs and procedures for detecting and mitigating degradation must be demonstrated using one of these methods.

It is recognized that many batteries are subject to a variety of inspection, test, replacement and/or refurbishment programs to address diverse functional requirements and various aging mechanisms. As such, to establish the adequacy of existing plant programs, several programs may be required for a given battery. Through a combination of such programs as necessary, the basis for safe and reliable operation throughout the component's entire service life is established.

The following is a discussion of the commonly used maintenance and surveillance programs determined from other aging studies to be effective in detecting manifestation of aging mechanisms and mitigating the degradation of batteries within acceptable limits.

This section first reviews the responses from utility questionnaires, NPRDS data summaries, and manufacturers' recommendations to determine what are the current practices for battery maintenance, surveillance, and testing. Industry standards, techniques, and programs for aging management of batteries are then reviewed, and the effectiveness of these programs to detect and mitigate battery aging is evaluated. This evaluation will determine which potentially significant degradation mechanisms are managed, and verify that the required functions of the batteries are maintained.

5.2.1 Utility Questionnaire Responses, NPRDS Data Review, and Manufacturers' Recommendations Review

The intent of this section is to survey current plant practices utilized, and their periodicities, as best accumulated from various data sources. This will later be compared to recommended practices and potential enhancements to improve aging detection and mitigation.

It must be recognized that the data set of utility questionnaire responses was limited (approximately 15% of operating units). Any interpretation of this data must be weighted by the small sample.

Utility Questionnaire Responses

Questionnaire responses were obtained from 6 utilities covering 17 plants, in varying degrees of detail. The questionnaire revealed most plants have some type of formalized maintenance procedure. Surveillance is the predominant activity performed, with 94% of the plants performing inspections and measurements quarterly, and 71% performing daily, monthly, or annual inspections. All of the plants surveyed perform a service or performance test on a cyclic (18-month) basis with 88.3% indicating that such tests are also performed at 54- or 60-

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month intervals. Table 5-2 summarizes the percentage of plants doing each maintenance activity at given frequencies.

NPRDS Database Results

An NPRDS search of testing activities revealed that 86% of the plants perform a check test, with most (54%) doing it on a weekly basis. Eighty-four of the plants perform functional testing, with most plants (23%) doing it on a cyclic basis. Only 13% of the plants perform a calibration test, with the majority (8%) doing it on a yearly, cyclic, or bi-annual basis. Table 5-3 summarizes the percentage of plants doing each testing activity at given frequencies.

Vendor Recommended Maintenance

Instruction and operating manuals for a major supplier of lead-acid batteries were reviewed to identify the vendor recommended maintenance. The vendor recommendations closely followed the recommended practices of IEEE STD 450-1987,[5.5] and in several instances, the vendor literature refers the reader to IEEE STD 450-1987. The vendor recommendations for monthly, quarterly, and annual inspections were identical to the IEEE recommendations, but the vendor literature recommended more stringent yearly performance tests as opposed to the five-year interval recommended in IEEE STD 450-1987. It should be noted, however, that IEEE STD 450-1987 recommends annual performance tests if the battery shows signs of degradation (i.e., reduced capacity) or has reached 85% of its expected service life.

Table 5-2. Battery Maintenance from Questionnaire Responses

Program	Activity	Frequency	Percentage of Plants
Surveillance	Inspect/Measure	18 Months	17.6
		Annually	70.6
		3 Months	94.1
		Monthly	70.6
		Weekly	17.6
		Daily	70.6
	Service or Performance Testing	60 Months	11.8
		54 Months	76.5
		18 Months	100.0

Note: Percentages total more than 100% because a single plant may perform several different types of inspections or tests at different frequencies.

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Table 5-3. Battery Testing (from NPRDS Data)

Activity	Frequency	Percentage of Plants
Check Testing	2 Years	2.5
	3 Months	2.5
	Monthly	10.2
	Weekly	54.4
	Daily	1.3
	2 Times/Day	1.3
	3 Times/Day	13.9
	Not Done	13.9
Functional Testing	5 Years	2.5
	2 Years	10.2
	18 Months	22.8
	Annually	11.4
	3 Months	6.3
	Monthly	16.4
	3 Times/Month	2.5
	Weekly	8.9
	Daily	1.3
	6 Times/Day	1.3
	Not Done	16.4
Calibration Testing	5 Years	1.3
	2 Years	2.5
	18 Months	2.5
	Annually	2.5
	3 Months	1.3
	Monthly	1.3
	Weekly	1.3
	Not Done	87.3

5.2.2 Common Programs and Techniques

The following programs and techniques, which are commonly used in the nuclear plant industry, are examined and analyzed for effectiveness:

- Preventive Maintenance Program
- Surveillance Program
- "Good Housekeeping" Practices - Operation Logs and Checklists
- On-Line Monitoring and Annunciator Response Procedures
- Corrective Maintenance Program
- Class 1E Battery Seismic Qualification
- Operational Experience Reviews and Trending

The following subsections describe these programs and evaluate their effectiveness for vented lead-acid, vented nickel-cadmium, and valve-regulated batteries of both types. A summary of these evaluations are presented in Tables 5-4 and 5-5 for lead-acid and nickel-cadmium batteries, respectively.

5.2.2.1 Preventive Maintenance Program

For a preventive maintenance procedure to be effective, it must be formalized, comprehensive and proactive in philosophy, with the intent of assuring maximum reliability and life in the units. Preventive maintenance activities consist of cleaning, examinations, measurements, calibration, and verification of proper operation. Such activities were reviewed for effectiveness in detecting and mitigating the subcomponent degradation mechanisms defined in Section 4, using the effectiveness criteria of Section 5.1. The established activities are derived from engineering experience, manufacturers' recommendations, environmental conditions, and feedback from past maintenance experience. The following paragraphs describe and evaluate preventive maintenance program activities.

The Preventive Maintenance Program for stationary batteries consists primarily of inspection procedures to provide a general assessment of the battery's condition, and to determine whether or not the battery is within its normal operating limits. The programs generally follow the guidance of applicable Regulatory Guides and IEEE standards. Among the guides and standards listed in Tables 3-4 and 3-5, NRC Regulatory Guide 1.129[5.6] and IEEE STD 450-1987[5.5] address the maintenance, testing, and replacement of large lead storage batteries. Nickel-cadmium storage batteries are covered by IEEE STD 1106-1987.[5.7] However, both standards are only applicable to the vented battery type. IEEE PAR 1188 (Unapproved Draft)[5.8] provides similar recommendations for valve-regulated lead-acid batteries. Currently, there is no IEEE standard covering the maintenance of valve-regulated nickel-cadmium batteries.

Inspections may be conducted on a weekly, monthly, quarterly, and/or yearly/refueling basis.[5.9, 5.10] The periodicity of inspections is mainly governed by plant Technical Specifications. The IEEE standards have recommendations for the scopes and intervals of inspection. The host utility measures and trends battery cell specific gravity and voltage weekly (pilot cell) and quarterly (all cells).

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Table 5-4. Summary of Effectiveness of Common Aging Management Programs for Lead-Acid Batteries

Aging Mechanism	Common Aging Management Programs					
	Preventive Maintenance	Surveillance	Class 1E Seismic Qualification	"Good Housekeeping" Logs and Checklists	On-Line Monitoring Annunciator Response	Corrective Maintenance
CONTAINER						
Material Chemical Changes	Visual Inspection Cleaning			Visual Observation		Cell Removal and Restoration
Fatigue	Visual Inspection			Visual Observation		Cell Removal and Restoration
ELECTROLYTE						
Material Chemical Changes	Visual Inspection Specific Gravity Measurements (Vented Design)	Capacity Testing		Float Voltage Logging Float Current Logging	Low Voltage Alarm	Equalize Charge
Gassing and Electrolyte Evaporation (Vented Design)	Electrolyte Level Check Cell Temperature Ambient Temperature Proper Float Voltage			Electrolyte Level Check Ambient Temperature Logging		
Dryout (Valve-Regulated Design)	Cell Temperature Ambient Temperature Proper Float Voltage	Capacity Testing		Ambient Temperature Logging		
Thermal Runaway (Valve-Regulated Design)	Cell Temperature Ambient Temperature Proper Float Voltage Minimize AC Ripple			Float Voltage Logging Float Current Logging Ambient Temperature Logging	High Voltage Alarm	
PLATES						
Material Chemical Changes	Visual Inspection	Capacity Testing		Float Voltage Logging Float Current Logging	Low Voltage Alarm	Equalize Charge
Corrosion	Visual Inspection Cell Temperature Ambient Temperature Proper Float Voltage	Capacity Testing		Float Voltage Logging Float Current Logging Ambient Temperature Logging	Low Voltage Alarm	
Fatigue	Visual Inspection		Qualification per Reg. Guide 1.158 and IEEE STD 535-1986			Cell Removal and Restoration
Gassing	Electrolyte Level Check Cell Temperature Ambient Temperature Proper Float Voltage			Electrolyte Level Check Ambient Temperature Logging		

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Table 5-4. Summary of Effectiveness of Common Aging Management Programs for Lead-Acid Batteries (continued)

Aging Mechanism	Common Aging Management Programs					
	Preventive Maintenance	Surveillance	Class 1E Seismic Qualification	"Good Housekeeping" Logs and Checklists	On-Line Monitoring Annunciator Response	Corrective Maintenance
STRAPS						
Corrosion	Visual Inspection Cell Temperature Ambient Temperature Proper Float Voltage	Capacity Testing		Float Voltage Logging Float Current Logging Ambient Temperature Logging		
Fatigue	Visual Inspection		Qualification per Reg. Guide 1.158 and IEEE STD 535-1986			Cell Removal and Restoration
SEPARATORS						
Material Chemical Changes	Visual Inspection Proper Float Voltage	Capacity Testing		Float Voltage Logging Float Current Logging	Low Voltage Alarm	
Thermal Aging	Cell Temperature Ambient Temperature Proper Float Voltage Minimize AC Ripple	Capacity Testing		Float Voltage Logging Float Current Logging Ambient Temperature Logging	Low Voltage Alarm	
TERMINAL POSTS						
Corrosion	Visual Inspection Ambient Temperature Connector Resistance Measurement			Visual Observation Ambient Temperature Logging		Termination and Intercell Connector Maintenance
Fatigue	Visual Inspection Connector Resistance Measurement			Visual Observation		Termination and Intercell Connector Maintenance
Fouling	Visual Inspection Connector Resistance Measurement			Visual Observation		Termination and Intercell Connector Maintenance
INTERCELL CONNECTORS						
Corrosion	Visual Inspection Ambient Temperature Connector Resistance Measurement			Visual Observation Ambient Temperature Logging		Termination and Intercell Connector Maintenance
Fatigue	Visual Inspection Connector Resistance Measurement			Visual Observation		Termination and Intercell Connector Maintenance

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Table 5-4. Summary of Effectiveness of Common Aging Management Programs for Lead-Acid Batteries (continued)

Aging Mechanism	Common Aging Management Programs					
	Preventive Maintenance	Surveillance	Class 1E Seismic Qualification	"Good Housekeeping" Logs and Checklists	On-Line Monitoring Annunciator Response	Corrective Maintenance
INTERCELL CONNECTORS (continued)						
Fouling	Visual Inspection Connector Resistance Measurement			Visual Observation		Termination and Intercell Connector Maintenance
TERMINAL POST SEALS						
Fatigue	Visual Inspection			Visual Observation		Cell Removal and Restoration
BATTERY RACK						
Corrosion	Visual Inspection			Visual Observation Ambient Temperature Logging		
Fatigue	Visual Inspection		Qualification per Reg. Guide 1.158 and IEEE STD 535-1986	Visual Observation		
PRESSURE RELIEF VALVE (Valve-Regulated Design)						
Wear	Cell Voltage Measurement	Capacity Testing				

Table 5-5. Summary of Effectiveness of Common Aging Management Programs for Nickel-Cadmium Batteries

Aging Mechanism	Common Aging Management Programs				
	Preventive Maintenance	Surveillance	"Good Housekeeping" Logs and Checklists	On-Line Monitoring Annunciator Response	Corrective Maintenance
CONTAINER					
Material Chemical Changes	Cleaning Visual Inspection		Visual Observation		Cell Removal and Restoration
Fatigue	Visual Inspection		Visual Observation		Cell Removal and Restoration
ELECTROLYTE					
Material Chemical Changes		Capacity Testing	Float Voltage Logging Float Current Logging	Low Voltage Alarm	
Gassing and Electrolyte Evaporation (Vented Design)	Cell Temperature Ambient Temperature Electrolyte Level Check		Electrolyte Level Check Ambient Temperature Logging		
Dryout (Valve-Regulated Design)	Cell Temperature Ambient Temperature Proper Float Voltage	Capacity Testing	Ambient Temperature Logging		

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Table 5-5. Summary of Effectiveness of Common Aging Management Programs for Nickel-Cadmium Batteries (continued)

Aging Mechanism	Common Aging Management Programs				
	Preventive Maintenance	Surveillance	"Good Housekeeping" Logs and Checklists	On-Line Monitoring Annunciator Response	Corrective Maintenance
PLATES					
Material Chemical Changes		Capacity Testing	Float Voltage Logging Float Current Logging	Low Voltage Alarm	
Memory Effect (Sintered Plate Design)		Capacity Testing			Complete Discharge/Recharge
SEPARATORS					
Thermal Aging	Proper Float Voltage Cell Temperature Ambient Temperature Minimize AC Ripple	Capacity Testing	Float Voltage Logging Float Current Logging Ambient Temperature Logging	Low Voltage Alarm	
TERMINAL POSTS					
Corrosion	Visual Inspection Ambient Temperature Connector Resistance Measurement		Visual Observation Ambient Temperature Logging		Terminal and Intercell Connector Maintenance
Fatigue	Visual Inspection Connector Resistance Measurement		Visual Observation		Terminal and Intercell Connector Maintenance
Fouling	Visual Inspection Connector Resistance Measurement		Visual Observation		Terminal and Intercell Connector Maintenance
INTERCELL CONNECTORS					
Corrosion	Visual Inspection Ambient Temperature Connector Resistance Measurement		Visual Observation Ambient Temperature Logging		Terminal and Intercell Connector Maintenance
Fatigue	Visual Inspection Connector Resistance Measurement		Visual Observation		Terminal and Intercell Connector Maintenance
Fouling	Visual Inspection Connector Resistance Measurement		Visual Observation		Terminal and Intercell Connector Maintenance
TERMINAL POST SEALS					
Fatigue	Visual Inspection		Visual Observation		
BATTERY RACK					
Corrosion	Visual Inspection		Visual Observation Ambient Temperature Logging		
Fatigue	Visual Inspection		Visual Observation		
PRESSURE RELIEF VALVE (Valve-Regulated Design)					
Wear	Cell Voltage Measurement Measurement	Capacity Testing			

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The following descriptions of inspection programs are given separately for the three battery categories.

Vented Lead-Acid Battery Inspections

Visual inspection covers the battery and battery installation area. The battery and area are inspected for cleanliness. Area or room temperature is recorded, and operation of the ventilation system is verified. Some battery rooms may have a hydrogen gas monitor. Battery cell jars, posts, vent and dust caps are examined for corrosion, damage, and cleanliness. Cell electrolyte level is checked and maintained between the high and low level marks on the cells. Distilled water is added if necessary. Terminal connection assemblies are also inspected for corrosion, looseness, and damage.[5.5, 5.9, 5.10]

Measurements are taken for battery voltage, cell voltage, cell specific gravity, and cell temperature. The corrected specific gravity is calculated using temperature and level correction factors. Charger voltage and charging current are also recorded. Battery float charging voltage is adjusted as necessary to avoid overcharging, which can result in water loss and excessive corrosion of the positive plate grids, straps, and terminal posts. Undercharging, which can cause the formation of lead sulfate on the plates resulting in low capacity, can also be prevented.[5.5, 5.9, 5.10]

Weekly or monthly inspection usually uses a pilot cell(s) for measuring cell voltage, electrolyte specific gravity, and electrolyte temperature. These parameters are checked for each cell during quarterly inspections.[5.5, 5.9, 5.10]

If signs of corrosion are observed on battery terminals and connectors during weekly, monthly, or quarterly inspections, the contact resistance of the questionable connections is measured. The terminals and connectors are cleaned if the resistance exceeds the acceptance criteria. Following cleaning, if the resistance reading is still unacceptable, a corrective work request is initiated. Additionally, cell-to-cell resistance of each terminal connection is checked annually or at refueling intervals, and any abnormal conditions are corrected. All cell connectors are torqued to the manufacturer recommended values specified by the procedure.[5.5, 5.9, 5.10]

Inspections also involve checking of the batteries and DC buses to ensure that no solid ground exists. Battery racks are checked for loose mounting bolts, bent supports, or corrosion. Cells are inspected for cracks, leakage, excessive dirt accumulation, signs of plate sulfation, cell hydration, plate deformation, copper contamination, and/or sediment accumulation. The batteries are cleaned as necessary during these inspections.[5.5, 5.9, 5.10]

Table 5-6 provides a tabulation of the activities and periodicities of inspection programs for vented lead-acid batteries. The battery degraded conditions or potential problems addressed by the inspection activities are also listed in the table.

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Table 5-6. Routine Inspections for Vented Lead-Acid Batteries and Addressed Battery Conditions

Routine Inspection Activities	Frequency	Battery Conditions
VISUAL INSPECTION		
General appearance and cleanliness of battery and battery area	W/M, Q, Y/R	External corrosion and fouling
Condition of ventilation	W/M, Q, Y/R	Environmental condition
Cracks in cells or signs of electrolyte leakage	W/M, Q, Y/R	Cracked container or post seals
Cell electrolyte level	W/M, Q, Y/R	Loss of water or electrolyte
Corrosion of terminals and connectors	W/M, Q, Y/R	Corrosion and high connection resistance
Individual cell condition	Y/R	Internal corrosion/flaking, plate growth, copper contamination, and sediment buildup
Retorquing connections for each cell	Y/R	Loose connections
Integrity of the battery rack	Y/R	Corroded or damaged structure
Cleaning as necessary	W/M, Q, Y/R	Corroded material and accumulated foreign substances
MEASUREMENTS		
Charger output voltage and current	W/M, Q, Y/R	Overcharging or undercharging
Battery terminal voltage	W/M, Q, Y/R	State of charge
Ambient temperature	W/M, Q, Y/R	Inadequate float charging
Pilot cell(s) voltage, temperature, electrolyte level, specific gravity	W/M, Q, Y/R	High or low float voltage, state of charge
Each cell voltage, temperature, electrolyte level, specific gravity	Q, Y/R	High or low float voltage, state of charge
Terminal and intercell connection resistance	Y/R	Faulty connections
W — Weekly Q — Quarterly R — At Refueling Outage M — Monthly Y — Yearly		

Vented Nickel-Cadmium Battery Inspections

Inspection of vented nickel-cadmium batteries is identical to that of vented lead-acid batteries except for the check of electrolyte specific gravity and the removal of any potassium carbonate formed on the top of the cell.[5.7, 5.10] Specific gravity measurements are not necessary for a nickel-cadmium battery, because the electrolyte is not altered by the electrochemical reactions during charge or discharge operation but merely acts as a conductor. The specific gravity of the electrolyte does not change during charging or discharging, and therefore specific gravity measurements do not provide any meaningful information regarding the charging status of the cell.

Carbonation of the electrolyte due to exposure to the atmosphere is not a concern for lead-acid batteries, but it is for nickel-cadmium batteries. Any potassium carbonate formed on the cell tops is removed to avoid the possibility of shorting or grounding. If the electrolyte itself is found to be carbonized (using the manufacturer's test kit), battery performance can be improved by replacing the electrolyte.[5.7, 5.10]

The inspection activities and intervals for vented nickel-cadmium batteries are listed in Table 5-7. The battery degraded conditions or potential problems addressed by the inspection activities are also listed in the table.

Valve-Regulated Battery Inspection

Valve-regulated batteries, also known as "sealed" batteries, are not completely sealed since a relief valve is provided to control battery internal pressure. Although there is no requirement for periodic water addition to the batteries, valve-regulated batteries are not maintenance free. The general inspection of a valve-regulated battery is mostly the same as that of a vented battery, with the differences lying in electrolyte level and specific gravity measurements (lead-acid type) due to the construction features of valve-regulated batteries.

The following activities are not performed on the valve-regulated batteries.

- Maintaining Electrolyte Level
- Measurement of Specific Gravity (lead-acid type)

The failure modes of valve-regulated batteries are to some extent different from that of vented batteries. Currently, the only IEEE standard addressing valve-regulated type batteries is the unapproved draft version of IEEE PAR 1188[5.8, 5.10] for valve-regulated lead-acid batteries.

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Table 5-7. Routine Inspections for Vented Nickel-Cadmium Batteries and Addressed Battery Conditions

Routine Inspection Activities	Frequency	Battery Conditions
VISUAL INSPECTION		
General appearance and cleanliness of battery and battery area	W/M, Q, Y/R	External corrosion and fouling
Condition of ventilation	W/M, Q, Y/R	Environmental condition
Cracks in cells or signs of electrolyte leakage	W/M, Q, Y/R	Cracked container or post seals
Cell electrolyte level	W/M, Q, Y/R	Loss of water or electrolyte
Corrosion of terminals and connectors	W/M, Q, Y/R	Corrosion and high connection resistance
Retorquing connections for each cell	Y/R	Loose connections
Integrity of the battery rack	Y/R	Corroded or damaged structure
Cleaning as necessary	W/M, Q, Y/R	Corroded material and accumulated foreign substances
MEASUREMENTS		
Charger output voltage and current	W/M, Q, Y/R	Overcharging or undercharging
Battery terminal voltage	W/M, Q, Y/R	State of charge
Ambient temperature	W/M, Q, Y/R	Inadequate float charging
Pilot cell(s) Voltage and temperature	W/M, Q, Y/R	High or low float voltage, state of charge
Each cell Voltage and temperature	Q, Y/R	High or low float voltage, state of charge
Terminal and intercell connection resistances	Y/R	Faulty connections
W — Weekly Q — Quarterly R — At Refueling Outage M — Monthly Y — Yearly		

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The visual inspections for valve-regulated batteries include the battery and battery area. The battery room or adjacent area is checked for cleanliness and ambient temperature is recorded. Area ventilation condition is verified. Cells or battery modules are inspected for cracks, distortion, or signs of electrolyte leakage. Battery posts and connections are examined for corrosion and damage. Inspection is also performed on the battery rack or battery module support. Since there is no access to the electrolyte, cell temperature is measured by touching the temperature probe against the negative terminal of each cell. Keeping cell temperature within the specified range can avoid accelerated grid corrosion (lead-acid cells), undercharging or overcharging, and thermal runaway (lead-acid cells). Corrective actions will be initiated if any problems are identified.[5.8, 5.10]

The periodic monitoring of battery float charge status for vented batteries also applies to valve-regulated batteries. Maintaining a proper float voltage is crucial to a valve-regulated lead-acid battery because of its vulnerability to thermal runaway failure resulting from overcharging. Excessive gassing is also a result of overcharging and will lead to premature dryout of the battery.[5.8, 5.10]

Intercell and termination connection resistances are checked annually or during each refueling outage. The integrity of all connections are inspected and ensured acceptable. These connections include cell-to-cell and battery to external circuit terminations. Acceptance criteria are provided for assisting in condition evaluation and determining whether a correction is required. High resistance can introduce excessive voltage drop or localized heating at the connection, causing damage in the event of a high rate of discharge operation. The connections are also retorqued to adequate tightness.[5.8, 5.10]

A summary of the inspection activities for valve-regulated batteries is shown in Table 5-8. The coverage of the program activities with respect to subcomponents is identified in the table.

EPRI NMAC Guidance

EPRI's Nuclear Maintenance Applications Center has addressed preventive maintenance techniques for stationary batteries[5.10] and emergency battery lighting units.[5.11] These documents describe the equipment and discuss degradation and failure modes. Recommended maintenance practices based on industry standards, industry papers, manufacturers' literature, regulatory guidance, and industry experience are then developed. Tables 5-9 through 5-12 summarize the recommended maintenance activities and periodicities presented in the NMAC maintenance guides. These EPRI guides should serve as a foundation in formulating and/or reviewing effective preventive maintenance programs for batteries.

5.2.2.2 Surveillance Program

The Surveillance Program involves periodic testing or observation to verify that plant systems, structures, and components continue to perform their required function or are in a state of readiness to perform their required function. Plants have Technical Specification surveillance procedures as well as operational surveillance procedures.

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Table 5-8. Routine Inspections for Valve-Regulated Batteries and Addressed Battery Conditions

Routine Inspection Activities	Frequency	Battery Conditions
VISUAL INSPECTION		
General appearance and cleanliness of battery and battery area	W/M, Q, Y/R	External corrosion and fouling
Cracks in cells or signs of electrolyte leakage	W/M, Q, Y/R	Cracked container or post seals
Corrosion of terminals and connectors	W/M, Q, Y/R	Corrosion and high connection resistance
Retorquing connections for each cell	Y/R	Loose connections
Integrity of the battery rack or support	Y/R	Corroded or damaged rack or support
Cleaning as necessary	W/M, Q, Y/R	Corroded material and accumulated foreign substances
MEASUREMENTS		
Charger output voltage and current	W/M, Q, Y/R	Overcharging or undercharging
Battery terminal voltage	W/M, Q, Y/R	State of charge
Ambient temperature	W/M, Q, Y/R	Inadequate float charging
Pilot cell(s) Voltage and temperature	W/M, Q, Y/R	High or low float voltage, state of charge
Each cell Voltage and temperature	Q, Y/R	High or low float voltage, state of charge
Terminal and intercell connection resistances	Y/R	Faulty connections
W — Weekly Q — Quarterly R — At Refueling Outage M — Monthly Y — Yearly		

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Table 5-9. Vented Lead-Acid Battery Recommended Inspection and Test Periodicities from NMAC Stationary Battery Maintenance Guide[5.10]

Inspection or Test	Recommended Periodicity
Visual Inspection	Monthly
Float Voltage Checks	Monthly (pilot cells) Quarterly (all cells)
Electrolyte Checks	Monthly (pilot cells) Quarterly (10% of cells) Annual (all cells)
Detailed Visual Inspection	Annually
Connection Resistance Measurements	Annually
Battery Rack Integrity Inspection	Annually
Performance Test	<ul style="list-style-type: none"> • Within first two years of service • Every five years until degradation is detected • Every two years if the battery has reached 85% of its expected service life and the battery capacity is still greater than 100% (no observed degradation) • Annually if battery degradation is detected or the battery has reached 85% of its expected service life and the battery capacity is less than 100%
Service Test	Typically established by Technical Specification requirements

Table 5-10. Valve-Regulated Lead-Acid Battery Recommended Inspection and Test Periodicities from NMAC Stationary Battery Maintenance Guide[5.10]

Inspection or Test	Recommended Periodicity
Visual Inspection	Monthly
Float Voltage Checks	Monthly (pilot cells) Quarterly (all cells)
Cell Impedance or Conductance	Quarterly
Cell Temperature Inspection	Quarterly
Detailed Visual Inspection	Annually
Connection Resistance Measurements	Annually
Battery Rack Integrity Inspection	Annually
Performance Test	Every two years until degradation is noted, and then annually thereafter
Service Test	Typically established by Technical Specification requirements

Table 5-11. Nickel-Cadmium Battery Recommended Inspection and Test Periodicities from NMAC Stationary Battery Maintenance Guide[5.10]

Inspection or Test	Recommended Periodicity
Visual Inspection	Monthly
Float Voltage Checks	Monthly (pilot cells) Quarterly (all cells)
Pilot Cell Temperature Check	Monthly
Connection Resistance Measurements	Annually
Battery Rack Integrity Inspection	Annually
Performance Test	<ul style="list-style-type: none"> • Within the first two years of service • Every five years until battery degradation is detected • Annually after battery degradation is detected
Service Test	Typically established by Technical Specification requirements

The Technical Specifications define the Limiting Conditions for Operation of the plant. The Technical Specifications also define testing requirements to ensure that these conditions are met. The operational surveillance requirements are the various periodic tests and checks not required by the Technical Specifications, but that are required for safe and efficient operation of the plant or to satisfy other regulatory requirements.

The surveillance procedures include appropriate quantitative or qualitative acceptance criteria for determining that important activities have been satisfactorily accomplished. The test results are reviewed for the identification of system problems and appropriate follow-up corrective action. This problem identification and corrective action should include examining for age-related degradation.

Many surveillance programs encompass the inspections and measurements discussed above under preventive maintenance. Additionally, battery surveillance consists of battery capacity tests, which are performed periodically to verify the capability of a battery to meet its design function. Capacity test results can provide more direct, conclusive information about the state of battery degradation. The inspections previously discussed in Section 5.2.2.1 can identify conspicuous problems, including battery external conditions, and assure certain battery parameters within the specified limits. Inspections do not necessarily provide specific information of the battery's present capacity. Capacity tests can give definitive indication of the battery's ability to carry the design loads.

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Table 5-12. Emergency Battery Lighting Unit Recommended Maintenance Practices from NMAC Emergency Battery Lighting Unit Maintenance and Application Guide [5.11]

Category	Description	Periodicity (Note 1)
Inspections and Checks	Visual Inspection	Semi-Annually
	Battery Inspection	Semi-Annually
	Float Voltage Check	Semi-Annually
	Lamp Alignment and Obstruction Check	(Note 2)
Tests	Functional Test	Monthly
	Blackout Operational Test	(Note 3)
	Battery Discharge Performance Test	Annually (Note 4)
Periodic Maintenance	Battery Replacement	(Note 5)
	Relamping	(Note 6)

Notes:

1. The recommended periodicities are intended to be a baseline. Plant-specific experience should be used to optimize test and inspection periodicities.
2. For an operating plant, the most likely time for EBL lamps to become misaligned or blocked is during an outage or similar period of intense maintenance and construction. It is recommended that the lamp alignment and obstruction check be coordinated with completion of the outage work.
3. A blackout operational test should be needed only once (ideally upon installation) to verify that the EBL can perform its design function. However, a reverification test may be appropriate if the engineered basis of the unit is permanently changed. Examples of changes that may affect the engineered basis of an EBL include:
 - Installation of new lamp fixtures that have significantly different illumination characteristics (e.g., beam pattern and lumen output)
 - An addition or change to the equipment to be illuminated
 - Equipment modifications that may significantly influence lamp beam patterns
4. Plants operating on an 18-month refueling cycle may find it more effective to do periodic battery discharge testing every 18 months, primarily to disassociate routine EBL maintenance from outage-related activities.
5. Whether or not the battery replacement periodicity is correct depends on numerous plant-specific variables. Factors to consider in determining an appropriate battery replacement schedule are discussed in Section 6.1 of the NMAC guide.
6. Periodic lamp replacement may or may not be appropriate. Section 6.2 of the NMAC guide provides an explanation of when periodic lamp replacement might prove effective.

IEEE STD 450-1987[5.5] and IEEE STD 1106-1987[5.7] contain recommendations of the periodicities and procedure for capacity tests for lead-acid and nickel-cadmium batteries, respectively. There are three different types of battery capacity tests, consisting of the following.

- Acceptance Test — This test is performed at the factory or upon initial installation, and determines whether the battery meets its specification or the manufacturer's rating, or both.
- Performance Test — This test is used to periodically determine whether the performance of the battery is within acceptable limits.
- Service Test — This test is performed, if required, to determine whether the battery, as found, meets the design requirements of the system to which it is connected.

Capacity tests are basically the same for both lead-acid and nickel-cadmium batteries, with some differences on parameter acceptance limits pertaining to the battery types. The following discussion of capacity tests applies to both types. The test methods and requirements for valve-regulated batteries are very similar to their vented counterparts. Discussions unique to valve-regulated batteries follow the general discussion of capacity tests.

The type and periodicity of capacity testing applied to a specific battery may vary depending on the application of the battery. Current industry practices generally follow the guidance of industry standards, manufacturer's recommendations, and plant Technical Specifications. For a safety-related battery, capacity tests typically include:

- A performance test within first two years of initial installation.
- A service test annually or at refueling cycles.
- Additional performance tests at five year intervals.
- Performance tests at annual or refueling intervals upon finding of battery degradation, or (for lead-acid batteries only) once the battery has reached 85% of its expected service life.

Acceptance testing is usually done at the factory. Batteries of less significant roles are very likely to be subject to the acceptance and performance tests just mentioned, but not the service test. Table 5-13 summarizes the test periodicities for each type and application of battery.

Acceptance Test

The acceptance test is exactly the same as the performance test described below. The only difference is that the acceptance test is completed at the factory or upon initial installation. [5.5, 5.7, 5.8, 5.9, 5.10]

Table 5-13. Capacity Discharge Tests for Large Stationary Batteries

Capacity Discharge	Test Periodicity for Vented Battery		Test Periodicity for Valve-Regulated Battery	
	Safety-Related	Non-Safety-Related	Safety-Related	Non-Safety-Related
Service Test	Annual or every refueling outage			
Performance Test (Under As-Found Condition)	Within first two years of service, five-year intervals thereafter	Within first two years of service, five-year intervals thereafter	Annual or every refueling outage	Annual or every refueling outage
	Annual or every refueling outage after signs of degradation or 85% of expected service life	Annual or every refueling outage after signs of degradation or 85% of expected service life	Semi-annual after signs of degradation or 85% of expected service life	Semi-annual after signs of degradation or 85% of expected service life
Acceptance Test	Upon initial installation or at the factory	Upon initial installation of at the factory	Upon initial installation or at the factory	Upon initial installation or at the factory

In the case when only individual cells of an installed battery require replacement, the acceptance test can be performed on those cells to avoid conducting a complete battery capacity test. By using this approach, the overall battery capacity will not be inadvertently degraded because of the replacement cells.

Performance Test

The performance test determines the capacity of a battery, based on the ability of the battery to supply the manufacturer's rated discharge current for a given reference duration under a specific set of conditions. Because of the design margins in the battery size, the manufacturer's rated discharge current is always higher than the actual system required current with sufficient margins. A performance test duration corresponding to the duty cycle duration can provide assurance that the battery can meet the requirements of its design function.[5.5, 5.7, 5.8, 5.9, 5.10]

The performance test may be carried out under either of two initial battery conditions: optimal and as-found. The former requires that the battery be equalized and inspected with all parameters within specification and any problems corrected prior to the test. The latter implies that the test is to be conducted without any preparation for the battery, unless there is a possibility of battery damage due to some discrepancy. Testing under the optimal condition can provide relatively accurate information for trending aging. Testing under the as-found condition will provide additional information concerning the effect of maintenance practices. Typically, the performance test is performed under the as-found condition, especially in the case of safety-related batteries where the performance test is always conducted in lieu of the service test when it is due.[5.5, 5.7, 5.10] Only the test under the as-found condition is described here.

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General inspections are always conducted with the performance test. Pre-test connection resistance, specific gravity (vented lead-acid batteries only), cell float voltage, electrolyte or cell temperature, and battery terminal voltage are verified and recorded. The battery to be tested should have been on float charge for a certain period of time, e.g. over seven days. During the test, the inter-cell connectors or posts are closely monitored for signs of excessive heating. The required discharge current rate is obtained using a temperature correction factor and is maintained within the specified range. Individual cell voltages and battery terminal voltage are measured at periodic intervals during the test and at the completion of the test.[5.5, 5.7, 5.10]

If one or more cells show an excessive voltage, the cell(s) will be jumped or removed and the test will continue with an adjusted battery terminal voltage. The test is stopped at the time when the cut-off voltage is reached. The battery capacity is calculated in percentage based on the elapsed discharge time in comparison to the rated time.[5.5, 5.7, 5.10]

The performance test interval for a vented lead-acid battery will be adjusted in situations when the battery shows signs of degradation or when the battery has reached 85% of its expected service life. The signs of degradation for a vented lead-acid battery include either of the following two conditions.

- Battery capacity drops more than 10% from the previous test or from its average of previous performance tests.
- The battery capacity is below 90% of the manufacturer's rating.

The expected service life of a battery is difficult to determine, and it may vary significantly depending on the battery's operating conditions and maintenance. The expected service life is typically specified by the manufacturer.

The performance test interval for a vented nickel-cadmium battery will be adjusted in situations when the battery shows signs of excessive capacity loss. Excessive capacity loss for a vented nickel-cadmium battery is indicated when the battery capacity drops more than 1.5% per year of rated capacity from its capacity on the previous performance test.

The performance test not only demonstrates the present capacity of a battery, but provides a mechanism to allow trending of capacity decrease by discharging the battery at a near constant current to a pre-defined cut-off point and comparing the actual discharge times to the rated discharge time. A vented lead-acid battery will be replaced if its capacity as determined in the test is below 80% of the manufacturer's rating.[5.5, 5.10] A vented nickel-cadmium battery will be replaced if its capacity indicates the remaining margin above service life capacity is approaching one year.[5.7, 5.10]

Service Test

The service test demonstrates the battery's ability, as-found, to meet the design basis discharge requirements of the associated DC system. In this case, the test takes into account the influence of the normal float charge operation and maintenance practices, and uses the design basis discharge rates and duty cycle, not the manufacturer's rated discharge current as used in

the performance test. The service test is also different from the performance test in evaluating a battery's capability. The service test verifies whether the battery can meet its design basis duty cycle requirements, while the performance test determines the battery's capacity in relation to its manufacturer's rating. The service test results can also be trended by comparing the recorded battery voltages from certain portions of the test duty cycle over a period of time.[5.5, 5.7, 5.8, 5.9, 5.10]

Generally, the service test is used only on safety-related stationary batteries with test periodicities established by the plant Technical Specifications. The decision of whether or not to perform a service test on a non-safety-related battery rests with the plant engineering and maintenance departments, and may depend on other plant-specific requirements. The service test is usually waived whenever the performance test is due to be conducted at the same time. The service test duty cycle is determined based on the actual DC system duty cycle. The duty cycle is always updated if there is any change of the load profile. Therefore, the test results reflect the battery's ability to meet the current DC system requirements.[5.5, 5.7, 5.8, 5.9, 5.10]

General inspections are always performed with the service test. Pre-test connection resistance, specific gravity (vented lead-acid battery only), cell float voltage, electrolyte or cell temperature, and battery terminal float voltage are verified and recorded. The discharge rates are determined for each portion of the duty cycle. A temperature correction factor to account for the design basis low temperature may be used to modify the discharge rates. Such a factor is often used because a battery tested on a warm day might not provide positive assurance that it would pass the test on the design basis cold day. The discharge current is maintained to match the load profile over the duty cycle. The intercell connections are monitored for indication of overheating. This will be evident if the connection becomes too hot to touch or starts to smoke. The battery voltage is closely monitored throughout the test to ensure that the test acceptance criteria are met (i.e., the voltage should not fall below the design limit during the entire duty cycle). Taking individual cell voltages and battery terminal voltage during the critical portion of the service test load profile provides information for trending analysis. If the battery fails the test, the situation will be reported and corrective action will be initiated.[5.5, 5.7, 5.8, 5.9, 5.10]

Capacity Tests for Valve-Regulated Batteries

The capacity tests for valve-regulated batteries are identical to those for vented batteries except for the test intervals. The test methods, requirements and limitations previously described for vented type batteries also apply to valve-regulated batteries. As mentioned before, there is no published IEEE standard addressing the maintenance of valve-regulated batteries. IEEE PAR 1188 (draft version)[5.8] is to provide maintenance recommendations for valve-regulated lead-acid batteries. The standard recommends annual performance tests for valve-regulated lead-acid batteries in the normal condition and semi-annual testing once degradation is noted.

Because valve-regulated batteries have no access for cell internal inspection, visual inspections may not effectively detect the incipient stage of predominant dryout failure. Considering this limitation of visual inspection, performance testing is even more critical for valve-regulated batteries than for vented batteries.[5.8, 5.10]

Valve-regulated batteries are not normally used in large DC distribution applications, but are typically used in situations where the battery voltage and capacity are low, such as engine cranking systems, small uninterruptible power supply (UPS) units, and emergency lighting units. Current maintenance practices related to such batteries are dependent on plant Technical Specifications, the relative importance of the batteries, and plant maintenance departments. For the batteries used in the emergency lighting units for safe shutdown, current plant practices usually include a monthly unit operability test and an annual, as-found, capacity discharge test. [5.8, 5.11]

5.2.2.3 "Good Housekeeping" Practices - Operation Logs and Checklists

General plant operating activities typically include inspections as part of the operator's watch standing guidelines. The guidelines are typically documented as part of an administrative work instruction, which is approved by the on-site operations committee and implemented in accordance with plant administrative procedures. Operators routinely tour the plant (i.e., operator walkdown) to observe equipment conditions and record results on a checklist that contains qualitative and quantitative acceptance criteria. Equipment operation is verified, and parameters such as ambient temperature, float voltage, and charging current are logged. Unusual noise, odor, leakage, or vibration are also noted. Individual checklist items are performed at various frequencies ranging from hourly to monthly. The frequency is established based on experienced rates of change or degradation potential for the observed item. If acceptance criteria are not met, the operator informs the shift supervisor who initiates corrective or investigative action.

Usually, there are plant prestart check requirements for the systems critical to nuclear plant operation after an outage. Plant prestart checklist procedures are used to verify the operational readiness of the plant systems, including the DC system batteries and the standby batteries. The general appearance and battery voltage readings are checked and ensured to be within acceptable ranges.

System daily or weekly logs may also be conducted to examine the system operating conditions. The general conditions and battery float voltages are observed and recorded. Obvious component defects or out-of-range parameter settings can be detected.

5.2.2.4 On-Line Monitoring and Annunciator Response Procedures

Alarm and/or indication control schemes for monitoring the stationary batteries and DC systems, or the important equipment or systems containing back-up batteries, are always provided in the main control room and often in the local area adjacent to the batteries. The annunciators and indicators supply operators with information regarding the operating or standby status of the batteries, DC systems, or systems with standby batteries and warn the operators of abnormal or fault conditions. Typical alarms include low output voltage, DC system trouble, DC bus ground, or high ambient temperature.

Typically, there are annunciator response procedures that prescribe the actions that operators must take in response to individual automatic alarms. The procedures are approved by the on-site review committee and are implemented in accordance with plant administrative procedures. The procedures include acceptance criteria and instructional steps to respond to an

annunciator alarm. If the operator cannot correct the alarming condition (as in a degraded state), then the operator reports the condition to the shift supervisor who initiates corrective or investigative actions.

Proper alarm setpoints are critical to the effectiveness of this program. If setpoints are too close to operating conditions, spurious alarms may be generated. Conversely, if setpoints are too far from normal operating conditions, alarms may annunciate too late to allow sufficient time for operators to take corrective actions. Setpoints are typically determined by plant personnel based on experience and the system ratings and loads.

5.2.2.5 Corrective Maintenance Program

Corrective maintenance is performed in response to abnormalities detected during operation, inspection, monitoring, or testing. Corrective maintenance is typically performed in response to a component or subcomponent failing to perform its required function, and as such is not effective at detecting or mitigating aging. However, there are certain activities that are typically performed or should be performed during corrective maintenance that are effective at mitigating future aging of battery subcomponents.

The typical corrective maintenance procedures for the batteries may include:

- Battery Equalizing Charge Procedure
- Battery Termination and Intercell Connector Maintenance Procedure
- Battery or Battery Cell(s) Removal and Restoration Procedure

The corrective maintenance procedures available to a particular battery installation differ among the applications and plants. The battery equalizing charge procedure provides guidance for conducting battery recovery charge after a battery discharge or the inspection finding of an undercharged condition. Battery termination and intercell connection maintenance may be performed on a regular basis or as needed based on conditions noted during other maintenance activities. The cell(s) removal and restoration procedure is intended to provide basic instructions for the removal and restoration, during replacement or preventive maintenance work, of one or more battery cells in a battery system while maintaining the battery's operability. Instruction manuals from the manufacturers, operation requirements, and previous experience are the basis for establishing the procedures.

The equalizing charge procedure ensures that the battery is maintained in a charged condition, effectively mitigating aging caused by undercharging such as sulfation or hydration, in lead-acid batteries, or a reduction in capacity due to the undercharged state. Proper adherence to the battery termination and intercell connector maintenance procedure will mitigate corrosion, fouling, and fatigue of these subcomponents. The battery cell(s) removal and restoration procedure will minimize fatigue and material chemical change failures of the containers, posts, and intercell connections due to the use of improper grease or solvents, mishandling, or other maintenance errors, as indicated in NRC Information Notices (see Section 3.6).

5.2.2.6 Class 1E Battery Qualification

The Equipment Qualification Program describes the process for generating, documenting, and maintaining evidence that electrical equipment important to safety within the scope of 10 CFR 50.49 can perform its safety function during its installed life. The Equipment Qualification Program is effective at mitigating virtually all aging of EQ equipment. Safety-related batteries are typically located in mild environments, and are therefore outside the scope of 10 CFR 50.49. However, seismic qualification is required for all Class 1E equipment in a nuclear power plant, including 1E batteries. The 1E batteries now in use in nuclear power plants were qualified to withstand a design basis seismic event, but most were not qualified at the end-of-life condition.

Prior to the issuance of Regulatory Guide 1.158,[5.12] Class 1E batteries were required to be qualified in accordance with Regulatory Guide 1.100.[5.13] IEEE STD 344-1987,[5.14] endorsed by Regulatory Guide 1.100, does not necessarily require the batteries to be brought to their end-of-life condition prior to seismic testing. This means that at the end-of-life condition, a qualified battery may be vulnerable to a seismic event even if the regular surveillance tests and preventive maintenance demonstrate the battery's ability to deliver its rated capacity at the time. The previously discussed maintenance activities will detect deterioration in a battery's capacity, but will not provide adequate information to assess the degradation of the battery's internal structure which may make it vulnerable to seismic events.

The increased vulnerability of a battery to seismic events is mainly caused by the progressive corrosion of cell plates and internal terminal straps over time. However, the severe corrosive effect only exists in lead-acid batteries. The phenomenon does not occur in nickel-cadmium batteries since the electrolyte is non-corrosive. Thus, relying on the analysis of battery aging mechanisms in Section 4, a nickel-cadmium battery qualified per Regulatory Guide 1.100 and IEEE STD 344-1987 can be considered as still qualified at the end of its service life. Therefore, only the seismic vulnerability of aged lead-acid batteries needs to be addressed.

Regulatory Guide 1.158, "Qualification of Safety-Related Lead Storage Batteries for Nuclear Power Plants,"[5.12] published in February, 1989, endorses IEEE STD 535-1986, "IEEE Standard for Qualification of Class 1E Lead Storage Batteries for Nuclear Power Generating Stations." [5.15] IEEE STD 535-1986 specifically requires lead-acid batteries to be aged to an anticipated qualified life before seismic testing. Although the regulatory guide stated the preference of qualification by testing naturally aged safety-related batteries, research and testing studies conducted by Sandia National Laboratories[5.16] concluded that the accelerated aging method contained in the IEEE standard provides an acceptable procedure for reproducing seismically significant age-related effects in lead-acid batteries. Therefore, newly installed lead-acid batteries qualified per IEEE STD 535-1986 will be able to withstand a design basis seismic event at the end of their qualified lives.

Section 6.1 contains further discussion on this topic.

5.2.2.7 Operational Experience Reviews and Trending

Most plants have some sort of formal or informal "operating experience review" procedure or personnel. This process is occasionally an independent body dedicated to detecting and resolving incipient or long-acting problems. The operating experience program is not credited for specifically detecting and mitigating aging of components, but is viewed as a substantial support towards effective aging management. The operating experience program tracks problems identified by in-house and external industry operating experience, and initiates corrective actions to mitigate those problems. This program supports the other aging management programs by providing feedback on battery failures or degradation. This program also captures 10 CFR 21 Notices, NRC Bulletins, Notices and Generic Letters, vendor experience reports, INPO Reports, Significant Operating Events Reports (SOERs), etc. and ensures that all known potential problems are addressed at the plant before failure occurs. Trending failure rates could lead to sufficient statistical data that could provide an indication of aging degradation. Surveillance, preventive maintenance, or replacement could then be scheduled more effectively on the basis of failure trends. The host utility trends battery cell specific gravity and voltage weekly (pilot cell) and quarterly (all cells). A trend program stores the data and generates a computer plot of the data trend.

5.3 Less Commonly Used Aging Management Techniques

This section describes alternative techniques which may be used to supplement the common plant practices described in Section 5.2 but which are not routinely used. Some of the techniques have not been proven or are still being studied. The alternative techniques and programs examined for effectiveness are:

- Continuous Environmental Monitoring and Mitigation
- Sample Cell Analysis
- Battery Charger Output Waveform Monitoring
- Battery Impedance Testing
- Battery Conductance Testing
- Infrared Thermographic Inspection
- Periodic Battery Replacement
- Potential Surveillance Tests for Detecting Seismic Vulnerability

The following subsections describe these programs and evaluate their effectiveness. A summary of these evaluations is presented in Table 5-14.

5.3.1 Environmental Monitoring and Mitigation

Temperature, humidity, and radiation can have significant impact on a battery's performance and service life. For the battery installations evaluated in this report, radiation levels in the normal condition do not constitute potentially detrimental influence on the battery's service life. The effect of humidity is very limited. The main concern is the effect of temperature deviation, as indicated in Section 4.

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Table 5-14. Summary of Effectiveness of Less Commonly Used Aging Management Programs

Aging Mechanism	Less Commonly Used Aging Management Programs							
	Environmental Monitoring	Sample Cell Analysis	Charger Output Waveform Monitoring	Impedance Testing	Conductance Testing	Infrared Thermographic Inspection	Periodic Battery Replacement (Small Batteries)	Potential Surveillance for Seismic Vulnerability
CONTAINER								
Material Chemical Changes		Removal and Analysis					Replace Battery	
Fatigue		Removal and Analysis					Replace Battery	Correlate Visible Degradation to Seismic Vulnerability
ELECTROLYTE								
Material Chemical Changes		Removal and Analysis					Replace Battery	
Gassing and Electrolyte Evaporation	Temperature Monitoring		Monitor and Adjust	Measure Impedance	Measure Conductance		Replace Battery	
Dryout (Valve-Regulated Design)		Removal and Analysis	Monitor and Adjust	Measure Impedance	Measure Conductance		Replace Battery	
Thermal Runaway (Valve-Regulated Lead-Acid Design)	Temperature Monitoring	Removal and Analysis	Monitor and Adjust				Replace Battery	
PLATES								
Material Chemical Changes		Removal and Analysis					Replace Battery	Precise Cell Voltage Measurement Internal Resistance Measurement
Corrosion (Lead-Acid Design)	Temperature Monitoring	Removal and Analysis	Monitor and Adjust	Measure Impedance	Measure Conductance		Replace Battery	Precise Cell Voltage Measurement Internal Resistance Measurement Impedance Measurement at Different Frequencies
Fatigue (Lead-Acid Design)		Removal and Analysis					Replace Battery	Precise Cell Voltage Measurement Internal Resistance Measurement Impedance Measurement at Different Frequencies
Memory/Effect (Valve-Regulated Sintered Plate Nickel-Cadmium Design)							Replace Battery	

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Table 5-14. Summary of Effectiveness of Less Commonly Used Aging Management Programs (continued)

Aging Mechanism	Less Commonly Used Aging Management Programs							
	Environmental Monitoring	Sample Cell Analysis	Charger Output Waveform Monitoring	Impedance Testing	Conductance Testing	Infrared Thermographic Inspection	Periodic Battery Replacement (Small Batteries)	Potential Surveillance for Seismic Vulnerability
STRAPS								
Corrosion (Lead-Acid Design)	Temperature Monitoring	Removal and Analysis	Monitor and Adjust	Measure Impedance	Measure Conductance		Replace Battery	Precise Cell Voltage Measurement Internal Resistance Measurement Impedance Measurements at Different Frequencies
Fatigue (Lead-Acid Design)		Removal and Analysis					Replace Battery	Precise Cell Voltage Measurement Internal Resistance Measurement Impedance Measurements at Different Frequencies
SEPARATORS								
Material Chemical Changes (Lead-Acid Design)		Removal and Analysis					Replace Battery	
Thermal Aging	Temperature Monitoring	Removal and Analysis	Monitor and Adjust				Replace Battery	
TERMINAL POSTS								
Corrosion	Temperature Monitoring	Removal and Analysis	Monitor and Adjust	Measure Impedance	Measure Conductance	Scanning	Replace Battery	
Fouling		Removal and Analysis		Measure Impedance	Measure Conductance	Scanning	Replace Battery	
Fatigue		Removal and Analysis					Replace Battery	
INTERCELL CONNECTORS								
Corrosion	Temperature Monitoring	Removal and Analysis	Monitor and Adjust			Scanning	Replace Battery	
Fouling		Removal and Analysis				Scanning	Replace Battery	
Fatigue		Removal and Analysis					Replace Battery	
TERMINAL POST SEALS								
Fatigue		Removal and Analysis					Replace Battery	

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Table 5-14. Summary of Effectiveness of Less Commonly Used Aging Management Programs (continued)

Aging Mechanism	Less Commonly Used Aging Management Programs							
	Environmental Monitoring	Sample Cell Analysis	Charger Output Waveform Monitoring	Impedance Testing	Conductance Testing	Infrared Thermographic Inspection	Periodic Battery Replacement (Small Batteries)	Potential Surveillance for Seismic Vulnerability
BATTERY RACK								
Corrosion	Temperature Monitoring							
Fatigue								
PRESSURE RELIEF VALVE (Valve-Regulated Design)								
Wear		Removal and Analysis					Replace Battery	

Continuous temperature monitoring of the battery installation area makes it possible to maintain the battery's environment temperature within a preferred range. Corrective actions can be taken if abnormal temperature readings are observed. Shielding, heating, forced air cooling, or ventilation adjustment may be used to normalize the battery area temperature. Temperature monitoring may only be useful for battery installations and situations where past operating experience justifies its use.

5.3.2 Sample Cell Analysis

One or more cells may be removed from an installed battery for special inspections and testing. The cells may be temporarily removed, tested, and then reinstalled, or they may be permanently removed for testing with new cells being installed. The inspections and testing can be any of the activities described in Sections 5.2 and 5.3. Sample cell analysis may be conducted on a periodic basis or in response to some particular concerns regarding the condition of a battery.

Examining sample cell(s) removed from the installed battery improves the accessibility to the cell. Detailed visual inspection can be fairly thorough for cells with clear containers, and testing can be easily done and closely monitored. Periodic sample cell analysis can provide information for trending and additional assurance. Sample cell(s) could also be taken from a battery for a special inspection or testing to further investigate unusual battery operating conditions or abnormal results obtained from regular inspections and testing. The sample cell(s) will have to be replaced by a new cell if the inspections and/or testing are destructive. This technique may be useful only to large battery installations in which a large number of cells are used.

5.3.3 Battery Charger Output Waveform Monitoring

The readings of battery charger output voltage from test meters do not convey the voltage waveform, which usually contains AC ripple superposed on the DC element. As the chargers age, the extent of AC ripple may increase significantly. The same happens to an improperly adjusted charger. As discussed in Section 4, AC ripple contributes to accelerated aging of lead-acid batteries. Periodic monitoring of voltage waveforms presents a chance for correction. It may also be necessary to have the charger's output voltage waveform checked whenever a repair, which may change the output characteristics, is performed on the charger. See Reference 5.17 for a discussion of aging of battery chargers.

5.3.4 Battery Impedance Testing

The impedance of a battery cell reflects, to some degree, the condition of its internal conduction path. The test capacitively couples a low frequency current to the battery cell and measures the resultant small voltage drop across the cell terminals. The impedance obtained from the current and voltage increases as the cell plate and terminal strap corrosion process progresses and/or the electrolyte reduces. Therefore, a cell in poor condition due to plate, strap, or internal connection degradation will exhibit a higher than normal internal impedance. Typically, a measurement of more than $\pm 20\%$ from the normal or new battery impedance may indicate a significant internal problem which could lead to battery failure. High impedance may also be correlated to the loss of battery capacity.

Impedance testing is applicable to both lead-acid and nickel-cadmium batteries. For nickel-cadmium batteries, the change in impedance value is mainly an indication of changes in the amount of cell electrolyte. The test can be used for both vented and valve-regulated types. It has been suggested that impedance testing be used on valve-regulated batteries for assessing battery capacity without deep discharge of the battery. This can help relax the maintenance requirement on capacity test frequency. The impedance test is simple and inexpensive to perform. However, there currently is a lack of baseline data for evaluation reference. The information from the test should only be used for qualitative analysis if correlation data applicable to the specific type of battery are not available.

5.3.5 Battery Conductance Testing

Conductance is inversely related to impedance and describes current carrying capability. The conductance of a battery cell directly reflects the condition of the current path inside a cell, including terminal posts, terminal straps, plates, and electrolyte.

In this test, an AC source is applied to a cell or battery. With the known voltage and measured in-phase current, the conductance can be calculated. The difference between the conductance test and the impedance test is that the former excludes the capacitive or inductive element in the test. A decrease in conductance indicates problems in the cell internal conducting path and can also mean a loss of capacity due to aging. Typically, if the conductance drops to less than 80% of its reference value, the cell or battery is in a degraded condition and a capacity test may be necessary to verify its design load carrying ability.

Similar to the impedance test, the conductance test is applicable to both lead-acid and nickel-cadmium batteries, either vented or valve-regulated. The conductance test may be used on valve-regulated batteries to assess battery capacity, and this can reduce the capacity test frequency for the batteries. Because of a lack of industry reference data, the test may only serve as a qualitative tool in assessing and predicting battery condition.

5.3.6 Infrared Thermographic Inspection

Infrared thermography is a relatively new maintenance tool, which converts thermal patterns of heat generation through an infrared imaging camera into equivalent visual patterns of temperature. Surface temperature differences as small as 0.3°C [0.5°F] are displayed in black and white or color "temperature maps." Bulk or "spot" local readings can be taken without touching the component or affecting its operation. A videocassette can be used to record local or bulk temperatures for given areas or components for future trending.[5.18]

Infrared thermography can be performed on a system while the equipment is still in service, and is used to detect "hot spots" in the equipment. Temperature differences can be measured quantitatively, and a qualitative examination can compare the temperature pattern of one component to another component under the same operating conditions.[5.18] This type of program is not typically a formal plant program at this time. However, many plants incorporate thermography in their preventive/predictive maintenance programs.

Thermographic inspection can be used to examine the electrical connections of a battery, including cell posts, intercell connections, and battery terminal to DC bus connections. Normal current flow through a loose or corroded connection results in abnormal, elevated temperature as a result of increased electrical resistance. The heating pattern can be seen through an infrared imaging camera long before it reaches the visible stage. The inspection should be conducted during battery discharge tests when the current flow is large enough to expose abnormal heating. An electrical connection problem can be identified by comparing the thermal patterns among the connections before and during the discharge. However, thermal inspection of battery cell internals, such as plates, straps, and terminal posts, is difficult because of the limited accessibility and materials of the jar.

Effective thermographic inspection programs should be developed in accordance with EPRI's Nuclear Maintenance Applications Center guidelines contained in Reference 5.19. Additional guidance is provided in the Infrasppection Institute's "Guidelines for Specifying and Performing Infrared Inspections." Results of thermographic inspections are used in conjunction with other maintenance program data to determine if corrective action is required to prevent further degradation.

5.3.7 Periodic Battery Replacement

This approach can be used for small scale battery installations which often receive less maintenance attention than large battery installations. The typical applications may include control circuit backup power and emergency lighting units. The batteries used in these applications are often designed with relatively short service life spans of five to six years.

Current maintenance practices on these batteries are usually very limited and sometimes inadequate as indicated in NRC information Notice No. 91-64.[5.20] From a cost-effectiveness standpoint, a periodic battery replacement program, combined with the properly minimized regular maintenance, can be a practical solution to the problem. Selection of replacement intervals can be derived from the manufacturer's recommendation and operating experience. The minimum maintenance activities provide necessary assurance that the batteries will fulfill their required function between replacement intervals. Periodic battery replacement is effective at mitigating all types of degradation in these batteries.

5.3.8 Potential Surveillance Tests for Detecting Seismic Vulnerability

Six potential surveillance tests are discussed in NUREG/CR-4457[5.9] for a preliminary investigation into the possibility of detecting the battery or cell internal aging condition that will cause the battery to be vulnerable to seismic events. The test methods still have not been proven or fully studied. Cross-correlation techniques were intended to be used to identify cells that are different from the average of those in the battery bank. The following provides a brief review of each test.

Precise Measurement of Cell Voltage - This test requires precise (within 1mV) measurement of each cell's voltage during a discharge of the battery bank. The cell voltages should be measured either continuously or frequent enough that a voltage versus time history can be obtained for each cell. Cells with a voltage curve significantly different from the average or normal would be considered as having internal problems. The problems most likely to occur are corrosion/oxidation of the internal straps, grids, terminals, and active material. The reflection in the test is abnormal voltage drop due to the increased cell internal resistance.

Measurement of Internal Resistance and Capacitance - Cell capacitance is measured by applying a step charge current of about 1 amp to a fully charged cell while recording the cell's voltage response. Cell internal resistance is measured by interrupting a relatively small discharge current (about 10% of rated) and recording the instantaneous rise in cell voltage. The resistance is calculated using the measured capacitance and the time constant. A lower-than-expected capacitance is postulated to be indicative of an internal problem involving shedding of active material or plugging of pores in the active material. The resistance is a measure of the condition of the grids, the integrity of the internal straps, and the attachment of the active material to the grids. A statistical basis has not been developed yet to correlate changes in capacitance or resistance with specific cell degradations.

Impedance Measurement at Different Frequencies - Impedance is measured during discharge by introducing an AC source over a range of frequencies from 10^{-2} to 10^4 Hz. Values for resistance, capacitance, and inductance can be calculated from the impedance values. The evaluation method is similar to that used in the previous discussion for resistance and capacitance. Since impedance is measured at several frequencies and several states of charge, more information is obtained and there will be more opportunity to detect a difference between a new battery and a degraded one. Problems related to introducing the AC voltage during discharge, as well as correlating differences in measured values with specific battery degradations, need to be investigated.

Frequency Spectrum Measurements While Exciting the Battery with Electrical White Noise - This method is an extension of the impedance measurement at various frequencies in that all frequencies are introduced simultaneously. This technique has been successfully used with other electrical systems, but there is no evidence that it has been applied to batteries. Here, the intention is to correlate the location and magnitude of peaks in the noise spectrum to battery aging conditions. Data taken from new batteries as well as batteries with known problems would be needed for evaluation.

Analysis of the Natural Electrical Noise Generated by the Battery During Discharge - This technique relies on analyzing the noise spectrum naturally generated by a battery during discharge. All electrical devices generate some electrical noise in their circuits, and this noise often changes as the characteristics of the device change. Again, the test has been applied to other devices, but not batteries. The noise generated by the batteries could be studied to determine if changes in frequencies and magnitude would be correlated with changes in the internal degradation of the battery.

Correlation of Visible Degradation to Seismic Vulnerability - EPRI Report NP-1558 [5.21] has suggested a correlation between growth of the positive plates and useful life of a lead-acid battery. This is based on the fact that battery aging may result in some visible effects. The report suggests that there might be a correlation between visible signs of degradation and seismic vulnerability.

The methods described above have not demonstrated the ability to detect the incipient degradation effectively enough to avoid seismic vulnerability. It is currently believed that the information obtained by these methods would only indicate the presence of severe degradation. None of the methods have been fully investigated, and all will require additional research to determine how effective they can be at detecting specific degradations and the degree of degradation, and also whether they can be practically implemented at nuclear power plants.

5.4 Criteria for Effective Aging Management

This section provides qualitative and quantitative criteria for use by inspectors, surveillance testers, and/or system engineers to compare plant-specific program coverage against the programs/techniques described in Sections 5.2 and 5.3, which were determined to be effective at detecting and mitigating the significant aging mechanisms identified in Section 4.3 and summarized in Tables 4-7 through 4-9. These discussions are grouped by aging mechanism/phenomenon.

The frequencies of conducting these programs/techniques are based on current codes and standards[5.5-5.11, 5.18, 5.19] as well as general industry practice. The failure data conclusions presented in Section 3.6 indicated that current industry practices are effective at detecting and mitigating aging of batteries. Other conclusions, also drawn from the failure data, that were considered in selecting the program/technique implementing intervals are:

- Since batteries are in continuous operation, at least some of the program activities should be implemented on shorter rather than longer intervals.

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- Since intercell connector failures are the largest identifiable failures in the NPRDS data, actions to detect aging of intercell connectors should be implemented on a shorter rather than longer implementing interval.
- Since the primary aging mechanisms for the intercell connectors are corrosion and fouling, the programs implemented more frequently should concentrate on detecting such aging degradations.

Because of cost-effectiveness considerations, approaches of aging management for large and small battery installations should be different. The stationary batteries are thus divided into two groups:

- Large Stationary Batteries - voltage level of 24 volts or above (Section 5.4.1)
- Small Stationary Batteries - voltage level of 12 volts or below (Section 5.4.2)

Evaluation of the programs are presented separately for the two battery installation groups.

5.4.1 Effective Programs/Techniques Applied to Large Stationary Batteries

Large stationary batteries are expensive to replace. The objective of aging management of these batteries is to maximize the battery's service life without jeopardizing safe operation. The following evaluation also addresses differences between lead-acid and nickel-cadmium batteries, and between vented and valve-regulated constructions, where appropriate.

5.4.1.1 Material Chemical Changes

Lead-Acid Batteries

Table 4-7 identifies material chemical changes as a potentially significant aging mechanism for the following lead-acid battery subcomponents.

- Container
- Electrolyte
- Plates
- Separators

Determining the presence of material chemical changes associated with these subcomponents is achieved through a combination of plant programs. Cleaning, visual inspections, and electrolyte specific gravity measurements, conducted in accordance with IEEE STD 450-1987[5.5] and the plant's Preventive Maintenance or Surveillance Programs, are effective at detecting material chemical changes of all of these subcomponents. Proper adjustment of the charger float voltage in accordance with manufacturers' recommendations and the plant's Preventive Maintenance Program will help mitigate material chemical changes of the separators. Capacity testing of the batteries conducted in accordance with IEEE STD 450-1987 and the plant's Surveillance Program is effective at detecting material chemical changes of the electrolyte, plates, and separators. Logging of the float voltage and current in accordance with the "Good Housekeeping" Practices - Logs and Checklists Program, along with visual observation while logging these parameters, will help detect and mitigate material chemical changes of all of these subcomponents. Low battery voltage alarms included as part of the plant's On-line

Monitoring - Annunciator Response Procedures are effective at detecting material chemical changes of the electrolyte, plates, and separators. An equalize charge conducted in accordance with the plant's Corrective Maintenance Program can mitigate certain material chemical changes in the plates and electrolyte.

Therefore, if visual inspections and cleaning of the cells, capacity testing of the battery, and electrolyte specific gravity measurements are conducted in accordance with IEEE STD 450-1987,[5.5] and if the charger float voltage is properly adjusted, and if the float voltage and current are logged once per shift, and if visual observation of the battery is made while logging these parameters, and if low battery voltage is alarmed, and if an equalize charge is performed when indicated by low cell voltages or following a battery discharge, then material chemical changes of these lead-acid battery subcomponents is effectively managed.

Nickel-Cadmium Batteries

Table 4-8 identifies material chemical changes as a potentially significant aging mechanism for the following nickel-cadmium battery subcomponents.

- Container
- Electrolyte
- Plates

Determining the presence of material chemical changes associated with these subcomponents is achieved through a combination of plant programs. Cleaning and visual inspections conducted in accordance with IEEE STD 1106-1987[5.7] and the plant's Preventive Maintenance or Surveillance Programs are effective at detecting material chemical changes of the container. Capacity testing of the batteries conducted in accordance with IEEE STD 1106-1987 and the plant's Surveillance Program is effective at detecting material chemical changes of the electrolyte and plates. Logging of the float voltage and current in accordance with the "Good Housekeeping" Practices - Logs and Checklists Program, along with visual observation while logging these parameters, will help detect and mitigate material chemical changes of all of these subcomponents. Low battery voltage alarms included as part of the plant's On-line Monitoring - Annunciator Response Procedures are effective at detecting material chemical changes of the electrolyte and plates.

Therefore, if visual inspections and cleaning of the cells and capacity testing of the battery are conducted in accordance with IEEE STD 1106-1987, and if the float voltage and current are logged once per shift, and if visual observation of the battery is made while logging these parameters, and if low battery voltage is alarmed, then material chemical changes of these nickel-cadmium battery subcomponents is effectively managed.

5.4.1.2 Corrosion

Lead-Acid Batteries

Table 4-7 identifies corrosion as a potentially significant aging mechanism for the following lead-acid battery subcomponents.

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- Plates
- Straps
- Terminal Posts
- Intercell Connectors
- Battery Racks

Determining the presence of corrosion associated with these subcomponents is achieved through a combination of plant programs. Visual inspections, ambient temperature measurements, and electrolyte temperature measurements conducted in accordance with IEEE STD 450-1987[5.5] and the plant's Preventive Maintenance or Surveillance Programs are effective at detecting and mitigating corrosion of all of these subcomponents. Proper adjustment of the charger float voltage in accordance with manufacturers' recommendations and the plant's Preventive Maintenance Program will help mitigate corrosion of the plates and straps caused by excessive gassing. Connector resistance measurements conducted in accordance with IEEE STD 450-1987 and the plant's Preventive Maintenance or Surveillance programs are effective at detecting corrosion of the terminal posts and intercell connectors. Capacity testing of the batteries conducted in accordance with IEEE STD 450-1987 and the plant's Surveillance Program will help detect corrosion of the plates and straps. Logging of the float voltage and current in accordance with the "Good Housekeeping" Practices - Logs and Checklists Program also helps to detect corrosion of the plates and straps. Logging of the ambient temperature will help to mitigate corrosion of all of these subcomponents. Visual observation of the battery while logging these parameters will help detect corrosion of the terminal posts, intercell connectors, and racks. Low battery voltage alarms included as part of the plant's On-line Monitoring - Annunciator Response Procedures can also help detect corrosion of the plates and straps. Termination and intercell connector maintenance conducted in accordance with the plant's Corrective Maintenance Program is effective at mitigating corrosion of the terminal posts and intercell connectors.

Therefore, if visual inspections, ambient and electrolyte temperature measurements, capacity tests, and connector resistance measurements are conducted in accordance with IEEE STD 450-1987,[5.5] and if the charger float voltage is properly adjusted, and if the ambient temperature, float voltage, and float current are logged once per shift, and if visual observation of the battery is made while logging these parameters, and if low battery voltage is alarmed, and if termination and intercell connector maintenance is performed in accordance with IEEE STD 450-1987, then corrosion of these lead-acid battery subcomponents is effectively managed.

Nickel-Cadmium Batteries

Table 4-8 identifies corrosion as a potentially significant aging mechanism for the following nickel-cadmium battery subcomponents.

- Terminal Posts
- Intercell Connectors
- Battery Racks

Determining the presence of corrosion associated with these subcomponents is achieved through a combination of plant programs. Visual inspections and ambient temperature measurements conducted in accordance with IEEE STD 1106-1987[5.7] and the plant's

Preventive Maintenance or Surveillance Programs are effective at detecting and mitigating corrosion of all of these subcomponents. Connector resistance measurements conducted in accordance with IEEE STD 1106-1987 and the plant's Preventive Maintenance or Surveillance programs are effective at detecting corrosion of the terminal posts and intercell connectors. Visual observation of the battery while logging operational parameters under the "Good Housekeeping" Practices - Logs and Checklists Program will help detect corrosion of the terminal posts, intercell connectors, and racks. Termination and intercell connector maintenance conducted in accordance with the plant's Corrective Maintenance Program is effective at mitigating corrosion of the terminal posts and intercell connectors.

Therefore, if visual inspections, ambient temperature measurements, and connector resistance measurements are conducted in accordance with IEEE STD 1106-1987,[5.7] and if visual observation of the battery is made while logging operational parameters, and if termination and intercell connector maintenance is performed in accordance with IEEE STD 1106-1987, then corrosion of these nickel-cadmium battery subcomponents is effectively managed.

5.4.1.3 Fatigue

Lead-Acid Batteries

Table 4-7 identifies fatigue as a potentially significant aging mechanism for the following lead-acid battery subcomponents.

- Container
- Plates
- Straps
- Terminal Posts
- Intercell Connectors
- Terminal Post Seals
- Battery Racks

Determining the presence of fatigue associated with these subcomponents is achieved through a combination of plant programs. Visual inspections conducted in accordance with IEEE STD 450-1987[5.5] and the plant's Preventive Maintenance or Surveillance Programs are effective at detecting fatigue of all of these subcomponents. Connector resistance measurements conducted in accordance with IEEE STD 450-1987 and the plant's Preventive Maintenance or Surveillance programs are effective at detecting fatigue of the terminal posts and intercell connectors. Seismic qualification of the batteries and racks in accordance with Regulatory Guide 1.158[5.12] and IEEE STD 535-1986[5.15] will effectively mitigate fatigue of the plates, straps, and racks. Visual observation while logging operational parameters in accordance with the "Good Housekeeping" Practices - Logs and Checklists Program will help to detect fatigue of the containers, terminal posts, intercell connectors, terminal post seals, and racks. Termination and intercell connector maintenance conducted in accordance with the plant's Corrective Maintenance Program is effective at mitigating fatigue of the terminal posts, intercell connectors, and terminal post seals.

Therefore, if visual inspections and connector resistance measurements are conducted in accordance with IEEE STD 450-1987,[5.5] and if the batteries and racks are seismically qualified in accordance with Regulatory Guide 1.158[5.12] and IEEE STD 535-1986,[5.15] and if visual observation of the battery is made while logging operational parameters, and if termination and intercell connector maintenance is performed in accordance with IEEE STD 450-1987, then fatigue of these lead-acid battery subcomponents is effectively managed.

Nickel-Cadmium Batteries

Table 4-8 identifies fatigue as a potentially significant aging mechanism for the following nickel-cadmium battery subcomponents.

- Container
- Terminal Posts
- Intercell Connectors
- Terminal Post Seals
- Battery Racks

Determining the presence of fatigue associated with these subcomponents is achieved through a combination of plant programs. Visual inspections conducted in accordance with IEEE STD 1106-1987[5.7] and the plant's Preventive Maintenance or Surveillance Programs are effective at detecting fatigue of all of these subcomponents. Connector resistance measurements conducted in accordance with IEEE STD 1106-1987 and the plant's Preventive Maintenance or Surveillance programs are effective at detecting fatigue of the terminal posts and intercell connectors. Visual observation of the battery while logging operational parameters under the "Good Housekeeping" Practices - Logs and Checklists Program will help detect fatigue of all of these subcomponents. Termination and intercell connector maintenance conducted in accordance with the plant's Corrective Maintenance Program is effective at mitigating fatigue of the terminal posts, intercell connectors, and terminal post seals.

Therefore, if visual inspections and connector resistance measurements are conducted in accordance with IEEE STD 1106-1987,[5.7] and if visual observation of the battery is made while logging operational parameters, and if termination and intercell connector maintenance is performed in accordance with IEEE STD 1106-1987, then fatigue of these nickel-cadmium battery subcomponents is effectively managed.

5.4.1.4 Wear

Lead-Acid and Nickel-Cadmium Valve-Regulated Batteries

Table 4-9 identifies wear as a potentially significant aging mechanism for the following lead-acid and nickel-cadmium valve-regulated battery subcomponent.

- Pressure Relief Valve

Determining the presence of wear associated with this subcomponent is achieved through a combination of plant programs. Cell voltage measurements conducted in accordance with IEEE PAR 1188 (draft version)[5.8] and the plant's Preventive Maintenance or Surveillance Programs

can provide an indication of low electrolyte level caused by excessive gas release due to a worn pressure relief valve. Capacity testing of the battery in accordance with IEEE PAR 1188 (draft version) and the plant's Surveillance Program can also indicate low electrolyte level caused by a worn pressure relief valve.

Therefore, if cell voltage measurements and capacity tests are conducted in accordance with IEEE PAR 1188 (draft version),[5.8] then wear of the pressure relief valve in lead-acid and nickel-cadmium valve-regulated batteries is effectively managed.

5.4.1.5 Thermal Aging

Lead-Acid and Nickel-Cadmium Batteries

Tables 4-7 and 4-8 identify thermal aging as a potentially significant aging mechanism for the following lead-acid and nickel-cadmium battery subcomponents.

- Separators

Determining the presence of thermal aging associated with these subcomponents is achieved through a combination of plant programs. Recording electrolyte and ambient temperatures in accordance with IEEE STD 450-1987[5.5] (vented lead-acid batteries), IEEE STD 1106-1987[5.7] (vented nickel-cadmium batteries), IEEE PAR 1188[5.8] (valve-regulated batteries), and the plant's Preventive Maintenance or Surveillance Programs will help to mitigate thermal aging of the separators. Proper adjustment of the charger float voltage in accordance with manufacturers' recommendations and the plant's Preventive Maintenance Program will help mitigate thermal aging of the separators caused by heat generation from excessive gassing and AC ripple. Capacity testing of the batteries conducted in accordance with IEEE STD 450-1987 (vented lead-acid batteries), IEEE STD 1106-1987 (vented nickel-cadmium batteries), IEEE PAR 1188 (valve-regulated batteries) and the plant's Surveillance Program can help detect thermal aging of the separators. Logging of the ambient temperature, float voltage, and float current in accordance with the "Good Housekeeping" Practices - Logs and Checklists Program will help detect and mitigate thermal aging of the separators. Low battery voltage alarms included as part of the plant's On-line Monitoring - Annunciator Response Procedures will also aid in detecting thermal aging of the separators.

Therefore, if the charger float voltage is properly adjusted, and if capacity testing of the batteries, and electrolyte and ambient temperature monitoring, are conducted in accordance with IEEE STD 450-1987[5.5] (vented lead-acid batteries), IEEE STD 1106-1987[5.7] (vented nickel-cadmium batteries), or IEEE PAR 1188[5.8] (valve-regulated batteries), and if the ambient temperature, float voltage, and float current are logged once per shift, and if low battery voltage is alarmed, then thermal aging of the separators in lead-acid and nickel-cadmium batteries is effectively managed.

5.4.1.6 Gassing and Electrolyte Evaporation

Vented Lead-Acid and Nickel-Cadmium Batteries

Tables 4-7 and 4-8 identify gassing and electrolyte evaporation as a potentially significant aging mechanism for the following battery subcomponent.

- Electrolyte
- Plates (lead-acid batteries only)

Determining the presence of gassing and electrolyte evaporation is achieved through a combination of plant programs. Visual inspections, specifically electrolyte level checks, cell temperature measurements and ambient temperature measurements conducted in accordance with IEEE STD 450-1987[5.5] (lead-acid batteries), IEEE STD 1106-1987[5.7] (nickel-cadmium batteries), and the plant's Preventive Maintenance or Surveillance Programs are effective at detecting gassing and electrolyte evaporation in vented batteries. Proper adjustment of the charger float voltage in accordance with manufacturers' recommendations and the plant's Preventive Maintenance Program will also help mitigate gassing and electrolyte evaporation. Logging of the ambient temperature and visual observation of the battery in accordance with the "Good Housekeeping" Practices - Logs and Checklists Program will help detect and mitigate gassing and electrolyte evaporation.

Therefore, if visual inspections, cell temperature measurements, and ambient temperature measurements are conducted in accordance with IEEE STD 450-1987[5.5] (lead-acid batteries) or IEEE STD 1106-1987[5.7] (nickel-cadmium batteries), and if the charger float voltage is properly adjusted, and if the ambient temperature is logged once per shift, and if visual observation of the battery is made while logging operational parameters, then gassing and electrolyte evaporation of vented lead-acid and vented nickel-cadmium battery electrolyte is effectively managed.

Valve Regulated Lead-Acid and Nickel-Cadmium Batteries

Table 4-9 identifies dryout, which is a specific form of gassing and electrolyte evaporation, as a potentially significant aging mechanism for the following valve-regulated lead-acid and nickel-cadmium battery subcomponent.

- Electrolyte

Determining the presence of dryout is achieved through a combination of plant programs. Cell voltage measurements and ambient temperature measurements conducted in accordance with IEEE PAR 1188[5.8] (draft version) and the plant's Preventive Maintenance or Surveillance Programs can be effective at detecting dryout of valve-regulated batteries. Proper adjustment of the charger float voltage in accordance with manufacturers' recommendations and the plant's Preventive Maintenance Program will help mitigate dryout. Capacity testing of the batteries conducted in accordance with IEEE PAR 1188 and the plant's Surveillance Program can also help detect dryout. Logging of the ambient temperature in accordance with the plant's "Good Housekeeping" Practices - Logs and Checklists Program will help mitigate dryout.

Therefore, if cell voltage measurements, ambient temperature measurements, and capacity testing of the battery are conducted in accordance with IEEE PAR 1188[5.8] (draft version), and if the float voltage is properly adjusted, and if the ambient temperature is logged once per shift, then dryout of valve-regulated lead-acid and nickel-cadmium batteries is effectively managed.

5.4.1.7 Fouling

Lead-Acid and Nickel-Cadmium Batteries

Tables 4-7 and 4-8 identify fouling as a potentially significant aging mechanism for the following lead-acid battery subcomponents.

- Terminal Posts
- Intercell Connectors

Determining the presence of fouling associated with these subcomponents is achieved through a combination of plant programs. Visual inspections and connector resistance measurements conducted in accordance with IEEE STD 450-1987[5.5] (lead-acid batteries), IEEE STD 1106-1987[5.7] (nickel-cadmium batteries), IEEE PAR 1188[5.8] (valve-regulated batteries) and the plant's Preventive Maintenance or Surveillance Programs are effective at detecting fouling of all of these subcomponents. Visual observation of the battery while logging operational parameters in accordance with the "Good Housekeeping" Practices - Logs and Checklists Program will also help detect fouling of these subcomponents. Termination and intercell connector maintenance conducted in accordance with the plant's Corrective Maintenance Program is effective at mitigating fouling of these subcomponents.

Therefore, if visual inspections and connector resistance measurements are conducted in accordance with IEEE STD 450-1987[5.5] (lead-acid batteries), IEEE STD 1106-1987[5.7] (nickel-cadmium batteries) or IEEE PAR 1188[5.8] (valve-regulated batteries), and if visual observation of the battery is made while logging operational parameters, and if termination and intercell connector maintenance is performed in accordance with IEEE STD 450-1987 (lead-acid batteries), IEEE STD 1106-1987 (nickel-cadmium batteries) or IEEE PAR 1188 (valve-regulated batteries), then fouling of these battery subcomponents is effectively managed.

5.4.1.8 Thermal Runaway of Valve-Regulated Lead-Acid Batteries

Table 4-9 identifies thermal runaway as a potentially significant aging phenomenon in valve-regulated lead-acid batteries. Determining the presence of thermal runaway is achieved through a combination of plant programs. Ambient temperature measurements conducted in accordance with IEEE PAR 1188[5.8] can help detect and mitigate thermal runaway in sealed lead-acid batteries. Proper adjustment of the charger float voltage in accordance with manufacturers' recommendations and the plant's Preventive Maintenance Program can prevent thermal runaway caused by excessive gassing and AC ripple. Logging of the float voltage and current, as well as the ambient temperature, in accordance with the "Good Housekeeping" Practices - Logs and Checklists Program will detect conditions that can lead to thermal runaway. High battery voltage alarms included as part of the plant's On-Line Monitoring - Annunciator Response Procedures can also detect thermal runaway.

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Therefore, if ambient temperature measurements are taken in accordance with IEEE PAR 1188,[5.8] and if the charger float voltage is properly adjusted, and if the ambient temperature, float voltage, and float current are logged once per shift, and if battery high voltage is alarmed, then thermal runaway of valve-regulated lead-acid batteries is effectively managed.

5.4.1.9 Memory Effect in Valve-Regulated Sintered Plate Nickel-Cadmium Batteries

Table 4-9 identifies memory effect as a potentially significant aging phenomenon in valve-regulated sintered plate nickel-cadmium batteries. Determining the presence of memory effect is achieved through a combination of plant programs. Capacity testing conducted in accordance with the manufacturer's recommendations and the plant's Surveillance Program will detect the presence of memory effect. Complete discharge and recharge in accordance with the manufacturer's recommendation and the plant's Corrective Maintenance Program is effective at mitigating memory effect.

Therefore, if capacity testing is conducted in accordance with the manufacturer's recommendations, and if complete discharge and recharge is applied as required, then memory effect in valve-regulated sintered plate nickel-cadmium batteries is effectively managed.

5.4.1.10 Conclusion

Based on the foregoing discussions, and the effectiveness evaluations in Section 5.2, minimum comprehensive aging management programs for large (24 Vdc or greater) lead-acid and nickel-cadmium batteries are presented in Tables 5-15 and 5-16, respectively. These tables identify the minimum recommended programs, specific activities, and implementing intervals to effectively manage all battery aging identified in this guideline. If all of these specific activities are implemented at the specified frequencies, then aging of the batteries will be effectively managed. Supplemental battery aging management programs and activities based on the effectiveness evaluations in Sections 5.2 and 5.3 are presented in Tables 5-17 and 5-18 for large (24 Vdc or greater) lead-acid and nickel-cadmium batteries, respectively. These programs and activities are considered desirable but not required to effectively manage battery aging.

Table 5-15. Minimum Recommended Aging Management Programs and Activities for Large Lead-Acid Stationary Batteries

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Preventive Maintenance or Surveillance	Inspect for General Cleanliness of the Battery, Battery Rack, and Battery Area	At Least Monthly	Material Chemical Changes Corrosion Fatigue Fouling	

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Table 5-15. Minimum Recommended Aging Management Programs and Activities for Large Lead-Acid Stationary Batteries (continued)

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Preventive Maintenance or Surveillance (continued)	Measure and Record the Float Voltage at the Battery Terminals	At Least Monthly	Material Chemical Changes Corrosion Thermal Aging Gassing and Electrolyte Evaporation Fouling Dryout (Valve-Regulated Design) Thermal Runaway (Valve-Regulated Design)	
	Measure and Record the Charger Output Current and Voltage	At Least Monthly	Material Chemical Changes Corrosion Thermal Aging Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design) Thermal Runaway (Valve-Regulated Design)	
	Check and Record Electrolyte Levels	At Least Monthly	Gassing and Electrolyte Evaporation	Vented Design Only
	Inspect for Cracks in Cells or Leakage of Electrolyte	At Least Monthly	Material Chemical Changes Fatigue	
	Inspect for Corrosion at Terminals, Connectors, and Racks	At Least Monthly	Corrosion Fouling	
	Record Ambient Temperature and Condition of Ventilation Equipment	At Least Monthly	Thermal Aging Corrosion Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design) Thermal Runaway (Valve-Regulated Design)	

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Table 5-15. Minimum Recommended Aging Management Programs and Activities for Large Lead-Acid Stationary Batteries (continued)

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Preventive Maintenance or Surveillance (continued)	Record Pilot Cell Voltage, Specific Gravity, and Electrolyte Temperature	At Least Monthly	Material Chemical Changes Corrosion Thermal Aging Gassing and Electrolyte Evaporation	Vented Design Only
	Record the Specific Gravity of Each Cell	3 Months	Material Chemical Changes Gassing and Electrolyte Evaporation	Vented Design Only
	Record the Voltage of Each Cell and the Battery Terminal Voltage	3 Months	Material Chemical Changes Corrosion Thermal Aging Wear (Valve-Regulated Design Only)	
	Record the Temperature of the Electrolyte in Representative Cells	3 Months	Thermal Aging Gassing and Electrolyte Evaporation	Vented Design Only
	Visually Inspect and Record the Condition of Each Cell	Annually	Material Chemical Changes Corrosion Fatigue Fouling	
	Measure and Record the Cell-to-Cell and Terminal Connection Detail Resistance	Annually	Corrosion Fatigue Fouling	
	Check and Record the Integrity of the Battery Rack	Annually	Corrosion Fatigue	

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Table 5-15. Minimum Recommended Aging Management Programs and Activities for Large Lead-Acid Stationary Batteries (continued)

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Surveillance	Perform a Battery Service Test	Annually or Once/Cycle	Material Chemical Changes Gassing and Electrolyte Evaporation Corrosion Thermal Aging	Safety-Related Vented Batteries Only
	Perform a Battery Performance Test Under As Found Conditions (Vented Batteries)	5 Years	Material Chemical Changes Gassing and Electrolyte Evaporation Corrosion Thermal Aging	If battery shows signs of degradation or has reached 85% of its expected service life, then increase frequency to annually or once/cycle.
	Perform a Battery Performance Test Under As Found Conditions (Valve-Regulated Batteries)	Annually or Once/Cycle	Material Chemical Changes Dryout Corrosion Thermal Aging	If battery shows signs of degradation or has reached 85% of its expected service life, then increase frequency to semi-annually.
Class 1E Seismic Qualification	Seismically Qualify the Batteries and Racks in Accordance with Reg. Guide 1.158 and IEEE STD 535-1986	Once	Fatigue	
"Good Housekeeping" Practices - Operation Logs and Checklists	Log Float Voltage and Current	Once/Shift	Material Chemical Changes Corrosion Thermal Aging Thermal Runaway (Valve-Regulated Design)	
	Log Ambient Temperature	Once/Shift	Corrosion Thermal Aging Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design) Thermal Runaway (Valve-Regulated Design)	

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Table 5-15. Minimum Recommended Aging Management Programs and Activities for Large Lead-Acid Stationary Batteries (continued)

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
"Good Housekeeping" Practices - Operation Logs and Checklists (continued)	Electrolyte Level Check	Once/Shift	Gassing and Electrolyte Evaporation	
	Visual Observation	Once/Shift	Material Chemical Changes Corrosion Fatigue Fouling	
On-Line Monitoring and Annunciator Response Procedures	Alarm for Low Battery Voltage	Continuous	Material Chemical Changes Corrosion Thermal Aging	
	Alarm for High Battery Voltage	Continuous	Thermal Runaway (Valve-Regulated Design)	
Corrective Maintenance	Perform an Equalize Charge	As Indicated by Low Cell Voltages or Following a Battery Discharge	Material Chemical Changes Thermal Aging	
	Clean and Tighten Terminations and Intercell Connectors	As Indicated by High Resistance Readings or Visible Corrosion or Fouling	Corrosion Fatigue Fouling	
	Properly Remove and Restore Cells During Battery Maintenance or Replacement	Whenever Battery Cells are Removed or Installed	Material Chemical Changes Fatigue	

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Table 5-16. Minimum Recommended Aging Management Programs and Activities for Large Nickel-Cadmium Stationary Batteries

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Preventive Maintenance or Surveillance	Inspect for General Cleanliness of the Battery, Battery Rack, and Battery Area	At Least Monthly	Material Chemical Changes Corrosion Fatigue Fouling	
	Measure and Record the Float Voltage at the Battery Terminals	At Least Monthly	Thermal Aging Gassing and Electrolyte Evaporation Fouling Dryout (Valve-Regulated Design)	
	Measure and Record the Charger Output Current and Voltage	At Least Monthly	Thermal Aging Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design)	
	Check and Record Electrolyte Levels	At Least Monthly	Gassing and Electrolyte Evaporation	Vented Design Only
	Inspect for Cracks in Cells or Leakage of Electrolyte	At Least Monthly	Material Chemical Changes Fatigue	
	Inspect for Corrosion at Terminals, Connectors, and Racks	At Least Monthly	Corrosion Fouling	
	Check and Record the Operability of the Ventilation Equipment	At Least Monthly	Thermal Aging Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design)	
	Record Pilot Cell Electrolyte Temperature	At Least Monthly	Thermal Aging Gassing and Electrolyte Evaporation	Vented Design Only

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Table 5-16. Minimum Recommended Aging Management Programs and Activities for Large Nickel-Cadmium Stationary Batteries (continued)

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Preventive Maintenance or Surveillance (continued)	Record the Voltage of Each Cell	3 Months	Material Chemical Changes Thermal Aging Wear (Valve-Regulated Design Only)	
	Measure and Record the Cell-to-Cell and Terminal Connection Detail Resistance	Annually	Corrosion Fatigue Fouling	
	Check and Record the Integrity of the Battery Rack	Annually	Corrosion Fatigue	
Surveillance	Perform a Battery Service Test	Annually or Once/Cycle	Material Chemical Changes Gassing and Electrolyte Evaporation Thermal Aging	Safety-Related Vented Batteries Only
	Perform a Battery Performance Test Under As Found Conditions (Vented Batteries)	5 Years	Material Chemical Changes Gassing and Electrolyte Evaporation Thermal Aging	If battery shows signs of degradation or has reached 85% of its expected service life, then increase frequency to annually or once/cycle.
	Perform a Battery Performance Test Under As Found Conditions (Valve-Regulated Batteries)	Annually or Once/Cycle	Material Chemical Changes Dryout Thermal Aging	If battery shows signs of degradation or has reached 85% of its expected service life, then increase frequency to semi-annually.
"Good Housekeeping" Practices - Operation Logs and Checklists	Log Float Voltage and Current	Once/Shift	Material Chemical Changes Thermal Aging	

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Table 5-16. Minimum Recommended Aging Management Programs and Activities for Large Nickel-Cadmium Stationary Batteries (continued)

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
"Good Housekeeping" Practices - Operation Logs and Checklists (continued)	Log Ambient Temperature	Once/Shift	Corrosion Thermal Aging Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design)	
	Electrolyte Level Check	Once/Shift	Gassing and Electrolyte Evaporation	
	Visual Observation	Once/Shift	Material Chemical Changes Corrosion Fatigue Fouling	
On-Line Monitoring and Annunciator Response Procedures	Alarm for Low Battery Voltage	Continuous	Material Chemical Changes Thermal Aging	
Corrective Maintenance	Clean and Tighten Terminations and Intercell Connectors	As Indicated by High Resistance Readings or Visible Corrosion or Fouling	Corrosion Fatigue Fouling	
	Properly Remove and Restore Cells During Battery Maintenance or Replacement	Whenever Battery Cells are Removed or Installed	Material Chemical Changes Fatigue	

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Table 5-17. Supplemental Aging Management Programs and Activities for Large Lead-Acid Stationary Batteries

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Environmental Monitoring	Temperature Monitoring of the Battery Area	Continuous As Needed (See Comments)	Corrosion Thermal Aging Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design) Thermal Runaway (Valve-Regulated Design)	This activity is effective only if past operating experience indicates temperature related problems.
Sample Cell Analysis	Remove One or More Cells for Special Inspections, Testing, and Analysis	As Needed (See Comments)	Material Chemical Changes Corrosion Thermal Aging Fatigue Fouling Gassing and Electrolyte Evaporation Wear (Valve-Regulated Design) Dryout (Valve-Regulated Design) Thermal Runaway (Valve-Regulated Design)	This activity is usually performed in response to a particular concern regarding the condition of the battery.
Charger Output Waveform Monitoring	Monitor and Adjust Charger Output Ripple Voltage with an Oscilloscope	As Needed (See Comments)	Corrosion Thermal Aging Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design) Thermal Runaway (Valve-Regulated Design)	This activity should be completed whenever a repair which may change the output characteristics is performed on the charger.
Battery Impedance Testing	Measure Cell Impedance Using a Capacitively Coupled Low Frequency Current	As Needed	Corrosion Thermal Aging Fouling Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design)	There currently is a lack of baseline data for these types of measurements.

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Table 5-17. Supplemental Aging Management Programs and Activities for Large Lead-Acid Stationary Batteries (continued)

Program	Activity	Frequency	Aging Mechanisms Addressed	Comments
Battery Conductance Testing	Measure Cell Conductance Using an Applied AC Source	As Needed	Corrosion Thermal Aging Fouling Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design)	There currently is a lack of baseline data for these types of measurements.
Infrared Thermographic Inspection	Scan Connections During Capacity Tests	Annually or Once/Cycle	Corrosion Fouling Fatigue	
Potential Surveillance for Seismic Vulnerability	Precise Measurement of Cell Voltage	As Needed	Material Chemical Changes Corrosion Fatigue	
	Measure Cell Internal Resistance and Capacitance	As Needed	Material Chemical Changes Corrosion Fatigue	
	Measure Impedance at Different Frequencies	As Needed	Corrosion Fatigue	

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Table 5-18. Supplemental Aging Management Programs and Activities for Large Nickel-Cadmium Stationary Batteries

Program	Activity	Frequency	Aging Mechanisms	Comments
Environmental Monitoring	Temperature Monitoring of the Battery Area	Continuous As Needed (See Comments)	Thermal Aging Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design)	This activity is effective only if past operating experience indicates temperature related problems.
Sample Cell Analysis	Remove One or More Cells for Special Inspections, Testing, and Analysis	As Needed (See Comments)	Material Chemical Changes Corrosion Thermal Aging Fatigue Fouling Gassing and Electrolyte Evaporation Wear (Valve-Regulated Design) Dryout (Valve-Regulated Design)	This activity is usually performed in response to a particular concern regarding the condition of the battery.
Charger Output Waveform Monitoring	Monitor and Adjust Charger Output Ripple Voltage with an Oscilloscope	As Needed (See Comments)	Thermal Aging Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design)	This activity should be completed whenever a repair which may change the output characteristics is performed on the charger.
Battery Impedance Testing	Measure Cell Impedance Using a Capacitively Coupled Low Frequency Current	As Needed	Thermal Aging Fouling Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design)	There currently is a lack of baseline data for these types of measurements.
Battery Conductance Testing	Measure Cell Conductance Using an Applied AC Source	As Needed	Thermal Aging Fouling Gassing and Electrolyte Evaporation Dryout (Valve-Regulated Design)	There currently is a lack of baseline data for these types of measurements.
Infrared Thermographic Inspection	Scan Connections During Capacity Tests	Annually or Once/Cycle	Corrosion Fouling Fatigue	
	Measure Impedance at Different Frequencies	As Needed	Corrosion Fatigue	

5.4.2 Effective Programs/Techniques Applied to Small Stationary Batteries

The small stationary batteries defined here are low voltage (12 Vdc or below), low capacity batteries. Typically, each consists of a single or a couple of multi-cell units. Unlike the large stationary batteries which are usually made of dozens of cells or multi-cell units, the cost of replacing the small stationary batteries is far less expensive. The typical applications of these small batteries include emergency battery lighting units and other small DC backup power for dedicated loads.

The maintenance programs described in Section 5.2 and the applicable IEEE standards are mainly developed for the large stationary batteries. It is not cost-effective to maintain the small stationary batteries by directly applying the same programs/techniques used for the large stationary batteries. Since the small stationary batteries have much shorter service life spans, often five to six years, a combination of routine inspection activities and a periodic battery replacement program will optimize maintenance costs without sacrificing safety. Table 5-19 summarizes the recommended programs for the management of aging degradation of the small stationary batteries.

The potentially significant aging mechanisms and susceptible subcomponents are identical for the small stationary batteries and large stationary batteries. Since the recommended practices are approached from a perspective of ensuring small stationary battery reliability through reducing the probability of age-related failures by periodically renewing the components, the regular maintenance activities can be substantially simplified in comparison to those used for the large stationary batteries.

The effectiveness of the recommended aging management programs are summarized in Table 5-20 for small lead-acid stationary batteries and Table 5-21 for small nickel-cadmium stationary batteries. Routine inspections primarily consist of visual examination of the battery exteriors and verification of float voltage. For the vented batteries, electrolyte level is to be ensured within adequate ranges. Detection of battery internal degraded conditions relies on the performance data obtained from the capacity discharge tests. Periodic replacements of the batteries are intended to limit the extent of aging degradation such that the batteries' availability is high and is not dominated by aging degradation mechanisms.

The program periodicities provided in Table 5-19 are for reference use. Requirements for a specific battery can be different and may be based on the surveillance requirements of plant Technical Specifications, related regulatory rules, and/or operating experience. Normally, capacity discharge tests are required for safety-related batteries. Replacement intervals are to be established based on the battery manufacturer's recommendation and operating experience. With careful selection of the interval, periodic replacement may justify relaxation of the frequencies of discharge tests, or even to eliminate the need for performance or service tests of non-safety-related batteries.

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Table 5-19. Recommended Programs/Techniques for Small Stationary Batteries

Programs/Techniques	Vented Lead-Acid Type	Vented Nickel Cadmium Type	Valve-Regulated Batteries	Comments
Routine Inspections				
<u>Monthly</u>				
• General appearance and cleanliness of battery and battery surrounding area	X	X	X	<ul style="list-style-type: none"> Frequencies of inspection may vary, depending on the requirements of plant Technical Specifications, related regulatory requirements or operating experience. Annual inspection can be performed in conjunction with capacity test.
• Battery electrolyte level	X	X		
• Signs of physical damage and electrolyte leakage	X	X	X	
• Verification of float voltage (use existing meter if available)	X	X	X	
<u>Annual (or refueling)</u>				
• Ensuring clean and tight terminal connections	X	X	X	
• If applicable, using a calibrated meter to verify the existing meter	X	X	X	
Capacity Tests				
• Performance or service test on an annual or a refueling outage basis	X	X	X	<ul style="list-style-type: none"> Test frequency may be determined by plant Technical Specifications, related regulatory requirements or operating experience.
• Acceptance test at initial installation (as necessary)	X	X	X	

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Table 5-19. Recommended Programs/Techniques for Small Stationary Batteries (continued)

Programs/Techniques	Vented Lead-Acid Type	Vented Nickel Cadmium Type	Valve-Regulated Batteries	Comments
Periodic Battery Replacement	X	X	X	<ul style="list-style-type: none"> Replacement intervals are to be established based on manufacturer's information and operating experience. Adequate replacement intervals may allow measures to relax capacity test frequencies, or even to eliminate capacity tests for non-safety-related batteries.

Table 5-20. Summary of Effectiveness of Recommended Aging Management Programs for Small Lead-Acid Stationary Batteries

Aging Mechanism	Recommended Aging Management Programs			
	Routine Inspections	Capacity Discharge Tests	Periodic Battery Replacement	Class 1E Battery Seismic Qualification
MATERIAL CHEMICAL CHANGES/CONTAMINATION				
Electrolyte Plates Separators Containers	<ul style="list-style-type: none"> Visual inspection Verification of float voltage Providing specific instructions for the use of cleaning solvents 	<ul style="list-style-type: none"> Performance or service test 	<ul style="list-style-type: none"> Periodic replacement 	
CORROSION				
Plates Internal Straps Terminal Posts (if applicable) Terminal/Intercell Connectors (if applicable) Racks (if applicable)	<ul style="list-style-type: none"> Visual inspection Ensuring adequate float voltage and electrolyte level* 	<ul style="list-style-type: none"> Performance or service test* 	<ul style="list-style-type: none"> Periodic replacement 	

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Table 5-20. Summary of Effectiveness of Recommended Aging Management Programs for Small Lead-Acid Stationary Batteries (continued)

Aging Mechanism	Recommended Aging Management Programs			
	Routine Inspections	Capacity Discharge Tests	Periodic Battery Replacement	Class 1E Battery Seismic Qualification
FATIGUE				
Plates Internal Straps Post Seals (if applicable) Containers Racks (if applicable)	• Visual inspection		• Periodic replacement	• Seismic qualification per RG 1.158 and IEEE STD 535-1986
WEAR				
Pressure Relief Valves (for valve-regulated design)		• Performance or service test	• Periodic replacement	
THERMAL AGING				
Separators		• Performance or service test	• Periodic replacement	
GASSING AND EVAPORATION				
Electrolyte	• Ensuring adequate float voltage and electrolyte level*	• Performance or service test	• Periodic replacement	
FOULING				
Battery	• Visual inspection		• Periodic replacement	
* Only applicable to vented design.				

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Table 5-21. Summary of Effectiveness of Recommended Aging Management Programs for Small Nickel-Cadmium Stationary Batteries

Aging Mechanism	Recommended Aging Management Programs			
	Routine Inspections	Capacity Discharge Tests	Periodic Battery Replacement	CLASS 1E Battery Seismic Qualification
MATERIAL CHEMICAL CHANGES/CONTAMINATION				
Electrolyte Plates Containers	<ul style="list-style-type: none"> Visual inspection Measurements of float voltage Providing specific instructions for the use of cleaning solvents 	<ul style="list-style-type: none"> Performance or service test 	<ul style="list-style-type: none"> Periodic replacement 	
CORROSION				
Terminal Posts (if applicable) Terminal/Intercell Connectors (if applicable) Racks (if applicable)	<ul style="list-style-type: none"> Visual inspection 	<ul style="list-style-type: none"> Performance or service test 	<ul style="list-style-type: none"> Periodic replacement 	
FATIGUE				
Post Seals (if applicable) Containers Racks (if applicable)	<ul style="list-style-type: none"> Visual inspection 		<ul style="list-style-type: none"> Periodic replacement 	
WEAR				
Pressure Relief Valves (for valve-regulated design)		<ul style="list-style-type: none"> Performance or service test 	<ul style="list-style-type: none"> Periodic replacement 	
THERMAL AGING				
Separators		<ul style="list-style-type: none"> Performance or service test 	<ul style="list-style-type: none"> Periodic replacement 	
GASSING AND EVAPORATION				
Electrolyte	<ul style="list-style-type: none"> Ensuring adequate float voltage and electrolyte level* 	<ul style="list-style-type: none"> Performance or service test 	<ul style="list-style-type: none"> Periodic replacement 	

Table 5-21. Summary of Effectiveness of Recommended Aging Management Programs for Small Nickel-Cadmium Stationary Batteries (continued)

Aging Mechanism	Recommended Aging Management Programs			
	Routine Inspections	Capacity Discharge Tests	Periodic Battery Replacement	CLASS 1E Battery Seismic Qualification
FOULING				
Battery	• Visual inspection		• Periodic replacement	
* Only applicable to vented design.				

Therefore, if routine inspections, capacity discharge tests, and periodic battery replacement are performed in accordance with Table 5-20 recommendations or justified equivalent, then material chemical changes, corrosion, fatigue, wear, thermal aging, gassing and electrolyte evaporation, and fouling of the small stationary batteries are effectively managed.

5.5 Comparison with NPAR Results

Table 5-22 compares the results and conclusions presented in this aging management guideline to the results and conclusions obtained in the NRC's Nuclear Plant Aging Research (NPAR) program. In general, the results of this guideline agree with the results of the NPAR program studies. The following paragraphs discuss the two main areas of disagreement.

The NPAR program results identified thermally induced oxidation (corrosion) of the grids and straps as the most common aging mechanism for lead-acid batteries. The most common aging mechanism for lead-acid batteries identified in this AMG (from NPRDS data) was also corrosion, however it was corrosion of the intercell connectors and terminal posts. The reason for this discrepancy is most likely due to the large number of age-related NPRDS failures that could not be attributed to a specific aging mechanism but were simply identified as "aging." These failures accounted for 62% of the identified age-related failures. Over 75% of these "aging" failures were attributed to general battery or cell failures due to low capacity, low specific gravity, or low voltage. It is not unreasonable to think that many of these failures could actually be due to corroded plates and straps.

The NPAR program results also suggest that the tests recommended by IEEE STD 450-1987[5.5] provide an indication of adequate seismic capability for lead-acid batteries that are operated and maintained in accordance with IEEE STD 450-1987 and Regulatory Guide 1.129[5.6]. This AMG takes the position that the tests recommended by IEEE STD 450-1987 will detect degradation in a lead-acid battery's ability to deliver its rated power capacity, but may not detect degradation of the internal structural strength of the battery.

This AMG concludes that if the battery has not been qualified in accordance with IEEE STD 535-1986,[5.15] it may be vulnerable to a design basis seismic event in the aged condition. Six potential surveillance tests for detecting seismic vulnerability of lead-acid batteries were

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reviewed (see Section 5.3.8). Section 6.1 presents three options for short term management of seismic vulnerability of lead-acid batteries not qualified to IEEE STD 535-1986.

Although the NPAR program results conclude that the IEEE STD 450-1987[5.5] tests can demonstrate seismic capability for lead-acid batteries operated and maintained in accordance with IEEE STD 450-1987 and Regulatory Guide 1.129,[5.6] they also conclude that seismic vulnerability is an issue for lead-acid batteries that are operated outside of the conditions recommended in IEEE STD 450-1987. For such batteries, the NPAR results recommend that advanced monitoring methods to detect degraded seismic ruggedness be developed, or that revised replacement criteria be implemented.

Table 5-22. Comparison of Results and Conclusions with NPAR Program Results and Conclusions

NPAR Report	NPAR Results/Conclusions	Aging Management Guideline Results/Conclusions
NUREG/CR-4457 Aging of Class 1E Batteries in Safety Systems of Nuclear Power Plants	The most common aging mechanism for lead-acid batteries is thermally induced oxidation of the grids and straps that are made of lead-calcium alloy.	The most common age-related failure cause identified from NPRDS data was corrosion of the intercell connectors and posts.
	Oxidation of the grids in lead-acid batteries causes plate growth.	Oxidation of the <u>positive plate</u> grids in lead-acid batteries causes plate growth.
	Plate growth in lead-acid batteries results in poor contact between the grid and active material, resulting in decreased battery capacity.	— Same —
	Plate growth in lead-acid batteries can stress the container and covers, causing cracks in the container and subsequent loss of electrolyte.	— Same —
	Leaking electrolyte from lead-acid batteries can corrode the battery racks.	— Same —
	Low electrolyte level due to loss of electrolyte can reduce battery capacity.	— Same —
	High temperatures can result from overcharging, AC ripple from the battery charger, or from the environment.	— Same —
	Ambient temperature increases from 25°C [77°F] to 35°C [95°F] can reduce the life of a lead-acid battery by 50%.	The service life of lead-acid batteries is usually halved for every 8°C [15°F] temperature increase above 25°C [77°F] (8°C versus 10°C).

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Table 5-22. Comparison of Results and Conclusions with NPAR Program Results and Conclusions (continued)

NPAR Report	NPAR Results/Conclusions	Aging Management Guideline Results/Conclusions
NUREG/CR-4457 (continued) Aging of Class 1E Batteries in Safety Systems of Nuclear Power Plants	Operating experience and testing of naturally aged batteries indicated that cracking of the container and oxidation (flaking) of the lead are significant problems for lead-acid batteries.	A cracked container was the most common identified failure mode for all battery failures in the NPRDS data. Corrosion was the most common age-related failure cause identified in NPRDS.
	Testing of naturally aged batteries has identified corrosion of the lead grids, straps, and terminals and deterioration of internal components as problems with lead-acid batteries.	Corrosion was identified as a potentially significant age-related degradation mechanism for the grids (plates), straps, and terminals of lead-acid batteries. Material chemical changes and thermal aging were identified as potentially significant age-related degradation mechanisms for the separators in lead-acid batteries.
	Old lead-acid batteries could be vulnerable to failure during seismic events due to oxidation and deterioration of internal components and terminals.	— Same —
	Newer lead-acid batteries qualified to IEEE STD 535-1986 are less vulnerable to seismic events because the standard requires seismic qualification with the batteries aged to end-of-life conditions.	— Same —
	Failures reported to databases are typically degraded or incipient failures (as opposed to complete failures) and include low specific gravity, insufficient charge, cracked containers, corrosion, defective or weak cells, and faulty connections.	The NPRDS failures reviewed typically involved degraded, rather than completely failed, conditions. Failure causes included design problems, human error, corrosion, manufacturer defects, dirt accumulation, high temperature, and plate expansion.
	The most common battery failures reported in LERs were due to low specific gravity (27%) and personnel errors in operations, maintenance, and testing (21%).	The most common failure causes reported in NPRDS were "aging" (32.8%) and "unknown" (20.6%) followed by design problems (8.5%) and human errors (8.1%).

Table 5-22. Comparison of Results and Conclusions with NPAR Program Results and Conclusions (continued)

NPAR Report	NPAR Results/Conclusions	Aging Management Guideline Results/Conclusions
NUREG/CR-4457 (continued) Aging of Class 1E Batteries in Safety Systems of Nuclear Power Plants	Total battery failures peaked in the period of 6 to 11 years after the batteries were placed into service.	Total battery failures plotted against service time tended to show a high initial failure rate that decreased with service time. Age-related battery failures showed a pronounced "wear out" peak at a service time of 9 years.
	Lead-acid batteries maintained in accordance with Regulatory Guide 1.129 and IEEE STD 450-1987 should be expected to provide reliable service for their qualified life.	The minimum recommended aging management program for lead-acid batteries is considered effective and is based heavily on IEEE STD 450-1987.
NUREG/CR-5448 Aging Evaluation of Class 1E Batteries: Seismic Testing	For lead-calcium batteries operated and maintained in accordance with IEEE STD 450-1987 and Regulatory Guide 1.129, adequate electrical capacity and seismic ruggedness will be retained in the batteries and battery racks.	Aged lead-acid batteries not qualified at the end-of-life condition may fail during a seismic event.
	For lead-calcium batteries operated and maintained in accordance with IEEE STD 450-1987 and Regulatory Guide 1.129, some internal damage to the plate separators may occur at the most severe seismic levels, but the battery should still be able to provide at least 80% of its rated capacity during and immediately following the most severe seismic event.	Seismic vulnerability of the separators was not specifically considered.
	Lead-calcium batteries should not be operated at elevated temperatures or charged excessively, because this could accelerate corrosion sufficiently at the joints between the positive plates and the positive plate strap so as to result in inadequate seismic ruggedness.	Elevated temperatures and overcharging can result in accelerated corrosion of the plates and straps in lead-acid batteries. Corrosion of the plates and straps can result in seismic vulnerability.

Table 5-22. Comparison of Results and Conclusions with NPAR Program Results and Conclusions (continued)

NPAR Report	NPAR Results/Conclusions	Aging Management Guideline Results/Conclusions
NUREG/CR-5448 (continued) Aging Evaluation of Class 1E Batteries: Seismic Testing	Because most aging mechanisms cause both decreased electrical capacity and reduced seismic ruggedness, it appears that the tests recommended by IEEE STD 450-1987 not only provide a method of monitoring electrical capacity of current nuclear generation station batteries, but also provide an indication of adequate seismic capability when the batteries are maintained and operated in accordance with IEEE STD 450-1987 and Regulatory Guide 1.129.	The tests recommended by IEEE STD 450-1987 will detect degradation in a lead-acid battery's ability to deliver its rated power capacity, but may not detect degradation of the internal structural strength of the battery. If the battery was not qualified in accordance with IEEE STD 535-1986, an aged lead-acid battery may be vulnerable to a design basis seismic event.
	The results of advanced surveillance methods that measure the internal resistance and capacitance of batteries (polarization and discharge current interruption tests) indicate that these tests provide consistent results and may be useful as an indication of battery condition. It appears that, for the results to be useful, the tests would have to be repeated as the batteries age so that a pattern for each battery (cell) could be established. These tests are not fully developed and are sensitive to the state-of-charge of the battery. A consistent practice must be established concerning charging and the time elapsed between charging and testing.	Measurement of internal resistance and capacitance is one of six potential surveillance tests for detecting seismic vulnerability of lead-acid batteries. A statistical basis has not been developed yet to correlate changes in capacitance or resistance with specific cell degradations.
	For batteries operated at conditions outside of those recommended in IEEE STD 450-1987, advanced monitoring methods that can detect degraded seismic ruggedness should be developed, or revised replacement criteria should be implemented.	Six potential surveillance tests for detecting seismic vulnerability are reviewed in Section 5.3.8. Section 6.1 presents three options for short term management of seismic vulnerability of lead-acid batteries not qualified to IEEE STD 535-1986.

5.6 References

- 5.1 Title 10, U.S. Code of Federal Regulations, 10 CFR Part 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants," December 13, 1991.
- 5.2 NUREG-1299, "Standard Review Plan for the Review of License Renewal Applications for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, Draft for Comment, November 1990.
- 5.3 Title 10, U.S. Code of Federal Regulations, 10 CFR Part 50.65, "Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants," July 10, 1991.
- 5.4 Title 10, U.S. Code of Federal Regulations, 10 CFR Part 50, Appendix B, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants," 1992.
- 5.5 ANSI/IEEE STD 450-1987, "Recommended Practice for Maintenance, Testing, and Replacement of Large Lead Storage Batteries for Generating Stations and Substations," Institute of Electrical and Electronics Engineers, March 9, 1987.
- 5.6 Regulatory Guide 1.129, "Maintenance, Testing, and Replacement of Large Lead Storage Batteries for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, Revision 1, February 1978.
- 5.7 ANSI/IEEE STD 1106-1987, "IEEE Recommended Practice for Maintenance, Testing, and Replacement of Nickel-Cadmium Storage Batteries for Generating Stations and Substations," Institute of Electrical and Electronics Engineers, April 4, 1988.
- 5.8 IEEE PAR-1188, "IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead-Acid Batteries for Stationary Applications," Institute of Electrical and Electronics Engineers, Unapproved Draft, March 1992.
- 5.9 NUREG/CR-4457, "Aging of Class 1E Batteries in Safety Systems of Nuclear Power Plants," Idaho National Engineering Laboratory, EG&G Idaho, Inc., July 1987.
- 5.10 EPRI NMAC TR-100248, "Stationary Battery Maintenance Guide, Final Report," Electric Power Research Institute, December 1992.
- 5.11 EPRI NMAC TR-100249, "Emergency Battery Lighting Unit Maintenance and Application Guide, Final Report" Electric Power Research Institute, October 1992.
- 5.12 Regulatory Guide 1.158, "Qualification of Safety-Related Lead Storage Batteries for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, February 1989.

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- 5.13 Regulatory Guide 1.100, "Seismic Qualification of Electric and Mechanical Equipment for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, Revision 2, June 1988.
- 5.14 ANSI/IEEE STD 344-1987, "IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations," Institute of Electrical and Electronics Engineers, August 3, 1987.
- 5.15 ANSI/IEEE STD 535-1986, "IEEE Standard for Qualification of Class 1E Lead Storage Batteries for Nuclear Power Generating Stations," Institute of Electrical and Electronics Engineers, June 25, 1986.
- 5.16 NUREG/CR-4098, "Seismic-Fragility Tests of New and Accelerated-Aged Class 1E Battery Cells," Sandia National Laboratories, January 1987.
- 5.17 SAND93-7046, "Aging Management Guideline for Commercial Nuclear Power Plants - Battery Chargers, Inverters, and Uninterruptible Power Supplies," Sandia National Laboratories, estimated February 1994.
- 5.18 John Snell, "Infrared Thermography - Answers to Questions You've Wanted to Ask," *Maintenance Technology*, June 1992.
- 5.19 EPRI NMAC NP-6973, "Infrared Thermography Guide," Electric Power Research Institute, Revision 1, March 1992.
- 5.20 NRC Information Notice 91-64, Supplement 1, "Site Area Emergency Resulting From a Loss of Non-Class 1E Uninterruptible Power Supplies," U.S. Nuclear Regulatory Commission, October 7, 1992.
- 5.21 EPRI NP-1558, "A Review of Equipment Aging Theory and Technology," Electric Power Research Institute, September 1980.

6. OTHER AGING MANAGEMENT CONSIDERATIONS

The stressors and aging mechanisms affecting the various battery components in the scope of this guideline were discussed in Section 4. Section 5 evaluated the significant aging mechanisms with respect to current maintenance, inspection, testing, and trending programs and techniques. For the significant aging mechanisms, it was determined that currently available programs and techniques are generally effective in detecting and/or mitigating degradation, and in ensuring long-term safe and reliable operation of the batteries.

Two remaining issues regarding battery aging management are the uncertainty of seismic vulnerability of aged Class 1E lead-acid batteries which are not qualified per IEEE STD 535-1986, and the replacement of rectangular battery cells with round-cell technology for improved aging resistance. These are discussed below.

6.1 Short-Term Management Options for Seismic Vulnerability

Current inspections and surveillance tests will detect degradation in a battery's ability to deliver its rated power capacity, but not the internal structural strength of the battery that may make it vulnerable to a design basis seismic event. Because the qualified electrical life of a lead-acid battery is probably longer than its seismic-qualified life, the aged batteries not seismically qualified at the end-of-life conditions may fail during a seismic event, even though the batteries are capable of delivering required capacity before the event. Practical methods for non-intrusively detecting or mitigating corrosion of relevant battery internal parts, which is the cause of the potential problem, are not available. Further research and development work is needed to find improved surveillance and monitoring techniques for identifying incipient seismic vulnerability of aged batteries.

The sample cell analysis approach, one of the alternative techniques described in Section 5.3, can be utilized to provide marginal assurance of a battery's reliability with respect to a seismic event. Three options for monitoring and estimating battery degradation condition related to seismic vulnerability are:

- Disassembly inspection of artificially aged sample cells
- Seismic testing of artificially aged sample cells
- Periodic disassembly inspection of actual sample cells

The use of the sample cell analysis technique is intended to avoid the high cost of replacing an existing battery system with a newly qualified battery, and still ensure the existing battery's reliability. A combination of the three options may be used to enhance the assessment of battery degradation condition.

6.1.1 Disassembly Inspection of Artificially Aged Sample Cells

The sample cell(s) from an installed battery undergo accelerated aging per IEEE STD 535-1986 to the expected or design service life. A discharge test is performed for the cells, then the cells are disassembled and inspected for the causes of seismic vulnerability, mainly corrosion of plates, bus straps, terminal posts, and their interconnecting joints.

The degradation condition assessment and seismic vulnerability evaluation are to be based on results from past research work and manufacturer's information. The analysis is likely to be on a qualitative basis. Conservative conclusions are necessary to account for the uncertainty. Artificial aging of the sample cells may use different ages among the cells. This can provide additional information for degradation condition prediction.

6.1.2 Seismic Testing of Artificially Aged Sample Cells

Similarly, sample cells are selected from the object battery and artificially brought to the expected end-of-life condition per IEEE STD 535-1986. After aging, discharge tests and seismic tests are performed to determine whether the aged cells are capable of performing before, during, and after a seismic event. The sample cells are tested without the rack since the major concern is the battery internal condition.

The selection of expected end-of-life age of the sample cells is based on the manufacturer's information and the operating experience associated with the battery model. It is recommended that a conservative approach be used in selecting the desired age.

6.1.3 Periodic Disassembly Inspection of Sample Cells

This method mainly relies on the trending of periodic inspection results. A periodicity of one to three years is recommended for the disassembly inspection interval. The intervals can be relatively long in the early period of operation and shortened as the battery ages. The inspection is to focus on the relevant subcomponents. Related information on aging degradation condition of battery subcomponents in relation to seismic vulnerability is necessary, and may be obtained from the manufacturer and results of research work. Analysis will only be on a qualitative basis.

6.1.4 Conclusion

A trending and predictive program based upon these three approaches will assist in monitoring and determining potential seismic vulnerability of aged batteries not qualified to IEEE STD 535-1986. This program must be weighed against the cost of battery replacements caused by system upgrades or other aging degradation factors.

6.2 Round-Cell Technology

AT&T has recently developed round-cell batteries for longer life applications and improved resistance to some of the common aging mechanisms associated with rectangular units. These units have undergone testing in the communications industry, and are beginning to be installed in U.S. nuclear plants. The round cells are designed to minimize or eliminate common station battery failures such as cracked cases or post-seal leakage. Reduced frequency of battery replacement surveillance and maintenance activities is also expected from the round-cell technology. When contemplating a battery system replacement or extended plant life, the round-cell technology may provide advantages for an effective aging management program.

APPENDIX A
ACRONYMS

AC	Alternating current
AMG	Aging Management Guideline
ANSI	American National Standards Institute
BWR	Boiling Water Reactor
CFR	Code of Federal Regulations
DC	Direct current
DG	(NRC) Draft Guide
DOE	U.S. Department of Energy
EBL	Emergency Battery Lighting unit
EPRI	Electric Power Research Institute
FSAR	Final Safety Analysis Report
IE	(NRC) Inspection and Enforcement
IEEE	Institute of Electrical and Electronics Engineers
IN	(NRC) Information Notice
INPO	Institute for Nuclear Power Operations
IPA	Integrated Plant Assessment
IPRDS	In-Plant Reliability Data System
I^2R	Resistance losses
IR	Industry Report
LCM	Life Cycle Management
LER	Licensee Event Report
LWR	Light Water Reactor
MG	Motor generator
MTBF	Mean time between failure
NMAC	Nuclear Maintenance Application Center (EPRI)
NPAR	Nuclear Plant Aging Research
NPE	Nuclear Power Experience (S.M. Stoller Corp.)
NPRDS	Nuclear Plant Reliability Data System (INPO)
NRC	U.S. Nuclear Regulatory Commission

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NUMARC	Nuclear Management and Resources Council
NUREG	Nuclear Regulatory (NRC publication)
PAR	Draft IEEE application or guidance document
PLIM	Plant Lifetime Improvement
PWR	Pressurized Water Reactor
RG	(NRC) Regulatory Guide
SBO	Station blackout
SC	Structure and component
SCSS	Sequence Coding and Search System
SER	Significant Event Report
SNL	Sandia National Laboratories
SOER	Significant Operating Experience Report
SRP	Standard Review Plan
SRP-LR	Standard Review Plan-License Renewal
SSCs	Systems, structures, and components
STD	Standard
UPS	Uninterruptible power supply

APPENDIX B DEFINITIONS[B.1]

accelerated aging artificial aging in which the simulation of natural aging approximates, in a short time, the aging effects of longer-term service conditions

acceptance criterion specified limit of a functional or condition indicator used to assess the ability of an SSC* to perform its design function

age (noun) time from fabrication of an SSC to a stated time

age conditioning simulation of natural aging effects in an SSC by the application of any combination of artificial and natural aging

age-related degradation synonym for **aging degradation**

aging (noun) general process in which characteristics of an SSC gradually change with time or use

aging assessment evaluation of appropriate information for determining the effects of aging on the current and future ability of SSCs to function within acceptance criteria

aging degradation aging effects that could impair the ability of an SSC to function within acceptance criteria

aging effects net changes in characteristics of an SSC that occur with time or use and are due to aging mechanisms

aging management engineering, operations, and maintenance actions to control within acceptable limits aging degradation and wearout of SSCs

aging mechanism specific process that gradually changes characteristics of an SSC with time or use

artificial aging simulation of natural aging effects on SSCs by application of stressors representing plant pre-service and service conditions, but perhaps different in intensity, duration, and manner of application

breakdown synonym for **complete failure**

characteristic property or attribute of an SSC (such as shape, dimension, weight, condition indicator, functional indicator, performance or mechanical, chemical, or electrical property)

* SSC = system, structure, or component

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combined effects net changes in characteristics of an SSC produced by two or more stressors

common cause failure two or more failures due to a single cause

common mode failure two or more failures in the same manner or mode due to a single cause

complete failure failure in which there is complete loss of function

condition the state or level of characteristics of an SSC that can affect its ability to perform a design function

condition surrounding physical state or influence that can affect an SSC

condition indicator characteristic that can be observed, measured, or trended to infer or directly indicate the current and future ability of an SSC to function within acceptance criteria

condition monitoring observation, measurement, or trending of condition or functional indicators with respect to some independent parameter (usually time or cycles) to indicate the current and future ability of an SSC to function within acceptance criteria

condition trending synonym for **condition monitoring**

corrective maintenance actions that restore, by repair, overhaul, or replacement, the capability of a failed SSC to function within acceptance criteria

degradation immediate or gradual deterioration of characteristics of an SSC that could impair its ability to function within acceptance criteria

degraded condition marginally acceptable condition of an unfailed SSC that could lead to a decision to perform planned maintenance

degraded failure failure in which a functional indicator does not meet an acceptance criterion, but design function is not completely lost

design basis conditions synonym for **design conditions**

design basis event any of the events specified in the station's safety analysis that are used to establish acceptable performance for safety-related functions of SSCs; events include anticipated transients, design basis accidents, external events, and natural phenomena

design basis event conditions service conditions produced by design basis events

design basis event stressor stressor that stems from design basis events and can produce immediate or aging degradation beyond that produced by normal stressors

design conditions specified service conditions used to establish the specifications of an SSC (generally includes margin of conservatism beyond expected service conditions)

AGING MANAGEMENT GUIDELINE FOR STATIONARY BATTERIES

design life period during which an SSC is expected to function within acceptance criteria

design service conditions synonym for **design conditions**

deterioration synonym for **degradation**

diagnosis examination and evaluation of data to determine either the condition of an SSC or the causes of the condition

diagnostic evaluation synonym for **diagnosis**

environmental conditions ambient physical states surrounding an SSC

error-induced aging degradation aging degradation produced by error-induced conditions

error-induced conditions adverse pre-service or service conditions produced by design, fabrication, installation, operation, or maintenance errors

error-induced stressor stressor that stems from error-induced conditions and can produce immediate or aging degradation beyond that produced by normal stressors

failure inability or interruption of ability of an SSC to function within acceptance criteria

failure analysis systematic process of determining and documenting the mode, mechanism, causes, and root cause of failure of an SSC

failure cause circumstances during design, manufacture, test, or use that have led to failure

failure evaluation synonym for **failure analysis**

failure mechanism physical process that results in failure

failure mode the manner or state in which an SSC fails

failure modes and effects analysis systematic process for determining and documenting potential failure modes and their effects on SSCs

failure trending recording, analyzing, and extrapolating in-service failures on an SSC with respect to some independent parameter (usually time or cycles)

functional conditions influences on an SSC resulting from the performance of design functions (operation of a system or component and loading of a structure)

functional indicator condition indicator that is a direct indication of the current ability of an SSC to function within acceptance criteria

AGING MANAGEMENT GUIDELINE FOR STATIONARY BATTERIES

inservice inspection methods and actions for assuring the structural and pressure-retaining integrity of safety-related nuclear power plant components in accordance with the rules of this Section [ASME Code, Section XI]

inservice life synonym for **service life**, (especially in discussions involving ASME Code Section XI)

inservice test a test to determine the operational readiness of a component or system [ASME Code, Section XI]

inspection synonym for **surveillance**

installed life period from installation to retirement of an SSC

life period from fabrication to retirement of an SSC

life assessment synonym for **aging assessment**

life cycle management synonym for **life management**

life management integration of aging management and economic planning to: (1) optimize the operation, maintenance, and useful life of SSCs; (2) maintain an acceptable level of performance and safety; and (3) maximize return on investment over the useful life of the plant

lifetime synonym for **life**

maintenance aggregate of direct and supporting actions that detect, preclude, or mitigate degradation of a functioning SSC, or restore to an acceptable level the design functions of a failed SSC

malfunction synonym for **failure**

mean time between failures arithmetic average of operating times between failures of an item [IEEE Std 100]

natural aging aging of an SSC that occurs under pre-service and service conditions, including error-induced conditions

normal aging natural aging from error-free pre-service or service conditions

normal aging degradation aging degradation produced by normal conditions

normal conditions operating conditions of a properly designed, fabricated, installed, operated and maintained SSC excluding design basis event conditions

normal operating conditions synonym for **normal conditions**

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normal stressor stressor that stems from normal conditions and can produce aging mechanisms and effects in an SSC

operating conditions service conditions, including normal and error-induced conditions, prior to the start of a design basis accident or earthquake

operating service conditions synonym for **operating conditions**

operational conditions synonym for **functional conditions**

overhaul (noun) extensive repair, refurbishment, or both

performance indicator synonym for **functional indicator**

periodic maintenance form of preventive maintenance consisting of servicing, parts replacement, surveillance, or testing at predetermined intervals of calendar time, operating time, or number of cycles

planned maintenance form of preventive maintenance consisting of refurbishment or replacement that is scheduled and performed prior to failure of an SSC

post-maintenance testing testing after maintenance to verify that maintenance was performed correctly and that the SSC can function within acceptance criteria

preconditioning synonym for **age conditioning**

predictive maintenance form of preventive maintenance performed continuously or at intervals governed by observed condition to monitor, diagnose, or trend an SSC's functional or condition indicators; results indicate current and future functional ability or the nature and schedule for planned maintenance

premature aging aging effects of an SSC that occur earlier than expected because of errors or pre-service and service conditions not considered explicitly in design

pre-service conditions actual physical states or influences on an SSC prior to initial operation (e.g., fabrication, storage, transportation, installation, and pre-operational testing)

preventive maintenance actions that detect, preclude, or mitigate degradation of a functional SSC to sustain or extend its useful life by controlling degradation and failures to an acceptable level; there are three types of preventive maintenance: periodic, predictive, and planned.

qualified life period for which an SSC has been demonstrated, through testing, analysis, or experience, to be capable of functioning within acceptance criteria during specified operating conditions while retaining the ability to perform its safety functions in a design basis accident or earthquake

3 of 3

random failure any failure whose cause or mechanism, or both, make its time of occurrence unpredictable [IEEE Std 100]

reconditioning synonym for **overhaul**

refurbishment planned actions to improve the condition of an unfailed SSC

remaining design life period from a stated time to planned retirement of an SSC

remaining life actual period from a stated time to retirement of an SSC

remaining service life synonym for **remaining life**

remaining useful life synonym for **remaining life**

repair actions to return a failed SSC to an acceptable condition

replacement removal of an undegraded, degraded, or failed SSC or a part thereof and installation of another in its place that can function within the original acceptance criteria

residual life synonym for **remaining life**

retirement final withdrawal from service of an SSC

rework correction of inadequately performed fabrication, installation, or maintenance

root cause fundamental reason(s) for an observed condition of an SSC that if corrected prevents recurrence of the condition

root cause analysis synonym for **failure analysis**

service conditions actual physical states or influences during the service life of an SSC, including operating conditions (normal and error-induced), design basis event conditions, and post design basis event conditions

service life actual period from initial operation to retirement of an SSC

servicing routine actions (including cleaning, adjustment, calibration, and replacement of consumable) that sustain or extend the useful life of an SSC

simultaneous effects combined effects from stressors acting simultaneously

stress synonym for **stressor**

stressor agent or stimulus that stems from pre-service and service conditions and can produce immediate or aging degradation of an SSC

AGING MANAGEMENT GUIDELINE FOR STATIONARY BATTERIES

surveillance observation or measurement of condition or functional indicators to verify that an SSC currently can function within acceptance criteria

surveillance requirements test, calibration, or inspection to assure that the necessary quality of systems and components is maintained, that facility operation will be within the safety limits, and that the limiting conditions of operation will be met [10 CFR 50.36] (for use only when specific regulatory and legal connotations are called for)

surveillance testing synonym for **surveillance**, **surveillance requirements**, and **testing** (use only when specific regulatory and legal connotations are called for)

synergistic effects portion of changes in characteristics of an SSC produced solely by the interaction of stressors acting simultaneously, as distinguished from changes produced by superposition from each stressor acting independently

testing observation or measurement of condition indicators under controlled conditions to verify that an SSC currently conforms to acceptance criteria

time in service time from initial operation of an SSC to a stated time

useful life synonym for **service life**

wearout failure produced by an aging mechanism

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