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A Study of NRC RG 1.89 Revision 2 and Its Applicability to Environmental Qualification for Long-Term Operation

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1. Introduction

1.1 Background

In recent years, the nuclear industry has faced increasing challenges associated with the long-term operation (LTO) of aging nuclear power plants. As many reactors approach or exceed their original design lifetimes, regulatory and technical frameworks must ensure that safety-related systems, structures, and components (SSCs) continue to perform their intended safety functions under normal and accident conditions. Key challenges include cumulative environmental degradation, evolving failure mechanisms, increased reliance on digital instrumentation and control (I&C) systems, and the need for defensible technical bases to support license renewal and subsequent license renewal (SLR).

The Fukushima Daiichi accident further highlighted the importance of strengthening regulatory requirements for equipment survivability under severe and prolonged environmental conditions. In the post-Fukushima regulatory environment, greater emphasis has been placed on aging management, design-basis event (DBE) robustness, and the integration of operational experience into regulatory guidance. Within this context, environmental qualification (EQ) has become a critical technical discipline for demonstrating that safety-related electrical equipment can withstand combined environmental stressors—such as temperature, radiation, humidity, and chemical exposure—throughout extended operating periods.

Historically, EQ programs relied on conservative, time-limited assumptions supported by accelerated aging tests, as reflected in NRC Regulatory Guide (RG) 1.89 Revision 1. While this approach ensured robust safety margins, it provided limited flexibility for plant-specific aging behavior, long-term operation beyond 60 years, and the qualification of modern digital equipment. To address these limitations, the U.S. Nuclear Regulatory Commission (NRC) issued RG 1.89 Revision 2 in 2023, introducing condition-based and evidence-driven qualification approaches and aligning NRC expectations with internationally harmonized standards such as IEC/IEEE 60780-323. As a result, the revised guidance provides a regulatory framework better suited to supporting long-term plant operation while maintaining safety margins under design-basis conditions.

1.2 Purpose and Scope

The purpose of this study is to examine the regulatory and technical evolution embodied in NRC RG 1.89 Revision 2 and to assess its implications for environmental qualification programs supporting long-term operation of nuclear power plants. This paper focuses on how the revised guidance addresses key challenges associated with aging management, condition-based qualification, and the integration of EQ with license renewal and SLR processes.

Specifically, this study analyzes the transition from time-based qualification assumptions to data-driven and condition-based approaches, evaluates the expanded treatment of thermal and radiation aging mechanisms, and discusses the applicability of the revised EQ framework to both existing and new reactor licensing structures. By clarifying the role of RG 1.89 Rev.2 in the context of long-term operation, this paper aims to provide practical insights for utilities, designers, and regulators involved in sustaining nuclear plant safety over extended operating lifetimes.

1.3 Methodology

This study uses a structured document-analysis approach to compare RG 1.89 Rev.1 and Rev.2 and to map Revision 2 requirements to practical EQ program activities (analysis, testing, monitoring, documentation, and change control). The methodology consists of:

- Primary-source review of RG 1.89 Rev.2 (including Appendices D and E) and key related guidance (e.g., RG 1.209; NUREG-1801;

NUREG-2191).

- Requirement clustering into comparable domains (thermal aging, radiation environment, seismic/DBE, digital equipment, and documentation/traceability).
- Crosswalk comparison against legacy baselines (RG 1.89 Rev.1 and IEEE 323) to identify additions, clarifications, and implementation impacts.
- Synthesis of supporting research on cable aging monitoring, digital equipment vulnerabilities (TID/SEE), activation energy measurement, and plant experience case studies.
- Development of a practical transition checklist that can be used to plan and audit the shift from time-based qualification assumptions to condition-based/evidence-driven approaches.

2. Historical Development of EQ Standards

2.1 NRC Origins and Early Frameworks

- The NRC's first EQ framework was outlined in NUREG-0588 and codified in 10 CFR 50.49 [2,3].
- IEEE 323-1974 formed the technical backbone of EQ, adopted in RG 1.89 Rev.1 (1984).
- These early frameworks were time-based, conservative, and relied heavily on accelerated testing.

2.2 Stagnation and Need for Modernization

- Although IEEE issued updates in 1983 and 2003, RG 1.89 did not explicitly endorse the later versions until Revision 2, creating a practical gap between NRC guidance and commonly used industry standards.
- Meanwhile, aging infrastructure, emerging failure modes, and the rise of digital instrumentation and control (I&C) systems necessitated an overhaul.

3. Key Revisions in RG 1.89 Rev.2

3.1 Standard Harmonization

- Approves IEC/IEEE 60780-323:2016, a harmonized global standard combining IEEE 323-2003 and IEC 60780:1998.
- Promotes standardization for international NPP industry.

3.2 Emphasis on Condition-Based Qualification

- Condition-based approaches allow using measured aging data rather than assumptions.
- Monitoring includes degradation indicators such as insulation resistance, capacitance, and radiation dose correlation.

3.3 Expanded Aging Analysis

- Arrhenius equation and activation energy principles are required for thermal aging models.
- Synergistic effects — like dose rate impact and radiation-temperature sequencing — are explicitly addressed.

3.4 Radiation Environment Guidance

Appendix D provides quantitative modeling for facility-specific radiation fields and references RG 1.183 for source term calculations.

3.5 Guidance on Digital Components

- Recognizes failure modes in microprocessor-based systems (e.g., latch-up, data corruption).
- Requires referencing RG 1.209 for EQ of computer-based safety systems.

4. Integration with Licensing and Aging Management

The regulatory scope of RG 1.89 Revision 2 extends beyond the technical realm of environmental qualification (EQ); it plays a vital role in the broader nuclear plant licensing and long-term operational strategy, particularly in relation to aging management and license renewal. As the nuclear power plant ages, many facilities are pursuing renewals for 60-year and even 80-year operational lifespans, necessitating robust technical justifications that their systems, structures, and components (SSCs) can perform their intended safety functions over extended periods. RG 1.89 Rev.2 is tightly integrated with the frameworks supporting such justifications.

4.1 License Renewal and SLR Support

One of the primary objectives of RG 1.89 Rev.2 is to support aging nuclear power plants through license renewal (LR) and subsequent license renewal (SLR) processes. These renewals, typically for extending operation from 40 to 60 years, and then from 60 to 80 years, require detailed analyses showing that critical equipment can maintain safety function under long-term degradation mechanisms.

To facilitate this, RG 1.89 Rev.2 explicitly aligns with two cornerstone NRC documents:

- NUREG-1801, also known as the Generic Aging Lessons Learned (GALL) Report, which outlines acceptable aging management programs (AMPs) for initial license renewal.
- NUREG-2191, known as the GALL-SLR, which provides extended guidance for plants seeking operation beyond 60 years.

Both documents offer standardized AMP templates that identify **T**ime-**L**imited **A**ging **A**nalyses (TLAAs), recommended inspection frequencies, and monitoring strategies. RG 1.89 Rev.2 integrates with these frameworks by ensuring environmental qualification is treated as a time-limited program that must be actively evaluated and updated during license renewal reviews.

4.2 Documentation Requirements

Appendix E of RG 1.89 Rev.2 introduces enhanced documentation expectations aimed at improving transparency, traceability, and regulatory consistency in EQ programs. The guide establishes a clear and standardized structure for documenting the qualification basis of safety-related electrical equipment.

The minimum documentation elements include:

- A complete list of equipment subject to environmental qualification, categorized by safety function and location.
- Definition of operating conditions, including radiation levels, temperatures, humidity, pressure, and other relevant environmental factors for each component.
- Summary of qualification testing or analysis used to justify the qualified life and applicable operating envelope.
- Description of methods used, such as accelerated aging, extrapolation models (e.g., Arrhenius method), or condition monitoring systems.

By establishing these requirements, RG 1.89 Rev.2 ensures that each component's qualification status is verifiable, reproducible, and defensible—particularly important during audits, inspections, or licensing proceedings. The document also emphasizes maintaining up-to-date records throughout the qualified life of the equipment, encouraging a lifecycle approach to qualification that aligns with modern asset management principles.

4.3 Applicability

RG 1.89 Rev.2 is carefully written to ensure applicability to both existing reactors and new nuclear plant designs, offering clarity across distinct regulatory frameworks under 10 CFR Part 50 and Part 52.

- 10 CFR Part 50 applies to existing operating reactors licensed under the traditional framework, which includes most of the U.S. NPP. For these plants, the guide supports the reevaluation and modernization of legacy EQ programs—many of which were originally based on outdated standards or limited operating experience.
- 10 CFR Part 52 governs combined licenses (COLs) for new reactor designs. For these newer plants, RG 1.89 Rev.2 provides a forward-looking framework that aligns with the latest international standards, ensuring that environmental qualification practices are embedded from the design phase and that future licensees start with a harmonized baseline.

By bridging both regulatory paths, RG 1.89 Rev.2 harmonizes expectations and helps to eliminate ambiguity for utilities, designers, and regulators navigating evolving requirements. This comprehensive applicability enhances regulatory predictability and simplifies long-term compliance planning across the nuclear industry.

5. Technical Foundation and Supporting Research

The development and modernization of RG 1.89 Rev.2 is firmly grounded in a wealth of empirical research and regulatory experience accumulated over several decades. This chapter explores four key technical domains that have directly influenced the evolution of environmental qualification (EQ) practices: cable aging and monitoring, digital equipment vulnerabilities, activation energy modeling, and real-world validation through plant-level case studies.

5.1 Research on Cable Aging and Monitoring

Electrical cables are among the most critical safety-related components in a nuclear power plant, often installed in harsh environments where they are exposed to elevated temperatures, humidity, radiation, and chemical agents over decades of operation. Recognizing the limitations of time-based qualification methods, NRC-sponsored research has increasingly focused on in-situ condition monitoring of cables to provide a more accurate understanding of material degradation.

These studies have emphasized the use of non-destructive evaluation (NDE) techniques to monitor parameters such as insulation resistance, capacitance, and dielectric strength. Advanced diagnostic tools, including Frequency Domain Reflectometry (FDR), Time Domain Reflectometry (TDR), and indenter modulus testing, have been deployed to assess aging indicators without removing cables from service. The ability to track the aging process in real-time enables more informed decisions on maintenance, replacement, or EQ life extension, aligning with the condition-based methodologies encouraged in RG 1.89 Rev.2.

5.2 Digital Equipment Vulnerabilities

As nuclear power plants continue to adopt digital and microprocessor-based instrumentation and control (I&C) systems, new vulnerabilities have emerged related to environmental stressors, particularly radiation. Research led by institutions such as Sandia National Laboratories and Oak Ridge National Laboratory has identified significant susceptibility of digital components—especially MOSFETs (Metal-Oxide Semiconductor Field-Effect Transistors)—to Total Ionizing Dose (TID) and Single Event Effects (SEE) [2].

These failure modes can result in signal drift, data corruption, latch-up, or permanent damage in sensitive circuits. TID effects accumulate over time, degrading semiconductor performance, while SEEs are caused by individual high-energy particles and can lead to unpredictable system behavior. These studies provided the technical basis for the guidance introduced in RG 1.89 Rev.2, which references RG 1.209 for qualification of digital safety systems. The integration of such research ensures that new-generation digital systems are held to rigorous EQ standards appropriate for long-term, radiation-exposed operation.

5.3 Activation Energy Measurement

A central aspect of thermal aging modeling is the determination of activation energy, which quantifies how temperature accelerates material degradation processes. RG 1.89 Rev.2 emphasizes the use of the Arrhenius model to estimate the effect of temperature over time on material properties. However, applying the model accurately depends on selecting an appropriate activation energy value for the specific material in question.

In their 2016 study, Bhang & Hong applied Thermo- gravimetric Analysis (TGA) to experimentally determine activation energies for non-metallic materials commonly used in nuclear plant electrical components. Their work demonstrated how experimental methods can validate or refine assumed values, reducing reliance on conservative estimates and improving the accuracy of qualified life predictions. RG 1.89 Rev.2 incorporates this approach, requiring justification for selected activation energy values and encouraging the use of empirical data over generic assumptions [4].

5.4 Case Study: Nine Mile Point

Perhaps the most compelling validation of condition-based qualification is found in the real-world experience of Nine Mile Point Nuclear Station, which implemented a robust in-situ monitoring program for EQ components. By collecting real-time environmental and performance data, engineers were able to demonstrate that many components retained adequate safety margins well beyond their conservatively assumed qualified life [3].

This case study has been cited as an example of extending EQ life through data-driven justification rather than default replacement. It also illustrates potential cost and safety benefits of integrating condition monitoring into long-term asset management. In this sense, RG 1.89 Rev.2 supports moving beyond conservative assumptions when such a transition is justified by traceable, high-quality data.

6. SWOT analysis

・ **S**(Strengths)

One of the most notable strengths of RG 1.89 Rev.2 is its alignment with real-world degradation mechanisms through the adoption of condition-based environmental qualification approaches. Unlike earlier, conservative time-based models, this revision emphasizes the use of actual degradation data to assess and extend the qualified life of safety-related equipment. This not only improves the accuracy of qualification assessments but also enables the implementation of **predictive maintenance strategies**, allowing nuclear power plant operators to anticipate failures and optimize maintenance schedules. Additionally, RG 1.89 Rev.2 addresses a significant regulatory gap by providing clear guidance for the qualification of **digital and microprocessor-based instrumentation and control (I&C) systems**, which are increasingly prevalent in modern nuclear facilities.

・ **W**(Weaknesses)

Despite these advancements, the revised guidance introduces substantial complexity in implementation. Condition-based qualification requires more sophisticated monitoring, data collection, and documentation processes compared to traditional methods. For utility operators, this may translate into a greater financial and technical burden, particularly in retrofitting older plants that lack integrated monitoring systems. The need for additional expertise, new instrumentation, and robust data management frameworks could pose challenges in ensuring consistent compliance across diverse facility types.

・ **O**(Opportunities)

RG 1.89 Rev.2 presents significant opportunities, especially for plants pursuing license renewal or subsequent license renewal (SLR). By incorporating real-time environmental and aging data into qualification analyses, operators can confidently extend the qualified life of equipment, supporting longer plant operation with robust scientific justification. This data-driven approach also enhances the transparency and defensibility of aging management programs (AMPs), strengthening the overall license renewal application process. The transition from assumed degradation to measured performance provides a pathway for cost-effective long-term operations.

・ **T**(Threats)

However, this approach also brings potential risks. Misapplication or incorrect modeling of activation energy parameters, a key component in thermal aging projections, could result in inaccurate life estimates and compromised safety margins. Similarly, inconsistencies in how condition monitoring data is interpreted—especially across different facilities or vendors—may lead to regulatory uncertainty. The increased reliance on data-driven methods demands high confidence in measurement accuracy, standardized interpretation frameworks, and clear regulatory expectations to prevent misalignment between utilities and oversight bodies.

7. Conclusion

RG 1.89 Rev.2 represents a regulatory update informed by accumulated operational experience and advancements in scientific understanding. It modernizes the approach to environmental qualification of safety-related electrical equipment by moving from conservative, time-based assumptions to methods based on empirical data and condition monitoring. The revision resolves longstanding inconsistencies in regulatory alignment, incorporates digital instrumentation considerations, and establishes a structured framework applicable to both existing and new nuclear facilities. Its adoption supports continued compliance and safety assurance in the context of extended plant operation, including periods beyond 60 years

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