A Logical Approch on Aging Management of Non-Metallic Parts in Active Mechanical Equipment In Connection With PSR

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1. Introduction

Equipment Qualification (EQ) is a process to verify that nuclear power plant equipment maintains its safety functions under environmental conditions, primarily applied to electrical equipment [1][2][3]. With the extension of plant operation life, the scope of EQ application has expanded to include mechanical equipment such as pumps and valves, as well as non-metallic components [4][5][6][7][8][9]. This study reviews and compares major EQ standards and illustrates an example framework for linking EQ with Periodic Safety Review (PSR**)**, aiming to enhance reliability of equipment during long-term operation.

2. Main Contents

2.1 Comparison of Major EQ Standards

EQ standards differ in scope of target equipment, test items, and aging evaluation methods. IEEE 323/344 and 10 CFR 50.49 primarily apply to Class 1E electrical equipment, whereas ASME QME-1 covers active mechanical equipment and non-metallic components [1][2][3][4][5][8]. NUREG-0800 Section 3.11 and NRC Issue 172 provide supplementary guidance [6][7]. Table 1 summarizes the scope and technical characteristics of the major EQ standards.

Table 1. Scope and Technical Characteristics of Major EQ Standards

Category	10 CFR 50.49	ASME QME-1 (QR-B)	NRC Issue 172	Reference (IEEE 323)
Applicable Equipment	**Class 1E electrical equipment** - Covers also mechanical systems and component integrity (10 CFR 50.49(b)(1))	**Active mechanical equipment and non-metallic components** (QR-B 1.2)	Recommends QME-1 application	Class 1E electrical equipment
Test Items	**Functional assurance** under environmental changes (10 CFR 50.49(e)(4))	**Expanded test items** – Temperature, radiation, humidity, **pressure, process fluid**, vibration, **etc.** (QR-B 2.3)	Recommends QME-1 test items	Temperature, radiation, humidity, vibration
Aging Evaluation	**Required** (10 CFR 50.49(e)(5))	**Applicable** (QR-B 3.1) **; e.g., FMEA** for non-metallic components	Recommends QME-1 guidance	Limited – electrical equipment only
Inclusion of Non-metallics	**Not included** – No explicit mention in regulation.	**Explicitly included** (QR-B 2.4)	Recommends QME-1	Not included

※ FSAR: Final Safety Analysis Report
※ Aging management: Management of equipment aging
※ FMEA: Failure Modes and Effects Analysis

2.2 Technical Necessity of EQ Expansion and Multi-Factor Analysis Structure or Framework

Conventional EQ has focused mainly on electrical equipment, which limits comprehensive reliability assurance of plant systems. Expanding EQ scope to mechanical equipment and non-metallic parts susceptible to aging degradation is necessary, as recommended by ASME QME-1 and NRC Issue 172 [4][5][7][8]. Moreover, EQ applicability to non-safety grade but safety-important equipment should be considered.

For non-metallic mechanical components, while manufacturers' manuals are partially referenced, integrating maintenance history (A), aging evaluation (B), and equipment importance (C) in a multi-factor analysis framework effectively enhances reliability. Table 2 presents an example logical structure and their technical meanings.

Table 2. Logical Structure for EQ Expansion and Technical Meaning

PSR Stage	Application Timing	Technical Meaning
Stage 1	**Initial PSR (~10 years)**	**Partial**: Identify safety-significant equipment; corrective actions recommended. **High-Risk**: Immediate action required.
Stage 2	**PSR (10–20 years)**	**Partial :** Monitor & Correct**.** Begin trend analysis for aging-related degradation. **High-Risk**: Immediate action or mitigation required.
Stage 3	**PSR (20–30 years)**	**Partial**: Monitor and corrective actions as needed. **High-Risk:** Implement maintenance or mitigation actions
Stage 4	**PSR (30~ years)**	**Final assessment:** Ensure Ideal condition **.** **Partial**: Monitor and maintain equipment; corrective actions if necessary. **High-Risk:** plan for replacement, decommissioning, or major refurbishment

Logical Structure	
Ideal :	$A \wedge B \wedge C$
Partial :	$((A \vee B) \wedge C) \wedge \neg(A \wedge B)$
High Risk :	$\neg A \wedge \neg B \wedge C$

※ Notation:
A = Maintenance history-based review
B = Aging evaluation based on life prediction model
C = Safety significance (C=0: Non-safety, non-critical equipment, C=1: Non-safety equipment but safety-important, C=2: Safety-class equipment)
$\wedge$ = AND, $\vee$ = OR, $\neg$ = NOT

The elements are detailed and evaluation states are defined as follows:

- **A (Maintenance History):** preventive maintenance, repair/replacement, failure/defect logs, performance tests, non-safety equipment management records, training/procedure compliance, organizational controls.
- **B (Aging Evaluation):** Arrhenius-based life prediction, degradation trend analysis using field data.
- **C (Equipment Importance):** safety significance assessment based on system function, (system function, impact scope, operational consequence of failure).
- **Ideal:** All criteria are satisfied, indicating fully qualified equipment with ensured safety and reliability.
- **Partial:** Some criteria are met, requiring monitoring and corrective actions if necessary.
- **High-Risk:** Criteria are not met, requiring immediate corrective actions, replacement, or maintenance.

The elements defined above provide the basis for the logic-based multi-factor evaluation. Integrating A, B, and C within the presented logical structure enables a systematic determination of EQ qualification across PSR intervals and particularly enhances reliability for aging equipment and non-metallic components.

2.3 Overview of PSR and EQ Linkage

Periodic Safety Review (PSR) is conducted every 10 years to evaluate equipment condition and safety [11]. Table 3 shows key PSR items related to EQ.

Table 3. Key EQ-Related Items in PSR

PSR Item	Linkage to EQ
Equipment Qualification	Direct reflection of EQ standards, test history, and life models
Aging Management	Aging Evaluation Based on EQ Data
Equipment Replacement Timing	Determined by EQ evaluation results

When EQ data are insufficient, PSR stage may require additional review, including QME-1 requalification or life reassessment using aging models. EQ is a management tool to secure reliability from design certification through long-term operation [4][5][6][7][8]. Table 4 summarizes the expanded EQ items and their linkage with PSR.

Table 4. Expanded EQ items and their linkage with PSR.

Expanded EQ Items	PSR Linkage	Technical Meaning and Expected Benefits
Inclusion of non-metallic components and non-safety grade equipment	Expanded evaluation scope and strengthened monitoring of important equipment	Strengthened aging management beyond safety grade equipment
Integration of maintenance and aging data	Improved accuracy of aging and performance evaluation through integrated data	Enhanced evaluation reliability and objectivity by linking diverse data sources
Integration of EQ and PSR inspection and evaluation criteria	Minimizes duplication and improves operational efficiency	Simultaneous resource saving and quality assurance in EQ and PSR
Risk-based maintenance enhancement under long-term operation	Prioritization and sophistication of maintenance systems based on risk	Supports risk-informed decision making and enhances reliability
Detailed equipment importance evaluation and reflection	Prioritized management of safety-important equipment and evaluation of important non-safety equipment	Achieves balance between safety and economy through differentiated management

In the long-term operation case of operating nuclear power plants, comprehensive consideration of mechanical equipment life prediction, EQ results, and replacement history have contributed to safety evaluation [10]. The utilization of EQ results in PSR increases, serving as a supplementary means for equipment condition assessment and determination of replacement timing under extended operation.

Based on this, key improvement tasks to enhance the effectiveness of the EQ system were identified and summarized in Table 5.

Table 5. Development Tasks and Details for Strengthening the Effectiveness of the Environmental Qualification (EQ) System

No.	Improvement Task	Details
1	Clear differentiation between electrical and mechanical EQ standards	Technical separation of applicable standards such as IEEE 323/344 and QME-1
2	Establishment of an independent EQ system for mechanical equipment	Separate EQ process for mechanical components including non-metallic parts
3	Expanded adoption of test-based aging models	Broader implementation such as the FMEA approach
4	Strengthened regulatory linkage	Ensure consistency with PSR, FSAR, RG 1.89, RG 1.100, etc.
5	Integrated analysis combining maintenance history and aging data	Develop a comprehensive evaluation framework that fuses operational history and aging characteristics

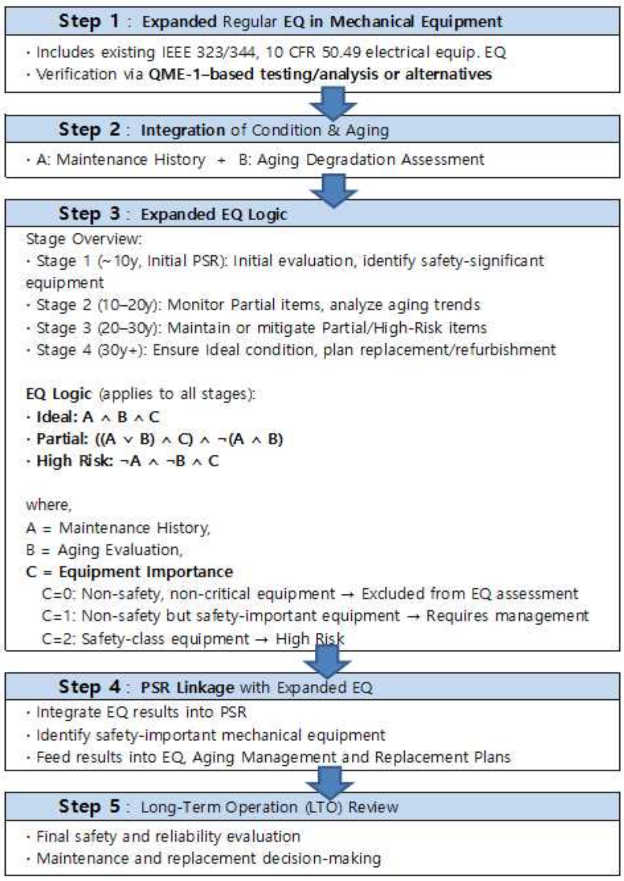

Figure 1. Flowchart of EQ, PSR, and Long-Term Operation Linkage

(Regular EQ results are reflected in aging evaluation, applied to PSR evaluation items, and ultimately used for long-term operation assessment.)

3. Conclusions

The study emphasizes that EQ scope has expanded from Class 1E electrical equipment to include active mechanical systems and non-metallic components, reflecting their importance in aging management and long-term plant reliability.

Based on this expanded scope, the study illustrates an example multi-factor framework integrating maintenance history (A), aging evaluation (B), and equipment importance (C) within PSR stages. The framework provides an example of how EQ results could be incorporated into PSR evaluations, supporting risk-informed inspection, maintenance prioritization, and long-term operational planning for mechanical and non-metallic equipment.

Linking EQ with PSR in this manner can further enhance the safety and reliability assessment of plant equipment, particularly for components susceptible to aging degradation.

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