Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 28–30, 2026

Extended Logical Approach for Aging Management of Non-Metallic Components in Active Mechanical Equipment In Connection with PSR-Based Decision Making

S. H. Youn[a,*], S. P. Hong[a], C. H. Ji[a], D. H. Shin[a]

[a]*TAEYANG Engineering Co., Operating Nuclear Power Plants Design, Room 502, 303 Hyeoksin-ro, Gimcheon-si, Gyeongsangbuk-do, Korea 39660*

**Corresponding author: shyoun@tyecl.com*

Keywords: Equipment Qualification (EQ), Aging Management, Mechanical Equipment, Non-Metallic Components, Periodic Safety Review (PSR)

Abstract

Equipment Qualification (EQ) has traditionally focused on demonstrating that safety-related equipment can maintain its required functions under specified environmental conditions. Previous studies proposed a logical framework integrating maintenance history (*A*), aging evaluation (*B*), and equipment importance (*C*) for aging management of non-metallic components in active mechanical equipment. Although the framework provided a useful conceptual basis, its binary logical structure limited its applicability to practical engineering decision making.

This study develops an extended logical approach that preserves the original logical relationships while introducing a semi-quantitative framework capable of representing different levels of degradation severity. Representative categories of non-metallic components are identified together with their dominant degradation mechanisms and evaluation indicators. A structured risk formulation combining maintenance history, aging condition, environmental severity, and equipment importance is proposed to support PSR-based decision making.

The proposed methodology is intended to provide a systematic intermediate layer between degradation assessment and engineering decisions, thereby improving the consistency, traceability, and practical utilization of aging-management information for long-term operation (LTO) of nuclear power plants.

1. Introduction

Equipment Qualification (EQ) has traditionally been understood as a process for demonstrating that nuclear power plant equipment can continue to perform its intended safety functions under specified environmental conditions. Historically, EQ programs have focused primarily on electrical equipment, particularly Class 1E equipment, for which qualification requirements have been well established through regulatory guidance and industry standards [2, 3, 4]. However, as nuclear power plants move into extended operating periods and LTO becomes increasingly important, attention has expanded toward active mechanical equipment and, in particular, non-metallic components that are susceptible to aging degradation under temperature, radiation, pressure, humidity, vibration, and process-fluid exposure [5, 6, 7, 8].

To address this issue, previous research proposed a logical approach for aging management of non-metallic parts in active mechanical equipment in connection with Periodic Safety Review (PSR) [1]. That study recognized the need to extend aging management considerations beyond conventional electrical EQ applications and suggested a structured framework based on maintenance history (*A*), aging evaluation (*B*), and equipment importance (*C*). The framework employed Boolean logic to classify equipment condition into qualitative states and discussed the potential role of EQ information within PSR activities.

The significance of the previous study lies in the fact that it moved beyond descriptive aging-management concepts and introduced a logical structure for integrating multiple evaluation factors. The proposed framework defined equipment condition through logical expressions representing Ideal, Partial, and High-Risk states, thereby providing a transparent basis for condition assessment and qualification review [1]. This approach established an important conceptual link between degradation evaluation and PSR-related engineering decision processes.

Despite these advantages, the original framework remains limited when applied to practical aging-management decisions. The primary limitation arises from its binary representation of degradation conditions. In actual plant environments, degradation does not occur as a simple transition between acceptable and unacceptable states. For example, elastomeric seals progressively lose elastic recovery through increasing compression set, polymer bearings accumulate wear over time, insulation materials experience gradual reduction in dielectric properties, and flexible hoses undergo hardening, swelling, and cracking before functional failure occurs. These degradation mechanisms develop continuously rather than discretely and therefore cannot be fully represented through binary logical variables alone [9, 10].

In addition, different categories of non-metallic components exhibit different degradation mechanisms, failure modes, and evaluation indicators. Consequently, a generalized logical classification alone may not provide sufficient information to support practical engineering actions such as enhanced monitoring, maintenance prioritization, replacement evaluation, or refurbishment planning. Furthermore, while the previous framework conceptually linked EQ and PSR, it did not explicitly define how condition assessment

results should be translated into decision-making activities within PSR stages.

For these reasons, this study develops an extended logical approach for aging management of non-metallic components in active mechanical equipment. The proposed framework preserves the conceptual foundation established in the previous study while introducing a semi-quantitative structure capable of representing different levels of degradation severity. The framework further incorporates environmental severity as an additional evaluation factor and establishes an explicit linkage between degradation assessment and PSR-based decision making. The objective is not to replace existing EQ methodologies or engineering judgment, but to provide a systematic intermediate layer that improves the traceability, consistency, and practical utilization of aging-management information for LTO of nuclear power plants.

2. Representative Categories of Non-Metallic Components

One of the key challenges in developing a generalized aging-management framework for non-metallic components is balancing research generality with engineering specificity. If the framework is developed for only a single component under a specific service condition, the result becomes a narrow case study with limited applicability. Conversely, if all non-metallic components are treated as a single group, the framework becomes overly abstract and loses physical meaning because different materials exhibit different degradation mechanisms and failure behaviors.

To address this issue, the present study adopts a component-category-based approach. The objective is to establish a framework that is sufficiently broad to support generalized aging-management applications while remaining sufficiently specific to preserve engineering relevance. Components are therefore classified according to similarities in functional role, material characteristics, and dominant degradation mechanisms.

The proposed categorization consists of four representative groups commonly found in active mechanical equipment: sealing components, polymer bearing components, insulation and coating materials, and elastomeric hose assemblies. Although individual components within each category may differ in geometry or application, they generally share similar degradation characteristics and evaluation methodologies.

Among these categories, sealing components are typically affected by loss of elastic recovery and compression set, while polymer bearings are primarily influenced by wear and dimensional changes. Insulation and coating materials are susceptible to degradation of dielectric or protective properties resulting from thermal and radiation exposure. Elastomeric hoses experience changes in material properties such as hardening, swelling, and cracking, which may eventually lead to leakage or rupture. Because these degradation mechanisms differ significantly, a single evaluation indicator cannot adequately represent all non-metallic components.

The classification presented in this study therefore serves as the foundation for the subsequent development of degradation indicators, semi-quantitative scoring methods, and risk-based decision support within the proposed aging-management framework.

3. Evaluation Criteria

The effectiveness of an aging-management framework depends not only on how degradation is quantified but also on whether the selected evaluation criteria are physically meaningful. For this reason, the present study distinguishes between degradation indicators supported by established engineering practice and the scoring structure proposed for decision-support purposes.

Because different categories of non-metallic components exhibit different degradation behaviors, a single evaluation parameter cannot adequately represent all component types. Instead, evaluation criteria should be selected according to the dominant degradation mechanism associated with each component category.

For sealing components, compression set is selected as the primary evaluation criterion because it directly reflects the loss of elastic recovery and sealing capability. For polymer bearings and sliding supports, wear rate or wear depth provides a meaningful measure of functional degradation. For insulation and coating materials, degradation is represented through insulation resistance reduction or equivalent loss of dielectric properties. For hoses and elastomeric flexible components, hardness change, swelling, or equivalent material-property shifts are appropriate indicators because they are closely related to flexibility loss, cracking susceptibility, and leakage potential.

To facilitate integration into the proposed decision-support framework, degradation conditions are represented using discrete state variables. Maintenance-history condition (A), aging condition (B), and environmental severity (D) are each assigned values of 0, 1, or 2 corresponding to low, moderate, and high degradation states, respectively. Equipment importance (C) is represented separately as a consequence factor reflecting the significance of functional failure.

It should be emphasized that the evaluation indicators shown in Table 2 are based on established degradation mechanisms and accepted engineering practices. In contrast, the proposed scoring structure is intended as a practical tool for structured assessment and decision support. Therefore, threshold values may be adjusted according to plant-specific design requirements, operational experience, inspection data, and maintenance history while preserving the overall framework proposed in this study.

4. Risk Formulation

The logical framework proposed in the previous study provided a structured method for classifying equipment condition through Boolean expressions involving maintenance history (A), aging evaluation (B), and equipment importance (C) [1]. While this approach offered conceptual clarity, it did not provide a mechanism for representing the degree of degradation or supporting quantitative comparison among components. As discussed in the preceding sections, degradation of non-metallic components is inherently progressive and therefore requires a formulation capable of reflecting different levels of condition deterioration.

Table 1: Representative Categories of Non-Metallic Components

Class	Component Type	Primary Function	Dominant Degradation Mechanisms	Typical Service Factors
Class 1	Seal / Gasket / O-ring / Packing	Sealing	Compression set, stress relaxation, hardening, thermal aging, leakage initiation	Temperature, pressure, fluid exposure
Class 2	Polymer Bearing / Bush / Sliding Support	Friction support and load transfer	Wear, creep, deformation, thermal aging	Load, friction, temperature
Class 3	Insulation / Coating	Electrical insulation or surface protection	Thermal aging, radiation degradation, cracking, dielectric property loss	Temperature, radiation, environment
Class 4	Hose / Elastomeric Flexible Part	Fluid transfer and flexible connectivity	Hardening, swelling, cracking, chemical degradation	Pressure, vibration, temperature, fluid chemistry

Table 2: Evaluation Criteria and Semi-Quantitative Structure

Class	Evaluation Criterion and Engineering Basis	Semi-Quantitative Scoring Structure
Seal / Gasket	Compression set. Increasing compression set reduces elastic recovery and sealing force, resulting in progressive increase of leakage potential.	0: Low degradation 1: Moderate degradation 2: High degradation
Polymer Bearing	Wear rate or wear depth. Progressive wear increases clearance, reduces load-transfer efficiency, and may lead to vibration or instability.	0: Low degradation 1: Moderate degradation 2: High degradation
Insulation / Coating	Insulation resistance reduction. Loss of dielectric integrity decreases insulation margin and increases probability of functional failure.	0: Low degradation 1: Moderate degradation 2: High degradation
Hose / Elastomer	Hardness change, swelling, or equivalent property shift. Material-property changes affect flexibility, crack resistance, and leakage susceptibility.	0: Low degradation 1: Moderate degradation 2: High degradation

To preserve continuity with the original logical structure while improving its practical applicability, the present study extends the logical variables into semi-quantitative engineering state variables. Maintenance-history condition (A), aging condition (B), and environmental severity (D) are each represented by discrete degradation scores:

$$A, B, D \in \{0, 1, 2\} \tag{1}$$

where:

- 0 : Low or acceptable degradation condition
- 1 : Moderate degradation requiring increased attention
- 2 : Significant degradation requiring engineering action

Equipment importance is treated separately as a consequence factor:

$$C \in \{1, 2, 3\} \tag{2}$$

where larger values indicate greater safety significance and operational consequence.

Based on these definitions, the overall risk value is expressed as:

$$R = C(A + B + D) \tag{3}$$

The additive term $(A + B + D)$ represents the cumulative degradation state of the component. This formulation reflects the engineering assumption that maintenance-related degradation, aging-related degradation, and environmental influences collectively contribute to overall condition deterioration. Although the interactions among these factors may be complex in practice, a cumulative representation provides a transparent and practical approximation suitable for engineering decision support.

The multiplication by the importance factor C reflects the fact that identical degradation conditions may result in different levels of risk depending on the consequence associated with component failure. For example, a degraded sealing component located in a safety-related system should receive greater attention than an equivalent component in a non-safety-related application.

To allow comparison among different components and systems, a normalized risk index is defined. Since the maximum possible risk value occurs when all degradation factors and importance are at their maximum values,

$$R_{\max} = 3(2 + 2 + 2) = 18 \tag{4}$$

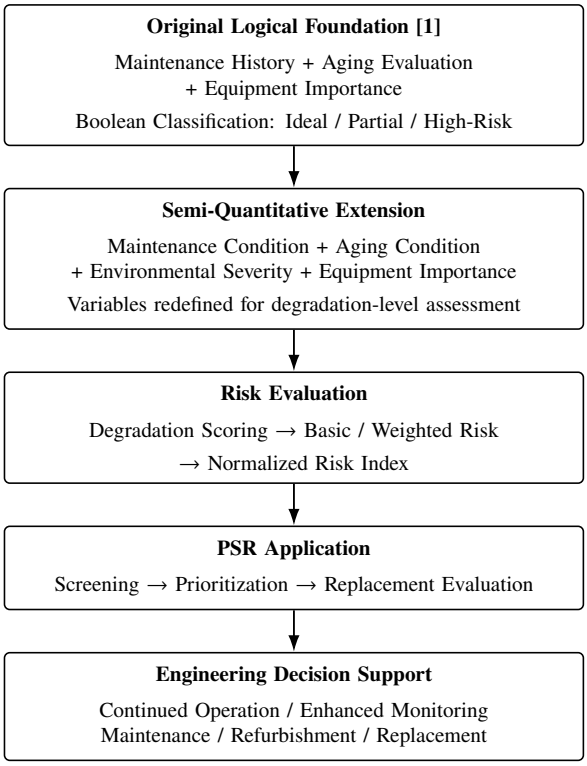


Figure 1: Flowchart of the extended aging-management framework for PSR-based decision support.

the normalized risk index becomes

$$R_N = \frac{R}{18} \tag{5}$$

$$0 \le R_N \le 1 \tag{6}$$

The normalized form provides a consistent basis for comparing degradation severity across different component categories and operating conditions.

In some applications, individual degradation factors may not contribute equally to overall condition deterioration. To accommodate such situations, a weighted formulation may also be introduced:

$$R = C(w_A A + w_B B + w_D D) \tag{7}$$

subject to

$$w_A + w_B + w_D = 1 \tag{8}$$

where w_A, w_B, and w_D represent weighting factors assigned according to the relative influence of maintenance history, aging condition, and environmental severity. This extension provides additional flexibility while preserving the basic structure of the proposed framework.

The resulting risk value is not intended to replace engineering judgment or existing qualification methodologies. Rather, it provides a structured intermediate layer between degradation assessment and PSR decision making, enabling condition information to be evaluated in a more systematic, traceable, and consistent manner.

The overall evolution from the original logical framework to semi-quantitative risk evaluation and PSR-based decision support is illustrated in Fig. 1.

Although the extended framework preserves the conceptual foundation proposed in [1], several important enhancements have been introduced to improve degradation representation, risk evaluation, and PSR applicability. The principal differences between the original logical framework and the extended methodology developed in this study are summarized in Table 3.

5. Regulatory Comparison

Existing regulatory and industry frameworks provide extensive guidance for Equipment Qualification (EQ), aging management, and Periodic Safety Review (PSR) activities. Documents issued by organizations such as the U.S. Nuclear Regulatory Commission (NRC), the American Society of Mechanical Engineers (ASME), and related industry programs establish requirements for qualification, inspection, monitoring, and aging management of safety-related equipment [4, 5, 6, 7, 8, 12].

These frameworks play an essential role in ensuring that degradation mechanisms are identified, monitored, and evaluated throughout the service life of plant equipment. Typical guidance includes the identification of aging mechanisms, qualification requirements under environmental conditions, inspection methods, monitoring intervals, and corrective-action processes. As a result, existing regulatory programs provide a strong technical basis for assessing equipment condition and maintaining plant safety.

However, although these documents define what should be evaluated and monitored, they generally do not provide a unified methodology for translating degradation information into a structured decision-support value within the PSR process. In practice, the transition from degradation assessment to engineering action is typically performed through engineering judgment, plant-specific procedures, expert review, and conservative decision-making processes.

The framework proposed in this study is intended to complement, rather than replace, existing regulatory requirements. The objective is not to introduce new qualification criteria or alternative aging-management requirements. Instead, the proposed methodology provides a structured intermediate layer that converts degradation information into a semi-quantitative risk value that can be more directly utilized during PSR decision-making activities.

The key distinction between the two approaches is therefore not the identification of degradation mechanisms themselves, but the manner in which degradation information is utilized. Existing frameworks primarily focus on condition assessment and qualification activities, whereas the proposed framework focuses on establishing a transparent connection between degradation assessment results and engineering decisions performed within PSR activities. Accordingly, the proposed methodology should be viewed as a complementary decision-support tool that enhances the traceability, consistency, and practical usability of existing aging-management information while remaining fully compatible with current regulatory and industry practices.

6. PSR Stage Linkage

One of the primary objectives of the proposed framework is to establish a practical connection between degradation

Table 3: Evolution of the Framework from Logical Classification [1] to Risk-Based Decision Support

Aspect	Original Framework [1]	Extended Framework (This Study)
Purpose	Logical condition classification	Semi-quantitative risk evaluation
Assessment Variables	Maintenance History (A) Aging Evaluation (B) Equipment Importance (C) $A, B, C \in \{0, 1\}$	Maintenance History (A) Aging Condition (B) Environmental Severity (D) Importance Factor (C) $A, B, D \in \{0, 1, 2\}$ $C \in \{1, 2, 3\}$
Evaluation Method	**Ideal** $A \wedge B \wedge C$ **Partial** $((A \vee B) \wedge C) \wedge \neg(A \wedge B)$ **High-Risk** $\neg A \wedge \neg B \wedge C$	**Degradation Score** $A + B + D$
Risk Formulation	Not provided	**Basic Model** $R = C(A + B + D)$ **Weighted Model** $R = C(w_A A + w_B B + w_D D)$
Output	Logical State Category (Ideal / Partial / High-Risk)	Risk Value (R) Normalized Risk Index (R_N)

Note: The extended framework does not directly reuse the Boolean variables defined in [1]. The original framework employed Boolean logical variables for condition classification ($A, B, C \in \{0, 1\}$), whereas the present study introduces semi-quantitative degradation scores ($A, B, D \in \{0, 1, 2\}$) together with an importance factor ($C \in \{1, 2, 3\}$) for risk evaluation and PSR decision support.

Table 4: Comparison Between Existing Regulatory and Industry Perspectives and the Proposed Framework

Aspect	Existing Regulatory / Industry Perspective	Proposed Framework
Primary Objective	Identification of degradation mechanisms, qualification requirements, inspection activities, and aging-management programs	Integration of degradation information into a structured and traceable PSR decision-support framework
Evaluation Output	Inspection results, test data, condition assessment, and degradation identification	Semi-quantitative risk value derived from maintenance history, aging condition, environmental severity, and equipment importance
Decision Method	Engineering judgment supported by procedures, technical reviews, and operational experience	Engineering judgment supported by a structured risk-based evaluation framework
PSR Integration	Indirect linkage through review processes and documentation	Direct linkage through explicit mapping of risk values to PSR decision activities
Consistency of Decision	Potential variation depending on evaluator experience and plant-specific practice	Improved consistency through common scoring structure and evaluation methodology
Role of Engineering Judgment	Primary decision-making mechanism	Retained as primary authority while supported by systematic quantitative information

assessment and engineering decision making within the Periodic Safety Review (PSR) process. While existing aging-management programs and qualification activities provide valuable information regarding equipment condition, the manner in which such information is translated into engineering actions is often dependent on plant-specific procedures and expert judgment. Consequently, the timing and priority of corrective actions may vary even when similar degradation conditions are observed.

The present study therefore proposes an explicit linkage between the calculated risk value and the major stages of the PSR process. The purpose of this linkage is not to replace engineering judgment, but rather to provide a structured basis for determining when degradation information should receive increased attention and how it can be utilized during LTO assessments.

The proposed relationship between risk evaluation and PSR activities is summarized in Table 5.

At the screening stage, the calculated risk value serves as an initial indicator for identifying components that may require additional attention. Components exhibiting relatively low risk values may remain under routine monitoring, whereas components showing increasing degradation trends can be selected for further review.

During the prioritization stage, risk values provide a consistent basis for comparing degradation conditions among

Table 5: Proposed Application of Risk Values within PSR Stages

PSR Stage	Primary Function	Role of Risk Value	Typical Engineering Action
Stage 1	Screening	Identify components exhibiting degradation trends or elevated risk levels requiring additional review	Selection of components for detailed evaluation and enhanced monitoring
Stage 2	Prioritization	Compare relative degradation severity among components and systems	Maintenance planning, inspection prioritization, and resource allocation
Stage 3	Replacement Evaluation	Assess components approaching functional limits or exhibiting significant degradation	Replacement review, refurbishment assessment, or major corrective-action planning
Stage 4	Final Decision Support	Integrate degradation information with engineering and operational considerations	Continued operation, refurbishment, replacement, or lifecycle-management decision

multiple components. This supports maintenance scheduling, inspection planning, and allocation of engineering resources toward equipment with greater potential impact on plant reliability and safety.

At the replacement-evaluation stage, the risk value becomes a supporting input for determining whether degradation has progressed to a level requiring formal replacement assessment or major corrective actions. At this point, the risk value is not used as a stand-alone decision criterion but rather as a structured indicator supporting engineering evaluation.

Finally, during the PSR decision stage, degradation information, risk evaluation results, operational experience, maintenance history, and engineering judgment are considered collectively. The calculated risk value therefore functions as a decision-support parameter that improves traceability and consistency throughout the review process.

The proposed linkage represents one of the principal distinctions between the present framework and conventional aging-management approaches. Existing programs primarily focus on identifying and evaluating degradation mechanisms, whereas the proposed methodology explicitly defines how degradation information may be utilized within PSR activities. In this manner, the framework provides a systematic bridge between condition assessment and engineering decision making while remaining compatible with existing regulatory and industry practices.

7. Example Calculation

To illustrate the application of the proposed framework, a representative Class 1 sealing component is considered. The component is assumed to be installed in active mechanical equipment operating under long-term service conditions. The observed condition is summarized as follows: maintenance records indicate repeated minor leakage events and corrective actions, aging evaluation shows a noticeable increase in compression set, environmental conditions include moderate temperature elevation, and the component is classified as safety-important equipment.

Based on these observations, the following scores are assigned:

$$A = 1, \qquad B = 2, \qquad D = 1, \qquad C = 3 \tag{9}$$

where $A = 1$ represents moderate degradation from maintenance history, $B = 2$ represents significant aging-related degradation, $D = 1$ represents moderate environmental severity, and $C = 3$ represents high equipment importance.

Using the unweighted risk formulation,

$$R = C(A + B + D) \tag{10}$$

the risk value is calculated as

$$R = 3(1 + 2 + 1) = 12 \tag{11}$$

The normalized risk index is then obtained as

$$R_N = \frac{R}{18} = \frac{12}{18} = 0.667 \tag{12}$$

This result indicates that the component is in a significant degradation region. From a PSR decision-support perspective, this condition would not necessarily imply immediate failure, but it would justify enhanced review, maintenance planning, or formal replacement evaluation depending on plant-specific criteria and engineering judgment.

For comparison, a weighted formulation may also be applied when aging degradation is considered the dominant contributor. Assuming the weighting factors are defined as

$$w_A = 0.2, \qquad w_B = 0.5, \qquad w_D = 0.3 \tag{13}$$

the weighted risk value becomes

$$R = C(w_A A + w_B B + w_D D) \tag{14}$$

$$R = 3(0.2 \times 1 + 0.5 \times 2 + 0.3 \times 1) = 4.5 \tag{15}$$

The maximum weighted risk is

$$R_{\max,w} = 3(0.2 \times 2 + 0.5 \times 2 + 0.3 \times 2) = 6 \tag{16}$$

and the normalized weighted risk index becomes

$$R_{N,w} = \frac{4.5}{6} = 0.75 \tag{17}$$

Although the numerical scales differ between the unweighted and weighted formulations, both results indicate that the component requires increased engineering attention. This example demonstrates how maintenance history, aging condition, environmental severity, and equipment importance can be integrated into a structured risk value that supports PSR-related engineering decisions.

8. Conclusions

This study has developed an extended logical approach for aging management of non-metallic components in active mechanical equipment, with explicit integration into PSR-based decision making for LTO of nuclear power plants.

The study began by recognizing the limitations of a previously proposed logical framework based on maintenance history (A), aging evaluation (B), and equipment importance (C) [1]. While the original framework provided a useful conceptual basis for condition classification, its binary structure limited its applicability to practical engineering decision support involving progressive degradation phenomena.

To address this limitation, the present study introduced a semi-quantitative extension of the logical framework. Representative categories of non-metallic components were identified according to their dominant degradation mechanisms, and physically meaningful evaluation criteria were selected for each category. Maintenance history, aging condition, and environmental severity were represented using structured degradation scores, while equipment importance was retained as a consequence factor reflecting the significance of failure.

Based on these variables, a risk formulation was proposed to integrate degradation information into a single decision-support value. The resulting framework enables degradation conditions to be evaluated in a more systematic and traceable manner while preserving continuity with the original logical approach.

The study also examined the relationship between the proposed framework and existing regulatory and industry practices. While current qualification and aging-management programs provide guidance for identifying and evaluating degradation mechanisms, the proposed methodology offers an additional layer that supports the translation of degradation assessment results into engineering decisions. In particular, explicit linkage between calculated risk values and PSR stages was established to support screening, prioritization, replacement evaluation, and LTO decisions.

The principal contribution of this work is therefore not the introduction of new degradation indicators, but the establishment of a structured bridge between degradation assessment and PSR decision making. By providing a transparent and semi-quantitative framework, the proposed approach has the potential to improve the consistency, traceability, and practical utilization of aging-management information for non-metallic components in active mechanical equipment.

Future work should focus on validation using plant operational data, refinement of scoring methodologies, and development of component-specific threshold criteria to further enhance the applicability of the proposed framework.

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