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Evaluation Study on Electrical Cable Life Extension for Nuclear Power Plant

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1. Introduction

For the safe and economically sustainable long-term operation of nuclear power plants (NPPs), maintaining the functional integrity of safety-related equipment is essential. Electrical cables, which play a critical role in reactor safety systems, must remain operable under harsh environmental conditions, and their continued performance is demonstrated through Cable Environmental Qualification (EQ). As the initial operating licenses of many NPPs approach expiration, license renewal activities for an additional 20 years of operation are being pursued, thereby requiring an evaluation of the service life extension of installed Okonite electrical cables.

This study aims to assess and justify the feasibility of a 20-year life extension for Okonite electrical cables beyond their original 40-year EQ life. A comprehensive evaluation framework was applied, combining analytical life assessment based on the Arrhenius methodology with on-site inspection data. The paper presents the overall cable life extension evaluation methodology, the application of the Arrhenius equation, life assessment results categorized by environmental conditions and electrical loading, findings from on-site inspections, and the final conclusions regarding life extension feasibility. In addition, the impact of conservative assumptions adopted during the evaluation process on the estimated remaining cable life is analyzed to enhance the robustness and reliability of the assessment results.

2. Methodology

2.1. Environmental Qualification (EQ) Background and Requirements

Electrical cables installed in nuclear power plants were originally environmentally qualified in accordance with the IEEE 323-1974 and IEEE 383-1974 standards [1, 2]. IEEE 323 establishes the qualification requirements for Class 1E electrical equipment, whereas IEEE 383 provides detailed test methods and acceptance criteria specific to cable qualification. Based on Environmental Qualification Test Reports (EQTRs) conducted by Okonite, the subject cables were qualified for a 40-year service life at a conductor temperature of 90 °C.

The initial EQ testing program included accelerated thermal aging of cable specimens using the Arrhenius methodology, followed by comprehensive performance evaluations under simulated harsh environmental conditions. These conditions encompassed radiation exposure, chemical spray, and Design Basis Accident (DBA) environments to demonstrate the continued operability of the cables under postulated accident scenarios.

For extended operation beyond the original qualified life, re-evaluation of existing EQ data represents a primary qualification approach, as described in IEEE 323-2003 [3]. In particular, the Arrhenius methodology provides a technically appropriate means to estimate remaining cable life under actual operating temperature conditions, given that insulation degradation is governed by temperature-dependent chemical reactions. In the United States, the regulatory basis for environmental qualification of safety-related electrical equipment is established in 10 CFR 50.49 [4].

2.2. The Cable Life Extension Evaluation Methodology

The extension of Qualified life that applied the following step-by-step methodology for the life extension of Okonite cables as follows:

A. Survey of Prior Research and Regulatory Trends: Reviewed life extension cases for electrical cables in U.S. nuclear power plants, relevant guidelines, and regulatory requirements to confirm the validity of the Arrhenius methodology and its acceptance by the U.S. NRC.

B. Analytical Evaluation (Application of Arrhenius Methodology):

- The difference between the assumed service life temperature (90°C) during the initial EQ test and the actual service life temperature (TSA) was applied to the Arrhenius equation to calculate the remaining useful life of the cables.

  The basic form of the Arrhenius equation is:

$$t_s = t_a e^{\frac{E_A}{k}\left(\frac{1}{T_S} - \frac{1}{T_A}\right)} \quad \text{(Eq. 1)}$$

  where t_s is the service life (years), t_a is the aging time in the oven (years), E_A is the activation energy dependent on the cable type (eV), K is the Boltzmann constant (8.617×10^{-5} eV/K), T_S is the assumed service life temperature (K), and T_A is the aging temperature in the oven (K).

- MPR defined t_u as the time used for the initial 40-year qualified life and utilized a rearranged Arrhenius equation, considering the actual service temperature T_{SA}:

$$t_u = 40 \cdot e^{\frac{E_A}{k}\left(\frac{1}{363.15} - \frac{1}{T_{SA}}\right)} \quad \text{(Eq. 2)}$$

  where 363.15K corresponds to 90°C.

Consideration of Environmental Types:

- Harsh Environments: Environments that can be affected by DBA conditions. Life usage is calculated separately for active load time (t_{active}) and inactive load time ($t_{inactive}$). The actual service temperature (TSA) includes contributions from ambient temperature (T_{Amb}), self-heating effects (ΔT_{SH}), and nearby heat sources (ΔT_{AH}).
- Mild Environments: Environments not experiencing DBA conditions, as defined in 10 CFR 50.49 [4]. Cables in mild environments do not undergo DBA conditions, so the margin obtained from DBA testing is considered as additional life.

Consideration of Load Types:

- Frequently Energized: Cables under continuous load, where self-heating effects are reflected in T_{SA}. The ratio of actual current to ampacity (I_A/I_{Amp}) was conservatively assumed to be 0.8.
- Intermittently Energized: Cables that are de-energized for significant periods, where mutual heating (ΔT_{MH}) from other co-located cables in the same tray/conduit is reflected in T_{SA} .ΔT_{MH} was conservatively assumed to be 12.5°C based on EPRI Report 1013475 [5].

C. On-site Walkdowns:

- Walkdowns were conducted in the Auxiliary and Control Buildings of the subject NPP. In addition, for benchmarking representative containment layout features, supplemental walkdowns were performed in the Containment Building of another NPP. Observations from the latter were used solely to support general assessments of cable routing configurations and proximity to heat sources and were not used as substitutes for plant-specific environmental input data..
- Visual inspections of cable tray and conduit layouts, ventilation status, and presence of nearby heat sources were performed to validate the input parameters for the analytical model.
- Notably, a localized hotspot was identified in the Main Steam Isolation Valve (MSIV) room. For cables in this area, a conservative adjusted ambient temperature of 71.4°C was applied in the evaluation.

3. Results

The analytical evaluation and on-site walkdowns results were integrated to calculate the additional qualified life (t_{AQL}) and new total qualified life (t_{New}) for each Okonite cable type.

- Minimum Additional Qualified Life: The minimum additional qualified life among all Okonite cables was found to be 34 years for Type 2 cables with Okonite-FMR insulation.
- Minimum New Total Qualified Life: For Type 2 cables, a minimum total qualified life of 74 years was secured.
- This minimum life was observed in intermittently loaded Type 2 cables exposed to harsh environments, specifically those subjected to the elevated temperature of 71.4°C in the MSIV room.
- Conservatism: The evaluation incorporated several conservative assumptions, such as using the maximum FSAR design limit temperature as the actual ambient temperature and assuming continuous maximum load operation for frequently energized cables. Despite these conservatisms, sufficient additional qualified life was confirmed for all cable types. The Arrhenius methodology tends to

overestimate aging effects at actual service temperatures lower than those tested, implying that the actual remaining life could be greater than the evaluated value.

4. Conclusion

This study successfully performed a life extension evaluation for Okonite electrical cables installed in a nuclear power plant. By integrating an analytical assessment based on the Arrhenius methodology with on-site inspection results, it was confirmed that all evaluated cable types achieved a minimum of 34 years of additional qualified life beyond their original 40-year environmental qualification. These results indicate that the plant can be safely operated for at least 60 years, including the 20-year license renewal period.

The conservative assumptions adopted in the evaluation—such as the use of the maximum FSAR design temperature as the continuous ambient temperature and the assumption of continuous operation at maximum electrical load for frequently energized cables—suggest that the actual remaining cable life is likely greater than the estimated values. For life extension considerations beyond 60 years of operation, more advanced approaches, including condition monitoring techniques and the implementation of aging management programs, may be required.

The results of this study provide technical insights and supporting data for the development of cable integrity management and life extension strategies, thereby contributing to the continued safe and reliable operation of nuclear power plants.

REFERENCES

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