

Economic optimization of EQ equipment replacement using WAT-based thermal aging life reassessment in nuclear power plants

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1. Introduction

Safety-related electrical and mechanical equipment in nuclear power plants (NPPs) must remain functional under normal operating conditions and design-basis events (DBEs), such as loss-of-coolant accidents (LOCAs) and high-energy line breaks (HELBs). Environmental qualification (EQ) programs are implemented to demonstrate that such equipment can perform required safety functions throughout a defined qualified life. In Korea, the importance of EQ has increased following the adoption of the Convention on Nuclear Safety in 1996 [1] and the institutionalization of the Periodic Safety Review (PSR) in 2001 [2], with further expansion in the context of long-term operation (LTO)[3].

Among environmental stressors affecting EQ equipment, temperature is widely recognized as the dominant factor governing long-term degradation of non-metallic materials. Polymeric components such as cable insulation, seals, and gaskets are particularly sensitive to prolonged thermal exposure, and their aging behavior is commonly described using Arrhenius-type temperature dependence[4, 5]. Although non-Arrhenius behavior and aging-compensation effects have been reported under certain accelerated aging conditions, their impact on the present analysis is limited by restricting the evaluation to service-relevant temperature ranges and by focusing on relative life comparisons rather than absolute lifetime extrapolation [4]. Under this constrained scope, the Arrhenius-based approach provides a reasonable and practical engineering approximation for assessing thermal aging.

Despite the critical role of temperature in long-term equipment degradation, many EQ evaluations continue to rely on conservative compartment temperatures specified in the Final Safety Analysis

Report (FSAR), which are typically established using bounding assumptions and limited plant-specific data [9]. As a result, EQ lifetimes may be overly conservative, leading to premature equipment replacement, increased maintenance costs, and unnecessary waste generation[10].

To address these limitations, the use of in-plant temperature monitoring data has been proposed to refine EQ lifetime evaluations. In particular, the weighted average temperature (WAT), derived from Arrhenius-based time-temperature integration, has been suggested as an effective means to represent cumulative thermal severity under time-varying conditions[11]. However, practical implementation has been limited by challenges related to data processing, uncertainty treatment, and integration with existing EQ and PSR frameworks [6, 7]

This study proposes a data-driven feedback framework that integrates in-plant temperature monitoring with Arrhenius-based WAT evaluation to reassess the thermal aging life of EQ equipment in an operating NPP. The framework compares EQ lifetimes based on FSAR, mean, and WAT temperatures and evaluates sensitivity to activation energy, with the aim of informing replacement scheduling and maintenance optimization within PSR and LTO while preserving regulatory safety margins.

2. Theoretical Background

2.1 Thermal Aging Mechanism

Thermal aging of polymeric and non-metallic materials used in EQ equipment—such as cable insulation, jackets, O-rings, and potting compounds—typically follows an Arrhenius-type temperature dependence[12]. In this framework, the rate of a thermally activated degradation process is expressed as:

$$k = A \cdot \exp\left(-\frac{E_a}{k_B T}\right) \quad (1)$$

where k is the degradation rate, A is the pre-exponential factor, E_a is the activation energy of the controlling degradation mechanism, k_B is the Boltzmann constant, and T is the absolute temperature in Kelvin. The activation energy E_a is material- and mechanism-dependent and is usually determined from accelerated aging tests.

Assuming that the end-of-life condition corresponds to a fixed level of degradation, the time to reach this condition (i.e., the qualified life) is inversely proportional to the degradation rate. The ratio of lifetimes at two different temperatures, T_1 and T_2 , can therefore be written as

$$\ln\left(\frac{t_1}{t_2}\right) = \frac{E_a}{k_B} \left(\frac{1}{T_1} - \frac{1}{T_2}\right) \quad (2)$$

where t_1 and t_2 are the lifetimes at temperatures T_1 and T_2 , respectively. This expression provides a convenient way to relate the qualified life at a conservative design temperature to that at a lower, more realistic service temperature.

In practical EQ applications, activation energies for cable and insulation materials typically fall within a range of roughly 0.6-1.2 eV, depending on material formulation, test conditions, and the specific degradation mechanism under consideration. Higher activation energies indicate stronger temperature sensitivity, implying that small changes in temperature can result in large changes in lifetime.

2.2 Weighted Average Temperature (WAT)

In actual plant environments, the temperature experienced by equipment is not constant but varies over time due to changes in operating mode, ambient conditions, and local heat sources. To apply the Arrhenius model to such a time-varying temperature history, it is convenient to replace the non-uniform temperature profile with a single equivalent constant temperature that produces the same cumulative thermal damage over the monitoring period[14]. This equivalent temperature is referred to in this study as the weighted average temperature (WAT).

For a discrete temperature history divided into n intervals, the temperature is assumed to be constant at T_i during each interval i with duration t_i .

The total monitoring time is

$$t_s = \sum_{i=1}^n t_i \quad (3)$$

The Arrhenius damage accumulated over the monitoring period can be expressed as the sum of contributions from each interval,

$$\sum_{i=1}^n t_i \exp\left(-\frac{E_a}{k_B T_i}\right) \quad (4)$$

Where E_a is the activation energy and k_B is Boltzmann Constant. The equivalent temperature T_e is defined such that a constant exposure at T_e for the same total time t_s yields the same cumulative damage, i.e.,

$$t_s \exp\left(-\frac{E_a}{k_B T_e}\right) = \sum_{i=1}^n t_i \exp\left(-\frac{E_a}{k_B T_i}\right) \quad (5)$$

Solving this expression for T_e gives the discrete WAT formula used in this work:

$$T_e = \left[-\frac{E_a}{k_B} \ln\left(\frac{1}{t_s} \sum_{i=1}^n t_i e^{-E_a/(k_B T_i)}\right) \right]^{-1} \quad (6)$$

By construction, T_e reduces to the constant temperature when all T_i are equal, and in general it places greater weight on higher temperature intervals than a simple arithmetic average. Consequently, WAT provides a more physically meaningful representation of the thermal aging severity associated with a time-varying temperature history

3. Methodology

3.1 Data-driven feedback framework

This study implements a data-driven feedback framework that links actual in-plant temperature data to EQ thermal aging life evaluation. The framework is organized as a closed-loop process, as illustrated conceptually in Figure 1, and consists of the following steps:

In-plant temperature monitoring at locations where EQ equipment is installed.

- a. Data collection and preprocessing.
- b. Calculation of WAT value over required evaluation period.
- c. Application of the Arrhenius-based formulation for selected activation energies.

d. Reassessment of Thermal aging life by comparing results obtained with FSAR, mean, and WAT.

e. Feedback of the results into the EQ and maintenance programs, including adjustment of replacement intervals and definition of management margins.

By systematically feeding back monitored temperatures into the EQ life evaluation process, the framework enables replacement schedules to be based on real operating conditions rather than solely on conservative design temperatures.

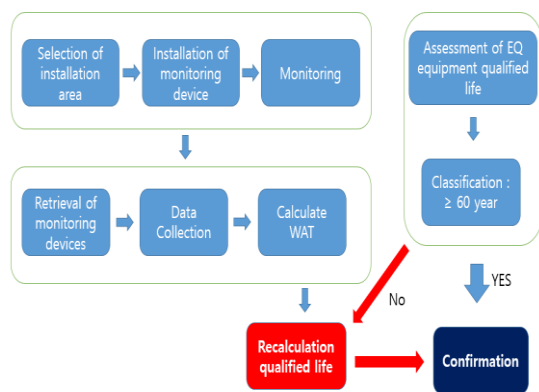


Figure 1. Diagram of Data-driven feedback framework

3.2 In-plant monitoring

Temperature loggers were installed at key locations within the containment, auxiliary, and nuclear fuel buildings of an operating Korean NPP, focusing on areas where safety-related EQ equipment is located. The installation points were selected to capture representative thermal environments, including regions near major heat sources, areas with limited ventilation, and locations at higher elevations where thermal stratification may occur.

Each monitoring device recorded temperature at regular intervals (e.g., every few minutes), producing a time-series record over the monitoring period. The instruments were chosen to have sufficient accuracy and resolution for thermal aging analysis, and were installed in such a way as to avoid interference with plant operation or safety systems.

3.3 Data collection and preprocessing

The temperature loggers were operated at 5min intervals during the monitoring period and stored all measurements in their internal memory. The devices were not connected to an online data acquisition system, and therefore the recorded data were not

transmitted or processed on a periodic basis during plant operation. Instead, the loggers were retrieved from the plant during a planned preventive maintenance outage. After removal from their installation locations, the stored time-series data were downloaded via a communication interface and transferred to a data-processing system for analysis.

Subsequent preprocessing steps included:

- Checking for missing, duplicated, or obviously erroneous data points;
- Verifying the integrity of the time stamps and correcting any clock offsets identified during retrieval;
- Removing data segments associated with logger installation and removal activities, as well as any abnormal plant conditions that were not representative of normal operation.

From the filtered data for each location, basic statistics such as minimum, maximum, and arithmetic mean temperatures over the selected monitoring interval were calculated. These statistics provide a first-level characterization of the thermal environment and serve as a basis for comparison with the Arrhenius-based WAT values derived in the following subsection.

3.4 WAT calculation

Using the filtered and preprocessed time-series data, the WAT was computed for each monitored location. The continuous temperature history was discretized into time segments, and the Arrhenius-based WAT expression described in Section 2.2 was applied.

Material-specific activation energies were selected based on literature values for typical EQ-relevant materials (e.g., cable insulation and elastomers). To account for uncertainty and variability in material properties, WAT was calculated for several representative activation energies within a realistic range. The resulting WAT values were then compared with corresponding FSAR design temperatures and arithmetic mean temperatures.

3.5 Thermal aging life reassessment

The equivalent temperature T_e obtained from WAT was used in the Arrhenius lifetime relationship to recalculate the qualified life for EQ equipment located at each monitored position. For comparison, the qualified life was also evaluated using:

- The FSAR compartment design temperature, T_{FSAR} .

- The arithmetic mean of the monitored temperature, T_{avg} .

The lifetime at each temperature was estimated relative to a reference condition, using the lifetime ratio formulation in Section 2.1. In practice, if the original EQ qualification had established a certain qualified life at the FSAR temperature, the WAT-based lifetime could be estimated as

$$L_{WAT} = L_{FSAR} \exp \left[\frac{E_a}{k_B} \left(\frac{1}{T_e} - \frac{1}{T_{FSAR}} \right) \right] \quad (7)$$

This approach allows the conservatism inherent in the FSAR-based evaluation to be quantified and provides a basis for extending or adjusting qualified life using measured temperatures.

3.6 Feedback to EQ/maintenance programs

The final step of the framework is to feed the WAT-based life evaluation back into the plant's EQ and maintenance programs. In particular, the following aspects are considered:

- Adjustment of replacement intervals: If WAT-based qualified life is significantly longer than the FSAR-based life, replacement intervals may be extended, subject to appropriate safety margins.
- Prioritization of maintenance: Locations where WAT is close to the FSAR temperature, or where thermal margins are small, can be prioritized for closer monitoring or more frequent inspection.
- Integration with PSR and LTO: The WAT-based assessment can be incorporated into PSR documentation and LTO strategies to justify changes in aging management plans.

By closing this loop, the framework enables EQ life evaluations to be continuously updated based on actual operating data, thereby improving both safety assurance and cost-effectiveness.

3.7 Introduction of Measuring Instrument

Portable electronic temperature loggers with built-in sensors were used as the primary measuring instruments in this study. The devices were selected to provide sufficient measurement range, accuracy, and resolution for Arrhenius-based thermal aging analyses in nuclear power plant environments. The main specifications are summarized in Table 1.

Table 1. Key specification of the temperature monitor

Item	Specification
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Measurement range(recorder)	Temperature(indicated): 0-70°C
Sensor capability	Temperature sensor operated range: 0-90°C
Battery capacity	Li-ion 7200mAh; expected service life(1.5-2.0 years)
Data storage	Non-volatile memory. With 5-min logging and no temperature change, retention up to - 10 years
Communication	Infrared (IrDA) between recorder and USB collector; USB between collector and PC.
Logging mode	Periodic, user-defined sampling interval (default 5 min).
Intended use	Long-term environmental monitoring for EQ: cabinet/compartments temperature trending, radiation dose accumulation, and effective-temperature (WAT) evaluation.

Each logger was equipped with an internal battery and non-volatile memory, allowing long-term autonomous operation without external power or cabling. The devices were designed to withstand typical ambient conditions in the containment, auxiliary, and nuclear fuel buildings and to avoid any adverse interaction with plant systems. The overall data acquisition and processing workflow is summarized in Figure 2.

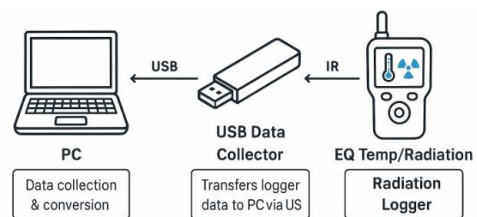


Figure 2. Data Acquisition Process

The external appearance and overall configuration of the temperature-monitoring device, including the sensor location and mounting arrangement, are illustrated in Figure 3. The logger body was installed at accessible positions for retrieval during preventive maintenance, while the sensing element was placed so as to represent the local ambient temperature experienced by the nearby EQ equipment. Before installation, all devices were calibrated according to the manufacturer's procedures, and the calibration records were maintained to support subsequent evaluation of measurement uncertainty.



Figure 3. A typical example of installing a temperature monitor.

3.7.1 Device Installation

Temperature-monitoring devices were installed near representative EQ equipment and structures within the containment, auxiliary, and nuclear fuel buildings of the plant. The monitoring points were selected to cover:

- Areas in the vicinity of major heat sources such as process piping and equipment rooms;
- Regions with potentially limited ventilation or dead-air spaces;
- Higher elevations where thermal stratification could lead to elevated ambient temperatures;
- Locations adjacent to safety-related electrical equipment subject to EQ requirements.

Each logger was mounted on existing structures or support frames so as not to interfere with plant systems or personnel access. The sensing element was positioned to represent the local ambient temperature experienced by the nearby EQ equipment, avoiding direct contact with hot surfaces or localized radiant heat unless such exposure reflected the actual service condition of the equipment.

The devices were installed prior to plant operation and remained in place for approximately 18 months. For the analysis presented in this paper, a representative 12-month interval within this period was selected to exclude transient effects associated with installation and removal activities and to focus on typical operating conditions.

3.7.2 Comparison of Thermal Life Based on Different Temperature Assumption.

To quantify the effect of using monitored temperature data in thermal aging evaluation, three representative temperature assumptions were compared: (i) the design-basis compartment temperature specified in the FSAR, (ii) the simple arithmetic average of the monitored temperature over the observation period, and (iii) the weighted average

temperature (WAT) over the observation period. For the same piece of equipment installed in the same compartment, the thermal aging life was recalculated under each assumption using the Arrhenius equation.

The FSAR-based temperature corresponds to the most conservative condition because it is defined to envelope long-term operation, local hot spots, and potential equipment heat-up during normal operation. As a result, the lifetime estimated with this temperature, L_{FSAR} , represents a lower-bound estimate of the thermal aging life.

In contrast, the arithmetic average temperature obtained from field monitoring tends to underestimate deterioration because it does not properly account for short, high-temperature excursions that disproportionately contribute to Arrhenius damage. As a result, the corresponding lifetime, L_{avg} , represents an upper-bound or optimistic estimate and, by itself, is not suitable as a justification for EQ. Owing to the exponential, non-linear dependence of reaction rate on temperature in the Arrhenius equation, the Arrhenius-equivalent temperature calculated from an actual, time-varying temperature history is inherently higher than the simple arithmetic average. Consequently, reliance on the arithmetic mean temperature systematically understates thermal degradation—an effect that becomes more pronounced as the amplitude of temperature fluctuations increases—whereas assuming continuous exposure at the maximum observed temperature produces an overly conservative, degradation-overestimating bound [11].

The WAT-based temperature, T_e , lies between these two extremes. Because WAT integrates the entire time-varying temperature history with an exponential weight, it preserves the damaging effect of high-temperature segments while still reflecting the generally lower in-plant environment compared to the FSAR assumption. The resulting lifetime, L_{WAT} , provides a realistic estimate of field aging that reduces unnecessary conservatism without losing safety margin.

For the monitored locations in the containment and auxiliary buildings considered in this study, T_e was typically about 5-12 °C lower than the corresponding FSAR compartment temperature, and in some cases approached the FSAR value when localized temperatures were relatively high. In locations where T_e was noticeably lower than the FSAR temperature, the WAT-based qualified life was extended by several times compared to L_{FSAR} , depending on the activation energy and material type. These results confirm that the use of measured, WAT-processed temperatures

can mitigate premature replacement and improve maintenance planning, particularly for equipment whose replacement requires radiation work permits or outage coordination.

To facilitate practical implementation, the comparison results can be summarized in a tabular form with the following items: equipment ID, installation area, FSAR temperature, monitored WAT, lifetime based on FSAR, lifetime based on WAT, and the life gain defined as

$$\text{Life Gain}[\%] = \left(\frac{L_{WAT}}{L_{FSAR}} - 1 \right) \times 100 \quad (8)$$

3.7.3 Sensitivity to Activation Energy and Management Margins

Because WAT and the corresponding lifetime ratio are derived from the Arrhenius equation, the results are inherently sensitive to the assumed activation energy E_a . In practice, EQ equipment contains multiple materials and components with different activation energies, and the dominant degradation mechanism may vary among locations and over time.

To examine the robustness of the proposed approach, a sensitivity analysis was performed by recalculating WAT-based lifetimes for several representative activation energies within a realistic range (e.g., 0.78–0.99 eV). For each location, the lifetime ratios L_{avg}/L_{FSAR} and L_{WAT}/L_{FSAR} were evaluated as functions of E_a . In addition, management margins were considered to account for uncertainties in activation energy, sensor accuracy, and the representativeness of the monitoring period. Rather than using the raw WAT-based lifetime directly, a conservative fraction (e.g., 70–90%) can be adopted as the effective qualified life for maintenance planning. This approach allows utilities to benefit from the realism of WAT-based assessment while preserving a transparent and defensible safety margin.

3.8 Assessment of replacement benefits

A solenoid valve is a representative component used to control liquids, gases, and pressure in nuclear power plants. According to the qualification test report, when the valve is installed in the containment building and assumed to be continuously energized, its thermally qualified life is 8 years. Eleven such valves are installed per reactor unit, and the replacement cost per valve is approximately 20,400 USD. Assuming a 60-year plant lifetime, seven replacements are required over the plant's operating life. When an annual inflation rate of 2% is applied, the cost of the final

replacement valve becomes at least twice the initial installation cost. Figure 4 illustrates the escalation of solenoid valve replacement costs over a 60-year plant lifetime, showing the cost at each 8-year replacement interval from the initial installation (year 0) to the final replacement at year 56.



Figure 4. Increase in solenoid valve replacement cost over a 60-year plant lifetime

4. Results and Discussion

4.1 Monitored Temperature Profiles

The monitored temperature profiles for representative locations in the containment, auxiliary, and nuclear fuel buildings exhibited clear seasonal and operational patterns. In general, temperatures followed ambient seasonal trends, with higher values in summer and lower values in winter, superimposed on plant-specific influences such as internal heat loads and ventilation conditions.

These observations confirm that the actual thermal environment experienced by EQ equipment can be significantly more complex than what is represented by a single conservative FSAR design temperature.

Figure 5-8 show typical time-series traces for selected monitoring points. During normal operation, each location experienced long periods of relatively moderate temperature, interrupted by occasional higher-temperature episodes associated with plant operating conditions or localized heat sources. Locations near process piping or in confined spaces tended to show higher and more variable temperatures than open or well-ventilated areas.

An important feature of these temperature profiles is the planned preventive maintenance (PPM) period from November to early January. During this time, plant operation and equipment status differ from continuous normal operation, and temperature logging is affected by activities such as logger removal, relocation, or handling. Consequently, data segments

acquired under these non-representative conditions within the PPM period were excluded from the thermal aging evaluation. The one-year interval used for WAT and lifetime calculations was therefore defined to encompass only continuous, steady-state plant operation outside the PPM window.

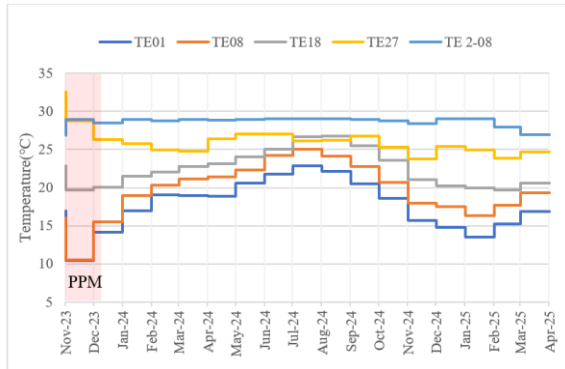


Figure 5. Recorded Compartment Temperature Trends for C-01

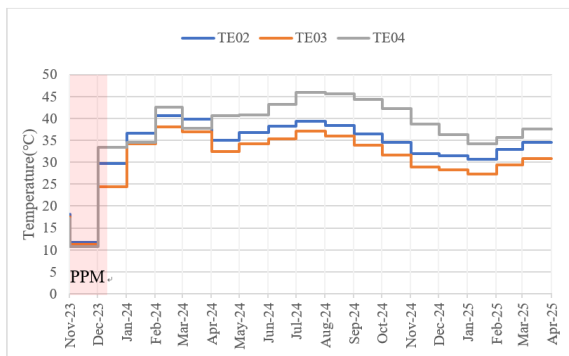


Figure 6. Recorded Compartment Temperature Trends for C-02.

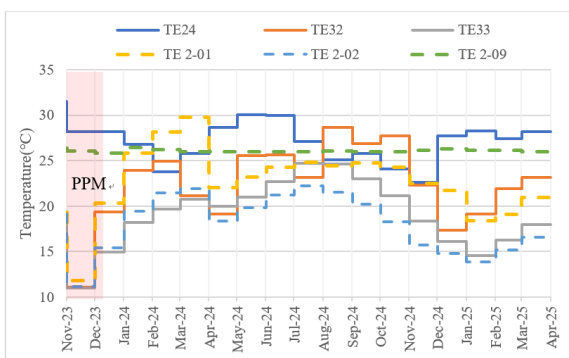


Figure 7. Recorded Compartment Temperature Trends for C-03.

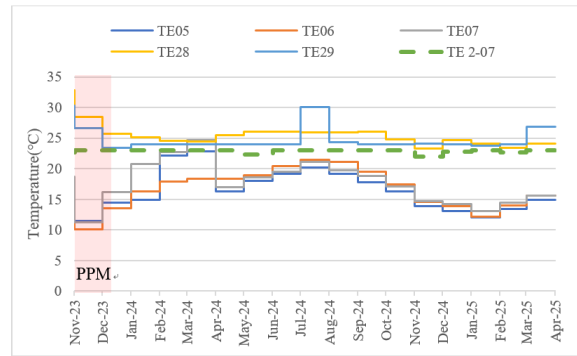


Figure 8. Recorded Compartment Temperature Trends for C-04

These observations confirm that the actual thermal environment experienced by EQ equipment is more complex and generally less severe than the single, bounding FSAR design temperature, they therefore justify the use of monitored data to refine thermal aging evaluations.

4.2 Comparison of FSAR, Mean, and WAT Temperatures

Table 2 summarizes, for each representative location, the FSAR design temperature, the arithmetic mean of the monitored temperature over the selected operating interval, and the WAT values derived from the same data for a representative activation energy. In virtually all locations, the monitored mean temperatures were significantly lower than the corresponding FSAR design temperatures, illustrating the conservatism inherent in the design assumptions.

The WAT values were generally close to, but slightly higher than, the arithmetic mean temperatures. This behavior is consistent with the Arrhenius weighting: short-duration high-temperature excursions, which contribute disproportionately to thermal damage, raise the WAT above the simple average. Nevertheless, for the locations examined in this study, the WAT remained well below the FSAR design temperature, even after peak events and seasonal variations were accounted for.

Table 2. FSAR Design Temperature and Monitor Averages by Location

ID. (Area)	Location	FSAR Design Temp. (°C)	Mean Temp. (°C)	Weighted Average Temp. (°C)
Auxiliary Building-1	Valve Room	40	24.76	25.92
Containment Building-2	Valve Gallery	48.8	17.53	19.8
Auxiliary Building-3	Penetration Room	45.5	39.25	41.53
Containment Building-4	Floor	48.8	21.87	28.73
Auxiliary Building-5	Corridor	40	22.12	23.52

This hierarchy of temperatures directly translates into corresponding differences in predicted qualified life.

4.3 Impact on Qualified Life

Table 3 presents the qualified life of representative EQ equipment at selected locations, calculated using three different temperature assumptions: FSAR design temperature T_{FSAR} , monitored mean temperature T_{avg} , and WAT T_e . For each case, the lifetime was evaluated using the Arrhenius relation, with the FSAR-based lifetime L_{FSAR} serving as the reference. The results show a strong dependence of predicted lifetime on the assumed temperature:

For the five illustrative locations analyzed in detail, FSAR-based qualified lives ranged from roughly 6 to 47 years, whereas WAT-based qualified lives ranged from about 20 to more than 300 years, depending on location and activation energy. This corresponds to lifetime extensions by factors of approximately 2-10.

These results clearly demonstrate that reliance solely on FSAR temperatures can significantly underestimate the true thermal life of EQ equipment, and that the WAT-based approach can recover a substantial portion of the conservatism while maintaining an appropriate safety margin. The results obtained from Equation 8 are shown in Table 3.

Table 3. Qualified Life Comparison: FSAR vs Mean vs WAT (years)

ID. (Area)	Activation Energy(eV)	L_{FSAR} (Years)	L_{Mean} (Years)	L_{WAT} (Years)
Auxiliary Building-1	0.88	47.13	249.9	218.85
Containment Building-2	0.94	6.3	59.65	49.14
Auxiliary Building-3	0.99	13.02	26.96	20.66

4.4 Sensitivity to Activation Energy

Because both WAT and the lifetime ratio are derived from the Arrhenius equation, the results are inherently sensitive to the assumed activation energy E_a . To investigate this effect, WAT-based lifetimes were recalculated for several representative activation energies within a realistic range for cable and insulation materials.

For a given location, the lifetime ratio between WAT-based and FSAR-based evaluations is given by

$$\frac{L_{WAT}}{L_{FSAR}} = \exp\left(\frac{E_a}{k_B}\left(\frac{1}{T_e} - \frac{1}{T_{FSAR}}\right)\right) \quad (9)$$

As E_a increases, this ratio grows rapidly for any fixed difference between T_e and T_{FSAR} . The sensitivity analysis showed that:

- For lower activation energies, L_{WAT}/L_{FSAR} increased moderately, corresponding to modest lifetime extensions.
- For higher activation energies typical of many insulation materials, the same temperature difference produced much larger increases in lifetime, emphasizing the importance of using conservative or well-justified values of E_a .

Given the variability and uncertainty in activation energy, the study recommends that utilities treat the WAT-based lifetime as an upper-bound technical estimate and then apply explicit management margins (e.g., using only 70-90% of L_{WAT}) when establishing replacement intervals. This approach allows the benefits of WAT-based realism to be realized while maintaining robust conservatism in the presence of material and modeling uncertainties.

4.5 Implications for Replacement Strategies and Maintenance

The extended qualified lives implied by WAT-based evaluation have direct implications for replacement strategies and overall maintenance planning. Under a conventional FSAR-based EQ program, equipment might be replaced on conservative intervals (e.g., every 5 years) to ensure that the qualified life is never exceeded during a 60 yr plant lifetime. If WAT-based evaluation indicates that the true qualified life is several times longer, replacement intervals can potentially be extended (e.g., to 10 or 15 years), even after applying conservative management margins.

For a 60 yr operating period:

- A 5-year replacement interval can result in up to 12 replacement cycles.
- A 15-year interval can reduce this to a maximum of 4 replacement cycles.

The impact of different replacement intervals on cumulative cost and waste generation over a 60 yr plant lifetime is illustrated in Figure 7. Reducing the number of replacement cycles in this way would decrease maintenance workload, spare parts consumption, radioactive and industrial waste. It would also reduce worker radiation exposure and the risk of human error associated with frequent component handling and outage activities.

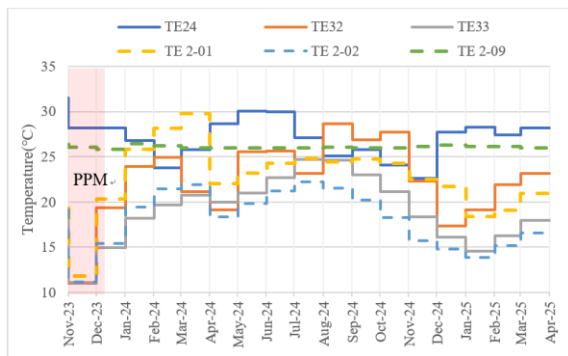


Figure 7. Recorded Compartment Temperature Trends for C-03.

These benefits are particularly relevant for equipment installed in areas where access requires radiation work permits or coordination with planned outages, such as the containment. In such cases, WAT-based thermal life reassessment can provide a strong technical basis for aligning replacement activities with existing outage schedules, thereby improving overall plant availability and resource utilization.

4.6 Uncertainties and Limitations

Several uncertainties and limitations should be considered in applying the results of this study:

- Measurement uncertainty: Temperature logger accuracy and calibration drift introduce some uncertainty into WAT calculations. However, the use of conservative activation energies and explicit management margins helps mitigate the impact of such errors.
- Representativeness of the monitoring period: The analysis is based on a one-year operating interval outside the November–January PPM period. While this interval captures typical seasonal and operational patterns, future changes in plant operation or configuration may alter the thermal environment.
- Material and mechanism variability: The selected activation energies are representative of common materials but may not precisely match every component in the EQ equipment. In practice, multiple degradation mechanisms may coexist.
- Other environmental stressors: This study focuses on thermal aging. A comprehensive aging management program must also consider radiation, humidity, and other stressors, as well as their potential synergistic effects.

In practice, repeating temperature monitoring campaigns at several-year intervals (e.g., every PSR cycle) would further reduce the uncertainty associated

with long-term changes in plant configuration and operation. Despite these limitations, the consistent trend of WAT-based life extension across multiple locations, combined with the explicit treatment of uncertainty, suggests that the proposed data-driven framework is robust and practically applicable as a tool for refining EQ life evaluations and optimizing maintenance in nuclear power plants.

5. Conclusion

1. A data-driven feedback framework was developed that links long-term in-plant temperature monitoring, Arrhenius-based WAT calculation, and qualified life evaluation, allowing EQ and maintenance programs to use effective temperatures derived from actual operating conditions instead of purely FSAR-based assumptions for normal operation.
2. Application to an operating Korean nuclear power plant showed that WATs at representative EQ equipment locations are typically 5–15 °C lower than the corresponding FSAR design temperatures. When used in the Arrhenius equation, these WATs resulted in qualified lives that were extended by up to several times compared with FSAR-based lives, while FSAR-based values can still be retained as a conservative lower bound.
3. Comparison with simple arithmetic mean temperatures confirmed that mean-based evaluations tend to underestimate thermal degradation because they do not properly account for short, high-temperature excursions. In contrast, WAT captures the disproportionate contribution of these excursions to Arrhenius damage and provides a more physically consistent representation of the thermal aging environment.
4. Sensitivity analysis over a realistic activation energy range for polymeric insulation and sealing materials indicated that the benefit of using WAT increases with activation energy. This behavior supports introducing explicit management margins between FSAR-based and WAT-based qualified lives so that utilities can optimize replacement intervals using WAT while preserving FSAR-based limits for regulatory justification.

5. An economic assessment using a representative solenoid valve(ex : Figure 9) demonstrated that WAT-based extension of the replacement interval can significantly reduce the number of replacements, cumulative replacement costs, and radioactive waste over a 60-year plant lifetime. Overall, integrating in-plant temperature monitoring and WAT-based evaluation into EQ programs offers a rational basis for optimizing replacement strategies, reducing unnecessary conservatism, and supporting long-term operation of nuclear power plants.

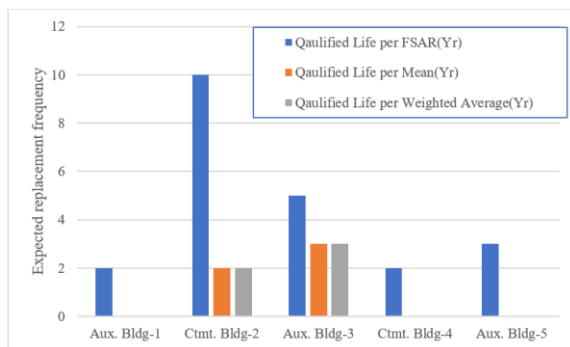


Figure 9. Impact of replacement strategy on cost/waste

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