Remaining Useful Life Prediction Method and Software for I&C Control Cards and Electronic Components Reflecting Real-Time High-Precision Temperature Variations

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1. Introduction

The electronic components and control cards (control modules) that constitute the instrumentation and control (I&C) systems of a nuclear power plant (NPP) perform safety functions, so confirming their integrity and replacing them at an appropriate time is essential for plant safety and reliability. To judge replacement timing reasonably, the Remaining Useful Life (RUL) — a quantitative measure of how much longer a component can be used — must be predicted.

Conventionally, the RUL of an electronic component is obtained by calculating its failure rate (λ) with a prediction model such as MIL-217F [1], and then sequentially deriving the Mean Time To Failure (MTTF) and the RUL. This procedure, however, is valid only under the assumption that every factor entering the model stays fixed until replacement, i.e., that the component operates at a single environmental condition with a constant failure rate. The relation $\mathrm{MTTF} = 1/\lambda$ itself requires the failure rate to remain constant up to the mean time to failure.

In an actual I&C cabinet room this fixed-factor assumption does not hold. Owing to cabinet ventilation conditions, heat generated by adjacent equipment, and seasonal or operating-state variations in room temperature, the ambient temperature to which a component is exposed is not fixed but varies in real time. In the MIL-217F model the temperature factor π_T increases as the ambient (or junction) temperature rises; therefore, when the ambient temperature varies in real time, the component failure rate λ also varies with time. Using a single-point failure rate then overestimates the RUL when an early low value is used, and is excessively conservative when the most severe value is used. A method and tool reflecting real-time temperature variation are thus required.

A prediction method for real-time varying environmental conditions was presented in a previous study [2, 3]. Considering expert opinion that electrical stress is difficult to apply to I&C control cards (an input-stage circuit normalizes the electrical load) and that the temperature step used previously was not realistic, the present work limits the dominant factor governing the component failure rate to the ambient temperature (real-time high-precision temperature variation), applies the methodology accordingly, and develops a software tool that implements it.

2. Time-Weighted Cumulative Failure-Rate Method and a Temperature-Dependent Failure-Rate Database for POSAFE-Q PLC Components

2.1 RUL prediction under temperature variation

The failure rate of an electronic component is computed from the part-type models of MIL-217F, each of which multiplies a base failure rate λ_b by correction (π) factors that reflect the operating conditions and environment:

$$\lambda_p = \lambda_b \cdot \pi_T \cdot \pi_S \cdot \pi_Q \cdot \pi_E \cdot \cdots \quad (1)$$

where π_T, π_S, π_Q, and π_E are the temperature, electrical-stress, quality, and environment factors, respectively. Assuming an exponential lifetime with a constant λ_p, the reliability and MTTF are

$$R(t) = \exp(-\lambda_p t), \quad \mathrm{MTTF} = 1 / \lambda_p \quad (2)$$

and the RUL is MTTF minus the total operating time accumulated so far. This single-value treatment, however, breaks down when the ambient temperature, and hence λ_p, varies over the operating period as illustrated in Fig. 1.

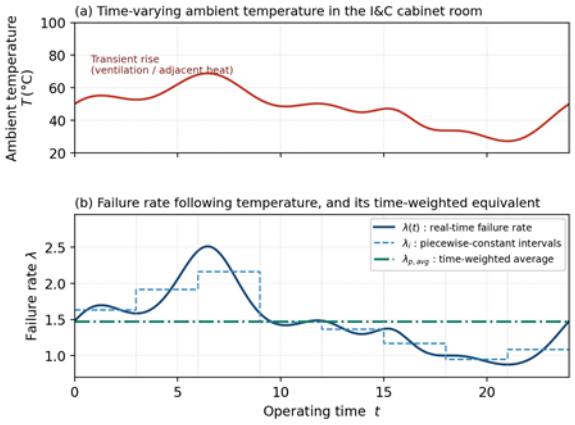


Fig. 1. Time-varying ambient temperature (a) and the resulting failure rate with its time-weighted equivalent (b).

To overcome this limitation, the time-varying failure rate over the whole operated period is averaged in time

and replaced by an equivalent constant value. For the interval from *a* to *b*, the time-averaged failure rate is

$$\lambda_{p,avg} = 1/(b-a) \cdot \int_a^b \lambda(t)\, dt \quad (3)$$

Because the continuous form of $\lambda(t)$ is hard to express in practice, the operating period is divided into a finite number of intervals over which the temperature, and thus the failure rate λ_i, is treated as constant (Fig. 1(b)). The integral then becomes a time-weighted sum:

$$\lambda_{p,avg} = (\Sigma_i \lambda_i t_i) / T , \quad T = \Sigma_i t_i \quad (4)$$

where each λ_i is obtained from the MIL-217F model at the temperature of interval *i*, and T is the total operating time. Assuming an exponential distribution with the representative rate $\lambda_{p,avg}$, the MTTF and RUL under real-time temperature variation are

$$MTTF = 1 / \lambda_{p,avg} , \quad RUL = MTTF - T \quad (5)$$

Note that RUL = MTTF − T is used as a preventive-maintenance life-consumption indicator, not the statistical mean residual life (which stays constant at MTTF for a stationary exponential). Because $\lambda_{p,avg}$ is updated at every step from the real temperature history, the process is non-stationary and MTTF itself decreases, so RUL is interpreted as the remaining allowable operating time until the predicted mean life is reached.

A control module (CM) is a set of components; conservatively assuming a series connection, its failure rate is the sum of the rates of the components that affect the CM function (those screened out by Failure Mode and Effect Analysis are excluded). Applying the time-weighting of Eq. (4) to each component first, the representative CM failure rate is

$$\lambda_{p,avg,CM} = \Sigma_i \lambda_{p,avg}(\text{component } i) \quad (6)$$

$$MTTF_{CM} = 1 / \lambda_{p,avg,CM} , \quad RUL_{CM} = MTTF_{CM} - T \quad (7)$$

Thus the same time-weighted cumulative-failure-rate concept consistently predicts the RUL of both single components and multi-component control cards.

2.2 Temperature-dependent failure-rate database

Equation (4) requires, as its core input, a database (DB) of how each component failure rate changes with temperature. Using the MIL-217F methodology (with the Reliability Workbench prediction module [4]), failure rates were computed for all components of the 12 POSAFE-Q PLC module types applied to the APR1400 Reactor Protection System (RPS): NCPU-2Q, NBUS-5Q, NSPS-2Q, NFD1-5Q, NFD1-6Q, NFD2-1Q, NI-D23Q, NQ-D23Q, NQ-A24Q, NHSC-1Q, NAD8-3Q and NADF-1Q, comprising about 900 components in total.

Ambient temperature was the controlled load. It was stepped from 20°C to 100°C in 10°C increments (9 conditions). The lower bound covers well-conditioned rooms (normal operation is about 30°C but can fall near 20°C), and the upper bound bounds the harshest case while enveloping the typical ≤ 85°C component operating range. Depending on part type, temperature enters through the junction temperature (microcircuits, transistors, diodes, optoelectronics), the ambient temperature (resistors, capacitors), or a hot-spot temperature (connectors, transformers, coils); for all of them the temperature factor, and hence λ, grows with temperature. The resulting DB construction is summarized in Fig. 2.

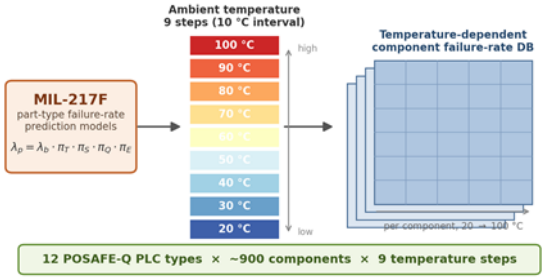


Fig. 2. Construction of the temperature-dependent component failure-rate DB (12 POSAFE-Q PLC types, ~900 components × 9 temperature steps).

3. A High-Precision, Real-Time Software Tool Reflecting 0.1°C Temperature Variation with Color-Coded RUL Visualization

3.1 Software functions

Based on the method of Section 2 and the temperature-dependent failure-rate DB, a software tool was developed with three functions. (i) *Component-information management* imports the DB, lets the user search and filter parts by card name, ID, part number, description and stress type, and plots each part's failure rate against temperature. To reflect high-precision temperature variation, the 10°C-interval data are extended to 0.1°C intervals by cubic-spline interpolation; both the raw and the interpolated curves are displayed for verification.

(ii) *Cabinet-room temperature management* provides the time-varying temperature input. A real-time measurement function (temperature signals logged from sensors installed in the I&C cabinet room) is implemented; because cabinet access is restricted during development, a random temperature-profile generator substitutes for it. The generator produces a profile over a user-defined temperature range and period at a 1-h interval with a 0.1°C minimum step, and can inject transient rises over selected spans to emulate ventilation faults or adjacent-equipment heat. Profiles spanning up to about 20 years can be accumulated, viewed in Hour/Day units, and exported to a spreadsheet.

(iii) *Component/control-card RUL prediction* is the main function. Driven by the temperature profile and the interpolated DB, it evaluates, at each step, the interval failure rate, accumulates the time-weighted

cumulative failure rate of Eq. (4), and derives the MTTF and RUL from Eqs. (5)–(7); START/STOP and reset controls manage the running calculation while the current total operating time and temperature are displayed.

3.2 RUL prediction results

The predicted RUL is compared with user-defined thresholds and classified into three states — Normal, Monitoring and Replacement — color-coded green, yellow and red. The default thresholds are 1200 / 600 days for components and 600 / 300 days for control cards, and are adjustable through a settings dialog. Components are grouped into the three state lists by their current RUL; because a control card is treated as a series connection of its components, a card is moved to the Replacement list as soon as any one of its constituent components reaches the Replacement state, which lets the user trace a card-level alarm down to the responsible part.

Results are shown as two synchronized trends — ambient temperature and RUL — selectable in Hour/Day/Month/Year units. A *Live* mode displays the most recent N points for real-time monitoring, while a *Show All* mode displays the whole operating history; the RUL value at the latest point is annotated on the graph. Figure 3 shows a representative output for a component: as the ambient temperature rises and fluctuates over the operating period (top), the predicted RUL decreases and its color shifts progressively from green through yellow to red (bottom). For the illustrated part (NSPS-2Q-007), the predicted RUL is about 2014 days at an operating time of 108 days. Because the prediction is driven by the time-weighted average of the whole temperature history rather than a single-point value, the resulting RUL is neither the optimistic value obtained from an early low-temperature condition nor the over-conservative value obtained from the harshest condition, but a balanced estimate that reflects the actual load the part has experienced. The control-card prediction reuses the same procedure, summing the time-weighted average failure rates of the contributing components (Eq. (6)) before deriving the card MTTF and RUL.

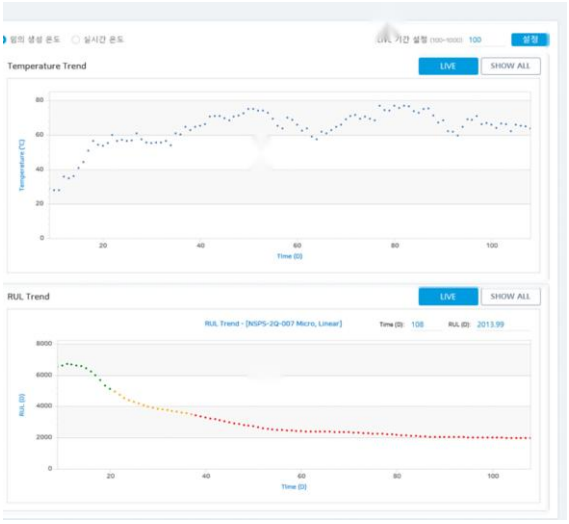


Fig. 3. Software output: ambient-temperature trend (top) and color-coded RUL trend (bottom) under real-time temperature variation.

4. Conclusions

A method that overcomes the fixed-condition limitation of the conventional MIL-217F-based RUL procedure was proposed by time-weighting the temperature-driven, time-varying failure rate into a single representative (cumulative) value, and by extending it to control cards through a series-connection assumption with FMEA screening. A temperature-dependent failure-rate DB was built for the 12 POSAFE-Q PLC types (~900 components) of the APR1400 RPS over 20–100°C, and a software tool was developed that interpolates the DB to 0.1°C, generates temperature profiles, and visualizes color-coded real-time RUL. The method and tool can support reasonable replacement-timing decisions and preventive-maintenance planning; linking measured data from temperature sensors in actual cabinet rooms would extend the tool into an in-situ RUL monitoring system.

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REFERENCES

[1] MIL-HDBK-217F, Military Handbook, Reliability Prediction of Electronic Equipment, Notice 2, 1995.
[2] Korea Atomic Energy Research Institute, Development of a Tool for Predicting the RUL of Electronic Components/Control Cards of I&C Platforms under Real-Time Varying Environmental Conditions, KAERI/TR-11044, 2025.
[3] I. Jang, C. H. Kim, Development of a software to predict the remaining useful life of electronic components of I&C system under dynamic temperature and electrical stress

conditions, Transactions of the Korean Nuclear Society Autumn Meeting, October 30-31, 2025, Changwon, Korea.
[4] Isograph Ltd., Reliability Workbench – Reliability Prediction Module, www.isograph.com.