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Original Article

Prediction of Remaining Useful Life (RUL) of Electronic Components in the POSAFE-Q PLC Platform under NPP Dynamic Stress Conditions

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ABSTRACT

In the Korean domestic nuclear industry, to analyze the reliability of instrumentation and control (I&C) systems, the failure rates of the electronic components constituting the I&C systems are predicted based on the MIL-HDBK-217F standard titled 'Reliability Prediction of Electronic Equipment'. Based on these predicted failure rates, the mean time to failure of the I&C systems is calculated to determine the replacement period of the I&C systems. However, this conventional approach to the prediction of electronic component failure rates assumes that factors affecting the failure rates such as ambient temperature and operating voltage are static constants. In this regard, the objective of this study is to propose a prediction method for the remaining useful life (RUL) of electronic components considering mean time to failure calculations reflecting dynamic environments, such as changes in ambient temperature and operating voltage. Results of this study show that the RUL of electronic components can be estimated depending on time-varying temperature and electrical stress, implying that the RUL of electronic components can be predicted under dynamic stress conditions.

1. Introduction

Instrumentation and control (I&C) systems in nuclear power plants (NPPs) serve as their central nervous system, playing an important role in that they measure thousands of process signals from the physical world (instrumentation function), monitor the NPP status (monitoring function), operate the NPP to limit the deviation of variables from set points (control function), and shut down the NPP in case of an emergency (protection function), thus guaranteeing safe operation [1,2]. Due to the significance of NPP I&C systems in terms of safety, the reliability of I&C systems is required to be analyzed and the results must be approved by regulatory bodies before the systems can operate in NPPs. In this light, in Korean domestic NPPs, the MIL-HDBK-217F standard ('Reliability Prediction of Electronic Equipment') Notice 2 – part stress method [3] is widely used for the reliability prediction of digital I&C systems among various kinds of methods such as Telcordia SR-332 [4], NSWC [5], IEC TR 62380 [6], FIDES [7], and others, since most of the electronic components in NPP I&C systems should comply with military standards [8].

In order to predict the reliability of I&C systems, the failure rates of the electronic components constituting the control modules (CMs) of the I&C systems should be calculated. After that, under the conservative assumption that the electronic components in CMs are connected in series, the failure rate (λ) of a CM can be simply predicted by a summation of the failure rates of all electronic components making up the CM as follows.

$$\lambda_{CM} = \sum_{n=i} \lambda_i \ (i = i_{th} \ \textit{electronic components constituting the CM}) \tag{1}$$

Using the exponential distribution with these predicted failure rates of the electronic components and CM, the reliability function and the mean time to failure (MTTF) can be respectively expressed as follows [9].

$$R(t) = e^{-\lambda t}, MTTF = \frac{1}{\lambda} \tag{2}$$

As can be noted in Eqs. (1) and (2), the starting point to analyze the reliability and MTTF of a specific system is to predict the failure rates of the electronic components constituting the system. As mentioned earlier, the most recognized failure rate prediction method in Korean domestic NPPs is MIL-HDBK-217F (hereafter, MIL-217F), and in current practice, all I&C systems are replaced based on the MTTF of the CMs predicted using MIL-217F.

In MIL-217F, in order to predict the electronic component failure rates, the design specifications or *physical parameters* of the electronic

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components such as manufacturing technology, package type, number of pins, rated voltage, thermal resistance, and so on should be analyzed. These physical parameters are determined in the design stage and are fixed features of the electronic components. Other parameters that should be analyzed are *application parameters*, which are determined according to the environment such as installed location, number of active pins, ambient temperature, operating voltage, and so on [10]. Unlike physical parameters, some application parameters such as ambient temperature and operating voltage can be dynamically changed according to external conditions. However, reliability analysts normally predict the failure rates and/or MTTF of electronic components under the assumption that the ambient temperature and electrical load are static constants until the predetermined replacement period of the system.

This assumption creates a critical limitation that if the ambient temperature or electrical load that electronic components are exposed to dynamically varies in the real world, the predicted failure rate and MTTF of the electronic components also change, consequently resulting in a shortened replacement period of the I&C systems. In the worst case, the I&C systems cannot be replaced in a timely manner due to the reduction in replacement period, resulting in an unwanted reactor trip. It is thus apparent that the above assumption has the potential to degrade the credibility of MTTF predictions.

In this light, the objective of this study is to propose a method to predict the remaining useful life (RUL), considering dynamically changed environments, of the electronic components in the POSAFE-Q programmable logic controller (PLC) platform, which is the platform that the safety I&C systems in the Advanced Power Reactor 1400 (APR1400) are built on. To this end, the RUL of the electronic components included in the 12 types of POSAFE-Q PLCs is predicted under dynamic stress conditions, and several electronic components that have a large contribution to the failure rate of the POSAFE-Q processor module are intensively investigated in this study. Results show that the RUL of electronic components can be estimated depending on time-varying temperature and electrical stress, implying that the RUL of electronic components can be predicted according to dynamic stress conditions.

The remainder of this paper is organized as follows. In Section 2, the background of the current approach for the prediction of the failure rates and MTTF of electronic components is explained. In Section 3, the dominant electronic components affecting the failure of the POSAFE-Q processor module are analyzed. In addition, electronic component failure rates according to combinations of predetermined stress factors are calculated to secure an electronic component failure rate database of the POSAFE-Q PLC platform. In Section 4, a method is proposed to predict the RUL of electronic components based on the failure rate database, and a case study is conducted to predict the RUL of electronic components using the proposed method. Finally, discussions are given in Section 5 including limitations and further work, and the conclusion of this study is provided in Section 6.

2. Background

2.1. Functions of the POSAFE-Q PLCs in the APR1400

The POSAFE-Q PLC platform is a digital safety I&C platform of Shin Hanul NPP units 1 and 2, both APR1400 type, in the Republic of Korea. The safety I&C systems in the APR1400, such as the reactor protection system (RPS), engineered safety features component control system (ESF-CCS), and qualified indication and alarm system–post accident monitoring instrumentation (QIAS-P), were developed based on appropriate combinations of POSAFE-Q PLCs [11–13]. In the case of the APR1400 RPS, 12 different POSAFE-Q PLCs are utilized to implement the RPS functions. The types and functions of the POSAFE-Q PLCs applied to the APR1400 RPS are briefly described as follows [14,15].

- NCPU-2Q (main processor module): The processor module, as a core part of POSAFE-Q, not only executes the programs downloaded from the POSAFE-Q engineering tool but also functions for system configuration management and the monitoring and control of other modules.
- NBUS-5Q (backplane module): The backplane module provides an interface for the sharing of data, addresses, and control lines between the unit modules. In addition, the backplane module transmits the output voltage of the power supply module to all controllers connected to the backplane module.
- NSPS-2Q (power supply module): The power supply module serves to supply power to each module. It converts the input voltage into 5 V DC, which is the operating power of each POSAFE-Q module, and supplies power to the modules connected to the backplane module.
- NFD1-5Q, NFD1-6Q (safety data link modules): The two safety data link modules are communication modules for transmitting safety-critical signals using unidirectional peer-to-peer communication methods., The modules are divided into NFD1-5Q and NFD1-6Q according to the signal type, i.e., optical and electrical.
- NFD2-1Q (safety data network module): The safety data network module is also a communication module that provides bidirectional N-to-N safety-critical data exchange.
- NI-D23Q (digital input module): The digital input module converts ON/OFF contacts of field devices into digital data to transmit them to the processor module.
- NQ-D23Q (digital output module): The digital output module transmits the execution result of application programs in the processor module as a discrete signal value (ON, OFF) to the field devices.
- NQ-A24Q (relay output module): The relay output module receives digital values from the processor module and outputs discrete signals (ON, OFF) to the field devices using relays.
- NHSC-1Q (pulse counter module): The pulse counter module converts frequency, voltage, time, etc. into electrical pulse signals and counts these signals.
- NAD8-3Q, NADF-1Q (analog input modules): The two analog input modules convert analog signals such as pressure, flow rate, and temperature from field devices into digital data to enable their use in the processor module. The modules are divided into NAD8-3Q and NADF-1Q according to the number of contacts, i.e., 8 and 16 contacts.

The number of electronic components in these 12 modules is about 900 based on the bill of material (BOM) from the equipment manufacturer, and accordingly the detailed types of components are very diverse and numerous. However, if the electronic components commonly used in the POSAFE-Q PLC platform are classified at a higher level according to MIL-217F, they can be broadly classified by type: microcircuits, discrete semiconductors, resistors, capacitors, inductive devices, switches, connectors, quartz crystals, and so on.

Depending on the broad type of component, the failure rate prediction model to be used is different. But even for the same broad type of electronic component, if the detailed (sub) component type is different, then the failure rate prediction model is also different. In Section 2.2, failure rate and MTTF prediction methods for representative electronic components in MIL-217F are briefly described.

2.2. Current approach for prediction of failure rate/MTTF of POSAFE-Q PLC electronic components

As introduced in Section 1, in order to prove the reliability of I&C systems, the MIL-217F standard is utilized since most of the electronic components in the I&C systems of NPPs must comply with military standards. In MIL-217F, various failure rate prediction models generally including a basic failure rate (λ_b), the factors affecting the failure rate (called π factors), etc., are provided according to the detailed type of electronic component. Table 1 shows the representative failure rate prediction models in MIL-217F (note that there are many other failure rate prediction models according to the detailed category of electronic components).

For example, the failure rate prediction model of microprocessor is provided as Eq. (3). Here, the failure rate unit is failure per million hours, denoted as Failure/10^6 h, which is commonly used in MIL-217F.

$$\lambda_p = (C_1\pi_T + C_2\pi_E)\pi_Q\pi_L \ \left(\text{unit : Failure} \big/ 10^6 \text{ hours}\right) \tag{3}$$

$$where, \lambda_p = Predicted\ failure\ rate$$

$$C_1 = Die\ complexity\ failure\ rate$$

$$C_2 = Package\ failure\ rate$$

$$\pi_T = Temperature\ factor$$

$$\pi_E = Environment\ factor$$

$$\pi_Q = Quality\ factor$$

$$\pi_L = Learning\ factor$$

In order to predict the failure rate of a specific microprocessor, the six factors in Eq. (3), namely C_1, C_2, π_T, π_E, π_Q, and π_L, should be determined. The die complexity failure rate C_1 can be determined based on Table 2 depending on the number of bits and the technology, such as bipolar or MOS.

The package failure rate C_2 is determined depending on the package type and the number of functional pins of the microprocessor based on Table 3. If the number of functional pins and the package type is 12 and hermetic surface mount technology (SMT), respectively, the package failure rate is 0.0041 as shown in Table 3. These factors, C_1 and C_2, are physical parameters (see Section 1) determined and fixed at the chip

Table 1
Representative failure rate models by MIL-217F section.

Section No.	Electronic component type	Representative failure rate model
Section 5	*Microcircuits*	$\lambda_p = (C_1\pi_T + C_2\pi_E)\pi_Q\pi_L$
Section 6	*Discrete Semiconductors*	$\lambda_p = \lambda_b\pi_T\pi_A\pi_R\pi_S\pi_Q\pi_E$
Section 7	Tubes	$\lambda_p = \lambda_b\pi_L\pi_E$
Section 8	Lasers	$\lambda_p = \lambda_{MEDIA}\pi_E + \lambda_{COUPLING}\pi_E$
Section 9	*Resistors*	$\lambda_p = \lambda_b\pi_R\pi_Q\pi_E$
Section 10	*Capacitors*	$\lambda_p = \lambda_b\pi_{CV}\pi_Q\pi_E$
Section 11	*Inductive devices*	$\lambda_p = \lambda_b\pi_Q\pi_E$
Section 12	Rotating devices	$\lambda_p = \lambda_b\pi_S\pi_N\pi_E$
Section 13	Relays	$\lambda_p = \lambda_b\pi_L\pi_C\pi_{CYC}\pi_F\pi_Q\pi_E$
Section 14	*Switches*	$\lambda_p = \lambda_b\pi_{CYC}\pi_L\pi_C\pi_E$
Section 15	*Connectors*	$\lambda_p = \lambda_b\pi_K\pi_P\pi_E$
Section 16	Interconnection assemblies	$\lambda_p = \lambda_b[N_1\pi_C + N_2(\pi_C + 13)]\pi_Q\pi_E$
Section 17	Connections	$\lambda_P = \lambda_b\pi_Q\pi_E$
Section 18	Meters	$\lambda_p = \lambda_b\pi_A\pi_F\pi_Q\pi_E$
Section 19	*Quartz crystals*	$\lambda_p = \lambda_b\pi_Q\pi_E$
Section 20	Lamps	$\lambda_p = \lambda_b\pi_U\pi_A\pi_E$
Section 21	Electronic filters	$\lambda_p = \lambda_b\pi_Q\pi_E$
Section 22	Fuses	$\lambda_p = \lambda_b\pi_E$

Note: Electronic components written in italics indicate the main components included in POSAFE-Q PLCs.
λ_p: predicted failure rate, C_1: die complexity failure rate, π_T: temperature factor, C_2: package failure rate, π_E: environmental factor, π_Q: quality factor, π_L: learning factor/load stress factor, λ_b: base failure rate, π_A: application factor, π_R: power rating factor/resistance factor, π_S: voltage stress factor/size factor, λ_{MEDIA}: lasing media failure rate, $\lambda_{COUPLING}$: coupling failure rate, π_{CV}: capacitance factor, π_C: contact form factor/complexity factor, π_{CYC}: cycling factor, π_F: application and construction factor/function factor, π_K: mating/unmating factor, π_P: active pin factor, N_1, N_2: number of plated through-holes (PTH) factor, π_U: utilization factor.

Table 2
Die complexity failure rate for microprocessor (C_1); adopted from Ref. [3].

No. of bits	Bipolar	MOS[1]
	C1	C1
Up to 8	.060	.14
Up to 16	.12	.26
Up to 32	.24	.56

[1] Metal oxide semiconductor.

Table 3
Package failure rate for all microcircuits (C_2); modified from Ref. [3].

Number of functional pins	Package type				
	Hermetic: DIPs[1] w/ solder or weld seal, PGA[2], SMT[3]	DIPs with glass seal	Flatpacks with axial leads on 50 mil centers	Cans	Nonhermetic: DIPs, PGA, SMT
3	.00092	.00047	.00022	.00027	.0012
4	.0013	.00073	.00037	.00049	.0016
6	.0019	.0013	.00078	.0011	.0025
8	.0026	.0021	.0013	.0020	.0034
10	.0034	.0029	.0020	.0031	.0043
12	.0041	.0038	.0028	.0044	.0053
14	.0048	.0048	.0037	.0060	.0062
16	.0056	.0059	.0047	.0079	.0072
18	.0064	.0071	.0058		.0082
22	.0079	.0096	.0083		.010
24	.0087	.011	.0098		.011
28	.010	.014			.013
36	.013	.020			.017
40	.015	.024			.019
64	.025	.048			.032
80	.032				.041
128	.053				.068
180	.076				.098
224	.097				.12

[1] DIP: Dual in-line package.
[2] PGA: Pin grid array.
[3] SMT: Surface mount technology.

Table 4
Temperature factor for all microcircuits ($\boldsymbol{\pi_T}$); modified from Ref. [3].

Junction temperature (°C)	Manufacturing technology				
	TTL[1]	BiCMOS[2]	IIL[3]	Digital MOS[4]	Memories
25	0.10	0.10	0.10	0.10	0.10
30	0.13	0.14	0.15	0.13	0.15
35	0.17	0.19	0.21	0.16	0.23
40	0.21	0.25	0.31	0.19	0.34
45	0.27	0.34	0.43	0.24	0.49
50	0.33	0.45	0.61	0.29	0.71
55	0.42	0.59	0.85	0.35	1.0
60	0.51	0.77	1.2	0.42	1.4
65	0.63	1.0	1.6	0.50	2.0
70	0.77	1.3	2.1	0.60	2.8
75	0.94	1.6	2.9	0.71	3.8
80	1.1	2.1	3.8	0.84	5.2
85	1.4	2.6	5.0	0.96	7.0
90	1.6	3.3	6.6	1.1	9.3
95	1.9	4.1	8.5	1.3	12
100	2.3	5.0	11	1.5	16
105	2.7	6.2	14	1.8	21
110	3.2	7.5	18	2.1	28

[1] TTL: Transistor–transistor logic.
[2] BiCMOS: Bipolar complementary metal oxide semiconductor.
[3] IIL: Integrated injection logic.
[4] Digital MOS: Digital metal oxide semiconductor.

design stage.

π_T, temperature factor, is determined based on Table 4 depending on the junction temperature and manufacturing technology of microprocessor; it should be noted that the temperature factor, along with the electrical factor, is a critical factor in this paper and is explained in detail in Section 3.1. If the junction temperature is 30 °C and the manufacturing technology is BiCMOS, π_T is determined as 0.14. However, since it is difficult to measure the junction temperature directly during NPP operation, the ambient temperature, which is relatively easy to measure, is converted into the junction temperature by the combination of ambient temperature, power dissipation, case-to-ambient thermal resistance, and junction-to-case thermal resistance. Thus the π_T factor includes both *physical parameters* (manufacturing technology, power dissipation, case-to-ambient and junction-to-case thermal resistance) and an *application parameter* (ambient temperature) that can be dynamically changed during NPP operation.

The environment factor π_E is determined based on Table 5 depending on the major area of equipment use. This factor in the I&C equipment room of NPPs is normally assumed as G_B in Table 5 since the example area of G_B explained in MIL-217F includes non-mobile in-ground scientific computer complexes, which is a similar environment as the I&C equipment room of NPPs. While the environment factor is originally one of the application parameters that vary depending on the area of equipment use, here it is regarded as a physical parameter because the area where electronic components are used in NPPs does not change.

Similar with the π factor quantifications explained above, the quality factor (π_Q) and learning factor (π_L) can be determined as physical parameters.

In summary, the failure rate of a microprocessor is predicted by quantifying the six factors of C_1, C_2, π_T, π_E, π_Q, and π_L, and this is accomplished by analyzing the physical parameters of microprocessor such as the technology, number of bits, package type, number of years in production, case-to-ambient thermal resistance, junction-to-case thermal resistance, power dissipation, and quality, and also analyzing the application parameters such as the ambient temperature and environment. It should be noted that the type and number of physical and application parameters are very diverse and differ depending on the detailed type of electronic component.

As such, the current approach briefly explained above for predicting the failure rates of electronic components has a critical limitation that representative *application parameters* such as ambient temperature and operating voltage are assumed to be statically fixed like physical parameters, which is unrealistic. To overcome this limitation, in Sections 3 and 4 a dynamic failure rate/MTTF/RUL prediction method for electronic components is proposed and a component failure rate database according to combinations of predetermined stress factors is presented.

3. Securing an electronic component failure rate database of the POSAFE-PLC platform

The purpose of compiling an electronic component failure rate database reflecting various stress conditions in Section 3 is to utilize the database to predict the RUL of electronic components of POSAFE-Q PLCs under dynamic stress conditions of NPPs in Section 4.

Table 5
Environment factor for all microcircuits (**π_E**); modified from Ref. [3].

Environment	π_E
Ground, Benign (G_B)	0.50
Ground, Fixed (G_F)	2.0
Ground, Mobile (G_M)	4.0
Naval, Sheltered (N_S)	4.0
Naval, Unsheltered (N_U)	6.0
Airborne, Inhabited Cargo (A_{IC})	4.0
Airborne, Inhabited Fighter (A_{IF})	5.0
Airborne, Rotary Winged (A_{RW})	8.0
Missile, Flight (M_F)	5.0
Missile, Launch (M_L)	12

In order to secure the electronic component failure rate database, both the physical parameters and application parameters, which are the input parameters to the failure rate prediction model, should be defined first based on the corresponding design specification of the electronic component. Note that physical parameters are not stress factors that change depending on the NPP environment, but are default input factors used to predict the failure rate of the electronic component. With consideration of various types of electronic components in MIL-217F, these parameters normally include the manufacturing technology, number of bits, memory size, package type, connection type, number of years in production, number of pins, case-to-ambient thermal resistance, junction-to-case thermal resistance, power dissipation, rated voltage, operating voltage, quality, ambient temperature, environment, and so on. After that, depending on the detailed type of electronic component, the application parameters that can dynamically change during NPP operation are determined in order to assign them as stress factors affecting the electronic component failure rates, as discussed in Section 3.1. Finally, based on the combinations of predetermined stress factors (stress conditions), the electronic component failure rate database is compiled by predicting the electronic component failure rates and changing the levels of stress conditions, as covered in Section 3.3.

3.1. Determination of stress factors affecting electronic component failure rates

First of all, in order to secure an electronic component failure rate database of the POSAFE-Q PLC platform, the stress factors that affect the failure rates of each electronic component in the POSAFE-Q PLCs should be analyzed. In this light, based on the failure rate prediction models and π factors in MIL-217F for each PLC electronic component, the application parameters that can dynamically change during NPP operation are determined as stress factors through a similar process introduced in Section 2.2.

Table 6 shows the analysis results of the stress factor determination for each electronic component in the POSAFE-Q PLCs. In the case of diodes (low frequency), for example, the failure rate prediction model is provided as follows.

$$\lambda_p = \lambda_b \pi_T \pi_S \pi_C \pi_Q \pi_E \ \left(\text{unit : Failure} \,/\, 10^6 \text{ hours}\right) \tag{4}$$

$where, \lambda_p = Predicted\ failure\ rate$

$\lambda_b = Base\ failure\ rate$

$\pi_T = Temperature\ factor$

$\pi_S = Electrical\ stress\ factor$

$\pi_C = Contact\ construction\ factor$

$\pi_Q = Quality\ factor$

$\pi_E = Environment\ factor$

As shown in Eq. (4), λ_b, π_C, and π_Q as physical parameters are determined depending on the diode type, contact method, and design quality specification, respectively. Otherwise, the stress factors that can dynamically change during NPP operation are analyzed as the junction temperature from π_T and the operating voltage stress ratio (ratio of operating voltage to rated voltage) from π_S. In detail, ambient temperature is possibly transformed into the junction temperature and the rated voltage of the diode is determined in the design stage, and therefore ambient temperature and operating voltage are selected as stress factors to compile the failure rate database of diodes (low

Table 6
Stress factors affecting electronic component failure rates of POSAFE-Q PLCs.

	Electronic component (Related section in MIL-217F)	Stress factor(s)	Brief description of stress factor(s)
1	Microcircuits (5.0)	☐ Junction temperature	☐ Affected by junction temperature (junction temperature can be calculated using ambient temperature and thermal resistance of electronic component)
2	Transistor, LF Bipolar (6.3)	☐ Junction temperature ☐ Voltage	☐ Affected by junction temperature ☐ Affected by the ratio of operating voltage (voltage, collector to emitter) to rated voltage (voltage, collector to emitter, base open)
3	Transistor, LF Si FET (6.4)	☐ Junction temperature	☐ Affected by junction temperature
4	Diode, Low Frequency (6.1)	☐ Junction temperature ☐ Voltage	☐ Affected by junction temperature ☐ Affected by the ratio of operating diode reverse voltage to rated diode reverse voltage (if the application of this diode is as a transient suppressor, voltage regulator, voltage reference, or current regulator, then the voltage stress ratio does not affect the component failure rate)
5	Diode, High Frequency (6.2)	☐ Junction temperature	☐ Affected by junction temperature
6	Resistor (9)	☐ Junction temperature ☐ Power	☐ Affected by junction temperature ☐ Affected by the ratio of operating power to rated power
7	Capacitor (10)	☐ Junction temperature ☐ Voltage	☐ Affected by junction temperature ☐ Affected by the ratio of operating voltage to rated voltage
8	Switch (14)	☐ Current	☐ Affected by the ratio of operating load current to rated resistive load current
9	Connector, General (15.1)	☐ Ambient temperature	☐ Affected by ambient temperature
10	Quartz Crystal (19)	☐ N/A[1]	☐ N/A[1]
11	Optoelectronics, (6.11)	☐ Junction temperature	☐ Affected by junction temperature
12	Transformer (11.1)	☐ Ambient temperature	☐ Affected by ambient temperature
13	Coils (11.2)	☐ Ambient temperature	☐ Affected by ambient temperature
14	Fuse (22)	☐ N/A[1]	☐ N/A[1]

1) N/A does not mean that the failure rates of these electronic components are always the same. The failure rates of these electronic components can vary by the characteristics of the parts (but not by external stress factors).

frequency).

Based on the analysis results in Table 6, the stress factors can be largely divided into two categories: temperature stress and electrical stress. In addition, it can be seen that the failure rates of most electronic components are affected by temperature stress only or the combination of temperature and electrical stress (hereafter, temperature–electrical stress). Using these two stress conditions, namely temperature stress and temperature–electrical stress, the component failure rates according to corresponding electronic components in the POSAFE-Q PLCs are collected in Section 3.3.

3.2. Analysis of dominant electronic components affecting the failure of POSAFE-Q PLCs

The component failure rate database includes the failure rates of the electronic components in the 12 POSAFE-Q PLCs introduced in Section 2.1. However, since the failure rate data of the (approximately 900) electronic components considering stress factors in the 12 PLCs are very numerous, the analysis results from now on are explained focusing on NCPU-2Q and the important electronic components in this module considering the stress conditions in Table 6 (temperature stress and temperature–electrical stress).

In order to analyze the electronic components that dominantly affect the failure of NCPU-2Q, the number and type of electronic components included in NCPU-2Q should be investigated based on the BOM provided from the equipment manufacturer. The number of electronic components in NCPU-2Q is 93 excluding the same electronic components, and in terms of component type, most are categorized as microcircuits, transistors, switches, diodes, quartz crystals, capacitors, resistors, emitters, and connectors. After the input information such as physical parameters for the component failure prediction models is analyzed

Table 7
Dominant electronic components affecting the failure of NCPU-2Q.

ID[1]	Category[2]	Failure rate (fpmh[3])	Contribution (%)
NCPU-2Q-04[4]	***Micro, Memory***	***1.017***	***28.29***
NCPU-2Q-01	***Microprocessor***	***0.7068***	***19.66***
NCPU-2Q-11	Microcircuits	0.3008	8.37
NCPU-2Q-22	Transistor	0.1901	5.29
NCPU-2Q-82	Switch	0.1669	4.64
NCPU-2Q-83	Switch	0.1412	3.93
NCPU-2Q-84	Switch	0.1412	3.93
NCPU-2Q-03	Micro, Memory	0.117	3.26
NCPU-2Q-05	Microcircuits	0.09611	2.67
NCPU-2Q-02	Microcircuits	0.08956	2.49
NCPU-2Q-57	Diode	0.07109	1.98
NCPU-2Q-14	Microcircuits	0.04433	1.23
NCPU-2Q-91	Connector	0.04396	1.22
NCPU-2Q-15	Microcircuits	0.04077	1.13
NCPU-2Q-81	Microcircuits	0.03252	0.9
NCPU-2Q-59	Quartz Crystal	0.03197	0.89
NCPU-2Q-09	Micro, Memory	0.02894	0.8
NCPU-2Q-16	Micro, Memory	0.02886	0.8
NCPU-2Q-12	Microcircuits	0.01938	0.54
NCPU-2Q-19	Microcircuits	0.01942	0.54
NCPU-2Q-20	Microcircuits	0.01942	0.54
NCPU-2Q-21	Microcircuits	0.01747	0.49
NCPU-2Q-07	Microcircuits	0.01633	0.45
NCPU-2Q-93	Quartz Crystal	0.01496	0.42
NCPU-2Q-06	Microcircuits	0.01491	0.41
NCPU-2Q-60	Quartz Crystal	0.01448	0.4
NCPU-2Q-24	Microcircuits	0.01103	0.31
NCPU-2Q-17	Microcircuits	0.01083	0.3
NCPU-2Q-18	Microcircuits	0.01083	0.3
NCPU-2Q-58	Diode	0.01075	0.3
NCPU-2Q-13	Microcircuits	0.008213	0.23
NCPU-2Q-92	Diode	0.007206	0.2
NCPU-2Q-08	Microcircuits	0.006651	0.18
NCPU-2Q-25	Diode	0.005396	0.15
NCPU-2Q-26	Diode	0.005396	0.15
NCPU-2Q-79	***Capacitor***	***0.004643***	***0.13***
NCPU-2Q-10	Microcircuits	0.003742	0.1
NCPU-2Q-44	Resistor	0.003773	0.1

1) The ID is arbitrarily designated to identify each component and manage the component failure rate database (the tables list the top 38 electronic components out of 93).

2) The category of each part is briefly described due to confidentiality issues.

3) Unit: failure per million hour (fpmh).

4) The electronic components written in italics and bold font are example components for calculating electronic component failure rates according to stress conditions in Section 3.3.

from the component datasheet/specifications, the failure rate–based dominant electronic components affecting the failure of NCPU-2Q are identified as shown in Table 7 under a fixed stress condition of an ambient temperature of 30 °C and electrical stress (ratio of operating to rated voltage) of 0.1 (it is assumed that this stress condition is close to normal NPP conditions).

As shown in Table 7, the most dominant electronic component affecting the failure of NCPU-2Q is NCPU-2Q-04 (Micro, Memory), with its contribution accounting for 28.29 %. In addition, the total contribution of micro-related electronic components to NCPU-2Q failure is about 74 %. In this light, NCPU-2Q-04 (Micro, Memory) and NCPU-2Q-01 (Microprocessor) are selected as example electronic components for predicting electronic component failure rates according to stress conditions in Section 3.3. However, since the failure rates of these two electronic components are affected by temperature stress only, as shown in Table 6, NCPU-2Q-79 (Capacitor) whose failure rate is affected by temperature–electrical stress is also selected as an example electronic component to apply the proposed RUL prediction method in this study.

3.3. *Calculation results of electronic component failure rates according to stress conditions*

In this section, the failure rates of the electronic components selected in Section 3.2 are calculated according to various stress conditions. That is, based on MIL-217F, the electronic component failure rates are predicted by changing the levels of stress conditions predefined in Section 3.1, and these calculation results are compiled into a database for use in the RUL prediction of the electronic components in Section 4. Based on the predetermined stress factors, various combinations of stress conditions can be intuitively explained by the matrix shown in Table 8.

As shown in Table 8, the temperature stress is given from 30 °C to 100 °C since it is assumed that the ambient temperature of the I&C equipment room of NPPs is approximately 30 °C and the operating temperature of most electronic components is guaranteed up to 125 °C in the component specifications. Electrical stress is given from 0.1 to 1 since MIL-217F guarantees the range of electrical stress from 0 to 1. As a result, the number of stress conditions, which are the combinations of temperature and electrical stress factors, is 80 in Table 8. Based on these 80 stress conditions, the electronic component failure rates are calculated, and the calculation results are compiled into the database (note that only 1 out of the 80 stress conditions is typically considered in traditional and current reliability predictions of electronic equipment). The six stress conditions labeled in Table 8 are briefly explained as follows.

- Case A: As the base case stress condition in this study, temperature stress is assumed to be 30 °C and electrical stress is assumed to be 0.1. (In traditional reliability prediction of electronic equipment, temperature stress is normally assumed to be 30 °C.)
- Case B: Temperature stress is designated as 40 °C for comparison with Case A.
- Case C: Temperature stress is designated as 100 °C representing the worst case in terms of temperature stress, and electrical stress is assumed as 0.1.
- Case D: Electrical stress is designated as 0.2 for comparison with Case A.
- Case E: Electrical stress is designated as 1 representing the worst case in terms of electrical stress (i.e., the operating voltage is the same as rated voltage), and temperature stress is assumed as 30 °C.
- Case F: As the worst-case stress condition in this study in terms of temperature–electrical stress, temperature and electrical stress are designated as 100 °C and 1, respectively.

Based on the 80 cases of stress conditions in Table 8, the failure rates of all electronic components included in the 12 POSAFE-Q PLCs introduced in Section 2.1 are calculated. In other words, the failure rates under 80 stress conditions are estimated for each electronic component, and the scope of this calculation covers the approximately 900 electronic components included in the 12 POSAFE-Q PLC modules as shown in Fig. 1, which is called the electronic component failure rate database in this study.

Although the failure rates of all electronic components are calculated according to various stress conditions as shown in Fig. 1, the failure rate calculation results according to various stress conditions are provided here for the three electronic components determined in Section 3.2: NCPU-2Q-04, NCPU-2Q-01, and NCPU-2Q-79. These three components are applied in the case study of the proposed method in Section 4 to predict component RUL under dynamic stress conditions.

Tables 9(a) to 9(c) show the failure rates of NCPU-2Q-04 (Micro, Memory), NCPU-2Q-01 (Microprocessor), and NCPU-2Q-79 (capacitor), respectively, according to various stress conditions. Note that the failure rates of these three electronic components are calculated based on the failure rate prediction models in MIL-217F, part-specific predetermined physical parameters, and various stress conditions. Tables 9(a) and 9(b) respectively show the failure rate calculation results under various stress conditions for the first (NCPU-2Q-04) and second (NCPU-2Q-01) priority electronic components that affect the failure rate of NCPU-2Q, as shown in Section 3.2. Since the failure rates of these electronic components are not affected by electrical stress as analyzed in Tables 6 and it can be confirmed that the failure rates of NCPU-2Q-04 and NCPU-2Q-01 do not change when electrical stress increases. In the case of an electronic component that is affected by temperature stress only, the failure rate calculation results are managed according to the format of Table 9 since the RUL prediction method in Section 4 is based on stress condition tables like Fig. 1 or Table 9. One important point found in Tables 9(a) and Table 9(b) is that as the temperature stress increases, the difference in failure rates between NCPU-2Q-04 and NCPU-2Q-01 increases, indicating that the MTTF of NCPU-2Q-04 is shortened more rapidly than that of NCPU-2Q-01. This is because the NCPU-2Q-04 junction-to-ambient thermal resistance as a physical parameter (combination of junction-to-case and case-to-ambient thermal resistance) is greater than that of NCPU-2Q-01, and as a result, even at the same ambient temperature, the junction temperature of NCPU-2Q-04 is higher than that of NCPU-2Q-01. In addition, as shown in Table 4, since the temperature

Table 8
Combination of stress factors to predict the electronic component failure rates of POSAFE-Q PLCs.

Electronic component in POSAFE-Q PLCs		Electrical stress (Ratio of operating to rated voltage)									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Temperature stress (°C)	**30**	A	D								E
	40	B									
	50										
	60										
	70										
	80										
	90										
	100	C									F

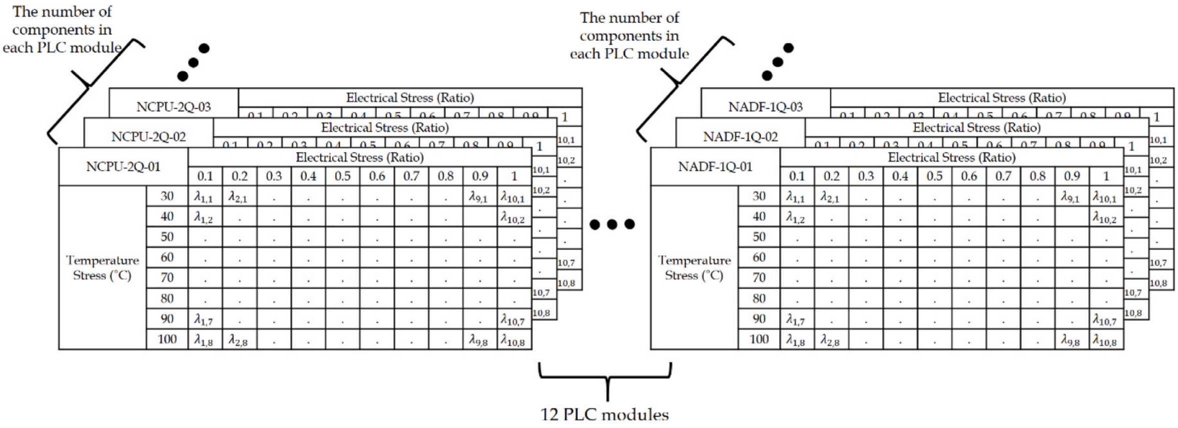

Fig. 1. Electronic component failure rate database for POSAFE-Q PLCs.

Table 9(a)
Failure rates (λ_p) of NCPU-2Q-04 according to stress conditions (unit: fpmh).

NCPU-2Q-04 (Micro, Memory)		Electrical stress (Ratio of operating to rated voltage)									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Temp. stress (°C)	30	1.017	1.017	1.017	1.017	1.017	1.017	1.017	1.017	1.017	1.017
	40	1.617	1.617	1.617	1.617	1.617	1.617	1.617	1.617	1.617	1.617
	50	2.516	2.516	2.516	2.516	2.516	2.516	2.516	2.516	2.516	2.516
	60	3.833	3.833	3.833	3.833	3.833	3.833	3.833	3.833	3.833	3.833
	70	5.727	5.727	5.727	5.727	5.727	5.727	5.727	5.727	5.727	5.727
	80	8.401	8.401	8.401	8.401	8.401	8.401	8.401	8.401	8.401	8.401
	90	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11
	100	17.19	17.19	17.19	17.19	17.19	17.19	17.19	17.19	17.19	17.19

Table 9(b)
Failure rates (λ_p) of NCPU-2Q-01 according to stress conditions (unit: fpmh).

NCPU-2Q-01 (Microprocessor)		Electrical stress (Ratio of operating to rated voltage)									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Temp. stress (°C)	30	0.7068	0.7068	0.7068	0.7068	0.7068	0.7068	0.7068	0.7068	0.7068	0.7068
	40	0.9664	0.9664	0.9664	0.9664	0.9664	0.9664	0.9664	0.9664	0.9664	0.9664
	50	1.307	1.307	1.307	1.307	1.307	1.307	1.307	1.307	1.307	1.307
	60	1.746	1.746	1.746	1.746	1.746	1.746	1.746	1.746	1.746	1.746
	70	2.303	2.303	2.303	2.303	2.303	2.303	2.303	2.303	2.303	2.303
	80	3.002	3.002	3.002	3.002	3.002	3.002	3.002	3.002	3.002	3.002
	90	3.867	3.867	3.867	3.867	3.867	3.867	3.867	3.867	3.867	3.867
	100	4.925	4.925	4.925	4.925	4.925	4.925	4.925	4.925	4.925	4.925

Table 9(c)
Failure rates (λ_p) of NCPU-2Q-79 according to stress conditions (unit: fpmh).

NCPU-2Q-79 (Capacitor)		Electrical stress (Ratio of operating to rated voltage)									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Temp. stress (°C)	30	0.004643	0.004793	0.005199	0.005991	0.007296	0.009243	0.01196	0.01558	0.02022	0.02602
	40	0.007125	0.007355	0.007979	0.009194	0.0112	0.01418	0.01835	0.0239	0.03103	0.03993
	50	0.01065	0.01099	0.01192	0.01374	0.01673	0.0212	0.02743	0.03572	0.04637	0.05967
	60	0.01553	0.01604	0.0174	0.02004	0.02441	0.03092	0.04002	0.05211	0.06765	0.08705
	70	0.02217	0.02288	0.02482	0.0286	0.03483	0.04413	0.0571	0.07437	0.09654	0.1242
	80	0.031	0.032	0.03472	0.04	0.04872	0.06172	0.07987	0.104	0.135	0.1737
	90	0.04257	0.04394	0.04767	0.05493	0.06689	0.08474	0.1097	0.1428	0.1854	0.2385
	100	0.05746	0.05931	0.06434	0.07414	0.09029	0.1144	0.148	0.1928	0.2502	0.322

factor for all microcircuits (π_T) according to junction temperature increase exponentially, the failure rate of NCPU-2Q-04 increases faster than that of NCPU-2Q-01, with the result that the difference in failure rates between NCPU-2Q-04 and NCPU-2Q-01 increase as the temperature stress increases. These findings are considered in the RUL predictions of electronic components in Section 4. In the case of NCPU-2Q-79 (capacitor) as shown in Table 9(c), the failure rates vary depending on the temperature–electrical stress, unlike NCPU-2Q-04 and NCPU-2Q-01. However, it can be seen that the failure rate itself is significantly lower than that of the other components under any stress condition (even under the worst stress condition of this study, temperature stress 100 °C and electrical stress 1).

Based on these results, namely the electronic component failure rate calculation database in Fig. 1 and Table 9(a–c), the RUL of the electronic components under dynamic stress conditions is predicted in Section 4.

4. Prediction of RUL of electronic components under dynamic stress conditions

4.1. RUL prediction method based on component failure rate database

Since this paper emphasizes that the operating conditions such as ambient temperature and electrical load that electronic components are exposed to can be dynamically varied in I&C equipment rooms of NPPs, a RUL prediction method for electronic components in dynamically varying environmental conditions of NPPs is proposed using the component failure rate database obtained in Section 3.3. In fact, this database is a collection of electronic component failure rates under various fixed stress conditions, meaning it does not account for electronic component failure rates when the stress conditions change in real time. That is, the component failure rate database reflects a collection of failure rates when the electronic components are continuously operated until they fail under a specific and/or fixed stress condition (e.g., a temperature stress of 50 °C and an electrical stress of 0.5 until component failure). Therefore, the RUL prediction method for electronic components in this study allows for RUL prediction when the stress condition dynamically changes in real time, as shown on the left in Fig. 2. In this light, the main idea of the proposed method is to adopt the concept of an average failure rate, which means the average of a component failure rate accumulated over a certain interval (operating time of the component) considering stress conditions that change in real time, as shown on the left in Fig. 2.

In this regard, the average of the component failure rate accumulated over the interval a to b in Fig. 2 can be expressed as Eq. (5).

$$\lambda_{p\_average} = \frac{1}{b-a}\int_a^b \lambda(t)dt \tag{5}$$

This equation can be simply interpreted as the average of the component failure rates that vary according to the stress conditions between a and b.

Then if the failure rate that continuously changes by stress condition with operation time (left side of Fig. 2) can be subdivided and expressed as a constant failure rate for a certain operation interval (right side of Fig. 2) under a specific stress condition, Eq. (5) can be expressed as Eq. (6) as follows.

$$\lambda_{p\_average} = \frac{1}{T}\sum_{n=i} \lambda_i t_i \ (if\ \lambda_i\ is\ constant\ for\ a\ certain\ operation\ interval) \tag{6}$$

$where, \lambda_i = i_{th}\ failure\ rate\ under\ specific\ temperature\ and\ electrical\ stress\ conditions$

$t_i = Operation\ time\ with\ \lambda_i\ (hr)$

$T = Total\ operation\ time\ (hr)$

This equation can be simply interpreted as the average failure rate in Eq. (5), which continuously changes over time, subdivided into a certain number of operation intervals with constant failure rates in order to calculate the average failure rate using the electronic component failure rate database in Section 3.3. It can be noted that if there is no identical stress condition to determine λ_i in Eq. (6) from the electronic component failure rate database, interpolated λ_i should be used.

Since it is known that the probability density function of electronic components/systems has an exponential distribution [16], the MTTF, which has an expectation of an exponential distribution with $\lambda_{p\_average}$ in this study, can be calculated in Eq. (7), and then the RUL of electronic components under dynamic stress conditions can be obtained by subtracting the total operation time from the MTTF of the electronic components.

$$MTTF = \frac{1}{\lambda_{p\_average}}, RUL = MTTF - T \tag{7}$$

Based on the RUL prediction method derived in this section and the component failure rate database in Section 3.3, a case study is performed in Section 4.2.

4.2. Case study

In the case study, the stress conditions for the electronic components in the I&C equipment room of an NPP are divided into a base case and a dynamic case. In the base case, the electronic components are exposed to a temperature stress of 30 °C and electrical stress of 0.1 for 10 years (the stress conditions are fixed as constants like the conventional MTTF calculation process). On the other hand, in the dynamic case to apply the proposed RUL prediction method, the electronic components are exposed to the following dynamically varying stress conditions for 10 years: (1) temperature stress of 30 °C and electrical stress of 0.1 for 1 year, (2) temperature stress of 60 °C and electrical stress of 0.5 for 4 years, (3) temperature stress of 90 °C and electrical stress of 0.9 for 3 years, and (4) temperature stress of 100 °C and electrical stress of 1.0 for 2 years.

The stress conditions (1) and (2) in the dynamic case are the stress conditions that the electronic components of the POSAFE-Q PLC platform located in the I&C equipment room of NPPs may potentially be exposed to. The stress conditions (3) and (4) of the dynamic case are practically unlikely to occur, but they are included here to clearly show the difference in results when the RUL of electronic components is predicted by the proposed method in this study.

Under the two cases of stress conditions (base case and dynamic case), RUL prediction is performed for the three electronic components selected in Section 3.2 based on Eq. (6), Eq. (7), and the component failure rate database. Results are shown in Table 10.

As shown in Table 10, the RUL differences between the base case and dynamic case for the three electronic components are 99 years, 122 years, and 23,710 years, respectively. For NCPU-2Q-04, in the base case, the RUL of this electronic component is 102 years, but under dynamically changing stress conditions, the RUL is confirmed to be 3 years after 10 years of total operation time. For the microprocessor of NCPU-2Q-01, the RUL is confirmed to be reduced from 151 years in the base case to 29 years in the dynamic case. For NCPU-2Q-79, since the failure rate of the capacitor is much lower than that of the memory and microprocessor, it can be seen that the MTTF is relatively large in both the base case and the dynamic case. In addition, since the failure rate of the capacitor is affected by both temperature stress and electrical stress, the difference in the RUL of the capacitor between the base case and the dynamic case is confirmed to be very large.

Since the MTTFs of electronic components calculated in Table 10 are quite long, namely on the order of 10 years, 100 years, and especially 10,000 years, it might be thought that the impact of NPP operations on the RUL of the electronic components is insignificant. However, it should be emphasized that the RUL prediction method in this study is

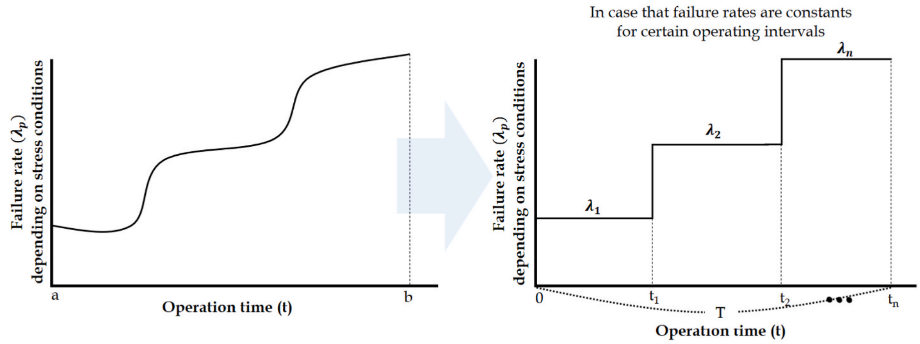

Fig. 2. Failure rates as stress conditions change over time.

basically proposed under dynamic stress conditions for one electronic component; if this method is applied to a system such as a CM in which hundreds of electronic components are combined, a more realistic level of RUL difference can be confirmed. This point is discussed in detail in Section 5.

From these observations, it is possible to say that the proposed RUL prediction method can be used for estimating the RUL of electronic components depending on time-varying temperature and electrical stress conditions. It is also anticipated that, by expanding the results of this study, the RUL of a specific system consisting of hundreds of electronic components can be predicted under dynamic stress conditions.

Table 10
Application of the proposed RUL prediction method to three electronic components of NCPU-2Q.

	Stress condition[1]	Failure rate[2]	Operation time (hr/yr)	Total operation time (hr/yr)	MTTF (hr/yr)	RUL (hr/yr)	RUL difference[3] (yr)
NCPU-2Q-04 (Micro, Memory)							
Base case	T30-E0.1	1.017	87,600/10	87,600/10	983,284 /112	895,684 /102	99
Dynamic case	T30-E0.1	1.017	8,760/1	87,600/10			
	T60-E0.5	3.833	35,040/4				
	T90-E0.9	12.11	26,280/3				
	T100-E1.0	17.19	17,520/2				
	$\lambda_{p\_average}{}^{4)}$: 8.7059				114,864 /13	27,264/ 3	
NCPU-2Q-01 (Microprocessor)							
Base case	T30-E0.1	0.7068	87,600/10	87,600/10	1,414,82 7/161	1,327,22 7/151	122
Dynamic case	T30-E0.1	0.7068	8,760/1	87,600/10			
	T60-E0.5	1.746	35,040/4				
	T90-E0.9	3.867	26,280/3				
	T100-E1.0	4.925	17,520/2				
	$\lambda_{p\_average}$: 2.91418				343,149 /39	255,549 /29	
NCPU-2Q-79 (Capacitor)							
Base case	T30-E0.1	0.004643	87,600/10	87,600/10	215,377, 988/24, 586	215,290, 388/24, 576	23,710
Dynamic case	T30-E0.1	0.004643	8,760/1	87,600/10			
	T60-E0.5	0.02441	35,040/4				
	T90-E0.9	0.1854	26,280/3				
	T100-E1.0	0.322	17,520/2				
	$\lambda_{p\_average}$: 0.1302483				7,677,64 3/876	7,590,04 3/866	

1) The stress condition denoted by T30-E0.1 means that temperature stress is 30 °C and electrical stress is 0.1.
2) The failure rate of each stress condition is referred from Tables 9(a), Table 9(b), and Table 9(c).
3) RUL difference means the difference between the base case RUL and the dynamic case.
RUL.
4) $\lambda_{p\_average}$ means the average failure rate of the electronic component in various stress conditions of the dynamic case.

5. Discussion

Before concluding this work, first, it should be discussed that even though temperature stress and temperature–electrical stress were selected to predict the electronic component failure rates under various stress conditions in Section 3, the dominant electronic components affecting the failure of NCPU-2Q were affected by temperature stress only. Since these results may be due to the particular characteristics of the electronic components of POSAFE-Q PLCs or may be general results, additional research seems to be required.

Second, as explained in Section 4.1, Eq. (6) was derived to predict the average failure rate of electronic components operated over a number of certain intervals with constant failure rates because the electronic component failure rate database, which is the input data in Eq. (6), provides constant failure rates under temperature stress at 10 °C intervals and electrical stress at 0.1 intervals. If the intervals of stress conditions of the electronic component failure rate database are subdivided in more detail, the results of RUL prediction for electronic components under dynamic stress conditions by Eq. (6) can be more accurate. Also, since the RUL prediction of electronic components in this study is based on the electronic component failure rate database, expansion of this database along with subdividing the intervals of the stress conditions will enhance the accuracy of RUL prediction for electronic components in both dynamic and static stress conditions. In addition, if the polynomial of a continuously changing failure rate can be obtained as shown on the left of Fig. 2, Eq. (5) is also expected to be useful to predict the average failure rates of electronic components.

Third, it should be noted that I&C systems are replaced on a CM basis, and the replacement period of the CMs is determined based on the predicted MTTF of CMs (normally 10 years) under fixed stress conditions in Korean domestic NPPs. However, as briefly described in Section 4.2, since the MTTFs calculated in this study are for electronic components, some of the RUL prediction results (e.g., NCPU-2Q-01 and NCPU-2Q-79 in Table 10) seem to be quite long even under dynamic stress conditions. If the failure rate of a CM is predicted as the sum of the failure rates of hundreds of electronic components obtained in this study under the assumption that the electronic components are connected in series, the results of the predicted RUL of the given CM applying the proposed RUL prediction method in this study are expected to be more realistic. In order to apply the proposed RUL prediction method for electronic components in this study to CMs, Eq. (8) should be further considered assuming that electronic components in CMs are connected in series.

$$MTTF_{CM} = \frac{1}{\lambda_{p\_avg\_CM}} = \frac{1}{\lambda_{p\_avg\_component(1)} + \lambda_{p\_avg\_component(2)} + \ldots + \lambda_{p\_avg\_component(n)}} \tag{8}$$

This point applying the proposed RUL prediction method for electronic components to CMs under dynamic stress conditions of NPPs will be scrutinized as a further study.

6. Conclusion

In Korean domestic NPPs, the reliability prediction of digital I&C systems has been performed by calculating the failure rates and MTTF of the electronic components constituting the digital I&C systems based on the MIL-217F standard. However, there is a critical limitation in this analysis process that certain factors are fixed, such as the ambient temperature and electrical stress affecting the failure rates of electronic components due to changes in the external environmental conditions, even if these factors can dynamically vary in the real world. To overcome this limitation and predict the RUL of the electronic components of the POSAFE-Q PLC platform under dynamically changing environments, an electronic component failure rate database for the 12 POSAFE-Q PLCs was obtained by calculating the failure rates of the (approximately 900) electronic components based on combinations of predetermined stress factors affecting the failure rates. In addition, a RUL prediction method for electronic components under dynamic stress conditions based on the component failure rate database was proposed and applied to important electronic components in the NCPU-2Q PLC as a case study.

In the results, it was observed that based on the RUL of specific electronic components predicted depending on time-varying temperature and electrical stress conditions, the RUL differences between the base case and dynamic case of stress conditions in the case study were significant. It can therefore be said that the RUL of electronic components can be predicted under the dynamic stress conditions based on the proposed method in this study.

In this research, various stress conditions (combinations of temperature and electrical stress) were considered to predict the RUL of electronic components in the POSAFE-Q PLC platform, enabling RUL prediction of electronic components in dynamic stress conditions. However, since the proposed method is based on the electronic component failure rate database including electronic component failure rates considering various stress conditions, extensive efforts have to be made to build the failure rate database. Nevertheless, applying the proposed method to other I&C systems would facilitate more realistic RUL predictions, which would lead to setting more appropriate replacement periods of the I&C systems.

Declaration of competing interest

N/A.

Acknowledgements

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