Part Failure Rate Prediction of Digital I&C System according to Various Environmental Conditions in Electrical Equipment Room

Inseok Jang [a*]
[a] *Advanced Instrumentation & Control Research Section, Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, Republic of Korea*
[*] *Corresponding author: isjang@kaeri.re.kr*

1. Introduction

Traditionally, the availability/reliability of digital I&C systems has been calculated before these I&C systems are applied to the nuclear power plants (NPPs). For the estimation of availability of digital I&C systems, the failure rates of programmable logic controller (PLC) modules consisting of the hundreds of electronic equipment/parts have to be obtained in advance [1]. The results of failure rate calculations of PLC modules are not only used for the availability estimation of I&C systems but also applied for the failure probability of the basic events in probabilistic safety assessment (PSA) models.

However, there are several assumptions when the failure rates of electronic parts are estimated. First, the ambient temperature of the location where the I&C systems are installed (electrical equipment room) is usually assumed as 30°C. Second, the operating electrical values such as operating voltage, current, and power applied to the electronic parts are fixed, not changed. Due to these assumptions, the part failure rates might be underestimated if the environmental conditions are dynamically changed. Therefore, in this study, the failure rates of electronic parts in POSAFE-Q PLC platform of APR1400 reactor protection system are predicted considering various environmental/electrical conditions.

2. MIL-217F: Reliability Prediction of Electronic Equipment

In nuclear domain, in order to predict the part failure rates, MIL-217F has been most widely used. The purpose of this handbook is to establish and maintain consistent and uniform methods of estimating the inherent reliability of military equipment and systems. It provides a common basis for reliability predictions during acquisition programs for military electronic systems and equipment [2].

MIL-217F provides the part failure prediction models and data according to the materials, manufacturing process, integration, environment, quality, and others. The failure rate of the identical function device can be changed according to the applied voltage, current and temperatures. The general failure rate model is shown as follows.

$$\lambda_p = \lambda_b \pi_T \pi_C \pi_V \pi_{SR} \pi_Q \pi_E$$

$$\lambda_p = predicted\ failure\ rate, \lambda_b = base\ failure\ rate$$

$$\pi_T = temperature\ factor, \pi_C = capacitance\ factor$$

$$\pi_V = voltage\ factor, \pi_{SR} = stress\ factor$$

$$\pi_Q = quality\ factor, \pi_E = environmental\ factor$$

Since MIL-217F contains the various categories of electronic parts such as microcircuits, diodes, transistors resistor, capacitors, and others, there are lots of part failure prediction models in Section 5 to 22 of MIL-217F. Even in the same sections (for example, section 9: resistors), various failure models are provided according to the sub-categories of the specific parts.

Table 1 shows the example sections related to the electronic parts of POSAFE-Q PLC, and their representative failure rate prediction models in MIL-217F.

Table 1: Representative Failure Rate Prediction Model of POSAFE-Q PLC

Section	Parts	Failure Rate Prediction Model
5	Microcircuits	$\lambda_p = (C_1\pi_T + C_2\pi_E)\pi_Q\pi_L$
6	Discrete Semiconductors (Diodes, Transistor)	$\lambda_p = \lambda_b\pi_T\pi_A\pi_R\pi_S\pi_Q\pi_E$
9	Resistors	$\lambda_p = \lambda_b\pi_R\pi_Q\pi_E$
10	Capacitors	$\lambda_p = \lambda_b\pi_{CV}\pi_Q\pi_E$
14	Switches	$\lambda_p = \lambda_b\pi_{CYC}\pi_L\pi_C\pi_E$
15	Connectors	$\lambda_p = \lambda_b\pi_K\pi_P\pi_E$
19	Quartz crystals	$\lambda_p = \lambda_b\pi_Q\pi_E$

$$\pi_L = learning\ factgor, \pi_A = application\ factor$$

$$\pi_R = resistance\ factor, \pi_{CV} = capacitance\ factor$$

$$\pi_{CYC} = cycling\ factor, \pi_C = contact\ forn\ factor$$

$$\pi_K = mating, unmating\ factor, \pi_P = active\ pins\ factor$$

3. Failure Rate Calculation for Electronic Parts in POSAFE-Q PLC

3.1 Investigation of General Factors affecting Part Failure Rate - Microprocessor, Digital [MIL-217F, Section 5.1]

In order to calculate the failure rate of microprocessor mounted in the processor module of POSAFE-Q PLC, many factors should be considered by referring MIL-217F Section 5.1. Based on the MIL-217F Section 5.1, the failure rate prediction model is shown as follows.

$$\lambda_p = (C_1\pi_T + C_2\pi_E)\pi_Q\pi_L$$

In order to find the constants and π factors, many tables in MIL-217F should be investigated as shown in Fig. 1, Fig.2, and other figures in MIL-217F.

Microprocessor
Die Complexity Failure Rate - C_1

No. Bits	Bipolar C_1	MOS C_1
Up to 8	.060	.14
Up to 16	.12	.28
Up to 32	.24	.56

Fig. 1. Die Complexity Failure Rate of Microprocessor

Package Failure Rate for all Microcircuits - C_2

Number of Functional Pins, N_p	Package Type: Hermetic: DIPs w/Solder or Weld Seal, Pin Grid Array (PGA)[1], SMT (Leaded and Nonleaded)	DIPs with Glass Seal[2]	Flatpacks with Axial Leads on 50 Mil Centers[3]	Cans[4]	Nonhermetic: DIPs, PGA, SMT (Leaded and Nonleaded)[5]
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

Fig. 2. Package Failure Rate of all Microcircuit

In summary, all of general factors (physical and application parameters) affecting the failure rate of microprocessor investigated in MIL-217F Section 5.1 are as follows.

- Physical Parameters
  - Technology
  - No of Bits
  - Package Type
  - No of Yrs in Production
  - No of Pins
  - Case to Ambient Thermal Resistance
  - Junction to Case Thermal Resistance
  - Quality
- Application Parameters
  - Quantity
  - Environment
  - Ambient Temperature
  - Power dissipation
  - Connection Type
  - No of Active Pins

Detailed analysis results of physical and application parameters according to POSAFE-Q PLC modules and parts are described in the reference 3 [3].

3.2 Investigation of Stress Factors affecting Part Failure Rate

As explained in Section 3.2, part failure rates are affected by both physical and application parameters. However, physical parameters and the part of application parameters cannot be changed after I&C systems are installed in NPPs. For example, memory size (number of bits), number of pins, connection type cannot be changed after they are designed. Since the purpose of this paper is to predict and generate various part failure rates within various changeable conditions, stress factors affecting part failure rates are analyzed according to the part categories as shown in Table 2.

Table 2: Stress Factor Identification for Various Parts in POSAFE-Q PLC

	Parts (MIL-217F section)	Description of Stress Factors
1	Microcircuits (5)	- Affected by Junction Temperature
2	Transistor, LF Bipolar (6.3)	- Affected by Junction Temperature - Affected by Ratio of Applied Voltage (Voltage, Collector to Emitter) to Rated Voltage (Voltage, Collector to Emitter, Base Open)
3	Transistor, LF Si FET (6.4)	- Affected by Junction Temperature
4	Diode, Low Frequency (6.1)	- Affected by Junction Temperature - Affected by Ratio of Applied Voltage to Rated Voltage (Diode Reverse Voltage) (Note: Not affected by voltage stress if application of diode is for Transient Suppressor, Voltage Regulator, Voltage Reference, Current Regulator)
5	Diode, High Frequency (6.2)	- Affected by Junction Temperature
6	Resistor (9)	- Affected by Junction Temperature - Affected by Ratio of Applied Power to Rated power
7	Capacitor (10)	- Affected by Junction Temperature - Affected by Ratio of Applied voltage (Applied D.C voltage + Peak A.C voltage) to Rated voltage
8	Switch (14)	- Affected by Ratio of Applied current (Operating Load Current) to Rated current (Rated Resistive Load Current)
9	Optoelectronics, (6.11)	- Affected by Junction Temperature
10	Transformer (11.1)	- Affected by Hot Spot Temperature (Ambient Temperature + Average Temperature Rise)

3.3 Results of Failure Rate Calculation according to Temperature and Electrical Stress

As shown in Table 2, most of stress factors affecting the part failure rate are temperature and/or electrical stress factors. For example, the failure rate of Transistor LF Bipolar is affected by both temperature and voltage stress. On the other hands, the failure rate of Microcircuit is affected by temperature stress only. In this light, the failure rate of one of the parts in the processor module of POSAFE-Q PLC (Part ID: NCxx-2Q-61) can be obtained according to the temperature and electrical stress as shown in Table 3. In this study, electrical stress is given from 0.1 to 0.9 since MIL-217F guarantees the range of electrical stress from 0 to 1. In addition, temperature stress is given from 30°C to 90°C since it is assumed that ambient temperature of electrical equipment room is 30°C normally and increases to about 90°C. (The unit of failure rate is used as Failure/10^6hr by referring the unit used in MIL-217F)

Table 3: Failure Rate of NCxx-2Q-61 according to Temperature and Electrical Stress (Unit: Failure/10^6hr)

NCxx-2Q-61		Electrical Stress (Ratio)				
		0.1	**0.3**	**0.5**	**0.7**	**0.9**
Temp Stress (°C)	**30**	4.37E-05	8.12E-05	0.00015	0.00028	0.00052
	50	6.71E-05	0.000125	0.00023	0.00043	0.00080
	70	9.80E-05	0.000182	0.00033	0.00062	0.00117
	90	0.000137	0.000255	0.00047	0.00088	0.00164

Moreover, the failure rate of one of the parts in the power supply module of POSAFE-Q PLC (Part ID: NSxx-2Q-007) can be also predicted according to the temperature stress only as shown in Table 4

Table 4: Failure Rate of NSxx-2Q-007 according to Temperature Stress (Unit: Failure/10^6hr)

NSxx-2Q-007		Electrical Stress (Ratio)				
		0.1	**0.3**	**0.5**	**0.7**	**0.9**
Temp Stress (°C)	**30**	5.71	5.71	5.71	5.71	5.71
	50	12.2	12.2	12.2	12.2	12.2
	70	24.6	24.6	24.6	24.6	24.6
	90	46.9	46.9	46.9	46.9	46.9

In order to obtain the failure rates of NSxx-2Q-007 and/or any part in POSAFE-Q PLC at 30°C temp stress and 0.1 electrical stress conditions, part failure rate calculation tool called 'reliability workbench' was used as shown in Fig. 3

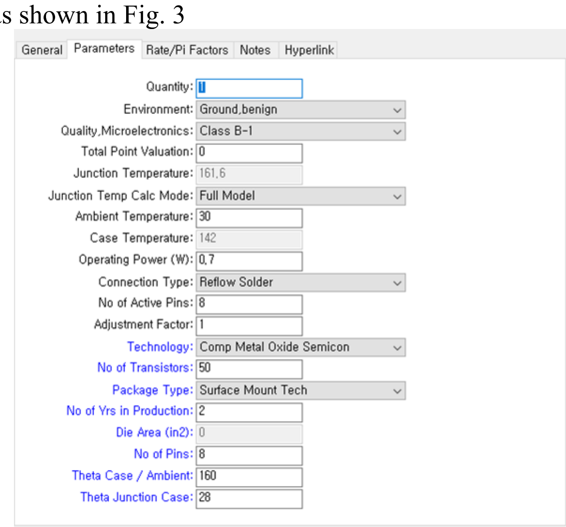

Fig. 3. Input Parameters for Calculating Failure Rate of NSxx-2Q-007

As shown in Fig. 3 and explained in section 3.1, various parameters should be investigated in advance in order to input them to appropriate failure rate prediction models. Based on the input parameters defined in Fig. 3, each π factor in the failure rate prediction models are calculated and finally failure rates of any part are predicted.

As shown in Table 3 and 4, we can find several insights from the results. (1) The results of failure rate calculation can be substantially different according to the electronic part within the identical stress conditions. For example, the part failure rate difference between two parts in Table 3 and 4 at 30°C temperature stress and 0.1 electrical stress condition is about 0.1 million times. It is because of the characteristics of part itself. (2) Regardless of high or low failure rate at static stress condition, the part failure rate increase with harsher environment if the corresponding part is affected by temperature and/or electrical stress conditions. (3) In case of NSxx-2Q-007 in Table 4, when the electrical stress is getting higher, the failure rate is constant since the part 'NSxx-2Q-007' is categorized as Microcircuit.

Using the results in Table 3, Table 4, and other analysis table not shown in this paper, it is expected that we can directly predict the part failure rates changing dynamically and update availability and mean time to failure of the parts/systems.

4. Conclusions

In this study, the part failure rates in POSAFE-Q PLC were estimated within various temperature and electrical stress conditions since the conventional part failure estimations were performed by considering only one static condition. The results showed that part failure rate can be dynamically changed by representative stress factors such as temperature and electrical factors. This result strongly implies that if the temperature and electrical factors in electrical equipment room are measured by additional effort, we can predict the mean time to failure of the electronic parts and/or system, and also prevent unnecessary reactor trips due to the I&C system failures.

The following topics require more research in future studies. Since the result in this paper is based on the analytic method, the part failure calculation results are always same if the input parameter or environmental stress is identical. However, as a part of KAERI project, the part failure data is going to be generated by both analytic methods explained in this study and experimental methods. Using the part failure data from analytic and experimental method, the appropriate AI-based failure prediction model will be developed for failure diagnosis technology of digital I&C system.

Acknowledgements

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government (Ministry of Science and ICT) (No. RS-2022-00144239).

REFERENCES

[1] J. K. Choi, Reliability Analysis Report of Safety Grade PLC (POSAFE-Q), KNICS-PLC-AR103 Rev.02, KAERI, 2008.
[2] MIL-HDBK-217F, N2, “Reliability Prediction of Electronic Equipment,” Department of Defense, 1995.
[3] I. Jang, Analyses of POSAFE-Q PLC Design Data for Part Failure Rate Calculation of APR1400 Reactor Protection System, KAERI/TR-9355, 2022.