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A Reliability Analysis on Safety-Related Digital Module in Nuclear Power Plants

Won Young Yun, Kyung Woo Choi
Korea Institute of Nuclear Safety
P. O. Box 114, Yusong Post Office,
Taejeon, Korea, 305-338

Abstract

Component failure rates and integrated system reliability of a Foxboro Spec 200 Micro module, which was developed with digital technology for the nuclear power plant control and protection, were analyzed. Analysis tool of the study was the part stress analysis technique suggested by the MIL-HDBK-217F. The input data such as base failure rates, operating factors and environmental factors etc. for the study was selected from the generic data sets of MIL-HDBK-217F. The calculation results shows that the average failure rate of digital components in the Foxboro Spec 200 Micro module are higher than that of conventional analog components. And the average reliability drop ratio of the module decreases from 5.7 % to 3.4 % for each two years operating interval up to 20 years assuming the normal operating conditions.

1. Introduction

It is commonly recognized that system reliability and functionality of digital systems are better than those of analog systems in general cases. Moreover, the digital system is superior in system operation and maintenance compared to the existing analog system. However, in spite of these advantages, there are also negative factors in the application of this new technology to the safety system design since there exists a potential in common mode failure of system operations.

Reliability prediction methods have been developed for the evaluation of failure potential and system operability in normal operating environments. It provides the rational basis of system designs and also provides the safety significance of system operations. Thus the various reliability prediction tools have been developed in recent decades. Among of them, the MIL-HDBK-217 method has been widely used as a powerful tool for the prediction of operating system reliability applicable to nuclear plant engineering and safety regulation.

This paper presents a case study of the reliability prediction method for the digital control module named as Foxboro Spec 2000 Micro module generally used in Korean Standard Nuclear Power Plants.

2. Reliability Prediction Model

The reliability prediction tool of the study is the part stress analysis method. The part stress analysis method is based upon the idea that the failure rate of any higher level assembly is a sum of the failure rate of its constituent components. The basic assumptions on part failure rates are summarized as follows;

1) Failure rates do not vary with the age of system.
2) Failure rates follow an Arrhenius relationship with operation temperature.
3) Failure rates are related to the quality control conditions.
4) Failure rates are related to overall environmental conditions.
5) Failure rates are related to the complexity of components particularly in micro electronic devices.
6) Failure rates are related to the operating stress conditions particularly in switching devices.

Consequently, the general expression for module failure rate λ_M is represented as the following equation and the part failure rates λp for individual components are represented in Table 1.

$$\lambda_M = \sum_{i=1}^{n} N_i (\lambda_p)_i \quad \text{------}(1)$$

λ_M = module failure rate
$(\lambda_p)_i$ = part failure rate for the i th specific part
N_i = quantity of the i th specific part
n = number of different specific part categories

Table 1. Component Failure Rate Model

Component Types	Failure Equation (Failure/10^6 hours)
Discrete Semiconductor	
Diode (Low Freq.)	$\lambda_p = \lambda_b \pi_T \pi_S \pi_C \pi_Q \pi_E$
Diode (High Freq.)	$\lambda_p = \lambda_b \pi_T \pi_A \pi_R \pi_Q \pi_E$
Transistor (Signal)	$\lambda_p = \lambda_b \pi_T \pi_A \pi_R \pi_Q \pi_E$
Transistor (High Power)	$\lambda_p = \lambda_b \pi_T \pi_A \pi_M \pi_Q \pi_E$
Passive Devices	
Resistor	$\lambda_p = \lambda_b \pi_T \pi_P \pi_S \pi_Q \pi_E$
Capacitor	$\lambda_p = \lambda_b \pi_T \pi_C \pi_V \pi_S \pi_R \pi_Q \pi_E$
Inductor (Coil)	$\lambda_p = \lambda_b \pi_T \pi_Q \pi_E$
Relay, Quartz, Filter	$\lambda_p = \lambda_b \pi_Q \pi_E$
Fuse (Instrument)	$\lambda_p = \lambda_b \pi_E$
Microcircuit	
Gate/Logic, CPU, Memory	$\lambda_p = (C_1 \pi_T \pi_V + C_2 \pi_E)\, \pi_Q \pi_L$
Linear Amp(OP Amp)	$\lambda_p = (C_1 \pi_T \pi_V + C_2 \pi_E)\, \pi_Q \pi_F \pi_L$

In the Table 1, the factors for failure rate calculation are represented as ;

λ_b = Base failure rate. It is expressed by a model relating the stresses on the component.

π_Q = Quality factor. It depends on the quality device as determined by inspection and test after the product has been manufactured.

π_T = Temperature acceleration factor. It depends on the steady-state operating temperature of the device

π_E = Environmental factor. It depends on the environment in which the device is operating.

π_V, π_S = Voltage stress factors. They depend on the ratio of the applied voltage to the rated voltage of the component

π_p, π_R = Power factors. They depend on the ratio of the applied power to the rated power of the component.

π_A, π_M, π_F = Application factors. They depend on the signal processing or transferring conditions.

π_L = Learning factor. It depends on how long the device has been in production.

C_1, C_1= Failure rate constants. They depend on the device complexity in microcircuit. C_1 and C_2 depend on the circuit complexity and the packing technology respectively.

3. Reliability Calculation of Foxboro Spec 200 Micro Module.

3-1. Design Descriptions

The Foxboro Spec 200 Micro Module is a microprocessor-based system developed for plant protection and control applications. It receives the plant parameters from analog field devices or control modules to provide the suitable output required for process controls and protections. In the design of the plant protection system of Korea Standard Nuclear Power Plant (KSNPP) supplied by ABB-CE company, the stand-alone type Foxboro Spec 200 Micro Module (N-2 CCA card) was introduced.

The N-2CCA control card is comprised of 3 circuit boards which are designated as the input board, output board and main processing board. The input board receives four floating differential analog input signals and the output board transmits two analog outputs to spec 200 analog modules. Both Input and output of N-2CCA module are 0 to 10 Vdc with an accuracy of $\pm$0.1% of span. The functional operations of the control module are processed in the main processing board. The component part lists installed in N-2CCA control card are represented in Table 2.

Table 2. N-2CCA Control Card Part List

Component Types	No. of Components		
	Input Board	Output Board	Processing Board
Diode, Schottky	-	2	-
Diode, Rectifier	8	-	-
Diode, High Frequency	22	16	11
Transistor, Signal, Bipolar	8	15	15
Transistor, High Power, Bipolar	8	1	2
Microcircuit, Processor(CPU)	1	2	2
Microcircuit, Gate/Logic	6	-	18
Microcircuit, Linear(OP AMP)	4	3	2
Microcircuit, ROM(CMOS)	-	-	18
Microcircuit, PROM(CMOS)	-	1	3
Resistor, Fixed, Composition	28	54	86
Resistor, Fixed, Film	75	-	-
Capacitor, Fixed, Electrolytic	3	5	3
Capacitor, Fixed, Ceramic	20	15	62
Capacitor, Fixed, Mica	-	2	6
Relay, Solid State	-	-	2
Crystal, Quartz	-	-	1
Fuse, Instrument	-	-	2

3-2. Input Data Selection

It is commonly recognized that the MIL-MDBK-217 provides realistic base line data of diverse component failure rates because of the efforts made by its sponsors to maintain the currency of the method in line with the rapid advances in technology. Therefore, input data for reliability calculations of this study were selected from the data sources in MIL-HDBK-217F with the following assumptions;

1) System failure is directly related to single component failure in the circuit.

2) Environmental factors of the study are selected from Ground Benign(G_B) level since the module is located in temperature-humidity controlled region.

3) Quality factors for microcircuits, semiconductors and passive devices are selected as class B, JANTX and class R respectively. The other quality factors are selected by engineering judgement considering manufacturing specifications.

4) Operating temperature of microcircuits, semiconductors, and other devices is selected as 40℃ and operating temperature of power driving devices is selected as 80 ℃ considering conservative approaches.

5) The other factors introduced in the component failure models are selected by engineering judgement from an aspect of safety conservatism.

6) The failure of mechanical components such as inter connects, cables, PCB board, etc. are not considered.

7) Preventive maintenance effects such as part replacement and component change are not considered.

Based on the above considerations, selected input data for each component is summarized in Table 3.

Table 3. Component Failure Data Selection

Component Types	l_b	p_T	p_Q	p_E	C_1	C_2	**Other Factors**
Diode, Schottky	$3.0x10^{-3}$	1.4	1.0	1.0	N/A	N/A	$\pi_C = 1, \pi_S = 1$
Diode, Rectifier	$3.0x10^{-3}$	1.6	1.0	1.0	N/A	N/A	$\pi_C = 1, \pi_S = 1$
Diode, High Freq	$3.8x10^{-3}$	1.4	1.0	1.0	N/A	N/A	$\pi_C = 1, \pi_S = 1$
Tr, Power, Bipolar	$3.8x10^{-2}$	0.38	1.0	1.0	NA/	NA/	$\pi_A = 2.2, \pi_M = 1$
Tr, Signal, Bipolar	$7.4x10^{-4}$	1.4	1.0	1.0	N/A	N/A	$\pi_A = 1.5, \pi_R = 1, \pi_S = 0.29$
I.C, Processor(CPU)	N/A	0.19	1.0	0.5	0.14	0.032	$\pi_L = 1$
I.C, ROM(CMOS)	N/A	0.31	1.0	0.5	0.0013	0.01	$\pi_L = 1$
I.C. PROM(CMOS)	N/A	0.31	1.0	0.5	0.0017	0.01	$\pi_L = 1$
I.C, OP Amp(Bipolar)	N/A	0.34	1.0	0.5	0.01	0.002	$\pi_F = 5.8, \pi_L = 1$
I.C,Gate/Logic(CMOS)	N/A	0.19	1.0	0.5	0.4	0.007	$\pi_L = 1$
Resistor, Composition	$1.7x10^{-3}$	1.5	0.1	1.0	N/A	N/A	$\pi_P = 0.76, \pi_S = 1$
Resistor, Film	$3.7x10^{-3}$	1.2	0.1	1.0	N/A	N/A	$\pi_C = 0.76, \pi_S = 1$
Capacitor, Electrolytic	$4.0x10^{-4}$	1.3	0.1	1.0	N/A	N/A	$\pi_C = 0.76, \pi_S = 1$
Capacitor, Metal	$5.1x10^{-4}$	1.3	0.1	1.0	NA/	NA/	$\pi_C = 2.0, \pi_V = 1$
Capacitor, Mica	$7.6x10^{-4}$	1.9	0.1	1.0	N/A	N/A	$\pi_C = 1, \pi_V = 1$
Inductor, Transformer	$2.2x10^{-2}$	1.4	1.0	1.0	N/A	N/A	N/A
Crystal, Quartz	$2.2x10^{-2}$	N/A	1.0	1.0	N/A	N/A	N/A
Fuse, Instrument	$1.0x10^{-2}$	N/A	1.0	1.0	NA	NA	N/A

3-3. Reliability Calculations and Discussions

The constant failure-rate reliability model wherein the reliability at time t is represented as ;

$$R_M(t) = \exp(-\lambda_M t) \text{ --(2)}$$

The failure rates, λ_M, are given by the device model which is calculated from the equation (1). The oval system reliability, R_M, considering long-term operations can be obtained by adjusting the corresponding time constant. The individual failure rate of components and overall system reliability for spec 200 Micro module are represented in Table 4.

Table 4. Component Failure Rate Calculation Results

Component Classification	**Component Types**	**No. of Comp.**	**Component Failure Rate**	**Total Failure Rate (per 10^6 Hours)**
Diode	Schottky	2	4.20×10^{-3}	8.40×10^{-3}
	Rectifier	8	4.80×10^{-3}	38.4×10^{-3}
	High Frequency	49	5.32×10^{-3}	260.68×10^{-3}
Transistor	High Power, Bipolar	11	31.77×10^{-3}	349.47×10^{-3}
	Low Freq., Bipolar	33	0.45×10^{-3}	14.85×10^{-3}
Resistor	Fixed, Composition	168	0.19×10^{-3}	31.92×10^{-3}
	Fixed, Film	75	0.34×10^{-3}	25.30×10^{-3}
Capacitor	Fixed, Electrolytic	11	0.04×10^{-3}	0.44×10^{-3}
	Fixed, Ceramic	97	0.13×10^{-3}	12.61×10^{-3}
	Fixed, Mica	8	0.14×10^{-3}	1.12×10^{-3}
Others	Transformer	3	22.0×10^{-3}	66.00×10^{-3}
	Fuse	2	10.0×10^{-3}	20.00×10^{-3}
	Crystal	1	22.0×10^{-3}	22.00×10^{-3}
Sub Total		**468**		**851.19×10^{-3}**
Microcircuits	Linear Amp(TTL)	9	25.52×10^{-3}	229.68×10^{-3}
	Gate/Logic(CMOS)	24	79.5×10^{-3}	1908.0×10^{-3}
	ROM(CMOS)	18	5.40×10^{-3}	97.20×10^{-3}
	PROM(CMOS)	4	5.53×10^{-3}	22.12×10^{-3}
	Processor(CPU)	5	42.6×10^{-3}	213.0×10^{-3}
Sub Total		**60**		**2479.0×10^{-3}**
Total		**528**		**3330.19×10^{-3}**

From the result of Table 4, it can be seen that the total failure rate of microcircuit components are higher than that of analog components excluding high-power transistor in the Spec 200 Micro module. Specifically, the failure rate of CMOS

Gate and CMOS Logic appear as the most critical factor affecting system reliability. This result is due to the system complexity of the microcircuit. In other words, since single microcircuit is composed of numerous analog/digital components, the failure rate of a microcircuit should be recognized as a group of individual components in the circuit. Based on this consideration, we can estimate the relative system failure rate with the simple calculation of those component failure rates.

And through the calculation of overall system reliability variations assuming continuous operations excluding system repair and maintenance, it is found that the reliability drop ratio decreases from 5.7 % to 3.4 % with plant operation at every two year and reaches a 45 % decrease approximately after 20 year of plant operations. The calculation results are represented in Fig. 1 and Table 5 respectively.

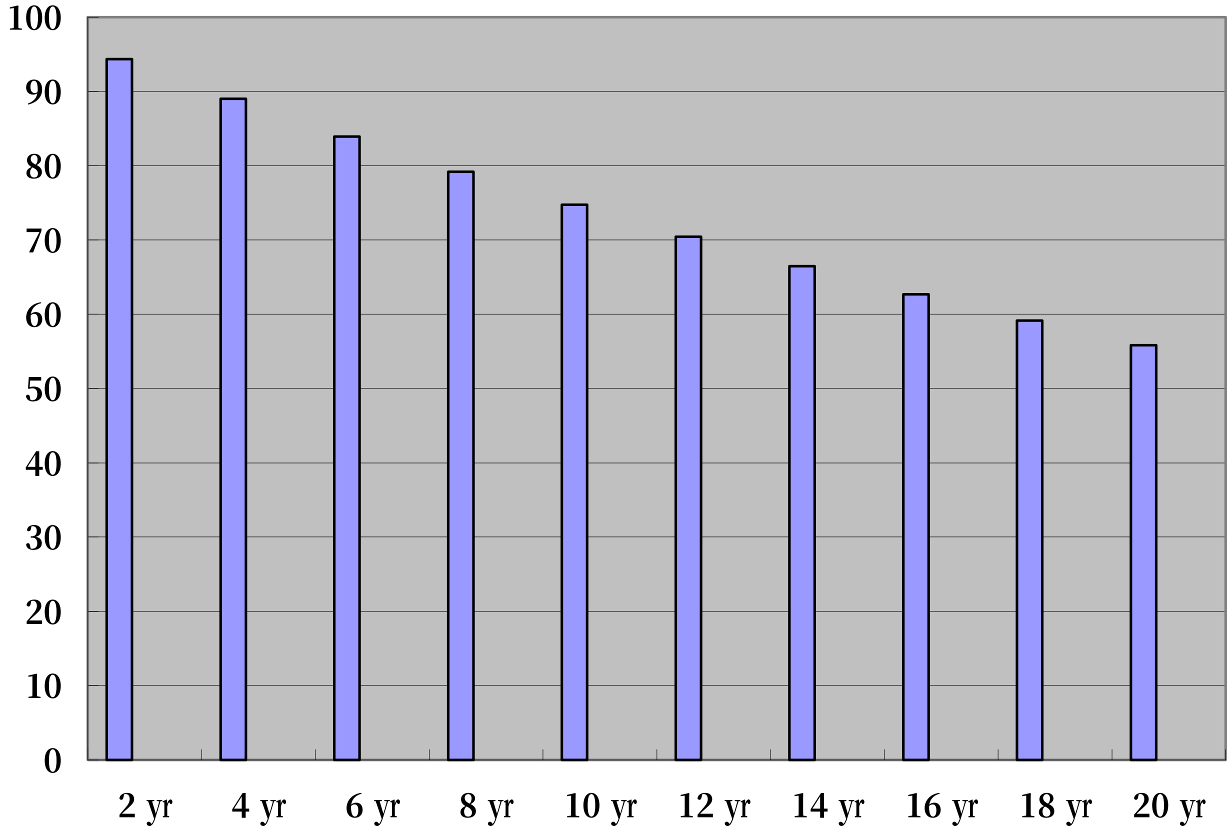

Fig.1 System Reliability Variations with Plant Operations(%)

Table. 5 System Reliability Values with Plant Operations

Operating Time(Years)	2 yr	4 yr	6 yr	8 yr	10 yr	12 yr	14 yr	16 yr	18 yr	20 yr
Reliability Values (%)	94.33	88.99	83.94	79.19	74.70	70.43	66.47	62.70	59.15	55.80

4. Conclusions

The reliability prediction is currently recognized as an essential need in safe and economic operation of nuclear power plant. It can provide the quantitative baseline information on safe significance of system operations and scheduling of system maintenance/refurbishment program. Particularly, there has been a great concern on digital system reliability in nuclear plant regulation recently.

However, due to the limitation of failure model prediction and available data, it can provide the relative information at this stage in the practical case. Thus the comparative study with the MIL-HDBK-217F method was performed in the study to analyze the component failure rate and integrated system reliability of a Foxboro digital module(Spec 200 Micro module). The reliability prediction tool of the study is the part stress analysis technique which has superior characteristics in the modeling of various component failure rates.

The calculation result shows that average failure rate of microcircuit components are higher than that of conventional analog components. And the average reliability drop ratio of Foxboro Spec 200 Micro module decrease from 5.7 % to 3.4 % every two years. Additionally, the result shows that the CMOS Gate/Logic is the most critical component affecting to system reliability and the cumulated module reliability reaches a 45 % decrease after 20 years operations.

Base on these, it is expected that the results of this study will contribute to safe operation and effective maintenance of digital control module in our nuclear power plants.

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