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Prediction of Remaining Life of Transistor embedded in Control Board of Nuclear Power Plant through Accelerated Life Test

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1. Introduction

A large number of electrical devices are being used in nuclear power plants (NPPs) and instrument and control (I&C) boards are installed to measure and control them. As the NPP operation goes on, the board failures could occur due to the component aging observed as their performance degradation. Therefore, it is important to diagnose the current state of the component correctly and to do a preventive measure before the failure occurring actually. Furthermore, being able to make a prognosis and to predict the remaining lifetime of the electronic component, it could prevent unexpected failure occurring more reliably. Thus, evaluation of embedded electric component aging should be preceded for integrity assessment of the boards.

In this study, accelerated life test (ALT) by multiple stress, such as thermal and electrical, was carried out for bipolar junction transistor (BJT), which is one of components of circuit breaker control board in NPPs. Since the BJT is being operated with large power, the degradation of the BJT is inevitably apparent and a number of studies are reported on it. [1, 2, 3]

The current gain (β) is one of the characteristics as the performance indicator of the BJT which is defined as the ratio of the collector to emitter current and the base to emitter current of the BJT. The current gain measured at regular intervals during the ALT was gradually reduced. [4, 5] Based on the analysis of the ALT results of the BJT, the remaining life of the BJT was predicted by physical-statistics based model.

This data will be used to develop “Condition Based Diagnostic System of Electrical Devices on Control boards of NPP”. Also, it is useful to effectively manage parts and systems and is expected to be applicable in many industries.

2. Accelerate Life Test

In this test, NPN transistor, MPQ2906 manufactured by Motorola, was used. Both stresses of thermal and electrical were applied to the BJT. The circuit used for ALT of the BJT for electrical stress is shown in figure 1 below.

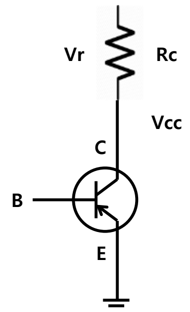

Fig. 1 Circuit Diagram for Accelerated Stress Condition

The thermal stress was applied at 90 ℃ and 140 ℃, and 3 electrical stresses shown below were applied at the same time. The stress conditions for ALT of the BJT are shown in table 1 below and the stresses were applied for about 1000 hours (44 days). To obtain statistical confidence in life analysis and prediction, more than 10 specimens were used for each stress condition.

Tab. 1 Stress Condition for ALT of BJT

Stress	Thermal	Electrical
Condition	140 ℃ (413.15 K)	Vcc: 24 V, Rc: 62.5 Ω, I: 335 mA
		Vcc: 19 V, Rc: 62.5 Ω, I: 260 mA
		Vcc: 24 V, Rc: 100 Ω, I: 212 mA
	90 ℃ (363.15 K)	Vcc: 24 V, Rc: 62.5 Ω, I: 335 mA
		Vcc: 19 V, Rc: 62.5 Ω, I: 260 mA
		Vcc: 24 V, Rc: 100 Ω, I: 212 mA

For each stress condition, the current gain (β) of all specimens was measured during the test and normalized to the initial value of the specimen.

3. ALT Data Analysis

Curve fitting by linear and exponential regression was performed for the data trends in the characteristics of BJT (current gain) measured under stress conditions during the ALT. Figure 2 below shows an example of a curve fitting of data measured under 140 ℃, 335 mA conditions. The unit of the x-axis is days and the unit of the y-axis is normalized % current gains. In the graph, the solid line is the average, and the dotted line reflects the standard deviation. In the same way, the trend curves of the BJT characteristics data measured under all stress conditions in table 1 were derived.

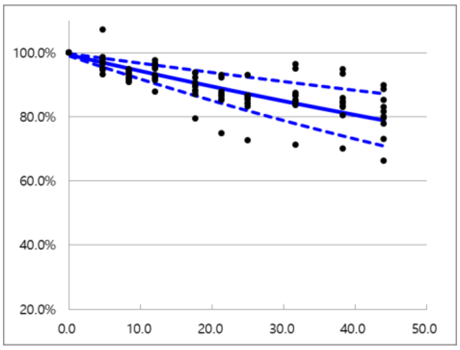

Fig. 2 Example of Curve Fitting (Data: 140 °C, 335 mA)

3.1 Arrhenius Model

Most electric components, including semiconductors, are accelerated degradation by high temperature more than normal operation condition (room temp., ~300K). The effect of temperature on the electrical device generally is used following the Arrhenius reaction rate relation equation.

$$K = S \cdot \text{Exp}\left(-{}^{E_a}/_{kT}\right) \tag{1}$$

Where, K: speed of reaction or reaction rate
S: constant
E_a: activation energy
k: Boltzmann constant (8.617343 eV/K)
T: absolute temperature [K]

In equation (1), it presupposes that the reaction speed (K) has a failure mechanism expressed by multiplying reaction coefficient S and exponential term. If algebra is applied to equation (1), the activation energy (E_a) is a constant determined by the slope in the reaction ratio curve. The life of a device (L) is terminated when aging (performance degradation, x) of the device reaches a specified limit (a).

$$x = K \cdot t = a \rightarrow L = t = a/K \tag{2}$$

$$\ln L = \ln a - \ln K \tag{3}$$

Substitution equation (1) into (3), equation (3) can be derived as follows:

$$\ln L = \ln({}^{a}/_{S}) + Exp\left({}^{E_a}/_{kT}\right) \tag{4}$$

The life of the device according to temperature can be derived as in the following equation (5).

$$L = A \cdot Exp\left({}^{E_a}/_{kT}\right) \tag{5}$$

The acceleration factor (A_F) can be expressed as the ratio of life in normal operating temperature to life in acceleration temperature as shown below.

$$A_F = {}^{L_0}/_{L_S} = Exp\left\{\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_s}\right)\right\} \tag{6}$$

Therefore, the life in normal operation temperature can be derived as shown in equation (7) below.

$$L_0 = L_S \cdot Exp\left\{\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_s}\right)\right\} \tag{7}$$

Where, L_0: life in operating condition
L_S: life under stress condition
E_a: activation energy
k: Boltzmann constant (8.617343 eV/K)
T_0: temperature of operating condition [K]
T_S: temperature for stress condition [K]

3.2 Inverse Power Rule Model

The inverse power rule model was derived by experience based on activation energy. The life of the device under stress condition to which this model is applied is reduced according to the n squared voltage or power given.

$$L_S = {}^{C}/_{V_S{}^n},\ C > 0 \tag{8}$$

Where, L_0: life in operating condition
L_S: life under stress condition
C, n: constant determined by character of electric element, structure of material, test method

The acceleration factor (A_F) of this model can be expressed as shown equation (9), and the life in normal operating condition can be derived as shown in equation (10) below.

$$A_F = {}^{L_0}/_{L_S} = \left({}^{V_S}/_{V_0}\right)^n = \left({}^{P_S}/_{P_0}\right)^n \tag{9}$$

$$L_0 = A_F \cdot L_S = \left({}^{P_S}/_{P_0}\right)^n \cdot L_S \tag{10}$$

Figure 3 below shows the life curve of BJT at 140 °C applied inverse power rule model in 0.1 Watt. In the graph, the unit of the x-axis is days and the unit of the y-axis is normalized % current gains.

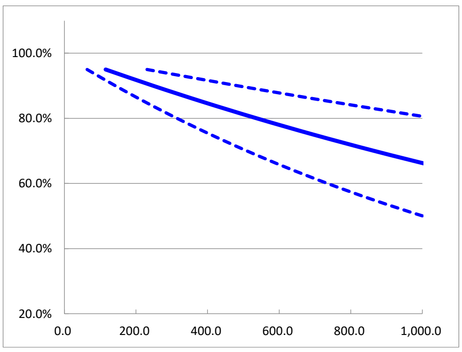

Fig. 3 Life Curve of BJT applying Inverse Power Rule Model

3.3 Combined Model

This model is applied when other stresses, such as temperature and voltage, are applied to ALT at the same time. This model is a combined model of the Arrhenius model and the invers power rule model, and the formula applied is shown in equation 11 below.

$$L_0/L_S = \left(P_S/P_0\right)^n \cdot Exp\left\{E_a/k\left(1/T_0 - 1/T_s\right)\right\} \quad (11)$$

Where, L_0: life in operating condition
L_S: life under stress condition
P_0: electric power in operating condition [W]
P_S: electric power in stress condition [W]
E_a: activation energy
k: Boltzmann constant (8.617343 eV/K)
T_0: temperature in operating condition [K]
T_S: temperature in stress condition [K]

3.4 Life Curve of BJT in Normal Operating Condition

The normal operating conditions of the BJT are room temperature (300 K) and 0.01 ~ 0.2 W. Applying the above combined model to the ALT results gives the following life curves as shown in figure 4 below. The following life curve is the result of applying to normal operating conditions for 0.1 Watt as electric power and 300 K as temperature. In the graph, the unit of the x-axis is years and the unit of the y-axis is normalized % current gains. The solid line is the average, and the dotted line reflects the standard deviation.

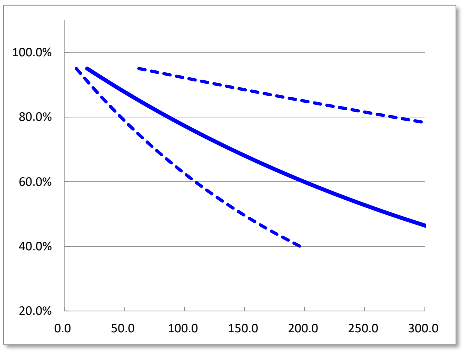

Fig. 4 Predicted Life Curve of the BJT in Operating Condition

4. Conclusions

In this study, ALT BJT by thermal and electrical stress is carried out. We traced the degradation of the current gain, which is one of important performance indicator of the BJT. And then life curve in normal operating condition is extracted. Failure mechanisms that reduce the current gain of BJT may be varied, but life curve is extracted by multiple stress based ALT.

Based on this study, we plan to diagnose and to predict remaining useful life for more components and even boards in electronic devices in the future. It is expected that the integrity of components will be evaluated and the management cycle can be predicted so that it can be effectively used to prevent problems caused by unexpected failure of the control board in NPPs.

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