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Prediction of Remaining Life of Photo-Coupler embedded in Control Board of Nuclear Power Plant through Accelerated Life Test

Young-Suk Jung [a*], Young-Il Oh [a], Eun-Kyung Lee [a], Jae-Soo Noh [a],
Chan-Sei Yoo [b], Hong-Ki Jang [c], Jong-Ho Kim [c], Joong-Soon Jang [d]
[a]ACT Co., Ltd., 1434, Yuseong-daero, Yuseong-gu, Daejeon, 34101, Republic of KOREA
[b]Korea Electronic Technology Institute, Yatop-dong, Seongnam-si, Gyeonggi-do, 13509, Republic of Korea
[c]Woojin N tec, Inc., Osan-dong, Hwaseong-si, Gyeonggi-do, 18481, Republic of KOREA
[d]Ajou University, 206, World cup-ro, Yeongtong-gu, Suwon-si, Gyeonggi-do, 16499, Republic of Korea
[*]Corresponding author: youngsuky@actbest.com

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 electronic component aging observed as their performance degradation. Therefore, it is important to diagnose the current state of the electronic component correctly and to do a preventive measure before the failure occurs 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 electronic component aging should be preceded for integrity assessment of the boards.

In this study, accelerated life test (ALT) by thermal stress was carried out for photo-coupler, which is one of components of circuit breaker control board (IO-11N) in NPPs. Since the photo-coupler is being operated between two circuits with different operating voltages, is used to completely separate the two circuits. The photo-coupler is a device able to transmit electrical signals by light, which simplifies and increases the reliability of two circuits with different operating voltages. [1]

The current transfer ratio (CTR) of the photo-coupler is a known principle performance indicator defined as the current ratio between the light-emitting part (Infrared LED) and the light-detector part of the photo-coupler. The CTR is decreased as the photo-coupler aging. The CTR measured at regular intervals during the ALT was gradually decreased. Based on the analysis of the ALT results of the photo-coupler, the remaining life of the photo-coupler 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]

2. Accelerate Life Test

In this test, photo-coupler H11D1 manufactured by ON Semiconductor was used. Thermal stress is applied to the photo-coupler. The simplified internal circuit diagram of the photo-coupler used in this study is shown in Figure 1 below.

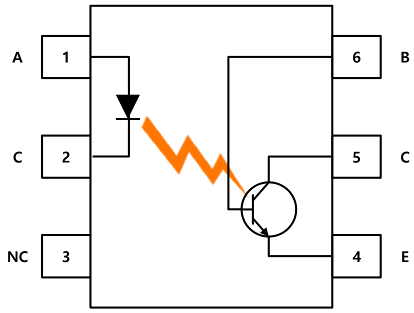
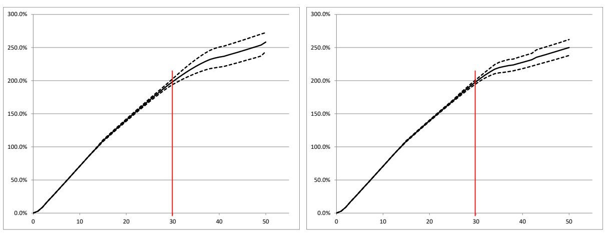


Fig. 1 Simplified Internal Circuit Diagram of Photo-coupler

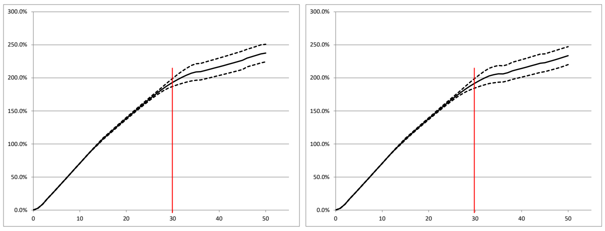
To obtain statistical confidence in life analysis and prediction, more than 20 specimens were used for each stress condition. The thermal stress was applied at 180 ℃ and 210 ℃ shown below were applied at the same time and the stresses were applied for about 661 hours (~ 27.5 days). For each stress condition, the CTR of all specimens was measured during the test and normalized to the initial value of the specimen.

The CTR trace curves measured from 0 ~ 50 V at 180 ℃ and 210 ℃ during ALT are shown in Figure 2 through Figure 6 below. It can be seen that the CTR value decreases over time under accelerated conditions during ALT and that the measured CTR value decreases steeply 210 ℃ than 180 ℃. In the graphs below, the x-axis is Vcc (V) and the y-axis is CTR (%).



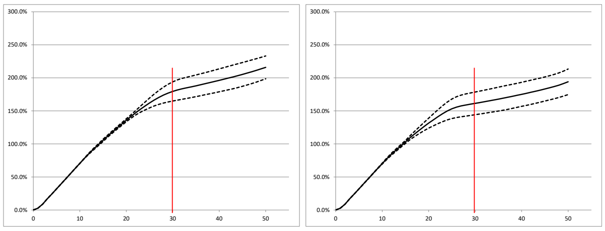
(a) 180 ℃ (b) 210 ℃

Fig. 2 CTR Trace at Initial Condition in ALT



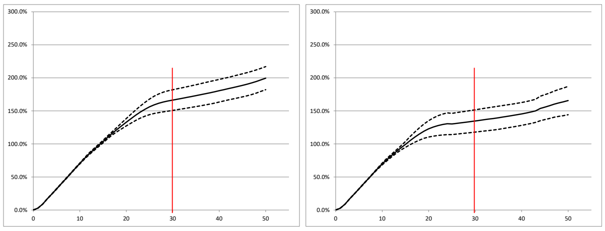
(a) 180 ℃ (b) 210 ℃

Fig. 3 CTR Trace at 202 hour (8.4 day) in ALT



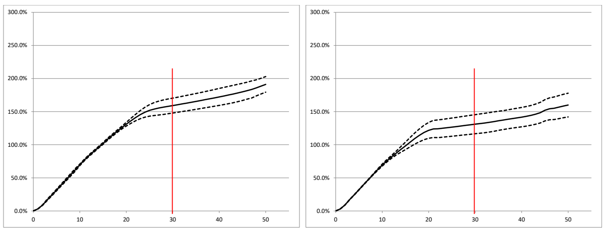
(a) 180 ℃ (b) 210 ℃

Fig. 4 CTR Trace at 426 hour (17.8 day) in ALT



(a) 180 ℃ (b) 210 ℃

Fig. 5 CTR Trace at 576 hour (24.0 day) in ALT



(a) 180 ℃ (b) 210 ℃

Fig. 6 CTR Trace at 661 hour (27.5 day) in ALT

3. ALT Data Analysis

Curve fitting by exponential regression was performed for the degradation trends in the CTR of photo-coupler measured under stress conditions during the ALT. Figure 7 and 8 below shows a curve fitting of data measured CTR at 30 V under 180 ℃ and 210 ℃ conditions. The x-axis is aging time (days) under accelerated condition and the y-axis is measured CTR value (%). In the graph, the solid line for the round point is the average, and the dotted line for the dash is reflected in the standard deviation (σ).

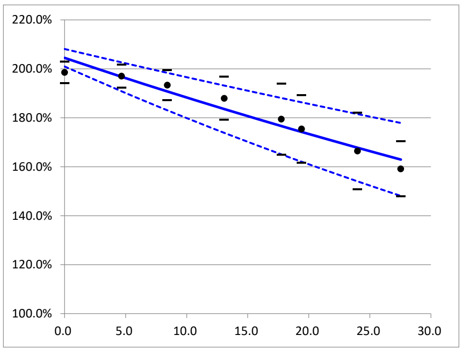


Fig. 7 CTR Trend Curve Fitting under 180 ℃ (Vcc = 30 V)

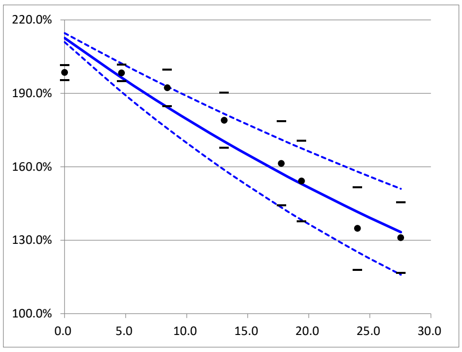


Fig. 8 CTR Trend Curve Fitting under 210 ℃ (Vcc = 30 V)

3.1 Arrhenius Model

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

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

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).

$$x = K \cdot t = a \;\rightarrow\; L = t = a/K \qquad (2)$$

$$\ln L = \ln a - \ln K \qquad (3)$$

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

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

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

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

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.

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

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

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

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 Life Curve of CTR of photo-coupler in Normal Operating Condition

The normal operating conditions of the photo-coupler is room temperature. Applying the above Arrhenius model to the ALT results gives the following life curves as shown in Figure 9 below. The following life curve is the result of applying to normal operating conditions for room temperature. In the graph, the x-axis is the cumulate operating duration (year) of the electronic component, photo-coupler, and the y-axis is CTR (%). A solid line in the graph is the average, and the dotted line reflects the standard deviation. [3], [4]

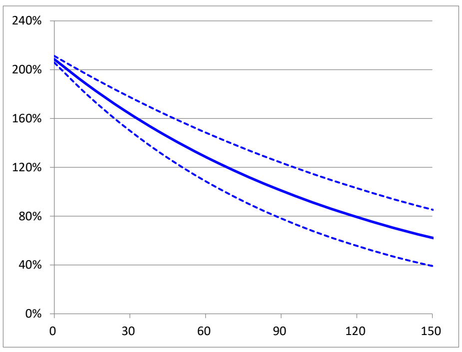


Fig. 9 Predicted Life Curve of the CTR of photo-coupler in Operating Condition

4. Conclusions

In this study, ALT by thermal stress for the photo-coupler is carried out. We traced the degradation of the CTR, which is most important performance indicator of the photo-coupler. And performance degradation curve for CTR of the photo-coupler at room temperature, which is normal operating condition, has extracted in this study. Failure mechanisms that decrease the CTR may be varied and should be identified, but the performance degradation curve has extracted by thermal 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.

ACKNOWLEDGMENTS

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