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Step-stress accelerated testing of high-power LED lamps based on subsystem isolation method

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ABSTRACT

The lifetimes of high-power light-emitting diode (LED) lamps are investigated by step-stress accelerated test. The entire lamp is divided into three subsystems, namely, the LED light source, the driver, and the mechanical fixture. Step-stress accelerated tests are conducted on the LED light source only, which is placed in a thermal chamber and connected to other subsystems outside the aging furnace. Thus, the highest possible stress level can be reached for the LED light source. The reliability characteristics of the LED light source are analyzed based on the step-stress accelerated degradation test model. The fault tree and Monte Carlo algorithm are used to deduce the reliability of the entire LED lamp. The case study shows that the tested samples underwent similar degradation mechanisms under three reasonable stress levels and that the proposed procedure is fast and effective in accelerating the decay process of LED lamps. The predicted LED lamp lifetime is close to the value specified by the LED lamp manufacturer. The proposed subsystem isolation method can overcome the obstacle resulting from the significant difference between the breakdown stress limits of each subsystem.

1. Introduction

Light-emitting diodes (LEDs) have triggered a revolution in illumination because of its distinct advantages, such as long lifetime, energy efficiency, and low environmental impact. However, when LEDs are subjected to electrical and thermal stresses, the resulting material degradation and structural damage could result in lumen degradation, color shift, or even early decommissioning of LEDs. The reliability of LED products has become a significant concern [1].

The lifetime of an LED lamp is defined by the Illuminating Engineering Society (IES) under the standards LM-79 and LM-80. Similarly, the Energy Star TM-21 procedure specifies the process for lumen maintenance over time with its current input and working conditions [2]. These procedures are time-consuming. LM-80 requires at least 6000 h of testing to achieve reliable long-term predictions. IES LM-84 and TM-28 require a minimum of 3000 h of testing [3]. In recent years, select studies have investigated reliability modeling and lifetime prediction for the LED lamp system. Villanueva et al. [4] presented a reliability testing method for LEDs based on overstress life test method. However, when they attempted to evaluate the reliability of portable lamps, only a few lamps passed the test [4]. Considering the degradation of the epoxy lens and plastic package, Koh et al. [5] introduced simplified Eyring models to predict the lifetime of a lighting system under changing conditions. Moreover, researchers have developed reliability models for lamp systems, such as a generic system level approach [6], an approach using design for reliability [7], a hierarchical life prediction model [8], and a nonlinear filter-based approach [9]. Evidently, a good reliability testing method for LED lamp systems has not been achieved.

Over the past decade, many studies were conducted on junction temperature measurement, modeling of reliability tests, and lifetime prediction of LED packages/modules [9,10]. However, the measurement or prediction of the lifetime of LED lamps or luminaires remains a challenging task. The significant temperature gap observed at the heat sink surface of lamps with/without lampshade [11] indicates that the thermal performance of an LED package or module is different from an LED package or module assembled in a lamp. Normally, an LED lamp is an integrated unit comprising four subsystems [12], namely, the LED light engine, the electronic driver, the mechanical housing, and the optical lens or bulb. The reliability profile of each subsystem and that of the integrated lamp system is closely related.

For an LED lamp with a long life span, acquiring life data under normal operating conditions is impractical. The traditional constant-stress accelerated tests usually require a long test duration, a complicated stress level selection process, large sample sizes, and high test costs. Step-stress accelerated degradation test (SSADT) methods are characterized by special advantages, such as suitability for long-life products, short testing times, and small sample size, which make them more suitable for LED products [13,14]. In previous studies [11], SSADT was used to evaluate the accelerated test method for LED systems using

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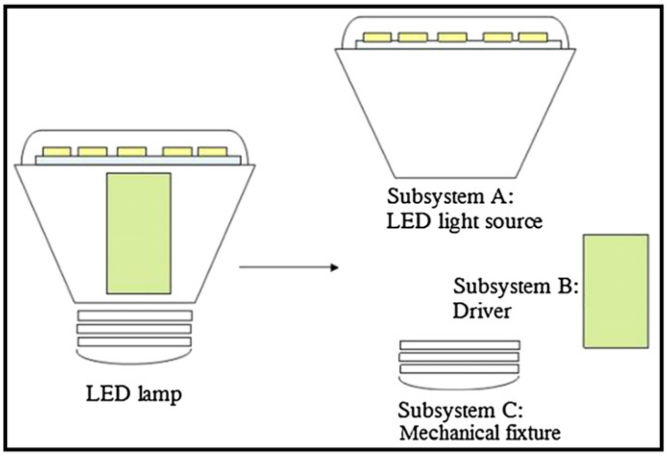

Fig. 1. Diagram showing the subsystems of the LED lamp.

commercially available LED bulbs and lamp cups. The effective degradation paths revealed that a fast lifetime qualification procedure can be developed for LED lamp systems using step-stress testing under ambient conditions. Many challenges on reliability testing of LED lamp systems were highlighted by previous studies [6,7,11]. First, many unexpected failure modes are observed at the system level after stress accelerated tests. Second, a considerable gap was observed between identified lifetime spans of subsystems. Third, models that are appropriate for assessing the LED system lifetime are lacking.

In this study, the integrated LED lamp is considered a system. First, the entire LED lamp system is divided into three subsystems, such that an objective subsystem can undergo a reliability test at the highest possible stress level. Second, SSADT is applied only to the LED light source subsystem to obtain its reliability distribution function. Then, the reliability of the LED light source subsystem is extrapolated using the SSADT model. Finally, the reliability of the entire LED system is deduced via the fault tree and Monte Carlo algorithm. The results of one case study are provided to analyze the feasibility of the proposed procedure.

2. Subsystem isolation reliability test procedures

2.1. Test setup and testing profile design

During a high thermal stress test, when the LED lamp fails, the electronic driver component fails before the LED module does [7], which is normally the result of the stress limit gap between subsystems. Given the complex system integration of LED lamps, the entire system is separated into several subsystems, such that each individual subsystem can undergo a reliability test using the highest possible stress levels. As

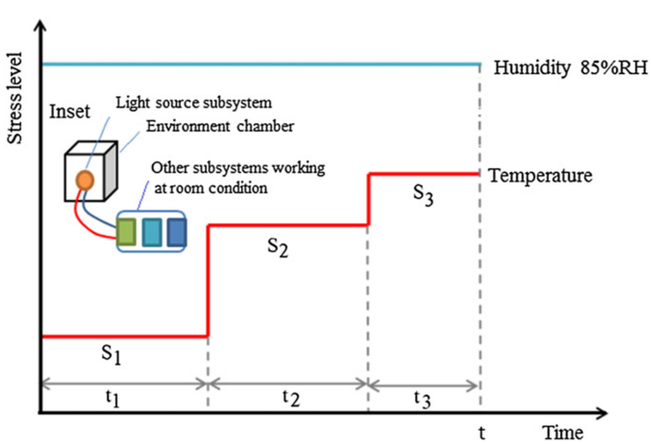

Fig. 2. The SSADT profile (inset: test setup schematic).

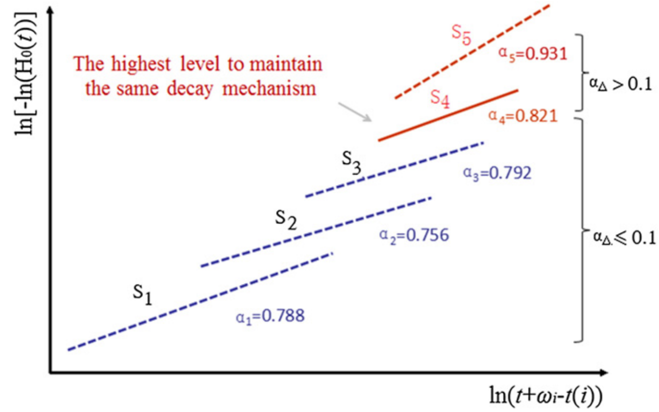

Fig. 3. Schematic diagram to verify the decay mechanisms at different stresses [14].

shown in Fig. 1, the lamp system is divided into three subsystems, namely, the driver, the fixture, and the LED light engine. The light engine subsystem consists of the lamp cover, LED module, and heat sink. All of these parts affect the light and thermal performances of the LED module during operation.

For the high-power LED module, one of the critical failure mechanisms (FMs) is the chemical degradation of LED packages with subsequent worsening of its optical properties [15]. A previous study has proven that the increase in stress temperature results in the increase in the degradation rate [15]. Furthermore, moisture is one of the factors that speed up the degradation process in actual operating environments [16]. Moreover, the maximum moisture concentration inside the package may be greater for a device at operating conditions, although the local environment has less humidity [17]. In this study, given the goal of speeding up the accelerated testing process for the LED light engine under the package-related FMs, SSADT method is used with constant humidity. As shown in Fig. 2, the stress profile consists of constant humidity (85% RH) and three-step thermal stresses. As shown in the inset of Fig. 2, the light source subsystem is accelerated inside a thermal chamber and connected to other subsystems outside the chamber.

The thermal stress levels are designed based on the thermal limit of the light source subsystem. Highly accelerated life testing (HALT) [18] is applied to identify the limits before using SSADT. During HALT, change in the parameters of the light source subsystem, such as lumen maintenance, color rendering index, chromaticity coordinate, junction temperature, and optical efficiency, is observed. Then, the temperature stress limit of the light source subsystem is identified based on the abnormal thermal stress level. In the present study, the stress limit will be verified by the data collected after the accelerated test. The duration of each stress phase is calculated using the accelerated factor with the same degradation quantity at each stress level. Tseng et al. [14] detailed the steps to calculate duration. During the test process, thermal and electronic parameters should be monitored regularly to ensure that the lamp is operating normally. Lumen maintenance of the light source should be measured more than three times in each stress level.

2.2. Methodology for calculating light source reliability

A known composite exponential model [19] is used to describe the degradation path of LED lamp and to conduct reliability extrapolation, as follows:

$$L(t|S_i) = \exp\{-\beta_i t^{\alpha}\}, \quad 1 \le i \le m \tag{1}$$

where parameter β_i depends on stress level S_i and α is a value associated with the decay mechanism of accelerated products and can detect the limit of stress in the reliability test [14]. Normally, α depends on the product used, is constant, and is independent of stress. In this study, α