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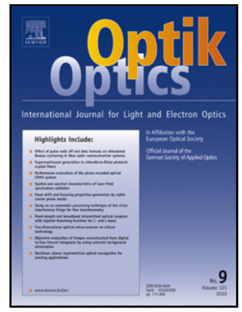

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PII: S0030-4026(18)31444-X
DOI: https://doi.org/10.1016/j.ijleo.2018.09.131
Reference: IJLEO 61570

To appear in:

Received date: 6-4-2018
Accepted date: 24-9-2018

Please cite this article as: Hao J, Rui-Qiang Y, Ke H-Liang, Sun Q, jing L, Analysis of the reliability of LED lamps during accelerated thermal aging test by online method, *Optik* (2018), https://doi.org/10.1016/j.ijleo.2018.09.131

Analysis of the reliability of LED lamps during accelerated thermal aging test by online method

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Abstract: In order to shorten the accelerated aging time, it is necessary to select a reasonable thermal stress without changing the failure mechanism. In this paper, a short-cycle step-stress test is introduced to determine the stress limitation of LED, which is about 90℃ for the samples used in this work. The online method which means the lumen degradation of samples is obtained at aging condition is applied, and the error of measured luminous flux is simulated by the software of Tracepro. In data procession, the exponential fitting and Bayesian method are firstly carried out to get the lifetime and failure probability of each lamp under accelerated stress. Then the characteristic lifetime and shape parameter of samples is calculated according to Weibull distribution. Finally, the Weibull distribution curve at room temperature can be obtained by using the Arrhenius model. For the samples in this work, the correspondent lifetimes are respectively obtained to be 32,251 hours with the failure probability of 63.2%. And compared with the method of Energy Star standards, it is confirmed that the method is effective.

1. Introduction

With vigorously implement of the plan of banning incandescent lamp in the global, LED products are widely used in various lighting fields. Although its advantages in energy conservation and environmental protection have been widely admitted, its long lifetime and good reliability are still being questioned [1-3]. An unavoidable issue appears that is how to acquire the lifetime of LED in a shorter test time. Currently, the test time in most reports is recommended to be at least 6000 hours, such as the IES LM-79 [4], IES LM-80 [5], IES TM-21 [6] and IES TM-28 [7] standards. The standards of IES TM-21 and IES TM-28 also recommend a relationship of 3 to 6 times between the actual lifetime and test time for different LED samples. Obviously the test time of 6000 hours restricts the replacement rate of LED products, and therefore various methods of accelerated aging test of LED have been proposed, such as constant-stress aging test [8-11] with elevated stresses such as temperature, humidity and current, or step-stress aging test [12-14] for LED light source module.

The lifetime of LED under normal operating conditions is normally projected by using the Arrhenius model with the accelerated lifetime predicted in an accelerated aging test. It is worth noting that the measurement of LED degradation behavior can be divided into the online method and offline method. In the online method, the degradation behavior of LED is obtained at the aging condition, while the LED has to be taken out of the aging condition for lumen measurement at room temperature in the offline method. In our previous works, the accelerated aging tests of LED lamps at various ambient temperatures are conducted where the lumen maintenances were measured by the online method, and then are used to deduce the accelerated lifetime of the lamp [15-18]. It has been verified that the accelerated lifetime of lamp given by online test is in a good agreement with that given by results in 6000 hours test at room temperature. However, there has been no report about the selection of accelerated stress and the lumen error of online measurement, to our best knowledge.

In this paper, a short-cycle step-stress test is applied, and the luminous flux of samples after different thermal stresses is recorded for determining the stress limitation. The Tracepro software is used to analysis the error of online measurement, and the failure probability is calculated by the Bayesian method.

2. Theory models

As we all know, the lumen maintenance of LED lamps meets the exponential decay, which is

$$\frac{\Phi_t}{\Phi_0} = \exp(-\beta_T t) \tag{1}$$

where $\frac{\Phi_t}{\Phi_0}$ is the lumen maintenance, β_T is the decay rate, *t* is the operating time, *T* is the junction temperature. When $\frac{\Phi_t}{\Phi_0}$ =0.7, the time *t* is considered to be the lifetime of LED products, namely,

$$t = -\frac{\ln(0.7)}{\beta_T} \tag{2}$$

According to Bayesian statistics [19], in the case of sample information and priori information, the posterior probability density of lifetime for the i-th failure luminaire is

$$h(F_i \mid r) = \frac{L(r_i \mid F_i)\pi(F_i)}{\int_0^1 L(r_i \mid F_i)\pi(F_i)}, i = 1,2,\ldots 10 \quad (3)$$

where $h(F_i \mid r)$ is the posterior probability density of failure probability, r represents the number of failures in the i-th group, $L(r_i \mid F_i)$ is the likelihood function of samples, $\pi(F_i)$ is the priori probability density function of samples. The correspondent expressions are

$$\begin{cases} L(r_i \mid F_i) = C_{s_i}^{e_i} F_i^{e_i}(1 - F_i)^{s_i - e_i}, 0 < F_i < 1 \\ \pi(F_i) = \iint_D \pi(F_i \mid a, b)\pi(a, b)dadb \end{cases} \quad (4)$$

where s_i is the sample numbers 10, $e_i = \sum_{j=1}^{i} r_i, i = 1,2,\ldots 10$, it's the numbers of cumulative failure, $\pi(F_i \mid a, b)$ is the Beta distribution, $\pi(a, b)$ is the prior distribution of two ultra parameters a, b , their expressions are as follows,

$$\begin{cases} \pi(F_i \mid a, b) = \dfrac{F_i^{a-1}(1 - F_i)^{b-1}}{B(a, b)} \\ \pi(a, b) = 1/(c - 1), 0 < a \le 1, 1 < b < c \end{cases} \quad (5)$$

where *B(a,b)* is the beta function, the expression is $B(a, b) = \int_0^1 t^{a-1}(1 - t)^{b-1} dt$, the value of c is 4, Bayes estimation $\hat{F}_{iB}(a, b)$ of F_i is as follows:

$$\hat{F}_{iB} = \int_0^1 h(F_i \mid x) F_i dF_i \quad (6)$$

The lifetimes of LED are consistent with Weibull distribution[20-21]:

$$F(t) = \hat{F}_{iB} = 1 - e^{-(\frac{t}{\eta})^m} \quad (7)$$

where $F(t)$ is the failure probability, m is the shape parameters, and η is characteristics lifetime.

2.2 Derivation of lifetime at room temperature

With characteristic lifetimes under two thermal stresses, the activation energy can be obtained according to equation (1):

$$E_a = \frac{k \ln(\eta_j / \eta_{j+1})}{1/T_j - 1/T_{j+1}} \quad (8)$$

where η_j and η_{j+1} are the characteristic lifetimes under j-th and (j+1)-th thermal stresses, respectively. The characteristic lifetime of LED product at ambient temperature of 25 ℃ is then calculated by:

$$\eta_{0j} = \eta_{T_j} \exp\left[\frac{E_a}{k}\left(\frac{1}{T_{0j}} - \frac{1}{T_j}\right)\right] \tag{9}$$

where η_{0j} is the characteristic lifetime at ambient temperature of 25 ℃, η_{T_j} is the accelerated characteristic lifetime, T_j is the junction temperature under accelerated condition and T_{0j} is the junction temperature under the ambient temperature of 25 ℃.

3. Experiments and analysis

3.1 Selection of accelerated stress

Before the accelerated aging test, it is necessary to determine the applied thermal stress, as to shorten the aging time of LED without changing the failure mechanism. However, the selection of thermal stress is always based on the experience such as in researches and the values provided by manufactures. In this research, a short-cycle step-stress test is applied, and the luminous flux of samples after different thermal stresses is recorded for determining the stress limitation. Finally the other LED samples from the same batch can be tested under the thermal stress selected below the stress limitation.

During the short-cycle step-stress test, the humidity is maintained to be 50% with the thermal stress less than 100℃, which gets meaningless with thermal stress exceeding 100℃. The thermal stress from 40℃ to 130℃ at an interval of 10℃ is used, and each stress is applied for 12 hours. Fig. 1 shows the applied short-cycle step-stress in this work. The LED samples are taken out of the thermal chamber after each aging step, and get cooled for 2 hours at room temperature of 25℃. Then the correspondent luminous flux at each aging step is measured at 25℃. Fig. 2 gives the measured luminous flux at each aging step, and each value is normalized to the value measured at 40℃ for each sample.

For the LED samples used in this work, the luminous flux can be maintained within 97% to 99% with the thermal stress less than 90℃, and decreases obviously with the thermal stress exceeding 90℃, which gives a lumen maintenance lower than 87% at 130℃. As a result, 90 ℃ is taken as the stress limitation of samples which represents the changing point of failure mechanism. To avoid the unexpected situations, 80℃ is selected as a higher accelerated aging temperature, and a lower one is 60℃.

3.2 Test platform and error analysis of online measurement

Fig. 3 is the platform of the accelerated aging test for LED samples by online method. The system is composed of the display system, control system, integrating sphere, rotary shelf, and thermostat box. The lamp can be rotated to the test channel between integrating sphere and thermostat box by rotary shelf of multi-position. The side opening of the integrating sphere is closely connected to the window of the chamber. To achieve thermal isolation between the integrating sphere and the chamber, a special hood made of vacuum glasses is placed at the window.

The diameter of light emitting surface of LED lamp is about 75mm, and the diameter of test window of integrating sphere is 150mm. Therefore, the measured luminous flux is not the total luminous flux of LED lamp, and part of luminous flux escapes from the window of integrating sphere. On the other hand, the position of lamp in the integrating sphere will also affect the measurement of luminous flux. In this paper, the Tracepro software is used to simulate the test system and analyze the two problems mentioned above. Fig.4 is the simulated test process.

The simulation results shows that only 65.8% of luminous flux of LED lamp can be tested when the front-head of lamp completely enters the integrating sphere as that in position 1 in Fig.4, which means nearly 35% of luminous flux gets lost. As the lamp is gradually pushed into the integrating sphere, the measured luminous flux gradually increases. 93.5% of luminous flux can be measured when the lamp is pushed into the 1/4 radius of integrating sphere as that in position 2. 93.8% of luminous flux can be measured when the lamp is pushed into the center of integrating sphere as that in position 3. In other words, the luminous flux tested in position 2 and position 3 makes no differences, and most luminous flux can be acquired. Therefore, the position 2 is selected as the test position of luminous flux as to reduce the difficulty in mechanical design.

3.3 Experiments

Samples are encapsulated by Lide company with the same components including LED chips from Epistar company, yellow phosphor ($Y_3Al_5O_{12}$:Ce) from Frirem Adnanced Materials company, 6630 potting glue, DX20C patch glue and driver from Lide company. Before the accelerated aging tests, samples have experienced environmental tests of vibration, shock, current and the high-low temperature. The junction temperature of the LED samples are acquired by means of diode forward voltage measurement with pulsed currents [22], which are about 338 K， 368 K and 386 K at ambient temperatures of 25℃, 60℃ and 80℃, respectively. Accelerated aging test of LED lamps are conducted by using of the online method. One group with 10 samples is aged at ambient temperature of 60 ℃ for 3000 hours, and another group is aged at 80 ℃ for 2000 hours. The lumen maintenance is shown in Fig.5, where Fig.5 (a) is the results at 60℃ and Fig.5 (b) is that at 80℃.

4 Data analysis

4.1 The date analysis of accelerated aging test

Firstly, the lumen maintenance of each lamp is fitted by the exponential decay law, and the accelerated lifetimes of ten lamps are obtained by Eq. (2). Table 1 lists the results of the accelerated aging tests. The second line is the failure time of 60℃, and the third line is the failure time of 80℃.

According to the Bayesian statistics as that in from Eq.(3) to Eq.(7), the value of $\hat{F}_{iB}(a,b)$ can be obtained as shown in Table 2. It can be seen that the number of cumulative failure gradually increases, and the failure probability becomes larger as the failure time increasing.

The least square method is used to fit the dates of failure time and failure probability in Table 2, and thereby the shape parameter and characteristic lifetime of Weibull distribution can be calculated. The characteristic lifetime and shape parameter are respectively 8401 hours and 4.1217 at 60℃, 5274 hours and 2.6575 at 80℃.

The activation energy can be calculated according to Eq. (8):

$$E_a = \frac{k\ \ln(\eta_{60}/\eta_{80})}{1/T_{60} - 1/T_{80}} = 0.3168\ eV \tag{10}$$

According to the equation (9), the lifetime of LED is calculated at room temperature as:

$$\eta_0 = \eta_{60}\exp(\frac{Ea}{k}(\frac{1}{T_0} - \frac{1}{T_{60}})) = 32251\ hours \tag{11}$$

As a result, the correspondent failure probability distribution over time can be calculated, and the characteristic lifetime of LED with different failure probability can be thereby obtained, which is 32251 hours.

4.2 Comparison with LM-84 combined with TM-21 standard test

To verify the effectiveness of the test method, we implement the lifetime test of the same type of lamps based on Energy Star standards which is 6,000 hours aging test at ambient temperature of 25℃. The number of sample is ten. Fig. 6 shows the variations of lumen maintenances of lamps over time. The lumen maintenances are then fitted by exponential function. As shown in Fig.6, the lifetimes of about 90% of samples are about 30,000.

Therefore, the selection of stress is reasonable and the failure mechanism of the samples was not destroyed. And the 93.8% of luminous flux can be used to deduce the lifetimes of LED lamps.

5. Conclusions

In this paper, twenty LED lamps are tested in the accelerated aging test with online method. Firstly, a short-cycle step-stress test is applied to select the thermal stress, and the aging temperatures are determined to be 60℃ and 80℃, which are below the stress limitation of 90℃. Secondly, the Tracepro software is used to analysis the lumen error in the measurement of online test, and the result shows that the 93.5% of luminous flux of LED lamp can be obtained in the online test of this work. The Bayesian method is used to calculate the failure probability, and the correspondent lifetimes is 32,251 hours with the failure probability of 63.2%. And compared with the method of Energy Star standards, it is confirmed that the method is effective.

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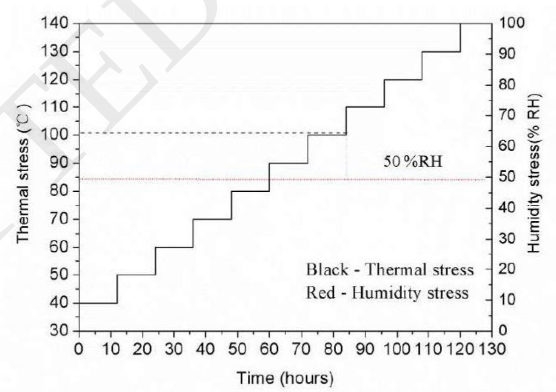


Fig.1 Applied short-cycle step-stress

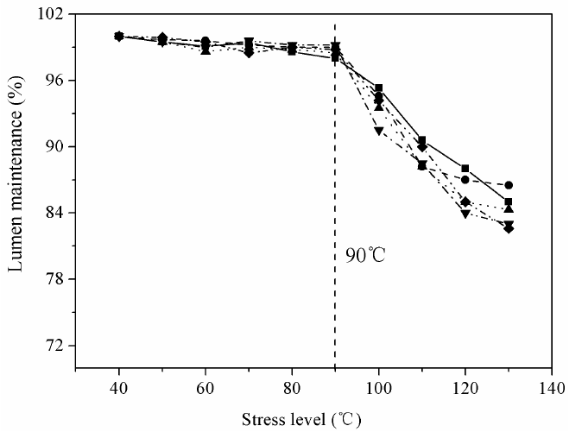


Fig. 2 Measured lumen flux at each step

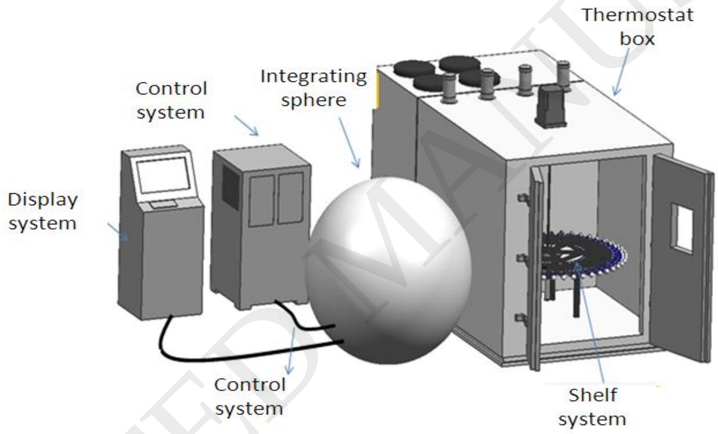


Fig.3 The platform of the accelerated aging test for LED lamps

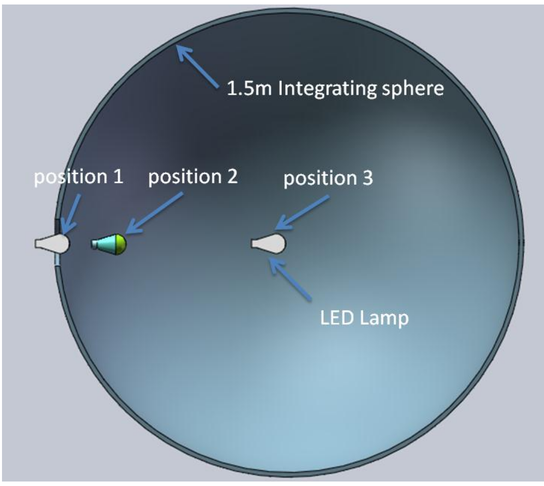
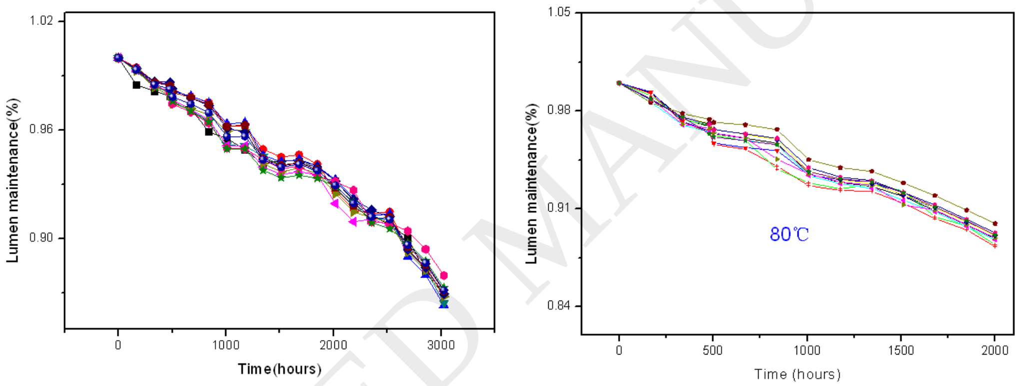


Fig.4 Simulated test process by use of Tracepro software



(a) (b)

Fig. 5 The change of lumen maintenance (a) at 60℃, (b) at 80℃

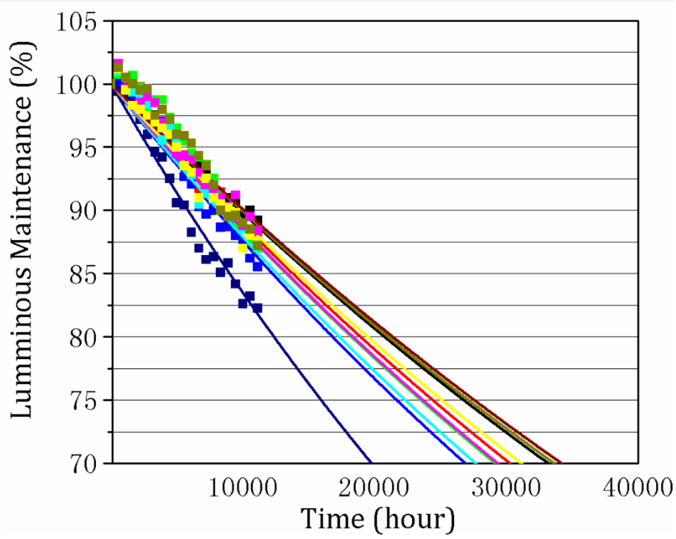


Fig. 6 The variation of lumen maintenance over time.

Table1 Calculated accelerated lifetime.

No.	1	2	3	4	5	6	7	8	9	10
t_{60} (hours)	7822	8033	8199	8553	8785	8895	9193	9240	9264	9991
$t_{80℃}$ (hours)	5052	5074	5110	5177	5635	5644	5819	6056	6182	6966

Table 2 Failure probability of cumulative failure numbers for LED lamps

i	1	2	3	4	5	6	7	8	9	10
$t_{60℃}$ (hours)	7822	8033	8199	8553	8785	8895	9193	9240	9264	9991
$t_{80℃}$ (hours)	5052	5074	5110	5177	5635	5644	5819	6056	6182	6966
<InlineImage4 1>	1	2	3	4	5	6	7	8	9	10
<InlineImage4 2>	46.21 %	55.96 %	62.67 %	67.58 %	71.33 %	74.31 %	76.72 %	78.71 %	80.39 %	81.82 %