The Design of Two-Step-Down Aging Test for LED Lamps Under Temperature Stress

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***Abstract*— In this paper, the step-down aging test for light-emitting diode (LED) lamps is designed according to the stopping rule of the IESTM-28 standard and experimental data. The step-down aging experiment is under the temperature stresses of 90 °C, 80 °C, 70 °C, and 60 °C, from which the temperatures for two-step-down aging test are selected. A Nelson model is used to calculate the equivalent time from one temperature to another, and a two-stage method is adopted to establish the reliability model of LED lamps under accelerated temperature. Then, the lifetime at the ambient temperature of 25 °C is deduced by the use of Arrhenius model. It is shown that the temperatures of 90 °C and 80 °C for two-step-down aging test are the best choice, with standard deviation of reliability and standard deviation of relative lifetime less than 11% and 20%, respectively. The accelerated aging time is <1200 h, which meets the requirement of quick lifetime prediction of LED lamps.**

***Index Terms*— Least square method (LSM), lifetime prediction, light-emitting diode (LED), two-stage method, two-step-down accelerated test, Weibull distribution.**

I. Introduction

AS THE new energy source of fourth generation, LED has been widely used in various lighting fields [1]–[3]. However, its advantages of long lifetime and good reliability are still being questioned. Currently, the aging test of LED products is all with the standard of IES as in [4]–[8], and the test time is recommended to be 6000 h at least. As a consequence, quick and accurate prediction method of lifetime and reliability for LED products becomes a new research focus [9]–[13]. Qian *et al.* [12] and Chan *et al.* [13] reported the accelerated aging tests under constant temperature stress. To deduce the lifetime at the ambient temperature of 25 °C from the data of accelerated aging tests, which needs the value of activation energy of LED, at least two groups of samples are required for two tests with different temperatures. Obviously, with this method, the inconsistency of two groups of samples leads to certain error in lifetime prediction of LED, and the total test time of two accelerated aging tests is long as using one set of equipment.

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In the step-stress accelerated test, the equivalent time under different stresses can be calculated based on the Nelson model. Liao *et al.* [14] reported a step-stress aging test for LED light source module under five temperatures from 25 °C to 105 °C, which was with total 10 000 h. Tang *et al.* [15] reported a step-stress aging test for LED light source module under three temperatures from 45 °C to 85 °C, which was with total 2300 h. Hu *et al.* [16] reported an improvement approach of algorithm in [15]. Ren *et al.* [17] also reported step-stress aging test for LED luminaires under three temperatures from 45 °C to 95 °C, which was with total about 2000 h. Obviously, the issues about quick prediction (such as 1200 h) of lifetime and best selection of temperatures in step-stress aging test for LED lamps have not been well solved.

In this paper, under the condition of Weibull distribution [18]–[21], the optimized design of step-down accelerated aging test for LED lamps is presented. First, the step-down aging experiment is conducted under four temperatures from 90 °C to 60 °C with a group of samples. From the experimental data, the temperatures for two-step-down aging test are selected with the criteria of minimum of standard deviation of reliability and minimum of standard deviation of relative lifetime of samples. Then, the accelerated lifetimes at selected temperatures are estimated by the two-stage method, and the lifetime of LED lamps at the ambient temperature of 25 °C is deduced by the use of the Arrhenius model.

The two-step-down accelerated aging test possesses two advantages. The use of one group of samples ensures the consistency of the measurement so as to achieve more accurate lifetime prediction, and the total time of accelerated aging test is shortened by the use of the Nelson model. The designed aging test is of quick lifetime prediction less than 1200 h in this paper.

II. Theory Models

A. Nelson Model

The lumen maintenance of LED lamps meets the exponential decay law

$$\Phi_j = \exp(-\beta_{T_j} t_j) \quad (1)$$

where Φ_j is the lumen maintenance under the jth ($j = 1, 2, \ldots, k$) temperature stress, β_{T_j} is the decay rate at junction temperature of T_j, and t_j is the accelerated time. It is considered by the Nelson model that the cumulative amount of degradation with working time of t_j and stress level of T_j is equal to the cumulative amount of degradation with working time of t_{j+1} and stress level of T_{j+1} for LED lighting products. That is

$$\Phi_{j+1}(t_{j+1}) = \Phi_j(t_j) \tag{2}$$

where t_{j+1} is the equivalent test time from T_j to T_{j+1}. Combining (1) and (2), we have

$$t_{j+1} = \beta_{T_j} \frac{t_j}{\beta_{T_{j+1}}}. \tag{3}$$

Then, the actual accelerated time can be obtained

$$t_{j+1\_\text{ture}} = t'_{j+1} + t_{j+1} \tag{4}$$

where t'_{j+1} is the accelerated time under T_{j+1} stress. Substituting (4) into (1), we have lumen maintenance under T_{j+1} stress as

$$\Phi_{j+1} = \exp(-\beta_{T_{j+1}} t_{j+1\_\text{ture}}). \tag{5}$$

When Φ_{j+1} equals 0.7, the time is considered to be the lifetime of τ_{j+1} of LED product. Therefore, the accelerated lifetime of LED lamp can be obtained under T_{j+1} stress

$$\tau_{j+1} = \frac{\ln(0.7) \times t_{j+1\_\text{ture}}}{\ln \Phi_{j+1}}. \tag{6}$$

Combining (4)–(6), we can obtain the accelerated lifetime of lamp.

B. Two-Stage Method

At the first stage of the two-stage method, the reliability model of a decay rate of LED lamp is consistent with Weibull distribution [18]–[21]

$$F(\beta_{T_j}) = 1 - R(\beta_{T_j}) = 1 - e^{-\left(\frac{\beta_{T_j}}{\eta_j}\right)^{m_j}} \tag{7}$$

where $F(\beta_{T_j})$ is the failure probability, $R(\beta_{T_j})$ is the reliability, m_j is the so-called shape parameter, and η_j is the characteristic parameter. Failure probability of each lamp is calculated by the use of median rank method, that is

$$\widehat{F}(\beta_{T_j}) = \frac{i - 0.3}{n + 0.4} \tag{8}$$

where i is the number of the ith lamp and n is the size of test samples. The shape parameter and the characteristic parameter in (7) can be then obtained by the use of least square method (LSM) [20].

The second stage is based on Monte Carlo simulation. N random decay rates in accordance with the acquired Weibull distribution are generated with the command of wblrnd in MATLAB Statistics Toolbox. Then, the procedure is divided into two paths. For path ①, the shape parameter and the characteristic parameter of Weibull distribution can be solved with the N decay rates by the use of LSM. For path ②, N lifetimes corresponding to the N decay rates are calculated according to (1). The failure probability with respect to time, $F(t)$, is then given by

$$F(t) = \frac{\text{Number of simulated first crossing times}}{N} \tag{9}$$

where numerator represents the number of lifetime less than or equal to t and denominator represents the total random number. The correspondent medium lifetime of samples is calculated as $F(t)$ equals 50%. Repeating the Monte Carlo simulation for five times, the averaged medium lifetime of $\tau_{0.5_j}$ is obtained.

C. Derivation of Lifetime at Ambient Temperature of 25 °C

According to the Arrhenius model, the activation energy can be obtained with the medium lifetimes under two temperature stresses

$$E_a = \frac{k \ln(\tau_{0.5_j}/\tau_{0.5_{j+1}})}{1/T_j - 1/T_{j+1}} \tag{10}$$

where $\tau_{0.5_j}$ and $\tau_{0.5_{j+1}}$ are the medium lifetimes under junction temperatures of T_j and T_{j+1}, respectively. With the acquired activation energy, the medium lifetime of sample at the ambient temperature of 25 °C can be calculated by

$$\tau_{0.5\_25} = \tau_{0.5_j} \exp\left[\frac{E_a}{k}\left(\frac{1}{T_{25}} - \frac{1}{T_j}\right)\right] \tag{11}$$

where $\tau_{0.5\_25}$ and T_{25} are the medium lifetime and the junction temperature at the ambient temperature of 25 °C, respectively.

III. Experiments and Results

A. Considerations in Design of Experiments

Confidence, reliability, and sample size have a relationship as follows:

$$C = 1 - R^n \tag{12}$$

where C is the confidence, R is the reliability, and n is the sample size. If the confidence is determined, the reliability of R corresponding to the sample size of n can be obtained. According to the IESTM-28 standard [8], the ratio of the accelerated lifetime of τ_{j+1} to test time of t should be less than six when the sample size is between 10 and 19. It can be expressed as

$$\frac{\tau_{j+1}}{t} \leq 6. \tag{13}$$

In this paper, the equal interval method is adopted in the allocation of temperature stress. The two-stage method in Section II-B is used to calculate the medium lifetime for each stress. The minimum of the standard deviation of reliability is set as optimization target, and the minimum of the standard deviation of relative lifetime is set as test target for the selection of two optimum stresses.

First, the failure probability of $\widehat{F}_i(\beta_{T_j})$ of decay rate of $\beta_{T_{ji}}$ for the ith sample under the jth stress is calculated by the use of the median rank method expressed in (8), and the correspondent reliability can be written as

$$\widehat{R}_i(\beta_{T_j}) = 1 - \widehat{F}_i(\beta_{T_j}). \tag{14}$$

After the second stage of Monte Carlo simulation, the failure probability of $F_i(\beta_{T_j})$ of the same decay rate is calculated by

Fig. 1. Reliable test system.

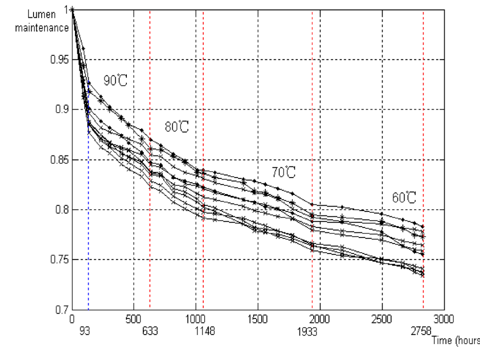

Fig. 2. Change of lumen maintenance.

the use of the solved Weibull distribution of path ①, and the correspondent reliability can be written as

$$R_i(\beta_{T_j}) = 1 - F_i(\beta_{T_j}). \tag{15}$$

The deviation of reliability for the ith lamp can be expressed as

$$\Delta R_i = \widehat{R}_i(\beta_{T_j}) - R_i(\beta_{T_j}). \tag{16}$$

The standard deviation of reliability for N lamps is calculated by

$$\sigma 1 \sqrt{\frac{\sum_{i=1}^{N} (\Delta R_i)^2}{N}}. \tag{17}$$

Second, the N accelerated lifetimes from the second stage of Monte Carlo simulation are calculated. Repeating the procedure for five times and making an average for each sample, the lifetime for the ith sample, τ_i, and the average lifetime for N samples, $\bar{\tau}$, can be obtained. Then, the standard deviation of the relative lifetime can be calculated by

$$\sigma 2 \sqrt{\frac{\sum_{i=1}^{N} \left(1 - \frac{\tau_i}{\tau}\right)^2}{N}}. \tag{18}$$

B. Analysis of Data of Step-Down Stress Test

As shown in Fig. 1, the system of the experiment consists of a high temperature box, an integrating sphere, and an optical color and electrical measurement system from ZVISION Company. The samples of LED lamps are from PHILIPS Company with the size of ten. The temperatures for four-step-down accelerated aging experiment are 90 °C, 80 °C, 70 °C, and 60 °C. The measurement of lumen maintenance of LED lamps is at the ambient temperature of 25 °C. The correlated color temperature of samples is ∼3000 K, and the color rendering indexes are greater than 80. The junction temperatures of the samples are actually measured by means of spectral analysis [22], which are 397.15, 389.15, 381.15, 373.15, and 347.15 K at the ambient temperature of 90 °C, 80 °C, 70 °C, 60 °C, and 25 °C, respectively. In accordance with (13), the accelerated aging time of t'_{j+1} is, respectively, 633, 515, 785, and 825 h under the stresses of 90 °C, 80 °C, 70 °C, and 60 °C. The acquired data of lumen maintenance are shown in Fig. 2, where the ordinate is the lumen maintenance and the abscissa is the accelerated test time. As shown in Fig. 2, the intersection point of red dotted line and the abscissa represents the deadline point of accelerated time under each stress. The data before 93 h have a relatively large drop, and thus, in accordance with standard [8], the data before the blue dotted line are not adopted.

TABLE I
ACCELERATED LIFETIMES (HOURS) UNDER DIFFERENT STRESSES

No.	90 °C	80 °C	70 °C	60 °C
1	2610	3641	4753	7329
2	2666	3657	4778	7534
3	2676	3710	5712	8187
4	2903	3726	6563	8968
5	2949	3982	6594	9808
6	2994	4647	6653	10270
7	3049	4751	7004	10360
8	3145	4771	7038	10595
9	3781	5011	7346	10751
10	3794	5048	7417	10959

With the data of lumen maintenance under the temperature of 90°, the accelerated lifetimes of the lamps for this stress are obtained by exponential fitting of (1). The results are listed in the second row of Table I. To calculate the accelerated lifetimes for the temperature of 80 °C, the data of lumen maintenance under the temperatures of 90 °C and 80 °C are used, together with the equivalent test time calculation of (3). Then, (5) is adopted for fitting and (6) is used to calculate the lifetimes of the lamps. The results are listed in the third row of Table I. Similarly, the lifetimes of the lamps for the stresses of 70 °C and 60 °C are calculated, respectively, with the data of lumen maintenance under the temperatures of 90 °C, 80 °C, and 70 °C, and the data of lumen maintenance under the temperatures of 90 °C, 80 °C, 70 °C, and 60 °C. The results are listed in the fourth and fifth rows of Table I, respectively. It is shown that the accelerated lifetimes under the stresses of 90 °C, 80 °C, 70 °C, and 60 °C are from 2610 to 3794 h, from 3641 to 5048 h, from 4753 to 7417 h, and from 7329 to 10 959 h, respectively.

At the first stage of data processing, the decay rate of $\beta_{T_{ji}}$ of the ith lamp is calculated by the use of (1), with the data in Table I. The failure probability of $\widehat{F}_i(\beta_{T_j})$ for the ith decay rate of $\beta_{T_{ji}}$ is calculated by the use of median rank method expressed in (8), and the results are listed in the second row

TABLE II
SHAPE PARAMETERS, CHARACTERISTIC PARAMETERS, AND MEDIUM LIFETIME UNDER DIFFERENT STRESSES

Stress	90 °C	80 °C	70 °C	60 °C
Shape parameter	8.0953	7.2471	5.7762	6.5185
Characteristic parameter	1.2549 e-04	9.0064 e-05	6.1868 e-05	4.1196 e-05
Medium lifetime(hours)	2978	4166	6143	9159

TABLE III
ACCELERATED LIFETIMES (HOURS) UNDER DIFFERENT STRESSES

No.	$\widehat{F}_i(\beta_{T_j})$	$F_i(\beta_{90_j})$	$F_i(\beta_{80_j})$	$F_i(\beta_{70_j})$	$F_i(\beta_{60_j})$
1	0.0673	0.0887	0.1584	0.2075	0.1940
2	0.1635	0.0911	0.1663	0.2178	0.2169
3	0.2596	0.3526	0.2286	0.2695	0.2360
4	0.3558	0.4295	0.2348	0.2759	0.2679
5	0.4519	0.4789	0.2696	0.3517	0.2812
6	0.5481	0.5221	0.6176	0.3663	0.3603
7	0.6442	0.5685	0.7889	0.3741	0.5525
8	0.7404	0.8065	0.7991	0.6460	0.7683
9	0.8365	0.8162	0.8315	0.9443	0.9199
10	0.9327	0.8670	0.8409	0.9490	0.9514

of Table III. It is noticed that the value of $\widehat{F}_i(\beta_{T_j})$ of the ith lamp is the same for different accelerated temperatures. The shape parameter m_j and the characteristic parameter η_j of Weibull distribution are calculated by the use of LSM with the data of decay rates and the failure probabilities, as described in Section II-B. They are, respectively, listed in the second row and the third row of Table II.

At the second stage of data processing, N (which is set to be 10 000, in this paper) random decay rates are generated, in accordance with the Weibull distribution acquired at the first stage, by the use of MATLAB Statistics Toolbox. In path ② of the second stage of data processing, N lifetimes corresponding to the N decay rates are calculated with (1). Then, the failure probability of N samples is obtained with (9), and the medium accelerated lifetime is calculated. Repeating the procedure for five times, we have the averaged medium accelerated lifetime. The results for the temperatures of 90 °C, 80 °C, 70 °C, and 60 °C are listed in the fourth row of Table II.

C. Selection of Stresses

First, the correspondent reliability of $\widehat{R}_i(\beta_{T_j})$ is calculated with the data in the second row of Table III. Through path ① of the second stage of data processing, the shape parameter and the characteristic parameter of Weibull distribution are solved with N decay rates. The failure probability of $F_i(\beta_{T_j})$ for the same decay rate is then calculated by the use of the solved Weibull distribution. The results are listed in the third, fourth, fifth, and sixth rows of Table III for the accelerated temperatures of 90 °C, 80 °C, 70 °C, and 60 °C, respectively. The correspondent reliability of $R_i(\beta_{T_j})$ is then calculated. The deviation of reliability is obtained with the solved $\widehat{R}_i(\beta_{T_j})$ and $R_i(\beta_{T_j})$. According to (17), the standard deviations of

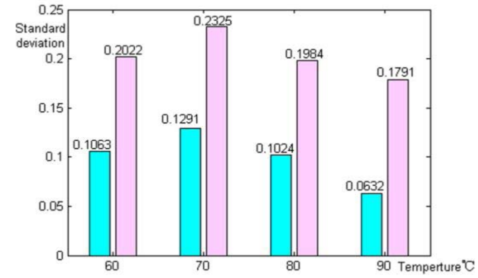

Fig. 3. Histogram of standard deviations of optimization and test target.

TABLE IV
SIMULATED ACCELERATED LIFETIME UNDER DIFFERENT STRESSES

No.	90 °C	80 °C	70 °C	60 °C
1	2203	2900	3752	6257
2	2211	2998	3953	6292
3	2214	3192	3979	6393
4	2230	3259	4012	6417
…	…	…	…	…
…	…	…	…	…
9997	7694	11308	22856	36666
9998	8013	12544	25332	38697
9999	11390	13282	26740	38708
10000	15786	15740	33449	61316

reliability are calculated, which are 0.0632, 0.1024, 0.1291, and 0.1063 for the temperature stresses of 90 °C, 80 °C, 70 °C, and 60 °C, respectively. These are shown as the blue-green histogram in Fig. 3. It can be seen that the standard deviation of reliability of 90 °C is the smallest, with that of 70 °C being the largest. The minimum of standard deviation of reliability is used to select the accelerated temperatures.

The minimum of standard deviation of relative lifetime is adopted as the test target to verify the above temperature choice. According to path ② of the second stage of data processing again, N accelerated lifetimes corresponding to N decay rates are calculated. Repeating the procedure for five times and making an average for each sample, the lifetime for the ith sample, τ_i, is calculated. The partial results of τ_i for the stresses of 90 °C, 80 °C, 70 °C, and 60 °C are listed in Table IV. It is shown that the lifetimes are from 2203 to 15786 h, from 2900 to 15 740 h, from 3752 to 33 449 h, and from 6257 to 61 316 h, respectively.

According to the data in Table IV, the average lifetimes for samples, $\bar{\tau}$, are obtained. The values of $\bar{\tau}$ for the stresses of 90 °C, 80 °C, 70 °C, and 60 °C are listed in the second row of Table V. The standard deviations of the relative lifetime are further calculated, which are listed in the third row of Table V and are also shown in Fig. 3 as the pinky histogram.

It can be seen from Fig. 3 that the temperatures of 90 °C and 80 °C are the best choice for two-step-down accelerated aging test according to minimum of standard deviation of reliability and minimum of standard deviation of relative lifetime. Besides with these two temperatures, the total time of accelerated aging test is the shortest. It is emphasized that this conclusion is correct only for the special samples of LED used in this paper. With other types of LED, the best

TABLE V
SIMULATED ACCELERATED LIFETIME UNDER DIFFERENT STRESSES

Stress	90 °C	80 °C	70 °C	60 °C
Average lifetime (hours)	3093	5046	7642	11161
Standard deviation	0.1791	0.1984	0.2325	0.2022

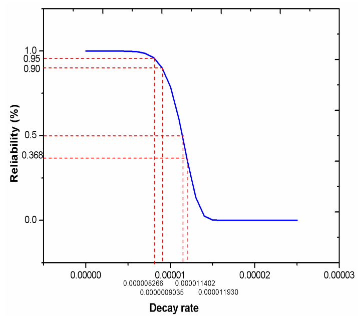

Fig. 4. Distribution of reliability.

choice of temperatures for two-step-down accelerated aging test might be different. It is noticed that the standard deviation of reliability and the standard deviation of relative lifetime under the temperatures of 70°C and 60°C are only a little bit higher than that under the temperature of 90°C, which means that these temperatures can also be chosen for two-step-down accelerated aging test in this paper.

D. Reliability Analysis

With the data of medium lifetimes at the accelerated temperatures of 90 °C and 80 °C in Table II, the activation energy of the samples is calculated by the use of (10), which is as

$$E_a = \frac{k \ln(\tau_{0.5_j}/\tau_{0.5_{j+1}})}{1/T_j - 1/T_{j+1}} = 0.5588 \text{ eV}. \tag{19}$$

Then, the medium lifetime at the ambient temperature of 25 °C is calculated, which is as

$$\tau_{25} = \tau_{T_j} \exp\left[\frac{E_a}{k}\left(\frac{1}{T_{25}} - \frac{1}{T_j}\right)\right] = 31281 \text{ hours}. \tag{20}$$

The shape parameter at the ambient temperature of 90 °C in Table II is 8.0953. We assume that the shape parameter at the ambient temperature of 25 °C, m_{25}, is the same of 8.0953. According to (1) and medium lifetime at the ambient temperature of 25 °C in (20), the correspondent decay rate of $\beta_{25\_0.5}$ is calculated, which is 1.1402e-05. The characteristic parameter at the ambient temperature of 25 °C, η_{25}, can be deduced by the use of (7)

$$\eta_{25} = \frac{\beta_{25\_0.5}}{\sqrt[m_{25}]{\frac{1}{R(\beta_{25\_0.5})}}} \tag{21}$$

where $R(\beta_{25\_0.5})$ is the correspondent reliability of a decay rate of $\beta_{25\_0.5}$. Then, η_{25} is as

$$\eta_{25} = \frac{0.000011402}{\sqrt[8.0953]{\ln\left(\frac{1}{0.5}\right)}} = 0.000011930. \tag{22}$$

Finally, the reliability curve is obtained as

$$R(\beta_{25}) = e^{-\left(\frac{\beta_{25}}{0.000011930}\right)^{8.0953}}. \tag{23}$$

Fig. 4 shows the distribution of reliability. It can be seen that as the reliability of $R(\beta_{25})$ is 36.8%, 50%, 90%, and 95%, corresponding to the confidence of C of 99.995%, 99.902%, 65.132%, and 40.126%, respectively, the decay rate of β_{25} is calculated to be 1.1930e-05, 1.1402e-05, 9.0347e-06, and 8.2660e-06, respectively. Then, the correspondent lifetimes are calculated by the use of (1), which are 29 897, 31 281, 39 478, and 43 149 h, respectively.

IV. CONCLUSION

The step-down aging experiment is conducted for a group of samples of LED lamps under four temperature stresses of 90 °C, 80 °C, 70 °C, and 60 °C. The two-stage method is used to establish the reliability model of the decay rates of samples. According to the criteria of minimum of standard deviation of reliability and minimum of standard deviation of relative lifetime of samples, the temperatures for two-step-down aging test are obtained, which are 90 °C and 80 °C in this paper. Under these temperatures, the standard deviations of reliability is <11% and the standard deviation of relative lifetime is <20%. Then, the reliability of LED lamps at the ambient temperature of 25 °C is obtained by the use of the Arrhenius model. It is shown that the corresponding lifetime is 29 897, 31 281, 39 478, and 43 149 h for the reliability of the decay rate of 36.8%, 50%, 90%, and 95%, respectively. The accelerated aging time is <1200 h, which meets the requirement of quick lifetime prediction of LED lamps.

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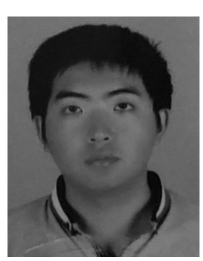

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