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Prediction of lifetime by lumen degradation and color shift for LED lamps, in a non-accelerated reliability test over 20,000 h

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Although the predicted lifetime of the classical 6000 h test given by Energy Star is taken as the normal lifetime of LED products in most research and applications, the aim of this study is to explore the error in lifetime prediction of LED lamps based on the 6000 h test. A non-accelerated aging test with 10 LED lamps is conducted for 20,000 h (from March 2016 to now) under room temperature, which is long enough for this kind of lamp reaching the real lifetime with the normalized luminous flux dropping to 70% naturally. At different aging periods, the correspondent lifetime of each sample is predicted by the lumen degradation, and the median lifetime $\tau_{0.5}$ of 10 samples is obtained by applying the Weibull distribution. Result shows that the $\tau_{0.5}$ of the real lifetime is 16,867 h in this work, and the aging time should be at least 9000 h to make the error in predicting the lifetime less than 3%. On the other hand, the $Du'v'$ values of 0.006, 0.007, and 0.008 are taken as the three thresholds for predicting the lifetime by color shift. For the case of 0.008, the calculated shape parameter of 8.4 in Weibull distribution is similar with that of the real lifetime, which means the $Du'v'$ of 0.008 for this kind of lamp gives the same failure mechanism as that of lumen degradation of 70%.

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1. INTRODUCTION

With vigorous implementation of the plan of globally banning incandescent lamps, LED products are widely used in various lighting fields. Although their advantages in energy conservation and environmental protection have been widely admitted, their long lifetime and good reliability are always being questioned, and the aging time of LED products with normalized lumen flux dropping to 70% is generally taken as the lifetime of LEDs [1–3]. As a result, the non-accelerated aging test and accelerated aging test are the two main methods used for evaluating the reliability and lifetime of LEDs.

Although the real lifetime of LEDs with lumen flux naturally dropping to 70% can be directly obtained in a non-accelerated aging test, the long-time aging process usually exceeding 10,000 hours cannot be waited in nowadays fast development of LED products. The well-known L-PRIZE [4] award was set up in 2008 to promote the development of LED lamps, and the final winner LED lamp remains a normalized luminous flux of 95.6% after 40,890 h aging at room temperature, which means it is not possible to reach the real lifetime naturally for this kind of LED lamp. To shorten and unify the aging time, the US Energy STAR proposes the classical 6000 h testing method for LED products [5,6], and the LED lifetime can be estimated by the measured lumen maintenance according to the analysis method in TM-21 [7]. Based on the testing method recommended by Energy STAR, Fan *et al.* [8], Park and Khim [9], and Lall and Wei [10] respectively report that the measured lumen maintenance of the sample is higher than 95%, 96%, and 90% after nearly 10,000 h aging in their research. As a result, the lifetime of LEDs can be just predicted by the lumen maintenance only dropping to about 95%–90%, and therefore there must be the error between the real lifetime and the predicted lifetime in the above research or 6000 h testing. Although the error may be slight, or significantly different for different kinds of LED lamps, we are indeed interested about the error and the error has not been reported yet.

The accelerated aging test under temperature stress is widely used for LED products to obtain the accelerated lifetime, and the lifetime under room temperature is predicted by using the Arrhenius model in most research [11–13], as well as in our former research [14–17]. However, the necessary parameter (activation energy, Ea) of LEDs in the Arrhenius model is a conception only defined for a single LED or LED module. For LED lamps, things get much more complicated, and the Ea of the LED module cannot be easily taken as that of the LED lamp. In our former research [18], although the LED module is the most aggressive part of the LED lamp which accounts for 70.5% of total lumen degradation, the lampshade and driver part can also degrade to different degrees. Yoon *et al.* [19] reports the compared experiment between the LED module and LED lamp, and the result shows that the performance of lumen degradation is totally different. In a step stress aging test, Cai [20] reports that the lifetime of each component of the LED lamp differs a lot, and there are many unpredictable failure mechanisms for the LED lamp. As a result, the real lifetime of the LED lamp usually cannot be accurately predicted by the accelerated aging test or by the lifetime of the LED module, owing to the undefined value of the Ea and complicated failure mechanisms.

Photometry (lumen degradation) and chromaticity (color shift) are considered to be the two main parts in the evaluation of LED reliability, and the chromaticity is often overlooked in applications such as streetlights, landscape lights, and general lights. However, the slight color shift of light in the applications of operating lights and some special occasion means a lot [21,22]. Some researchers focus on the degradation mechanism of chromaticity, including the degradation of the LED chip itself [23], the reduction of phosphor conversion efficiency [24], and the yellowing of the lampshade and lens [25]. Although the Energy Star [5,6] recommends that the color shift of LEDs should be less than 0.007 during the 6000 h test, and the U. S. Department of Energy [26] also suggests to use the color shift as a failure criterion to estimate the reliability of LEDs, the method for lifetime prediction by chromaticity, and the relationship between lumen degradation and color shift are not given specifically.

Although 6000 h is such a long time and the 6000 h test is generally applied, the main purpose of this paper is to analyze the error between the real lifetime and the predicted lifetime in the 6000 h test. In this work, 10 LED lamps were lightened since March 2016, and were already aged for 20,000 h at room temperature up to now. The real lifetime of the LED lamps with the normalized lumen flux dropping to 70% is naturally obtained after 20,000 h aging. To analyze the error in lifetime prediction at the different cutoff times, the lifetime of each sample is obtained by the exponential law, and the medium lifetime of 10 samples is obtained by the maximum likelihood function and Weibull distribution. As a result, the errors are analyzed and compared at the different cutoff times. On the other hand, the variation of chromaticity is also measured during 20,000 h, and we attempt to estimate lifetimes by color shift. Finally, the LED lifetimes predicted by lumen maintenance and color shift are compared.

2. THEORY

The lumen maintenance of LEDs meets the exponential decay law, which is

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

where Φ_t/Φ_0 is the lumen maintenance, β is the decay rate, and t is the aging time. The lifetime of LED products is considered to be the time t when Φ_t/Φ_0 drops to 70%, namely,

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

The lifetimes of all LED samples are consistent with Weibull distribution [3,17], and the probability density function of $f(t)$ and cumulative failure probability function of $F(t)$ can be written as

$$f(t) = \frac{m}{\eta}\left(\frac{t}{\eta}\right)^{m-1} \exp\left(-\left(\frac{t}{\eta}\right)^m\right), \tag{3}$$

$$F(t) = 1 - \exp\left(-\left(\frac{t}{\eta}\right)^m\right), \tag{4}$$

where m is the shape parameter, and η is the characteristics lifetime. In this work, the unknown parameters of m and η are solved by using the maximum likelihood function method. The correspondent logarithm of likelihood function, L, can be written as

$$L = \sum_{i=1}^{m} \ln\left(\frac{m}{\eta}\left(\frac{t}{\eta}\right)^{m-1} \exp\left(-\left(\frac{t}{\eta}\right)^m\right)\right), \tag{5}$$

and m and η can be obtained by applying

$$\frac{\partial L}{\partial m} = 0 \quad \text{and} \quad \frac{\partial L}{\partial \eta} = 0. \tag{6}$$

The procedure from Eqs. (3) to (6) is actually executed by the command of "wblfit" in the statistics toolbox of the software MATLAB. Then the correspondent lifetime τ of different failure probabilities can be obtained by

$$\tau = \eta\left(\ln\left(\frac{1}{1 - F(\tau)}\right)\right)^{\frac{1}{m}}. \tag{7}$$

When $F(\tau) = 0.5$, the correspondent lifetime is called the medium lifetime of $\tau_{0.5}$.

3. EXPERIMENTS

In this work, the bulb LED lamp which is manufactured by the LiDe company of HeBei province in China is taken as the sample, and the nominal power, luminous flux, correlated color temperature (CCT), and lifetime of the sample are respectively 5 W, 350 lm, 3500 K, and 15,000 h on the operating instruction. The main parameters of each subsystem of the LED lamp are listed in Table 1.

Table 1. Main Parameters of Each Subsystem

	Composition	Thirty 0.15-Watt, GaN-Based White LEDs Converted by $Y_3Al_5O_{12}$:Ce
LED Source	**input/output**	**135mA (DC)/350 lm, 3500 K**
Driver	Input/output	220 V(AC)/135 mA(DC)
Lampshade	Material	PMMA
Heat sink	Material	Aluminum

To obtain the real lifetime of LEDs with lumen maintenance of 70% naturally, the total aging time is set to be as long as 20,000 h at room temperature. The test endures such a long time that the aging process is conducted in a small room, as to make the room temperature stabilized to 22°C–25°C. The samples are arranged with five samples upward placed and five samples downward placed owing to different fluxion of heat power within the LED lamp, which is the aging arrangement recommended by Energy Star, as shown in Fig. 1. At an interval of 500 h, the optical parameter of the sample is measured by an integrating sphere system using 4π measurement, and the system is mainly composed of an integrating sphere with the diameter of 1.5 m, a spectrometer of USB-2000 of Ocean Optics, and 220 V AC power. The preheating time for each sample should be at least 20 min in the integrating sphere to obtain a stable and reliable optical parameter. As shown in Fig. 2, the lumen flux of sample 1 increases at the beginning, and then reaches a stable level after 20 min. The needed preheating time is always found to be about 20 min during 20,000 h.

During 20,000 h aging, the lifetime of the LED is analyzed and compared respectively by lumen degradation and chromaticity shift as follows.

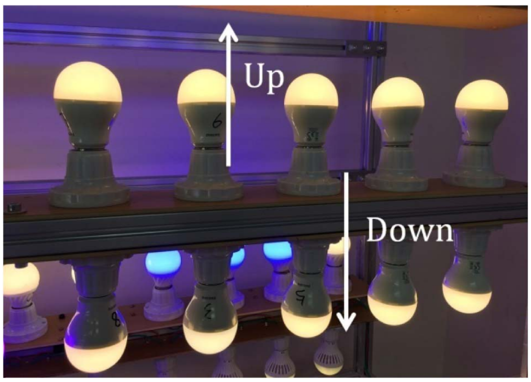

Fig. 1. Aging process of LED lamps with five samples upward placed and five samples downward placed.

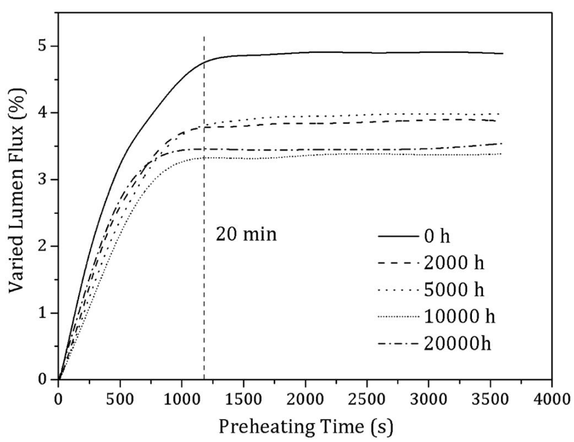

Fig. 2. Needed preheating time for sample 1 at different aging periods.

4. LUMEN DEGRADATION

A. Real Lifetime after 20,000 h Aging

Figure 3 shows the lumen maintenance of 10 LED samples during 20,000 h aging with 40 testing points totally, and each lumen flux is normalized to the value at $t = 0$. Although the lumen flux reaches a stable level after 20 min preheating as shown in Fig. 2, the lumen flux cannot always be the same one in several tests at one testing point, owing to the instability of temperature, integrating sphere system, and LED lamp itself. In Fig. 3, the error bars less than 1.5% give the fluctuation of lumen flux in three time tests at one testing point. Obviously, the lumen maintenance gives a significant fluctuation in the initial 1500 h for all samples, mainly owing to the effect of LED annealing. Although the initial fluctuation can be removed from the calculation of LED lifetime in some research, it is considered to be a part of the aging process, and remained for the calculation of LED lifetime in this work, owing to most LED products also missing the preaging part before getting into the market. During the aging period from 1500 h to 20,000 h, the lumen maintenance decays in a conventional way, and the lumen maintenance of nine samples drops to 62%–68% after 20,000 h, and it is 56% for sample 3.

Owing to the lumen maintenance less than 70% after 20,000 h aging, the real lifetime is obtained directly, as shown in Table 2, in which the real lifetimes of 10 samples are in a range from 12,127 to 19,662 h. As described in the theory part, the lifetimes of the samples are consistent with Weibull distribution, and the maximum likelihood function method is applied to solve the unknown parameters m and η of Weibull distribution. Based on Eqs. (5) and (6), the m and η correspondent to real lifetime is respectively obtained to be 8.6 and 17,474 h. Therefore, the probability density function $f(t)$ and the cumulative failure probability function $F(t)$ are then obtained based on Eqs. (3) and (4), and they are shown in Fig. 4. The medium lifetime of the real lifetime for the 10 samples is calculated to be 16,867 h.

B. Predicted Lifetime Without Sufficient Aging Time

To investigate the lifetime predicted by the measured lumen maintenance of 6000 h aging or insufficient aging time for reaching the real lifetime, the time points of 3000 h, 6000 h, 9000 h, 12,000 h, and 15,000 h are set to be the cutoff times, and the lifetime of each sample is predicted according to

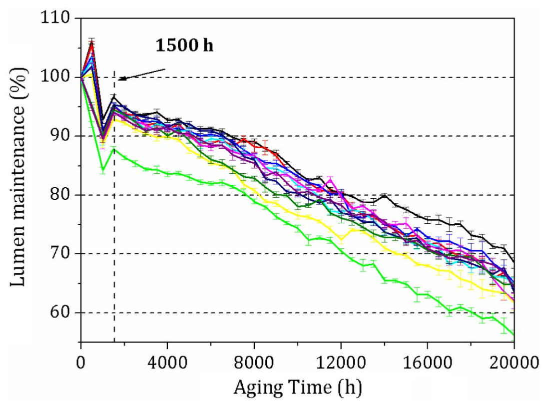

Fig. 3. Lumen maintenance for 10 samples during 20,000 h aging.

Table 2. Real Lifetime of Each Sample

Sample	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10
Real lifetime (*h*)	19,662	17,230	12,127	18,642	16,733	17,804	14,621	16,653	16,375	16,533

Eqs. (1) and (2) at each cutoff time. The calculated lifetimes are shown in Table 3.

Then the probability density function $f(t)$, the cumulative failure probability function $F(t)$, and the medium lifetime are respectively calculated at each cutoff time. In Fig. 5, the curve of $f(t)$ gradually moves to the direction of long lifetime as the aging time increases from 3000 to 9000 h, and then get stabilized after 9000 h, which means the aging time should be at least 9000 h to reach a stable and reliable lifetime. It is worth nothing that the peak value of $f(t)$ gradually gets higher and the full width at half-maximum gets smaller as the aging time exceeds 9000 h, indicating that the predicted lifetime gradually gets more accurate. The calculated $F(t)$ is shown in Fig. 6, and it can also be seen that the medium lifetime with 50% failure probability gradually gets stabilized after 9000 h aging.

The correspondent m, η, and $\tau_{0.5}$ at each cutoff time are also shown in Table 3. The shape parameter of m can reflect the variation of the failure mechanism of the LED during aging to a certain degree, and it increases from 7.1 to 8.5 in the initial 9000 h, which means that although the aging process is performed under room temperature, the failure mechanism can also be changed as aging. The m gets stabilized to 8.5–8.9, which is similar with the m of 8.6 in Fig. 4, indicating a same failure mechanism maintained after 9000 h aging. Figure 7 shows the calculated medium lifetime of $\tau_{0.5}$ at different cutoff times and the fitting curve. Obviously compared with the real lifetime of 16,867 h, $\tau_{0.5}$ remains a reliable value after 9000 h aging. The result shows that the errors in predicting the lifetime at the cutoff times of 3000 h, 6000 h, 9000 h, 12,000 h, and 15,000 h are respectively 37.5%, 8.2%, 2.7%, 2.4%, and 1.4%, which means that the aging time should be at least

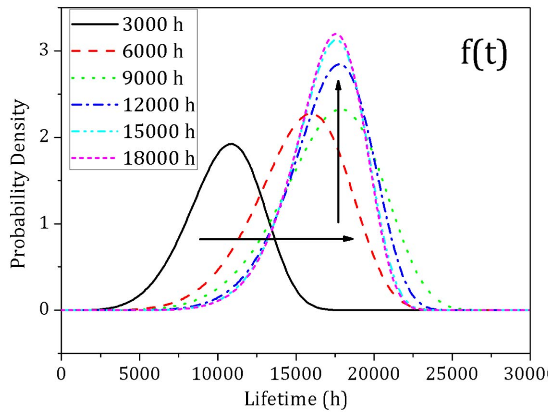

Fig. 5. Probability density function of $F(t)$ at each cutoff time.

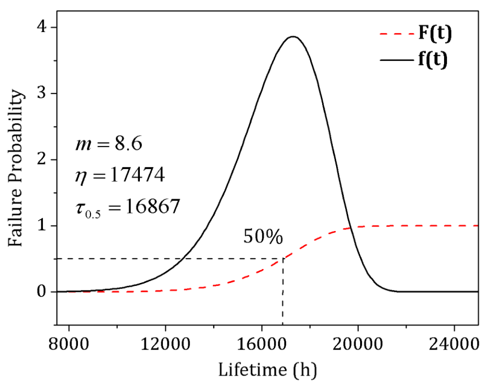

Fig. 4. Probability density function $f(t)$ and the cumulative failure probability function $F(t)$ of LED real lifetime.

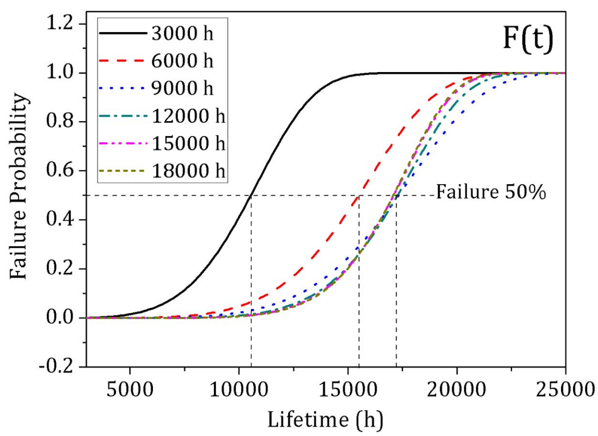

Fig. 6. Cumulative failure probability function of $F(t)$ at each cutoff time.

Table 3. Predicted Lifetime of Each Sample at Each Cutoff Time

Cutoff	Predicted Lifetime (*h*)										Parameters		
Time (*h*)	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	m	$\eta(h)$	$\tau_{0.5}(h)$
3000	14,470	11,611	5063	11,638	10,409	10,333	8819	12,709	9748	9323	7.1	11,324	10,542
6000	19,914	16,104	8386	17,028	15,955	15,034	12,572	18,600	13,859	15,031	7.5	16,443	15,484
9000	22,346	20,022	10,630	19,242	18,102	17,354	13,199	18,326	14,430	16,854	8.5	18,370	17,322
12,000	20,986	19,522	11,450	19,263	17,555	18,234	13,412	17,230	15,053	17,054	8.6	18,111	17,266
15,000	20,855	18,451	11,797	18,285	17,251	18,212	14,076	16,937	15,523	17,119	8.9	17,853	17,095

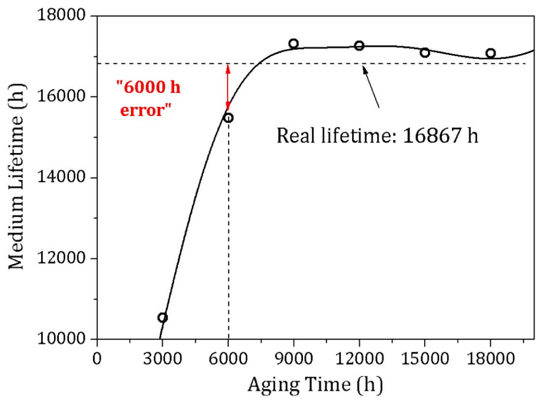

Fig. 7. Medium lifetime of $\tau_{0.5}$ at each cutoff time.

9000 h to make the error less than 3%, and the error in lifetime prediction by the classical 6000 h is 1383 h (8.2%) shorter in this work.

5. CHROMATICITY SHIFT

The chromaticity of white light can be expressed either by the CCT or the $Du'v'$ on the CIE1967 ($Du'v'$) diagram, and the $Du'v'$ is expressed as

$$Du'v' = \sqrt{(u_1' - u_2')^2 + (v_1' - v_2')^2}, \quad (8)$$

where (u_1', v_1') and (u_2', v_2') are respectively the chromaticity coordinates of the LED before and after aging. Figure 8 shows the chromaticity coordinates of samples at the cutoff times of 0 h, 6000 h, and 20,000 h. The initial CCT of the samples gives at about 3070 K, and it is nearly 3180 K after 20,000 h aging, which means the chromaticity of the samples drifts toward the direction of cold white with both decreased value of u' and v'. As a result, the $Du'v'$ can be calculated at different cutoff times by Eq. (8) with respect to the initial (u', v'). As shown in Fig. 9, the $Du'v'$ after 6000 h aging is less than 0.007 for all samples, which just meets the requirement in LM-80 [6] of Energy Star.

The $Du'v'$ values of 0.006, 0.007, and 0.008 are taken as the three thresholds for failure assessment in this work. Owing to the measured points at different cutoff times, the variation of $Du'v'$ is fitted by a two exponential law to estimate the aging time when the $Du'v'$ just reaches the thresholds. The two exponential law is written as

$$y = a \exp(bx) + c \exp(dx), \quad (9)$$

where a, b, c, and d are constants. Figure 10 shows fitting results of $Du'v'$ of sample 1, and the R-square of fitting is 0.9847, which indicates that the variation of $Du'v'$ is in good agreement with the two exponential law. Table 4 gives the $Du'v'$ fitting results for 10 samples. The predicted lifetimes of the 10 samples by the three thresholds are thereby obtained, as shown in Table 5.

In Fig. 11, the median lifetimes of the 10 samples correspondent to different aging periods and different thresholds of $Du'v'$ are obtained by applying the Weibull distribution as that in Section 4. The (shape parameter, characteristic parameter, and median lifetime) of Weibull distribution are respectively obtained to be (5.8, 8331 h, and 7,806 h) for the threshold of 0.006, (7.5, 11,949 h, and 11,380 h) for that of 0.007, and (8.4, 18,795 h, and 17,992 h) for that of 0.008. The characteristic parameter of 8.4 for the threshold of 0.008 is similar with the result of 8.6 in Fig. 4, which means for the samples in this work, the variation of $Du'v'$ of 0.008 in chromaticity shift and 70% degradation of lumen flux remains a same failure mechanism, and the $Du'v'$ of 0.008 is suitable for this lamp to evaluate the lifetime by color shift.

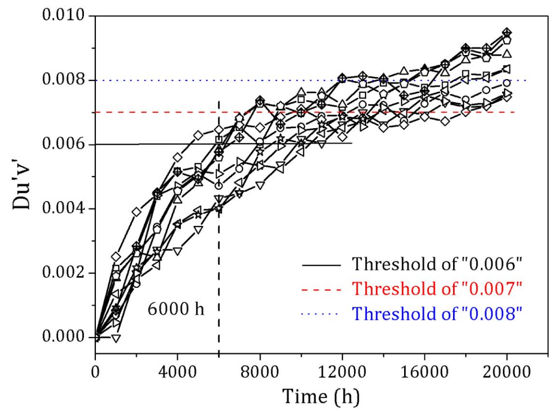

Fig. 9. $Du'v'$ of samples during 20,000 h aging.

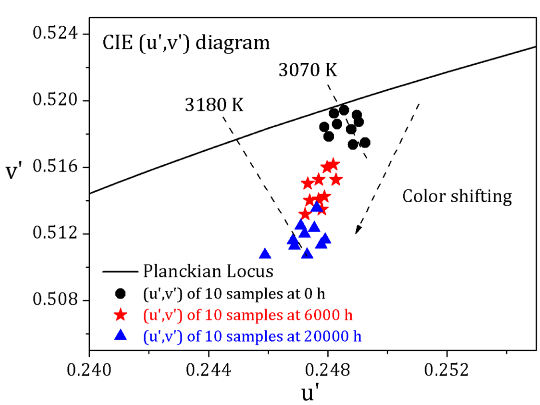

Fig. 8. Chromaticity shift of samples during 20,000 h aging.

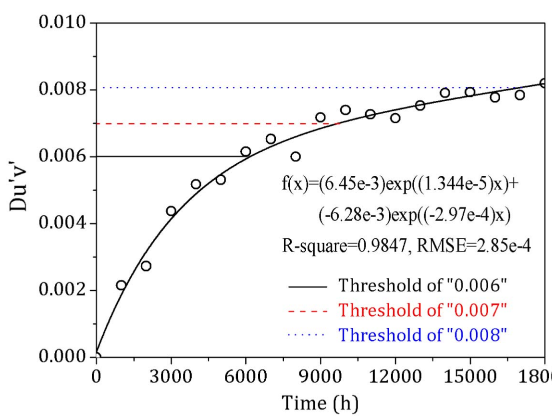

Fig. 10. $Du'v'$ fitting result of sample 1 by the two exponential law.

Table 4. $Du'v'$ Fitting Results for 10 Samples

	a	*b*	*c*	*D*	*R*-Square	RMSE
No. 1	6.45e – 3	1.34e – 5	−6.28e – 3	−2.97e – 4	0.9487	2.85E – 04
No. 2	6.10e – 3	2.01e – 5	−5.85e – 3	−2.65e – 4	0.9568	2.87E – 04
No. 3	5.89e – 3	1.56e – 5	−6.45e – 3	−2.55e – 4	0.9645	2.90E – 04
No. 4	6.88e – 3	1.88e – 5	−6.32e – 3	−3.12e – 4	0.9568	2.87E – 04
No. 5	6.45e – 3	1.42e – 5	−6.02e – 3	−3.57e – 4	0.9514	2.86E – 04
No. 6	6.12e – 3	1.56e – 5	−5.12e – 3	−3.02e – 4	0.9612	2.89E – 04
No. 7	5.55e – 3	1.32e – 5	−5.45e – 3	−2.85e – 4	0.9813	2.95E – 04
No. 8	5.95e – 3	2.06e – 5	−5.78e – 3	−2.65e – 4	0.9765	2.93E – 04
No. 9	6.32e – 3	1.88e – 5	−5.44e – 3	−2.98e – 4	0.9688	2.91E – 04
No. 10	6.55e – 3	1.54e – 5	−5.33e – 3	−2.45e – 4	0.9599	2.88E – 04

Table 5. Predicted Lifetimes Corresponding to the Three Thresholds of $Du'v'$

	Lifetime (*h*)									
Threshold	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10
$Du'v' = 0.006$	6215	8122	5699	8902	6026	5112	9658	8869	9365	8639
$Du'v' = 0.007$	9845	12,036	8563	12,789	9120	8126	13,056	12,965	13,021	12,063
$Du'v' = 0.008$	16,768	20,122	12,965	18,652	16,125	14,236	18,023	21,569	18,663	19,983

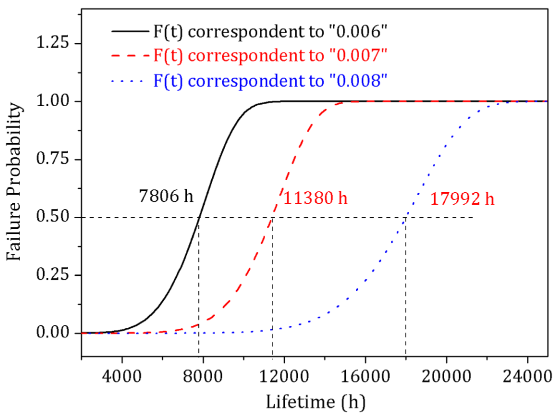

Fig. 11. Failure probability F(t) correspondent to the three thresholds of $Du'v'$.

6. CONCLUSIONS

To investigate the error in lifetime prediction of LED lamps by using the well-known 6000 h test, 10 normal LED lamps are aged at room temperature for 20,000 h, and the real lifetime with normalized lumen flux of 70% can be obtained during the test naturally. The lumen maintenance and color shift are used for evaluating the correspondent lifetime at different aging periods. The maximum likelihood function is used for calculating the shape parameter of m and characteristic parameter of η, which are the two main parameters of Weibull distribution. Then the median lifetime $\tau_{0.5}$ of 10 samples correspondent to different aging periods can be obtained and compared.

In the estimation of lumen maintenance, the lumen maintenance of the samples drops to about 65% after 20,000 h aging, and the shape parameter, characteristic parameter, and median lifetime of the real lifetime of the 10 samples are calculated to be 8.6, 17,474 h, and 16,867 h. Compared with the predicted median lifetime at different aging periods, the aging time should be at least 9000 h to make the life prediction error less than 3%. The error in lifetime prediction by the classical 6000 h is 1383 h (8.2%) shorter in this work.

In the estimation of color shift, to compare with the $Du'v'$ of 0.007 set in LM-80 [6] of Energy Star, the $Du'v'$ of 0.006, 0.007, and 0.008 are taken as the three thresholds for evaluating the color shift in this work, and the correspondent median lifetime at different aging periods is predicted by the variation of $Du'v'$. The result shows that the calculated shape parameter of 8.4 is similar with that of the real lifetime in the case of 0.008, which means the lumen maintenance of 70% and the color shift of 0.008 remains a same failure mechanism. As a result, the $Du'v'$ of 0.008 is suitable for evaluating the lifetime by the color shift method for this kind of LED lamp.

Although the samples in this work are placed as recommended by Energy Star with different heat distribution of LED lamps, the obtained lumen degradation between the two groups makes no big difference, as well as color shift. In our previous work [18], the LED light source is the most aggressive part for this kind of LED lamp, and the junction temperature of the LED can have a significant effect on the LED light source. Although the heat distribution of LED lamps is different between the two groups, the junction temperature of the LED remains a same level, which is the highest temperature within the LED. As a result, the degradation of the LED lamp makes no big difference.

As a starting point, the scope of this study is limited to the LED lamp used in this research. For other kinds of LED lamps with different subsystems, materials, structures, and so on, the error of the predicted lifetime should by experimentally determined, but we do believe that the error does exist and varies for different LED lamps, and the traditional 6,000 h aging test can always provide a reliable LED lifetime to a certain degree.

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