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Determination of cut-off time of accelerated aging test under temperature stress for LED lamps[*]

Jian HAO[1,2], Lei JING[3], Hong-liang KE[2], Yao WANG[1,3], Qun GAO[3],
Xiao-xun WANG[1,3], Qiang SUN[†‡3], Zhi-jun XU[3]
(*[1]University of Chinese Academy of Sciences, Beijing 100049, China*)
(*[2]Science and Technology on Vacuum Technology and Physics Laboratory, Lanzhou Institute of Physics, CAST, Lanzhou 730000, China*)
(*[3]Opto-Electronics Technology Center, Changchun Institute of Optics, Fine Mechanics and Physics,
Chinese Academy of Sciences, Changchun 130033, China*)
[†]E-mail: sunq@ciomp.ac.cn

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Abstract: To acquire a rational minimum cut-off time and the precision of lifetime prediction with respect to cut-off time for the accelerated aging test of LED lamps, fifth-order moving average error estimation is adopted in this paper. Eighteen LED lamps from the same batch are selected for two accelerated aging tests, with 10 samples at 80 °C and eight samples at 85 °C. First, the accelerated lifetime of each lamp is acquired by exponential fitting of the lumen maintenances of the lamp for a certain cut-off time. With the acquired lifetimes of all lamps, the two-parameter Weibull distribution of the failure probability is obtained, and the medium lifetime is calculated. Then, the precision of the medium lifetime prediction for different cut-off times is obtained by moving average error estimation. It is shown that there exists a minimum cut-off time for the accelerated aging test, which can be determined by the variation of the moving average error versus the cut-off time. When the cut-off time is less than this value, the lifetime estimation is irrational. For a given cut-off time, the precision of lifetime prediction can be computed by average error evaluation, and the error of lifetime estimation decreases gradually as the cut-off time increases. The minimum cut-off time and medium lifetime of LED lamps are both sensitive to thermal stress. The minimum cut-off time is 1104 h with the lifetime estimation error of 1.15% for the test at 80 °C, and 936 h with the lifetime estimation error of 1.24% for the test at 85 °C. With the lifetime estimation error of about 0.46%, the median lifetimes are 7310 h and 4598 h for the tests at 80 °C and 85°C, respectively.

Key words: LED lamp; Accelerated aging test; Medium lifetime; Moving average error
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1 Introduction

With the advantages of long lifetime, high energy conservation, and good environmental protection, light-emitting diodes (LEDs), as the fourth-generation energy source, are being widely used in various lighting fields (Koh *et al.*, 2011; Ignacio *et al.*, 2012; Hu and Qian, 2013; Jafrancesco *et al.*, 2015; Shi *et al.*, 2015). While long lifetime and good reliability are desirable, an unavoidable issue is how to estimate the lifetime of LEDs during a shorter test time. IES LM-79 (IES, 2008b), IES LM-84 (IES, 2014a), and IES TM-28 (IES, 2014b) standards report the test and calculation method for LED products, and the test time is at least 6000 h under an ambient temperature of 25 °C. The standards IES LM-80 (IES, 2008a) and IES TM-21 (IES, 2011) recommend a lifetime test method for LED products, in which the test temperature is 25 °C and the test time is at least 6000 h. IES LM-80 and IES TM-21 standards recommend a lifetime test method in which three tests under different temperatures are required and the test

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[‡] Corresponding author

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ORCID: Jian HAO, http://orcid.org/0000-0002-2419-25083 time is also at least 6000 h. Narendran and Gu (2005) reported the lifetime estimation of white light LEDs by a two-step method. The lifetimes of nine groups of LEDs were acquired by aging tests, with the test time of 6000 h for each, under different T-point temperatures first, and then the lifetime estimation under 25 °C was achieved by fitting the acquired lifetimes. Chang *et al.* (2012) reviewed the reliability of LEDs with the test time of 6000 h, including the general lifetime estimation methods and advanced lifetime estimation methods using analytical tools, simulation, and prototype testing. Fan *et al.* (2012) compared four methods of lifetime estimation for high-power white LED, with the test time of 10 000 h, including the IES TM-21 method, approximate method, analysis method, and two-stage method. Fan *et al.* (2014) also reported a precise lifetime prediction method for LEDs compared to the IES TM-21 method, using the Kalman filter (KF) model to process the initial data of lumen maintenances. The test time was 6000 h. Lall and Wei (2015) reported a more precise lifetime prediction method in comparison with the KF model using the extended KF (EKF) model to process the initial data of lumen maintenances. The test time was also 6000 h. Obviously, the test time of at least 6000 h restricts the replacement rate of LED products, and therefore various methods of accelerated aging test of LEDs have been proposed.

Koh *et al.* (2013) reported the accelerated aging test of LED light source modules under the ambient temperature of 55 °C. The cut-off time was 3600 h with the criterion of lumen maintenance of 95%. Qian *et al.* (2015) reported the same accelerated aging test with different LED products, and the cut-off time was 2000 h. Tan and Singh (2014) reported the accelerated aging tests of LED packages under the conditions of ambient temperature of 85 °C and humidity levels of of 95%, 85%, and 70%, respectively. The cut-off times were within 1000 h, with the criterion of lumen maintenance of 85%. Cai *et al.* (2015) reported the accelerated aging tests of LED packages under the ambient temperatures of 65, 85, and 95°C, respectively, and with a humidity of 85%. The cut-off times were within 1400 h with the criterion of a lumen maintenance of about 90%. Tang *et al.* (2012) reported a step-stress accelerated aging test for LED light source modules under ambient temperatures of 45, 65, and 85 °C. The cut-off time was 2300 h with the criterion of a lumen maintenance of 95%. Ren *et al.* (2012) reported several step-stress accelerated aging tests for LED light source modules under ambient temperatures of 45, 85, and 95 °C. The cut-off time was fixed as 2100 h for all tests. In all the above references, the cut-off times of the accelerated aging tests of LEDs were determined by stipulated values of lumen maintenances; obviously, the longer the cut-off time, the more precise the lifetime estimation.

In this paper, a new approach to determining the cut-off time of the accelerated aging test of LED lamps based on the moving average error evaluation is proposed. Two accelerated aging tests with the same type of lamp are arranged under the ambient temperatures of 80 °C and 85 °C, respectively. The order of moving average error calculation is selected to be five, which yields a satisfactory evaluation result. The proposed approach gives not only a rational minimum cut-off time of the accelerated aging test but also the lifetime estimation error for different cut-off times.

Table 1 gives the notations used in this paper.

Table 1 Notations used in this paper

Notation	Description
Φ_t/Φ_0	Lumen maintenance
β_T	Decay rate
T	Junction temperature
t	Test time
τ	Lifetime
$F(t)$	Two-parameter Weibull distribution failure probability
m	Shape parameter
η	Characteristic lifetime
$\tau_{0.5}$	Medium lifetime
$\rho(l)$	Moving average error of order h

2 Theoretical analysis

2.1 Arrhenius model and two-parameter Weibull distribution

The lumen maintenance of an LED product obeys the exponential decay law:

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

where Φ_t/Φ_0 is the lumen maintenance, β_T is the decay rate at the junction temperature T, and t is the operating time. When Φ_t/Φ_0=0.7, the operating time in Eq. (1) is considered to be the lifetime τ:

$$\tau = -\frac{\ln 0.7}{\beta_T}. \tag{2}$$

The failure probability of LED lamps over time follows two-parameter Weibull distribution (Zhang *et al.*, 2006):

$$F(t) = 1 - \exp[-(t/\eta)^m], \tag{3}$$

where $F(t)$ is the failure probability, m represents the so-called shape parameter, and η represents the characteristic lifetime. The unknown parameters of Eq. (3) can be solved by the maximum likelihood function method together with the acquired lifetimes of the lamps. Actually, we complete this process using the command 'Wblfit' in the MATLAB software toolbox. Then the lifetime τ for different failure probabilities can be obtained by

$$\tau = \eta\left(\ln\frac{1}{1-F(\tau)}\right)^{\frac{1}{m}}. \tag{4}$$

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

2.2 Analysis of errors

In this work, the moving average error $\rho(l)$ is used to evaluate the error of the medium lifetime prediction; it can be expressed as

$$\rho(l) = \frac{1}{h}\sum_{k=l-h+1}^{l}\left|1 - \frac{\tau_{0.5,\,k}}{\tau_{0.5,\,k-1}}\right| < \varepsilon\%, \tag{5}$$

where h represents the order of the moving average error with $h\geq 1$, $\tau_{0.5,k}$ and $\tau_{0.5,k-1}$ represent the kth and (k–1)th medium lifetimes, respectively, $\tau_{0.5,k}/\tau_{0.5,k-1}$ is called the relative error, and ε is a suitable value given beforehand. Assuming that the number of processed medium lifetimes is N, $l=h+1, h+2, \ldots, N$. The number of relative errors is N–1. When $\rho(l)$ is less than ε, the accelerated aging test can be stopped.

In the data processing of a dynamic test, 5th-order to 11th-order moving average error estimation is usually adopted, and in this work fifth-order moving average error estimation is used. Thus, h=5 and l=6, 7, …, N. So, Eq. (5) can be written as

$$\rho(l) = \frac{1}{5}\sum_{k=l-4}^{l}\left|1 - \frac{\tau_{0.5,\,k}}{\tau_{0.5,\,k-1}}\right| < \varepsilon\%. \tag{6}$$

3 Experiments and results

3.1 Experiments

Fig. 1 shows the platform for the accelerated aging test for LED samples. The online test system was composed of the thermostat box, integrating sphere of 0.5 m from Labsphere, AC power source, spectral radiometer, and the computer. A multi-position rotary shelf in the thermostat box was controlled by the command of the computer. Eighteen samples were divided into two groups for two accelerated aging tests. One test, with 10 samples, was conducted under the accelerated temperature of 80 °C. The total accelerated aging time was 1296 h. The other eight samples were tested at 85 °C. The total accelerated aging time was 1056 h. The samples were encapsulated by Lide with the same components including chips from ES, the green phosphor from Nakamura-Yuji, red phosphor from Grirem, 6630 potting glue, DX20C patch glue, and the driver from Lide. The correlated color temperature of these samples was about 3500 K. Before the accelerated aging tests, the samples were subjected to environmental tests including vibration, shock, and current. In this way, defects in the drivers, such as bad soldering joints and defective electronic components, were excluded. Data were acquired once every 24 h. For each data acquisition, the rotary shelf was rotated by eight laps to obtain eight values of the luminous flux, and the average luminous flux was then obtained. The results of the acquired lumen maintenance for each lamp are shown in Fig. 2.

3.2 Data processing for the test at 80 °C

First, the acquired lumen maintenances of Fig. 2a before a cut-off time t were fitted by the exponential decay law (1), and the accelerated lifetimes of 10 lamps were obtained with the criterion given by Eq. (2). The results are listed in columns 2–11 of Table 2. With the acquired accelerated lifetimes of 10 lamps, the two unknown parameters of the Weibull distribution of the failure probability of LED lamps in

Eq. (3) were solved by the maximum likelihood function method for each cut-off time. This fitting was done by a program with the command of ‘Wblfit’ in the MATLAB Statistics Toolbox. Then the medium lifetime was obtained by Eq. (4) with the solved two-parameter Weibull distribution. The results for different cut-off times are listed in Table 2.

Fig. 1 Platform of the accelerated aging test for LED lamps
1, thermostat box; 2, integrating sphere of 0.5 m; 3, multi-position rotary shelf; 4, AC power source; 5, spectral radiometer

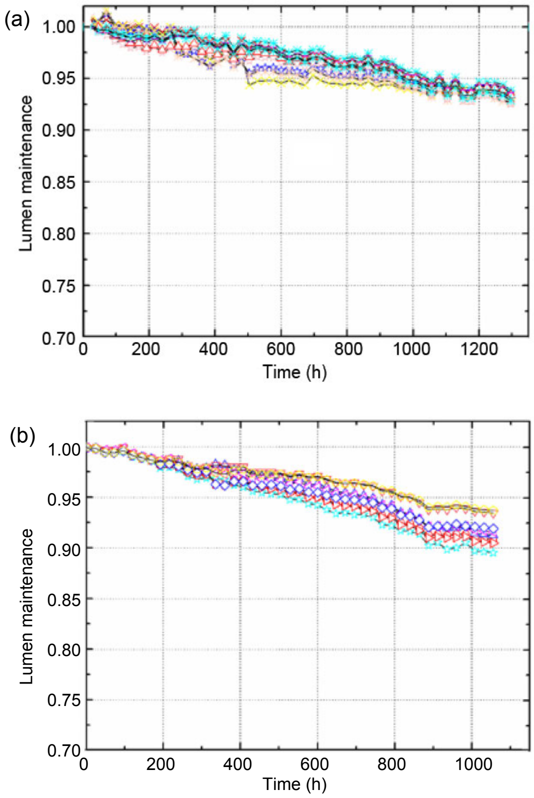

Fig. 2 Variation of the acquired luminous fluxes: (a) at 80 °C; (b) at 85 °C

The variation of the medium lifetime with the cut-off time is shown in Fig. 3. It can be seen that the medium lifetime varies in an irregular manner at cut-off times less than 936 h and shows a declining trend as the cut-off time becomes greater than 936 h. This gives us a clue of the initial cut-off time to start the calculation of the moving average error because the declining trend of lifetime with cut-off time is reasonable in practice. Then the 16 medium lifetimes in Table 2, from the 27th row (cut-off time of 936 h) to the 42nd row (the last row), were used to calculate the relative error $\tau_{0.5,k}/\tau_{0.5,k-1}$ with the initial value of k=2. It is clear that the number of relative errors is 15, and the calculated values are listed in Table 2.

The precision of the acquired medium lifetimes was then evaluated by the fifth-order moving average error method. According to Eq. (6), the value of l can be 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, and 16. Clearly, the number of moving average errors of $\rho(l)$ is 11. The moving average errors were calculated and listed in Table 2. Fig. 4 shows the variation of the moving average error with respect to the cut-off time.

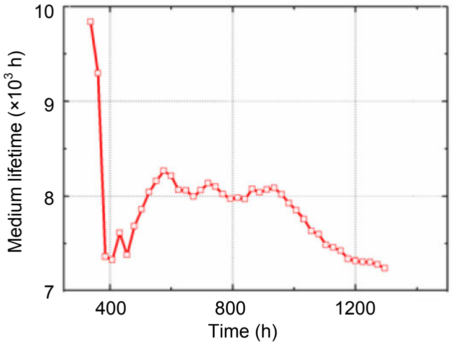

Fig. 3 Variation of medium lifetime with cut-off time for the test at 80 °C

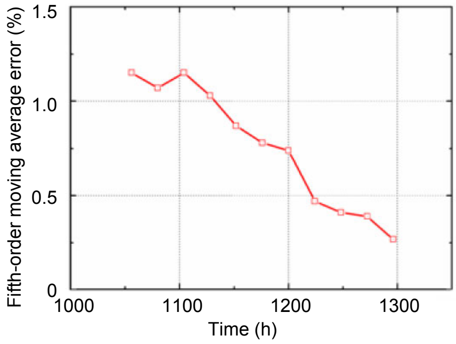

Fig. 4 Variation of the moving average error versus cut-off time for the test at 80 °C

Table 2 The accelerated lifetimes of 10 lamps and related parameters in the test at 80 °C

Cut-off time (h)	Accelerated lifetime (h)										$\tau_{0.5}$ (h)	$\tau_{0.5,k}/\tau_{0.5,k-1}$ (%)	$\rho(l)$ (%)
	1	2	3	4	5	6	7	8	9	10			
336	17316	28914	4165	4885	8491	7562	9623	8559	9091	8825	9839	–	–
360	15993	21263	4222	4945	8269	7588	9210	8356	8783	8569	9299	–	–
384	11291	12129	3920	4520	6860	6527	7441	6943	7192	7068	7364	–	–
408	11144	11238	4033	4641	6850	6640	7415	6968	7295	7080	7331	–	–
432	11814	11166	4243	4904	7099	6987	7674	7254	7464	7359	7614	–	–
456	11120	10157	4294	4944	6962	6922	7420	7101	7261	7181	7379	–	–
480	11603	10469	4472	5154	7259	7252	7720	7410	7565	7488	7684	–	–
504	11886	10384	4614	5323	7430	7572	7872	7625	7748	7686	7862	–	–
528	12083	10373	4788	5535	7628	7862	8009	7833	7921	7877	8044	–	–
552	12204	10230	4956	5726	7745	8073	8102	7973	8038	8006	8163	–	–
576	12281	10093	5121	5919	7849	8278	8197	8108	8152	8130	8271	–	–
600	11950	9820	5216	6023	7816	8310	8117	8081	8099	8090	8217	–	–
624	11519	9418	5269	6076	7685	8231	7954	7956	7955	7956	8069	–	–
648	11342	9208	5370	6205	7677	8291	7940	7969	7954	7962	8060	–	–
672	11085	8988	5441	6292	7603	8296	7860	7920	7890	7905	7997	–	–
696	11084	8947	5568	6454	7650	8418	7908	7992	7950	7971	8063	–	–
720	11120	8920	5689	6615	7713	8548	7960	8074	8017	8045	8138	–	–
744	10952	8773	5751	6699	7666	8548	7910	8042	7976	8009	8100	–	–
768	10704	8686	5764	6735	7581	8490	7817	7962	7890	7926	8024	–	–
792	10528	8544	5810	6791	7524	8462	7763	7917	7841	7879	7974	–	–
816	10462	8478	5882	6884	7527	8499	7770	7932	7851	7892	7985	–	–
840	10364	8390	5934	6951	7502	8506	7754	7921	7837	7879	7970	–	–
864	10462	8434	6052	7102	7586	8655	7858	8033	7946	7989	8078	–	–
888	10335	8339	6089	7142	7545	8629	7824	7999	7912	7956	8042	–	–
912	10318	8319	6157	7226	7561	8679	7852	8031	7941	7986	8072	–	–
936	10263	8280	6210	7293	7557	8706	7862	8042	7952	7997	8089	–	–
960	10106	8176	6222	7296	7493	8641	7808	7981	7894	7937	8019	0.87	–
984	9913	8048	6209	7274	7403	8537	7722	7887	7805	7846	7927	1.15	–
1008	9753	7944	6201	7262	7333	8455	7652	7813	7733	7773	7853	0.93	–
1032	9568	7829	6176	7225	7241	8345	7560	7715	7638	7676	7757	1.22	–
1056	9338	7684	6130	7158	7128	8202	7450	7593	7522	7558	7634	1.59	1.15
1080	9247	7628	6139	7165	7093	8163	7421	7559	7490	7525	7600	0.45	1.07
1104	9029	7497	6092	7096	6991	8027	7311	7443	7377	7410	7483	1.54	1.15
1128	8960	7455	6103	7104	6966	7998	7286	7417	7351	7384	7458	0.33	1.03
1152	8864	7408	6092	7094	6943	7955	7264	7387	7325	7356	7424	0.46	0.87
1176	8712	7313	6061	7045	6870	7860	7185	7305	7245	7275	7341	1.12	0.78
1200	8656	7285	6072	7050	6851	7834	7164	7283	7224	7253	7321	0.27	0.74
1224	8615	7267	6088	7062	6841	7820	7153	7272	7213	7242	7310	0.15	0.47
1248	8580	7258	6106	7077	6836	7814	7148	7266	7207	7237	7306	0.05	0.41
1272	8536	7235	6116	7083	6823	7737	7133	7251	7192	7222	7281	0.21	0.39
1296	8456	7188	6107	7065	6789	7679	7097	7212	7154	7183	7242	0.53	0.27

It can be seen that the moving average error decreases as the cut-off time increases from 1056 h to 1080 h; then it increases as the cut-off time increases from 1080 h to 1104 h. This variation characteristic of $\rho(l)$ is irrational in practice, because $\rho(l)$ should be smaller for a longer cut-off time. The moving average error has a monotonically declining trend after the cut-off time of 1104 h, and this implies a minimum cut-off time for this accelerated aging test. Correspondingly, the estimated medium lifetime is 7483 h with the evaluation error of 1.15%. It can be seen from Table 2 that, as the cut-off time increases to 1152, 1200, 1248, and 1296 h, the lifetime estimation errors are 0.87%, 0.74%, 0.41%, and 0.27%, respectively. The corresponding medium lifetimes are 7424, 7321, 7306, and 7242 h, respectively.

3.3 Data processing for the test at 85 °C

The same method as in Section 3.2 was used for data processing. First, the accelerated lifetimes of eight lamps were obtained by exponential fitting of the lumen maintenances in Fig. 2b for different cut-off times (Table 3, columns 2–9). With the acquired accelerated lifetimes of eight lamps, the two unknown parameters of the Weibull distribution of the failure probability of LED lamps were solved. Then the corresponding medium lifetimes were obtained with the solved two-parameter Weibull distribution (Table 3).

The variation of the medium lifetime versus the cut-off time is shown in Fig. 5. It can be seen that the medium lifetime varies without any regular pattern as the cut-off time is less than 720 h, and then it shows a declining trend. The value of 720 h is the initial cut-off time to start the calculation of the moving average error. Then, 15 medium lifetimes in Table 3, from the 7th row (cut-off time of 720 h) to the 31st row (the last row), were used to calculate the relative error $\tau_{0.5,k}/\tau_{0.5,k-1}$ with the initial value k=2. It is clear

Table 3 The accelerated lifetimes of eight lamps and related parameters in the test at 85 °C

Cut-off time (h)	Accelerated lifetime (h)								$\tau_{0.5}$	$\tau_{0.5,k}/\tau_{0.5,k-1}$ (%)	$\rho(l)$ (%)
	1	2	3	4	5	6	7	8			
360	3774	4518	5789	6227	5132	4058	4013	5025	4881	–	–
384	3719	4425	5832	6368	5174	4008	3999	5194	4905	–	–
408	3693	4420	5924	6554	5241	4030	4047	5418	4982	–	–
432	3638	4327	5824	6457	5154	4001	4035	5483	4932	–	–
456	3617	4272	5763	6451	5131	3991	4063	5543	4921	–	–
480	3618	4246	5727	6500	5150	4004	4128	5647	4945	–	–
504	3635	4245	5729	6549	5186	4028	4187	5777	4952	–	–
528	3616	4224	5689	6523	5168	4028	4212	5848	4983	–	–
552	3628	4231	5739	6621	5225	4068	4269	5986	5041	–	–
576	3619	4210	5702	6646	5217	4062	4299	6067	5047	–	–
600	3620	4206	5707	6719	5235	4075	4342	6181	5079	–	–
624	3601	4196	5679	6741	5225	4077	4363	6240	5083	–	–
648	3572	4174	5614	6708	5190	4060	4372	6260	5061	–	–
672	3576	4161	5561	6684	5159	4053	4388	6283	5049	–	–
696	3575	4160	5524	6703	5149	4057	4411	6330	5053	–	–
720	3589	4156	5487	6703	5129	4054	4434	6376	5055	–	–
744	3597	4156	5446	6704	5112	4052	4456	6413	5054	0.02	–
768	3580	4129	5362	6641	5061	4029	4453	6404	5019	0.69	–
792	3573	4099	5302	6597	5009	3999	4438	6382	4972	0.94	–
816	3559	4087	5247	6548	4975	3987	4425	6343	4956	0.32	–
840	3547	4058	5158	6475	4909	3957	4407	6297	4910	0.93	0.58
864	3536	4021	5052	6368	4832	3921	4379	6232	4851	1.20	0.82
888	3493	3967	4922	6214	4732	3866	4325	6118	4761	1.86	1.05
912	3474	3933	4827	6110	4659	3833	4296	6049	4703	1.22	1.11
936	3443	3908	4745	6026	4600	3807	4277	5999	4657	0.98	1.24
960	3248	3898	4688	5984	4567	3795	4279	5984	4632	0.54	1.16
984	3436	3896	4655	5950	4545	3793	4282	5970	4620	0.26	0.97
1008	3428	3887	4645	5941	4537	3781	4270	5959	4609	0.24	0.65
1032	3415	3872	4635	5932	4528	3770	4259	5949	4598	0.24	0.45
1056	3406	3864	4628	5921	4519	3763	4252	5941	4590	0.17	0.29

that the number of relative errors is 14, and the calculation results are listed in Table 3.

The precision of the acquired medium lifetimes was then evaluated by the fifth-order moving average error method. The value of l can be 6, 7, 8, 9, 10, 11, 12, 13, 14, and 15, so the value of $\rho(l)$ is 10. The moving average errors were calculated and listed in Table 3. Fig. 6 shows the variation of the moving average error versus the cut-off time.

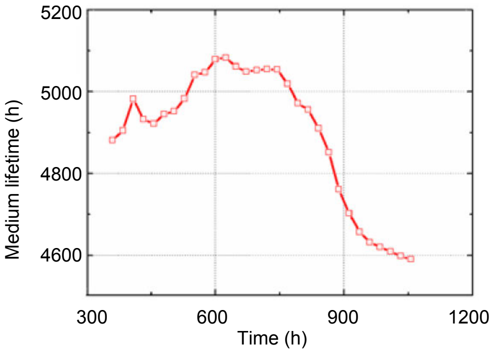

Fig. 5 Variation of medium lifetime with cut-off time for the test at 85 °C

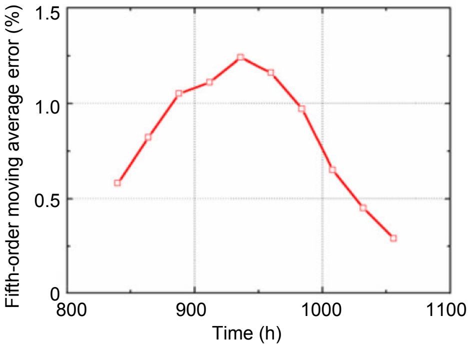

Fig. 6 Variation of the moving average error versus cut-off time for the test at 85 °C

It can be seen that the moving average error increases as the cut-off time increases from 840 h to 936 h, and then it decreases monotonically. This variation characteristic of $\rho(l)$ implies that the minimum cut-off time for this accelerated aging test is 936 h. Correspondingly, the estimated medium lifetime is 4657 h with the evaluation error of 1.24%. As the cut-off time increases to 984, 1032, and 1056 h, the lifetime estimation errors are 0.97%, 0.45%, and 0.29%, respectively. The corresponding medium lifetimes are 4620, 4598, and 4590 h, respectively.

4 Conclusions

We have proposed a new approach to determine the minimum cut-off time and to calculate the error of lifetime estimation with different cut-off times for the accelerated aging test of LED lamps, based on moving average error evaluation. Two accelerated aging tests with the LED lamps from the same batch were performed under the ambient temperatures of 80 °C and 85 °C.

It was shown that an initial cut-off time to start the calculation of the moving average error of lifetime estimation is needed, which can be acquired from the variation curve of the medium lifetime versus the cut-off time. There exists a minimum cut-off time for the accelerated aging test of LED lamps, which can be determined based on the variation of the moving average error versus the cut-off time. When the cut-off time is less than the minimum value, the lifetime estimation of LED lamps is irrational. It was demonstrated that for a given cut-off time of the accelerated aging test, the precision of lifetime prediction can be evaluated by the average error method. As the cut-off time increases, the error of lifetime estimation decreases gradually.

It is also shown in a comparison between the two accelerated aging tests that the minimum cut-off time and the medium lifetime are sensitive to thermal stress. The minimum cut-off time is 1104 h with the lifetime estimation error of 1.15% for the test at 80 °C, whereas it is 936 h with the lifetime estimation error of 1.24% for the test at 85 °C. With the lifetime estimation error of about 0.46%, the medium lifetime of the LED lamp is 7310 h for the test at 80 °C, whereas it is only 4598 h for the test at 85 °C.

Note that the number of samples is less than or equal to 10 in this work. According to the relationship between confidence, reliability, and the number of samples, the reliability is 85% with a confidence of 0.8. Furthermore, the minimum cut-off time and precision of lifetime estimation for different cut-off times given in this study are applicable only to this type of LED lamp under thermal stress accelerated aging. For other types of LED lamp, both parameters should be determined by particular experiments. We believe that the experiments for various types of LED lamps will yield valuable references in the field of lifetime prediction, which will be our next research task.

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