Product Level Accelerated Lifetime Test for Indoor LED Luminaires

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Abstract

A 2-stage acceleration theory for luminous flux depreciation testing at LED lamp/luminaire level is developed to reduce the test time from 6,000 hours to less than 2,000 hours. Such an acceleration theory is based on the exponential decay model and Arrhenius acceleration equation. Three key parameters, namely, activation energy, operating junction temperature, and accelerated testing junction temperature are obtained from massive proven LM80 data sets, nominal junction design temperature, and maximum allowed ambient temperature in operating conditions. A "master curve" that describes the minimum requirement of the luminous decay is defined, and the curve is associated with a certain design junction temperature. Such a design junction temperature matches the maximum junction temperature where LM80 data are enveloped in the master curve. The corresponding acceleration test procedures have been established by considering the currently available measurement capabilities. Considerable amount of representative lamp/luminaire samples, which directly came from market, have been tested to validate the theory. The results show that the proposed accelerated lifetime test is equivalent to the current 6000h test. In addition, the newly developed accelerated test can eliminate those products with either poor LED sources, or poor system thermal design, or poor electronics system (including driver system) that cannot sustain sufficient temperature storage period.

Keywords: LED, indoor, luminous flux depreciation, 2-stage, lifetime, Arrhenius model, accelerated test, product level.

1. Introduction

Solid state lighting (SSL) is an emerging technology, with high potential of green, energy saving, and smart controlling capability, and provides new experience of lighting. SSL is a perfect combination of illumination and semiconductors science. New technology development, new material application and fast industrial implementation is the characteristics of LED technology.

As one of the green /energy saving product aspects, SSL applications often last much longer than most incandescent replacement products, such as compact fluorescent lamps (CFLs). This also requires much longer time for lifetime testing for a proper designed LED product, compared to the conventional lighting products. However, such long testing time is hazard to the fast growing LED industry and technology, under the high society's expectation of LED replacement. It is essential to develop proper acceleration methods for LED products, based on illumination and electronics requirements.

The first attempt was to reduce the testing time by dropping test-to-fail concept, but testing the LED products until 70% luminous maintenance time, which is denoted as L_{70} time. The principle is based on the fact that the light output of a LED product will gradually depreciate during normal usage and 30% luminous drop is what human eyes can detect [1]. Illumination Engineering Society (IES) developed lamp/luminaire level lumen maintenance testing and lumen measurement method [2], so-called LM80 test. Energy Star developed a 6,000hrs product level testing procedure. Such a test time, which is almost 9 months, is too long to be practical in fast growing LED industries.

This paper focuses on the lumen depreciation for indoor luminaires, such as LED retrofit bulb, LED spot light, and LED downlight products. The accelerated test method is developed by a two-stage acceleration theory in both temperature and time. Arrhenius equation and exponential luminous flux decay model are used. The activation energy is determined so that it can envelope the most LM-80 data by many brand LED manufacturers. A "master curve", which describes the minimum requirement of the luminous flux decay, is defined. In order to have the master curve envelop desired LM-80 dada from various LED sources, the nominal junction temperature must match the maximum junction temperature of those LM80 data under the master curve. Accelerated ambient temperature is carefully selected in the range of 35^{o}C to 55^{o}C and below the highest nominal lamp/luminaire operating temperature so that no new failure modes are artificially introduced.

The proposed test method has been validated through extensive experimental data from carefully selected several indoor luminaries from various companies.

2. Theory

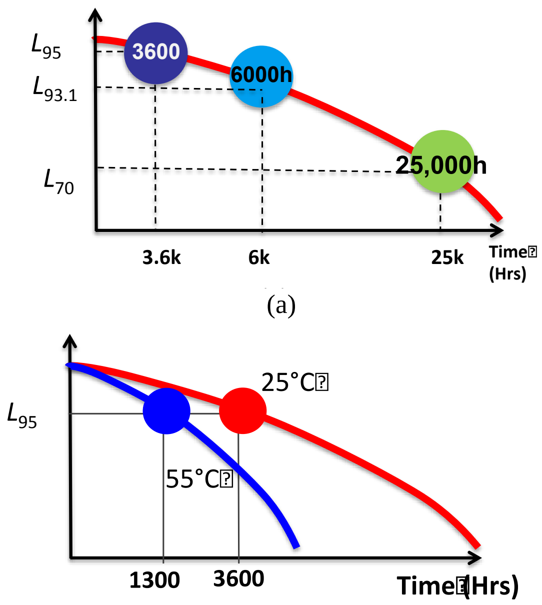
It is well known that the deprecation over time of LEDs products follows the exponential luminous decay model [3], shown below:

$$\phi(t) = \beta e^{-\alpha t} \qquad (1)$$

where $\phi(t)$ represents the lumen output; t the time. β the pre-factor, and α is depreciation parameter. When $\phi(t)$ is normalized, β equal to 1.0. According to Arrhenius function, α can be written as:

$$\alpha = A e^{\frac{-E_{act}}{k_b T}} \qquad (2)$$

where A is the pre-factor, E_{act} is the activation energy, k_b is the Boltzmann constant (8.617385x10^{-5}eV/K) and T is temperature in Kelvin.



(a)

(b)

Figure 1 Application of the 2-state acceleration model.
(a) Exponential luminous decay
(b) Temperature acceleration.

The abovementioned theory can be applied as follows:

Apply the exponential luminous decay model: when T is the junction temperature of LED under operating condition, we define $t_{70}|_{T_1}$, $t_{95}|_{T_1}$ and $t_{91.8}|_{T_1}$ are the times when the lumen decay to $\phi(t)$=0.7, $\phi(t)$=0.95 and $\phi(t)$=0.918, respectively. Assume $t_{70}|_{T_1} = 25{,}000$ hrs, we can calculate $\alpha|_{T_1} = 1.426 \cdot 10^{-5}$ from Eq (1), and obtain:

$$t_{95}|_{T_1} = \frac{\ln(0.95)}{-1.426 \cdot 10^{-5}} \approx 3600\text{hr}. \qquad (3)$$

Eq (3) can be illustrated in Figure 1 (a) for time acceleration by following exponential decay model.

A "master curve", with $\alpha = 1.426 \cdot 10^{-5}$, is defined to describe the minimum requirement of the luminous decay. Along this master curve, we have $\phi(t)$ =0.7, $\phi(t)$=0.95 and $\phi(t)$=0.918, respectively. If a luminaries operates within this curve over time, it passes the minimum requirement. However, we need to determine at which junction temperature, T_1, the luminaries operate.

Apply the Arrhenius equation: furthermore, when the temperature changes from T_1 and T_2, we have

$$t_{95}|_{T_1} = -\frac{\ln(\emptyset=0.95)}{\alpha(T_1)}$$

$$t_{95}|_{T_2} = -\frac{\ln(\emptyset=0.95)}{\alpha(T_2)}.$$

Follow Eq (2), one can derive:

$$\frac{t_{95}|_{T_1}}{t_{95}|_{T_2}} = \frac{\alpha(T_2)}{\alpha(T_1)} = e^{-\frac{E_a}{k}\left(\frac{1}{T_2}-\frac{1}{T_1}\right)} \qquad (4)$$

When T_2>T_1, the accelerated test time $t_{95}|_{T_2}$ can be calculated from Eq(4), as shown in Figure 1 (b). This is the second stage for temperature acceleration.

Note that, due to the independence of exponential luminous depreciation and Arrhenius function, the sequence of first and second stage abovementioned is exchangeable, as illustrated in Figure 2.

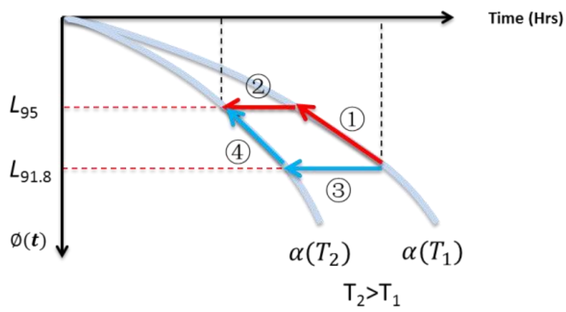


Figure 2 Sequential Exchangeability in 2-stage method.

To determine the final testing time at the accelerated temperature T_2 using equation (4), three parameters must be determined: activation energy, T_1 , and T_2.

Many LED light sources which satisfy LM-80 have been analyzed for the depreciation parameters α as a function of temperature. Then by Equation (2), one can calculate the activation energy Eact. More than 30 types of products [4], which cover the most of manufacturers all over the world, have been analyzed. Table 1 shows the first 10 data sets in the research. To envelop the most of the LED light sources, the activation energy of 0.45 eV is applied, as a most aggressive choice. Please note that the data analyzed here use junction temperature of LEDs, not the soldering temperature used in TM21 recommendations.

Table 1 LM-80 data and activation energy

Product	Temperature (°C)	A	E_{act} (eV)
1	62.22	2.02378E-06	0.414
	92.22	3.55335E-06	
	112.22	4.6638E-06	

2	32.22	1.36831E-06	0.409
	62.22	3.69266E-06	
	92.22	7.18047E-06	
3	69.45	2.72083E-06	0.402
	99.45	2.77558E-06	
	132.45	3.25869E-06	
4	28.10	2.69102E-06	0.408
	58.10	3.67888E-06	
	88.10	6.05326E-06	
5	56.65	3.70724E-06	0.419
	86.65	3.40194E-06	
	106.65	4.51976E-06	
6	56.65	1.84193E-06	0.428
	86.65	3.53013E-06	
	106.65	4.00894E-06	
7	56.65	1.56E-06	0.430
	86.65	3.14899E-06	
	106.65	3.74858E-06	
8	56.65	2.11659E-06	0.430
	86.65	2.33428E-06	
	106.65	4.32307E-06	
9	75.64	1.1208E-06	0.355
	105.64	1.08987E-05	
	125.64	1.95909E-05	
10	27.06	4.44739E-06	0.329
	57.06	4.54829E-06	
	87.06	6.26427E-06	

On the other hand, based on the minimum requirement of $t_{70}|_{T_1} = 25{,}000$, and we obtain $\alpha|_{T_1} = 1.426 \cdot 10^{-5}$ from Eq (1) for the master curve, as noted above. Figure 3 plots the LM80 data at the junction temperature less than 105°C. This means our master curve can envelope most of LEDs operating at a junction temperature of 105°C. This value matches the nominal junction design temperature of 110°C. Therefore, T_1 is chosen as 110°C for master curve.

The master curve may be defined differently, which will change the junction temperature associated with. For example, the nominal temperatures are defined as 105°C, 104°C and 96°C for $t_{70}|_{T_1} = 25{,}000$, for $t_{70}|_{T_1} = 30{,}000$ and $t_{70}|_{T_1} = 35{,}000$, respectively. The selected nominal temperatures are close to the junction temperature of real products [4].

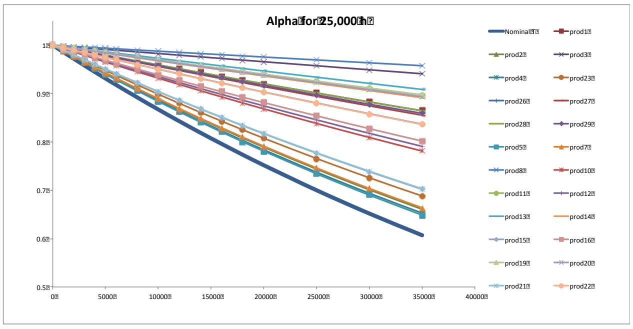


Figure 3 $\alpha|_{T_1}$ under the condition of $t_{70}|_{T_1} = 25{,}000$h for T_1 ≤105°C

Under the assumption of that the electronic controller will preform stable during the acceleration test, it is advantage that to apply the 2-stage acceleration model to lamp/luminaire level as luminous acceleration test.

3. Implementation

The lamp/luminaire luminous acceleration test procedure has been developed in this section to validate the 2-stage acceleration model. Such procedure includes several steps, including sample selection, acceleration temperature judgment, acceleration test and pass/fail criterion setting, as described in the following.

(1) Sample Selection

Sample group are formed by randomly selecting luminaires from two production batches in which all products has identical type of driver, heat sink and mechanical structure, were made by the same production line, and should be made by the same kind of material, components and LEDs.

Seasoning should be done for all samples by the manufacture before the test.

(2) Define the Acceleration Temperature

The depreciation of LEDs is highly depended on the junction temperature T_j. A high temperature will accelerate the depreciation of LEDs. However, the high temperature could possibly cause other failure modes other than depreciation. For example, high environment temperature might trigger the over temperature protection, which will reduce the current input from driver. Therefore, it is important to choose a temperature which will only accelerate the lumen depreciation instead of other failure modes.

To scientifically define the acceleration temperature for a product, 1 sample is taken out randomly from sample group, and measure the light output (in terms of lumen or light flux). Next, locate the sample inside the temperature oven, which has known/controlled glass window. We set the oven under temperature of 40°C, 50°C and 60°C. When the sample is under the specified oven temperature and under operation, the light output has been measured outside the oven through the window. Afterwards, the sample will be taken outside the oven and measure the light output in room temperature.

The measurement fluctuation at room temperature should be less than 5%, in order to prove that the lumen decay is neglectable. If the difference between measurements within and out of oven is less than 10%, one could assume that the oven temperature minus 5°C can be reasonable acceleration temperature testing for acceleration test.

First, the initial luminous flux of the sample is measured at room temperature, with normal convection. Then the sample is put into the test cabinet and installed, following the product manual. The sample works at rated voltage in the cabinet which is set to the acceleration temperature decided in the last section and the ambient RH can't be over 65%.

The temperature difference between LED sample temperature at outer surface and ambient temperature should not have a variation larger than 3°C when the sample works at the acceleration temperature and the room temperature. After working for the required test duration, the sample is taken out from the test cabinet. The luminous flux of the sample is measured until the sample recovers in the room temperature ambient and reaches the thermal stabilization. The measurement is finished within 8 hours after the sample is out of the test cabinet. The acceleration luminous flux maintenance ratio is the percentage of measured luminous flux in initial luminous flux. In the acceleration test, all samples' parameters were measured using same equipment at the same conditions, ensuring the consistency of measurement results. Also all measured results were recorded to make them traceable.

According to the calculation based on the theory developed in this paper, including activation energy and nominal temperature, one can calculate the expected accelerated lifetimes under the expected room temperature lifetime of 25khrs, 30khrs or 35khrs. Following Eq (2), these calculation results as listed in Table 2.

Table 2 Proposed accelerated lifetime test time

Expect lifetime (h)	A*	Acceleration temperature (°C)	α	L_{95} (h)
25000	14.3	35	2.0369E-05	2550
		45	2.8564E-05	1800
		55	3.9399E-05	1300
30000	12.8	35	1.7038E-05	3050
		45	2.3976E-05	2150
		55	3.3177E-05	1550
35000	14.3	35	2.9533E-05	3500
		45	2.1096E-05	2450
		55	2.9533E-05	1750

*: A is the pre-factor from Eq (2).

During the test, no catastrophic fail is allowed. Otherwise, the sample is considered to fail the test and its predicated lifetime is shorter than its claimed lifetime. The predicted lifetime of a specific product is considered to reaches its claimed lifetime only when the number of failed samples is no more than the minimum allowed failure number listed in Table 2.

4. Validation

Various LED based integrated lamps have been selected from major manufactures. These products are designed from various market segments. Each type of the samples contains 8 samples. All samples are fresh samples that directly from the manufacturer with the functional certification and following the standard manufacturing procedure. 1 sample is used for build-up material (BoM) list in order to investigate the failure mechanism/modes after the acceleration test (part of the BoM are shown in Figure 4), the rests are used for the validation test.

The samples are subjected to the temperature loading as listed in Table 3 with nominal operation condition. Only the 25°C group is located under the room temperature, the rests are in the standard oven. The measurement frequency is high at first 1000 hrs and measured every 168 hrs afterwards. The samples are first removed from the oven, cool down to the room temperature and are measured by 2-m integrated sphere. The total measurement duration is limited to be less than 8 hrs, and the samples will be replaced into the oven immediately after measurement. The accumulate loading-time is defined as the time that the oven and LED products are operated normally.

Table 3 Temperature loading and sample size

Temperature loading group	Sample size
25°C (room temperature)	2
55°C	3
85°C	2

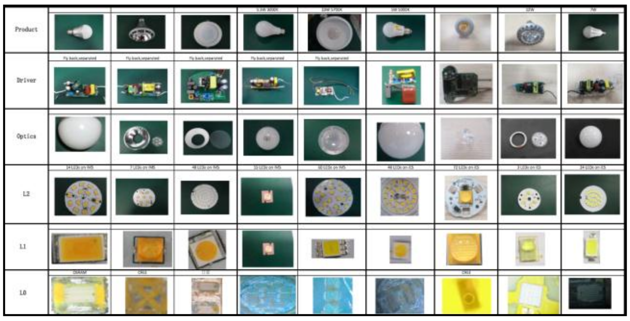


Figure 4 BoM analysis of the test samples

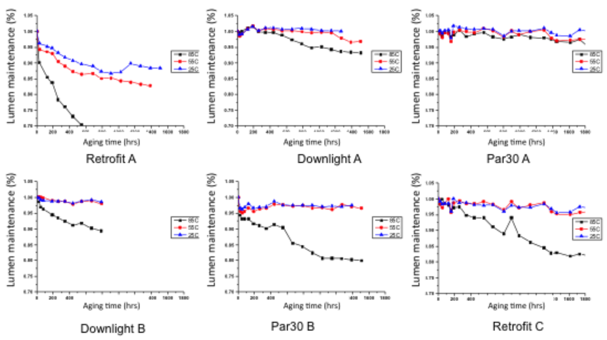


Figure 5 Lumen maintenance test result

Figure 6 and 7 shows the test result at 25 ^{o}C (room temperature) and 55 ^{o}C environmental conditions. The 25^{o}C was chosen for simulating the conventional luminous maintenance test condition. The solid line in Figure 6 shows the pass/fail criteria of $t_{70}|_{T_1} = 30{,}000$ hrs and $\alpha]_{T_1} = 1.189 \cdot 10^{-5}$. It is clear that prod3 and prod5 fails under the room temperature test. Similarly, The solid line in Figure 6 shows the pass/fail criteria of $\alpha]_{T_1+55}$. It is clear that prod3 and prod5 fails under the 55 oC test after 1600 hrs. Note that the prod7 and prod8 in Figure 7 is the known good products, which would not fail during the acceleration test.

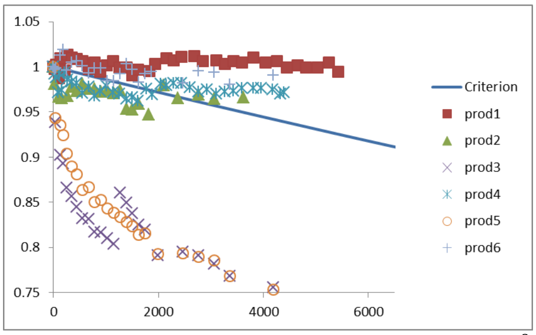


Figure 6 Luminous maintenance test results at 25^{o}C

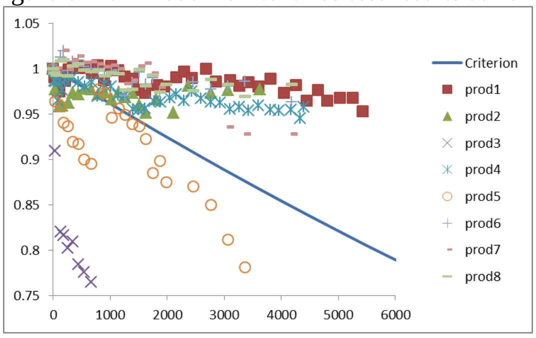


Figure 7 Luminous maintenance test results at 55^{o}C

5. Discussion

First, the proposed acceleration test could test luminous maintenance capability of the light source under reliable heat dissipation mechanism and the stable current supply from driver electronics.

In the detail study of the luminous decaying model in Figure 6 and 7, not all products will perfectly follow the exponential decay rule, due to that the large difference among lamp/luminaire designs and complex decaying mechanism. However, the acceleration model from this paper provides clear pass/fail criteria for 25^{o}C and 55^{o}C, as shown in Figure 6 and 7. This is because of that, such criteria has been set by carefully defining of the activation energy and nominal temperature (as indicated in Eq (2)).

US DOE applied the fact of that the lumen depreciation of LED products mostly follows exponent role, considered the lamp/luminaire lumen measurement accuracy and developed next acceleration method by 6,000 hours room test (follows IES LM-79-08) and extrapolate to nominal life time. This test method is applicable for integrated LED lamps [5] and SSL luminaires [6]. However, according to Eq (1), US DOE intent to use same α for both integrated lamp and SSL luminaire, regardless the junction temperature difference between these two applications. Such consideration might induce an unbalance development of the LED product development, due to misleading the market towards high lifetime expectation of the integrated lamps and low expectation of the SSL luminaires (e.g., street lighting).

6. Conclusion

Accelerated luminous depreciation method at lamp/luminaire level has been established by 2-stage acceleration theory, carefully selecting acceleration parameters, testing method and experimental validation. The 2-stage acceleration theory is based on the exponential luminous depreciation model and Arrhenius equation. The activation energy and nominal temperature has been set by considering LM80 data sets from more than 30 types of products. Considering the measurement accuracy and product technology currently available, the corresponding testing procedure has been established. Through the real product validation, the theory and its parameters have been proved. It indicated that the 2-stage acceleration method could provide a clear boundary between the pass/fail criterions.

Moreover, this paper provides a deep understanding of the physical meaning of depreciation parameter α as function of the LED junction temperature. As the junction temperature varies among different applications, α should be chosen from the thermal characteristics of the integrated lamps / SSL luminaires to achieve balance LED industry growth.

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References

1. John Bullough, Y. G., Nadarajah Narendran, Jennifer Taylor (2005). "LED Life for General Lighting." *Alliance for Solid-State Illumination Systems and Technologies* (ASSIST) 1(7).
2. Illuminating Engineering Society, LM-79-08 Electrical and Photometric Measurements of Solid-State Lighting Products, 2008.
3. Illuminating Engineering Society, TM-21-11 Projecting Long Term Lumen Maintenance of LED Light Sources, 2012.

4. CSSL, "Philips Master Glow, 7W, measurement result," 2011
5. US DOE, "ENERGY STAR® Program Requirements for Integral LED Lamps Partner Commitments", 2010.
6. US DOE, "ENERGY STAR® Program Requirements for Solid State Lighting Luminaires", 2008.
7. van Driel W.D. and Fan X.J. Solid State Lighting Reliability Components to Systems, Springer, 2012.