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Development of a Predictive Life Test Method for LED Luminaires, Light Engines, and Integral Lamps

Principal Investigator:

Nadarajah Narendran, Ph.D., FIES

Professor and Director of Research

Lighting Research Center (LRC)

Rensselaer Polytechnic Institute, Troy, NY 12180

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Project Team:

- Nadarajah Narendran (PI)
- Yi-wei Liu
- Xi Mou
- Dinusha R. Thotagamuwa
- Jennifer Taylor

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Preface

The project described in this report was built on prior work conducted by Rensselaer Polytechnic Institute's Lighting Research Center (LRC). LRC started investigating this topic in 2009 under Alliance for Solid State Illumination Systems and Technologies (ASSIST) program sponsorship to develop a cost-effective, accelerated life test method that can predict the life of LED systems for a given application environment and on-off switching pattern. The study was an attempt to address the problem of current industry test methods that often do not produce accurate lifetime estimates for LED systems. The results of the initial studies indicated that system failure acceleration using delta T (ΔT or DT, the temperature difference between the stabilized operating temperature during on-time and the stabilized temperature during off-time) and dwell time (the time of operation at stabilized operating temperature during on-time) showed promise in predicting the failure of LED systems under different operating conditions. Funding from the Bonneville Power Administration, the New York State Energy Research and Development Authority (NYSERDA), and the Alliance for Solid State Illumination Systems and Technologies (ASSIST) allowed the LRC to expand its earlier work to a wider range of LED systems, including LED lamps, light engines, and luminaires, to validate the developed test method and move the method forward toward broad industry adoption and standardization. The anticipated benefit at the conclusion of this new study is that a cost-effective, short duration (less than three months) LED system life test method will be available for manufactures to reliably determine the expected life of LED lighting products. This will help to assure BPA and New York State rate-payers that when they purchase an LED lighting product, it will operate reliably for the period claimed by the manufacturer.

Goals and Scope of this Project:

The objectives of this project were to:

- Develop a cost-effective, short duration testing method for LED lighting products, which will allow accurate determination of system life when used in a given environment and use pattern.
- Validate the test method developed in previous LRC studies for LED lighting luminaires, light engines, and lamp types.
- Estimate system light color shift at end of life.
- Move the testing method forward toward wide industry adoption, standardization, and use.

EXECUTIVE SUMMARY

LED products have started to displace traditional light sources in many lighting applications. One of the commonly claimed benefits for LED lighting products is their long useful lifetime in applications. Today there are many replacement lamp products and luminaires using LEDs in the marketplace. Typically, the lifetime claims of these products are in the 25,000 - 50,000 hour range. According to current industry practice, the time for the LED light output to reach the 70% value is estimated according to IESNA LM-80 and TM-21 procedures, and the resulting value is reported as the whole system life. LED products generally experience different thermal environments and switching (on-off cycling) patterns when used in applications. Current industry test methods often do not produce accurate lifetime estimates for LED systems because only one component of the system, namely the LED, is tested under a continuous-on burning condition without switching on and off, and because they estimate for only one failure type, lumen depreciation. The objective of the study presented in this report was to develop a test method that could help predict LED system life in any application by testing the whole LED system, including on-off power cycling with sufficient dwell time, and considering both failure types, catastrophic and parametric.

The study results showed that both failure types, catastrophic and parametric, exist for the LED A-lamps and LED MR16 lamps tested in this study. The on-off cycling encourages catastrophic failure, and maximum operating temperature influences the lumen depreciation rate and parametric failure time. It was also clear that LED system life is negatively affected by on-off switching, contrary to commonly held belief. In addition, the study results showed that most of the LED systems failed catastrophically, much before the LED light output reached the 70% value. This emphasizes the fact that life testing of LED systems must consider catastrophic failure in addition to lumen depreciation, and the shorter of the two failure modes must be selected as the system life. The results of this study show that a test procedure with a shorter time, less than 3000 hours, can be developed to accurately predict LED system life in any application by knowing the LED temperature and the switching cycle.

For the LED downlight luminaires tested, only parametric failure (i.e., reduced light output) was observed during the test period. It is worth pointing out that some LED systems employ feedback control circuits to detect LED temperature and under-drive the devices so that they do not exceed certain temperatures that would lead to system failure. Such systems will emit lower light output at higher junction temperatures, a tradeoff to prevent the systems from failing. The proposed test method to estimate LED system life may not work well with systems that use feedback control. In such cases, parametric failure may be the only failure mode present. It is safe to say that the majority of the LED lighting systems in the marketplace do not employ feedback control because such features tend to increase product price.

Post-mortem analysis showed that in the case of the LED A-lamps, the majority of the failures (greater than 80 percent) were due to failure of the LED solder that attaches the LED to the printed circuit board, and a small percentage were due to driver failures. In the case of LED MR16 lamps, the majority of the failures (greater than 95 percent) were due to driver failure. These findings show that in LED systems there could be many failure modes. The proposed test method encourages some failures such as solder failure and driver component failure, including capacitor and or diode, but it may not encourage other types of failure that may exist in some applications. For example, outdoor fixtures may fail due to terminal corrosion and volatile organic compounds (VOC)-induced component deterioration encouraged in sealed fixtures. Additional studies are required to determine other failures that may be unique in certain applications.

The proposed test procedure described in this report is useful for determining the lifetime of LED products more accurately than the current industry practice. Even though it may not catch all failure modes, it would certainly encourage failure modes typically found in LED fixtures used in most indoor applications. Adopting this procedure would help users gain more confidence in the lifetime numbers reported by product manufacturers and would help create more accurate payback analysis calculations, which are commonly used in the lighting industry when making decisions to replace existing lighting products.

1. INTRODUCTION

Light-emitting diode (LED) technology has evolved rapidly, and today it is considered the preferred light source for many lighting applications. One of the claimed benefits for LED lighting systems (lamps and luminaires) is long life. Today there are many LED lighting products in the marketplace. Typically, the lifetime claims of these products are in the 25,000 - 50,000 hour range. When customers purchase these products, they expect these products to last the advertised lifetime hours in all applications where they would use them. For example, LED A-lamps are used in many lighting fixtures in homes and offices, including table lamps, ceiling-mounted fixtures, wall sconces, recessed downlights, and many others. The LED lamps experience different thermal environments and switching (on-off cycle) patterns in these different applications. Even though it is known that LED system life varies depending on the application environment, presently no studies have shown how to estimate LED system life accurately when used in an application. Therefore, the objective of this study was to develop an accelerated test method for LED lighting systems that allows for accurate determination of system life if the LED junction temperature in the application environment and the on-off switching pattern are known.

According to current industry practice, LED system (lamp or luminaire) lifetime is defined as the time it takes for the LED light output to reach 70% of its initial value (L70) in hours, as defined by the Illuminating Engineering Society of North America's standard, IESNA LM-80 [1]. The LED used in the luminaire is tested according to IESNA LM-80 and the time to reach the 70% value is projected according to IESNA TM-21 [2]; the resulting value is reported as the whole system life. An LED system has many components, including the LED or LED array, printed circuit board (PCB), heat sink, mechanical housing, electronic driver, electrical connectors, optics, and others. Failure of any one of these components can lead to the failure of the entire LED lighting system. Defining the entire system life based on the failure time of an LED, which has a very long lifetime compared to other components in the system, is incorrect. Furthermore, an LED system failure can be catastrophic, in which the LEDs do not produce any light, or parametric, in which the LEDs produce light but the luminous flux is reduced or the color of the light has shifted from the initial value.

During the past few years, the lighting industry has been requesting shorter testing times to help speed up the introduction of new lighting products using the latest LED packages with higher lumen and luminous efficacy values. In response to this request, several studies have addressed the issue of shorter life testing by investigating highly accelerated life-test methods for LED luminaries [3-7]. Most of these methods consider lumen depreciation as the failure mode. However, there are studies that have considered the fatigue failure of other power semiconductors by power cycling [8]. These studies emphasize that failure can be parametric or catastrophic, and therefore it is important to consider both types of failure.

Starting in 2009, we, the Lighting Research Center, began investigating LED system life testing. The objective of these studies was to develop an accelerated test method that could help predict LED system life in any application. The conclusions from these studies were that to accurately estimate LED system life, the whole lighting system must be tested, the test procedure must include on-off power cycling with sufficient dwell time, and both failure types, catastrophic and parametric, must be considered [9,10]. Some of these key points have been recognized and documented by industry groups studying the same issue [11]. In 2014, IESNA published a standard, LM84-14, for testing LED systems. Even though this is an improvement over the use of the LM-80 test method to rate LED system life because it tests the whole system rather than just the LED, the drawbacks are that LM-84 recommends continuous-on operation and considers only lumen depreciation failure [12].

Therefore, the objective of this study was to develop a test method that could help predict LED system life in any application by testing the whole LED system, including on-off power cycling with sufficient dwell time, and considering both failure types, catastrophic and parametric. In addition, chromaticity (color) shift of products would be measured and tabulated.

2. EXPERIMENT

As mentioned earlier, some of the preliminary studies conducted in the LRC's laboratory using integral LED lamps indicated that delta temperature (ΔT) and dwell time (t) showed the strongest correlation for catastrophic failure [10]. In the current study, three different types of LED systems, namely LED A-lamp, LED MR16 lamp, and LED downlight, purchased from the commercial marketplace were tested. All the products sampled in this study were ENERGY STAR rated and were procured during the latter part of 2014. Each LED system was subjected to different ΔT values and different dwell time conditions. A total of 287 LED products were used in this study.

2.1. LED A-lamp

Typically A-lamps are used in different operating environments such as open air, semi-ventilated and enclosed lighting fixtures resulting in different junction temperatures. A commercially available ENERGY STAR rated LED A-lamp product, marketed as a 75W incandescent replacement, was selected as the system to validate the test method. The next step was to determine the junction temperatures experienced by the LED A-lamp when used in the above mentioned environments. Usually the A-lamps experience the lowest junction temperature when used in applications such a table lamps and highest temperature when used in 3-lamp surface-mount fixtures (see Fig. 2.1-1). The measured junction temperatures ranged from 96 °C to 145 °C corresponding to ΔT of 66 °C to 115 °C.

Fig. 2.1-1: Luminaire and LED A-lamps used in the study to determine LED junction temperature change when the lamps are turned on and off.

Temperature measurements were taken using thermocouples attached at two different locations on the lamp (the lamp housing and the LED pin) once the lamp within the fixture reached thermal stability. The pin temperature and the thermal resistance coefficient of the LED package, reported by the respective LED manufacturer, enabled the estimation of the LED junction temperature, Tj [13]. This also provided the relationship between the lamp housing temperature and the LED junction temperature. The procedure allowed us to estimate the LED junction temperatures without disturbing integrity of the lamps.

Past studies showed that delta temperature (ΔT) and dwell time (t) affected the time to catastrophic failure. Therefore, three ΔT values, namely, 80, 90, 100 °C that were within the temperature range usually experience by the A-lamps when used in applications were selected to obtain the relationship between ΔT and time to failure.

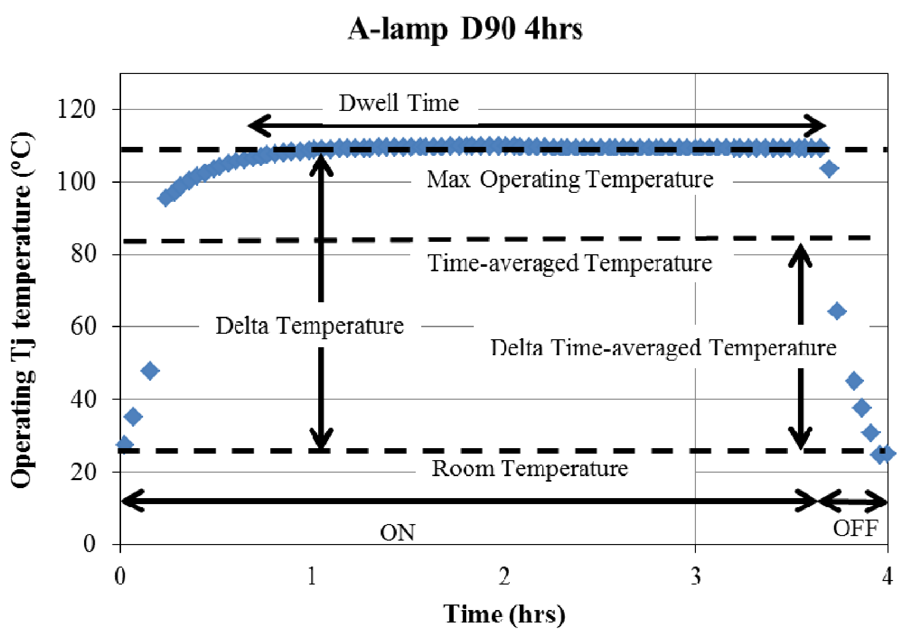

Fig. 2.1-2: Measured temperature profile during one operating cycle of an LED A-lamp (ΔT=90°C; dwell time, 4 hrs).

Figure 2.1-2 illustrates a sample temperature profile experienced by the junction of the LED as a function of time. This figure illustrates the parameters used in this study. The ΔT is defined as the temperature difference between the maximum operating temperature during on-time and the room temperature during off-time. The dwell time is defined as the time of operation at stabilized operating temperature while the lamp is switched on. Because the temperature experienced by the LED junction changes between room temperature and the maximum operating temperature during on-off cycles the temperature experienced by the LED is the time averaged temperature.

It is worth noting here that even though the dwell times were designed for 2 hours and 4 hours the measured values were different because of the warm-up and cool-down time (see Table 2.1-1).

Table 2.1-1: A-lamp – Measured average on time, dwell time, and off time duration at each delta temperature (ΔT).

Nominal Condition	ΔT (°C)	On Time (hours)	Dwell Time (hours)	Off Time (hours)
2hrs	80	1.7	1.1	0.6
	90	1.6	1.1	0.6
	100	1.6	1.2	0.7
4hrs	80	3.4	2.8	0.7
	90	3.6	2.8	0.7
	100	3.7	3.1	0.8

2.1.1. Experimental Variables

Sample size: A total of 90 16W rated LED A-lamp samples, 75W incandescent lamp equivalent

Independent variables: delta temperature (ΔT): 80/90/100°C; dwell time (t): 2-hrs, 4-hrs, and continuous-on. Please see Table 2.1-1 for details.

Dependent variables: light output, spectral power distribution (chromaticity coordinates), input power, input current, lamp housing temperature

2.1.2. Experiment Setup

Figure 2.1-3 shows the schematic and two pictures of the experiment setup. LED A-lamps were placed inside a downlight fixture. A heater pad was wrapped around the downlight housing to control the junction temperature of the test lamp (Tj). Five of these downlight cans were placed inside a wooden box. A light sensor box was attached to the opening of the downlight to monitor the light output and detect catastrophic failure or lumen depreciation for each lamp. A thermocouple was attached to the housing of the LED A-lamp to estimate the LED junction temperature. In an initial study, the relationship between the LED A-lamp housing temperature and the LED pin temperature was determined by attaching a thermocouple to each location, namely the LED A-lamp housing and the LED case. Using the published thermal resistance value of the LED used in the A-lamp, the junction temperature was estimated. Control circuits switched the lamps and the heater pad on and off at the designed dwell time and ΔT. As described earlier, for each ΔT, lamps were switched on and off to achieve 2-hour and 4-hour dwell times and in the third case kept the lamp powered on continuously. Each test condition had 10 lamp samples and altogether 90 lamp samples were used at the three ΔT with three dwell time conditions. A sample size of 5 to 10 lamps is recommended by the Energy Star Product Specification for Lamps (Light Bulbs) [14]. All test boxes were placed on a rack, and each lamp test assembly was connected to a data acquisition system for continuous monitoring and recording of the dependent variables: light output, input power, input current, and lamp housing temperature. Spectral power distribution was measured with a spectroradiometer every 500 to 1000 hours.

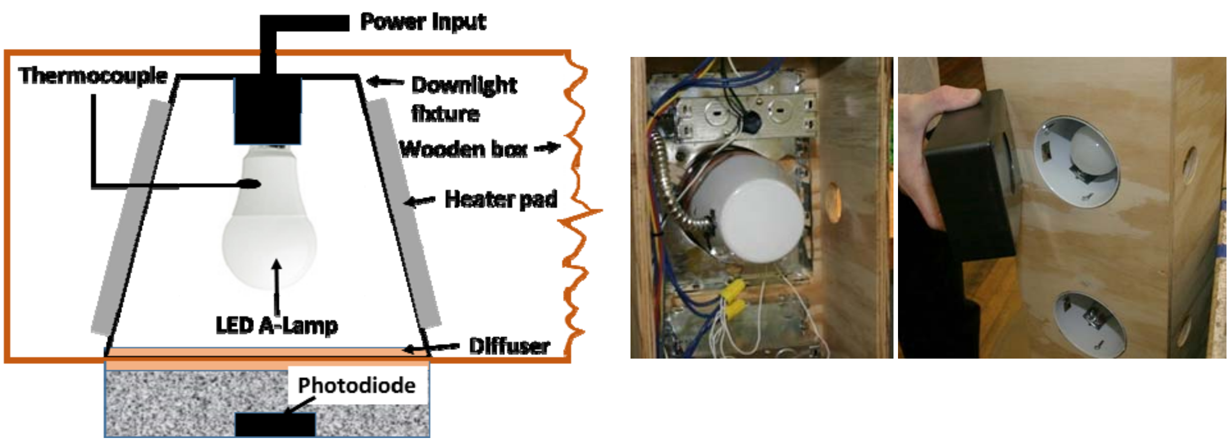

Fig. 2.1-3: Experimental setup.

2.1.3 Results

2.1.3(a). LED A-lamp failure – Catastrophic

Figures 2.1-4 (a) through (f)* show catastrophic failure of LED A-lamps as a function of time for each test condition, ΔT and dwell time. The average time between the 5th and the 6th lamp failures denotes the median life, indicated by the solid line in Figure 2.1-4. As seen in this figure, the median lamp life due to catastrophic failure depends on ΔT and the dwell time. A post-mortem analysis showed that 84% of the failures were due to failure of the solder between the LED and the PCB, and the remaining 16% were due to driver failure.

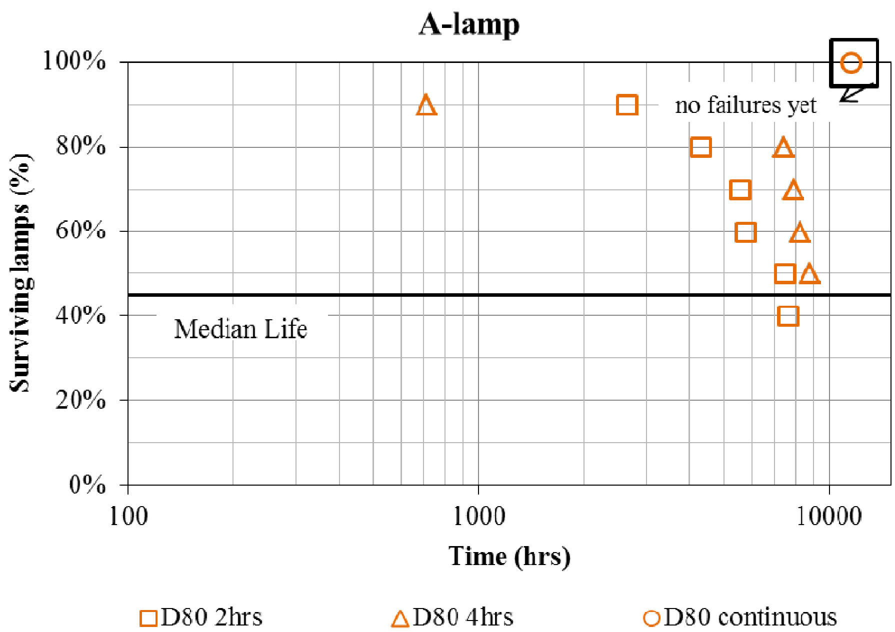

Fig. 2.1-4(a): LED A-lamp catastrophic failure as a function of time for D80 test condition, for 2 hours and 4 hours dwell times and continuous-on operation. Note that for the D80 continuous-on case, all lamps had no failures yet.

*The following note applies to Figures 2.1-4(a) through (f):

The x-axis is the cumulative time in hours, and for all graphs the x-axis was plotted in the logarithmic scale in the range between 100 – 100,000. Some data points fall outside the range and are not displayed.

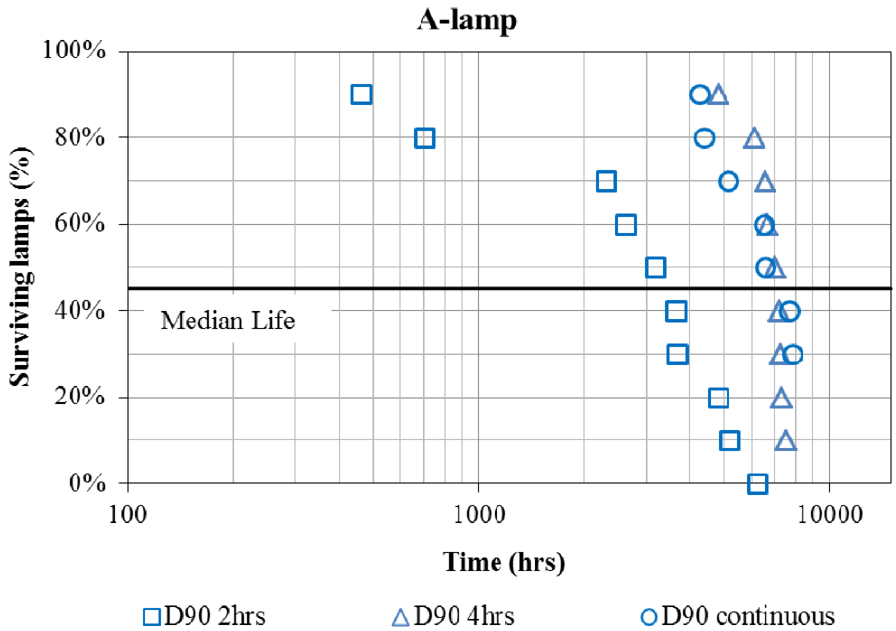

Fig. 2.1-4(b): LED A-lamp catastrophic failure as a function of time for D90 test condition, for 2 hours and 4 hours dwell times and continuous-on operation.

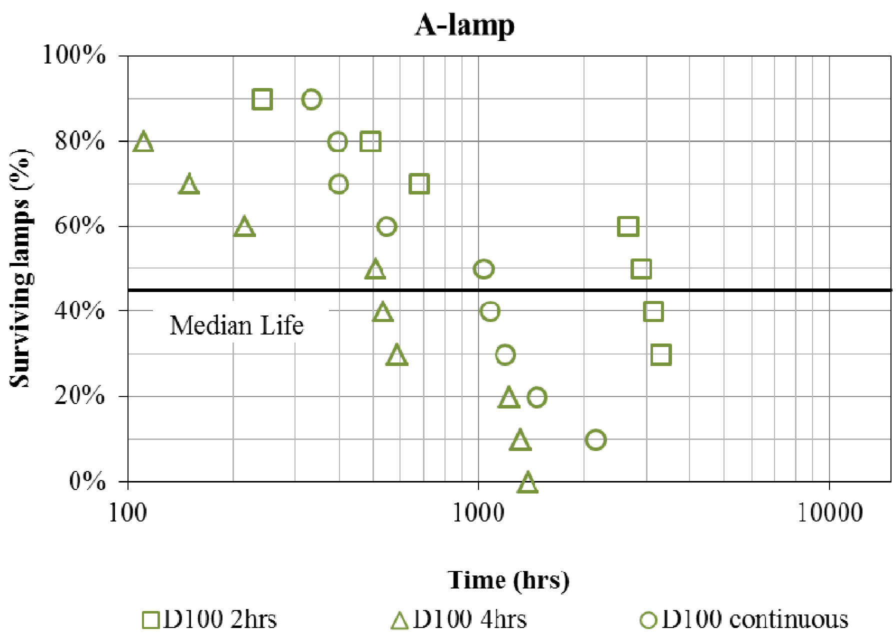

Fig. 2.1-4(c): LED A-lamp catastrophic failure as a function of time for D100 test condition, for 2 hours and 4 hours dwell times and continuous-on operation.

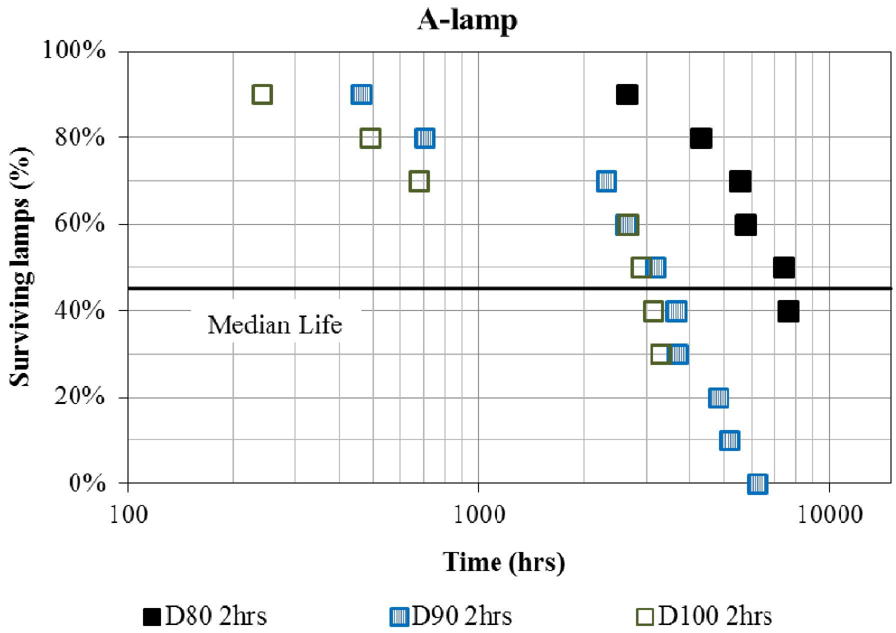

Fig. 2.1-4(d): LED A-lamp catastrophic failure as a function of time for D80, D90, and D100 test conditions, for 2 hours dwell time.

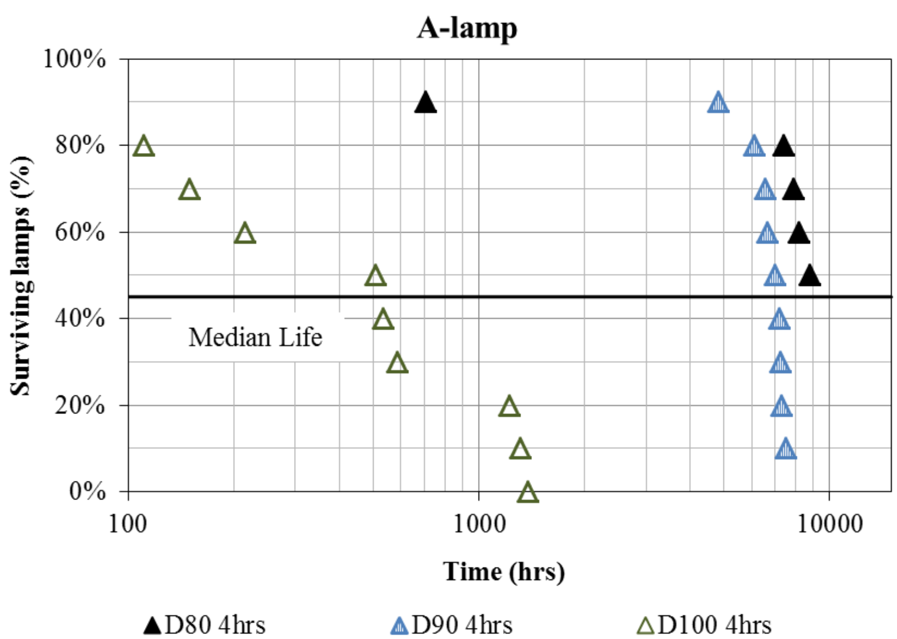

Fig. 2.1-4(e): LED A-lamp catastrophic failure as a function of time for D80, D90 and D100 test conditions, for 4 hours dwell time.

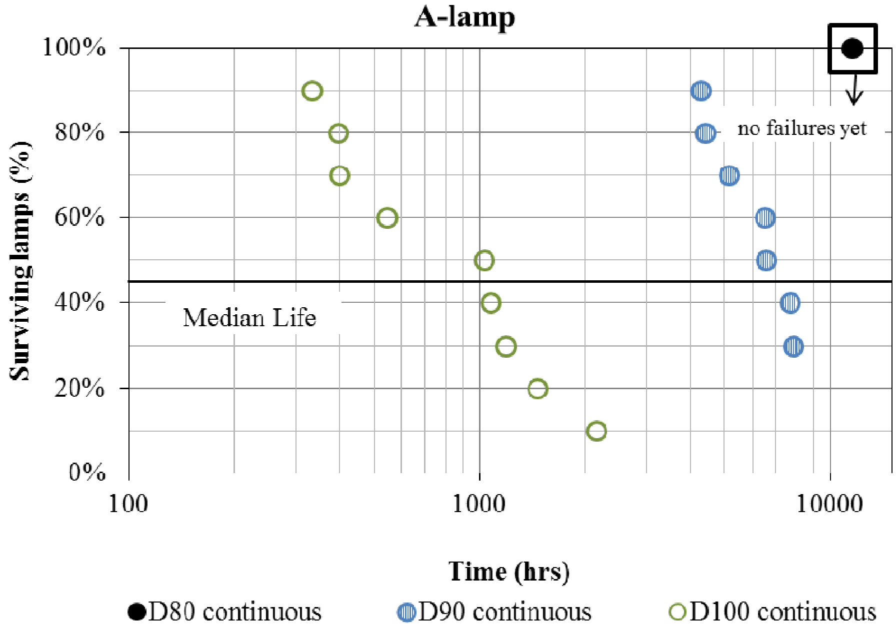

Fig. 2.1-4(f): LED A-lamp catastrophic failure as a function of time for D80, D90, and 100 test conditions, for continuous-on operation. Note that all lamps in the D80 condition had no failures yet.

Table 2.1-2: Delta time-averaged temperature (ΔTavg) values and time to failure values for the different ΔT and dwell time conditions.

	Delta time-averaged temperature (°C)		**Time to failure (median life) (hours)**	
ΔT/Dwell Condition	2 hours	4 hours	2 hours	4 hours
80°C	48	60	7,516	8,801
90°C	61	69	3,411	7,091
100°C	69	82	3,225	521

Table 2.1-2 shows the delta time-averaged temperature and median life in hours for the tested conditions. As seen in Table 2.1-2, higher ΔT conditions result in shorter time to failure for both dwell time conditions. Also, shorter dwell times result in shorter time to failure for 80°C and 90°C but not for 100°C ΔT conditions. For the median time to failure for ΔT at 100°C, the 4-hr dwell time was shorter than 2-hr dwell time. This is because the failure takes place due to cumulative

damages caused at each transition that are also dependent on the temperature change during this transition. Temperature change during transition stresses the interface between the LED and the electronic board, namely, the solder interface layer that ultimately fails due to fatigue. Therefore, with increasing delta temperature the number of transitions reduces. For a given maximum junction temperature with reduce number of transitions per unit time that the time-averaged temperature experienced by component will increase. In the case of ΔT at 100°C and 4-hour dwell time, the time-averaged temperature is relatively higher compared with others and results in a fewer number of transitions before failure. This further emphasized in Figure 2.1-5, where cycles to failure (median life) as a function of delta time-averaged temperature shows an inverse linear relationship with high goodness-of-fit, (R^2) > 0.9.

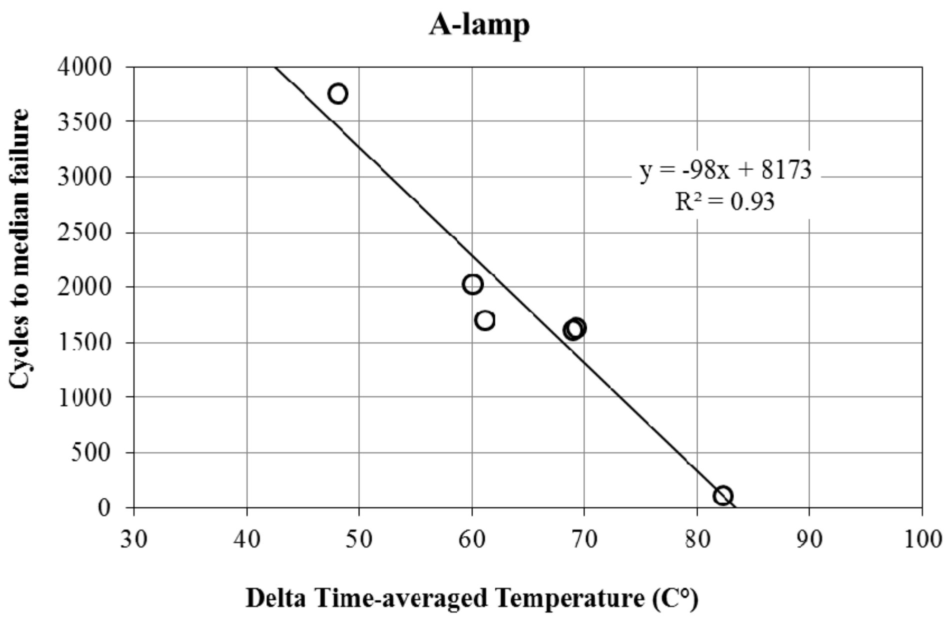

Fig. 2.1-5: Cycles to failure as a function of delta time-averaged temperature (ΔTavg) (°C).

The results from this study clearly show that the life of an LED system is affected by switching it on and off. The ability to switch LED lights frequently without affecting life has been a commonly touted benefit over other light sources like compact fluorescent (CFL), but this is clearly not the case. It is also worth noting that the absolute number of hours for lifetime observed for this particular lamp should not lead to conclusions that other LED A-lamps will have similar lifetime.

2.1.3(b). LED A-lamp failure – Lumen depreciation

Figure 2.1-6 shows lumen depreciation values measured just prior to catastrophic failure for the different test conditions. These results indicate that, for the tested lamp, most lamps underwent catastrophic failure before reaching L70. This finding emphasizes the point that a power cycling test is essential to determine the life of LED systems accurately.

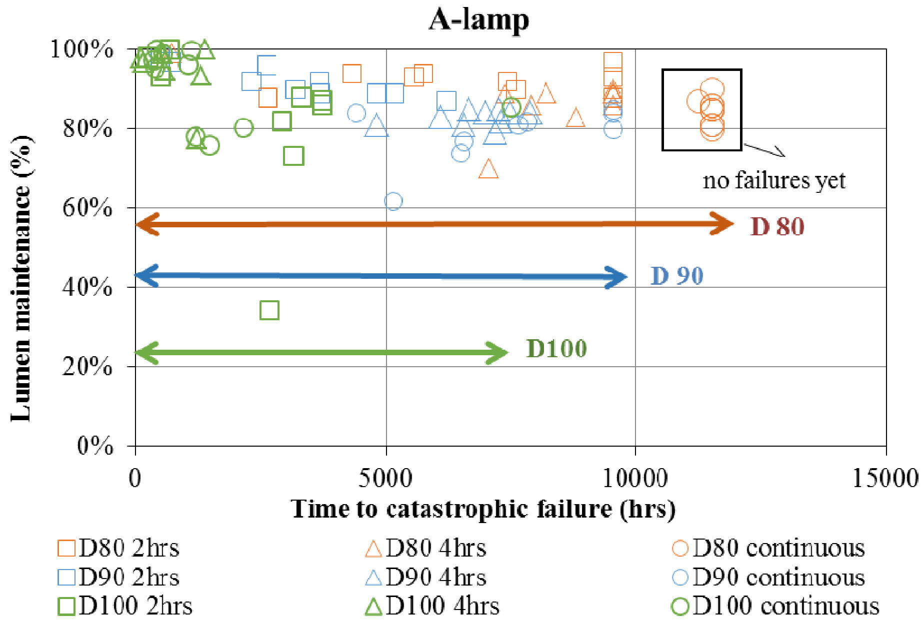

Fig. 2.1-6: Measured lumen depreciation values just prior to catastrophic failure for the different test conditions.

These measured lumen depreciation data were extrapolated to determine L70 values for each condition. To ensure the accuracy of the projected values were similar for 80°C, 90°C, and 100°C at each ΔT, the considered data for extrapolation had a similar lumen depreciation value, 10%. The median lamp life, based on L70 in hours, is shown in Table 2.1-3. Figure 2.1-7 shows that for the product tested, time to failure L70 (median life) as a function of maximum operating temperature has an inverse linear relationship with goodness-of-fit, $R^2 > 0.9$.

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The projected L70 values decrease as a function of increasing ΔT condition. However, the cycling seems to have minimum effect. As a result, the projected L70 values for 2-hr and 4-hr dwell times and continuous-on condition for each ΔT are similar.

Table 2.1-3: Maximum operating temperature and time to L70 failure for the different ΔT and dwell conditions.

	Maximum operating temperature (°C)			**Time to L70 (hours)**		
ΔT/**Dwell Conditions**	2 hrs	4 hrs	Continuous-on	2 hrs	4 hrs	Continuous-on
80°C	106	108	108	25,528	20,998	23,979
90°C	125	124	124	11,019	12,185	11,657
100°C	131	136	131	7,289	5,308	5,171

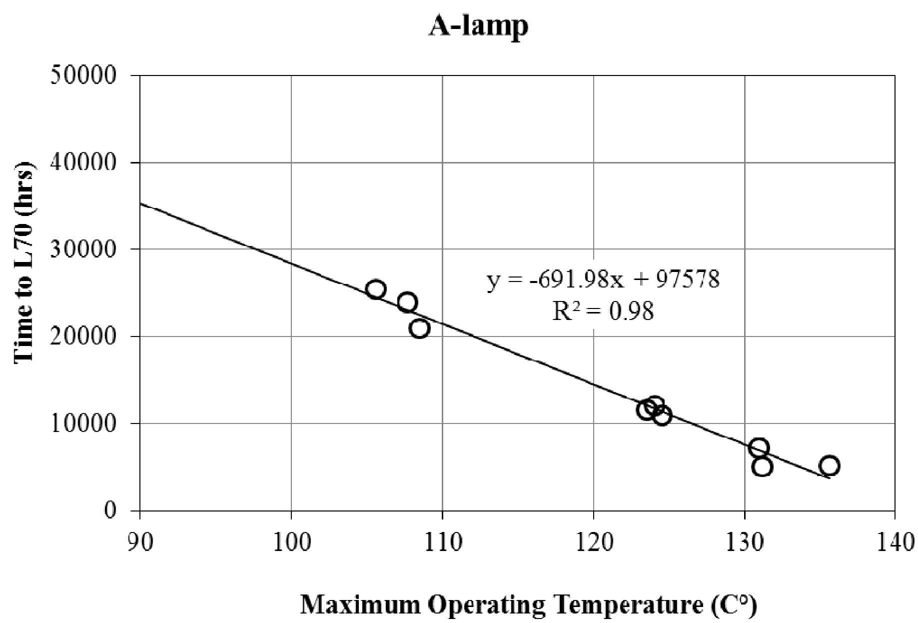

Fig. 2.1-7: Time to failure based on lumen depreciation, L70, as a function of maximum operating temperature.

2.1.3(c) LED A-lamp – Color shift

For many LED lamps, the materials in the LED package could deteriorate over time and result in changing the spectrum of the output light. Figure 2.1-8 shows the chromaticity shift, in number of MacAdam ellipse steps, as a function of time for all LED A-lamps under different operating conditions. The majority of the lamps had chromaticity shift values less than a 4-step MacAdam ellipse by the time they reached failure. The industry generally considers less than 4 steps as an acceptable chromaticty shift because the color change may not be obviously visible to observers.

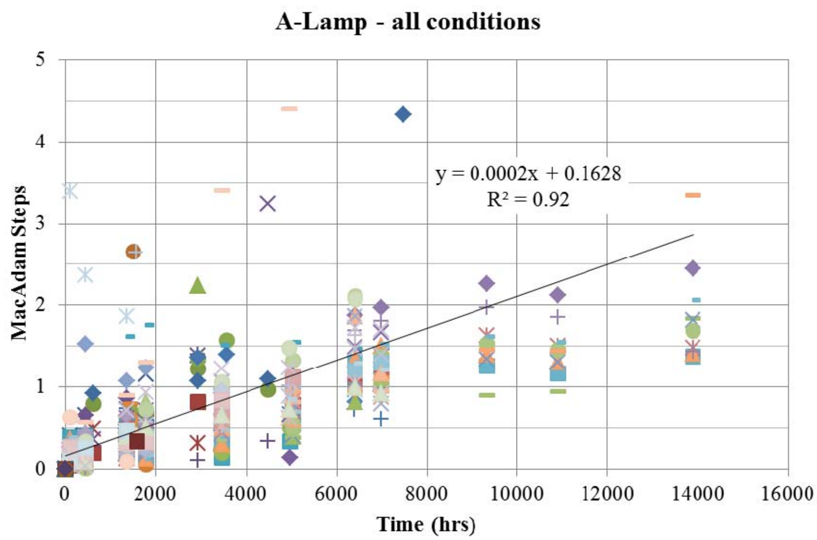

Fig. 2.1-8: Chromaticity shift as a function of time for all LED A-lamps under different operating conditions.

2.1.4. Discussion

The study results show for the LED A-lamps tested, both failure types, catastrophic and parametric, exist. The on-off cycling encourages catastrophic failure, and maximum operating temperature influences the lumen depreciation rate and thus the parametric failure time. The reason why on-off switching results in catastrophic failure is because of the stresses experienced by the interface material, namely the solder due to thermal expansion mismatch between the different layers in the system that lead to fatigue failure. Parametric failures such as lumen depreciation and color shift are caused by the yellowing of the binding materials used in the LED packages that hold the phosphor particles. Such failures become rapid at higher temperatures. Therefore, transitions taking place during on-off cycling encourage catastrophic failure, and LED device operation at maximum temperature accelerates parametric failure.

When both failure types exist, the shorter of the two times to failure should be considered as the lifetime of the product. In applications, LED systems will experience both types of failure and depending on the operating conditions, one failure type could dominate. For the lamps tested, catastrophic failure times were shorter than lumen depreciation, L70, failure times. Therefore, the results from this study show that to obtain accurate life estimates for LED systems, unlike current industry test standards and practices, life testing must include on-off switching.

For the A-lamps tested, the chromaticity shift for most of the lamps was less than a 4-step MacAdam ellipse by the time they reached end of life. However, we cannot generalize this to any LED A-lamp product on the market because they would have different amounts of chromaticity shift.

2.1.5. Estimating lifetime in different applications

To illustrate the usefulness of this test method and the results, two applications where LED A-lamps are commonly used were selected and the lamp life in each application was estimated.

<u>Table lamp</u>: The first application example considered is a table lamp with the LED A-lamp tested in this study. It is assumed that the table lamp is switched on for 3 hours per day and off during the rest of the day. The maximum operating junction temperature experienced by the LED within the A-lamp, Tj, is 95°C, and the room temperature, Troom, is 30°C. The estimated time-averaged temperature, Tavg, is 80°C, and therefore ΔTavg = (Tavg – Troom) is 50°C. From Figure 2.1-5 the cycles to failure at 50°C is estimated as 3250 cycles, corresponding to 3250 days or 8.9 years. Likewise, from Figure 2.1-7 at 95°C maximum operating temperature, the time to L70 can be estimated as 32,000 hrs by extrapolating the linear fit to 95°C. This corresponds to 29 years. Therefore, in the table lamp application the estimated lifetime of the LED A-lamp is 8.9 years.

Non-IC Downlight: Following the same approach, a second application considered is a recessed downlight (non-IC type) switched on for 2 hours per day. The maximum Tj is 129°C at room temperature, Troom, which is 30°C, and the corresponding ΔTavg is 77°C. The estimated lamp life values for catastrophic failure and lumen depreciation failure, from Figures 2.1-5 and 2.1-7, are 1.9 years (700 cycles to failure) and 12.3 years (9000 hours to L70), respectively. Therefore, in the downlight application the estimated lamp life for the same LED A-lamp is only 1.9 years.

These examples show that the lifetime of LED systems depends on the application environment and the use pattern.

2.1.6. Time required for life testing

The time required for life testing LED systems is an important consideration for manufacturers, who prefer a shorter time. The question is what will be a reasonable time needed to implement a test similar to the one described here for other systems. The approach is to identify a suitable ΔT and dwell time so that the lamps fail due to failure modes usually present during applications. Overstressing will introduce additional failure modes that may not be present in typical applications and could lead to underestimating system lifetimes. Therefore, by looking at Figure 2.1-5, designing a test procedure such that the time-averaged temperature is in the range of 75°C to 85°C, the total time for testing can be within 3000 hours. However, this hypothesis needs verification by testing several lamps in the marketplace.

From the results of this study and from earlier studies, we are encouraged that a test procedure can be developed to accurately predict LED system life in any application by testing the whole LED system, including on-off power cycling with sufficient dwell time, and considering both failure types, catastrophic and parametric.

2.2. LED MR16 lamp

For the second part of this study, a commercially available, ENERGY STAR rated LED MR16 lamp product, marketed as a 50W incandescent replacement, was selected as the system to be tested to validate the test method. As before, the first step was to determine the appropriate ΔT. One 9W LED MR16 lamp was placed inside an in-ground fixture and another inside a track lighting fixture (see Fig 2.2-1).

Fig. 2.2-1: Luminaires (an in-ground fixture and a track lighting fixture) used for testing the LED MR16 lamps to determine LED junction temperature and the corresponding change in temperature when the lamps are turned on and off.

Temperature measurements were taken using thermocouples attached at two different locations on the lamp, namely the lamp housing and the LED pin, once the fixture reached thermal stability. The pin temperature and the thermal resistance coefficient of the LED package used in the lamp enabled the estimation of the LED junction temperature, Tj, and also provided the relationship between the LED housing temperature and the LED junction temperature. This procedure allowed us to estimate the junction temperatures of the lamps without disturbing the integrity of the lamp. The measured LED junction temperatures were in the range of 114°C to 124°C for the LED lamps tested in the two fixtures. When switched on and off, the resulting ΔTs were in the range of 84°C to 94°C. Figure 2.2-2 illustrates a sample temperature profile experienced by the junction of the LED as a function of time as well as the parameters used in this study. As before, ΔT is defined as the temperature difference between the stabilized operating temperature during on-time and the stabilized temperature during off-time. The dwell time is defined as the time of operation at stabilized operating temperature while the lamp is switched on. It is worth noting here that even though the dwell time was designed for 4 hours at 90°C, the measured value is 2.6 hours because of the warm-up and cool-down time (see Table 2.2-1).

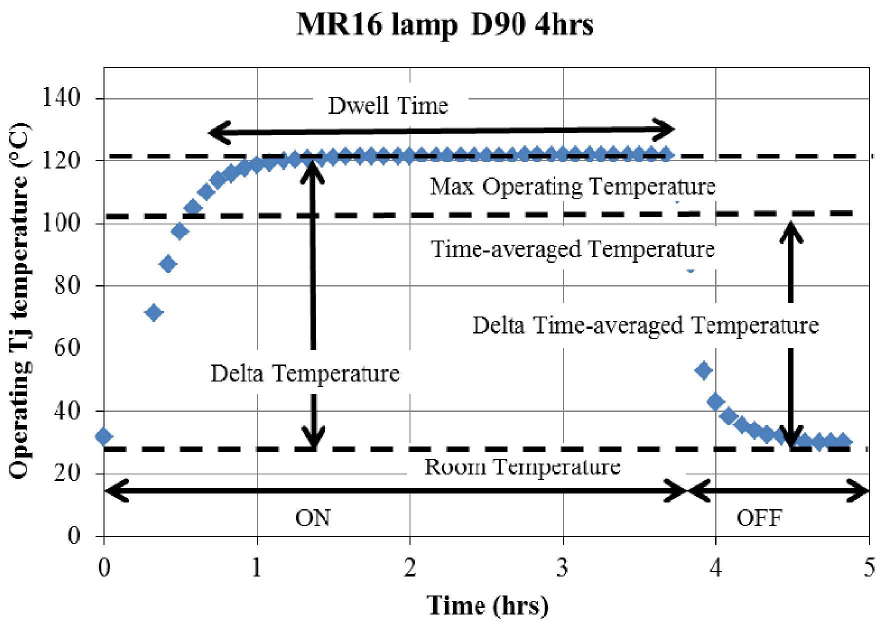

Fig. 2.2-2: Measured temperature profile during one operating cycle of an LED MR16 lamp (ΔT=90°C; dwell time, 4hrs).

Table 2.2-1: LED MR16 lamp – Measured average on time, dwell time, and off time duration at each delta temperature (ΔT).

Nominal Condition	ΔT (°C)	**On Time (hours)**	**Dwell Time (hours)**	**Off Time (hours)**
2 hrs	80	1.5	1.3	0.6
	90	1.4	1.2	0.6
	100	Not available		
4 hrs	80	3.6	3.0	0.8
	90	3.6	2.6	0.7
	100	3.4	2.9	0.8

2.2.1. Experimental Variables

Sample size: A total of 90 9W rated LED MR16 lamp samples, 50 W incandescent lamp equivalent

Independent variables: delta temperature (ΔT): 80/90/100°C; dwell time (t): 2-hrs, 4-hrs, and continuous-on

Dependent variables: light output, spectral power distribution (chromaticity coordinates), input power, input current, lamp housing temperature

2.2.2. Experiment Setup

Figure 2.2-3 shows the schematic and two pictures of the experiment setup. Similar to the LED A-lamp test setup, the LED MR16 lamps were placed inside a downlight fixture. A heater pad was wrapped around the downlight housing to control the junction temperature of the test lamp (Tj). Five of these downlight cans were placed inside a wooden box. A light sensor box with a photodiode was attached to the bottom opening of the downlight to monitor the light output and detect catastrophic failure and lumen depreciation for each lamp. A thermocouple was attached to the housing of the LED MR16 lamp to estimate the LED junction temperature. In an initial study, the relationship between the LED MR16 lamp housing temperature and the LED pin temperature was determined by attaching a thermocouple to each location, namely the LED MR16 -lamp housing and the LED case. Using the published thermal resistance value of the LED used in the LED MR16 lamp, the junction temperature was estimated. Control circuits switched the lamps and the heater pad on and off at the designed dwell time and ΔT. As described earlier, for each ΔT, lamps were switched on and off to achieve 2-hour and 4-hour dwell times and in the third case kept the lamp powered on continuously. Each test condition had 10 LED MR16 lamp samples and altogether 90 lamp samples were used at the three ΔT with three dwell time conditions. All test boxes were placed on a rack, and each lamp test assembly was connected to a data acquisition system for continuous monitoring and recording of the dependent variables: light output, spectral power distribution, input power, input current, and lamp housing temperature.

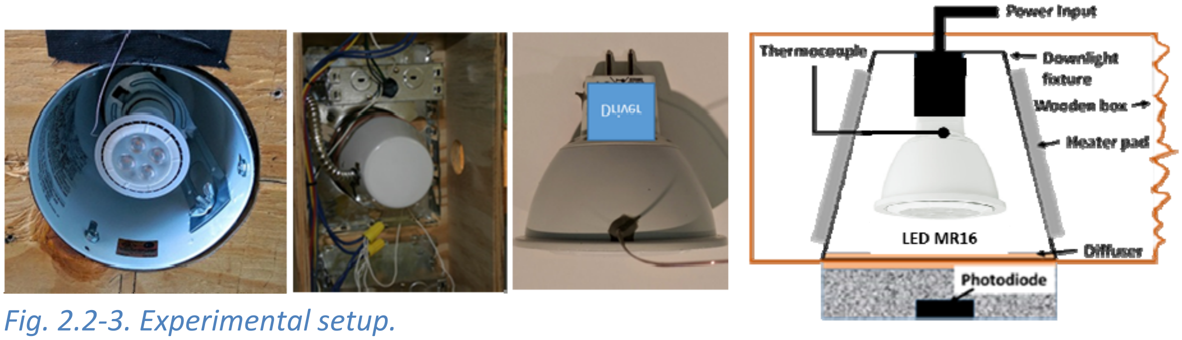

Fig. 2.2-3. Experimental setup.

2.2.3 Results

2.2.3(a). LED MR16 lamp failure – Catastrophic

Figures 2.2-4 (a) through (f)* show catastrophic failure of the LED MR16 lamps as a function of time for each test condition, ΔT and dwell time. The average time between the 5th and the 6th lamp failures denotes the median life, indicated by the solid line in Figure 2.2-4. As seen in these figures and in Table 2.2-2, the median lamp life due to catastrophic failure depends on ΔT and the dwell time. A post-mortem analysis showed almost 98% of the failures were due to driver failure—a different failure mode compared to the LED A-lamp.

*The following note applies to Figures 2.2-4(a) through (f):

The x-axis is the cumulative time in hours, and for all graphs the x-axis was plotted in the logarithmic scale in the range between 100 – 100,000. Some data points fall outside the range and are not displayed.

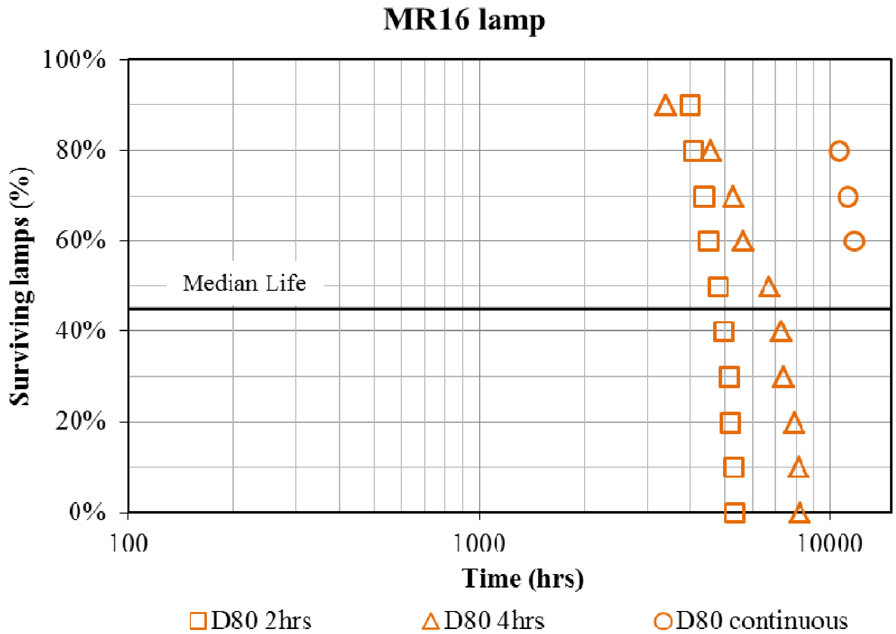

Fig. 2.2-4(a): LED MR16 lamp catastrophic failure as a function of time for the D80 test condition, for 2 hours and 4 hours dwell time and continuous-on operation. Note that for the D80 continuous case, some lamps have not failed yet.

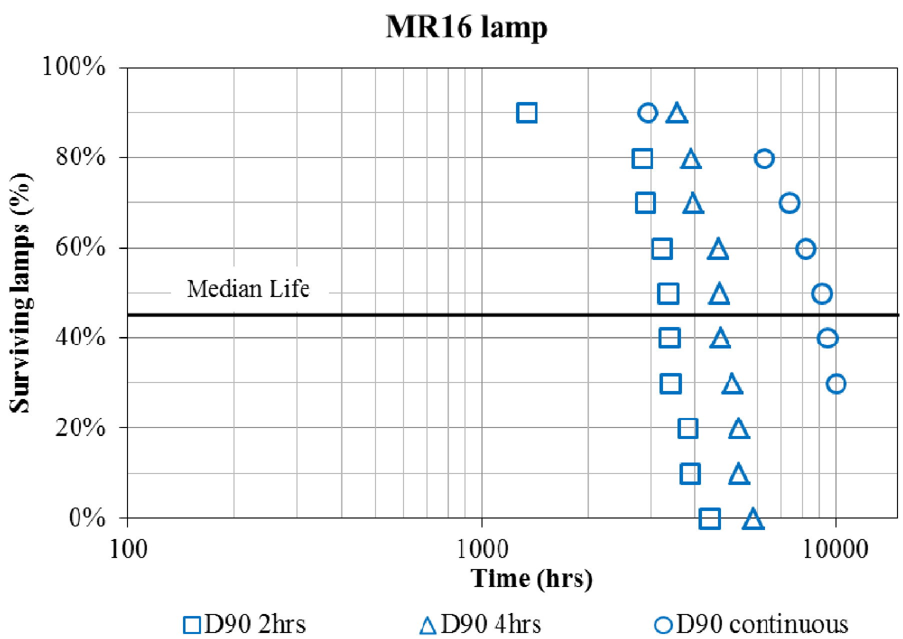

Fig. 2.2-4(b): LED MR16 lamp catastrophic failure as a function of time for the D90 test condition, for 2 hours and 4 hours dwell time and continuous-on operation.

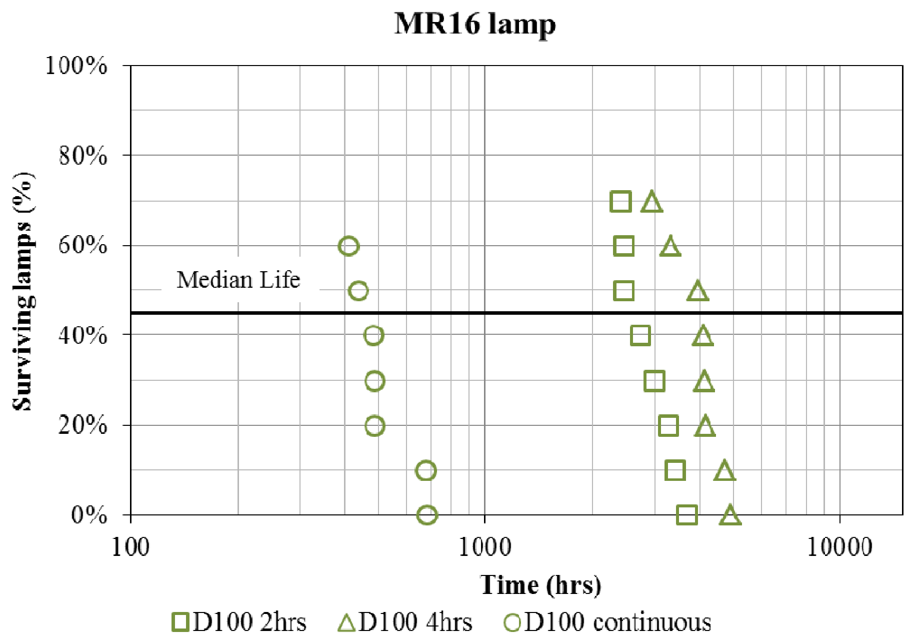

Fig. 2.2-4(c): LED MR16 lamp catastrophic failure as a function of time for the D100 test condition, for 4 hours dwell time and continuous-on operation.

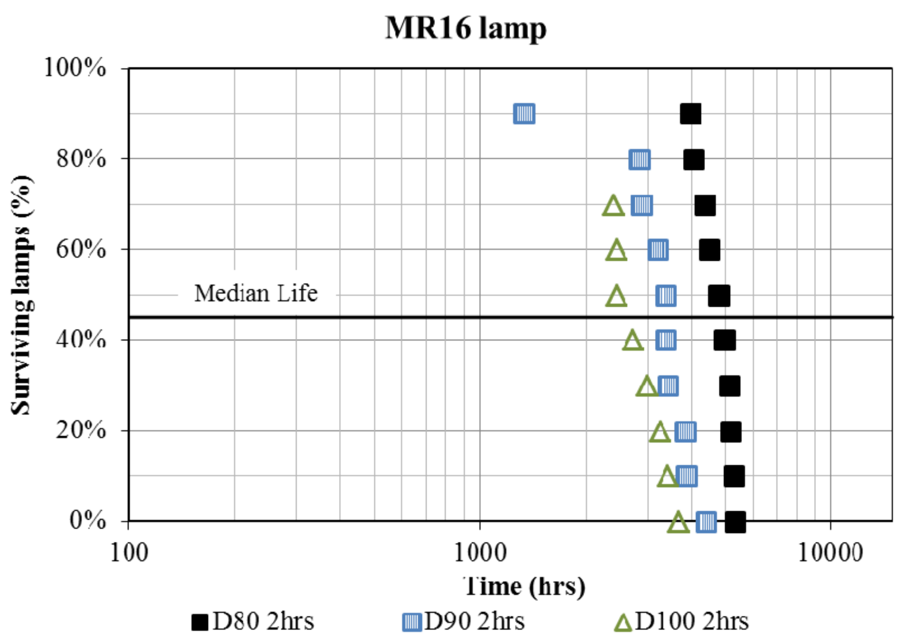

Fig. 2.2-4(d): LED MR16 lamp catastrophic failure as a function of time for D80 and D90 test conditions, for 2 hours dwell time.

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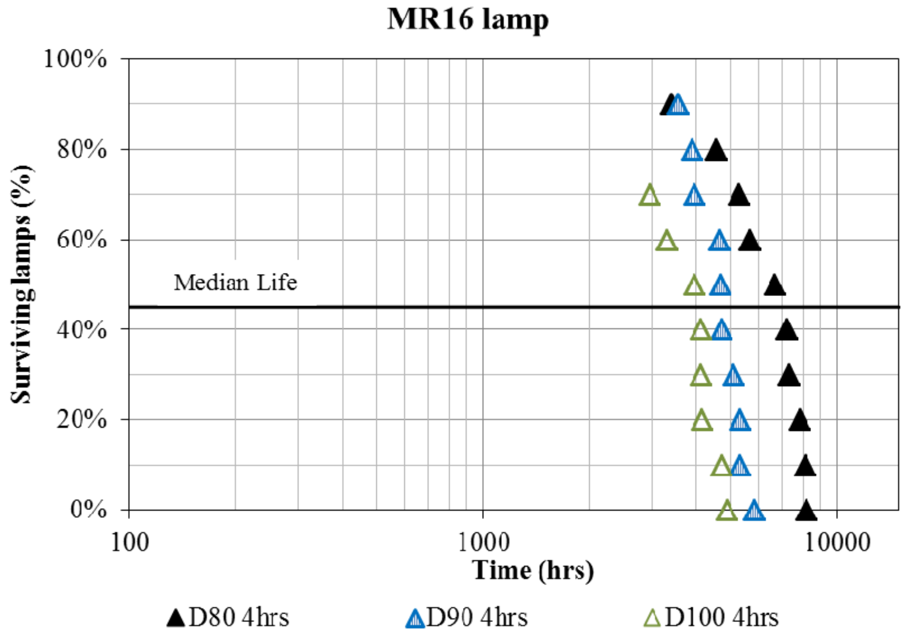


Fig. 2.2-4(e): LED MR16 lamp catastrophic failure as a function of time for the D80, D90, and D100 test conditions, for 4 hours dwell time.

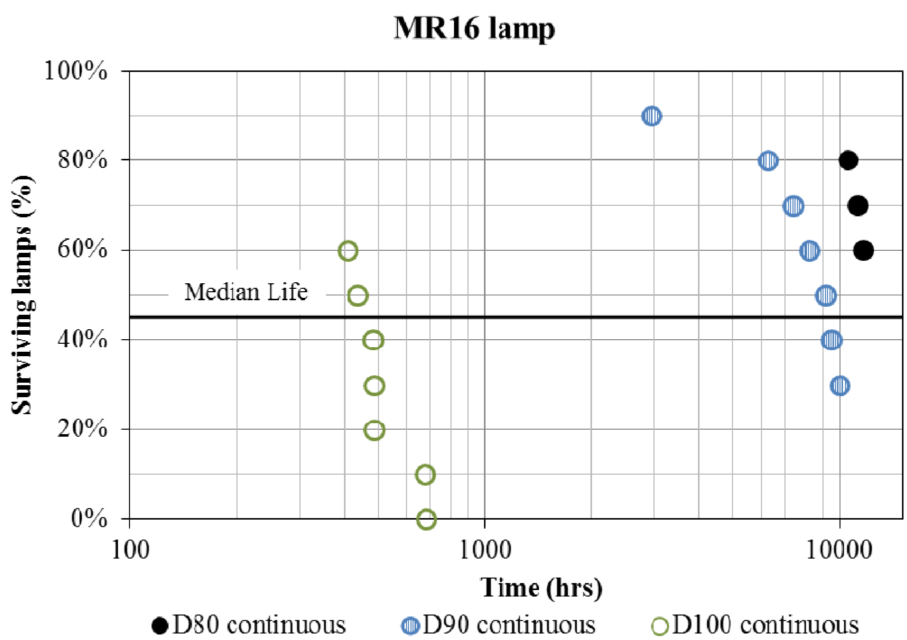


Fig. 2.2-4(f): LED MR16 lamp catastrophic failure as a function of time for the D80, D90, and D100 test conditions, for continuous-on operation.

Table 2.2-2: Delta time-averaged temperature (ΔTavg) values and time to failure values for the different ΔT and dwell time conditions.

	Delta time-averaged temperature (°C)		**Time to failure (median life) (hours)**	
ΔT / Dwell Condition	2 hours	4 hours	2 hours	4 hours
80°C	61	69	4874	6953
90°C	68	76	3373	4702
100°C	70	80	2582	4028

As seen in Table 2.2-2, higher ΔT results in shorter time to failure for both dwell time conditions. Also, shorter dwell time results in shorter time to failure for 80°C and 90°C ΔT. In the case of ΔT 100°C with 2-hour dwell time condition, the samples came from a different batch due to the limited number of lamps from the original order from the same source. In addition, the heater pads used in these test boxes were unable to achieve ΔT 100°C for these lamps; instead they achieved only ΔT 92°C. As a result, the delta time-averaged temperature was limited to 70°C instead of 75°C.

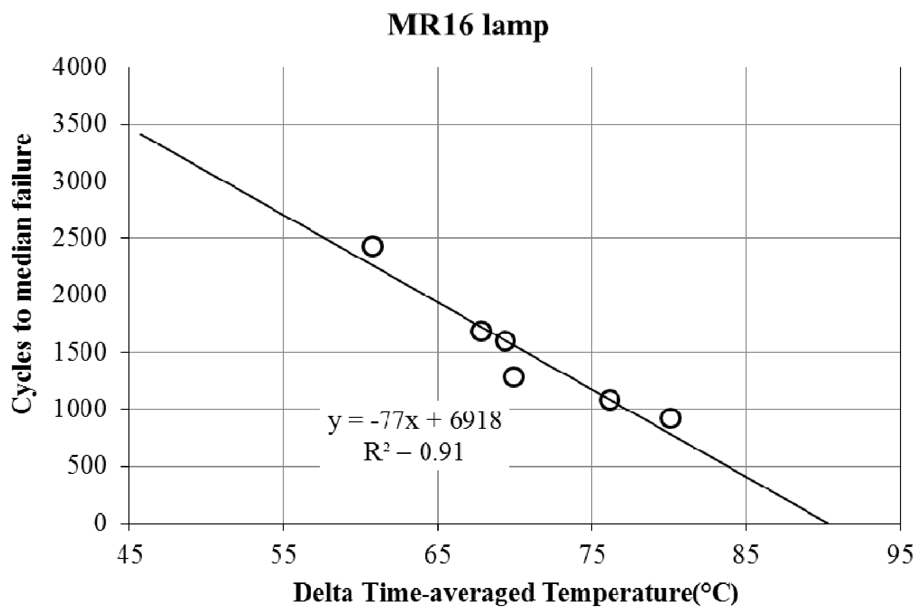


Fig. 2.2-5: Cycles to failure as a function delta time-averaged temperature (ΔTavg) (°C).

As seen in Fig. 2.2-5, cycles to failure (median life) as a function of delta time-averaged temperature shows an inverse linear relationship with high goodness-of-fit, (R^2) > 0.91. Once again, the results from the LED MR16 life test study also clearly show that the life of an LED system is affected by switching it on and off.

2.2.3(b). LED MR16 lamp failure – Lumen depreciation

Figure 2.2-6 illustrates data for lumen depreciation values measured just prior to catastrophic failure. Here, too, similar to the LED A-lamp test results, most LED MR16 lamps underwent catastrophic failure before reaching L70. Lumen depreciation data was extrapolated to determine L70 values. Since the measured lumen values did not change much during the period the lamps were on, it was difficult to project L70 values for all conditions. As a result, in this study only the continuous-on lumen depreciation data was used to project L70 values. Here, too, the projections were possible for D80 and D90, but for D100 the lamps failed too fast and projecting L70 was not possible. The median lamp life, L70 in hours, is shown in Table 2.2-3. Figure 2.2-7 shows that for the product tested, time to failure L70 (median life) as a function of maximum operating temperature shows an inverse linear relationship. Having only two data points was not the best to illustrate the L70 life relationship with maximum operating temperature. It is worth noting here that in the case of MR16 lamps, the failures were catastrophic due to driver failure, but lumen depreciation is due to optical and electrical parameter changes. That is partly the reason why it was not easy to project L70 values for the different conditions. Switching on and off cycling seems to have minimum effect on parametric failure.

Table 2.2-3: Maximum operating temperature and time to L70 failure for the different ΔT and dwell conditions. (L70 value is 25,000 hours when projected values exceed 25,000 hours.)*

	Maximum operating temperature (°C)	**Time to L70 (hours)**
ΔT / Dwell Conditions	Continuous-on	Continuous-on
80°C	111	25000*
90°C	118	17903*
100°C	131	Failed too fast to predict

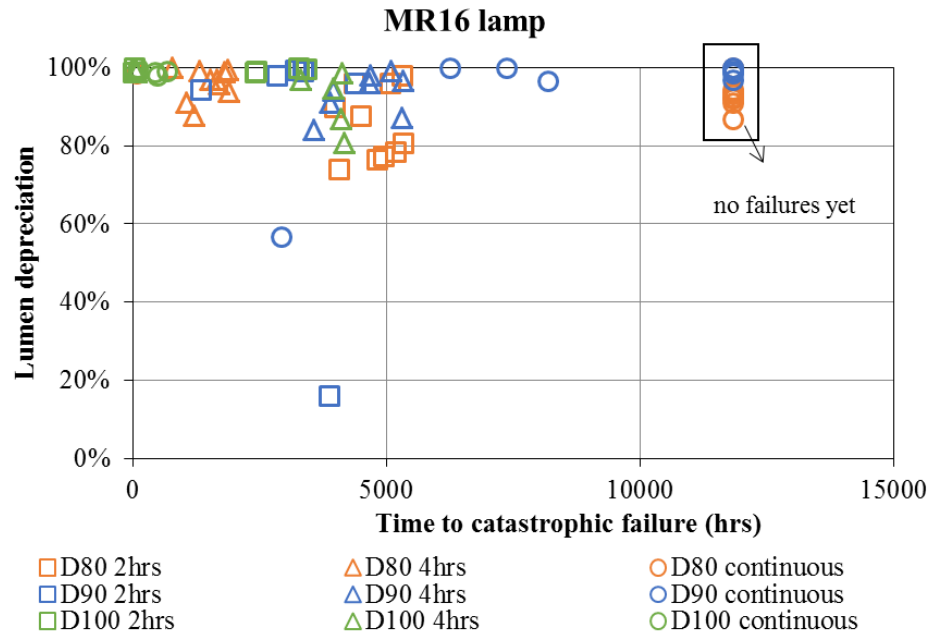


Fig. 2.2-6: Lumen depreciation values just prior to catastrophic failure.

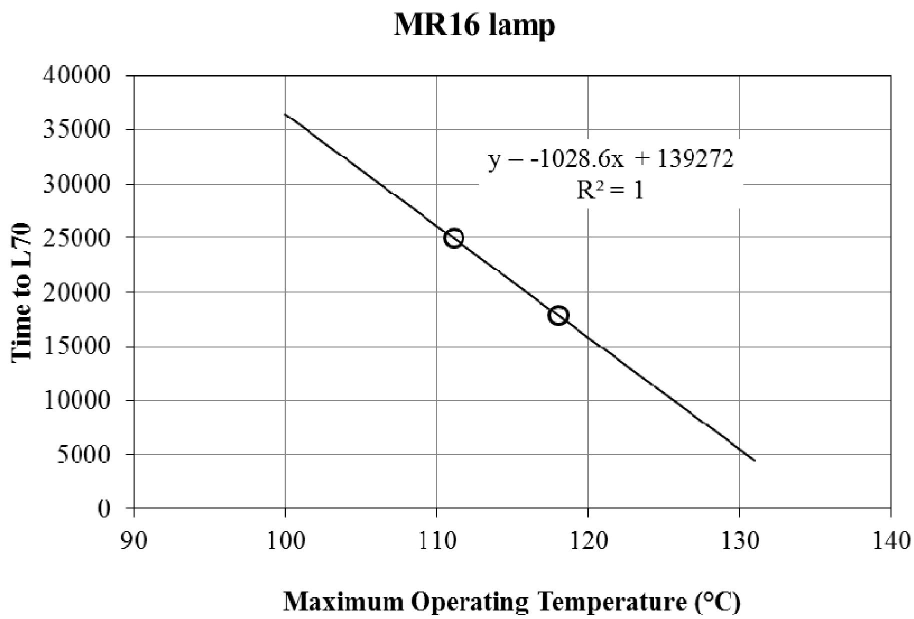


Fig. 2.2-7: Time to failure due to lumen depreciation, L70, as a function of maximum operating temperature.

2.2.3(c). LED MR16 lamp – Color shift

Figure 2.2-8 shows the chromaticity shift, in number of MacAdam ellipse steps, as a function of time for all LED MR16 lamps under different operating conditions. The majority of the lamps had chromaticity shift values less than 4 MacAdam ellipse steps by the time they reached 3000 hours and some had greater than 4 steps. Compared to the LED A-lamps, the MR16 lamps had greater chromaticity shift.

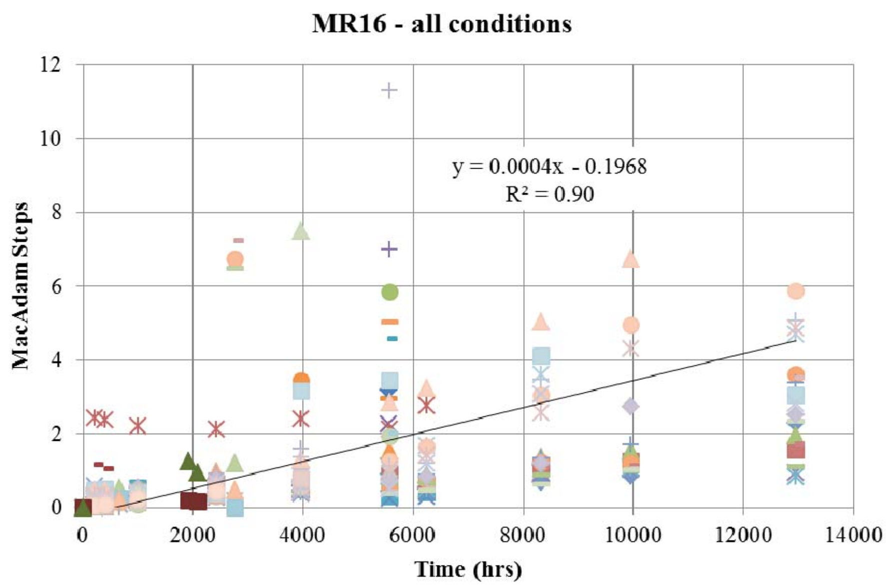


Fig. 2.2-8: Chromaticity shift as a function of time for all LED MR16 lamps under different operating conditions.

2.2.4. Discussion

The MR16 study results showed both types of failure, catastrophic and parametric. Similar to LED systems, drivers also can have catastrophic and parametric failures. The catastrophic failures of the MR16 lamps were mainly due to catastrophic failures of the driver caused by the heat and the on-off cycling. In the case of parametric failure in driver, the current can increase and result in light output increase. The change in light output over time, parametric failure of the MR16 lamp, can be caused by increasing in driver output current and or reducing in optical transmission of encapsulate. In the MR16 lamp, heat can degrade both the driver and the optics. If the degrading driver effect is greater, the result is increasing light output. Alternatively, if the degrading optical effect is greater, then the result is decreasing light output.

As mentioned earlier, the shorter of the two times to failure should be considered as the lifetime of the product because in applications, LED systems will experience both types of failure and depending on the conditions, one failure type could dominate. For the MR16 lamps tested, catastrophic failure times were shorter than lumen depreciation, L70, failure times. The results from this study, too, show that to obtain more accurate life estimates of LED systems, life testing must include on-off switching.

For the LED MR16 lamps tested, the chromaticity shift became significant, greater than a 4-step MacAdam ellipse after 3000 hours.

2.2.5. Time required for life testing

As stated earlier, the time required for life testing LED systems is an important consideration for manufacturers, who prefer a shorter time. As before, the approach is to identify a suitable ΔT and dwell time so that the lamps fail due to failure modes usually present during applications. Overstressing will introduce additional failure modes that may not be present in typical applications and could lead to underestimating system lifetimes. Here, too, by designing a test procedure such that the time-averaged temperature is in the range of 70°C to 85°C, the total time for testing can be within 3000 hours.

2.3 LED Downlight

For the third part of this study, two commercial ENERGY STAR rated LED downlight luminaires, 1 and 2, 14W and 11 W respectively, marketed as replacements for 75W to 60W incandescent downlights, were selected. As before, the first step was to determine the appropriate ΔT. The downlight luminaire was placed inside an enclosed fixture (see Fig 2.3-1).

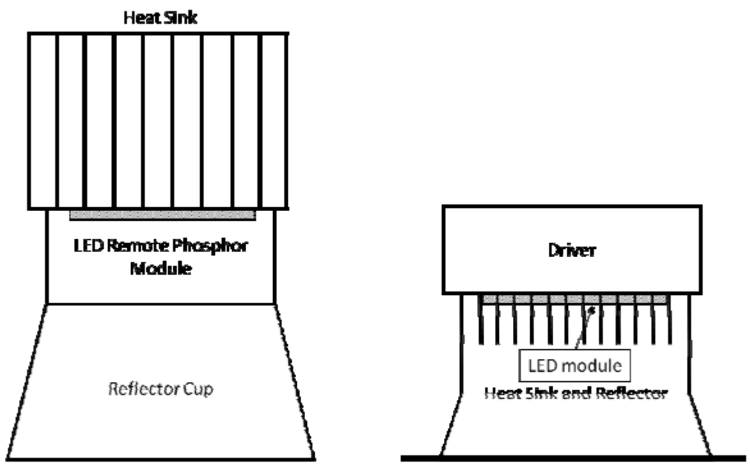


Fig. 2.3-1: LED downlight luminaires 1 (left) and 2 (right).

Temperature measurements were made using thermocouples attached at two different locations on the downlight, namely the housing and the LED pin, once the fixture reached thermal stability. The pin temperature and the thermal resistance coefficient of the LED package used in the lamp enabled the estimation of the LED junction temperature, Tj, and also provided the relationship between the LED housing temperature and the LED junction temperature.

The measured LED junction temperature for the LEDs in downlight 1 was 92°C in a non-IC downlight condition. This means the ΔT would be 62°C if the fixture was switched on and off. Initially, downlight 1 was subjected to ΔT values of 50, 60, and 70°C. No catastrophic failures were observed for a test time over 3000 hours. Then the experiment setup was modified to achieve ΔT values of 90, 100, 110°C for the same downlight. Figures 2.3-2 and 2.3-3 illustrate a sample temperature profile experienced by the LED junction in downlights 1 and 2 as a function of time. The figures also illustrate the parameters used in this study. As before, the ΔT is defined as the temperature difference between the stabilized operating temperature during on-time and the stabilized temperature during off-time. The dwell time is defined as the time of operation at stabilized operating temperature while the lamp is switched on.

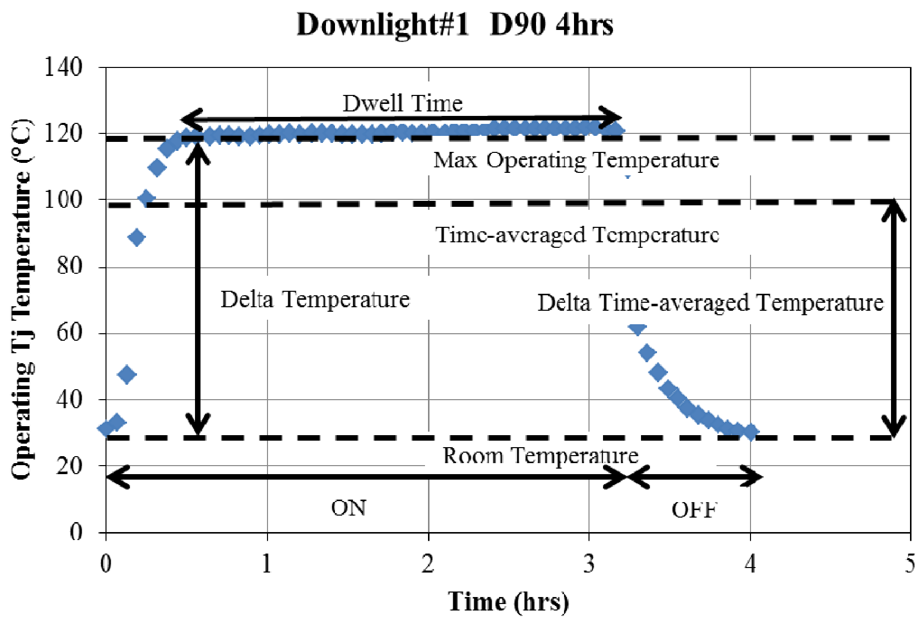


Fig. 2.3-2: Measured temperature profile during one operating cycle of the LED downlight luminaire 1 (ΔT=90°C; dwell time, 4hrs).

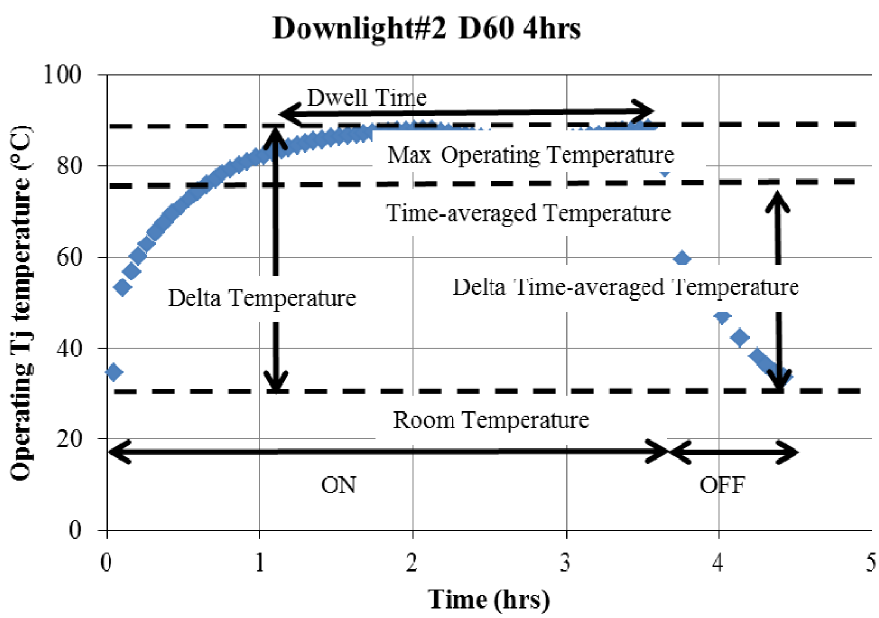


Fig. 2.3-3: Measured temperature profile during one operating cycle of the LED downlight luminaire 2 (ΔT=90°C; dwell time, 4hrs).

The measured dwell time durations at each ΔT condition are shown in Tables 2.3-1 and 2.3-2.

Table 2.3-1: LED downlight 1 – Measured average on time, dwell time, and off time duration at each delta temperature (ΔT).

Nominal Condition	ΔT	On Time (hours)	Dwell Time (hours)	OFF Time (hours)
2 hrs	90°C	1.4	1.1	0.9
	100°C	1.4	0.9	1.1
	110°C	1.4	1.0	1.0
4 hrs	90°C	3.2	2.8	1.2
	100°C	3.3	2.7	1.5
	110°C	3.3	2.8	1.3

Likewise, the measured LED junction temperature for the LEDs in downlight 2 was 78°C in a non-IC condition and 81°C in an IC condition. Downlight 2 was subjected to 60°C ΔT only with dwell times of 2 hrs, 4 hrs, and continuous operation. No catastrophic failures were observed for test time over 5000 hours.

Table 2.3-2: LED downlight 2 – Measured average on time, dwell time, and off time duration at each delta temperature (ΔT).

Nominal Condition	ΔT	On Time (hours)	Dwell Time (hours)	OFF Time (hours)
2 hrs	60°C	1.5	0.6	0.7
4 hrs	60°C	3.5	2.3	0.9

2.3.1. Experimental Variables

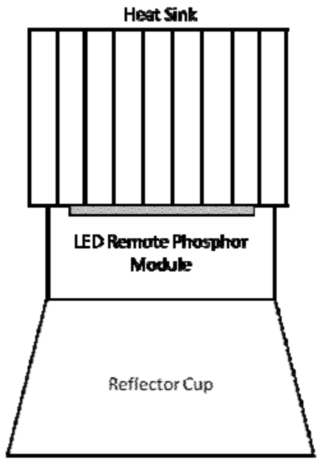
Sample size: A total of 80 14.3W rated LED downlight #1 samples and 27 11 W rated LED downlight # 2 samples.

Independent variables: Downlight # 1 – delta temperature (ΔT): 90/100/110°C; dwell time (t): 2-hrs, 4-hrs, and continuous-on, but for 110°C there were only two dwell times (2 hrs and 4 hrs). Downlight # 2 – delta temperature (ΔT): 60°C; dwell time (t): 2-hrs, 4-hrs and continuous-on. In each case there were 9 downlight #2 samples. (See Table 2.3-1 and 2.3-2 for details).

Dependent variables: light output, spectral power distribution (chromaticity coordinates), input power, input current, lamp housing temperature

2.3.2. Experiment Setup

Figures 2.3-4 and 2.3-5 shows two pictures of the experiment setup to measure LED junction temperatures. Similar to before, thermocouples were attached to the body of the fixture and the LED pin. Heater pads were wrapped around the downlight housing to control the temperature of the LED junction (Tj). The heater pads were used to mimic realistic operating temperature environments such as semi-ventilated and enclosed lighting fixtures. Five of these downlights were placed inside a wooden box. As before, light sensors were attached to the bottom opening of the downlight to monitor the light output and detect catastrophic failure and lumen depreciation. Control circuits switched the fixture and the heater pad on and off at the designed dwell time and ΔT. As described earlier, for each ΔT, fixtures were switched on and off to achieve 2-hour and 4-hour dwell times and in the third case kept the lamp powered on continuously, except at 110°C where there were only two dwell time conditions (2 hrs and 4 hrs). Each test condition had 10 fixture samples and altogether 80 fixtures (for downlight 1) were used at the three ΔT with three dwell time conditions. All test boxes were placed on a rack, and each lamp test assembly was connected to a data acquisition system for continuous monitoring and recording of the dependent variables: light output, spectral power distribution, input power, input current, and lamp housing temperature.



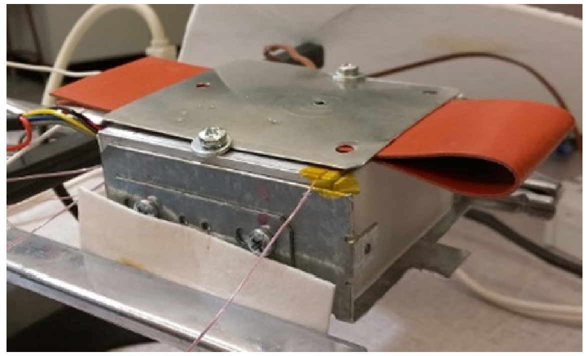
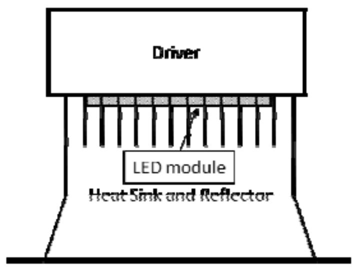


Fig.2.3-4: Experiment setup for downlight 1.



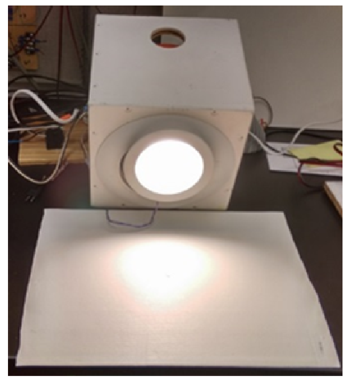


Fig. 2.3-5: Experiment setup for downlight 2.

2.3.3. Results

2.3.3(a). LED Downlight failure – Catastrophic

There were no catastrophic failures observed in downlight 1 and downlight 2.

2.3.3(b). LED Downlight failure – Lumen depreciation

Downlight 1: A sample lumen depreciation curve for downlight 1 is shown in Fig. 2.3-6. During the test period, 7000 hours, the lumen depreciation was up to 8 percent for D100°C.

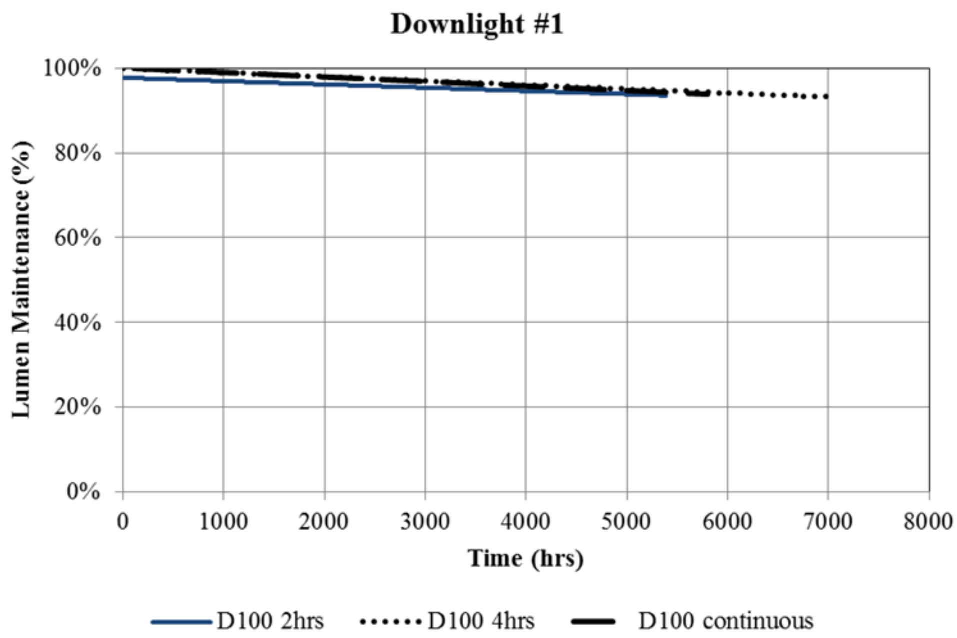


Fig. 2.3-6: Lumen depreciation of downlight 1 as a function of time.

It appears that downlight 1 had feedback control to avoid high lumen depreciation. As mentioned earlier, when products have feedback control it is difficult to project lumen depreciation to L70 accurately. Figure 2.3-7 shows how lumen maintenance and input power changes as a function of time for downlight 1 at ΔT100°C continuous condition. It is evident from this figure that until about 3500 hours, the input power remained constant but the lumen output depreciated about 5%. Then beyond that the power started increasing and slowed the lumen depreciation and even increased it slightly. Using this data to project L70 would yield erroneous results. One way to overcome this difficulty is to use only lumen depreciation data during the constant input power period and project to estimate time to L70. This method was used to project time to L70 for the different test conditions and the resulting plot is shown in Fig 2.3-8.

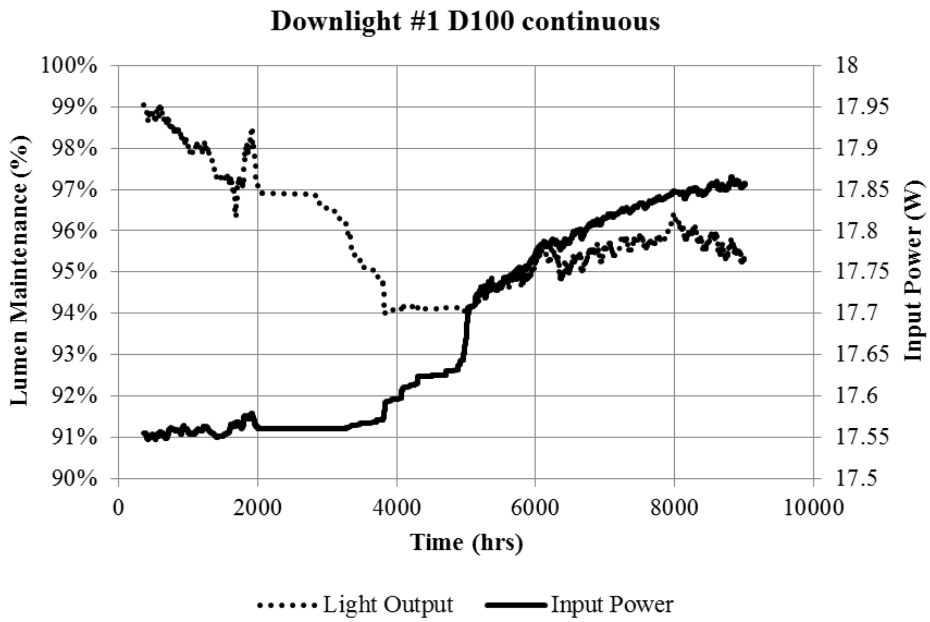


Fig. 2.3-7: Lumen maintenance and input power as a function of time for downlight 1 at D100 continuous-on condition.

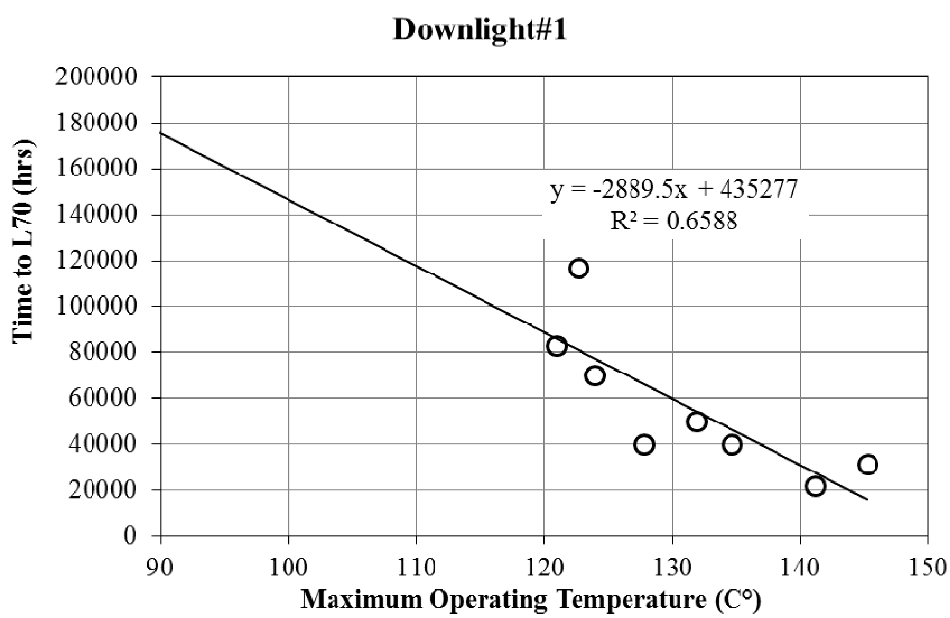


Fig. 2.3-8: Time to failure due to lumen depreciation, L70, as a function of maximum operating temperature for downlight 1.

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Downlight 2: The lumen depreciation for downlight 2 is shown in Fig. 2.3-9. During the test period, 5000 hours, there was obvious lumen depreciation, reaching 78% lumen maintenance after 5000 hours. Table 2.3-3 shows estimated L70 values.

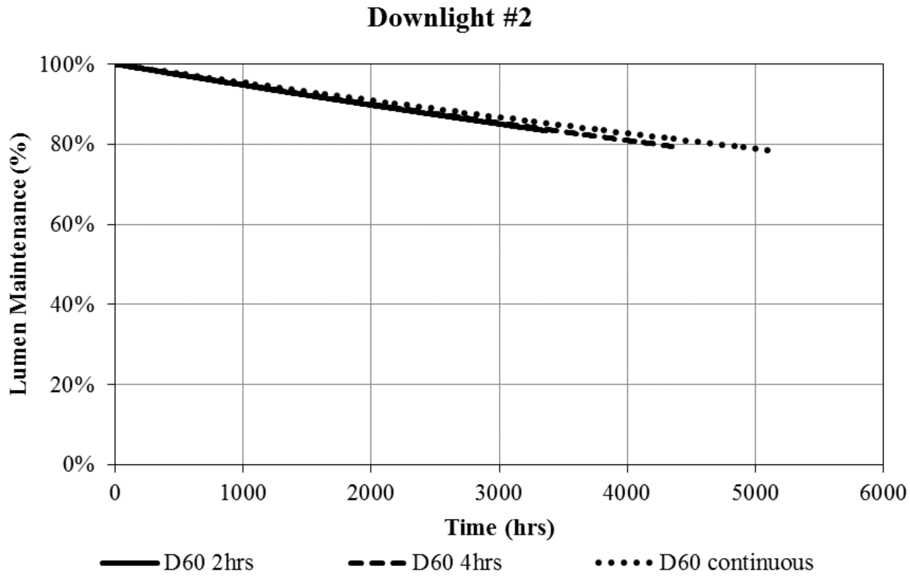

Fig. 2.3-9: Lumen depreciation data for downlight 2 as a function of time.

Table 2.3-3: LED downlight 2 – Measured maximum operating temperature in °C and the estimated L70 values in hours.

ΔT/Dwell Conditions	2 hrs	4 hrs	Continuous on
60°C	90.1°C	90.3°C	91.4°C
ΔT/Dwell Conditions	2 hrs	4 hrs	Continuous on
L70	10492 hrs	9012 hrs	9627 hrs

2.3.3(c). LED Downlight – Color shift

The overall color shift of downlight 1 was less than 2 MacAdam ellipse steps (Fig. 2.3-10).

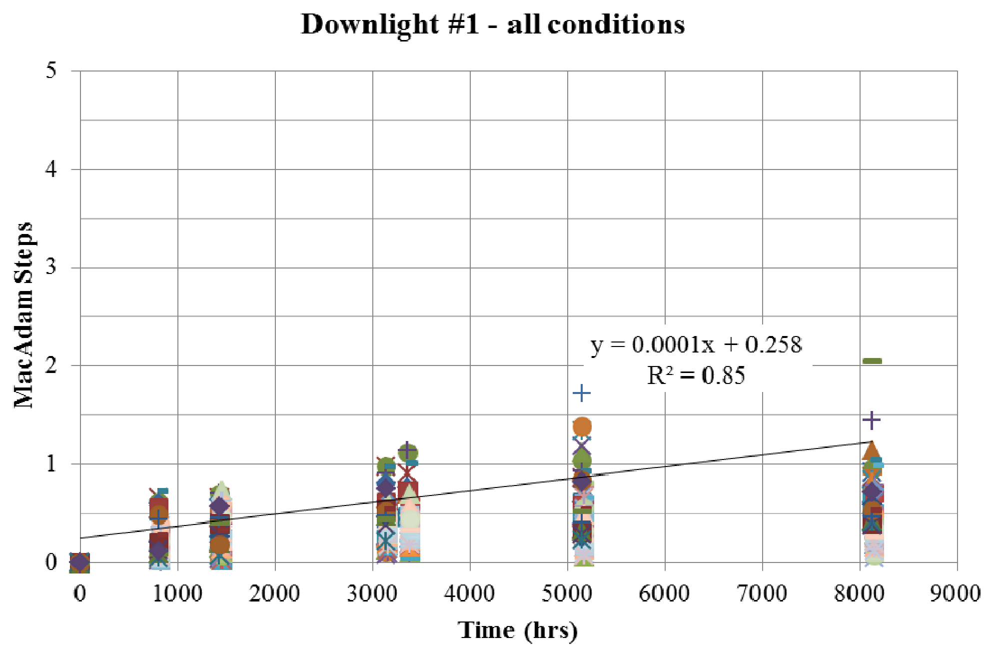

Fig. 2.3-10: Chromaticity shift as a function of time for all LED downlight 1 samples under different operating conditions.

2.3.4. Discussion

Both downlights 1 and 2 seem to have feedback control. This is a probable reason for not seeing catastrophic failures in the downlight group. However, both systems had lumen depreciation failure.

3. RESULTS SUMMARY

Section 2 described the results for the three types of LED lighting systems tested in this study. The results showed that both failure types, catastrophic and parametric, exist for the LED A-lamps and LED MR16 lamps. The on-off cycling encourages catastrophic failure while maximum operating temperature influences lumen depreciation and resulting parametric failure. It was also clear that LED system life is negatively affected by switching on and off. Results for the LED A-lamp and LED MR16 lamp showed that most of the systems failed catastrophically much ahead of the LED light output reaching the 70% value. This emphasizes the fact that life testing of LED systems must consider catastrophic failure in addition to lumen depreciation, and the shorter of the two failure modes must be selected as the system life.

For the LED downlight luminaires tested, only parametric failure was observed during the test period. It is worth pointing out that some LED systems employ feedback control circuits to detect LED temperature and under-drive the devices so that they do not exceed certain temperatures that would lead to system failure. Such systems will emit lower light output at higher temperatures, a tradeoff to prevent the systems from failing. The proposed test method to estimate LED system life may not work well with systems that use feedback control. In such cases, parametric failure (i.e., reduced light output) may be the only failure mode present. It is safe to say that the majority of the LED lighting systems in the marketplace do not employ feedback control because such features tend to increase product price.

Post-mortem analysis showed that in the case of the LED A-lamps, the majority of failures (greater than 80 percent) were due to failure of the LED solder that attached the LED to the printed circuit board, and a small percentage of failures were due to driver failures. In the case of LED MR16 lamps, the majority of failures (greater than 95 percent) were due to driver failure. These findings show that in LED systems there could be many failure modes. The proposed test method encourages some failures such as solder failure and driver component failures, including capacitor and or diode, but it may not encourage other types of failure that may exist in some applications. For example, in outdoor fixtures there may be failures due to terminal corrosion or volatile organic compounds (VOC)-induced component deterioration in sealed fixtures. Additional studies are required to determine other failures that may be unique in certain applications.

4. DISCUSSION

The results of this study show a shorter time, less than 3000 hours, test procedure can be developed to accurately predict LED system life in any application by knowing the LED temperature and the switching cycle. Using the life-test method described in this study will yield time to failure due to catastrophic and parametric failures. The shorter of the two failure modes is the system lifetime.

As discussed earlier, when systems employ feedback control to limit temperature rise or prevent lumen depreciation, the proposed test method may not yield desired results. Other methods must be investigated to handle such systems.

The proposed test procedure is useful for determining the lifetime of LED products more accurately than the current industry practice. Even though it may not catch all failure modes, it would certainly encourage failure modes typically found in LED fixtures used in most indoor applications. Adopting this procedure would help users gain more confidence of the lifetime numbers reported by product manufacturers and would help create more accurate payback analysis calculations that are commonly practiced in the lighting industry when making decisions to replace existing lighting products.

5. DISSEMINATION OF INFORMATION

A final objective of this project is to move the testing method forward toward wide industry adoption and standardization. The test method validated in this study and some of the results have been presented already at industry meetings, conferences, webinars, and via dedicated web pages. Additional presentations will be made during 2017. These include:

1. http://www.lrc.rpi.edu/programs/solidstate/LEDSystemLife.asp

2. Narendran, N., and Y. Liu. 2015. LED life versus LED system life. In: SID '15 Digest of Technical Papers, paper 62-2, SID Display Week 2015: International Symposium, Seminar and Exhibition, May 31-June 5, 2015, San Jose, CA.

3. Narendran, N., Y. Liu, X. Mou, D.R. Thotagamuwa, and O.V. Madihe Eshwarage. 2016. Projecting LED product life based on application. *Proceedings of SPIE* 9954, Fifteenth International Conference on Solid State Lighting and LED-based Illumination Systems, 99540G (September 14, 2016); doi: 10.1117/12.2240464.

4. Project presentations, ASSIST annual meeting, November 10th 2016, Lighting Research Center, Troy, NY.

Future Events:

5. Strategies in Light Conference, February 28 – March 2, 2017, Anaheim, CA

In addition, during the next several months, LRC researchers will approach the IESNA standards committee for consideration of the test method for new industry standards.

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