Some Don't Like It Hot: the Effect of Temperature and Switching Patterns on Screw-based LED Lamps

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ABSTRACT

While LED lamps are becoming the primary lighting technology promoted in many utility program portfolios, significant uncertainties exist with respect to actual average LED lamp life in real-world applications. To address this knowledge gap, we initiated a large-scale laboratory test of screw-based LED lamps designed to provide the empirical basis for developing adjustments to the useful life assumptions for LED lamps included in California's investor-owned utility programs. The experimental design used in the test centers on evaluating the impact of the most common stress condition found in typical LED applications – high temperatures (from operating in recessed downlights and enclosed fixtures) and thermal "cycling" (i.e. the heating up and cooling down of LED lamps due to on-off switching patterns). The sample design included over 600 individual lamps, covering over 100 of the highest market-share models of A-lamps, reflectors, globes, and torpedo lamps available in California – including California Quality Specification-compliant lamps, ENERGY STAR-certified lamps, and non-ENERGY STAR-certified lamps.

Overall, the results produced by this study provide strong evidence that thermal cycling and elevated operating temperature are indeed significant stress conditions that can lead to early catastrophic failures in LED lamps. While the vast majority of the lamps in the experiment have a rated life of 25,000 hours, we observed overall failure rates of approximately 24% after 4,000 hours of operation, with A-lamps in enclosed ceiling fixtures and recessed downlights accounting for the highest failure rates (40% and 35%, respectively). These results provide important information to regulators, utility program staff, manufacturers, international standards and testing bodies, and lighting researchers on the expected life of LED lamps.

Introduction

LED lamps have seen explosive market growth in recent years and now are the primary lighting technology promoted in utility program portfolios across the country. The high efficacy and longer rated life combine to promise attractive lifecycle cost savings of LED lamps over incandescent and even CFL alternatives. Utility program planners and administrators can readily and reasonably assess the impact that LED lamp efficacy has on energy savings and lifecycle costs through in-field metering and logger studies. However, significant uncertainties exist with respect to actual, average LED lamp life in real-world applications. These uncertainties stem primarily from the fact that current standardized tests focus on lumen depreciation as the primary measure of LED lamp life and do not directly account for catastrophic failures due to heat, humidity, vibration, voltage fluctuations, and other real-world stress conditions.[1] Consequently, both regulators and program administrators are increasingly wary of repeating the

[1] Catastrophic failure refers to when the lamp suddenly stops producing any light (i.e. it "burns out"). Part of the reason that current tests focus on lumen depreciation is because long-term lumen depreciation can be reasonably estimated with a relatively short test (e.g. 6000 hours). There are currently no similarly short tests to reliably estimate catastrophic failure rates.

product-quality and resulting customer-perception dynamics that occurred with the early generations of CFLs – particularly with respect to LED reliability.

In 2015, the California Public Utilities Commission (CPUC) funded a large-scale laboratory study to gain a better understanding on LED lamp longevity. Specifically, the CPUC's goals were to better assess the following questions:

- How does switching LED lamps on/off impact the life and performance of the LED lamps?
- Are the manufacturers' specifications of LED rated life accurate?
- Are the IOUs' LED workpaper assumptions properly stated?

With significant participation from relevant California and national stakeholders, we developed a research plan designed to assess the impacts of the most prevalent stress conditions in residential homes and, simultaneously, the most tractable to evaluate in a laboratory setting. Of the primary stress conditions identified by stakeholders, we identified high operating temperature and thermal cycling (on-off switching patterns that cause lamps to fully heat up and then fully cool down) as the most prevalent stress conditions in residential homes.[2] These stress conditions were also tractable to investigate in a laboratory setting using a limited number of experiments, which would allow the test to be administered to a large, representative sample of lamps. Given this assessment, the research objectives were:

- To assess the effect of temperature and thermal cycling on efficacy, color quality, useful life, etc.
- To assess differences in performance between California Quality Spec-compliant LED lamps with the non-Spec competitors.

This paper details the experimental design we utilized in the laboratory, the sample design we utilized to procure test LED lamps, and the key results we found related to failure rates. We note that a more detailed discussion of this experiment and its results will to be included in a forthcoming CPUC final report on this project, expected to be released in the fall of 2017. This report will provide complete documentation and results, as well as the results of a post-mortem lamp failure analysis that was not yet complete at the time of writing this paper.

Experimental Design

In field application, LED lamps are expected to experience variations in operating conditions that differ from conditions defined by the Illuminating Engineering Society's (IES) test procedures currently utilized to develop the "rated values" of LED lamp life and performance. While these variations between laboratory conditions and field conditions may impact LED lamp life and performance, these relationships are largely undocumented. Significant knowledge gaps remain concerning how much operating conditions typically vary between laboratory conditions and field conditions, which parameters (e.g. temperature, voltage, humidity, etc.) are most likely to see variation that impact lamp life and performance, and how much variability exists between specific LED lamp models in terms of resiliency to changes in operating conditions.

Based on stakeholder feedback and research on the parameters most likely to impact LED lamp life, this experiment focused on evaluating the impact on LED lamp life from thermal conditions typically found in residential applications. Specifically, we looked at the impact of high heat and thermal cycling on LED lamps following the procedures and operation conditions defined in IES LM-84, except as specified in

[2] The primary stress conditions identified by stakeholders and in the research literature were temperature, humidity, switching patterns, voltage, vibration, and interactions with controls (particularly dimmers).

this section below.[3] LED lamps were operated at elevated temperatures and with near-full thermal cycling (e.g. LED lamps turned on for a complete warm-up and then turned off for a complete cool-down) for extended periods of time.

In order to achieve elevated temperatures typical of residential applications, test lamps were operated in three common residential luminaire types: recessed downlights, ceiling fixtures, and bare sockets (see Figure 1).[4] Because of their design and expected normal application, some LED lamp types were only tested one or two luminaires. For example, reflector LED lamps were tested in recessed downlights and bare sockets but not in enclosed fixtures because their field application in enclosed fixtures is considered unlikely. For each lamp model-luminaire combination, we tested three samples of the same model.[5]

Figure 1. Examples of recessed downlights (left), enclosed ceiling fixtures (middle), and bare sockets (right).

The overall experiment was composed of the three main elements: thermal testing, photometric testing, and maintenance testing. Each of these testing elements is described in more detail in the sections below.

Thermal Testing

In order to assess the impact of thermal cycling, it was first necessary to determine the time required for test lamps to achieve thermal equilibrium after they were turned on or off through an initial set of thermal testing. These data were needed in order calculate the switching cycles to be used for the longer maintenance test. In selecting switching cycles, our goal was to select warm-up and cool-down times that were long enough to allow lamps to at least reach 95% of their thermal stabilization point while also trying to maximize the total number of thermal cycles and total on-time per day.

Each test unit was placed in its assigned luminaire type and was operated for a warm-up period of at least 12 hours and then and cool-down period of at least 12 hours. The temperature of a characteristic spot on the test lamp was measured and recorded at 1-minute intervals. The location of the

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[3] IES LM-84 is the current industry testing standard for producing rated values of lumen maintenance over time for LED lamps. It is important to note that rated life values are currently based exclusively on estimates of lumen depreciation, i.e. the average time required for the lumen output of an LED lamp to decrease to 70 percent of its initial output.

[4] These three luminaire types account for nearly two-thirds of the installed residential lighting fixtures in California according to the 2012 California Lighting and Appliance Saturation Survey (DNV GL, 2014).

[5] It should be noted that some LED lamps are explicitly labeled as not being compatible with enclosed fixtures. However, we chose not to use this compatibility information as a criterion for determining the lamp model-luminaire combinations to test. This choice is related primarily to the likelihood that such compatibility information is not always followed by consumers. As such, we wanted to explicitly evaluate the performance of these LED lamps in "incompatible" luminaires.

thermal measurement spot varied slightly among lamp models based on their shapes and sizes. However, the usual the measurement point was at the midpoint of the lamp that housed the lamp driver and associated electronics. The axial location of the temperature measurement spot was selected randomly. Figure 2 illustrates an example of what the results from the thermal testing look like for one test lamp.

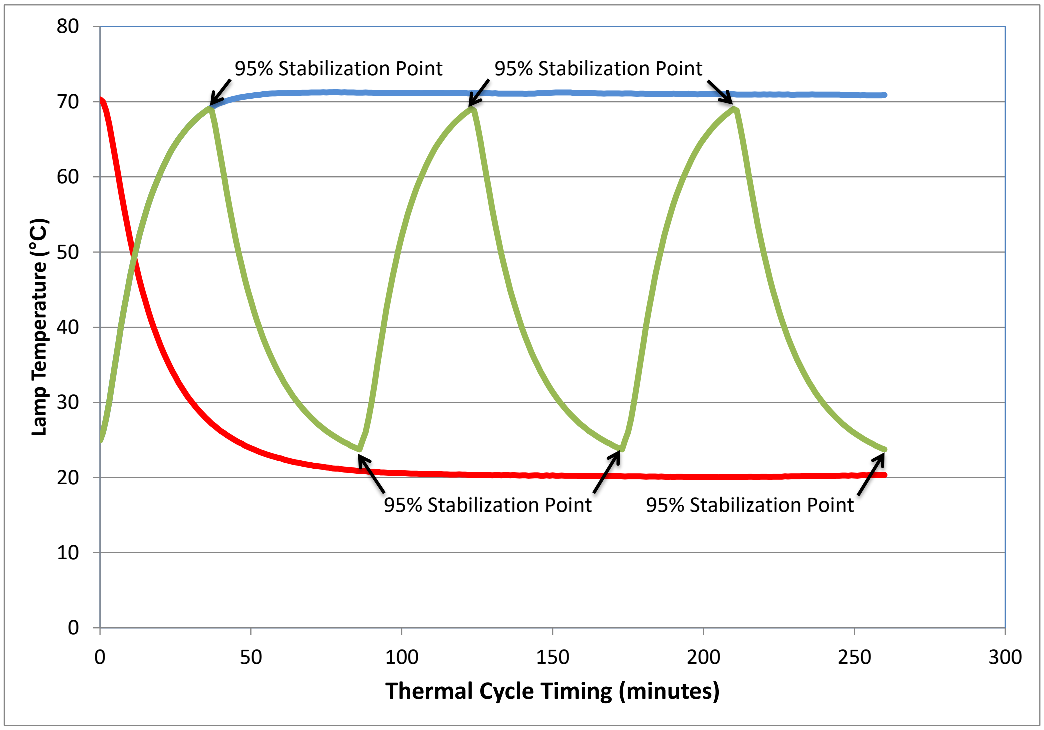

Figure 2. Example of a thermal cycle for an LED lamp

The lamp shown in Figure 2 experienced a temperature change of 46°C, rising from room temperature of 25°C to a maximum temperature of 71°C after 80 minutes (blue line). This lamp experienced 95% of this temperature increase (to 69°C) after 37 minutes. This test indicates that this lamp could be put on a switching cycle with a warm-up time of 37 minutes or longer. This allows the lamp to achieve a near-full warm up while doubling the number of thermal cycles the lamp could be subjected to over a fixed period of time compared to an approach requiring 100% thermal stability. Figure 2 also shows the cool down time for this lamp (red line). The lamp experienced and overall temperature decrease of 51°C, dropping from a maximum temperature of 71°C to a room temperature of 20°C after 205 minutes. However, the lamp experienced 95% of this total temperature decrease (to 23°C) after 60 minutes. The green line illustrates what the associated switching cycle for this lamp would look like for our experiment. The lamp would be turned on for 37 minutes until it reached 95% of its maximum temperature and then turned off for 60 minutes to allow it to cool down to near room temperature. In this example, a complete warm-up and cool-down cycle would take 97 minutes, allowing this lamp to be thermally cycled 14.7 times a day. Using this approach, we identified the switching cycles that would produce full or near-full thermal cycles for each test lamp. To be clear, the switching cycles established via the thermal testing were designed to maximize the number of thermal cycles that each test lamp could be subjected to over a fixed period of time so that we could assess thermal cycling as a stress condition that leads to catastrophic failure of LED lamps.

Photometric Testing

Following the thermal tests, we conducted photometric testing on each test lamp. These photometric tests were conducted on bare lamps (i.e. without luminaires) in an integrating sphere according to IES LM-79. The specific photometric and electrical measurements included: power input, lumen output, power factor, total harmonic distortion (THD), color rendering index (CRI), correlated color temperature (CCT) and spectral power distribution (SPD) for each test unit. SPD data may be used later to calculate color characteristics using the new IES TM-30 metrics. All photometric tests were repeated on all surviving test units at the end of the experiment to assess changes in lumen output, color temperature, and other performance metrics.

For the most part, the results of the photometric testing are not discussed in this paper as they do not relate directly to LED lamp longevity. The exception is results that are related to lumen depreciation which, when substantial, is considered a failure mode for LEDs. Readers interested in the detailed results from the photometric testing should reference the forthcoming CPUC final report for this project.

Maintenance Testing

Following the initial photometric tests, all test units were placed in test luminaires and "maintenance testing" was initiated where lamps were switched on and off according to the thermal cycle timing established from the thermal testing. This varies from the test conditions described in IES LM-84 where lamps are continuously operated at 25°C ± 5°C in open air. Otherwise, all other conditions were identical with those in IES LM-84. The maintenance testing was initiated in February 2016 and ran through April 2017.

Recessed downlights were placed 12" on center from each other, had a least 12" of unobstructed area beneath them, and were covered in 3" of fiberglass insulation to simulate typical ceiling installations. Enclosed ceiling fixtures were installed with a minimum spacing of 24" on center and 18" vertically. Bare sockets lamps were tested in 12"x12"x12" cavities. Half of bare socket lamps were tested in a "base-up" orientation while the other half were tested "base-down." An automated control and data acquisition system was used to turn test units on and off as well as to record failure times. Each test unit had a photosensor associated with it and failure times were recorded when these photosensors registered a sudden drop in light output. The failures were confirmed physically with a technician going to the failure location and ensuring the lamp has in fact failed.

The control system used to turn test subjects on and off had 22 control circuits or "zones." Each control zone could be programmed with a specific on-time and off-time and all test units on that control zone would then be turned on and off according to these settings. The test units with similar thermal cycle timing were grouped together and placed in the same control zone. In this way, the on-time and off-time of each cycle could be defined to be as short as possible. Again, this approach maximized the number of thermal cycles each test unit was subjected to while allowing all test units to reach at least 95% thermal stability. Since the thermal cycle timing for each group was defined so that the test units with the longest warm-up and cool down times were able to reach 95% thermal stability, most lamps were operated for longer periods than were necessary to achieve 95% stability. As shown previously in Figure 2, test units on each control zone were repeatedly subject to a warm-up period and then a cool down period long enough to at least achieve 95% thermal stability. Table 1 provides the on-time and off-times of each of the 22 control cycles, the amount of on-time and number of thermal cycles per day lamps and retrofit kits on these cycles experienced, and the quantities of each luminaire type in each control cycle.

Table 1. Timing and luminaire distribution for each cycle zone.

Control Zone	Control Zone Settings				Number of Luminaires per Control Zone				
	On-time (min)	Off-time (min)	On-time per day (hrs)	Thermal Cycles per day	Recessed Downlight	Ceiling Fixture	Base-up Socket	Base-down Socket	Total
1	56	89	9.3	9.9	25	0	15	0	40
2	72	102	9.9	8.3	21	0	0	3	24
3	89	117	10.4	7.0	24	0	7	0	31
4	75	94	10.7	8.5	24	0	0	12	36
5	76	114	9.6	7.6	26	0	18	0	44
6	89	129	9.8	6.6	26	0	0	14	40
7	105	140	10.3	5.9	26	0	4	0	30
8	48	60	10.7	13.3	0	0	0	48	48
9	58	80	10.1	10.4	0	0	0	34	34
10	73	112	9.5	7.8	0	0	0	28	28
11	144	202	10.0	4.2	24	0	0	0	24
12	62	94	9.5	9.2	0	0	15	0	15
13	65	87	10.3	9.5	0	0	34	0	34
14	51	67	10.4	12.2	0	0	39	0	39
15	41	107	6.6	9.7	24	0	0	0	24
16	49	81	9.0	11.1	26	0	0	5	31
17	38	57	9.6	15.2	0	18	0	0	18
18	43	61	9.9	13.8	0	21	0	0	21
19	45	67	9.6	12.9	0	27	0	0	27
20	54	67	10.7	11.9	0	24	0	0	24
21	59	91	9.4	9.6	0	27	0	0	27
22	78	109	10.0	7.7	0	27	0	0	27
Total					246	144	132	144	666

Sample Design

In order to support the research objectives discussed earlier, we developed a sample design of specific lamp models within each stratum such that roughly 50% of the models are compliant with the California (CA) Quality Spec, 25% are ENERGY STAR® certified but not compliant with the CA Quality Spec, and 25% are the least expensive non-ENERGY STAR products available. Next, we developed a model-level sample design that was representative of the current California market for screw-based LED lamps. This sample design allows comparative analysis between cohorts of CA Quality Spec-compliant, ENERGY STAR certified but not CA Quality Spec-compliant, and non-ENERGY STAR certified LED products. Following the development of this model-level sample design, the next step was to begin procuring multiple units of each model identified in the sample design. All LED test lamps that we procured for this study were "off the shelf" (i.e. via retailers), as opposed to via direct procurement from manufacturers.

Table 2 below summarizes the final sample of LED lamps procured for the test and how those lamps were distributed by fixture type for testing. The table also includes the estimated market shares of the specific models procured in each stratum based on data from the 2015 California Retail Lighting Shelf Survey (DNV GL, 2015). In total, the final test sample included 627 individual lamps covering 92 lamp models and 39 individual trim kits covering 13 trim kit models (666 test units total). The estimated market share of final sample of LED lamps is 44% of the total LED lamp market in California and 53% of the in-scope lamp market.[6]

Table 2. Summary of final test sample of LED lamps and downlight retrofit trim kits.

Lamp Type	Base Type	Lumen Bin (rated)	Models	Units Tested in:			Market Shares:		
				BS*	RD*	EC*	Total CA	Sample	Intra-Strata
A-LAMP	MSB (E26)	201-400	4	12	12	12	2.6%	1.3%	51%
A-LAMP	MSB (E26)	401-600	10	30	30	30	18.5%	7.4%	40%
A-LAMP	MSB (E26)	601-800	10	30	30	30	17.0%	8.1%	47%
A-LAMP	MSB (E26)	801-1,000	5	15	15	15	8.9%	1.2%	13%
A-LAMP	MSB (E26)	1,001-1,200	5	15	15	15	4.3%	2.8%	64%
A-LAMP	MSB (E26)	1,401-1,600	4	12	12	12	3.4%	2.3%	67%
GLOBE	MSB (E26)	201-400	4	12	0	0	3.0%	1.6%	55%
GLOBE	MSB (E26)	401-600	5	15	0	0	5.6%	5.3%	95%
TORPEDO	Candelabra (B10)	1-200	4	12	0	12	3.3%	1.4%	42%
TORPEDO	Candelabra (B10)	201-400	6	18	0	18	8.8%	5.9%	66%
TORPEDO	MSB (E26)	201-400	4	12	0	0	2.4%	1.5%	64%
BR30	MSB (E26)	601-800	8	24	24	0	10.4%	6.8%	65%
BR40	MSB (E26)	1,001-1,200	3	9	9	0	1.7%	1.0%	58%
PAR20	MSB (E26)	401-600	4	12	12	0	1.3%	0.8%	57%
PAR30	MSB (E26)	601-800	4	12	12	0	2.1%	1.6%	75%
PAR38	MSB (E26)	801-1,000	4	12	12	0	1.7%	1.5%	88%
PAR38	MSB (E26)	1,001-1,200	4	12	12	0	1.6%	1.0%	62%
R20	MSB (E26)	401-600	4	12	12	0	3.3%	2.6%	80%
TOTAL TEST LAMP SAMPLE			105	276	246	144	100%	53.9%	N/A
TRIM KITS (4")	N/A	N/A	6	0	18	0	N/A	N/A	N/A
TRIM KITS (6")	N/A	N/A	7	0	21	0	N/A	N/A	N/A

* BS = bare socket; RD = recessed downlight; EC = enclosed ceiling fixture

Results

In the section below, we first present some of the key results from the initial thermal tests. For the sake of brevity, we then focus on the failure rates recorded during the maintenance test, rather than the lumen depreciation results since the observed lumen depreciation rates were not significant. Indeed, the average lumen maintenance for all surviving test lamps was 99.5% (0.5% lumen depreciation). Only eight test lamps experienced significant lumen depreciation (i.e. final light output less than 70% of initial lumen output), while over 300 test lamps actually experienced increases in lumen output over the course of the maintenance testing.[7] Detailed analyses of observed lumen depreciation will be included in final CPUC report.

Figure 3 shows the maximum lamp temperature recorded by lamp wattage and fixture type (R = Recessed Downlight, C = Ceiling Fixture, U = Base-Up Bare Socket, D = Base-Down Bare Socket), as well as the overall correlation coefficients between lamp wattage and maximum lamp temperature by fixture type. As expected, the highest lamp temperatures were found on higher wattage lamps in constrained-

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[6] Note that recessed downlight retrofit kits (often called trim kits) were added to the scope of our study through separate funding from the IOUs. However, the sample of trim kits tested reflects the products offered through IOU upstream programs at the time of our sample procurement, not the larger LED trim kit market in California.

[7] Note that we were unable to conduct a second set of photometric tests on failed lamps, which leaves open the possibility that failed lamps also suffered significant lumen depreciation.

air fixtures, i.e. enclosed ceiling fixtures and recessed downlights.[8] Perhaps more importantly, however, Figure 3 shows that maximum lamp temperatures for lamps in constrained-air fixtures exhibited a stronger correlation with wattage compared to lamps in bare sockets.

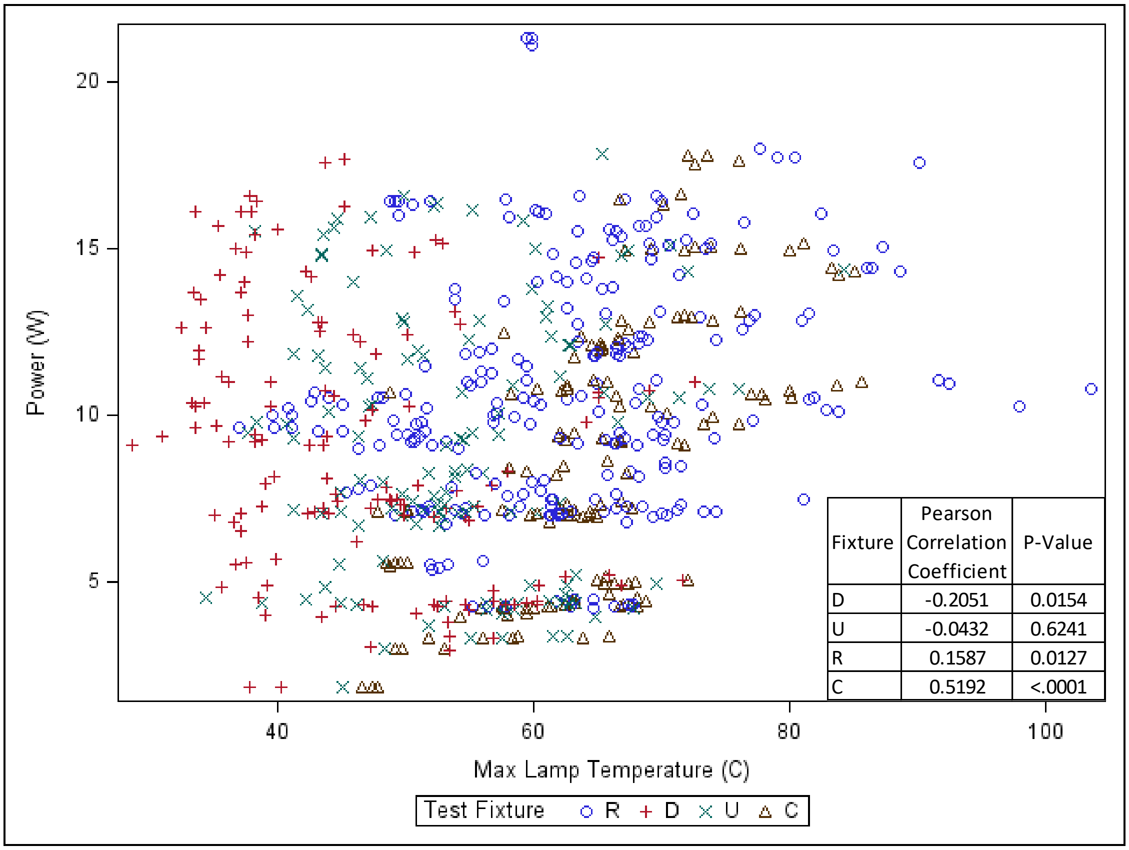

Figure 3. Maximum lamp temperature versus measured lamp input power by fixture type.

Figure 4 shows near-ambient maximum air temperature by lamp wattage and fixture type. This figure shows that while air temperature inside each luminaire trends very strongly with lamp wattage, it does not vary significantly by fixture type.[9] It should be noted that the near-ambient air temperatures shown below are in the same range as the ambient air temperatures specified in ENERGY STAR's current elevated temperature test (55°C for directional lamps over 20W, 45°C for most other lamp types). These new near-ambient air temperature data may be useful to help further refine such screening tests by accounting for the strong ambient temperature/lamp wattage relationship shown below so that lamps are tested in ambient temperatures closer to what would be expected in the field.

[8] We measured lamp temperature at a single point on each lamp. While the process for placing the thermocouples was consistent, differences in lamp designs as well as some random effects (e.g. placement of thermocouple near particularly hot components) likely contribute the variability of these results.

[9] Note that the thermal tests included only a few near-air measurements for bare socket fixtures, mainly to confirm that air temperatures near lamps in these open air fixtures were minimal as compared to constrained-air fixtures.

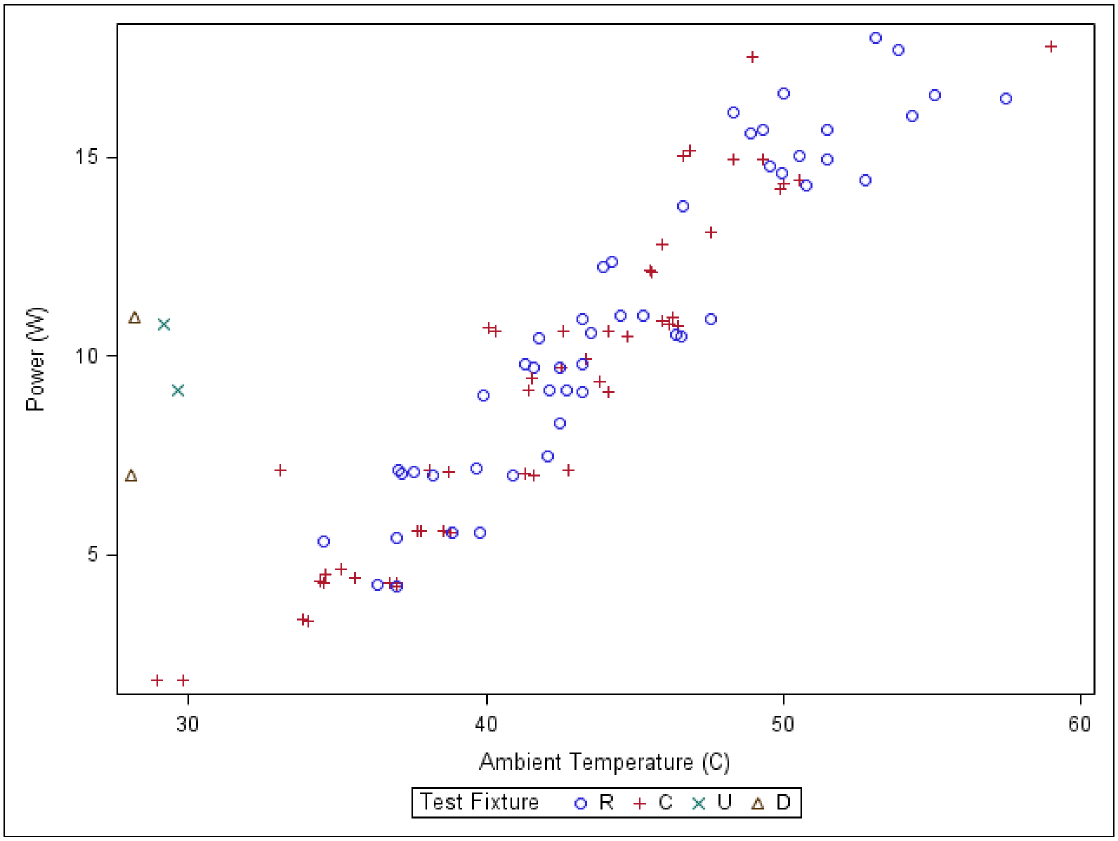

Figure 4. Near-ambient air temperature versus measure lamp input power by fixture type

Table 3 provides a summary of the overall catastrophic failure rates observed during the maintenance testing. As the table shows, 130 out of 666 lamps tested experienced catastrophic failures – representing a 20% overall failure rate across all lamps tested. By lamp type, catastrophic failure rates were highest among A-lamps (33%), with those tested in enclosed ceiling fixtures and recessed downlights experiencing the highest catastrophic failure rates observed across all lamp-fixture combinations tested (40% and 35%, respectively). The overall failure rates for globe, torpedo, and reflector lamps were all comparatively lower – between 6% and 4%. Notably, none of the downlight retrofit trim kits tested experienced catastrophic failure.

Table 3. Summary of catastrophic failure rates observed across all lamp-fixture combinations.

Lamp Type	Lamp Specification	Total Lamps Tested	**Total Catastrophic Failure Rate (%)**				
			Test Fixture Type				
			Ceiling	Recessed	Bare, Down	Bare, Up	Total
A-LAMP	CEC and EStar	72	0%	25%	8%	0%	18%
	EStar-only	144	56%	44%	35%	55%	48%
	Not Estar	126	31%	31%	14%	14%	25%
	All	342	40%	35%	22%	27%	33%
GLOBE	CEC and EStar	3	-	-	0%	50%	33%
	EStar-only	18	-	-	0%	0%	0%
	Not Estar	6	-	-	0%	0%	0%
	All	27	-	-	0%	8%	4%
TORPEDO/BULLET	CEC and EStar	6	0%	-	0%	0%	0%
	EStar-only	21	0%	-	0%	0%	0%
	Not Estar	45	22%	-	0%	0%	9%
	All	72	13%	-	0%	0%	6%
SPOTLIGHT/REFLECTOR	CEC and EStar	48	-	8%	0%	0%	4%
	EStar-only	78	-	8%	0%	0%	4%
	Not Estar	60	-	20%	0%	0%	10%
	All	186	-	12%	0%	0%	6%
TRIM KIT	CEC and EStar	39	-	0%	-	-	0%
	EStar-only	0	-	-	-	-	-
	Not Estar	0	-	-	-	-	-
	All	39	-	0%	-	-	0%
Total	CEC and EStar	168	22%	9%	4%	4%	10%
	EStar-only	261	47%	28%	15%	21%	28%
	Not Estar	237	28%	26%	5%	6%	18%
	All	666	35%	21%	9%	12%	20%

Comparing the catastrophic failure results across “lamp specification”, Table 3 also shows that lamps that are compliant with the CA Quality Spec (labeled “CEC” above) experienced 10% catastrophic failures (17 out of 168 units tested). ENERGY STAR-certified but not CA Quality Spec-compliant (labeled “EStar-only”) lamps along with non-ENERGY STAR-certified lamps experienced relatively higher catastrophic failure rates (28% and 18%, respectively).

In addition to catastrophic failures where test lamps stopped working completely, lab technicians also observed and systematically recorded lamps that experienced “pre-failure” conditions, such as severe flickering and dramatically reduced light output (i.e. <70% rated lumen output). In some cases, lamps that exhibited pre-failure conditions eventually experienced catastrophic failure. In other cases, such lamps continued to function through the duration of the maintenance tests. From a consumer perspective, we believe it is reasonable to treat such pre-failure lamps as equivalent to lamps that have catastrophically failed, since it is likely that consumers would replace such lamps as soon as pre-failure behavior manifests itself. To this end, Table 4 below provides a summary of lamps that exhibited pre-failure characteristics.

As the table shows, 4% of all lamps tested exhibited pre-failure behavior but not catastrophic failure during the maintenance tests.

Table 4. Summary of pre-failure rates observed across all lamp-fixture combinations.

Lamp Type	Lamp Specification	Total Lamps Tested	Total Pre-Failure Behavior Rate (%)				
			Test Fixture Type				
			Ceiling	Recessed	Bare, Down	Bare, Up	Total
A-LAMP	CEC and EStar	72	0%	8%	0%	0%	3%
	EStar-only	144	2%	6%	4%	9%	5%
	Not Estar	126	5%	7%	10%	0%	6%
	All	342	3%	7%	5%	4%	5%
GLOBE	CEC and EStar	3	-	-	0%	0%	0%
	EStar-only	18	-	-	0%	13%	6%
	Not Estar	6	-	-	0%	0%	0%
	All	27	-	-	0%	8%	4%
TORPEDO/BULLET	CEC and EStar	6	0%	-	0%	0%	0%
	EStar-only	21	0%	-	0%	0%	0%
	Not Estar	45	11%	-	7%	8%	9%
	All	72	7%	-	5%	5%	6%
SPOTLIGHT/REFLECTOR	CEC and EStar	48	-	0%	0%	0%	0%
	EStar-only	78	-	3%	12%	0%	4%
	Not Estar	60	-	0%	0%	17%	3%
	All	186	-	1%	4%	4%	3%
TRIM KIT	CEC and EStar	39	-	0%	-	-	0%
	EStar-only	0	-	-	-	-	-
	Not Estar	0	-	-	-	-	-
	All	39	-	0%	-	-	0%
Total	CEC and EStar	168	0%	2%	0%	0%	1%
	EStar-only	261	2%	5%	5%	5%	4%
	Not Estar	237	7%	4%	5%	6%	5%
	All	666	3%	4%	4%	5%	4%

Taken together, Tables 3 and 4 indicate that the bulk of the observed lamp "failures" (i.e. catastrophic failures and pre-failure behavior) were concentrated A-lamps that are ENERGY STAR-certified (but not CA Quality Spec-compliant) lamps and non-ENERGY STAR-certified lamps. However, it is important to understand that these failures were not evenly distributed across all ENERGY STAR and non-ENERGY STAR lamp models that were tested. Indeed, quite the opposite is true. Figure 5 shows how more than two-thirds of all failures came from 12 specific models that performed particularly poorly, with 50% or more of the units from those models that were tested experiencing either catastrophic failure or pre-failure behavior. Among those models, one was ENERGY STAR-certified under the latest version of the ENERGY STAR product specification (v2.0), seven were ENERGY STAR-certified under the first version of (v1.0), and four were not ENERGY STAR-certified.

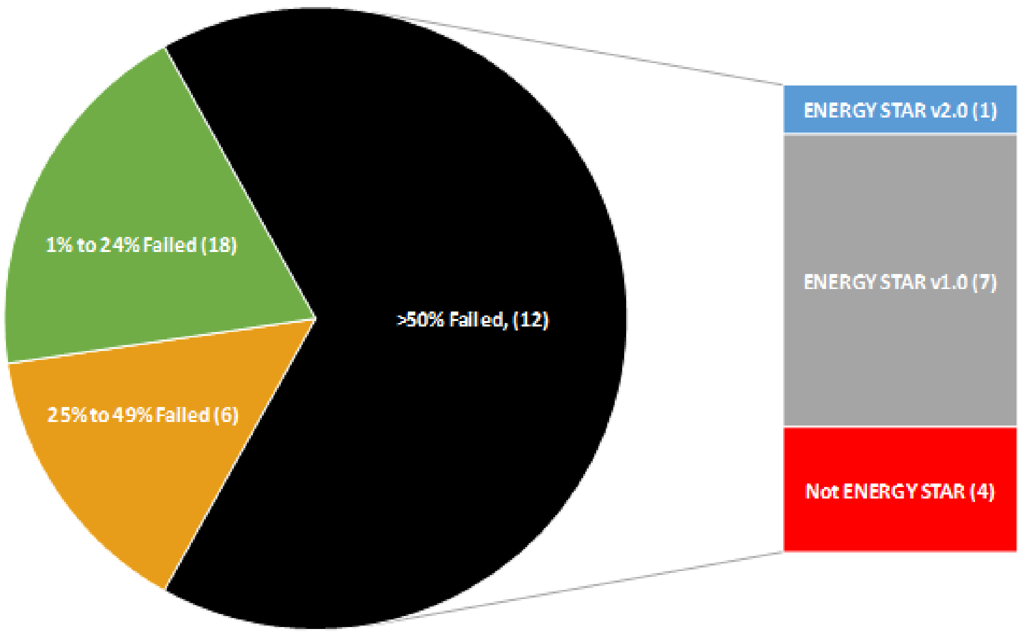

Figure 5. Distribution of failed lamp models (in parentheses) relative to the number of test units per model that failed (expressed as percent of all units of a given model that were tested).

Conclusions

Overall, the results produced by this study provide strong evidence that two stress conditions commonly found in residential homes – thermal cycling and elevated operating temperature (due to restricted airflow and relative lamp position within the luminaire) – do indeed have a significant impact on the effective useful life of LED lamps. At the same time, our results also show that a significant portion of all observed failures were concentrated in a few specific lamp models – indicating that readers should be careful not to overly extrapolate these results to the larger LED lamp market. However, from an energy efficiency program planning and evaluation perspective, it should be understood that even minor adjustments to the ex ante EUL assumptions (based on rated values) may have an important impact on lifecycle savings and cost-effectiveness estimates. While developing such EUL adjustments was beyond the scope of this study, the results represent an important empirical foundation for more formal EUL adjustments, such as those developed by Close (2015). This study also provides an empirical foundation for potential adjustments to testing and life-rating protocols to account for temperature-related failure modes and temperature-related field conditions.

References

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