

CALiPER

Report 20.3:

Robustness of LED PAR38 Lamps

December 2014

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Solid-State Lighting Program

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Preface

The U.S. Department of Energy (DOE) CALiPER program has been purchasing and testing general illumination solid-state lighting (SSL) products since 2006. CALiPER relies on standardized photometric testing (following the Illuminating Engineering Society of North America [IES] approved method LM-79-08¹) conducted by accredited, independent laboratories.² Results from CALiPER testing are available to the public via detailed reports for each product or through summary reports, which assemble data from several product tests and provide comparative analyses.³ Increasingly, CALiPER investigations also rely on new test procedures that are not industry standards; these experiments provide data that is essential for understanding the most current issues facing the SSL industry.

It is not possible for CALiPER to test every SSL product on the market, especially given the rapidly growing variety of products and changing performance characteristics. Instead, CALiPER focuses on specific groups of products that are relevant to important issues being investigated. The products are selected with the intent of capturing the current state of the market at a given point in time, representing a broad range of performance characteristics. However, the selection does not represent a statistical sample of all available products in the identified group. All selected products are shown as currently available on the manufacturer's web page at the time of purchase.

CALiPER purchases products through standard distribution channels, acting in a similar manner to a typical specifier. CALiPER does not accept or purchase samples directly from manufacturers to ensure that all tested products are representative of a typical manufacturing run and not hand-picked for superior performance. CALiPER cannot control for the age of products in the distribution system, nor account for any differences in products that carry the same model number.

Selecting, purchasing, documenting, and testing products can take considerable time. Some products described in CALiPER reports may no longer be sold or may have been updated since the time of purchase. However, each CALiPER dataset represents a snapshot of product performance at a given time, with comparisons only between products that were available at the same time. Further, CALiPER reports seek to investigate market trends and performance relative to benchmarks, rather than as a measure of the suitability of any specific lamp model. Thus, the results should not be taken as a verdict on any product line or manufacturer. Especially given the rapid development cycle for LED products, specifiers and purchasers should always seek current information from manufacturers when evaluating products.

To provide further context, CALiPER test results may be compared to data from LED Lighting Facts,⁴ ENERGY STAR[®] performance criteria,⁵ technical requirements for the DesignLights Consortium[®] (DLC) Qualified Products

¹ IES LM-79-08, *Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products*, covers LED-based SSL products with control electronics and heat sinks incorporated. For more information, visit <http://www.iesna.org/>.

² CALiPER only uses independent testing laboratories with LM-79-08 accreditation that includes proficiency testing, such as that available through the National Voluntary Laboratory Accreditation Program (NVLAP).

³ CALiPER application reports are available at <http://energy.gov/eere/ssl/caliper-application-reports>. Detailed test reports for individual products can be obtained from <http://www.ssl.energy.gov/search.html>.

⁴ LED Lighting Facts[®] is a program of the U.S. Department of Energy that showcases LED products for general illumination from manufacturers who commit to testing products and reporting performance results according to industry standards. The DOE LED Lighting Facts program is separate from the Lighting Facts label required by the Federal Trade Commission (FTC). For more information, see <http://www.lightingfacts.com>.

⁵ ENERGY STAR is a federal program promoting energy efficiency. For more information, visit <http://www.energystar.gov>.

List (QPL),⁶ or other established benchmarks. CALiPER also tries to purchase conventional (i.e., non-SSL) products for comparison, but because the primary focus is SSL, the program can only test a limited number.

It is important for buyers and specifiers to reduce risk by learning how to compare products and by considering every potential SSL purchase carefully. CALiPER test results are a valuable resource, providing photometric data for anonymously purchased products as well as objective analysis and comparative insights. However, photometric testing alone is not enough to fully characterize a product—quality, reliability, controllability, physical attributes, warranty, compatibility, and many other facets should also be considered carefully. In the end, the best product is the one that best meets the needs of the specific application.

For more information on the DOE SSL program, please visit <http://www.ssl.energy.gov>.

⁶ The DesignLights Consortium Qualified Products List is used by member utilities and energy-efficiency programs to screen SSL products for rebate program eligibility. For more information, visit <http://www.designlights.org/>.

1 Outline of CALiPER Reports on PAR38 Lamps

This study is part of a series of investigations performed by the CALiPER program on LED PAR38 lamps. Each report in the series covers the performance of up to 44 LED PAR38 lamps (some tests were not performed on all of the available samples) that were purchased in 2012 or 2013. Summaries of the testing are covered in each report, as follows:

Application Summary Report 20: LED PAR38 Lamps (November 2012, addendum September 2013)⁷

A sample of 44 LED PAR38 lamps, as well as 8 halogen and 2 CFL benchmarks, underwent photometric testing according to IES LM-79-08. CALiPER Application Summary Report 20 focuses on the basic performance characteristics of the LED lamps compared to the benchmarks, as well as performance relative to manufacturers' claims. This report follows numerous similar reports on different product types, which have been published by the CALiPER program.

Report 20.1: Subjective Evaluation of Beam Quality, Shadow Quality, and Color Quality for LED PAR38 Lamps (October 2013)⁸

This report focused on human-evaluated characteristics, including beam quality, shadow quality, and color quality. Using a questionnaire that included rank-ordering, opinions on 26 of the Report 20 PAR38 lamps were gathered during a demonstration event for members of the local IES chapter. This was not a rigorous scientific experiment, and the data should not be extrapolated beyond the scope of the demonstration. The results suggest that many of the LED products compared favorably to halogen PAR38 benchmarks in all attributes considered. LED lamps using a single-emitter design were generally preferred for their beam quality and shadow quality, and the IES members' ranking of color quality did not always match the rank-order according to the color rendering index (CRI).

Report 20.2: Dimming, Flicker, and Power Quality Characteristics of LED PAR38 Lamps (March 2014)⁹

This report focused on the flicker and power quality performance of the Series 20 lamps at full output and various dimmed levels. All of the Series 20 PAR38 lamps that manufacturers claimed to be dimmable (including all halogen lamps) were evaluated individually (one lamp at a time), both on a switch and under the control of a phase-cut dimmer designed for use with "all classes of bulbs." Measurements of luminous flux, flicker, and power quality were taken at 10 dimmed settings and compared with operation on a switch.

The dimmed performance of many LED lamps is often dependent on the phase-cut dimmer used and the number of lamps are connected to the dimmed circuit. Some manufacturers recommend specific dimmers that work better with their product(s), as well as the minimum and maximum number of lamps per circuit. Because only a single unit of each lamp was evaluated on a single dimmer make and model, which may or may not have been recommended by its manufacturer, this report focuses on the performance of the products relative to each other, rather than on the best-case performance of each lamp or the variation in performance delivered from each lamp. Despite these limitations, the results suggest that LED lamp performance is improving, and performance trends are beginning to emerge, perhaps due in part to the identification of preferred LED driver strategies for lamp products.

Report 20.3: Robustness of LED PAR38 Lamps (this report)

Three samples of 40 of the Series 20 PAR38 lamps (including LED and benchmark conventional lamps) underwent multi-stress testing, whereby samples were subjected to increasing levels of simultaneous thermal, humidity, electrical, and vibrational stress. The results do not explicitly predict expected lifetime or reliability,

⁷ Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_20_summary.pdf

⁸ Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_20.1_par38.pdf

⁹ Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_20-2_par38.pdf

but the LED products can be compared with one another, as well as with benchmark conventional products, to assess the relative robustness of the product designs.

On average, the 32 LED lamp models tested were substantially more robust than the conventional benchmark lamps. As with other performance attributes, however, there was great variability in the robustness and design maturity of the LED lamps. Several LED lamp samples failed within the first one or two levels of the ten-level stress plan, while all three samples of some lamp models completed all ten levels. One potential area of improvement is design maturity, given that more than 25% of the lamp models demonstrated a difference in failure level for the three samples that was greater than or equal to the maximum for the benchmarks. At the same time, the fact that nearly 75% of the lamp models exhibited better design maturity than the benchmarks is noteworthy, given the relative stage of development for the technology.

Report 20.4: Lumen and Chromaticity Maintenance of LED PAR38 Lamps (pending)

The lumen depreciation and color shift of 40 lamps is currently being monitored for an extended period of time at Pacific Northwest National Laboratory (PNNL).

2 Introduction

Testing results from CALiPER Application Summary Report 20 showed that the LED PAR38 lamps had much higher efficacies than conventional halogen lamps, while offering comparable lumen output and luminous intensity distributions—at least in the target range of lamps comparable in output to 75 W halogen PAR38s. Most of the LED PAR38 lamps had correlated color temperatures (CCTs) similar to those of the conventional lamps they were intended to replace and CRIs that were good (80s) or excellent (90s). Further, feedback from lighting professionals during a demonstration event indicated that a number of LED PAR38 lamps had better beam quality, shadow quality, and color quality than halogen benchmark products. At the same time, the LED products exhibited a wide range of dimming, flicker, and power quality characteristics—three attributes that are (typically) not well quantified—and often not included—in manufacturer data. While many LED PAR38 lamps appear to be good alternatives to halogen lamps, sometimes tradeoffs in one or more of these attributes may be necessary.

Two other important aspects of LED product performance are lifetime and reliability. For more discussion on the difference between lifetime and reliability—and the importance of both—please see the DOE SSL fact sheet *LED Lifetime and Reliability*.¹⁰ While LED products are generally understood to be superior to their halogen counterparts in terms of lifetime and reliability, comprehensive metrics for those attributes are elusive.¹¹ Alternatively, it can be useful to examine the robustness of products—i.e., their resistance to catastrophic or parametric failure when exposed to electrical, mechanical, and environmental stresses—as well as their lumen and chromaticity maintenance (the focus of Report 20.4).

The present report focuses on an evaluation of robustness, which was accomplished by stress-testing a small sample of each product; that is, simultaneously subjecting them to increasing levels of voltage variation, vibration, temperature change, and humidity change, all in a cyclic pattern. Robustness testing is not necessarily predictive of long-term performance, but allows for quantitative comparisons of products that have undergone a systematic exposure to environmental stresses, and may expose potential future failure modes. The relevance of robustness testing is further enhanced by including benchmark conventional products, which provide a familiar baseline for comparison.

CALiPER Stress Testing

In 2011, PNNL developed and executed a stress testing procedure for the L Prize 60 W replacement lamp competition. The Failure Mode Verification Testing (FMVT) protocol used to evaluate the L Prize lamps was established in partnership with Intertek. Following the announcement of the L Prize award, a comparable set of stress-testing equipment was assembled and commissioned at PNNL, in conjunction with a similar (but not identical) stress-testing procedure. More information on FMVT and the L Prize characterization can be found in the DOE report *Stress Testing of the Philips 60W Replacement Lamp Entry* (April 2012).¹²

Principally, the PNNL stress test apparatus simultaneously applies multiple types of stresses—as opposed to applying stressors individually—which facilitates a very rapid time to failure. By recording the time to failure and the relative distribution of failures in time, and (if possible) determining the cause of failure, the robustness of each product can be compared (relatively) among the others tested. In this case, three types of stress were applied to the test lamps: electrical (voltage), mechanical (vibration), and environmental (thermal and humidity).

For this investigation, three samples each of 40 different products—including 32 LED, two CFL, one ceramic metal halide (CMH), and five halogen PAR38 lamps—were subjected to the same sequence of stressors. Due to

¹⁰ Available at: <http://ssl.energy.gov/factsheets.html>

¹¹ See, for example, *LED Luminaire Lifetime: Recommendations for Testing and Reporting*, available at: http://www.nglia.org/pdfs/led_luminaire_lifetime_guide_sept2014.pdf

¹² Available at: http://www.lightingprize.org/pdfs/lprize_60w-stress-testing.pdf

testing apparatus limitations, only 12 lamps could be tested at one time. Thus, the procedure was repeated 10 times until all lamps had either failed or survived the highest level of stress that the apparatus could deliver.

3 Methods

The test procedure subjected the lamps to 10 increasingly greater levels of stress, with measurement and performance verification prior to stress testing and in between each stress level. Test time was minimized by using two test apparatus configurations, which allowed for nearly continuous testing. Each stress level, implemented over 24-hour periods, included a daytime and a nighttime phase, with different stress profiles based on the capabilities of the associated configuration. Functional verification testing following the completion of each stress level took place using a separate apparatus.

Test Apparatus and Equipment

The stress application apparatus included a custom-built vibrational stress chamber and an environmental chamber (EnviroFST 600), as shown in Figure 1. The vibrational stress chamber was coupled to the environmental chamber, using ventilation ducts and a flexible hose, so that all stressors could be applied simultaneously during the daytime test phases. Use of the ventilation hose, however, significantly slowed the rate of temperature and humidity changes in the vibrational stress chamber. In order to deliver greater environmental stress to the lamps (steeper temperature change ramps), they were directly installed and operated in the environmental chamber during the nighttime phase, when no vibrational stress was applied.

During both the daytime and nighttime stress application phases, the lamps were mounted in 12 medium screw-base lamp sockets positioned around the perimeter of an aluminum disc, equidistant from the center coupling point. The sockets were wired in parallel for nominal alternating current (AC) operation, and connected to a digitally controlled AC power supply (California Instrument 1501iX), programmed to implement the electrical stress sequence. During the daytime phase of each level, this mechanical and electrical interface disc was coupled to a vibration/shock table that was mounted inside the insulated vibrational stress chamber. During the nighttime phase, the disc was simply placed in the environmental chamber. All mechanical and thermal stresses were verified with independent sensors.

The functional verification measurement chamber (Figure 2) was a 24-inch cubical box painted flat black inside and out. A 6-inch-diameter aperture, centered in the top of the box, allowed for interfacing with an overhead lamp mount. Pins were fixed in each quadrant of the measurement chamber floor—equidistant from the center—to allow rapid and repeatable positioning of a chroma meter (Minolta CL-200) that was used to measure relative luminous flux and chromaticity. A power quality meter (Yokogawa WT210) was used to measure electrical characteristics.



Figure 1. LEFT: Mechanical stress chamber housing 12 lamps. RIGHT: Environmental chamber that provided the thermal stresses.

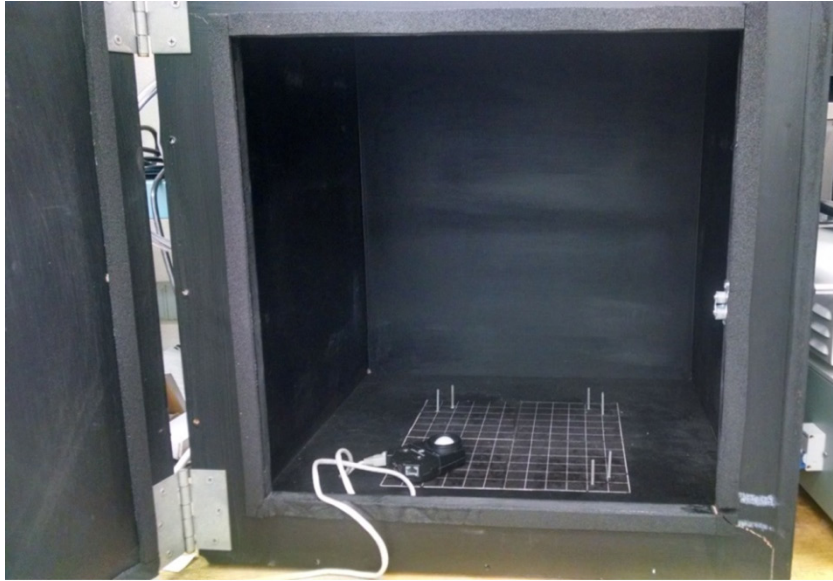


Figure 2. Measurement chamber used to evaluate lamps before and between the levels of the stress plan.

Stress Sequence

The voltage, vibration, temperature, and humidity stresses were simultaneously applied at 1 of 10 levels. The first stress level corresponded to typical use, while the tenth and final stress level was equivalent to the maximum equipment capability. The intermediate stress levels were evenly distributed between the endpoints, as listed in Table 1. The lamp positioning around the disk perimeter resulted in the stress experienced by the lamps being greater than the stress applied to the center of the disk; as the plate will oscillate for a short time, the total energy delivered is also greater.

Each of the ten stress levels consisted of two phases: one during the day and one overnight. During the daytime phase, all four stresses were applied over a six-hour period. Starting at ambient, the temperature was increased over 45 minutes to a maximum set point, held for 60 minutes, reduced over a 45-minute period to a minimum set point, held for 60 minutes, ramped up over 45 minutes back to the maximum set point, held for 60 minutes, then held at room temperature for 45 minutes (see Figure 3). During the second temperature ramp-up, relative

Table 1. Stress characteristics for the ten levels.

Level	Max. Voltage (V)	Min. Voltage (V)	Haversine			Center Stress (peak g)	Perimeter Stress (peak g)	Perimeter Stress (RMS g)	Max. Temp (°C)	Min. Temp (°C)	Temp. Ramp (°C)	Relative Humidity (%)
			Voltage Ramp (V)	Pulse Width (ms)								
1	126	114	12	8	3	5.0	0.42	50.0	-20.0	70.0	20	
2	132	108	24	8	5	8.3	0.84	56.7	-24.4	81.1	20	
3	138	102	36	7	7	11.7	1.22	63.3	-28.9	92.2	20	
4	144	96	48	7	9	15.0	1.57	70.0	-33.3	103.3	20	
5	150	90	60	6	11	18.3	2.28	76.7	-37.8	114.5	20	
6	162	78	84	6	13	21.7	2.66	83.3	-42.2	125.5	20	
7	174	66	108	4	15	25.0	3.03	90.0	-46.7	136.7	20	
8	186	54	132	4	17	28.3	3.45	96.7	-51.1	147.8	20	
9	198	42	156	3	19	31.7	3.94	103.3	-55.6	158.9	10	
10	210	30	180	3	21	35.0	4.39	110.0	-60.0	170.0	10	

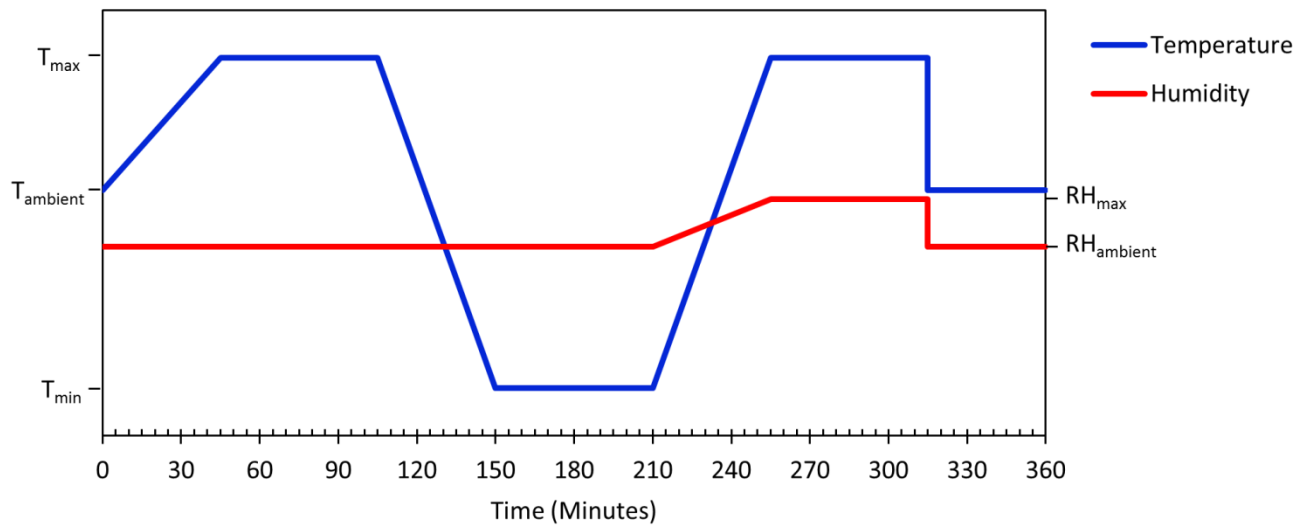


Figure 3. Temperature and humidity profiles during the daytime phase.

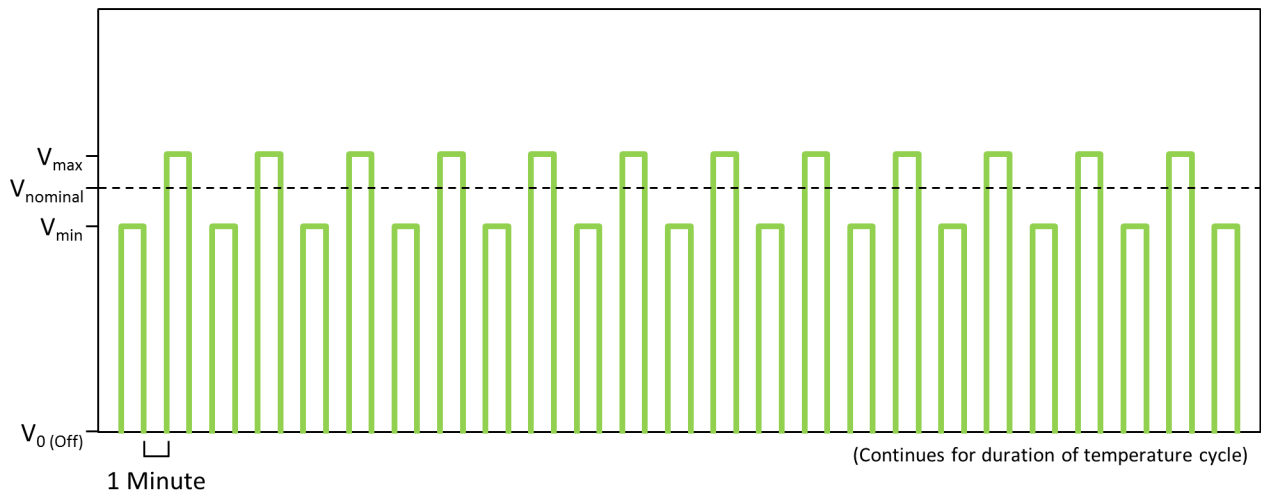


Figure 4. Voltage cycling profile during both the daytime and nighttime phases.

humidity (RH) was simultaneously increased from ambient to the maximum set point of 20%. Simultaneously, voltage was applied at either a minimum or maximum set point for a two-minute period, with a 50% duty cycle (i.e., one minute on, one minute off) (Figure 4). The voltage cycling was repeated for the duration of the daytime phase. Vibration was applied with a haversine negative pulse sine wave at a two-second interval (Figure 5).

During the nighttime phase, voltage, temperature, and humidity stresses were applied over a 15-hour period (Figure 6). The temperature was ramped from ambient to the maximum set point as fast as possible,¹³ held at that temperature for two hours, then transitioned to the low temperature set point as fast as possible and held

¹³ The EnviroFST 600 is capable of heating at a rate of 20°C per minute and cooling at a rate of 12°C per minute. Although the ramps are shown as instantaneous in Figure 6, they were as short as two minutes and as long as 15 minutes depending on the exact amount of change.

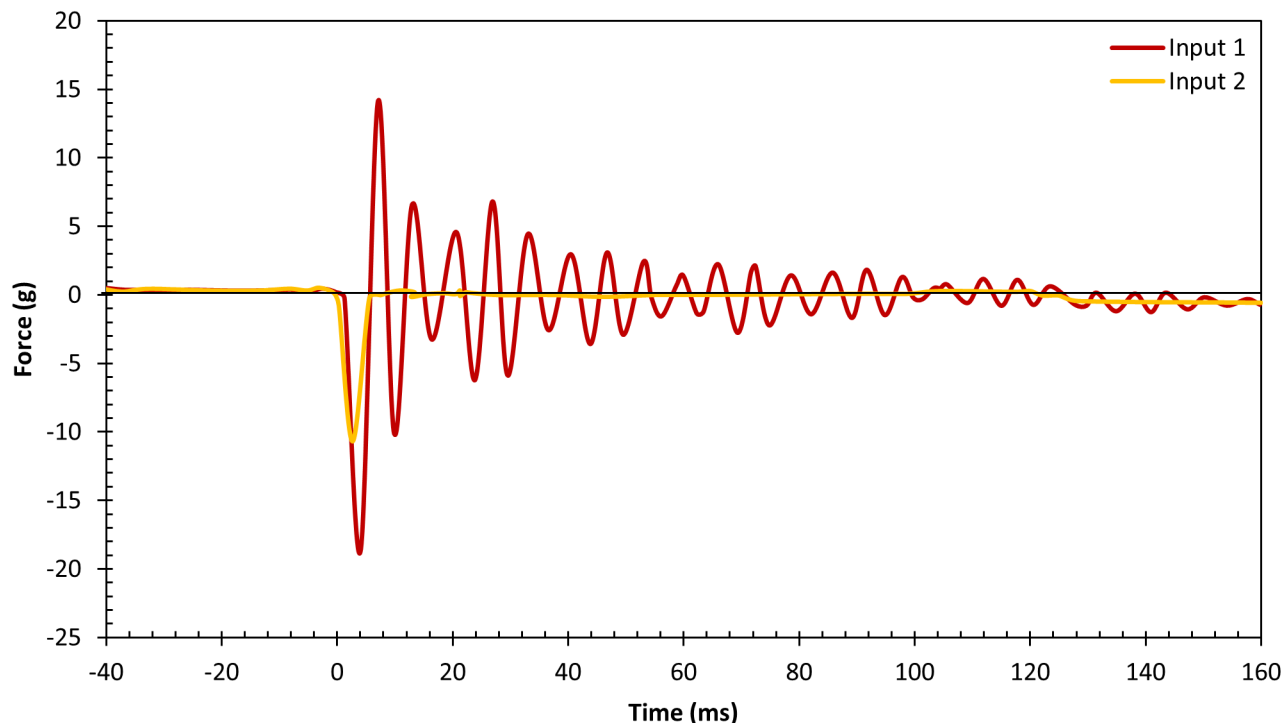


Figure 5. Typical vibrational stress profile. Stress was applied continuously during the daytime phase.

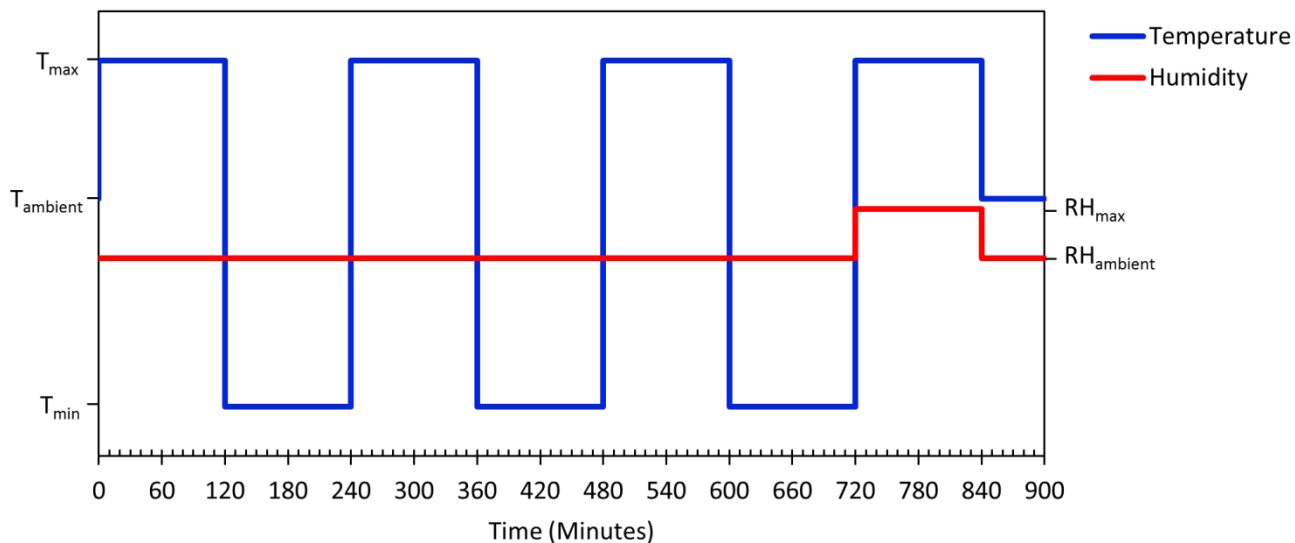


Figure 6. Temperature and humidity profiles during the nighttime phase.

there for another two hours. This cycle occurred two more times before a final temperature and humidity ramp to the maximum set points, after which the conditions were returned to ambient (room temperature and humidity) and held for one hour. The voltage cycling matched the daytime phase profile.

Functional Verification

After each of the two phases, the lamps were inspected for physical damage. If any damage required removal of the lamp (such as those in Figure 7, for example), then an equivalent lamp was installed in its place to maintain a consistent weight for subsequent vibrational stress. Some forms of minor damage, such as deforming of a plastic lens or a minor crack in the base, did not require lamp replacement. At the same time, some lamps that were removed could still illuminate, but they were deemed unsafe. The lamps were then powered at line voltage (120 VAC) and visually inspected for function. If a lamp failed to light or behaved erratically, then the lamp was similarly removed and replaced with an equivalent lamp.

In addition to visual monitoring for catastrophic failures, the luminous flux (characterized using illuminance measurements), chromaticity, power, current, power factor, and apparent power were measured for each lamp prior to the start of the testing and after each stress level. Measurements of (relative) luminous flux and chromaticity were taken using the chroma meter at four locations on the bottom of the functional verification measurement chamber, with the light output measurements averaged and normalized to the pre-test readings. Parametric failure due to lumen depreciation was deemed to have occurred if the measured average illuminance was less than 70% of the initial value. Parametric failure due to color shift was determined to have occurred if $\Delta u'v'$ exceeded 0.007. While lamp power draw was evaluated during functional verification, no test samples were deemed to have failed as a result of those measurements, as there are no standardized or otherwise commonly used criteria for deeming parametric failure due to an increase in power draw. The power draw performance of the halogen benchmarks may be useful for establishing power draw failure criteria for future studies. Notably, parametric failure was evaluated post hoc, so the lamps continued to be stressed even after parametric failure occurred.



Figure 7. Examples of products experiencing physical damage that prevented further testing and therefore constituted catastrophic failure.

4 Results

This is the first time that the CALiPER program has conducted robustness testing on a wide variety of lamps. Previous DOE SSL Program testing for the L Prize lamp, using a similar test approach, failed to produce any failures in the LED lamps. In contrast, the present evaluation of PAR38 LED lamps produced failures for most products and further demonstrated substantial variation in the maximum stress-level step completed before failure—either catastrophic or parametric—as shown in Figure 8. Some products performed similarly to the prototype L Prize lamps, but others failed early in the stress test procedure.

Product identification is provided in Appendix A. Notably, the results described in this report are for lamps originally purchased in 2012, with additional samples purchased in early 2013. Thus, the products may no longer be available on the market. New lamp designs from the same manufacturer may perform quite differently (i.e., better or worse), so the analysis is generally focused on variation rather than on identifying outstanding products or features that lead to greater robustness.

Four of the 32 LED products tested completed the stress test plan without a single sample failing, whereas all three samples for one product failed (parametrically) during the second stress step, and two of three samples for another product type did not even last through the first stress test. Notably, all but the two previously mentioned poor-performing products exhibited greater robustness than the halogen or CFL benchmarks. Of the benchmarks, the CMH lamp exhibited the greatest robustness, although the CMH and CFL lamps were not evaluated for parametric failure because of inaccurate pre-test data resulting from their inadequate warmup times.

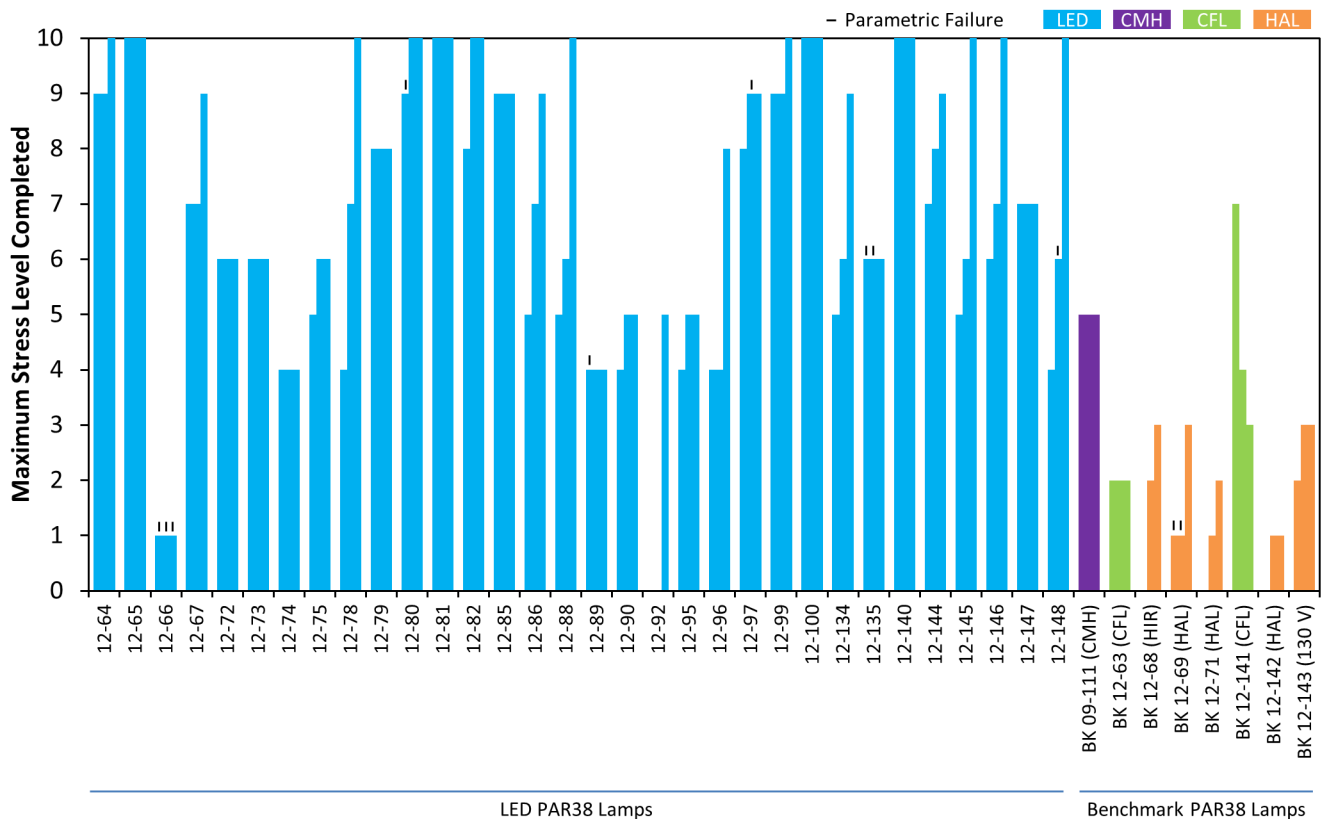


Figure 8. Maximum stress level completed without catastrophic or parametric failure for each lamp sample. The dashes indicate parametric failures; the other lamps failed catastrophically or reached the end of the stress plan (level 10) without failing. Four of the LED products (12-65, 12-81, 12-100, and 12-140) did not have any samples fail during the entire stress test.

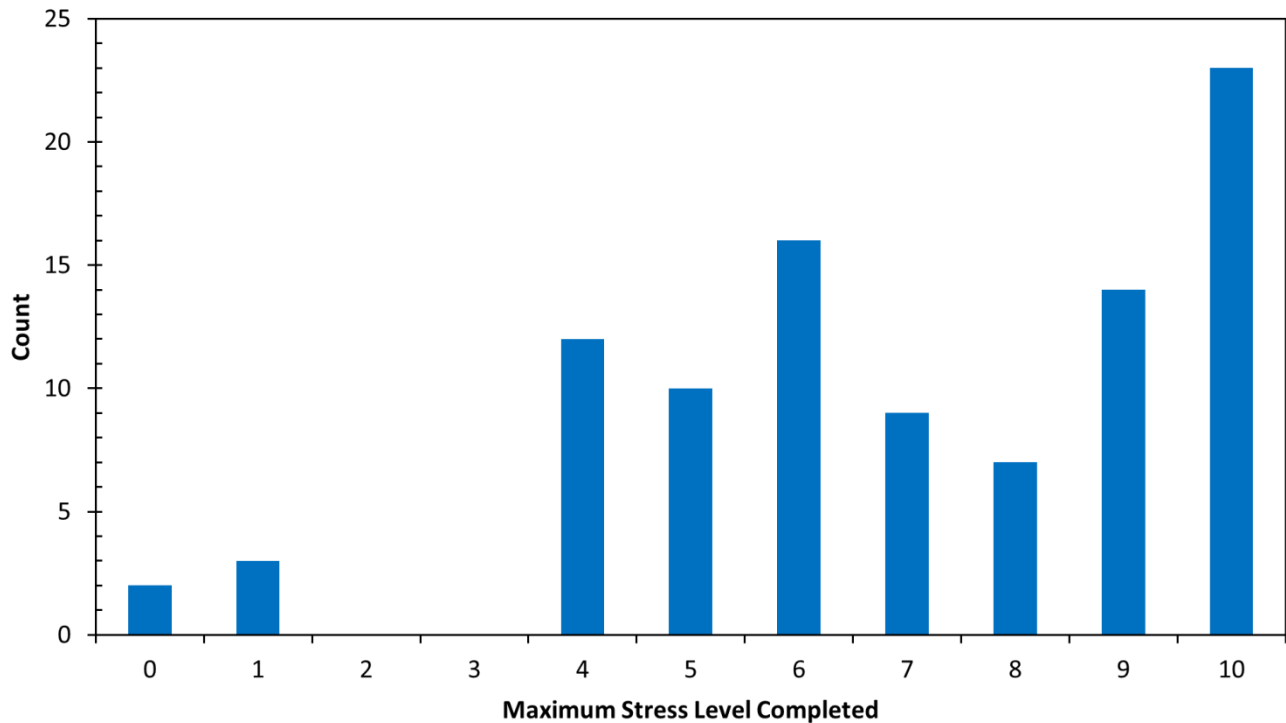


Figure 9. Histogram of the maximum stress level completed for the Series 20 LED products.

In this context, averaging the mean time to failure can be misleading. Instead, Figure 9 provides a histogram of the maximum stress level completed for each test sample. With the exception of the two product types resulting in five early failures, all of the LED products completed stress level four or higher. In contrast, the maximum stress level completed by a halogen lamp was level three.

Approximately one-quarter of the LED lamp samples did not fail during the entire testing regimen, and nearly half of the LED samples completed stress level eight or higher. The distribution of maximum stress level completed was not statistically normal.

Failure Modes

Only 10 of 96 LED lamp samples were deemed to have failed due to lumen depreciation or color shift—the two characterized measures of parametric failure. Likewise, only 2 of 15 halogen lamp samples experienced parametric failure—the CMH and CFL benchmarks could not be evaluated for parametric failure. Further analysis shows that of the ten LED parametric failures, six were due to lumen depreciation alone, one was due to color shift alone, and three were due to simultaneous lumen depreciation and color shift. In some cases, color deviation from the pre-test condition returned (after failure) to within the $\Delta u'v'$ tolerance of 0.007; these products were considered to have failed after the first instance of exceeding the $\Delta u'v'$ tolerance. Of the remaining 86 samples, 63 exhibited catastrophic failure. The other 23 samples did not fail.

Figures 10 and 11 document the lumen and color maintenance for each lamp sample throughout the investigation. Once catastrophic failure occurred, no data could be collected, but data was recorded for the levels after which parametric failure occurred. As is evident, parametric failure tended to be sudden rather than gradual. That is, the changes did not occur slowly and continuously over the course of the stress levels.

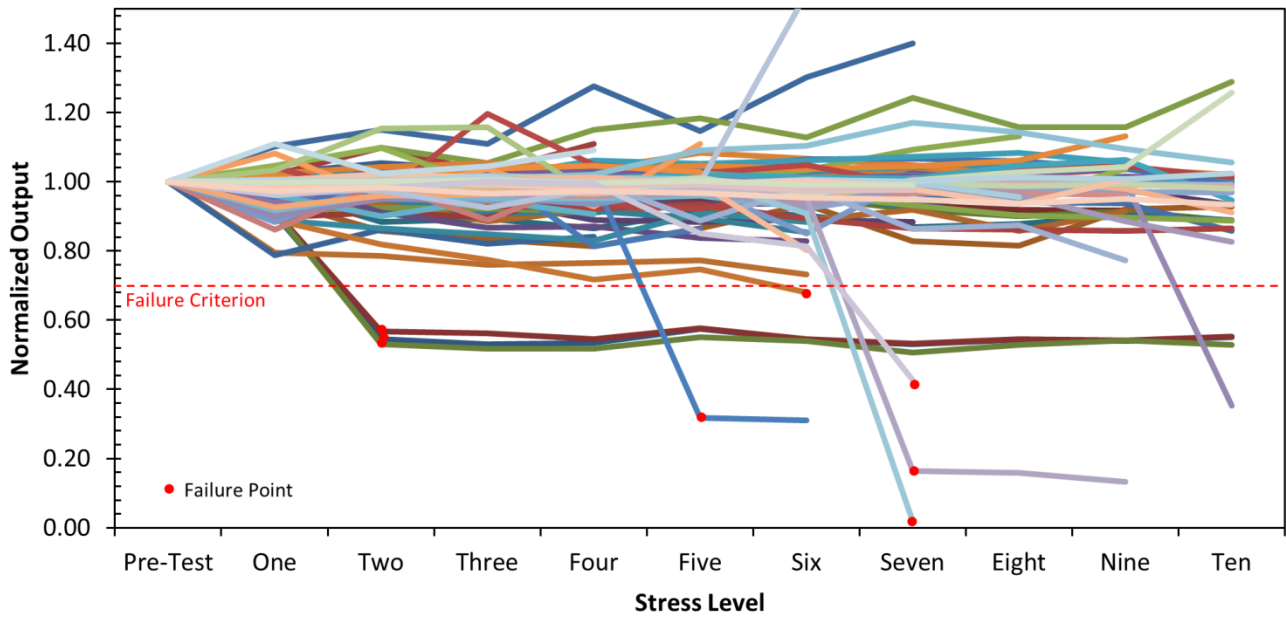


Figure 10. Relative light output for each LED lamp sample throughout the stress plan. Data collection was discontinued after catastrophic failure. Data collection was continued after parametric failure (demarcated by a red dot). Only a small percentage of lamps failed parametrically.

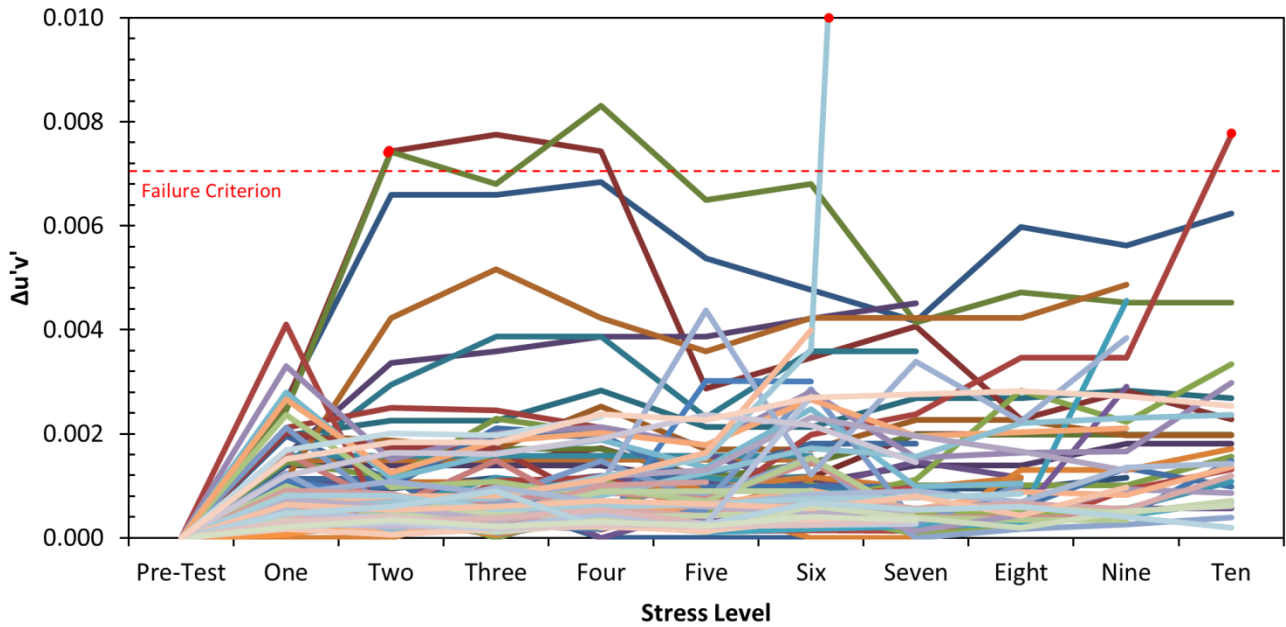


Figure 11. $\Delta u'v'$ for each LED lamp sample throughout the stress plan. Data collection was discontinued after catastrophic failure. Data collection was continued after parametric failure (demarcated by a red dot). Only a small percentage of lamps failed parametrically.

A vast majority of the lamps remained within $\pm 15\%$ of their initial lumen output and had a $\Delta u'v'$ of less than 0.003 throughout the duration of the investigation. Notably, Figure 12 shows that this deviation, while relatively small, was much greater than the level of deviation in power draw. While the measurement uncertainty was likely higher for light output, it is also plausible that some deviation in light output resulted from optical changes or changes to phosphors—as opposed to being entirely the result of changes to the driver or LED (electrical components). Figure 12 further illustrates that some of the lamp samples that exhibited lumen depreciation failure did so as power draw decreased (i.e., electrical component failure), whereas others exhibited lumen depreciation failure without a simultaneous change in power draw (i.e., optical component failure). Those products characterized by optical system parametric failure typically continued to operate for one or more levels following the failure designation, whereas those samples characterized by electrical component failure typically experienced catastrophic failure during the next stress level.

Figures 13–15 document the measured power, current, and power factor of the LED lamps over the course of stress testing. Data is not reported after either a parametric (lumen depreciation or color shift) or a catastrophic failure. For all three metrics, performance was generally within $\pm 5\%$ of the normalized pre-test measurement. A notable outlier is one sample for which the measured power factor was about 10% higher for the second through ninth stress level. This may have resulted from measurement error in the pre-test state.

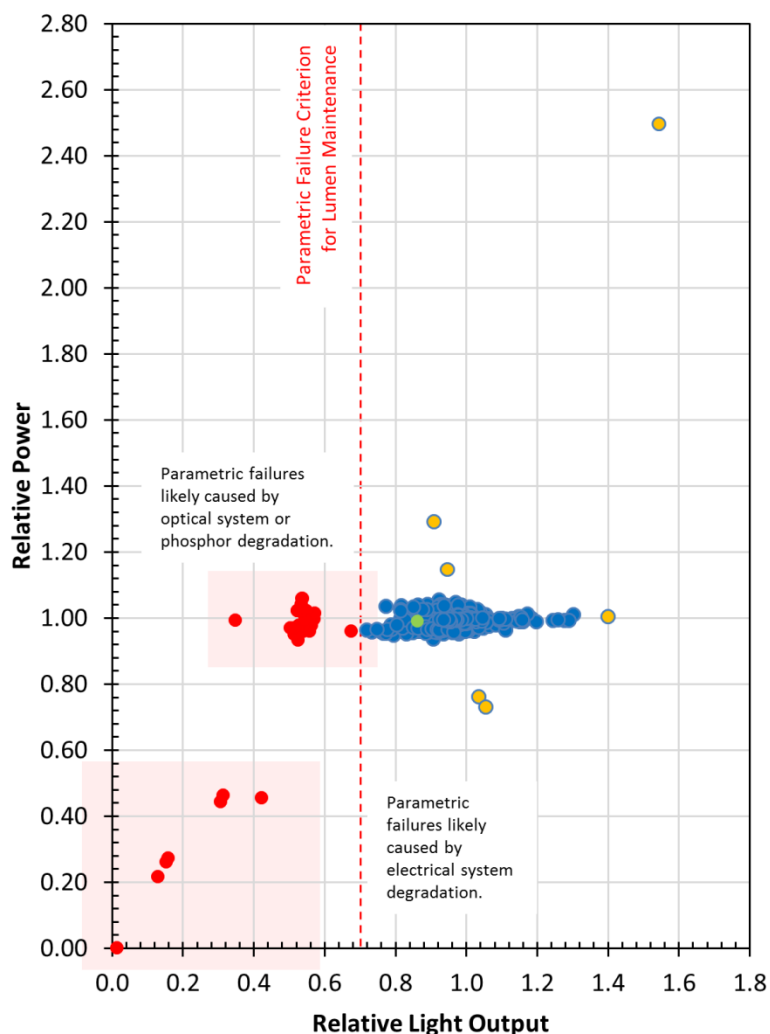


Figure 12. Relative power versus relative light output (all measurements over all stress levels) for the LED products. The variation in light output was much higher than the variation in power draw. The red points denote parametric failures, with some occurring because of optical system degradation (identifiable when only light output decline occurs) and some occurring due to electrical system degradation (identifiable by a combination of power and light output decline). A number of outlier points, colored orange, were measurements from the last completed stress test before catastrophic failure.

- Lumen depreciation failure (may also include color shift)
- Color shift failure
- Operating lamps
- Operating lamps; Catastrophic failure at subsequent step

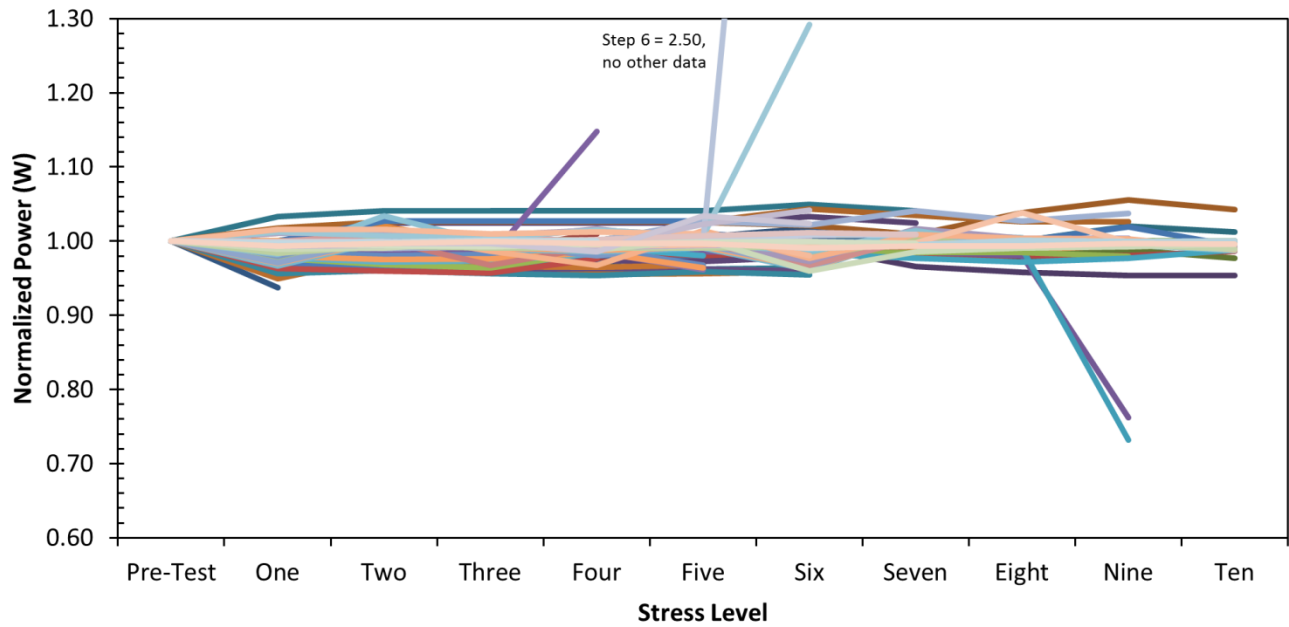


Figure 13. Normalized power measurements for each LED lamp sample after each completed stress level. The variation is small, except for five measurements indicating substantial change immediately prior to the step during which failure occurred.

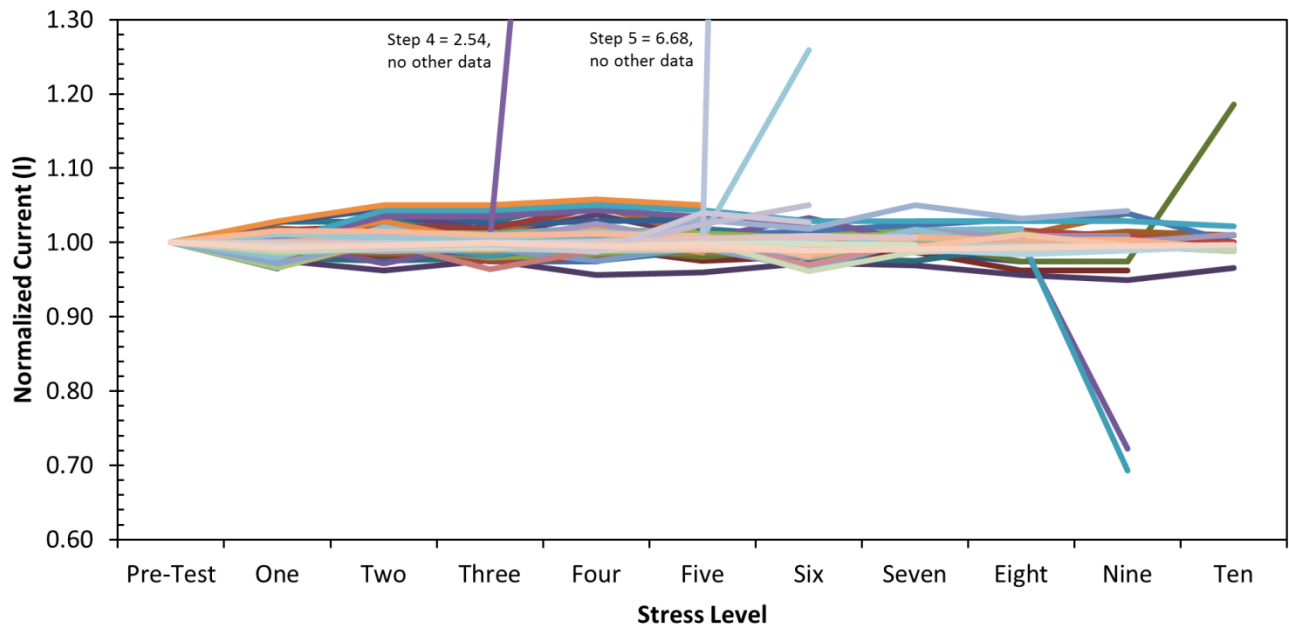


Figure 14. Normalized current measurements for each LED lamp sample after each completed stress level. The variation is small, except for six measurements indicating substantial change immediately prior to the step during which failure occurred.

The halogen benchmarks demonstrated an increase in power of as much as 15% prior to catastrophic failure. Notably, if that threshold had been used as a power-draw failure criterion, three LED lamp samples would have been deemed to fail one stress level earlier than was otherwise recorded.

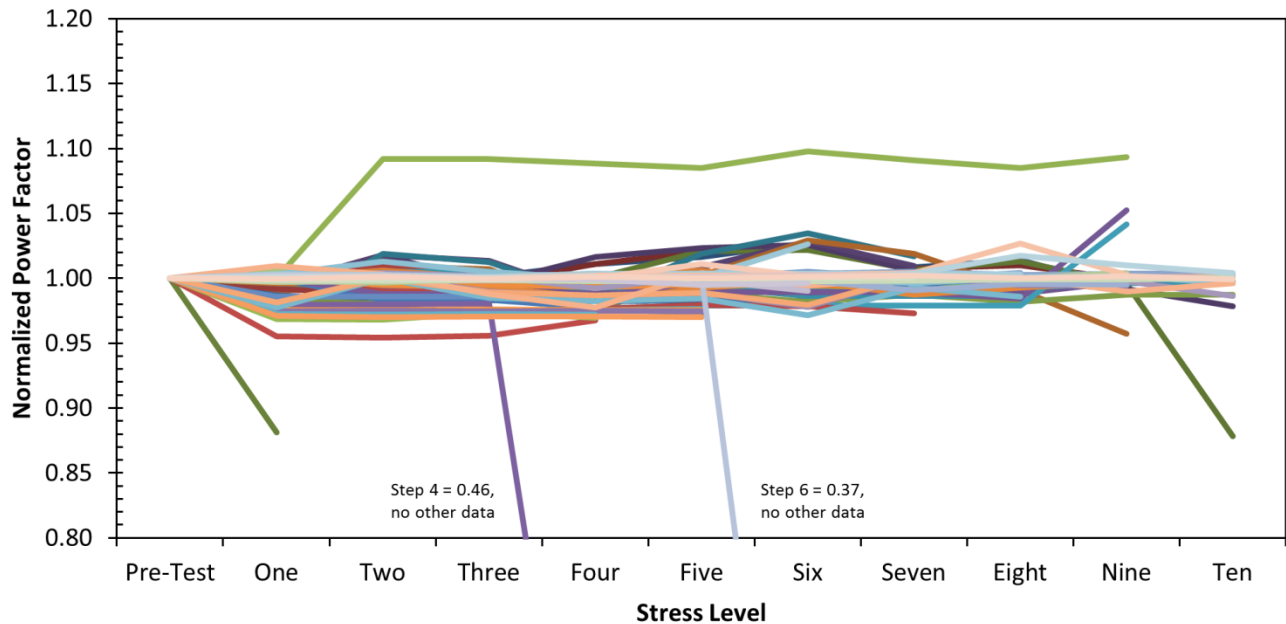


Figure 15. Normalized power factor measurements for each LED lamp sample after each completed stress level. The variation is small, except for a small number of measurements indicating substantial change immediately prior to the step during which failure occurred. One product exhibited a 10% increase in power factor after the second stress level, then remained approximately stable until catastrophic failure during the tenth stress level.

In general, figures 13–15 demonstrate substantial, rapid changes in the electrical properties of the lamps for the step immediately prior to recorded failure. In some cases, changes in one characteristic, such as current, were not commensurate with changes in another characteristic, such as power. This may indicate that the rapidly changing measurements simply identify a lamp sample that was in the process of failing. Of particular note is a change in power factor, which may be attributable to degradation of one or more capacitors. No lamp samples demonstrated a significant deviation of an electrical property followed by a recovery to the (near) nominal value; this indicates good reliability for the measurement system.

Design Maturity

FMVT testing typically allows for the evaluation of design maturity, which quantifies the spread or distribution of individual failure modes in a product by calculating the ratio between the time to first failure and the average time between failures. Given the small sample size for each lamp type in this investigation, calculating design maturity could be misleading. Instead, Figure 16 simply indicates the variation in maximum completed stress level for the three test samples of each product type. Thirteen of the LED lamp products had a variation of zero, the result of all three samples failing after the same stress step—potentially indicating higher predictability and reliability. Greater variations potentially indicate a weak failure mode or multiple failure modes.¹⁴

Twenty of the 32 LED products tested had a variation in maximum completed stress level of one step or less. Nine of the remaining 12 products had a variation greater than four levels, the maximum difference observed for the benchmark lamps. As with other performance attributes, there is substantial variation in the design maturity of LED lamps, with some showing excellent design maturity and others not showing it.

¹⁴ For more information, see the L Prize report *Stress Testing of the Philips 60W Replacement Lamp Entry*, which is available at: http://www.lightingprize.org/pdfs/lprize_60w-stress-testing.pdf

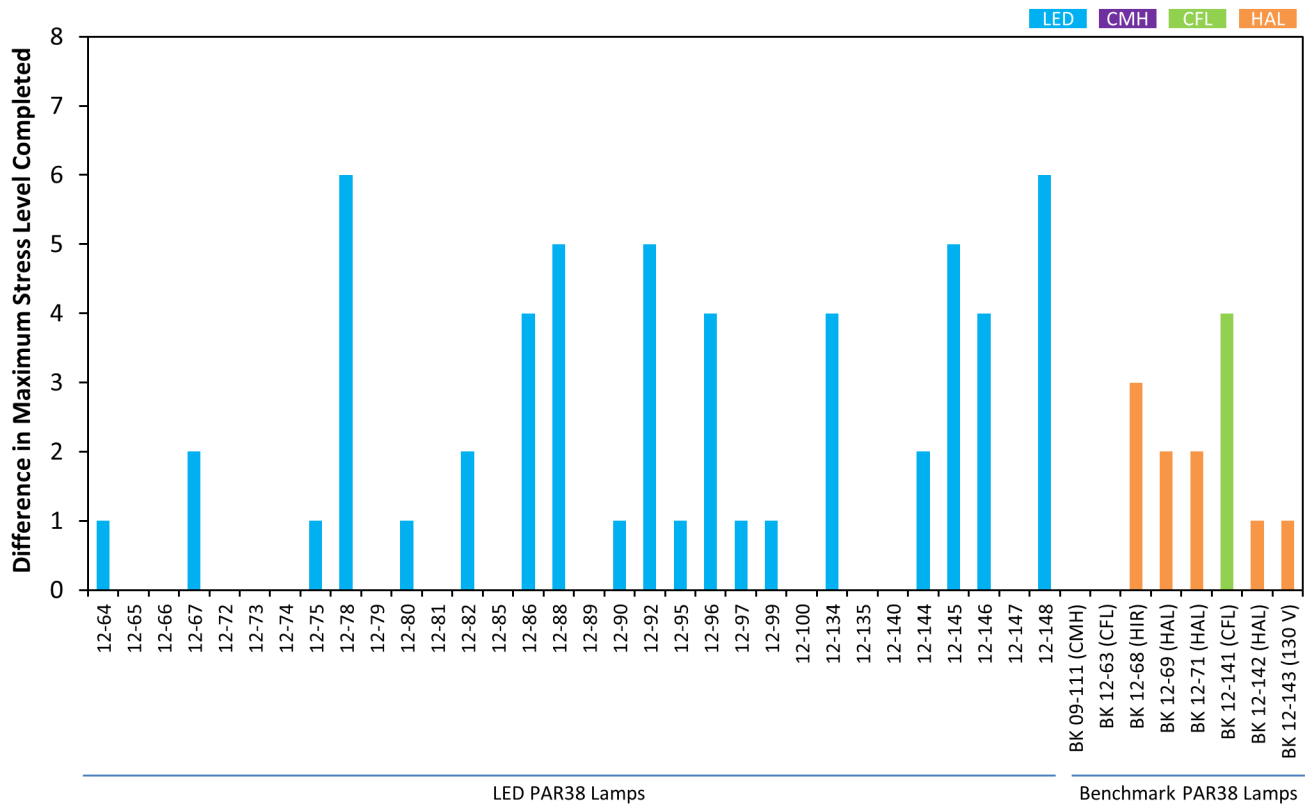


Figure 16. Difference in the maximum stress level completed without failure for the three samples of each lamp type. For products with a value of zero, all three samples failed after the same stress step, or completed the maximum stress level without failing.

5 Conclusions

The CALiPER stress-testing protocol evaluates a lamp's robustness but does not explicitly predict expected lifetime or reliability. Stress testing can facilitate comparisons to other lamps undergoing the same testing, and can also potentially identify and characterize weaknesses in a lamp's design. Notably, most of the stress conditions are unlikely to occur during normal operation.

Aside from testing of the L Prize lamp, this is the first set of stress-test data produced by CALiPER. Although the products tested are now nearly two years old, the results are still likely to be indicative of current performance trends. The LED lamps were generally more robust than the conventional benchmark lamps, with a couple of exceptions. However, as with other performance attributes, there was great variability in the robustness and design maturity of the LED lamps. More than 25% of the lamps exhibited greater difference in the first and last failure than the conventional benchmarks, indicating room for improvement; this could be seen as a positive, though, given the relative age of LED lamp technology compared to incandescent lamp technology.

At this point, it would be incorrect to assume that the robustness of LED lamps is improving; in fact, the opposite is equally likely. While lamp designs are continually refined, there is continual market pressure to reduce cost, which can lead to designs that are less robust. An important consideration is the level of robustness that is needed in a given application; for some applications, lower-cost, less-robust designs may be acceptable or even preferred. Further, design maturity may be particularly important for some users. For mature product designs, all samples of a given lamp ideally fail (nearly) simultaneously, indicating a single, consistent failure mode. For users, the behavior facilitates predictable replacement times and potentially lower maintenance costs. Such designs also facilitate the ability to engineer the lamp to have more or less robustness, depending on the needs of the application.

Although LED lamp manufacturers may conduct similar stress testing, the data from that testing are seldom, if ever, made public. Thus, identifying robust lamps with consistent failure mechanisms may be difficult for specifiers and consumers. While for some users the manufacturer warranty may be a suitable proxy for data demonstrating robustness (or perhaps even projected lifetime and reliability), other factors besides product performance typically play a role in determining product warranty durations

Appendix A: Lamp Identification

Table A1. Identifying information for the lamps included in the CALiPER PAR38 stress-testing investigation.

ID	Brand	Model
12-64	TCP	LED17E26P3830KNFL
12-65	Lighting Science Group Definity	DFN 38 W27 V2 NFL 120
12-66	Eiko	LEDP-11WPAR38/SP/830-DIM
12-67	Cree LED Lighting	LRP38-10L-30K-12D
12-72	Sylvania	LED21PAR38/DIM/P/930/FL30 (78745)
12-73	Feit Electric	PAR38/HP/LED
12-74	Satco Products, ColourOne	S8853
12-75	GE Lighting	LED17P38S830/17 (64035)
12-78	Toshiba E-CORE	19P38/835SP8 (LDRB2035NE6USD)
12-79	Westinghouse	18PAR38/LED/DIM/30 (03434)
12-80	MaxLite MaxLED	SKR3817SPDLED30
12-81	Halco Lighting ProLED	PAR38/16WW/NFL/LED (80034)
12-82	Litetronics	LP15566FL4D (64350)
12-85	LEDnovation	LED-PAR38-90-1WD-1WF
12-86	Solais Lighting	LR38/10/30K/18W/1025/GY
12-88	Lumena	MS-PAR38-120V60-27
12-89	NuVue	NV-PAR38I20W26C (NV/PAR38/9.2 WW NFL 26 CR)
12-90	Acculamp	ALSP38 900L R9
12-92	Samsung	SI-P8V181DBOUS (SLA0-PAR38-75-AYD-830-25R)
12-95	MSI Solid State Lighting	IPAR3830101D
12-96	Array Lighting	AE26PAR38183010
12-97	Havells	16W/LED/PAR38/FL (48541)
12-99	LEDirect NaturaLED	LED17PAR38/DIM/NFL/30K
12-100	aleddra	PAR38-S-D-45-30
12-134	Duracell	DL-P38F-60-30K-WH
12-135	Axiom	AP10W27V120
12-140	Philips	BC19.5PAR38/AMB/3000K/ FL25 DIM 120V
12-144	Solais Lighting	LRP38/25/30
12-145	Seesmart	15W Warm White 45° LED PAR 38 (180025)
12-146	Zenaro	SL-PAR38C/H/P16/50/E30/TD/26/LAC
12-147	Lights of America	2213DLEDNP38 - LF3-8
12-148	LEDWaves	LW10-NYC-008-WW-DM
BK09-111	Philips	CDM-i 25W/PAR38/FL/3K
BK12-63	Philips	EL/A PAR38 23W 2PC (9292689721102)
BK12-68	GE	60PAR/HIR/FL30 (18626)
BK12-69	Sylvania	75PAR/CAP/SPL/WSP12 120V
BK12-71	Philips	75PAR38/HAL/SP10
BK12-141	Feit Electric	ESL23PAR/ECO
BK12-142	Eiko	75PAR38/H/WFL-120V (49547)
BK12-143	OSRAM SYLVANIA	75PAR/CAP/SPL/SP9 130V (14516)

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