CFL Laboratory Testing Report

Results from a CFL Switching Cycle and Photometric Laboratory Study

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LIST OF ABBREVIATIONS

C	Celsius
CCT	Correlated Color Temperature
CFL	Compact Fluorescent Lamp
CPUC	California Public Utilities Commission
CRI	Color Rendering Index
IEC	International Electrotechnical Commission
IES	Illuminating Engineering Society
IOU	Investor-Owned Utility
ITL	Independent Testing Laboratory
K	Kelvin
LED	Light Emitting Diode
LM	Lighting Measurement
lm	Lumens
LRC	Lighting Research Center
pf	Power Factor
SCE	Southern California Edison
ULP	Upstream Lighting Program
V	Volts
W	Watts

1 Introduction

The life of compact fluorescent lamps (CFLs) is reduced by frequent switching, but available quantitative data on this relationship is limited. This lack of data adds uncertainty to estimates of in situ CFL lifetime and, thus, energy savings and payback. Recent field studies have shown that average on-time in residential CFL applications is approximately one half hour, which is far less than the three-hour on-time used in establishing CFL rated life (KEMA, Inc., 2005) (KEMA, Inc., 2010).

To develop quantitative data on the relationship between switching cycles and CFL life, the Energy Division of the California Public Utilities Commission (CPUC) and Southern California Edison (SCE) initiated a multi-year laboratory study in September 2010. A sample of 3,601 medium-base CFLs, consisting of 72 models (approximately 50 lamps per model) selected to represent the types of CFLs available in the market, was procured from various retail outlets in California. This sample was then separated into 10 groups of approximately 360 CFLs – each group containing five lamps of each of the 72 CFL models[1]. Each group was then subjected to a unique, automated switching frequency, which ranged from on-periods of 2 minutes to 720 minutes (12 hours) and a 5-minute off-period – a total of 10 different switching cycles. For each of the 10 switching cycles, the hours of operation until each lamp failed was recorded and this duration was used to develop a plot of the number of surviving lamps over time. The test was originally designed to operate for 2 years but was extended several times, eventually running until May 2014 (3.5 years). This test is referred to as the "switching cycle experiment" throughout this document.

An additional, related study also looked at the electrical and photometric characteristics of the sampled CFLs. One-third of the lamps included in the switching cycle experiment, or approximately 1,200 CFLs, were marked for periodic testing that included measurements of lumen output, power, color temperature, color rendering index, and power factor. Initial electrical and photometric tests of all marked lamps were conducted after a 100-hour seasoning period. This experiment generated data that allows initial lumen output and efficacy to be compared to the CFLs' rated lumen output and efficacy. While some of these marked lamps failed during cycle testing before subsequent electrical and photometric testing could be conducted, others survived and were retested at multiple points of their lives. Lamps that were retested provided information on lumen depreciation, i.e., the degree to which light output for a CFL degraded as a function of operation. This test is referred to as the "photometric experiment" throughout this document.

The switching cycle and photometric experiments were based on standard Illuminating Engineering Society (IES) testing protocols. The results presented in this report are for the test data collected between September 2010 (initiation of experiments) and May 2014 (completion of testing).

1.1 Definitions

Because terms such as "switching" and "cycle" are used in very specific ways in this report, it is useful to define these and related terms for clarity. The following terms are used in the discussion of the switching cycle experiment:

- On-Period (or on-time) – The length of time a lamp is operated (i.e., the time between switching a lamp on and switching it off).

[1] In some rare cases, groups had four or six lamps of the same model rather than five.

- Off-Period (or off-time) – The length of time between lamp operations (i.e., the time between on-periods).
- Run-Time – The total amount of time a lamp has been operated for (i.e., the sum of all the lamp's on-periods).
- Lamp Failure – The point where a lamp stops operating.[2]
- Failure Time – The run-time of a lamp at the point of lamp failure.
- Rated Life – The expected lamp life as specified by the manufacturer. Generally rated life is estimated assuming on-periods of 180 minutes.
- Normalized Lamp Life – The ratio of the median failure time for a group of lamps to the average rated life of that group of lamps, for a given switching frequency.
- Cycle – One on-period followed by one off-period.
- Cycling – The process of repeatedly turning a lamp on and off.
- Switching Cycle – A protocol in which lamps are repeatedly turned on for a defined period of time and then turned off for a defined period of time. For example, one of the switching cycles described in this report turned lamps on for 180 minutes and then off for 5 minutes repeatedly.[3]
- Switching Frequency – The specific on-times and off-times that are utilized by a switching cycle.
- Switching Cycle Experiment – An experiment in which multiple switching cycles are utilized in order to evaluate the effect of switching frequencies on sample survival.
- Mortality Curve – A plot in which the number of surviving lamps on a switching cycle experiment is plotted against the switching cycle's run-time (or other time-based variable). Also sometimes known as a "Survivorship Curve."

The following terms are used in the discussion of the photometric experiment:

- Luminous Flux – The total amount of visible light generated by a light source, measured in lumens. Also known as light output or lumen output.
- Light Output – see luminous flux.
- Lumen Output – see luminous flux.
- Initial Light Output – The luminous flux of a source after a 100-hour seasoning period.
- Lumen Maintenance – The luminous flux of a lamp at a given time expressed as a percentage of that lamp's initial light output. For example, if a CFL with an initial light output of 1,000 lumens generates only 700 lumens after 4,000 hours of operation, it will have lumen maintenance of 70% at 4,000 hours.

[2] This definition of lamp failure does not include excessive lumen depreciation (e.g. if a CFL is still providing any measurable light, it was not considered to have failed). Those wishing to look at lamp failure rates using a broader definition that includes excessive lumen depreciation may consider combining the lamp failure results determined in the switching cycle study with the lumen depreciation results determined in the photometric experiment.

[3] This study involved 10 different switching cycles with 10 different on-periods and each of these cycles utilized a 5-minute off-period. Thus, for brevity in this report, we at times refer to switching cycles by only referencing their on-periods (e.g. "the 180-min switching cycle" rather than "the 180-min on-period / 5-min off-period switching cycle").

- Lumen Depreciation – The decrease in the luminous flux of a lamp at a given time expressed as a percentage of that lamp's initial light output. For example, a CFL with a lumen maintenance value of 70% will have experienced a lumen depreciation of 30%.
- Luminous Efficacy – The luminous flux of a source divided by the source's power, measured in lumens per watt.

1.2 Background

The IES recommends determining the rated life of a CFL lamp by cycling a sample of lamps for on-periods of 180 minutes and off-periods of 20 minutes and recording the runtime required for 50% of the sample to fail. This procedure is specified by the IES's test procedure LM-65-10 and is referenced by ENERGY STAR in its CFL Specification (Illuminating Engineering Society, 2010) (Environmental Protection Agency, 2009).[4] LM-65-10 does not specify any other cycling protocols, nor does it specify how to adjust rated life when lamps are operated at frequencies other than 180 minutes on, 20 minutes off.

It has long been known that frequent cycling can shorten the life of fluorescent lamps by increasing the rate of degradation of the emissive materials on the lamps' electrodes (Vorlander & Raddin, 1950) (Illuminating Engineering Society, 2011). Fluorescent lamps will quickly fail (i.e., burn out) when the electrode emissive materials are exhausted and these materials are consumed considerably more quickly during lamp ignition than during normal operation. It is also possible, though less documented, that other fluorescent lamp or ballast materials could fail more quickly when cycling increases due to increased electrical and/or thermal shocking.

In the late 1990s, the Lighting Research Center (LRC) conducted testing to quantify the effect of cycling on CFLs (Ji, Davis, & Chen, 1998) (O'Rourke & Figueiro, 2000). These studies established the survival of 440 CFLs (40 lamps each from 11 different models) operated at six unique switching frequencies (see Table 1).

Table 1: Summary of Testing Variables from LRC's Switching Cycle Experiment

Switching frequency	Number of models	Lamps per model	Lamps per cycle
5 minutes on; 20 seconds off	11	8	88
5 minutes on; 5 minutes off	11	8	88
15 minutes on; 5 minutes off	11	8	88
60 minutes on; 5 minutes off	11	8	88
180 minutes on; 5 minutes off	11	4	44
180 minutes on; 20 minutes off	11	4	44

The results of LRC's experiment did show a significant drop in lamp life as cycling increased, particularly for the very rapidly switched cycles. Figure 1 shows a summary of the results from the LRC experiment by plotting the normalized lamp life of the eight models tested against the on-period switching frequency (Ji, Davis, & Chen, 1998). The limited sample size and the now 15-year-old CFL models

[4] At the time of sample procurement and initial testing, the ENERGY STAR Program Requirements and Criteria for CFLs – Version 4.2 was the governing ENERGY STAR specification for CFLs. Unless specified otherwise, when we refer to ENERGY STAR specifications, requirements, or criteria in this document, we are referring to those specified in this document.

evaluated may limit the applicability of LRC's test results. However, the methodology used by LRC has been useful in informing the experimental design for this study.

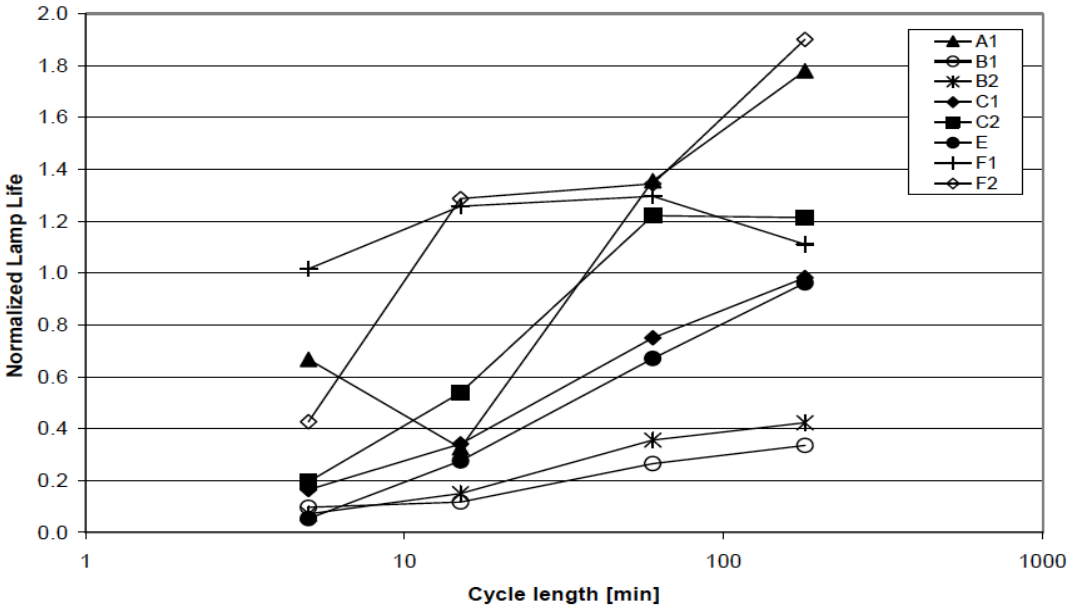


Figure 1: Summary of Results from LRC's Switching Cycle Experiment

KEMA conducted a residential metering study of CFLs in 2003-04 which collected data on, among other things, the switching frequency of CFLs (KEMA, Inc., 2005). A subsequent study analyzed the KEMA results to determine how often each switching frequency occurred, as shown in Figure 2 (Jump, Hirsch, Peters, & Moran, 2008). This study further compared the results from the LRC study to the results of the KEMA study in order to provide an average normalized lamp life estimate for CFLs in residential applications. This was accomplished by comparing the expected CFL lamp life at a given switching frequency (from LRC) to information on the distribution of switching frequencies that occur in residential applications (from KEMA). The result from this analysis was that the average normalized lamp life was 0.526. In other words, when a typical CFL with a rated life of 10,000 hours is placed in a typical residential application, it can be expected to have an "observed" life of 5,260 hours.

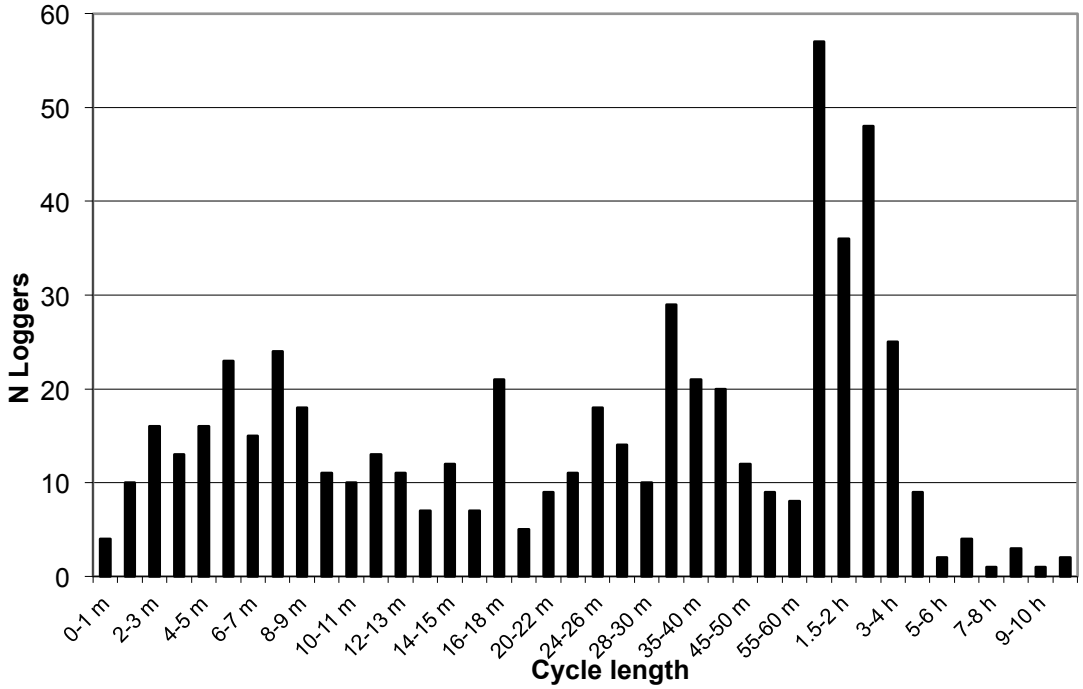


Figure 2: Distribution of Average CFL On-Times from Metered Study

1.3 Objectives

The first objective of this study was to characterize the relationship between CFL life and parameters inherent to the CFL itself as well as parameters related to its application. Parameters inherent to the CFL itself include:

- Lamp type
- Make and model
- Rated life

Parameters related to the application of the CFL include:

- Hours of operation
- Number of cycles experienced
- Lamp orientation (i.e., whether lamps were operated in a base-up or base-down orientation)

By establishing these relationships, more accurate estimates of real-world CFL life can be made by applying these relationships to typical CFL deployment and usage patterns found in practice.

A second objective of this study was to characterize the electrical and photometric performance of CFLs at various points of their lives. This characterization provides information allowing the rated efficacy of CFLs to be compared to their measured efficacy. It also provides information on the degree to which efficacy and/or light output may degrade as a function of operational and/or CFL-inherent characteristics. These results also provide information that could be useful in adjusting estimates of CFL life, as excessive lumen depreciation could be considered a failure mode.

2 Experimental Design and Setup

This section describes the experimental design and setup of the switching cycle and photometric experiments. These experiments were conducted in Loveland, Colorado, by Independent Testing Laboratories (ITL) – a laboratory that has a 50-year history of conducting independent, third-party photometric testing and is accredited by the National Voluntary Laboratory Accreditation Program (NVLAP).

2.1 Switching Cycle Experiment

As previously discussed, CFL life is typically defined as the time required for a sample of lamps to reach 50% sample failure when operated at a switching frequency with an on-period of 180 minutes and an off-period of 20 minutes. As such, CFL life testing generally cycles a large sample of CFLs at this frequency until at least 50% sample failure is reached to create a "mortality curve" that plots the number of surviving lamps versus the sample's cumulative on-time.

This general method of developing mortality curves was adopted for this study with notable exceptions. The primary variation was that switching frequencies with 10 unique on-periods were utilized rather than just on-periods of 180 minutes. This change was intended to address the primary objective of the switching cycle experiment: determining how variations in the number of cycles CFLs are exposed to affect their operational lives. This approach allowed us to develop mortality curves for each of the switching frequencies used.

2.1.1 Switching Frequency

Switching frequencies were selected at intervals that ranged from very rapid cycling (2-minute on-period, 5-minute off-period) to cycles with very long on-periods (720-minute on-period, 5-minute off-period). Table 2 shows the switching frequencies for each switching cycle used in this study. Nine of the 10 switching cycles operated such that lamps were repeatedly operated with an on-period followed by a cooldown off-period of 5 minutes.[5] This protocol was continued until the lamps failed or the duration of the switching cycle was completed. The 10th cycle was designed with a variable on-period and is discussed in section 2.1.2.

[5] Five minutes was selected as an off-period rather than the traditional cooldown period of 20 minutes. This decision was made after weighing the added value of allowing the lamps additional time to cool after each operation against the increased duration of the test with longer cooling time. A review of LRC test results (which indicated no significant differences between results with 5- and 20-minute cooldown periods) as well as interviews with industry sources indicated that CFLs could technically be considered to have cooled after 5 minutes and that CFL manufacturers often use significantly shorter cooldown periods (e.g., 1 minute or less) when testing internally. Ultimately it was determined that utilizing 5-minute off-periods is adequate and would allow the test cycles to run well beyond 50% sample failure, which was an objective of the experiment design.

Table 2: Switching Cycles Used in the Switching Cycle Experiment

Switching Cycle	On-period (minutes)	Off-period (minutes)
1	2	5
2	5	5
3	15	5
4	30	5
5	30*	5
6	45	5
7	60	5
8	90	5
9	180	5
10	720	5

*Variable on-period, averaging 30 minutes. Discussed further in Section 2.1.2.

Because metering studies have reported that CFLs in residential applications have average on-periods of approximately 30 minutes, five of the 10 switching cycles were chosen to have on-periods between 15 and 60 minutes to characterize the effect of switching on CFLs at these switching frequencies (KEMA, Inc., 2005) (KEMA, Inc., 2010). Switching frequencies of 180 minutes and 720 minutes were selected to allow for comparisons to CFL rated life values (which are based on 180-minute on-periods) and to provide insights that might be more relevant to commercial applications where on-periods are typically longer than those in residential applications.

The duration allotted for each switching cycle to operate varied, as the switching cycles with more rapid cycling were expected to need less time to experience 50% sample failures than the cycles with longer operating periods. The test was originally designed with durations that would be likely to reach 75% sample failure from all cycles. Subsequent testing extensions allowed for sample failures to exceed 90% on all switching cycles except the 720-minutes sample, which had a sample failure of approximately 80% at the end of testing.

2.1.2 Variable Switching Cycle

One of the switching cycles was designed to operate such that its on-periods varied from operation to operation while the off-periods remained fixed at 5 minutes. This specific switching cycle was designed to mimic the variability of operation (i.e., a mix of short, medium, and long on-periods) that has been documented by prior residential metering studies of CFL usage and shown in Figure 2. While on-periods varied from under 10 seconds to over 120 minutes, the weighted average of the on-time (i.e., the length of time of each on-period weighted by the frequency in which it occurs) was 30 minutes. This allowed us to directly compare this variable switching cycle to the fixed 30-minute switching cycle in order to determine what, if any, effects these variations between operating periods may have on CFL life. Table 3 shows the 14 on-time durations that were used by the 30-minute variable cycle and how frequently each of these cycles occurred.

Table 3: Duration and Frequency of On-Times of 30-minutes Variable Cycle

On-time duration (minutes)	Frequency of operation	Total on-time at each on-time duration (minutes)
0.11	1.2%	<0.01
0.53	4.4%	0.02
1.60	4.6%	0.07
3.21	8.7%	0.28
5.35	7.5%	0.40
8.02	9.0%	0.73
11.23	4.1%	0.46
16.05	11.8%	1.89
22.47	10.4%	2.34
32.10	12.3%	3.94
44.94	7.8%	3.53
57.78	4.9%	2.86
96.30	10.6%	10.19
128.39	2.6%	3.29
Total	**100%**	**30.00**

2.1.3 Apparatus for Switching Cycle Experiment

An apparatus constructed for conducting the switching cycle experiment consisted of seven switching racks, each containing approximately 376 test cubicles capable of testing a lamp at a specific switching frequency.[6] Photographs of the apparatus and its associated test cubicles are shown in Figure 3 through Figure 5.

The majority of testing cubicles were 12" x 12" x 12" cavities that included a medium screw-base socket (which received an operating voltage at the specified switching frequency), a light sensor directed at the test lamp, and a baffle to limit ambient light from the surrounding environment from reaching the light sensor. The light sensors in the testing cubicles were used to flag potential failures (see section 2.1.4.5) but were not used for any other purpose, such as recording lumen output or lumen maintenance. Each testing cubicle had five partially covered sides painted flat black and one side that was open to the environment. Half of these cubicles had sockets mounted on the bottom surface (for base-down operation) and half had sockets mounted on the top surface (for base-up operation). Fifty-two test cubicles were dedicated for reflector lamp testing and varied slightly from the others. These test cubicles had twice the height of the standard cubicle to accommodate the incandescent downlight housings and all were dedicated for base-up operation. The apparatus utilized a custom-designed control and data acquisition system that automated the switching frequencies of each switching cycle and recorded the time each lamp registered a failure. When the data acquisition registered lamp

[6] Seven racks were built for the switching cycle experiment rather than 10 (the number of switching cycles in the experiment) because three of the racks were used for two switching cycles each (i.e., two of the shorter cycles could be tested consecutively on a single rack).

failures, which occurred when light sensors detected sudden and significant drops in light output, technicians would physically inspect the lamps to verify the failure.



Figure 3: Photograph of Multiple Testing Racks for Switching Cycle Experiment



Figure 4: Photograph of Base-Down Testing Cubicles in Testing Apparatus

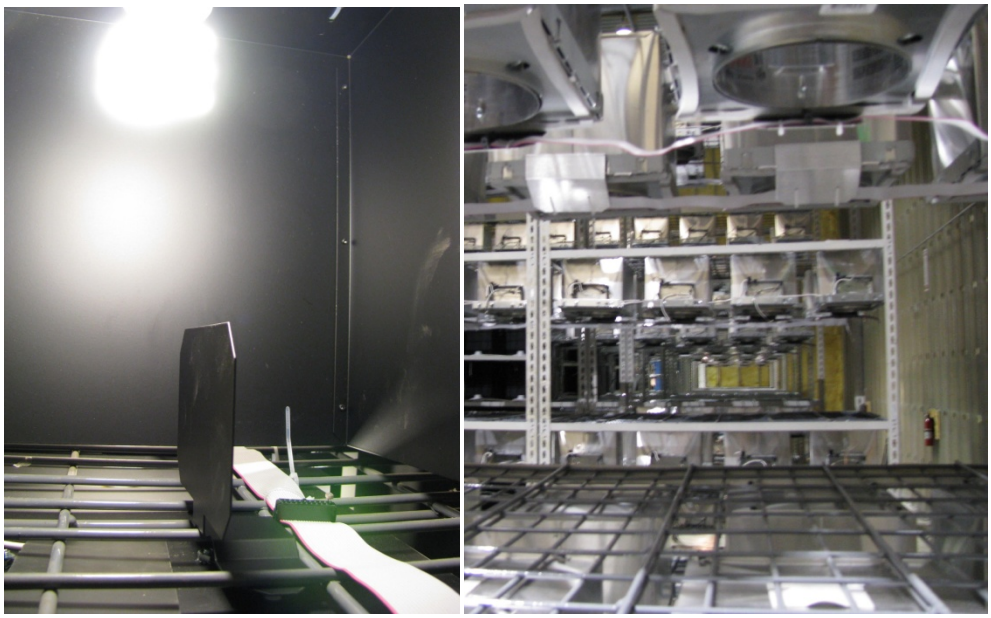


Figure 5: Photographs of Testing Cubicles

Standard Testing Cubicle Showing Test Lamp, Baffle, Light Sensor, and Data Acquisition Materials (left) and a Reflector Testing Cubicle (during construction, right)

2.1.4 Operating Conditions

The operating conditions for the experiment were based on those recommended in IES LM-65-10 (Life Testing of Compact Fluorescent Lamps), except where noted otherwise in this section (Illuminating Engineering Society, 2010). Variations in operating conditions from IES LM-65-10 recommendations were generally made to explicitly study the effects these modifications (e.g., switching frequency) have on CFL life. This section briefly discusses key operating conditions.

2.1.4.1 Switching Frequency

See section 2.1.1.

2.1.4.2 Ambient Temperature

The ambient temperature of the testing facility was maintained at 25º C +/- 5º C. LM-65-10 requires testing to be between 15º C and 35º C.

2.1.4.3 Input Voltage

Input voltage was 120 V +/- 2%. This is consistent with LM-65-10.

2.1.4.4 Lamp Orientation

The majority of CFL models tested (including spiral, globe, and A-lamp shapes) was designed to operate in either base-up or base-down orientations, while a minority of models (reflector shapes) was designed primarily for base-up-only orientation. For models designed to operate in either base-up or base-down orientation, 50% of lamps on each switching cycle were operated in the base-up orientation and 50% of lamps were operated base-down. All reflector lamps were operated base-up and inside Halo® model H7UICAT incandescent downlight housings and in a manner consistent with ENERGY STAR Program Requirements and Criteria for CFLs – Version 4.2 (Environmental Protection Agency, 2009). These orientations are consistent with LM-65-10.

2.1.4.5 Recording Failures

Failure time was recorded within 15 minutes of failure. When lamps failed, a "flag" was triggered in the data acquisition system indicating a probable failure. Technicians would then verify the failure by visual observation. Once the failure was verified, the time recorded by the data acquisition system was designated as the failure time. LM-65-10 recommends recording intervals of no more than 1% of the rated life of the CFL (e.g., at least every 100 hours for a CFL with a rated life of 10,000 hours).

2.2 Photometric Experiment

This section describes the photometric experiment, associated testing apparatus, test conditions, and key outputs.

The light output of fluorescent lamps generally decreases over their lives. This effect is described by a lamp's "lumen maintenance," which is defined as the light output of a source at a given time as a percentage of its initial light output. If a lamp's light output drops enough, it may be considered to have "failed" even though it may still be producing some light (Illuminating Engineering Society, 2011).

ENERGY STAR requires that qualifying CFLs have a lumen maintenance of at least 90% after 1,000 hours and a lumen maintenance of at least 80% after 40% of the lamp's rated life (i.e., 4,000 hours for a CFL with a rated life of 10,000 hours). ENERGY STAR does not impose testing requirements beyond 40% of

rated life, in part because of the time and cost associated with longer lumen maintenance testing (Environmental Protection Agency, 2009).

A failure based on insufficient lumen maintenance generally would not be registered by the switching cycle experiment because of relatively gradual light depreciation and the fact that the lamp may still be producing some light. In order to characterize lumen maintenance failures, a photometric and electrical experiment (called "photometric experiment" throughout this report) was initiated. This experiment also characterizes several parameters unrelated to lumen maintenance (such as power quality and color measurements), as these measurements could be included in the experiment at a marginal added cost.

2.2.1 Photometric Experimental Design

One-third of the CFLs being tested in the switching cycle experiment (approximately 1,200 CFLs) were also included in the photometric experiment. These lamps were evenly distributed across the switching cycles and test models.[7] A testing protocol and schedule were established such that these lamps would be characterized after an initial seasoning period of 100 hours and then characterized again at four discrete intervals over the lamps' lives. Lamp characterization consisted of measuring the photometric and electrical characteristics summarized in Table 4.

Table 4: Metrics Included for Photometric and Electrical Lamp Characterization

Metric	Units
Luminous Flux	Lumens
Correlated Color Temperature	Kelvin
Color Rendering Index	Unitless
Input Power	Watts
Operating Voltage	Volts
Power Factor	Unitless
Total Harmonic Distortion	%

The testing intervals varied by switching cycle so that testing periods were distributed over the planned duration of each switching cycle. As such, the more rapid cycles – which have much shorter cumulative on-times over their testing duration – received testing at earlier intervals than did the longer cycles. The timing of the scheduled intervals is shown in Table 5. The 2-minute on-period switching cycle received only three photometric measurements because this cycle did not have a long enough total run-time to justify more frequent photometric characterization.

[7] The process for selecting lamps for the photometric experiment is discussed in section 2.3.

Table 5: Timing of Photometric Testing for Lamps for Each Switching Cycle

Switching Cycle (on-time, minutes)	Timing of Photometric Testing (total on-time, hours)			
	1	2	3	4
2	100	1,000	2,000	–
5	100	1,000	2,000	3,000
15	100	1,000	2,000	3,000
30 – fixed	100	1,000	2,000	4,000
30 – variable	100	1,000	2,000	4,000
45	100	1,000	2,000	4,000
60	100	2,000	4,000	6,000
90	100	4,000	6,000	–
180	100	4,000	6,000	10,000
720	100	4,000	6,000	10,000

Each time a switching cycle reached a cumulative on-period for which a photometric characterization was scheduled, the switching cycle was suspended (for approximately one week) and all surviving lamps that were marked for photometric testing were characterized.[8] Due to lamp failures, the number of lamps characterized decreased at each testing interval and only a fraction of the original 1,200 CFLs characterized were expected to survive for all four planned photometric measurements.[9]

2.2.2 Apparatus for Photometric Experiment

Photometric and electrical characterization of lamps was conducted with the use of a 1-meter integrating sphere, a spectrophotometer, and a power analyzer. These instruments were affixed to a movable testing cart that could move to the switching cycle testing cubicles of the lamps to be characterized. Lamps were then removed from their testing cubicles, characterized in the photometric testing apparatus (after a warm-up and stabilization period described in section 2.2.3.3), and then replaced in their testing cubicles.

2.2.3 Operating Conditions

The operating conditions for the experiment were based on those recommended in IES LM-66-11 (Electrical and Photometric Measurements of Single-Ended Compact Fluorescent Lamps), except where noted otherwise in this section (Illuminating Engineering Society, 2011). This section briefly discusses key operating conditions. Because variations in operating conditions can have a large impact on

[8] Aside from delaying the results for a period equal to that of the suspension, the switching cycle experiment should not be impacted by these shutdowns because the lamps already experience cooldown during the off-periods of normal testing, and the start-up conditions after the suspension are identical for the lamps as those during normal testing start-up conditions.

[9] Note that it is not possible to replace failed lamps in the photometric experiment with surviving lamps that had not been marked for inclusion in the experiment because the potential replacements would lack the necessary 100-hour baseline measurements.

photometric measurements, operating conditions were maintained within a narrower range for the photometric experiment than they were for the switching cycle experiment.

2.2.3.1 Operating Temperature

Operating temperature was 25º C +/- 1º C. This is consistent with LM-66-11.

2.2.3.2 Input Voltage

Input voltage was 120 V +/- 0.2%. LM-66-11 recommends 120 V +/- 0.1%. This tolerance was increased in order to reduce testing costs and was not expected to have a significant impact on measured results.[10]

2.2.3.3 Lamp Stabilization

Lamps were turned on for a fixed interval of 15 minutes prior to photometric measurement. This varies somewhat from LM-66-11 recommendations that describe a protocol in which lamp stabilization is established when measurements over a 5-minute period do not vary by more than 1%.

2.3 Sample Procurement

Significant consideration went into determining the quantity and composition of the CFLs to be included in the test, as well as the logistics required to acquire the lamps. The overall goal for the sample procurement was to obtain a sample that was:

- Representative of the types of CFLs that had been used in the 2006-08 Upstream Lighting Program (ULP) and/or were likely to be used in future programs (KEMA, Inc., 2010)
- Procured from retail channels that were representative of those utilized by California IOU customers
- Large enough to provide meaningful results

Initial plans called for testing approximately 2,000 CFLs. While this quantity was nearly five times larger than LRC's previous study, several parties invited by the CPUC to review the initial experimental plan raised questions about whether the sample size was sufficient. To address these concerns, the sample size was ultimately increased to 3,601 CFLs.[11]

A detailed evaluation of CFL shipments from the ULP was conducted in order to determine the types of CFLs most rebated by the IOUs. Based on this evaluation, representatives from CPUC, SCE, and KEMA developed and refined a list of eight targeted CFL types for inclusion in the test, shown in Table 6.

[10] While the allowable tolerance was 120.0V +/- 0.2%, a large majority of the actual measurements were conducted within the LM-66-11 recommended range of 120.0 +/- 0.1%.

[11] The test nominally involves 3,600 CFLs (five lamps each from 72 different models on 10 different switching cycles). In rare cases four or six lamps of a model were used on a cycle rather than five. This resulted in 3,601 total CFLs being included in the experimental sample.

Table 6: Types of CFLs Included in Sample

CFL Type	Notes
Reflector	Reflector-type CFLs
Covered	CFLs covered with lens or diffuser, including A-lamp, globe, and candle shapes
Spiral 9-15W	Standard, dimmable, and 3-way spiral CFLs with wattages between 9-15W
Spiral 16-20W	Standard, dimmable, and 3-way spiral CFLs with wattages between 16-20W
Spiral 23W A	Standard, dimmable, and 3-way spiral CFLs with wattages of 23W (makes and models used in large volumes in the 06-08 cycle ULP)
Spiral 23W B	Standard, dimmable, and 3-way spiral CFLs with wattages of 23W (makes and models NOT used in large volumes in the 06-08 cycle ULP)
Spiral 24W+	Standard, dimmable, and 3-way spiral CFLs with wattages 24W and above
Non–ENERGY STAR	CFLs without ENERGY STAR certification, including reflector, covered, and spiral CFLs

Two of the spiral categories were devoted to 23W models, as 23W spiral models played a dominant role in the 06-08 cycle ULP. The Spiral 23W A category included makes and models that were utilized in large volumes in the 06-08 cycle ULP, while those in the Spiral 23W B category were not used in large volumes in the program. The non–ENERGY STAR category was chosen to provide a comparison between IOU-discounted CFLs and nondiscounted CFLs, as all discounted lamps required ENERGY STAR certification. Additionally, targets were established to fill approximately 15% of the spiral lamps from dimmable or 3-way models. Overall, specialty lamps (reflector, covered, dimmable, and 3-way) were overrepresented relative to the ULP shipments, as these lamps were projected to make up an increasing proportion of future IOU programs.

KEMA was selected to procure the CFL sample. Seventy-two specific models (nine models each from each of the eight CFL types) were targeted for procurement based on several factors including their inclusion in the ULP, expected retail availability, and a desire to obtain a sample that was representative of the market. Between May and July 2010, KEMA purchased CFLs from nearly 200 separate retail outlets across California. Retail outlets included discount, drug, grocery, hardware, home improvement, mass merchandise, and membership stores.

Table 7 shows the retailers from which purchases were made.[12]

[12] CFLs were purchased in multiple locations for many of these retailers.

Table 7: Retailers from Which CFLs Were Purchased

99 Cents Only	Lucky
Ace Hardware	Orchard Supply Hardware
Albertsons	Orient Market
Big Lots	Pavilions
California DO It Center	Ralphs
Costco	Rite Aid
CVS	Safeway
Dixieline Lumber	Sam's Club
Dollar Tree	Smart & Final
Food 4 Less	Stater Brothers
Grocery Outlet	Target
Home Depot	True Value
IKEA	Vons
Kc's Superstore	Walgreens
Kmart	Walmart
Lowe's	

For each CFL model to be tested, 60 lamps were required – five lamps for each of the 10 switching cycles and 10 additional lamps for spares. KEMA was able to procure 60 or more lamps for 69 of the 72 models targeted. Three of the non–ENERGY STAR models were unavailable, and ultimately three ENERGY STAR models (one covered, one spiral 9-15W, and one spiral 23W) were procured as substitutes for the unattainable models.

Table 8 shows information on the CFL models tested in the study.

Table 8: CFL Models Included in Test

Model ID	Make ID	CFL Category	CFL Type	Rated Lumens	Rated Wattage	Rated Life	Control Type	ENERGY STAR CFL?
1a	1	Reflector	Reflector	750	15	10,000	Standard	Yes
1b	1	Reflector	Reflector	1,300	23	10,000	Standard	Yes
1c	2	Reflector	Reflector	720	15	6,000	Standard	Yes
1d	2	Reflector	Reflector	1,300	26	10,000	Standard	Yes
1e	3	Reflector	Reflector	750	16	10,000	Standard	Yes
1f	4	Reflector	Reflector	1,200	23	8,000	Standard	Yes
1g	5	Reflector	Reflector	640	14	8,000	Standard	Yes
1h	6	Reflector	Reflector	640	14	8,000	Standard	Yes
1i	6	Reflector	Reflector	1,200	23	8,000	Standard	Yes
2a	2	Covered	Globe	500	11	10,000	Standard	Yes
2b	7	Covered	A-Lamp	450	7	10,000	Standard	Yes
2c	3	Covered	Globe	500	9	8,000	Standard	Yes
2d	3	Covered	A-Lamp	800	14	8,000	Standard	Yes
2e	4	Covered	Globe	495	9	8,000	Standard	Yes
2f	4	Covered	A-Lamp	800	14	8,000	Standard	Yes
2g	6	Covered	Globe	495	9	8,000	Standard	Yes
2h	6	Covered	A-Lamp	800	14	8,000	Standard	Yes
2i	2	Covered	Candle	430	9	10,000	Standard	Yes
2j	7	Covered	Globe	495	9	8,000	Standard	Yes
3a	8	Spiral 9-15W	Spiral	800	13	8,000	Standard	Yes
3b	2	Spiral 9-15W	Spiral	825	13	8,000	Standard	Yes
3c	2	Spiral 9-15W	Spiral	900	15	10,000	Dimmable	Yes
3d	9	Spiral 9-15W	Spiral	830	14	8,000	Standard	Yes
3e	10	Spiral 9-15W	Spiral	1,100	15	10,000	Standard	Yes
3f	4	Spiral 9-15W	Spiral	825	13	12,000	Standard	Yes
3g	6	Spiral 9-15W	Spiral	900	14	10,000	Standard	Yes
3h	6	Spiral 9-15W	Spiral	800	14	10,000	Standard	Yes
3i	11	Spiral 9-15W	Spiral	825	13	10,000	Standard	Yes
3j	7	Spiral 9-15W	Spiral	500	9	10,000	Standard	Yes
4a	12	Spiral 16-20W	Spiral	1,100	18	10,000	Standard	Yes
4b	1	Spiral 16-20W	Spiral	1,150	20	6,000	3-way (medium)	Yes
4c	1	Spiral 16-20W	Spiral	1,170	18	8,000	Standard	Yes
4d	7	Spiral 16-20W	Spiral	1,200	20	10,000	Standard	Yes
4e	2	Spiral 16-20W	Spiral	1,200	20	8,000	Standard	Yes
4f	4	Spiral 16-20W	Spiral	1,200	19	6,000	3-way (medium)	Yes
4g	5	Spiral 16-20W	Spiral	1,200	19	10,000	Standard	Yes
4h	6	Spiral 16-20W	Spiral	1,200	19	10,000	Standard	Yes
4i	11	Spiral 16-20W	Spiral	1,200	20	10,000	Standard	Yes
5a	1	Spiral 23W A	Spiral	1,600	23	8,000	Dimmable	Yes
5b	5	Spiral 23W A	Spiral	1,400	23	10,000	Dimmable	Yes
5c	1	Spiral 23W A	Spiral	1,600	23	10,000	Standard	Yes
5d	1	Spiral 23W A	Spiral	1,600	23	10,000	Standard	Yes
5e	5	Spiral 23W A	Spiral	1,600	23	10,000	Standard	Yes
5f	5	Spiral 23W A	Spiral	1,600	23	10,000	Standard	Yes
5g	5	Spiral 23W A	Spiral	1,500	23	10,000	Standard	Yes
5h	7	Spiral 23W A	Spiral	1,600	23	12,000	Standard	Yes
5i	7	Spiral 23W A	Spiral	1,600	23	12,000	Standard	Yes
6a	12	Spiral 23W B	Spiral	1,600	23	10,000	Standard	Yes
6b	13	Spiral 23W B	Spiral	1,600	23	10,000	Standard	Yes
6c	2	Spiral 23W B	Spiral	2,150	29	10,000	3-way (high)	Yes
6d	14	Spiral 23W B	Spiral	1,650	23	10,000	Standard	Yes

Model ID	Make ID	CFL Category	CFL Type	Rated Lumens	Rated Wattage	Rated Life	Control Type	ENERGY STAR CFL?
6e	15	Spiral 23W B	Spiral	1,650	23	10,000	Standard	Yes
6f	16	Spiral 23W B	Spiral	1,625	23	10,000	Standard	Yes
6g	4	Spiral 23W B	Spiral	1,640	23	12,000	Standard	Yes
6h	6	Spiral 23W B	Spiral	1,400	23	10,000	Dimmable	Yes
6i	6	Spiral 23W B	Spiral	1,600	23	10,000	Standard	Yes
6j	2	Spiral 23W B	Spiral	1,600	23	10,000	3-way (medium)	Yes
7a	6	Spiral 24W+	Spiral	1,750	27	10,000	Standard	Yes
7b	1	Spiral 24W+	Spiral	2,050	30	6,000	Standard	Yes
7c	2	Spiral 24W+	Spiral	1,750	26	8,000	Standard	Yes
7d	2	Spiral 24W+	Spiral	1,700	26	10,000	Dimmable	Yes
7e	2	Spiral 24W+	Spiral	2,700	42	12,000	Standard	Yes
7f	17	Spiral 24W+	Spiral	1,700	26	8,000	Standard	Yes
7g	18	Spiral 24W+	Spiral	1,750	26	8,000	Standard	Yes
7h	4	Spiral 24W+	Spiral	2,000	30	6,000	Standard	Yes
7i	11	Spiral 24W+	Spiral	1,750	26	10,000	Standard	Yes
8b	19	Non–ENERGY STAR	A-Lamp	550	11	10,000	Standard	No
8c	19	Non–ENERGY STAR	Globe	260	7	10,000	Standard	No
8d	1	Non–ENERGY STAR	Candle	330	7	8,000	Standard	No
8g	6	Non–ENERGY STAR	Reflector	700	16	8,000	Standard	No
8h	6	Non–ENERGY STAR	Globe	700	17	8,000	Standard	No
8i	6	Non–ENERGY STAR	Spiral	1,400	27	10,000	Standard	No

* Note: Model 6C and Model 6J are the same 3-way model but are treated as separate models in the study, as 6C was operated at the high setting (29W) and 6J was operated at the middle setting (23W).

2.4 Sample Preparation

After the sample was procured, it was delivered to ITL and prepared for inclusion in the switching cycle and photometric experiments. Sample preparation primarily consisted of dividing the sample into 10 similar subsamples – one for each of the 10 switching cycles – such that differences between the subsamples were minimized. Sample preparation also consisted of confirming the lamps were functional, selecting one-third of the lamps to be included in the photometric experiment, determining the lamp orientation for cycle testing (base-up or base-down), and labeling lamps with a unique ID code.

The process for preparing a model for testing consisted of the following steps (which were repeated for all 72 models and illustrated in Figure 5).

1. All lamps of a model were located and separated into batches associated with the date and location of their purchase. (KEMA had labeled all lamps with this information.)
2. Lamps were removed from their packages and tested for functionality.
3. Lamps were re-sorted into 10 batches of five lamps each plus an 11th batch for spares. This re-sort was done such that lamps acquired at the same location were split evenly between batches so that any potential differences between locations (e.g., one store might have a version of a model from a different production run than another store) would not bias the sample.
4. One-third of lamps were marked for photometric testing. This was done using the following process which ensured both random selection and a spread of selected lamps across the 10 batches. First, a random number from 1 to 5 was selected and this number determined the first lamp in batch 1 to be marked for photometric testing (e.g. if the random number was 2, the 2nd of the 5 lamps in batch 1 would be marked). Next, every third lamp was subsequently marked for inclusion in the photometric experiment. Using the example

above, lamp 3 and 4 from batch 1 would be skipped but then lamp 5 would be marked. Then lamp 1 and 2 from batch 2 would be skipped and lamp 3 would be marked, and so on.

5. Alternating lamps were marked for operating orientation (except for reflector lamps, which were all marked for base-up operation).
6. Lamps were labeled with a unique seven-digit code. The digits in the code corresponded to the switching cycle on which the lamp would be placed (first digit), the model ID (second and third digits), the purchase location (fourth digit), the lamp number (fifth digit), whether the lamp was marked for photometric testing (sixth digit), and the lamp orientation (seventh digit). For example, an ID code of 34C24YD signified a lamp of model type 4C that would be placed on the third switching cycle in a base-down orientation and included in photometric testing.
7. Lamps were placed back in their boxes and/or in bubble wrap, transported to their testing cubicles, and installed for testing.



Figure 6: Photographs of CFL Sample Preparation

Checking for lamp functionality (step 2, top left); sorting a model into 10 batches of five lamps each (step 3, top right); sorted subsamples ready to be installed for testing (step 7, bottom)

3 Results

This section presents the results from the switching cycle experiment (section 3.1) and the photometric experiment (section 3.2). The results that are presented in this section are those based on analysis directly related to this study's objectives stated in section 1.3. In recognition that the complete results from this study may be of use to various parties and these parties may wish to conduct their own analysis of these results based on their own objectives, the CPUC is providing as an Appendix to this report two Excel spreadsheets that includes the raw test results as well as some basic analytical tools (discussed in section 3.3).

3.1 Switching Cycle Experiment Results

The switching cycle results presented in this section should be viewed in conjunction with the following explanations:

- During sample sorting and start-up procedures for this experiment, 22 lamps (out of 3,608, or 0.6%) were found to be nonoperational. These lamps were all replaced with functional lamps of the same model at the time of initiation of the experiment. As it could not be determined conclusively whether these pretest failures resulted from manufacturer defects and/or handling during sample shipping and sorting, the results presented in this report do not account for these initial failures. If these lamps had been included, failure rates would be marginally higher.
- During testing, 7 lamps (out of 3,608, or 0.2%) were broken or damaged. These events generally occurred when lamps were removed from the testing rack for photometric testing. Because these failures were not a function of the quality of the lamps themselves, these lamps (and any data previously collected from them) were removed from the sample. This reduced the sample from 3,608 to 3,601 CFLs.
- The 2-, 5-, and 15-minute switching cycles were each originally planned to operate for approximately nine months. At the end of this initial testing period, the surviving samples for these three switching cycles were removed and placed into storage. As previously mentioned, the switching cycle experiment was originally planned for 2 years but was extended several times. One impact of these extensions was that, because of lamp failures over time, sufficient space on the testing rack became available to restart testing of the surviving 2-, 5-, and 15-minute cycles lamps. Thus, after approximately one year in storage, the surviving 2-, 5-, and 15-minute cycles lamps were removed from storage and returned to the test rack. While care was taken when removing, storing and reinstalling these lamps, 21 of 127 lamps (16.5%) that were operational when removed were found to be non-operational one year later upon reinstallation. It is not clear if these failures were a product of moving and storing the lamps, an "aging effect" from when the lamps were in storage, or some combination of the two. These 21 lamps were maintained in the sample and were assigned failure times that matched their run times at the point at which they were placed into storage.

3.1.1 Mortality Curves by Run-Time

Figure 7 provides an overview of the results of the switching cycle experiment by plotting the mortality curves of all 10 of the switching cycles included in the experiment. This plot shows the survival rates of

the approximately 360 lamps in each of the 10 switching cycles as a function of each lamp's run-time. Lamp survival rates decreased consistently as switching frequency was increased. We also note that the failures associated with the removal, storage, and reinstallations of the lamps on the 2-, 5-, and 15-minute cycles (discussed in 3.1) can be seen as sudden drops in survival rates for these three cycles.

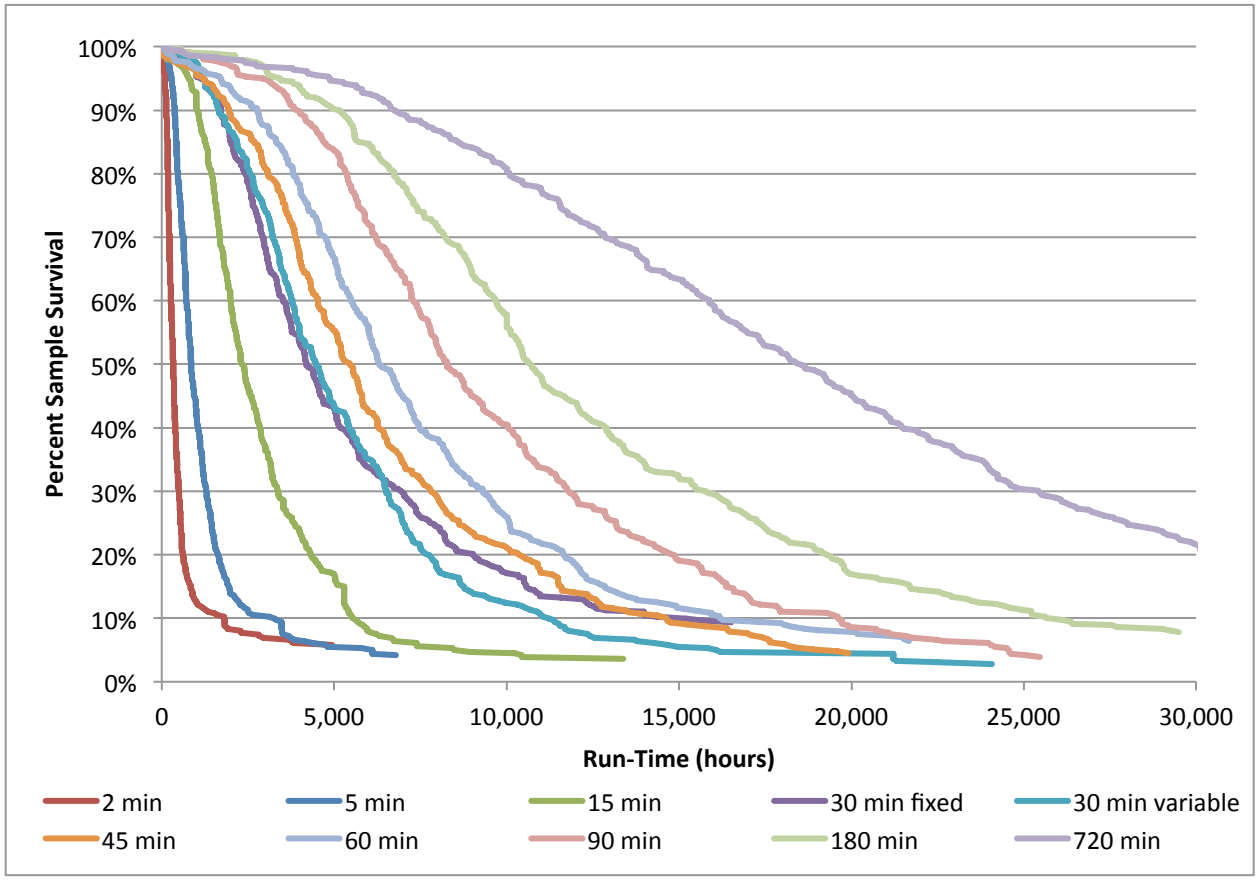


Figure 7: Mortality Curves by Switching Cycle and Run-Time

3.1.2 Mortality Curves by Switching Cycle

Figure 8 shows the same data as Figure 7, except in this case mortality curves are plotted as a function of the number of cycles experienced rather than lamp run-time. The cycles with on-times of 30 minutes or less display similar curves and each reach median sample failure near 10,000 cycles. For cycles of 45 minutes and greater, increased cycle on-time results in a decrease in the number of cycles required to reach median sample failure.

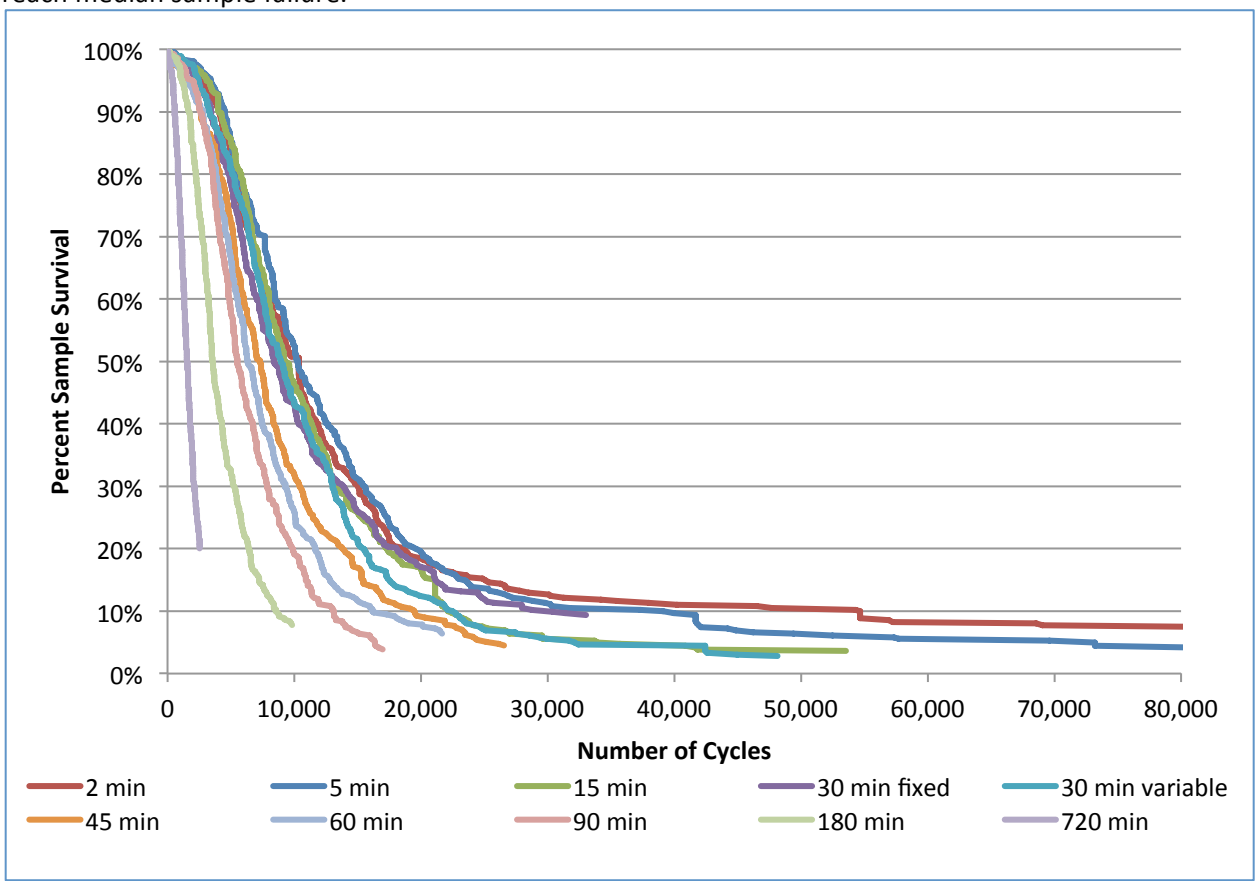


Figure 8: Mortality Curves as a Function of Cycles

3.1.3 Median Life by Switching Cycle

Table 9 shows the run-time and number of cycles that each switching cycle reached during testing as well as the failure rates for each switching cycle at the completion of the switching cycle experiment. Also included in Table 9 is the run-time and number of cycles at the median failure point for each cycle. Finally, the table includes the average rated life for the lamps in each switching cycle as well as each switching cycle's normalized lamp life.[13]

Median failure times are shown to drop rapidly with increased switching frequency. We note that rated life (as defined by IES LM-65-10) is based on switching cycles that use 180-minute on-times and that the average life of all CFLs on the 180-minute switching cycle in this study exceeded the average rated life of the CFLs tested on that cycle (10,712 hours measured life vs 9,217 hours rated life).

Figure 9 plots the normalized rated life as a function of switching cycle on-period.

Table 9: Final Run-time, Number of Cycles, and Failure Rates by Switching Cycle

	Switching Cycle									
	2	5	15	30 fixed	30 variable	45	60	90	180	720
Run-time (hours)	4,943	8,935	13,478	16,722	25,963	21,312	22,008	26,436	30,390	30,978
Total # of cycles	148,282	107,223	53,911	33,445	51,925	28,416	22,008	17,624	10,130	2,581
Failure %	94.2%	95.8%	96.4%	90.6%	97.2%	95.4%	93.6%	96.1%	92.3%	79.9%
Run-time at 50% sample failure (hours)	345	857	2,356	4,191	4,480	5,469	6,323	8,272	10,712	18,576
# of cycles at 50% failure	10,362	10,281	9,424	8,382	8,960	7,292	6,323	5,515	3,571	1,548
Average rated life (hours)	9,221	9,224	9,222	9,229	9,224	9,239	9,226	9,230	9,217	9,220
Normalized Lamp Life (%)	3.7%	9.3%	25.5%	45.4%	48.6%	59.2%	68.5%	89.6%	116.2%	201.5%

[13] The average rated life of all 72 models was 9,222. Because of slight variations in the number of CFLs of each model used on each switching cycle, the average rated life of all CFLs on each switching cycle varied between as low as 9,217 hours (180-min cycle) and as high as 9,230 hours (90-min cycle).

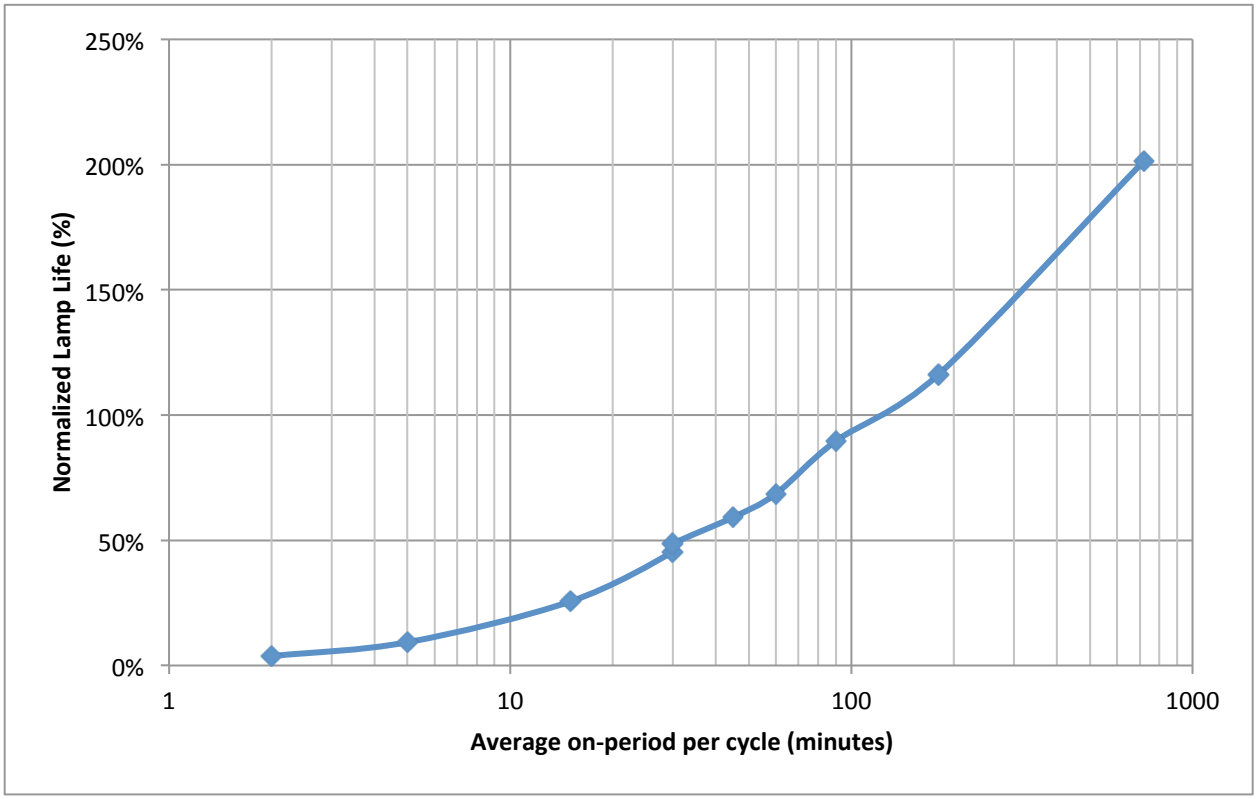


Figure 9: Normalized Lamp Life as a Function of Average On-Period

3.1.4 Failure Results by Make and Model

While Figure 9 shows the average normalized lamp life as a function of on-period for all 72 models included in the sample, it is important to note that a large variability in survival rates between models was observed. To illustrate this point Figure 10 plots the normalized lamp life for each of the 72 models on each of the 10 switching cycles (with the exception of 33 occurrences where a model had not reached median sample failure for a particular cycle). While it may be possible to note some models that over- or underperform their peers across multiple cycles, we have primarily included this plot to highlight the high level of variability in sample survival between different models.

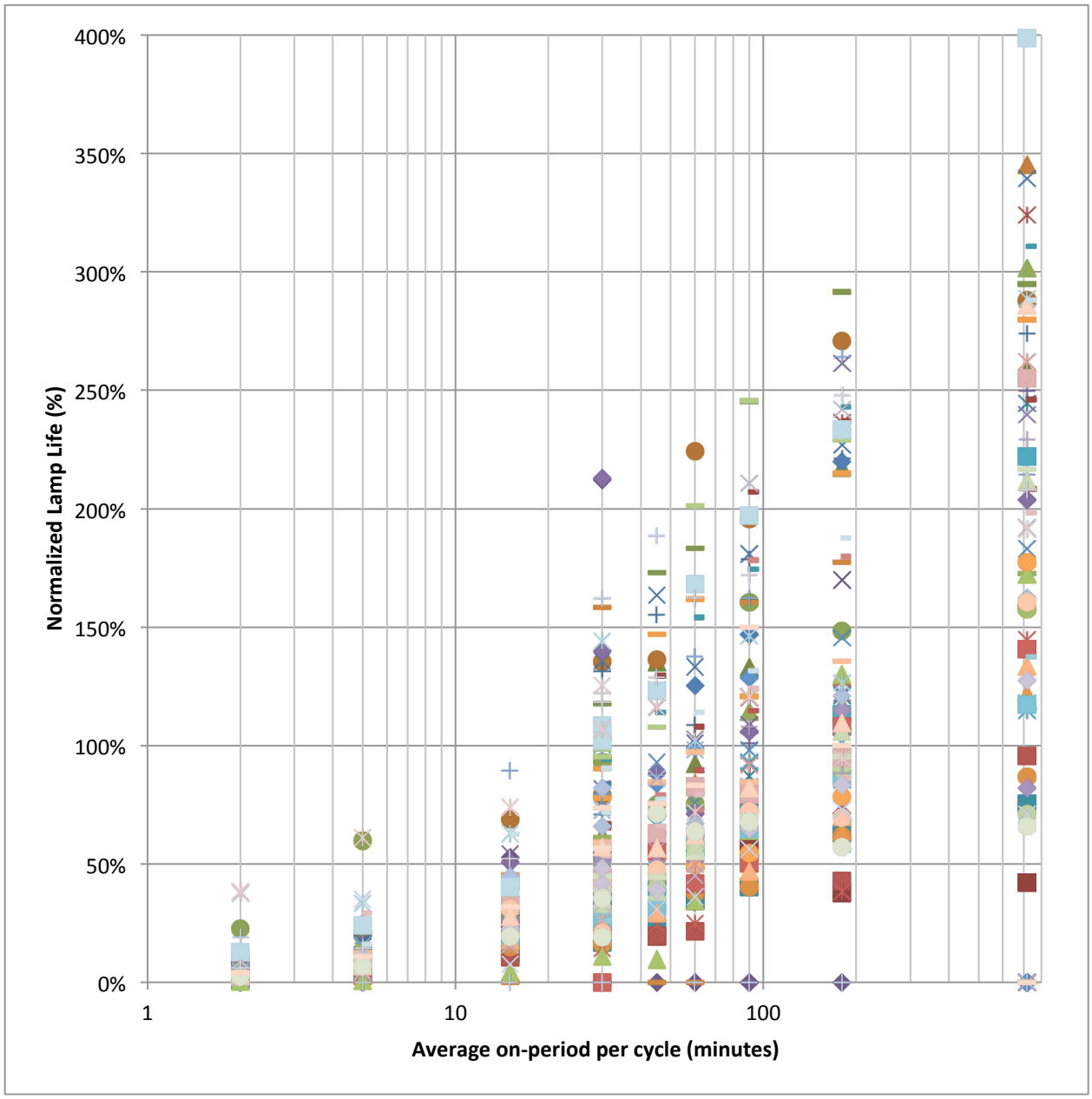


Figure 10: Normalized Lamp Life for Each CFL Model

The 72 CFL models included in the study include those from 19 different brands or makes. Figure 11 presents average mortality curves from all 10 switching cycles for the 10 makes that had multiple models included in the study (the remaining 9 makes only had one model each and are not represented in this graph)[14]. Several makes (specifically makes 1 and 12) appear to underperform versus their peers.

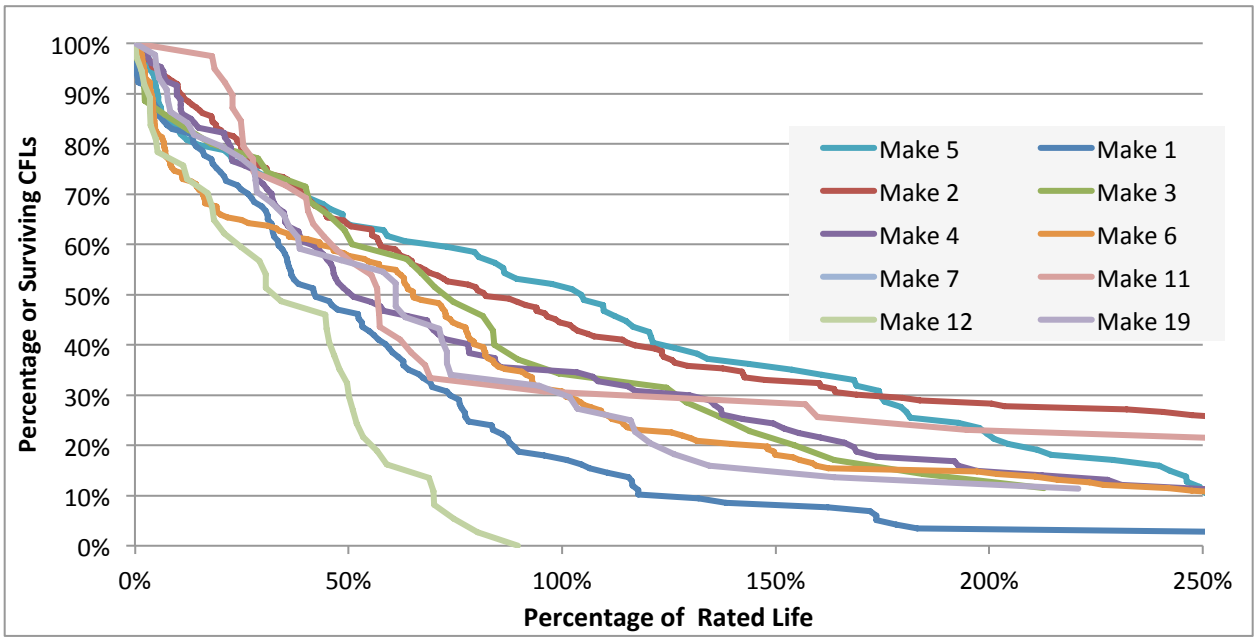


Figure 11: Mortality Curves by Make Type

3.1.5 Variable Switching Cycle vs. Fixed Switching Cycle

As discussed in section 2.1.2, two switching cycles were included in the study that had identical average on-times and average number of cycles per day, but in which one had fixed on-times and the other had variable on-times. We compared the results of these two cycles to determine if would be necessary to consider the variability of on-times when estimating CFL life or if estimates could be based solely on average on-time and average cycles per days. The mortality curves for these two switching cycles are shown in Figure 12.

The two curves appear to track closely with one another but do have slight differences, with the fixed cycle initially having an accelerated failure rate versus the variable cycle. The fixed cycle reached the 50% failure rate at 4,191 hours while the variable cycle didn't reach the 50% failure rate until 4,480 hours. Later, at around 6,400 with approximately 1/3 the CFLs in each cycle surviving, these failure

[14] Note that this and subsequent similar plots are averaging results from all 10 switching cycles. While these comparisons can be useful for comparing the relative failure rates of based on CFL model attributes (make type, ENERGY STAR certification, control type, rated life, etc.), the absolute results follow directly from the timing of the 10 switching cycles. For example, if we had included more cycles with shorter on-times, the absolute results of these mortality curves would likely have shown accelerated failure rates.

curves cross, and beyond this point the variable cycle has an accelerated failure rate versus the fixed cycle.

We conducted a Kolmogorov-Smirnov test for equality between the two failure distributions in order to determine if the observed variation was statistically significant. The Kolmogorov-Smirnov test is based on looking for the largest difference between the distributions and considering whether this difference can be explained by chance. A small p-value is evidence against chance as an explanation; a large p-value indicates that the difference between the curves is indistinguishable from chance variation. The commonly used cutoff value is 5%, meaning that a p-value less than 5% would lead us to reject the hypothesis of no effect in favor of the hypothesis that fixed and variable intervals affect failure times differently. The p-value for the Kolmogorov-Smirnov test was 14.4%, which suggests that the differences between these two cycles are not statistically significant but rather are within the range of what would be expected by chance variability.

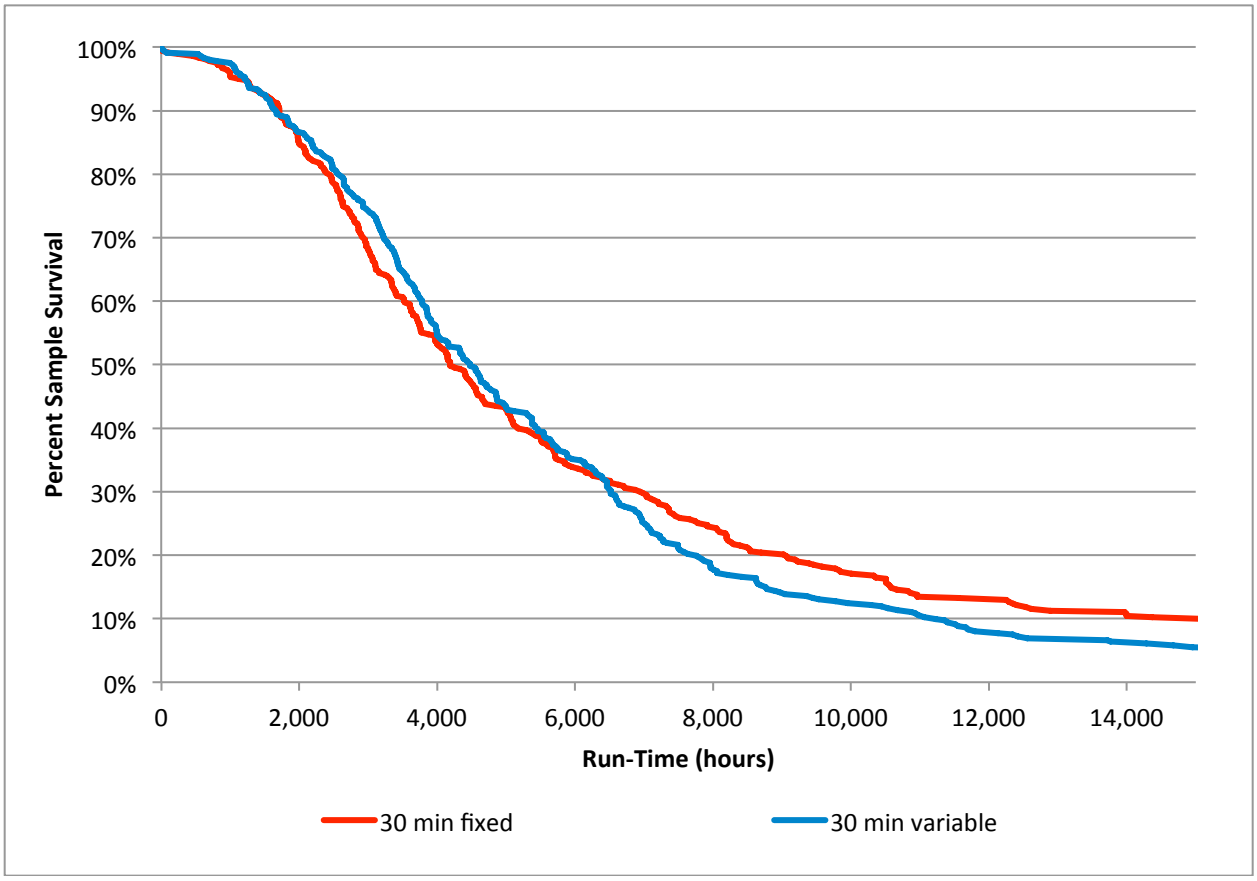


Figure 12: Mortality Curves for 30-Minute Fixed and 30-Minute Variable Switching Cycles

3.1.6 ENERGY STAR Lamps

Of the 72 models included in the test, 66 were ENERGY STAR certified and six were not ENERGY STAR certified. Figure 13 graphs the mortality curves of all 3,302 ENERGY STAR CFLs and all 299 non-ENERGY STAR CFLs. As this plot shows, ENERGY STAR models initially have higher failure rates than their non-ENERGY STAR peers while failure rates equalize when overall failure rates exceed 75%. While this result suggests that ENERGY STAR certification does not appear to ensure longer survivability, it is difficult to make any definitive statements to this effect because of the limited size of the non-ENERGY STAR sample.

Another way to look at the performance of the ENERGY STAR certified lamps is to look at their survival rates versus ENERGY STAR criteria. The ENERGY STAR specification includes a rapid cycle test in which six CFL samples are cycled at 5-minutes on, 5-minutes off for 1 cycle for every 2 hours of rated life (e.g. a CFL with a rated life of 10,000 hours would be cycled 5,000 times). Models pass this test if 0 or 1 sample fails during the rapid cycle test. We can directly compare the results of our 5-minutes cycle to the ENERGY STAR rapid cycle test criteria, as the cycle timing is identical. Because we utilized sample sizes of 5 in most cases (rather than 6), there are some cases where it is unclear if the model would have passed the ENERGY STAR test. For models that had 2 or more of their 5 samples fail after 1 cycle per 2 hours of rated life, we can state that the model would fail the ENERGY STAR test (e.g., had there been one more sample, that model would still have 2 or more failures regardless if that additional sample failed or not). For models that had 0 failures from their 5 samples, we can say that they would pass the ENERGY STAR test (e.g., even if the additional sample were to fail, the model still would only have 1 failure and thus would pass the test). For models that only had 1 sample of the 5 fail, we cannot definitively state if the models would pass or fail the ENERGY STAR test (e.g., if the additional sample were to fail, the model would fail; but if the additional sample were to survive, the model would pass the test). Figure 14 summarizes the results of the 66 ENERGY STAR models against the ENERGY STAR rapid cycle test criteria. Of the 66 ENERGY STAR models, 44 models (67%) passed the rapid cycle test, 8 models (12%) failed the test, and 14 models (21%) had 1 of their 5 samples fail after 1 cycle per 2 hours of the models rated life, so we were unable to definitively state whether these models would have passed or failed this test had there been six samples included in the test.

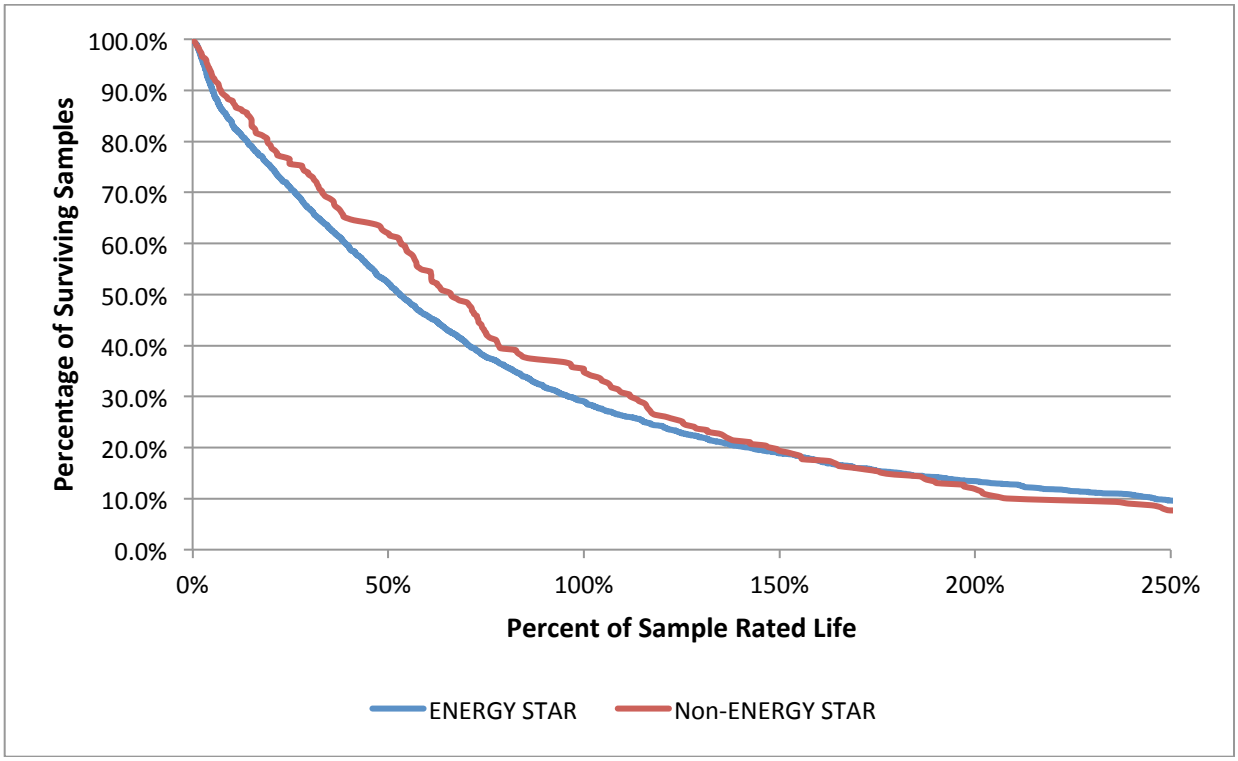


Figure 13: Mortality Curves for ENERGY STAR and non-ENERGY STAR CFLs

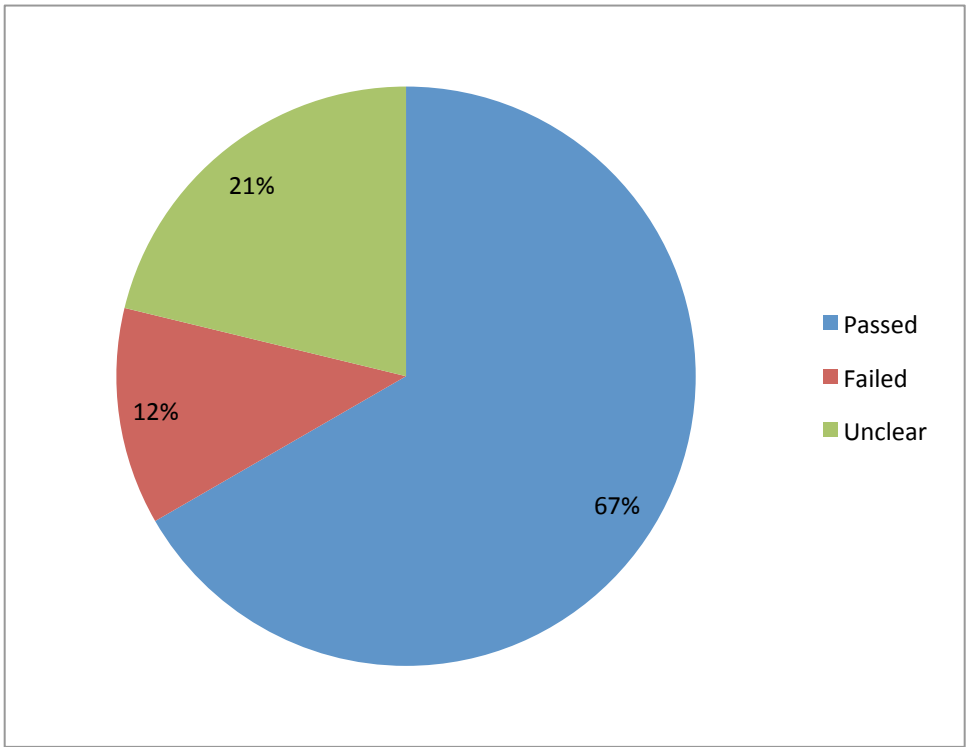


Figure 14: ENERGY STAR Models Performance Versus ENERGY STAR's Rapid Cycle Test Criteria

3.2 Photometric Experiment Results

As mentioned earlier, approximately one-third of the overall test sample, or approximately 1,200 CFLs, were included in the photometric experiment. Initial photometric and electrical measurements of these CFLs were made after a 100-hour seasoning period and then these CFLs were placed back in the switching cycle experiment. Periodically the switching cycle experiment was paused so that CFLs included in the photometric experiment could be retested. This section presents the results of these photometric and electrical measurements.

We note that two of the 10 cycles (45- and 60-minute switching cycles) were found to have errors in their baseline 100-hour readings. These lamps were retested at 350 hours. The results presented here do not include the measurements from these two cycles.[15]

3.2.1 Initial Lumen Output vs. Rated Lumen Output

Figure 15 presents a histogram showing how measurements of initial luminous flux (lumen output) compared to the lamps' rated values[16]. Of the 941 lamps that were photometrically characterized at 100 hours, 591 (62.8%) were found to deliver less light output than their rated output. Seventy-nine lamps (8.4%) provided 80% or less of their claimed lumen output while 129 lamps (13.7%) provided 110% or more of their rated output.

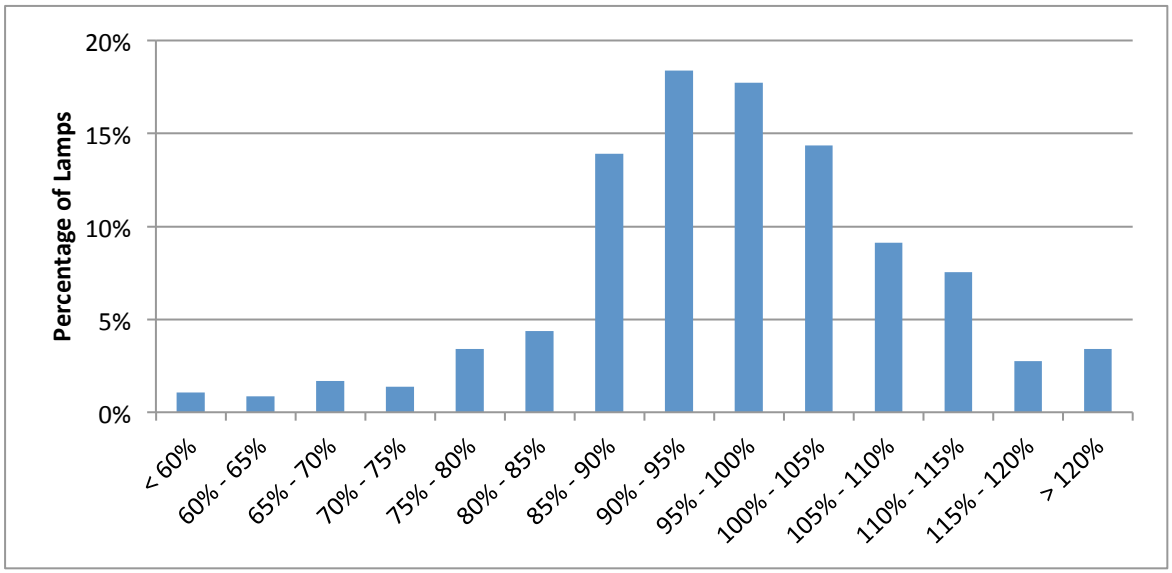


Figure 15: Measured Initial Lumen Output vs. Rated Lumen Output

[15] While it is likely that these 350-hour results would closely approximate 100-hour readings (even without making corrections), we chose not to include these measurements in the photometric evaluations because the measured sample with valid 100-hour readings was so large (941 lamps).

[16] ENERGY STAR defines rated luminous flux or lumen output as "initial lumen rating (based on the average 100-hour lumen output measurement), which is specified by the manufacturer."

3.2.2 Initial Efficacy vs. Rated Efficacy

Figure 16 shows the initial efficacy (lumens/watt or lm/W) of the measured CFLs. Efficacy can generally be seen to increase as power increases. Several outliers with very low efficacies (30 lm/W and under) can be seen – possibly from lamps that are defective and/or failing.

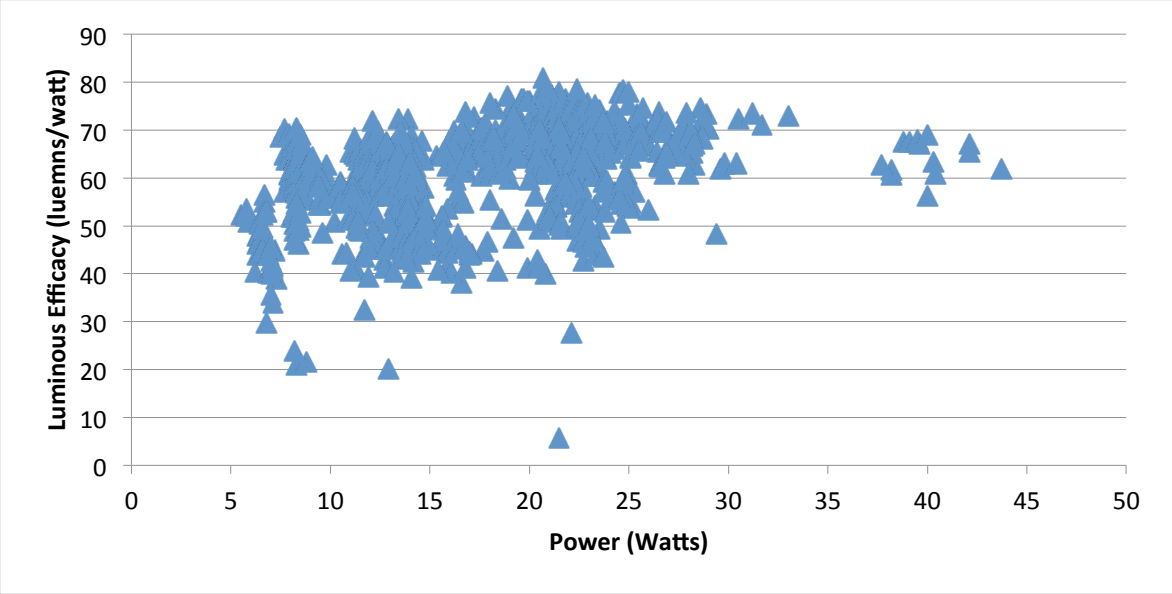


Figure 16: Luminous Efficacy vs. Power

ENERGY STAR–certified CFLs are required to have initial efficacies that meet or exceed specified minimum levels. These minimum levels vary by CFL type and wattage, as shown in Table 10.

Table 10: Minimum Efficacy Levels for ENERGY STAR CFLs

Reflector	lm/w
<20W	33
>= 20W	40
Covered	
<=7W	40
7 - 15W	45
15-25W	50
>=25W	60
Spiral	
<10W	50
10-15W	55
>=15W	65
Dimmable/3-Way	
<15W	50
>=15W	60

Figure 17 shows how the initial efficacy of each lamp compared to both its ENERGY STAR minimum requirements as well as to its rated efficacy (defined as rated lumen output divided by nominal wattage). The histogram represented by the blue bars compares measured efficacy to ENERGY STAR minimums of the appropriate value for that lamp, per Table 10. Non–ENERGY STAR lamps were not included in the histogram. The histogram represented by the red bars compares measured efficacy to the lamps' rated efficacy and includes both ENERGY STAR and non–ENERGY STAR lamps. For example, consider a 23 W spiral CFL with a rated lumen output of 1,600 lm which was found to draw 21.2 W and produce 1432 lm (67.5 lm/W) during testing. The ENERGY STAR efficacy requirement for this CFL is 65 lm/W (spiral, greater than 15 W in Table 10) meaning that this CFL would have an efficacy of 103.5% of the ENERGY STAR minimum and be represented in the 100%-105% "vs. ENERGY STAR" bin in Figure 17. The measured efficacy is found to be 97.0% of its rated efficacy and thus this CFL would also be represented in the 95%-100% "vs. Rated Efficacy" bin in Figure 17.

Overall, 38.9% of lamps were found to have an initial efficacy lower than their rated efficacy, while 61.1% of lamps met or exceeded their rated efficacy. A total of 13.4% of ENERGY STAR–certified lamps were found to have efficacies below the ENERGY STAR minimum requirements for efficacy, while 86.6% of these lamps met or exceeded the ENERGY STAR efficacy requirements.

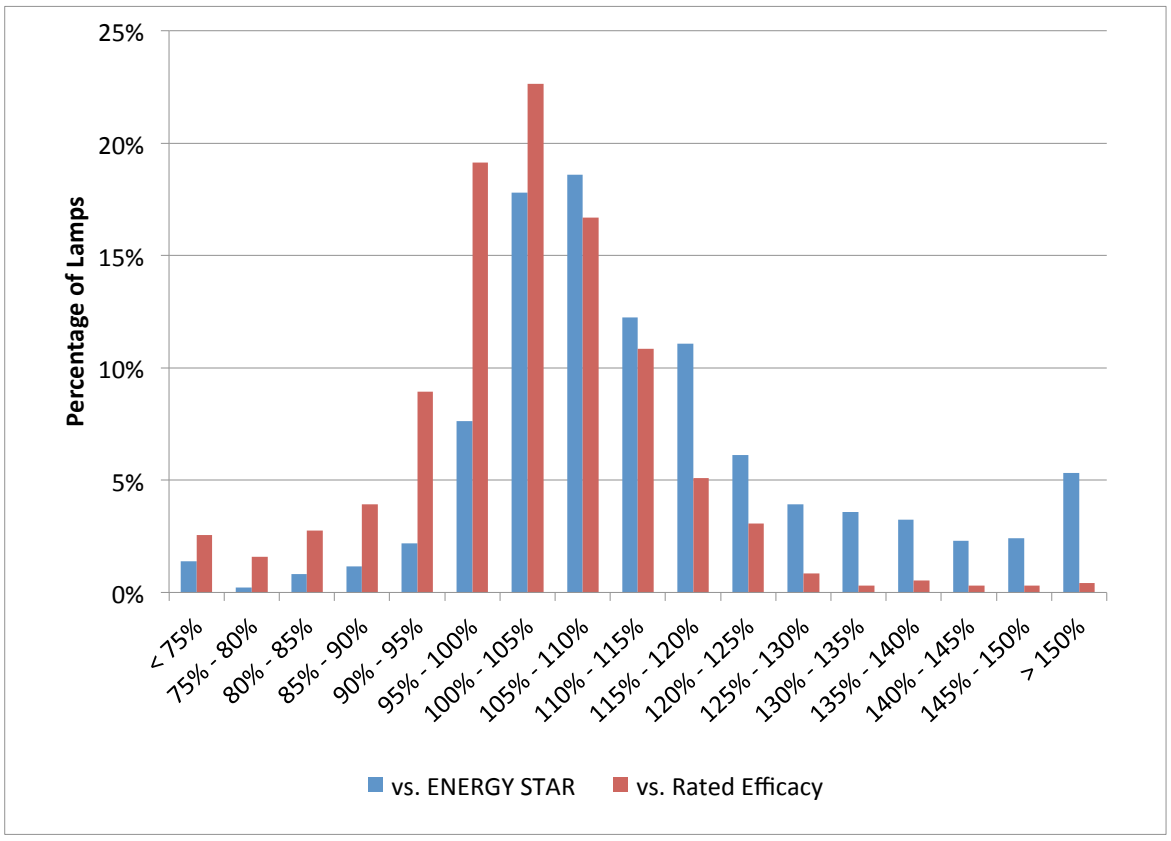


Figure 17: Measured Efficacy vs. ENERGY STAR Minimum Efficacy and vs. Lamp Rated Efficacy

3.2.3 Lumen Maintenance by Switching Cycle

This section reviews lumen maintenance as a function of switching cycles. When testing for lumen maintenance at multiple time periods, the number of CFLs measured will typically decrease over time (e.g., a CFL measured at 4,000 hours might fail before it can be measured at 10,000 hours). When analyzing the results, it is possible to either calculate lumen depreciation at each testing period using all available results or by only using results from lamps that survived through all testing periods. There are advantages and disadvantages to each approach. Looking only at lamps that survive through all testing periods allows for the clearest view of the effect of run-time and/or cycling on lumen maintenance. In this case, the sample is fixed and changes in overall lumen maintenance rates can be attributed to the changes in the measured CFLs over time. A disadvantage of this approach is that removing lamps that fail before the final measure period may bias the overall sample. For example, if CFLs that fail earlier also have lower rates of lumen maintenance, then eliminating them from the sample may result in an overestimation of overall CFL lumen maintenance. On the other hand, analyzing all available results allows for calculations of lumen maintenance at interim periods to be made with larger sample sizes and may more accurately represent the expected CFL population at each testing period. But the composition of the sample will change with each testing period, making it difficult to determine to what extent changes in overall lumen maintenance results are attributable to changes in the individual CFLs' performance or are attributable to changes in the sample composition.

Table 11 provides the average lumen maintenance of measured CFLs by switching cycle and on-period using both of the methods discussed above. Results labeled “All” include all testing results from each sample, and those labeled “Fixed” only include CFLs that survived though all testing periods for a given switching cycle. Also, as previously mentioned, the 45- and 60-minute cycles are not included in this analysis because they do not have 100-hour results for baselining lumen maintenance.

We note that there are large variations in the sample sizes used to calculate these results. Switching cycles with high rates of early failures had fewer CFLs included (e.g., only 11 CFLs for the “Fixed” results on 5-minute switching cycle) while switching cycles with low rates of early failures included higher numbers of CFLs in their results (e.g., 84 CFLs for the “Fixed” results on the 720-minute switching cycle).

With the exception of the 30-minute variable switching cycle, lumen maintenance appears to be relatively independent of switching cycle, with an approximate drop in light output of 15-20% over the first 3,000-4,000 hours of operation for all cycles. Based on results from the longer switching cycles (90-, 180-, and 720-minute), lumen output seems to level off after an initial drop during the first 4,000 hours of operation.

Table 11: Maximum, Minimum, and Average Lumen Depreciation of Lamps as a Function of Switching Cycle and Operating Hours

Switching Cycle	Sampling Type	Lumen Maintenance after X Hours of Operation					
		1,000	2,000	3,000	4,000	6,000	10,000
2	All	93%	N/A	N/A	N/A	N/A	N/A
	Fixed	93%	N/A	N/A	N/A	N/A	N/A
5	All	98%	83%	N/A	N/A	N/A	N/A
	Fixed	91%	83%	N/A	N/A	N/A	N/A
15	All	95%	88%	86%	N/A	N/A	N/A
	Fixed	97%	89%	86%	N/A	N/A	N/A
30 fixed	All	91%	89%	N/A	85%	N/A	N/A
	Fixed	91%	93%	N/A	85%	N/A	N/A
30 variable	All	93%	88%	N/A	91%	N/A	N/A
	Fixed	94%	91%	N/A	91%	N/A	N/A
90	All	N/A	N/A	N/A	84%	81%	N/A
	Fixed	N/A	N/A	N/A	83%	81%	N/A
180	All	N/A	N/A	N/A	84%	82%	82%
	Fixed	N/A	N/A	N/A	84%	82%	82%
720	All	N/A	N/A	N/A	81%	77%	79%
	Fixed	N/A	N/A	N/A	81%	77%	79%

Five switching cycles (30-minute fixed, 30-minute variable and 90-, 180-, and 720-minute) were photometrically characterized at 4,000 hours. Figure 18 shows the lumen maintenance at 4,000 hours for all lamps on these five switching cycles. Average lumen maintenance, as well as the percentage of lamps with lumen maintenance of 80% or below, is described in

Table 12.

ENERGY STAR requires that certified CFLs have lumen maintenance above 80% at 4,000 hours. Approximately a quarter of the lamps failed to meet the ENERGY STAR standard for 4,000-hour lumen maintenance, and lumen maintenance seems to drop slightly as switching cycle on-periods increase. Again, the 30-minute variable is seen to experience greater lumen maintenance at 4,000 hours than the other switching cycles.

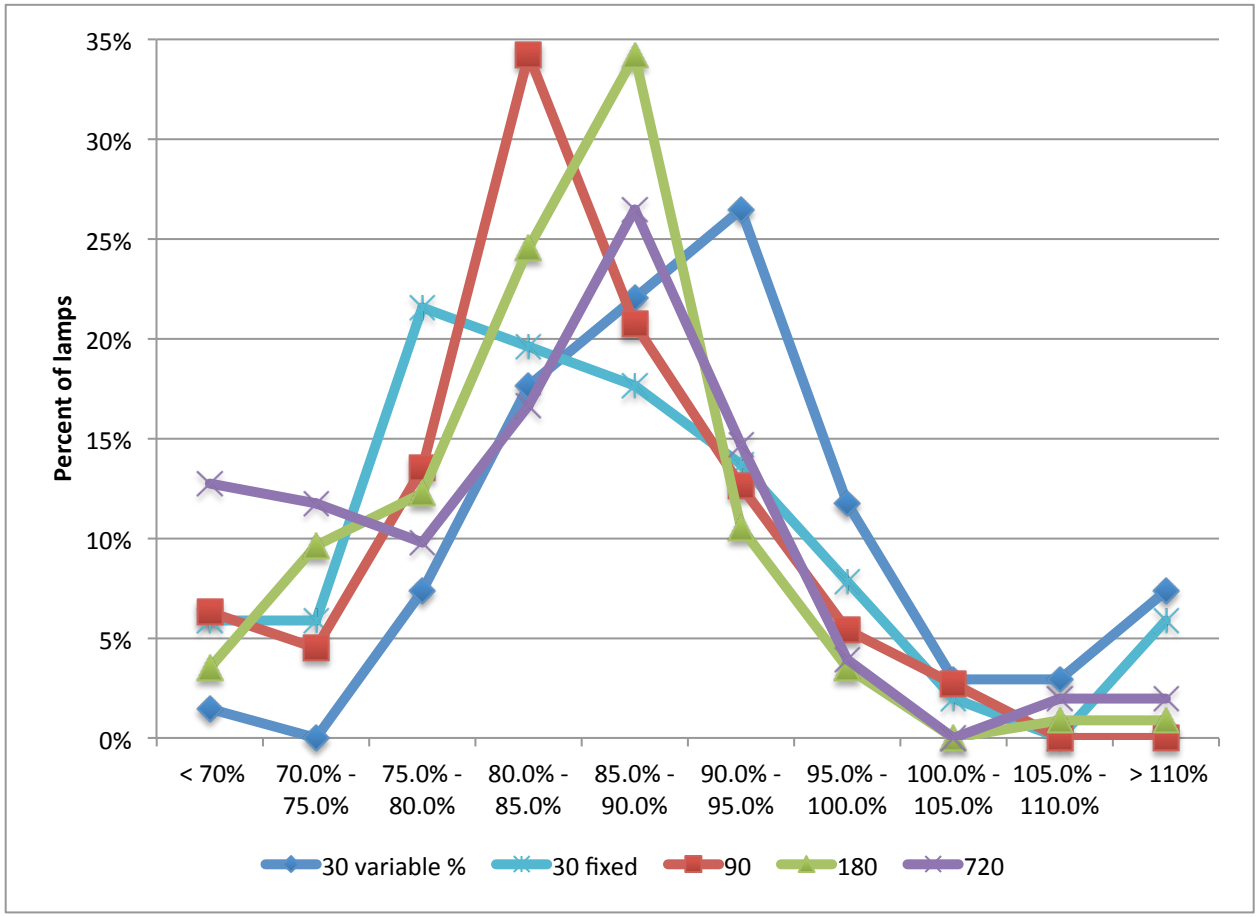


Figure 18: Lumen Maintenance at 4,000 Hours as a Function of Switching Cycle

Table 12: Lumen Maintenance at 4,000 Hours as a Function of Switching Cycle

Switching Cycle	Average Lumen Maintenance	% of Lamps with Lumen Maintenance of 80% or Below
30 variable	91%	9%
30 fixed	85%	33%
90	83%	24%
180	84%	25%
720	81%	34%

3.2.4 Lumen Maintenance by Lamp Type

Figure 19 and

Table **13** provide information on lumen maintenance for all lamps tested at 4,000 hours as a function of CFL types. The table also indicates the percentage of lamps that failed to meet the ENERGY STAR specification of lumen maintenance of 80% or higher at 4,000 hours.

Lumen depreciation is fairly consistent across CFL types, with the exception of the non–ENERGY STAR category, which is the only category to register an average drop in light output of more than 20% over the first 4,000 hours.

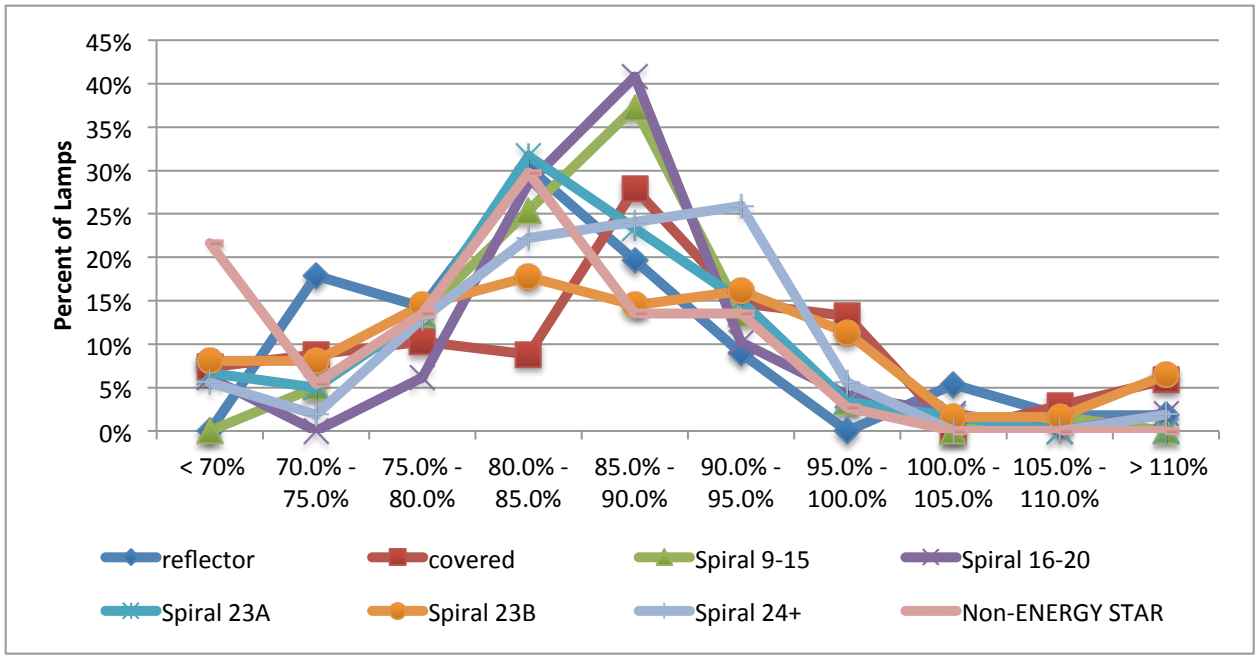


Figure 19: Lumen Maintenance at 4,000 Hours as a Function of CFL Type

Table 13: Lumen Maintenance at 4,000 Hours as a Function of CFL Type

CFL Type	Average Lumen Maintenance	% of Lamps with Lumen Maintenance 80% or Below
Reflector	83.7%	32.1%
Covered	86.8%	26.5%
Spiral 9-15	85.5%	18.6%
Spiral 16-20	85.8%	12.2%
Spiral 23A	81.3%	25.0%
Spiral 23B	85.7%	30.6%
Spiral 24+	85.2%	20.4%
Non–ENERGY STAR	77.7%	40.5%

3.2.5 Long Term Lumen Maintenance

At the completion of the switching cycle experiment, surviving CFLs with valid 100-hour photometric baseline measurements were photometrically characterized one last time. Figure 20 shows the lumen maintenance at 4,000, 6,000, 10,000 and over 30,000[17] hours for the 34 CFLs from the 180-minute and 720-minute switching cycles that survived through all photometric testing periods.[18] This figure shows a drop in lumen maintenance of approximately 20% over the first 4,000 hours and an additional drop of approximately 10% over the next 24,000 hours.

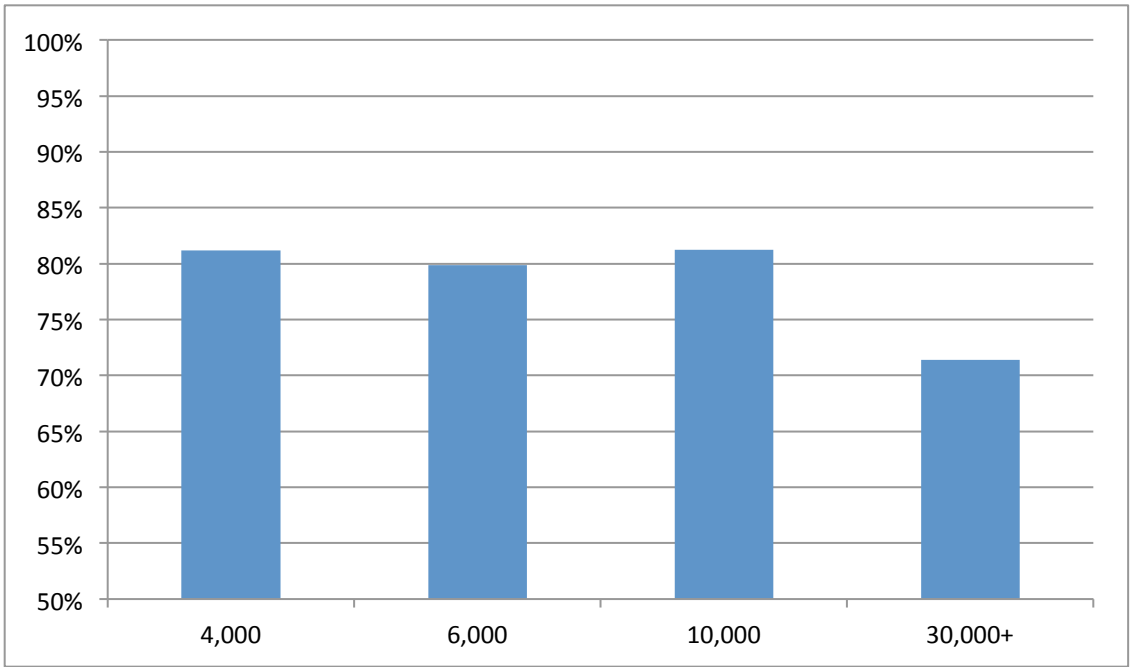


Figure 20: Long-Term Lumen Maintenance on 180-minute and 720-minute Switching Cycles

[17] CFLs on the 180-minute switching cycle were measured at 30,400 hours while CFLs on the 720-minute switching cycle were measured at 30,900 hours.

[18] While an additional 23 CFLs from the shorter switching cycles were measured, these results are not included here because their run-times at their final readings were significantly shorter than 30,000 hours and the sample sizes per switching cycle were much smaller than those from the 180-minute and 720-minute cycles.

3.2.6 Color Measurements

Figure 21 plots correlated color temperature (CCT) and the color rendering index (CRI) of all lamps tested at 100 hours. Of these lamps, 91.0% had a CRI greater than or equal to the ENERGY STAR minimum of 80. Lamps are clustered around CCTs of 3,000K (warm white), 5,000K (cool white), and 6,500K (daylight). Three outliers, with CCTs above 9,000K, are daylight models.

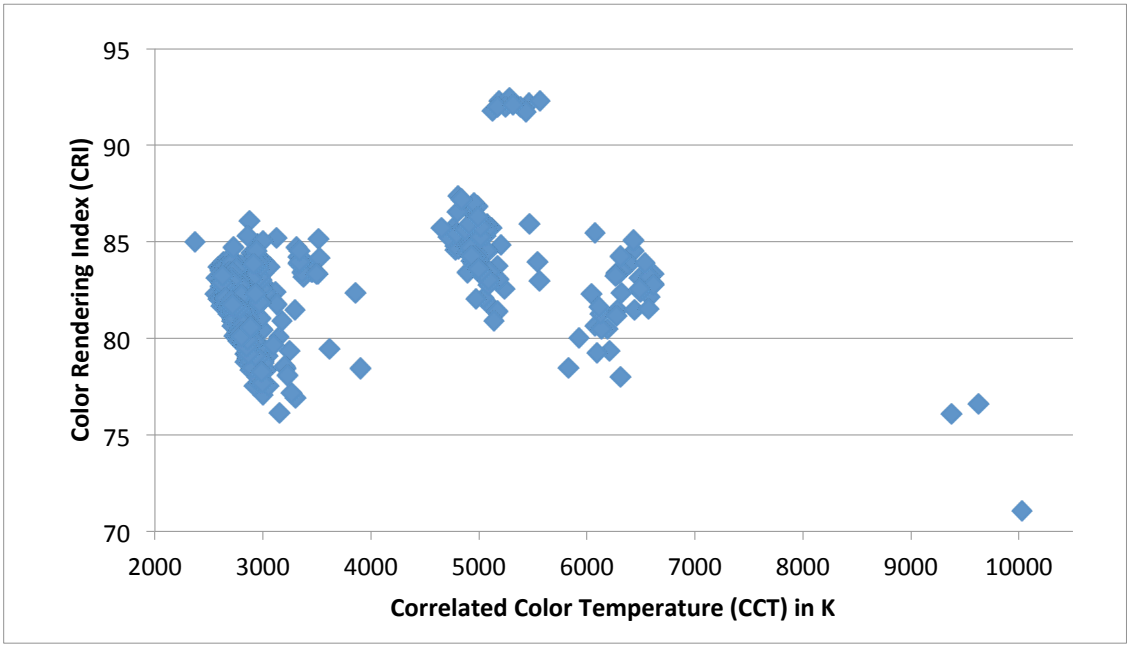


Figure 21: Correlated Color Temperature and Color Rendering Index

3.2.7 Power Factor Measurements

Figure 22 shows a histogram of the power factor (pf) readings for all lamps measured at 100 hours. The lamps with power factors above 0.9 consisted of three specific models, each of which was dimmable. Six tested lamps (four from ENERGY STAR models and two from non–ENERGY STAR models) had power factor readings under the ENERGY STAR minimum of 0.5.

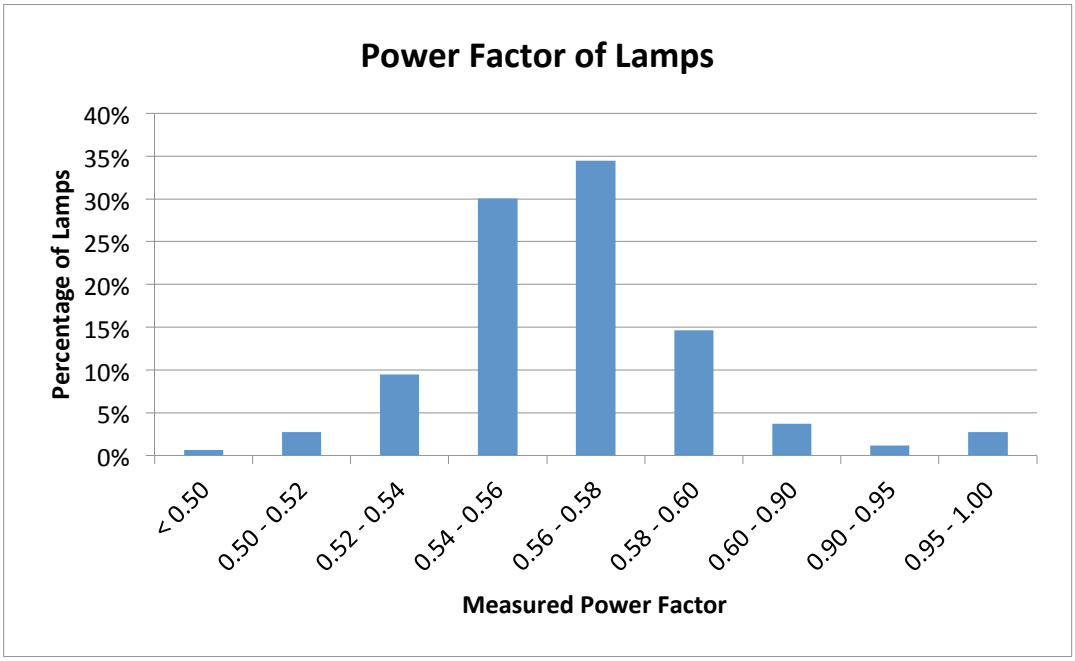


Figure 22: Power Factor of Lamps

3.3 Results Appendices

Several results appendices are included in this report in order to allow the readers to evaluate and analyze the test results. These include the following two Microsoft Excel spreadsheets:

- Appendix A: Lamp Sample Database: The Lamp Sample Database profiles all relevant test information on each of the 3,601 CFLs included in the study. This includes information on traits that are inherent to the CFL model (e.g., rated life, rated wattage, make type, etc.), information on traits that are inherent to the tests that the CFL was subjected to (e.g., switching cycles, lamp orientation, whether or not the CFL was included in the photometric experiment), and all test results (e.g., failure time, results from photometric testing, if applicable, etc.). This database allows users to easily sort and/or filter data to look at specific areas of interest (e.g., failure rates of 23W CFLs tested base-up on the 15-minutes switching cycle.)
- Appendix B: Graphing Database: The Graphing Database processes the data from the Lamp Sample Database to automatically produce several failure analysis plots. Users can adjust the input parameters to these graphs (e.g., define if x-axis is “operating hours” or “percent of rated life”; set filters that exclude specific lamps types or switching cycles, etc.). This database allows users to quickly look at “slices” of the switching cycle experimental results in order to explore specific findings and/or to inform further analysis.

4 Discussion

The switching cycle and photometric experiments documented in this report were operated for over 3.5 years – over 1.5 years longer than originally planned. This extra testing time has allowed us to collect a more complete picture of CFL failure dynamics than was originally planned. At the end of testing, 3,355 of the original 3,601 CFLs had failed, or more than 93% of the total sample.

The switching cycle experiment succeeded in its primary objective of developing quantitative relationships between CFL life and parameters inherent to the CFL (e.g., lamp model) as well as parameters inherent to the application in which the CFL is placed (e.g., cycling frequency). A key result in this area is impact of cycling frequency on CFL life (Figure 9). The relationships documented in this study can be used to estimate how much longer or shorter than their rated lives CFLs might be expected to survive for a given switching frequency.

As described in section 1.2, previous studies have estimated CFL life by comparing results from a CFL switching study (Figure 1) to metered field data on usage patterns (Figure 2). We developed updated estimates for CFL life by conducting the same analysis as this previous study but substituted the LRC switching cycle results with the results presented in this report.[19] This re-analysis yielded an average normalized lamp life of 0.547. This value is very near to that found using the LRC switching study results (0.526). Using these updated results, the expected "observed" CFL life would be slightly longer than previously estimated (5,470 hours vs. 5,260 hours for a CFL with a rated life of 10,000 hours).

We also note the following with respect to the experimental results:

- Cycling and run-time both appear to affect CFL life. At switching frequencies of less than 60 minutes, cycling appears to be the dominant parameter; at frequencies of more than 60 minutes, cycling and run-time appear to play a combined role.
- CFLs on the market at the time the sample was procured appear to be designed to accommodate 10,000 cycles or fewer over their lives. This can be seen by the convergence of the mortality curves for the 2-, 5-, 15, and 30-minute switching cycles when plotted vs. the number of cycles (Figure 8).
- Large variations in survival rates between CFL models were observed. The longest lasting models (top 10%) were found to last over four times as long as the shortest lasting models (bottom 10%), across all switching cycles (Figure 10).
- Twelve percent of ENERGY STAR models failed to pass the ENERGY STAR rapid cycle test (Figure 14) and ENERGY STAR models were not found have improved survival rates versus non-ENERGY STAR models (Figure 13).
- CFLs on the market at the time the sample was procured seem to have slightly exaggerated initial luminous flux claims, with 63% of measured lamps registering initial lumen output values that were lower than their rated lumen output values (Figure 15).
- Thirteen percent of ENERGY STAR–certified lamps failed to meet ENERGY STAR minimum efficacy levels (Figure 17).

[19] For a full description this analysis procedure, refer to the referenced ACEEE report.

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