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2013-2014 Work Order ED_I_Ltg_1: LED Lab Test Study

Final Research Plan

Submitted to:
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Introduction

As part of the portfolio of 2013-2014 Evaluation, Measurement, and Verification (EM&V) activities, the California Public Utilities Commission (CPUC) has contracted with Itron to conduct a large-scale laboratory test of the performance of light-emitting diode (LED) lamps. In the section below, we provide additional background, introduce the study team, and provide a roadmap to this research plan document.

1.1 Study Origins and Background

During the 2010-2012 EM&V cycle, the CPUC and Southern California Edison (SCE) funded a large-scale laboratory test of CFL lamps in order to address uncertainties in available estimates of CFL rated life (and therefore lifecycle energy savings and cost-effectiveness). Specifically, the CFL lab test study focused on quantifying the relationship between switching cycles and CFL lamp life.

As part of the 2013-2014 EM&V Roadmap for Lighting, the CPUC set aside $500,000 to conduct an analogous study focusing on LEDs to address the same set of core questions, specifically:[1]

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

1.2 Study Team

For this study, the key contributors to the CFL lab test study will play similar roles in order to build upon the knowledge gained and lessons learned from the previous effort – Jeorge Tagnipes (Energy Division) will be the overall CPUC project manager, Erik Page (Erik Page & Associates, Inc.) will be the lead investigator, and Jeff Hirsch (JJH & Associates, Inc.) will serve as technical advisor. Itron, as one the prime contractors for the 2013-2014 EM&V cycle, will

[1] http://www.cpuc.ca.gov/NR/rdonlyres/7350FF48-9AFC-449E-8AD2-19E520E2A7F5/0/20132014_EMV_EvaluationPlan_v4.pdf

facilitate the required contracting and provide day-to-day project management and support to Erik Page. The key members of the study team and their respective roles are summarized in Table 1-1 below.

Table 1-1: Study Team Members

Name	Organization	Role in CFL Study	Role in LED Study	Contact Information
Jeorge Tagnipes	CPUC	ED project manager	ED project manager	(415) 703-2451 jeorge.tagnipes@cpuc.ca.gov
Mike Ting	Itron	None	Prime contractor, project manager	(510) 844-2883 michael.ting@itron.com
Erik Page	Erik Page & Associates	Lead investigator, project manager	Subcontractor, lead investigator	(415) 448-6575 erik@erikpage.com
Jeff Hirsch	JJH & Associates	Contract manager, technical advisor	ED consultant, technical advisor	(805) 553-9000 James.J.Hirsch@gmail.com

1.3 Team Roles

Jeorge Tagnipes will manage the study on behalf of the CPUC. Mr. Tagnipes will also facilitate coordination and outreach activities with LED stakeholders and across related studies in the Lighting Roadmap.

The bulk of the study will be executed under the direction of Erik Page and Mike Ting (Itron), with strategic guidance from Jeff Hirsch. Specifically, Mr. Page will be leading the following activities:

- Development of the experimental design and the overall research plan
- Selection, training, and oversight of the testing facility
- Development of the final analysis and reporting deliverables

Mr. Ting will be responsible for the following activities:

- Day-to-day project management
- Development of the sample design
- Procurement of the test samples
- Supporting analysis of the test results and final reporting deliverables

1.4 Roadmap to Research Plan

The remainder of this document presents the specific research objectives, experimental design, sample design, analysis, and reporting proposed by Itron and Erik Page & Associates to meet the highest-priority needs of the CPUC, the IOUs, and the larger LED industry.

The report sections are organized as follows:

- **Section 2** provides an overview of the programmatic context for LEDs in California and an assessment of the most pressing knowledge gaps in the LED industry as a way to frame the specific research objectives defined for this study
- **Section 3** provides an overview of the proposed experimental design
- **Section 4** provides an overview of the proposed sample design and test sample procurement approach
- **Section 5** provides an overview of the proposed test lab selection, engagement, and management approach
- **Section 6** provides an overview of the proposed data analysis and reporting deliverables
- **Section 7** provides an overview of the specific tasks, task budgets, and milestone schedule associated with the proposed research plan and an overview of the proposed study coordination and technical advisory activities
- **Appendix A** provides the written input submitted by PG&E in response to the CPUC's request for input related to defining the research objectives for this study
- **Appendix B** provides the written input submitted by SCE in response to the CPUC's request for input related to defining the research objectives for this study
- **Appendix C** provides a detailed analysis of the impact of retail channel on CFL lamp performance

2

Research Objectives and Scope

In this section, we provide an overview of the larger technology, regulatory, and programmatic context within which this LED lab test study will be conducted. We then draw from these contexts to frame the specific research objectives defined for this study.

2.1 LED Market Context

The LED lamp market has been evolving and expanding rapidly over the last decade. Shipments of omnidirectional LED lamps grew by a factor of 50 from 2008 to 2012, and shipments of directional LED lamps grew by a factor of nearly 100 over the same period.[2] At the same time, the luminous efficacy of LED replacement lamps (lumens per watt) has steadily increased (from an average of 40 lm/W in 2008 to 65 lm/W in 2012), and average prices have steadily decreased (from $250/klm in 2008 to $40/klm in 2012). These trends are expected to continue going forward, with average prices expected to drop by another 50% over the next two years and average lamp performance expected to exceed 200 lm/W by 2020.[3]

Clearly then, the dynamic nature of the LED lamp market must be taken into account when designing a large-scale lab test in order to avoid or minimize the prospect of testing products that are no longer available by the time the study is completed. Further complicating this issue is the fact that the rated useful life of LED replacement lamps is significantly longer than analogous CFL lamps – typically 25,000 hours or longer – which adds to the tension between the time needed to design and execute a large-scale lab test and the dynamic nature of the LED market.

2.2 National Program Context

There are three national programs that currently support high-performance LED replacement lamps – the U.S. Environmental Protection Agency's (USEPA) Energy Star program, the U.S. Department of Energy's (USDOE) LED Lighting Facts program, and the USDOE's Commercially Available LED Product Evaluation and Reporting (CALiPER) program. All three of these programs feature standardized laboratory testing of LED replacement lamps to establish compliance with voluntary product specifications (Energy Star), independently verify

2 http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led-adoption-report_2013.pdf

3 http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_trend-analysis_2013.pdf

manufacturer claims (Lighting Facts), or track trends in product performance over time (CALiPER). In this respect, we wanted to avoid duplicating the tests performed (and information generated) under those three programs and identify LED lamp performance issues that are not adequately addressed with the current suite of standardized tests.

2.2.1 IES Test Procedures

All three of the national programs listed above rely on industry-standard tests promulgated by the Illuminating Engineering Society (IES) that are focused on measurements of initial photometric performance (LM-79-08) and lumen maintenance over time (LM-80-08 and LM-84-14). LM-79 provides a wide range of photometric performance data (e.g. lumen output, luminous efficacy, color temperature, color rendering index, etc.) on a snapshot basis. LM-80 focuses on producing standardized measurements of lumen maintenance over time for LED light sources, which can then be used to estimate and verify total useful life using a projection formula developed and published by IES in 2011 (TM-21-11). The recently adopted LM-84 is similar to LM-80 but includes LED lamps and Luminaires in its scope, recognizing that components in these systems other than the LED light sources may also impact lumen maintenance. IES has also recently released TM-28-14 which provides methods for projecting lumen maintenance for LED lamps and luminaires based on LM-84 test results.

Energy Star and Lighting Facts use IES test procedures in order to essentially verify manufacturer claims of LED replacement lamp performance.[4,5] As such, the testing required under these two programs has produced a comprehensive source of test-based, basic product performance data. Light Facts, for example, currently has verified performance data available for over 5,000 commercially available LED replacement lamps.

However, in order to assess the relative value of that collective set of product performance data, we must view the current set of data based on IES procedures for what it is – a comprehensive set of performance data that reflects pre-specified, constant, laboratory conditions. Additionally, the total useful life estimates generated from LM-80 and TM-21 as well as LM-84 and TM-28 are defined strictly in terms of lumen maintenance levels over time and do not reflect any projections or estimation of catastrophic failure rates.

2.2.2 CALiPER Stress Testing

The CALiPER program has largely conducted lab testing of LED lamps (using IES test procedures) to support longitudinal analyses of LED market trends, especially related to basic photometric performance and price. In recent years, however, the CALiPER program has also

4 https://www.energystar.gov/sites/default/files/ENERGY%20STAR%20Lamps%20V1%201_Specification.pdf

5 http://www.lightingfacts.com/About/Content/VTPolicy

begun to focus on stress testing LED lamps, i.e. examine photometric performance and catastrophic failure under more variable and extreme operating conditions.

In December 2014, the CALiPER program published the results of its first two stress tests. The first focused on measuring the performance of PAR38 LED reflector lamps under simultaneous exposure to a range of voltage, vibration, temperature, and humidity conditions (as opposed to isolated exposure to each condition individually).[6] The second focused on measuring the performance of LED A-lamps when connected a range of different phase-cut dimmers in order to identify compatibility issues and undesirable behaviors such as noise and flicker.[7]

Both of these CALiPER studies made important contributions to the LED testing literature in that they focused on measuring LED lamp performance under variations in operating conditions (the PAR38 study) and performance in typical system configurations (the A-lamp study). However, CALiPER's stress test studies were limited to very small sample sizes which limit the applicability of their results to the larger market of LED lamp products.[8]

2.3 California Program Context

In addition to the national programs summarized above, there are a host of regulatory and program issues specific to California that are critical to take into account when defining the research objectives for this LED lab test effort. Below we provide an overview of the specific regulatory and program context in which LED replacement lamps are promoted through utility rebate programs in California.

2.3.1 Voluntary California Quality LED Specification

In December 2012, the California Energy Commission (CEC) adopted the *Voluntary California Quality LED Specification* (CA Quality Spec) that established performance standards to help identify and promote high quality LED lamps.[9] The impetus behind the development and adoption of the CA Quality Spec was born directly from California's collective experience with compact fluorescent lamps (CFLs), where public perceptions of CFLs were severely tainted by early customer experiences with poor product quality, e.g. light color, flicker, noise, lack of dimmability, and early failure.

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6 http://energy.gov/sites/prod/files/2015/01/f19/caliper_20-3_par38.pdf

7 http://energy.gov/sites/prod/files/2015/01/f19/caliper_retail-study_3-1.pdf

8 The PAR38 study tested a total of 44 lamp models. The A-lamp study tested a total of 15 lamp models in combination with 4 dimmer products.

9 http://www.energy.ca.gov/2012publications/CEC-400-2012-016/CEC-400-2012-016-SF.pdf

In order to avoid the pitfalls experienced with CFLs and help ensure that early customer experiences with LEDs are positive (and lead to additional LED purchases), the CEC designed the CA Quality Spec to focus on six specific attributes of LED lamp quality:

- Color temperature
- Color consistency
- Color rendering
- Dimmability
- Rated life/warranty
- Light distribution

Relative to the Energy Star product specification for LED lamps, the CA Quality Spec uses the same core set of photometric performance criteria and the same test methods as Energy Star. The key exceptions that differentiate the CA Quality Spec from the Energy Star criteria for LEDs are summarized in Table below.

Table 2-1: Summary of Key Differences between Energy Star Product Criteria and California Quality Specification for LED Lamps[10]

Performance Metric	Energy Star Criteria	CA Quality Spec Criteria
Color Rendering Index (CRI)	≥80	≥90
Warranty Period	≥3 years	≥5 years
Dimmability	Lamps claimed as dimmable must dim to 20% of max light output	All lamps must dimmable to 10% of max light output
Power Factor	≥0.7	≥0.9
Noise	n/a	Must operate free of noise through full dimming range

It is also important to note that the CA Quality Spec excludes several criteria that are included in the Energy Star specification, most notably luminous efficacy. The CEC rationalized this exclusion by noting that the range of LED efficacies available on the market (at that time) was narrow and that minor variations in efficacy were secondary to customer perceptions of product quality compared to attributes such as color rendering, noise, etc.

As part of the development and adoption of the CA Quality Spec, the CEC also identified the highest priority research needs related to supporting future revisions to the CA Quality Spec:

[10] Note that the CA Quality Spec also include minor differences (compared to Energy Star) with respect to the light distribution requirements specifically for floodlights and narrower tolerances for color temperature requirements.

- Development of a practical measure of visual and nonvisual flicker and noise from LEDs and other light sources, including a measure of color flicker in addition to brightness flicker
- Development of an improved color quality metric, to be based on studies of residential consumers
- Development (if necessary) of an LED life-testing method that emulates the power quality found in homes (low power quality test), along with typical residential switching patterns and thermal environments
- Agreement on how LED life testing (using the IES LM-80 and TM-21 methods) should account for early failure and midlife failure of LED sources
- Development of a standard for color shift of LEDs when they are dimmed, to replicate the color shift that consumers are accustomed to for incandescent lamps
- Ongoing market surveys and consumer research to determine if a future specification shall require an even narrow tolerance range for color temperature performance

The CEC has since made one revision to the CA Quality Spec, which was finalized and adopted by the CEC on January 15, 2015. The revisions to the CA Quality Spec were minor in scope and focused exclusively on aligning the specification with the revisions to the Energy Star product criteria that were adopted by the USEPA in September 2014.[11]

To supplement the CEC's written positions with respect to high-priority research needs, we also conducted an informal interview with Ken Rider of the CEC (Appliances and Existing Buildings Office, Efficiency Division), who helped author the CA Quality Spec. Mr. Rider indicated a strong need to assess the performance of the most direct "competitors" to CA Quality Spec-compliant lamps, which are perceived to be the lowest-priced, non-compliant LED lamps, in order to identify product quality and performance issues not currently addressed by the CA Quality Spec or Energy Star.

2.3.2 CPUC Regulatory Context and Objectives

Shortly before the CEC had finalized and adopted the first version of the CA Quality Spec, the CPUC issued a decision (D.12-05-015) as part of the larger energy efficiency proceeding (R.09-11-014) that required the investor-owned utilities' (IOUs) LED program offerings to be compliant with the CA Quality Spec.[12] Specifically, the decision required all of the LED lamps

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11 http://www.energy.ca.gov/appliances/led_lamp_spec/documents/2014-12-10_Resolution_Voluntary_California_Quality_Led_Lamp_Specification_Resolution_No_14-1210-09_TN-74289.pdf

12 http://docs.cpuc.ca.gov/PublishedDocs/WORD_PDF/FINAL_DECISION/166830.PDF

offered through the IOUs' statewide upstream lighting program to be compliant with the CA Quality Spec, once it had been finalized and adopted by the CEC.

A subsequent CPUC decision (D.12-11-015) clarified that, in order to allow adequate time to prepare new offerings, the IOUs were allowed one year (from the time the CA Quality Spec was adopted by the CEC) to transition the LED products in their upstream lighting program to be only products in compliance with the CA Quality Spec.[13] Pursuant to this decision, the IOUs have been offering only CA Quality Spec-compliant LED products in their upstream lighting program since January 2014. In the CPUC regulatory context, therefore, the CA Quality Spec is an important lens through which to assess and identify the highest priority research objectives for this LED lab testing effort.

In addition to this, the CPUC also expressed the following high-level objectives that this LED lab test study should be designed to address:

- Generate results that can help inform updates to ex ante estimates of effective useful life (EUL) and energy savings impacts for LED replacement lamps
- Generate results that can help inform the design and evaluation of IOU upstream lighting programs for LED replacement lamps
- Generate results in the near-to-midterm (6-12 months) in order to inform 2016 program offerings and avoid maintain pace with a rapidly evolving LED market

2.3.3 IOU Perspectives and Program Needs

As part of the development of this research plan, we solicited open-ended, written input from the electric IOUs in California. In response to this request, representatives from PG&E and SCE provided their collective perspectives on the highest-priority research needs related to a large-scale laboratory test of LED replacement lamps.[14] We then conducted follow-up interviews with the same representatives from PG&E and SCE in order to get more clarity on particular responses and discuss their overall perspectives in more depth.

Although some of the specific commentary and responses differed, one area of strong consensus between PG&E and SCE was the need to conduct testing under a wider range of field conditions with an eye towards identifying field conditions that lead to catastrophic failure of LED lamps and not just decreased lumen maintenance. SCE noted that the life of LED lamps will be affected by application, ambient conditions, and use-cycle pattern. Similarly, PG&E pointed to the need to assess LED useful life under ranges of temperature, humidity, voltage, and switching

[13] http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M034/K299/34299795.PDF

[14] See Appendices A and B for the complete responses provided by PG&E and SCE, respectively. Note that Appendix A includes the solicitation letter from the CPUC.

conditions that are likely to occur in real world applications. In our follow-up discussions, both PG&E and SCE made it clear that their perspectives are rooted in the overriding context of trying to ensure a positive customer experience with LED technology in general.

SCE also called out interactions with LED controls (sliding dimmers, step dimmers, 3-way switches, occupancy sensors, etc.) as a potentially important source of early, catastrophic failure and recommended that this LED lab test study examine that specific dimension and include performance testing over each product's claimed dimmable range.

2.4 Current Knowledge Gaps Related to LED Performance and Performance Testing

We also solicited informal input from a wide variety of LED industry stakeholders and experts nationally and internationally. These included the Natural Resources Defense Council (NRDC), the National Electrical Manufacturers Association (NEMA), the Lighting Research Center (LRC), the USEPA Energy Star program, the USDOE, the International Energy Agency's 4E Solid State Lighting (SSL) Annex, RTI International, and the California Lighting Technology Center (CLTC). We also received informal input from some manufacturers of LED lamps, systems, and luminaires. The subsection below provides a high-level summary of the feedback we received as a result of this outreach.

RTI International is studying the reliability of integrated SSL luminaires and accelerated test methods for LED devices under funding from the USDOE.[15] They indicated that some of the methods they had piloted in stress testing of LED luminaires provide a guide for methods that could be used in evaluating LED lamps. However, more study is needed to determine the best methods for lamp testing. They indicated they had some internal evaluation of LED lamps on a very small sample and might release results later in 2015. They recommended considering conducting "post-mortems" on failed LED lamps to determine failure modes and suggested that there may be opportunities for partnerships for this effort. The details on this partnership have yet to be determined.

NRDC stated their support for testing a wide cross-section of LED lamps initially and then over time at standard (e.g. IES) test conditions as well as at conditions more likely to stress lamps (e.g. high heat and humidity) in attempt to quantify the impact of ambient conditions.

NEMA felt that existing testing provided at the national level by the USDOE and by the manufacturing community was sufficient and raised concerns that added state-level regulations could slow LED market growth.

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[15] For more information on the research being conducted by the USDOE's LED Systems Reliability Consortium see: *http://energy.gov/eere/ssl/product-performance-guides*

CLTC indicated that they had conducted life testing on directional and omnidirectional LED lamps and would be willing to collaborate where appropriate.[16]

LRC indicated that based on their laboratory studies, they found power and thermal cycling (of a certain pattern) were critically important to LED lamp life testing. They indicated they had recently initiated a 2-year evaluation of this impact on a small-medium sized sample of several LED system types (lamps, light engines, and integrated downlights) for the Bonneville Power Authority (BPA) and NYSERDA with the goal of developing a suitable accelerated test method for predicting LED system life.

USEPA agreed that testing "real-world" conditions would be valuable and would add to the knowledge base. They specifically recommended focusing on testing LED lamps at high heat.

4E SSL Annex supported the effort to test in real-world applications and specifically at elevated temperatures with thermal cycling. They indicated that similar testing may be initiated soon in Sweden.

LED manufacturers gave several indications that LED lamp testing may be more valuable than LED light source testing (e.g. LM80), as the LED drivers are believed to be common failure point. Luminaire manufactures expressed some concerns that LED lamps can reach temperatures inside recessed and enclosed luminaires that not only compromise the LED lamp's performance but may also exceed relevant UL requirements.

2.5 Research Objectives Defined for CPUC Study

Given the market, regulatory, programmatic, and knowledge gap contexts summarized above, we then attempted to refine the high-level objectives set forth by the CPUC in the 2013-2014 EM&V Roadmap for Lighting into a more specific set of research objectives around which we could develop a coherent experimental design, sample design, and analysis plan.

At the highest order, the research objectives must be achievable within the total budget and time constraints defined for this study. Specifically, this translates into a total scope of effort that cannot exceed $500,000 and generates results that can inform 2016 program offerings.

Secondly, we have a clear obligation to focus the research objectives on assessing the performance of CA Quality Spec-compliant products against their non-compliant competitors in order to align our efforts against the regulatory and program environment in California.

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[16] For more information on CLTC's research in this area see: http://cltc.ucdavis.edu/publication/performance-testing-report-omni-directional-led-replacement-lamps and http://cltc.ucdavis.edu/publication/directional-led-lamps-laboratory-testing-program

Third, there was a strong consensus across the IOUs, the CEC, and other LED industry stakeholders around the need for stress testing LED lamps in conditions beyond those reflected in current industry-standard tests in order to identify conditions that cause early/catastrophic failure. The specific stress conditions identified by stakeholders and in the research literature as potentially important were temperature, humidity, switching patterns, voltage, vibration, and interactions with controls (particularly dimmers).

Given this consensus, we then assessed the scope of stress testing that could be feasibly executed within the budget and time constraints of this study. This assessment indicated, not surprisingly, that we face significant tradeoffs between the scope of the testing (i.e. number of experiments) and the scope of the test sample (i.e. the number of lamps). More specifically, the authorized budget can support either a limited number of experiments (i.e. 2-4) across a large, representative sample of lamps or a broader set of experiments across a much smaller sample of lamps. The tradeoff we face, therefore, is between generating a narrow, focused set of results based on representative samples and generating a wider range of results based small, anecdotal samples.

When viewed through the lens of the larger body of LED research, conducting a large-sample test of narrowly-defined stress conditions would complement the small-sample, more extreme/multi-dimensional stress testing recently done/being done by CALiPER, LRC, CLTC and others. When viewed through the lens of IOU programs in California, conducting a large-sample test of narrowly-defined stress conditions would allow the IOUs and the CPUC to use the results of the tests to make regulatory and program design decisions with more certainty over the immediate term (i.e. 2016) than a small-sample test of more widely-defined stress conditions where follow-on tests (and funding) would likely be required to establish statistical validity.

We also attempted to assess which stress condition (among those identified by stakeholders) is most prevalent in residential homes in California and also most tractable to evaluate in a laboratory setting. Of the six specific stress conditions identified by stakeholders, we agree with stakeholders that high operating temperature and thermal cycling (due to specific switching patterns) are the two most prevalent stress conditions in California homes and the most tractable to evaluate in a laboratory setting using a limited number of experiments, which would allow the test to administered to a large, representative sample of lamps.

We acknowledge the potential importance of analyzing the other stress conditions identified in the research literature and by stakeholders. In particular, we acknowledge the potentially important interactions with dimmers and controls (per SCE’s input), especially given the emphasis of dimmers and occupancy sensors in Title 24. However, due to the number of experiments that would be required to get comprehensive results, we would necessarily be limited to testing very small samples of lamps.[17] This would in turn limit our capacity to defensibly compare the performance of CA Quality Spec lamps against non-compliant lamps under those conditions.

Given the assessments summarized above, the specific research objectives defined for this study are therefore:

- To assess the effect of temperature and switching patterns (thermal cycling) on the performance (efficacy, color quality, useful life, etc.) of a representative sample of LED replacement lamps
- To assess differences in performance (under the test conditions above) between CA Quality Spec-compliant LED replacement lamps and their cheapest, non-Spec competitors

The next section presents a summary of the proposed experimental design developed to support these specific research objectives.

[17] In order to assess the impact of interactions between lamps and dimmers/controls, we would likely need to test each lamp model with multiple types of dimmers/controls, each set at multiple output levels (e.g. 100%, 80%, 60%, 30%, and 10%). Given the diversity of dimmer/control products available, this quickly leads to 25+ experiments per lamp model tested, without accounting for luminaire/application type.

3

Experimental Design

In this section, we describe the experimental design proposed for this LED lab test study. This discussion first focuses on some of the technical and budgetary factors that were considered when developing the proposed experimental design. Next, we present the proposed experimental design and test methods themselves in some detail. Lastly, we provide a brief discussion of potential follow-up testing.

3.1 Overview of Experimental Approach

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

We propose to document the impact of operating conditions on LED lamps by subjecting a representative sample of LED lamps to a variety of operating conditions thought to be typical of residential application. There are a variety of field conditions identified by stakeholders that may stress LED lamps and consequently impact their life and/or performance. These include high temperature operation, thermal cycling (e.g. the change in temperature a lamp experiences between its on-state and its off-state), voltage variations, high humidity, and dimming.

Ideally we want to test a representative sample of LED lamps for each parameter evaluated. Each sample would be tested by varying one parameter at a time, while fixing all other parameters (e.g. testing LED lamps at high heat while holding all other parameters at IES conditions). Such an approach would allow us to isolate the impact of each parameter independently. Unfortunately, each additional parameter evaluated proportionally increases costs associates with sampling and testing. Given a fixed budget, increasing the number of parameters evaluated necessitates decreasing the number of LED lamps tested per parameter. Based on our initial estimates of the anticipated cost for sample procurement and testing, we determined that an experiment focusing on more than three parameters could necessitate a sample size of LED lamps so small that it may no longer be considered representative.

Consequently, we propose to initially focus on parameters most likely to impact LED lamp life and performance. Specifically, we propose to initially focus on two parameters – high heat and thermal cycling. Stakeholder feedback and prior studies suggest that few parameters are likely to be as impactful temperature variations. The specific details of the proposed test are discussed below in Section 3.2.

We estimate that sampling and testing LED lamps on these two parameters for a 12-month period will cost approximately $200,000 including analysis and reporting.[18] Accordingly, an initial test of this size would allow a significant portion of our total authorized budget to be withheld for additional, follow-on testing as the project advances. This would allow us the flexibility to adjust follow-on phase of testing based on knowledge acquired during initial testing, additional CPUC and stakeholder feedback, and any significant changes that have occurred in the greater LED lamp market. Section 3.3 provides an expanded discussion of what additional testing would be considered.

3.2 Test Procedure

We propose to operate LED lamps according to the operation conditions defined in IES LM-84, except as specified in this section below. LED lamps would be operated at elevated temperatures and with full thermal cycling (e.g. LED lamps turned on for warm-up and then turned off for cool-down) for extended periods of time. This portion of the test is referred to as “maintenance testing” and is describe in Section 3.2.1 below. Periodically, this maintenance testing would be suspended, and the LED lamps would be measured according to IES LM-79. This portion of the test is referred to as “photometric testing” and is described in section 3.2.2 below.

3.2.1 Maintenance Testing

Rather than operating lamps continuously at 25°C ± 5°C in open air, as specified in IES LM-84, we propose to cycle LED lamps inside luminaires typical of residential application. In these applications, the heat generated by the LED lamps will likely result in the lamps operating at temperatures higher than those specified by LM-84 but at temperatures that are more representative of field application. A room-ambient temperature (e.g. the temperature of the room in which the test luminaires are housed) of 25°C is proposed, with humidity levels maintained at 50 ± 5% and airflow minimized. Note that we may need to expand the tolerance levels for temperature and/or humidity depending on the relative cost quoted by testing labs.

[18] Actual cost will depend on the final details of the sample design as well the testing costs negotiated with the selected laboratory.

We propose to establish cycle timing that allows LED lamps to experience nearly their full thermal cycle while maximizing the number of cycles experienced per day. Because lamp temperatures can be expected to change rapidly after initial switching and then more slowly near stabilization, this may mean allowing lamps to reach 90-95% stabilization rather than full stabilization in order to increase the number of thermal cycles evaluated. We propose to investigate the potential of running a "pre-test" on each LED lamp model and luminaire model combination to determine optimized cycle timing for that combination and using this information customized cycling timing for the LED lamp models included in maintenance testing.

We propose to select three specific models of luminaires to house the LED lamp models under test. The selection of these specific luminaires is based on two specific criteria:[19]

- Prevalence: Luminaires that represent those most commonly used in residential applications and in which LED lamps are likely to be placed.
- Temperature: Luminaires likely to lead to LED lamps to operating over the full range temperatures experienced in residential applications.

Table 3-1 summarizes these three attributes for the most commonly used residential luminaire types. The values in the "prevalence" column are calculations of the percentage of all A-lamp, spiral, and reflector lamps by luminaire type from the 2012 California Lighting and Appliance Saturation Survey (CLASS).[20] The temperature column represents our estimate of the relative temperature that LED lamps are likely to be operated at by luminaire type.

Table 3-1: Summary of Prevalence and Temperature by Luminaire Types

	Prevalence	Temperature
Ceiling Mount	18.9%	Medium
Wall Mount	20.5%	Medium
Floor/Table	15.6%	Low
Ceiling Fan	11.0%	Low
Suspended	5.6%	Low
Recessed	22.9%	High
Other	5.5%	N/A

[19] Ideally, we would also include average hours of use as a criterion in order to properly weight luminaire types with the highest usage rates. However, the recent lighting logger studies conducted in California do not provide the granularity required with respect to luminaire type to align with the luminaire types shown in Table 3-1.

[20] Available at: https://websafe.kemainc.com/projects62/Default.aspx?tabid=190

Based on the above analysis, we recommend the following three luminaire types for testing:

Recessed Downlight

This application sees that vast majority of reflector lamp application as well as 10% of A-lamp LED applications.[21] This application represents the most extreme temperature conditions and also has significant operating hours. Figure 3-1shows a typical 6" recessed downlight designed for insulated ceiling environments. In recognition that this luminaire typically housed in non-controlled spaces and covered by insulation, we recommend this luminaire is placed in a 30°C ± 5°C environment and covered in insulation during maintenance testing.

Figure 3-1: Example of Recessed Downlight

Enclosed Ceiling Fixture

Along with wall mount luminaires, this application is the most popular for A-lamp replacement lamps. Ceiling fixtures are recommended over wall fixtures because the temperatures are expected to be higher (though still lower then recessed downlights). Figure 3-2 shows an example of the type of luminaire being considered. In order to harmonize with IES test procedures and in recognition that this luminaire is typically housed in temperature-controlled spaces, we recommend this luminaire is placed in a 25°C ± 5°C environment.

[21] See http://www.calmac.org/publications/WO13_CA_Res_Ltg_Mkt_Status_Report_-_FINALES.pdf

Figure 3-2: Example of Enclosed Ceiling Fixture

Bare Socket

The last "luminaire type" is not a luminaire at all but rather a bare socket. This application is recommended because it can serve as a good proxy for table and floor lamps as well as non-enclosed ceiling and wall mounted luminaires. This application would also represent the lowest temperature application that LED lamps might be expected to operate in. Half of the bare sockets would be base down (e.g. floor, table lamps), and half would be base up (e.g. ceiling mount). Figure 3-3 shows an example of a bare socket being considered. In order to harmonize with IES test procedures and in recognition that this luminaire typically housed in temperature-controlled spaces, we recommend this luminaire is placed in a 25°C ± 5°C environment.

Figure 3-3: Example of Bare Socket Fixture

Because of their design and normal application, there may be some LED lamp models which would only be tested in one or two luminaires. For example, a reflector LED lamp might only be tested in a downlight because its field application in the other luminaire types (e.g. table lamp or enclosed ceiling fixture) is considered unlikely. We may consider testing some LED lamps in applications that they are not labeled for if we consider their application in these applications to be likely (e.g. testing an omni-directional LED lamp labeled "not for use in enclosed fixtures" in an enclosed fixture).

During maintenance testing, the temperature of critical points on each LED lamp and inside each luminaire will be monitored. Temperature measurement points will be determined based on manufacturer literature and/or based on the recommendations detailed in Annex A of IES LM-84. The cumulative run time and number of thermal cycles experienced would be recorded for any LED lamps that fail catastrophically during maintenance testing.

It should be noted that we considered an alternative approach whereby rather than testing inside luminaires, we would operate lamps in open air at elevated temperatures (e.g. in a thermal chamber) which were representative of field application. We rejected this approach for two reasons. First, documentation is lacking on the temperatures typically encountered by LED lamps in field application making it difficult to select appropriate elevated temperature ranges. By testing inside luminaires, not only do we no longer need to know these temperature ranges to design the test, we would have the opportunity to document typical temperatures of LED lamps and their near-ambient temperature in luminaires. Second, specific LED lamps are likely to operate at different ambient temperatures in field application. For example, a 12-watt LED lamp is likely to operate at a higher ambient temperature than a 7-watt LED lamp for given application because the heat from the lamp will have a great impact of its near-ambient environment. While the impact of this difference would be lost in an open-air, elevated temperature test, these effects could be documented when operating LED lamps inside luminaires.

A discussion of the analysis and expected results from the maintenance testing is presented in Section 6.

3.2.2 Photometric Testing

We propose to conduct photometric testing on each functioning LED lamp in the study before the maintenance testing is initiated and every three months during the maintenance testing period.[22] LED lamps would be removed from their luminaires and tested in an integrating sphere according to LM-79.[23] Photometric and electrical measurements would include: power input, lumen output, power factor, total harmonic distortion (THD), color rendering index (CRI), and correlated color temperature (CCT). If budget allows, LED lamp flicker and hum will also be measured.

As noted earlier, LED lamp performance is likely to be impacted by the operating conditions inside the luminaires used for maintenance, i.e. the higher temperature experienced inside the

[22] We may consider conducting more frequent photometric testing early in the test period and then transitioning to less frequent testing later if initial lumen maintenance trends support less frequent testing. The testing schedule and the number of test periods may also be influenced by the testing costs quoted by testing laboratories, (i.e. lower than anticipated testing costs may allow for more frequent testing or vice versa).

[23] Note that we will also evaluate (depending on cost) the possibility of conducting a sub-set of the photometric tests on lamps within luminaires in order to characterize the possible impact of in-situ conditions (i.e. luminaires) versus test chamber conditions on photometric performance.

luminaire would likely generate lumen output values which would be lower than those when tested at the 25°C condition specified by LM-79. Given this, we considered conducting photometric testing inside luminaires, rather than per LM-79. We decided against this approach primarily because we are more concerned with documenting the long-term impact of these field operating conditions have on LED lamps, and we felt that periodic testing of the LED lamps themselves per LM-79 would be more accurate for this purpose.

A discussion of the analysis and expected results from the photometric testing is presented in Section 6.

3.3 Follow-up Testing

We expect that after the initial 12-month testing period (Phase 1) there will be significant funds remaining for additional follow-up laboratory testing (Phase 2). Rather than committing those remaining funds to specific testing now, we believe it is prudent and strategic to maintain budget flexibility. As mentioned earlier, follow-up testing may be impacted by a number of variables including knowledge acquired during initial testing, additional CPUC and stakeholder feedback, and any significant changes that occur in the rapidly evolving LED lamp market. Follow-up testing would likely involve one or more of the following:

- <u>Extension in initial testing, if needed</u>: While we expect to gather valuable insights on the thermal parameters discussed above during the initial testing period, it is difficult to estimate with certainty the ideal duration of this test. It depends in part on how rapidly the LED lamps fail and/or decay. It is possible that an extension of the test could be beneficial for analysis. Holding back roughly half of the testing budget will allow researchers to weigh the relative value of extending the initial test against committing funding to other tests (e.g. evaluating other parameters). This evaluation will be more meaningful when informed by the test results gathered during the initial testing period.
- <u>Evaluation of additional parameters with matching sample composition</u>: We propose to "over-sample" initially so that we can set aside some number of unused LED lamps for future testing. Specifically, we propose to purchase enough LED to allow two additional parameters to be evaluated later using the same sample composition of LED lamps as the original test. This would allow for additional parameters to be tested later and results to be compared to the initial test results while minimizing concerns that observed results are influenced by differences in the sample composition. We feel the modest incremental cost of increasing the sample would be justified by the added flexibility of having a comparable sample available for future use, if needed. Other parameters that have been mentioned by stakeholders and may be considered for follow-up testing include: voltage variation, dimmer interaction, humidity variations, and exposure to vibrations.

- Evaluation of same and/or additional parameters with updated sample composition: Since the LED lamp market is evolving rapidly, there may be value in procuring a fresh sample of LED lamps for the follow-up round of testing. Retaining testing funds to procure and test an updated sample of LED lamps would allow researchers to document the changing LED marketplace. If new testing focuses on evaluating parameters not evaluated in the initial test, care would need to be taken to differentiate between changes associated with changes in sample design and changes associated with experimental design. Note that it may be possible to utilize a subset of the over-sampled lamps procured from the original Phase 1 sample as a control to help with this evaluation.

4

Sample Design and Procurement

In this section, we present an overview of the proposed sample design for the LED lab test study and our proposed sample procurement approach.

4.1 Current LED Market Shares and Trends

As noted earlier in Section 2, the LED lamp market has been evolving and expanding rapidly over the last decade. Shipments of omnidirectional LED lamps grew by a factor of 50 from 2008 to 2012, and shipments of directional LED lamps grew by a factor of nearly 100 over the same period.[24] In order to develop a sample design that enables us to select and procure test lamps that are representative of the current market for LED replacement lamps, we first assembled as much primary and secondary data on the relative market shares of LED lamp products (both nationally and California-specific) that were readily available, i.e. the relative market share of LED A-lamps compared those for LED reflector lamps, globe lamps, candelabra lamps, etc.

We began by examining all of the California-specific market data available through recent 2010-2012 EM&V studies. These data included on-site survey data collected as part of the Commercial Saturation Study (WO24) and the Downstream Lighting Impact Evaluation (WO29), point-of-sales (POS) data acquired for the Residential Market Share Tracking Study (WO23), IOU standard program tracking (SPT) data (for both the 2010-2012 and 2013-2014 program cycles), and retail lighting shelf survey (RLSS) data collected as part of the Upstream Residential Lighting Impact Evaluation (WO28). These California-specific data were supplemented with national shipment data published by the USDOE.

We then assessed the completeness, product detail, and vintage of each of these sources to determine their respective usefulness as a basis for sample design. With respect to the onsite data available from WO24 and WO29, although LED lamp model information was collected, no product characteristics were appended to each record (i.e. model lookups). In practical terms, this means that leveraging the onsite would have required additional data development (and cost) for an unknown value. With respect to the POS data available from WO23, we determined the vintage of that data (2011) to be too old to be representative of current LED market shares, given the market dynamics noted previously.

[24] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led-adoption-report_2013.pdf

This left us with three sources of meaningful LED market share data for sample design purposes – USDOE shipment data, RLSS data, and SPT data. To be clear, each of these sources comes with its own imperfections.[25] Nonetheless, they represent the most recent, comprehensive sources for estimates of LED market shares that are available. Table 4-1 presents a comparison of the relative market shares of LED lamps by type as reflected in the IOU program tracking data, the RLSS data, and the national shipment data.

Table 4-1: Comparison of Relative Market Share Estimates of LED Lamp Types

Lamp Type:	**Relative Market Shares (%)**			**Remaining Potential (TWh)**
	2013 RLSS	2012 USDOE	2014 SPT	2012 USDOE
A-lamp	33%	49%	77%	822
R/BR/PAR	30%	28%	2%	174
MR-16	3%	12%	0%	65
Globe/Candelabra/Torpedo/Night Light	33%	12%	21%	298

The key takeaway from Table 4-1 is that the current LED lamp market appears to be fairly well distributed across A-lamps, R/BR/PAR, and globe/torpedo/candelabra lamps, while MR-16 lamps appear to account for a relatively smaller share (given the aggregations shown in the table). In terms of growth trends, Table 4-1 also includes the USDOE's assessment of remaining savings potential associated with LED replacement lamps at the national level by lamp type. These potential estimates reinforce the importance of A-lamps as a focal point for IOU programs and growth sector for the LED market in general and the comparatively marginal importance of MR-16 lamps.

4.2 Sample Size and Strata

Of the three data sources shown in Table 4-1, the source with the model-specific detail required to support sample design development for this study is the 2013 RLSS data. Strictly speaking, these data represent the relative availability of different LED lamp products in California, rather than their relative sales volumes. However, in the absence of up-to-date, comprehensive POS

[25] In strict terms, the RLSS data reflect the relative availability of LED products in retail stores and not purchase volumes. Similarly, the USDOE estimates reflect the relative volume of LED products shipped from manufacturers to distributors and retailers and do not reflect actual sales volumes during that period. Finally, the IOU SPT data – which do reflect relative volumes of LED products purchased via IOU programs – suffer from a lack of detail regarding lamp type. Over 80% of the LED claims in the IOU SPT data lack information on lamp type. As such, the market shares shown in Table 4-1 are based on roughly ~20% of LED records in the SPT data.

data for LED lamps, the RLSS data represent the best proxy for relative sales volumes available for purposes of developing a sample design for this LED lab test effort.[26]

Using the 2013 RLSS data, we began defining sample strata as unique combinations of lamp type (e.g. A-lamp, globe, PAR30, PAR38, etc.), base type (medium screw base, GU, etc.), dimmability, lumen output, and color temperature. Using these strata definitions, we then examined the relative market shares of each stratum in order to identify the specific strata that account for the majority of LEDs lamps currently available in retail stores. These strata are shown in Table 4-2 below and account for 61% of the total retail availability in California in 2013. If we normalize the market shares of the strata below against the total market shares of only those lamp types (i.e. excluding lamp types with market shares <5%), the strata shown in Table 4-2 below account for 74% of the total retail availability in California in 2013.[27]

Table 4-2: Proposed Sample Strata and Their Relative Market Shares in 2013

Type/Subtype	Dimmability	Lumens	Base	Color Temp	Share of All LED Lamps	Share within Type
All A-lamps					***33.1%***	**--**
A-lamp	Dimmable	401-600	MSB (E26)	2700	3.0%	9.1%
A-lamp	Dimmable	401-600	MSB (E26)	3000	11.3%	34.2%
A-lamp	Dimmable	601-800	MSB (E26)	5000	2.0%	6.1%
A-lamp	Dimmable	601-800	MSB (E26)	2700	2.7%	8.2%
A-lamp	Dimmable	601-800	MSB (E26)	3000	1.7%	5.2%
A-lamp	Dimmable	801-1,000	MSB (E26)	5000	0.5%	1.4%
A-lamp	Dimmable	801-1,000	MSB (E26)	3000	5.1%	15.4%
All Torpedo/Bullet					***11.8%***	**--**
Torpedo/Bullet	Dimmable	1-200	MSB (E26)	2700	0.5%	4.2%
Torpedo/Bullet	Non-dimmable	1-200	MSB (E26)	2700	0.8%	6.5%
Torpedo/Bullet	Non-dimmable	1-200	Candelabra (B10)	3000	2.7%	23.0%
Torpedo/Bullet	Dimmable	1-200	MSB (E26)	3000	0.7%	6.3%
Torpedo/Bullet	Dimmable	1-200	Candelabra (B10)	3000	0.7%	6.0%
Torpedo/Bullet	Dimmable	201-400	MSB (E26)	2700	0.4%	3.5%
Torpedo/Bullet	Dimmable	201-400	Candelabra (B10)	2700	0.6%	5.4%
Torpedo/Bullet	Dimmable	201-400	Candelabra (B10)	3000	2.9%	24.7%
All Reflector					***33.7%***	**--**

[26] While it is possible to purchase POS data that includes LED lamps, such data sets are expensive to acquire and process and do not account for all retail channels through which LED lamps are sold (e.g. home improvement stores).

[27] Lamp types with market shares below 5% are: globe, BR20, MR11, PAR16, PAR20, and R40. Note that the market share for night lights is 17%. However, since the primary objective of this research is to help contribute to high levels of customer satisfaction with direct LED replacements for high-use incandescent and CFL lamps, we chose to focus our sample design on LED lamps with MSB and candelabra base types.

Type/Subtype	Dimmability	Lumens	Base	Color Temp	Share of All LED Lamps	Share within Type
All BR30						***19.1%***
BR30	Dimmable	601-800	MSB (E26)	5000	0.2%	3.9%
BR30	Dimmable	601-800	MSB (E26)	2700	5.5%	85.4%
All BR40						***10%***
BR40	Dimmable	601-800	MSB (E26)	2700	0.3%	8.1%
BR40	Dimmable	801-1,000	MSB (E26)	2700	0.3%	9.7%
BR40	Non-dimmable	801-1,000	MSB (E26)	2700	0.2%	6.2%
BR40	Dimmable	1,001-1,200	MSB (E26)	2700	2.6%	76.0%
All MR16						***10.2%***
MR16	Dimmable	1-200	GU Base	3000	0.6%	17.6%
MR16	Non-dimmable	1-200	GU Base	2700	0.5%	14.9%
MR16	Dimmable	201-400	Pin Base	3000	0.3%	9.8%
MR16	Dimmable	201-400	Pin Base	5500	0.2%	5.5%
MR16	Dimmable	201-400	GU Base	3000	0.9%	27.3%
MR16	Dimmable	401-600	Pin Base	3000	0.4%	12.4%
All PAR30						***14.2%***
PAR30	Dimmable	201-400	MSB (E26)	3000	0.3%	7.0%
PAR30	Dimmable	401-600	MSB (E26)	2700	0.3%	5.7%
PAR30	Dimmable	601-800	MSB (E26)	3000	3.6%	75.4%
PAR30	Dimmable	801-1,000	MSB (E26)	5000	0.3%	7.1%
All PAR38						***15.0%***
PAR38	Dimmable	601-800	MSB (E26)	3000	0.3%	5.7%
PAR38	Dimmable	801-1,000	MSB (E26)	3000	0.6%	11.4%
PAR38	Dimmable	1,001-1,200	MSB (E26)	3000	2.5%	49.5%
PAR38	Dimmable	1,001-1,200	MSB (E26)	5000	0.3%	5.8%
PAR38	Dimmable	1,001-1,200	MSB (E26)	2700	0.2%	3.7%
PAR38	Dimmable	1,201-1,400	MSB (E26)	5000	0.4%	7.3%
PAR38	Dimmable	1,201-1,400	MSB (E26)	3000	0.3%	5.5%
All R20						***15.3%***
R20	Dimmable	201-400	MSB (E26)	2700	0.2%	4.2%
R20	Dimmable	401-600	MSB (E26)	2700	4.7%	91.0%

Strategically limiting our sampling to the 40 strata shown above allows us to concentrate our procurement and testing expenditures on the specific lamp types that account for the majority of the current market for LED replacement lamps in California.

Given the total authorized budget for this effort ($500,000), the amount we propose withholding to allow for a second phase of follow-on testing ($200,000), and the amount of funding needed to support research planning, project management, and reporting, we anticipate that the maximum budget that we can dedicate to the first phase of sample procurement and testing will be roughly $200,000. Based on that $200,000 spending cap and our current best-guess estimate of the testing costs associated with our proposed experimental plan ($200/lamp), the largest test sample that appears to be feasible is between roughly 2,200 lamps and 1,500 lamps.[28] This total sample size would allow us to procure and test 8-10 specific models within each of the 40 strata shown in Table 4-2, depending on the actual testing costs quoted by qualified test facilities.[29]

In order to support the experimental design summarized in Section 3, we propose procuring a selection of specific lamp models within each strata such that roughly 50% of the models will be compliant with the CA Quality Spec, 25% will be Energy Star qualified but not compliant with the CA Quality Spec, and 25% will be the least expensive, non-Energy Star products available.[30] Within these general three categories, we propose to use the approach summarized below to select the specific lamp models to be procured and tested:

- CA Quality Spec-compliant:
  - These products will be identified using IOU approved product lists
  - If the IOUs currently do not offer products in a given strata, then CA Quality Spec-compliant products will be identified using the CRI and warranty length criteria as shown in Lighting Facts[31]
  - If necessary, brand shares (from RLSS) will be used to identify the dominant brands within a given strata
- Energy Star qualified, but not CA Quality Spec-compliant:
  - These products will be identified using Lighting Facts
  - If necessary, brand shares (from RLSS) will be used to identify the dominant brands within a given strata

[28] This sample size estimate is based on the following assumptions: 1) $200/lamp testing cost (based on actual costs incurred in CFL lab test study and relative complexity of those experiments compared to those proposed for this effort), 2) $15-20/lamp procurement costs (based on prices of top selling products currently available at Home Depot, Lowe's, and Costco), and 3) 6 samples procured per model (3 for testing, 3 for backup and/or phase 2 testing). Note that while the USDOE requires 10 test samples per model for regulatory compliance, the previous CFL lab test study and recent CALiPER studies have shown that performance variations between samples of a model are much smaller than variations between models.

[29] Based on results from first phase of testing, we may decide that there are some subsequent tests that are more appropriate to conduct with the existing sample of lamps rather than a new sample of lamps in order to eliminate "changes in sample composition" as a source of bias. To be clear, however, this is a contingency plan, so it is possible these lamps would never actually be tested.

[30] Note that candelabra and globes do not comply with the current CA Quality Spec because of technical issues. In these cases, the sample will be composed of Energy Star and non-Energy Star products.

[31] In some limited cases, products are now being marketed as "California compliant". However, in cases where such labelling does not exist, we will use CRI and warranty length as proxies for compliance (or likely future compliance) with the CA Quality Spec.

- Not Energy Star or CA Quality Spec-compliant:
  - These products will be identified using brand shares, prices, and Energy Star label presence info from RLSS

To illustrate the approach above, we provide an example case using the stratum defined by: lamp type = A-lamp, base type = medium screw base, lumen output = 400-600 lumens, dimmability = yes, and color temperature = 2700K. This stratum accounted for roughly 15% of all LED replacement lamps stocked at retail stores in California in 2013.

We first used the list of IOU-approved products, Lighting Facts, and product cut sheets to identify the following CA Quality Spec-compliant products in this stratum:

- Cree BA19-04527OMN-12DE26-1U110
- Feit BPAGOM450/927/LED
- TCP RLAO7W27K95

To identify the Energy Star-compliant (but not CA Quality Spec compliant) products in this stratum, we first identified the dominant brands within that stratum according to the 2013 RLSS, as shown in Table 4-3 below.

Table 4-3: Brand Shares within MSB, A-lamp, 400-600 lumen, dimmable, 2700K Stratum based on 2013 RLSS

Brand	Share in Stratum
CREE	6.7%
ECOSMART	4.3%
UTILITECH	1.4%
FEIT	27.8%
SYLVANIA	0.9%
TCP	1.0%
PHILIPS	0.9%
GE	1.0%

As Table 4-3 shows, the dominant brands in this stratum are Feit, Cree, and Ecosmart. However, Ecosmart does not currently offer any Energy Star-compliant A-lamps, and neither does the next largest brand Utilitech. In this case, we move down the list until we identify a brand/manufacturer that offers Energy Star-compliant lamps. We then used the Energy Star product list to identify Energy Star-compliant products offered by those brands within that specific stratum that do not meet the CA Quality Spec.[32] In this case, the results of that process yielded the following representative products:

- Feit BPA15/LED/RP
- Cree BA19-04527OMF-12DE26-3U100
- OSRAM 6W LED A19 270

To identify the least expensive, non-Energy Star and non-CA Quality Spec-compliant products within this stratum, we used the current online price lists from Home Depot and Lowe's and cross checked for compliance using Lighting Facts and the Energy Star product list. This yielded the following representative products for this stratum:

- TCP LA527ND
- Utilitech LA450830LED

It is important to note here that the strata definitions and brand shares referenced above are based on RLSS data from 2013. DNV GL is currently conducting another wave of the RLSS in support of the 2013-2014 EM&V Roadmap for Lighting, which is on schedule to be completed in early February with results available by early March. As such, we propose using the market shares and price data from the 2015 RLSS to make the final determination of sample strata and model selections within each stratum. Additionally, we propose finalizing the total sample size after the actual testing costs required to execute our experimental design have been quoted by testing facilities. We propose to communicate the final proposed sample strata definitions, model selections within each stratum, total sample size, and testing costs via a technical memorandum to be delivered in March.

4.3 Sample Procurement

We propose to procure all of the sample LED lamps for this study "off the shelf" (i.e. via retailers), as opposed to via direct procurement from manufacturers. Several stakeholders, notably NRDC and SCE, noted the importance of using "off the shelf" procurement for this effort to eliminate the possibility of bias due to "bait and switch" tactics on the part of manufacturers.

The CFL lab test study also used an "off the shelf" procurement approach that used field staff from DNV GL to physically purchase test lamps at a sample of retail stores that was representative of the distribution of CFL sales across geographies and retail channels in

[32] We used CRI (<90) and warranty length (<5 years) as the primary identifiers of products not compliant with the CA Quality Spec.

California. The CFL lab test study team chose to use this “boots on the ground” procurement approach based on the hypothesis that some retail channels were more likely than others to receive and sell “bad batches” of lower priced CFLs from CFL manufacturers and distributors. One major consequence of this procurement approach, however, was that it was relatively costly, and the effort required roughly $80,000 to procure 3600 test lamps at an average procurement cost of $22/lamp.[33]

Given relative price premium for LED lamps (compared to CFLs), we wanted to explore opportunities to reduce procurement costs by leveraging direct online procurement (with shipping direct to testing facility to also save time) wherever possible. However, that approach assumes that such “retail channel effects” are statistically insignificant. In consultation with the CPUC, we decided to test this hypothesis using the CFL test data to determine if retail channel had any statistically significant impact on CFL lamp performance.[34] The results of this analysis indicated that retail channel did not have a statistically significant impact on CFL lamp performance. The details of this analysis are presented in Appendix A.

Since the per-unit price for LED replacement lamps is higher than that for CFLs, we recommend procuring the LED test sample using online procurement (with shipping directly to testing facility) wherever possible in order to minimize procurements costs and maximize the total sample size for this effort. To guard against potential retail channel effects that may be unique to LEDs, we will attempt to structure the online procurement so as to procure same-model lamps from multiple vendors if at all possible. It should be noted, however, that it may not be possible to procure the entire test sample using online procurement due to some LED products not being offered via online retailers. Specific examples of this situation include certain CA Quality Spec-compliant products that are only available via brick-and-mortar retailers and not yet available for online purchase and products that are branded and sold exclusively for membership clubs. In these cases, we propose to use field staff to physically purchase test lamps at the associated brick-and-mortar retailers.

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33 For perspective, the average retail price of “basic” CFL twister lamps (i.e. 10W-15W) was roughly $3/lamp during the same period, according to the results of the *CPUC 2010-2012 Ex Ante Measure Cost Study* (Itron, 2014).

34 Note that this analysis ended up not being done as part of the CFL lab test study.

5

Test Lab Selection and Management

The laboratory testing itself will be conducted by an established, independent photometric testing laboratory. This section describes the processes we propose for soliciting bids from testing laboratories, the criteria we propose for selecting a laboratory partner, and our proposed approach to managing the testing laboratory over the course of the project.

5.1 Solicitation and Selection Process

In order to determine the most appropriate testing laboratory with which to engage for this effort, we propose using a targeted solicitation and selection process. Specifically, we propose a laboratory selection process consisting of the steps described below.

5.1.1 Develop Short List of Candidate Laboratories

We propose developing a list of 5-10 independent, third-party laboratories (i.e. not affiliated with or maintained by LED manufacturers) to target for soliciting structured pricing proposals.[35] This short list of candidate testing laboratories will be based largely on Mr. Page's industry knowledge and previous experience working with third-party testing laboratories and his assessment of the laboratories that have the experience required to successfully the experimental design proposed here. Note that we will explicitly include as many qualified California-based laboratories on this shortlist as possible, per the CPUC's stated preference to engage with California-based testing facilities if possible and appropriate

5.1.2 Prepare Solicitation Document

We propose to develop a written solicitation document that specifies the core set of testing requirements needed to execute our experimental plan, solicits documentation of each laboratory's experience and capabilities, and solicits specific approaches (and corresponding costs) to execute the full-scale test. Importantly, we also propose allowing respondents some freedom to offer (and price out) specific refinements and enhancements to the experimental plan that would allow us to more cost-effectively and/or empirically achieve our research objectives.

[35] Note that there are currently 100 testing laboratories approved by the USDOE to provide verification testing for the Lighting Facts programs (http://www.lightingfacts.com/ApprovedLabs). However, the vast majority of these laboratories are affiliated with lighting manufacturers. In this sense, we do not consider manufacturer-affiliated facilities to be truly independent, third-party entities.

In this sense, we propose developing a solicitation document that strikes a balance between gathering enough information about the experience and expertise of the bidders and minimizing the burden required by bidders to respond – in order to not dissuade qualified laboratories from submitting proposals.

5.1.3 Develop Scoring Criteria

In parallel to the development of the solicitation document, we will develop a specific set of criteria against which we will then evaluate each laboratories technical and pricing proposal. In order to select the most appropriate testing laboratory to execute the experimental design described previously, we propose to evaluate candidate testing laboratories based on a set of criteria primarily focused on experience/expertise and cost.

We consider ***experience and expertise in testing LEDs*** to be paramount. The test that we are proposing varies in important ways from standard IES procedures. While we consider having a partner with significant experiment testing LEDs per IES procedures to be important, we consider a laboratory's depth of knowledge about both LED technology itself and photometry generally to be equally important, such that they can competently execute a test plan that diverges from standard procedures. And while we expect to provide a fairly precise set of testing requirements to candidate laboratories (necessary in order for them to provide meaningful price quotes), we will expect each candidate laboratory to demonstrate the specific knowledge and expertise required and will allow candidates to offer specific refinements and enhancements to the experimental plan that would allow us to more effectively address our experimental objectives.

Beyond the technical expertise specific to the testing of LEDs, the laboratory should also have demonstrated ***experience managing large, long-term testing efforts***. The logistics involved in such an experiment are considerable and may not be fully appreciated by laboratories that have only conducted smaller studies. Key logistical challenges include designing and constructing the physical testing structures, developing tracking systems for test samples, and developing data collection and analysis tools capable of storing and tracking the large volume of data the experiment is expected to generate.

Cost will of course be a key consideration as well. The exact number of LED lamps to be tested has not been specified in the experimental plan because this value is tied directly to the cost of testing per LED lamp. The larger the sample of LED lamps we are able to test, the more confidence we will be able to have that the sample is representative of the market and thus that our laboratory results themselves are representative. Given a fixed budget, laboratories that provide lower cost-per-lamp quotes (all else equal) would allow us to increase our overall number of LED lamps tested which would improve our ability to characterize the market.

We will produce a draft set of selection criteria and weights for review by the CPUC and its technical advisors. The final, approved set of selection criteria and weights will then be used in the evaluation and scoring of each proposal submitted.

5.1.4 Release Solicitation to Shortlisted Laboratories

Once the solicitation document and scoring criteria have been reviewed and approved by the CPUC, we will then release the solicitation electronically to the shortlisted laboratories. We propose to allow candidate laboratories two weeks to respond to the solicitation, although it may be necessary to extend the response window if we receive enough feedback that a 2-week response window hinders the ability of multiple candidate laboratories to respond adequately.

5.1.5 Evaluate Bids and Select Laboratory for Engagement

Once the response window has closed and/or a sufficient number of proposals have been received, we will conduct an in-depth review of all responses and score each proposal according to the selection criteria and weights developed previously. These evaluations will be conducted jointly by the study team, the CPUC, and the CPUC’s technical advisors. The proposal that is found to have the highest average score from all reviewers will be selected as the winning bidder.

5.1.6 Notify Winning Bidder and Establish Contract/SOW

The winning bidder will be notified electronically, and we will move directly to drafting a contract and a scope of work that reflects the tasks identified in the solicitation, potentially altered/amended by information included in the winning bidder’s response. We anticipate this step will take up to 4 weeks to complete, but it could take less time if there are minimal differences between the bidder’s response and the original solicitation or longer if major differences are present.

Table 5-1 below summarizes the solicitation process presented above our estimates of the time required for each step. Overall, we estimate that the proposed solicitation process will require approximately 2 months to complete before work can begin.

Table 5-1: Summary of Proposed Solicitation Process and Timeline

Step	Time Required
Develop Short List of Candidate Laboratories	1 week*
Prepare Solicitation Document	2 weeks*
Develop Scoring Criteria	2 weeks*
Release Solicitation to Shortlisted Laboratories	2 weeks
Evaluate Bids and Select Laboratory for Engagement	1 week
Notify Winning Bidder and Establish Contract/SOW	1 month

* These tasks will be executed in parallel

5.2 Test Lab Set Up

Because of the size of the proposed test as well as the details of the experimental plan, the selected test laboratory will likely need to make significant modifications to their facilities in order to perform the proposed experimental work. This set-up work will likely include modification of hardware (e.g. testing racks) and software (e.g. controls systems for cycling control; data acquisition), sorting the test sample (e.g. into “sample groups”), labeling test lamps, and pre-testing samples to makes ensure they are functional at the start of the test.

As part of the solicitation, we expect to ask bidders to describe the modifications to their existing facilities that they would need to make and to estimate how much time they would require from establishing a contract to being ready to full-scale implementation of the experimental design.

5.3 Design and Build Results Database

We consider it to be critical for the testing laboratory to have a solid plan for designing a results database. A properly designed database can be expected to assist the laboratory in tracking test lamps and organizing test data, assist in quality control during testing, and ultimately assist in the evaluation and analysis of results. We plan to require bidders to discuss their proposed data management approach as well as to discuss the experience they have in managing large datasets. We expect to include a deliverable in the winning bidders contract in which we will require the laboratory to a present a database and/or database management plan for our approval.

5.4 Test Lab Management

Once testing is underway, we plan to require monthly test reports from the laboratory.[36] These test reports will allow us to ensure that testing is proceeding as planned while also allowing us to

[36] Note that a well-designed data management tool may allow these results to be largely automatically produced.

make adjustments as needed based on the results we are receiving. For example, based on how quickly the test lamps are experiencing lumen depreciation, we may wish to accelerate or delay the timing of subsequent measurements. We also expect to have regular, informal communications with the test laboratory to address any technical or logistical matters that may occur for the duration of the test laboratories involvement.

6

Analysis and Reporting

In this section, we discuss the key technical results that we expect to be generated based on the experimental design (Section 3) and sample design (Section 4) presented earlier. We also discuss how these results could potentially be used to inform CPUC and stakeholder efforts going forward.

6.1 Experimental Results

6.1.1 Results and Analysis from Maintenance Testing

The key results expected from the Maintenance Testing (as described in Section 3.2.1) are the following:

- Documentation of LED lamp failure rates: Elevated-temperature operation and thermal cycling may lead some LED lamps to fail catastrophically. Some studies have suggested that LED drivers are particularly susceptible to this failure mode, but this effect is not well documented for LED lamps.[37] Other studies of LED PAR lamps have indicated that failure rates may vary widely between lamp models, but these studies have been limited in sample size.[38] Regardless of our test outcomes, we expect that quantifying this impact on a large, representative sample of LED lamps would have value. Specifically, if catastrophic failures are minimal during 12 months of testing, it may be possible to dismiss thermal impacts as a primary quality concern for current LED lamp designs. Alternatively, if catastrophic failures are significant and/or vary significantly between models, this may indicate a need to increase the use of thermal-related screening tests and/or a need to update calculations of expected-useful life of LED lamps.
- Documentation of early LED lamp failure rates: While this result is a subset of the overall failure rate analysis discussed above, we wanted to highlight the importance of documenting and evaluating early failures, i.e. failures that are likely to occur in the first several months of use and significantly influence customer perceptions. While data is limited, anecdotal evidence suggests that some LED lamps experience accelerated catastrophic failure rates in the first few months of usage before failure rates stabilize.

[37] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/hammer-testing_Dec2013.pdf

[38] http://energy.gov/sites/prod/files/2015/02/f19/caliper_20-4_par38_0.pdf

Anecdotal evidence is provided both from the consumer side, where early failures are often cited in online product reviews, and from the manufacturer side, where we have been told that quality control is such that a small percentage of drivers fail after 600-1,000 cycles. These early failures may be of particular interest for two reasons. First, early failures are more likely to frustrate consumers and perhaps make them question the quality of LED lighting products in general. Second, testing for early failures would be relatively inexpensive and quick, should additional safeguards be needed.

- <u>Documentation of LED lamp operating temperatures</u>: Limited documentation exists on the operating temperatures and stabilization times of LED lamps in typical residential applications. Testing is sometimes done with an ambient temperature of 45°C in an attempt to accelerate testing and/or to simulate field conditions, but it is not clear how representative of field conditions this temperature really is. Furthermore, testing at a fixed ambient temperature does not account for the impact that the design and input power of the LED lamp itself has on ambient temperatures in the sense that higher wattage LED lamps are likely to generate more heat and thus experience a higher ambient operating temperature than lower-wattage LED lamps. We expect that documenting lamp temperatures on a large, representative sample of LED lamps during typical use would greatly add to the body of knowledge in this area. These data could be used in many different ways including allowing for a better understand of:
  - the relationship between lamp temperatures and catastrophic failures, lumen maintenance, and color shift
  - the relationship between lamp wattages and lamp temperatures
  - the potential for safety concerns or violations related to LED lamps operating above UL approved levels
- <u>Documentation of LED lamp ambient temperature in typical luminaires</u>: Limited documentation exists on near-ambient environments that LED lamps typically are housed in (i.e. the temperature inside the luminaire). While these temperatures are likely to be impacted by the wattage of the LED lamps themselves, we are not aware of any publically available models describing these relationships. By documenting typical near-ambient operating conditions, it may be possible to refine future thermal testing in a manner that is more targeted and/or cost-effective. Specifically, with a better knowledge of “typical” or “worst-case” near ambient temperatures, LED lamps could potentially be tested in thermal chambers rather than luminaires, which would provide a well-grounded scientific rationale for modifying the 45°C ambient temperature sometimes used to simulate field operating temperatures.

6.1.2 Results and Analysis from Performance Testing

The key results from the Performance Testing (as described in Section 3.2.2) are the following:

1. Verification testing of initial performance: Verification testing of initial performance can be done by comparing initial measured values of key metrics (e.g. lumen output, efficacy, CCT, CRI, and pf) against rated values and the applicable minimum quality standards (e.g. CA Quality Spec, ENERGY STAR). Regulators commonly use verification testing even when a robust compliance mechanisms are in place as products can fall out of compliance for a variety of reasons (e.g. unreported changes in product design or components, drop in quality control, gaming of original compliance testing, etc.). Verification testing on a large, representative sample will help document the veracity of existing compliance mechanisms and provide insights on whether additional programmatic safeguards are needed to ensure performance and quality standards are being met.

- Documentation of LED lamp lumen depreciation and color shift rates: The proposed quarterly photometric assessments of LED lamps would allow us to document lumen depreciation and color shift over time. These measurements could be evaluated in combination with lamp and luminaire temperature measurements collected during maintenance testing in order document any relevant correlations. Recent studies have documented significant performance differences between LED lamp models with respect to lumen depreciation and color shift rates, but sample sizes were limited.[39] Our proposed measurements on a large, representative sample of LED lamps would allow us to further document the variations between LED models in these performance parameters. This will provide insights as to whether proper safeguards are in place to ensure these metrics are being adequately addressed.
- Benchmark testing: All the metrics discussed above would help to characterize the level of performance and quality of the LED lamps on the market at the time the sample was collected. Subsequent sampling and testing would allow us to identify how the LED lamp market is evolving over time. This information may be useful in helping evaluate the impacts of IOU programs (e.g. increases in market average efficacy, CRI, lamp failure rates, etc.) or help to identify changes in the market that may require regulatory intervention (e.g. evidence of newer, low-cost models entering the market that sacrifice performance and/or quality).

6.1.3 Data Available for Accelerated Test Method Development

While we are not proposing to develop an accelerated test method for evaluating LED lamp life ourselves, we wish to note that the failure, lumen depreciation, color shift, and temperature

[39] See, for example, http://energy.gov/sites/prod/files/2015/02/f19/caliper_retail-study_3-2.pdf

testing data may prove valuable for such an effort. We propose to release the raw data from the proposed tests publically (perhaps anonymizing make and model information). Other researchers may find these data useful for developing models correlating life and/or performance to temperature. These models may lead to a better understanding of these relationships and may assist the development of an accelerated, high temperature test (e.g. at temperatures above our proposed test levels and above actual field application).

Related to releasing the raw data for other researchers to analyze, we also propose to work with the CPUC to make any lamps that experience catastrophic failure during our tests available to other researchers for detailed post-mortem analysis and electronic component testing. Such post-mortem analysis is beyond the scope of this effort, however, and would require additional funding and institutional support.

6.2 Reporting

We plan to produce an Interim Report shortly after we receive the test reports on all initial performance testing. We estimate that this report would be delivered to the CPUC by July 2015. The Interim Report would summarize all the performance testing results performed at the test start-up. This includes documenting the initial performance (e.g. efficacy, CRI, CCT, pf) of the sample and comparing these results to rated values and relevant quality standards, as discussed above. The Interim Report will also include a discussion of the sample procurement and sample composition. The test procedures for both the maintenance test and the performance test would also be discussed.

At the conclusion of Phase 1 testing on the initial sample, a Final Report will be produced by updating and appending the Interim Report to include all testing results. This will include the addition of the results from the maintenance testing on failure rates and temperature testing as well as the addition of performance testing from the proposed quarterly photometric testing periods. A data appendix with the testing raw data would also be prepared to support the Final Report.

7

Task Budgets, Schedule, and Study Coordination

This section provides an overview of the specific tasks, task budgets, deliverables, and milestone schedule associated with the proposed research plan, as well as an overview of the proposed study coordination and technical advisory activities. Note that the tasks below are those defined for Phase 1 of this LED lab test effort. We intend to define with the specific scope, tasks, and budget associated with Phase 2 testing following completion of Phase 1.

7.1 Task Definitions

Below we delineate and describe the specific tasks required to execute our proposed research plan, as well as the deliverables associated with each task.

Task 1: Project Management

Under this task, we will conduct all activities associated with the operational management, coordination, and administration required to facilitate execution and completion of the study.

Deliverable: On-going project management as needed.

Task 2: Research Plan Development

In Task 2, we will develop a detailed research plan for review and approval by the CPUC. The research plan will specify the research objectives, experimental design, sample design, sample procurement strategies, test lab recruitment and management approach, expected results and analyses, and reporting. The research plan will also specify the associated tasks, task budgets, deliverables, and milestone schedule.

Deliverable: Draft and final research plan.

Task 3: Sample Design Development

In Task 3, we will develop a sample design that can be used to identify and procure a representative sample of LED lamps for laboratory testing. This sample design will be based on the best available market data regarding LED lamp market shares, prices, and product characteristics.

Deliverable: Draft and final sample design memorandum.

Task 4: Test Lab Solicitation and Engagement

In Task 4, we will develop a written solicitation for pricing proposals to execute the experiment design specified in the approved research plan which will then be released to a short list of independent, third-party testing facilities. We will then evaluate all pricing proposals received using scoring criteria developed in collaboration with the CPUC, select the most appropriate laboratory for engagement, and establish a corresponding contract and scope of work.

Deliverable: Draft and final solicitation document and scoring criteria; evaluations of pricing proposals.

Task 5: Phase 1 Sample Procurement

In Task 5, we will procure the specific lamp models (and quantities) identified in the final sample design. Test lamps will be procured "off the shelf" through a combination of direct online purchases and in-store purchases (where appropriate with respect to product availability) and shipped to the testing facility.

Deliverable: Procurement and delivery of all test lamps to the testing facility.

Task 6: Phase 1 Testing and Management

In Task 6, the selected testing laboratory will prepare the testing apparatus, controls, and databases required to execute the Phase 1 tests and track and record all test results. The testing laboratory will then begin full-scale implementation of the testing regime specified in the scope of work and record all results in a database that meets the study team's requirements. We will oversee the performance of the testing laboratory via monthly test reports and conference calls to monitor progress and address and technical or logistical issues that arise.

Deliverable: Complete database of all Phase 1 test results.

Task 7: Analysis of Phase 1 Test Results

In Task 7, we will conduct a comprehensive analysis of the results from the Phase 1 testing. This will include an analysis of the initial verification tests, which we will summarize in a technical memorandum within the first two months of Phase 1 testing. Once the complete testing regime has been completed, the complete database of results will be read into an analytic platform (e.g. Excel or SAS), where we will develop comprehensive summaries of LED lamp failure rates, operating temperatures, ambient temperature inside typical luminaires, and lumen depreciation and color shift rates. These data will then be used to analyze the relationship between lamp temperatures and catastrophic failures, lumen maintenance, and color shift and the relationship between lamp wattages and lamp temperatures.

Deliverable: Technical memorandum summarizing results of initial Phase 1 performance tests; complete set of workbooks and/or SAS scripts and databases that contain all of the cleaned raw data and Phase 1 testing analyses, as well as a complete data dictionary, per CPUC staff's standard requirements for data deliverables for all IOU- and CPUC-led EM&V studies.

Task 8: Phase 1 Reporting

In Task 8, we will develop a comprehensive project report that provides detailed documentation of the experimental design and equipment set up, test sample, and analysis results from Phase 1 testing.

Deliverable: Draft and final Phase 1 project report.

7.2 Task Budgets and Milestone Schedule

Based on the specific Phase 1 tasks delineated above, we developed corresponding task-level budgets and milestone schedule, which are summarized in Table 7-1. Note that we intend to define with the specific scope, tasks, and budget associated with Phase 2 testing following completion of Phase 1.

Table 7-1: Task Budgets, Schedule, and Deliverables

Task	Initial Budget	Start Date	End Date	Deliverables
1. Project Management	$20,000	Oct-14	Oct-17	On-going project management as needed
2. Research Plan Development	$30,000	Nov-14	Feb-15	Draft and final research plan
3. Sample Design Development	$30,000	Jan-15	Apr-15	Draft and final sample design memo
4. Test Lab Solicitation and Engagement	$10,000	Apr-15	May-15	Draft and final solicitation doc and scoring criteria
5. Phase 1 Sample Procurement	$30,000	Apr-15	May-15	Delivery of all test lamps to testing lab
6. Phase 1 Testing and Management	$150,000	Jun-15	May-16	Database of all phase 1 test results
7a. Analysis of Phase 1 Test Results - Interim	$20,000	Jul-15	Aug-15	Phase 1 interim results memo
7b. Analysis of Phase 1 Test Results - Final		May-16	Jun-16	Workbooks and/or SAS scripts containing all analyses
8. Phase 1 Reporting	$10,000	Jun-16	Jul-16	Draft and final phase 1 report
PHASE 1 TOTAL	$300,000	Oct-14	Jul-16	-
PHASE 2 TOTAL	$200,000	Jun-16	Oct-17	TBD
TOTAL PROJECT	$500,000	Oct-14	Oct-17	-

7.3 Study Coordination

We will leverage the Project Coordination Group (PCG) organized by the CPUC for all lighting-related 2013-2014 EM&V studies as the main point of outreach and coordination with the IOUs (and their consultants). The Lighting PCG meets on a monthly basis, and we plan to use this forum to provide regular project updates, notify the IOUs of any upcoming opportunities for IOU input or review, and discuss any cross-study coordination issues that may arise.

We also plan on soliciting voluntary, informal reviews of the draft Phase 1 report, the draft Phase 2 research plan, and the draft Phase 2 report from the same group of LED experts and industry stakeholders that provided input into this research plan, namely the CEC, NRDC, NEMA, LRC, USEPA, USDOE, 4E SSL Annex, and RTI International.

Appendix A

PG&E Input on Research Objectives

---------- Forwarded message ----------
From: **Thayer, David** <D1TQ@pge.com>
Date: Sun, Nov 30, 2014 at 9:44 PM
Subject: RE: Voluntary Feedback to CPUC Laboratory Evaluation of LED Lamps
To: Jeorge Tagnipes <jeorge.tagnipes@cpuc.ca.gov>, "erik@erikpage.com" <erik@erikpage.com>
Cc: "Weiner, Carolyn" <C1Wa@pge.com>, "Chansanchai, Mananya" <M7CE@pge.com>, "Kasman, Robert" <REKL@pge.com>, "Caruth, Doreen R" <D6CX@pge.com>, "Dewey, Meghan" <MKDC@pge.com>

Jeorge and Erik,

Thanks for the opportunity to comment on the proposed lab evaluation.

While LED lamps have tremendous potential for California IOU efficiency programs, there is concern the current lifetime testing for LED lamps does not adequately reflect all of the potential failure modes of lamps in the market. Lumen maintenance testing, while critical for photometric performance, is not necessarily a robust proxy for how a lamp will perform in the "real world" over its lifetime.

To address the real world performance concerns, Pacific Gas and Electric recommends the Commission use the proposed lab evaluation to address gaps in LED lamp performance testing knowledge. Integral LED lamps should be tested off the shelf in an environment with increased levels of heat, humidity, voltage, and on/off switching. This type of accelerated lifetime testing, also known as hammer testing, is commonly used to determine failure modes for products in the electronics industry.

The Illuminating Engineering Society and Department of Energy continue to develop methodologies for accelerated lifetime testing. We recommend surveying current testing methodology for best practices to replicate in this large-scale laboratory evaluation. With current lifetime testing for ENERGY STAR certification and the speed at which the LED industry moves, LED lamps in stores are often replaced by a new generation before their full lifetime test is complete. This is a tremendous hurdle for manufacturers as well as IOU efficiency programs that rely on lifetime testing for savings justification.

Thermal management is one of the most critical aspects to LED performance and useful life. Increasing the temperature a lamp is operating in will accelerate LED degradation and may lead to other component failures. ENERGY STAR tests lamps at 25^0 C (ambient temperature), while accelerated tests have been documented at 45^0 C and 75^0 C.

Increasing humidity in a test chamber can generate a number of mechanical and electronic failure modes. Combined with high-temperatures, semiconductor lifetime models (e.g. The Peck Model) can extrapolate the expected life an LED and lamp components with very short test periods. Humidity points from 40% to 95% appear in testing methodologies.

Voltage spikes and inrush current also lead to potential failure modes for LED lamps. DOE has developed a test methodology that incorporates variations in heat, humidity and voltage for accelerated lifetime testing approaches.

While frequent switching reduced the useful life of CFLs, the impact switching has on LED lamps is less clear. It is possible that frequent switching could actually help with chip thermal management and increase the useful life of chips. Frequent switching is still a valuable test because of potential failure modes created by the inrush current needed to energize an LED lamp.

Additional results that would be useful to have are:

- All of the criteria required to meet the CEC Voluntary California Quality LED Lamp Specification.

- Performance testing for specific applications (i.e. A-Lamps, globes, and PAR lamps in increased humidity conditions because of their common use in bathroom vanities, exhaust vents and outdoor fixtures.)

We hope this laboratory study will build on the work that has already been done and build the case to implement a robust accelerated lifetime test for integral LED lamps. The industry is in need of an accelerated hammer test that consumer advocates and efficiency programs can rely on for whole-lamp performance. Pacific Gas and Electric recommends developing a reliable LED lamp lifetime test that includes increased heat, humidity, voltage and on/off switching.

Thanks again,

David Thayer

Sr. Product Manager

PG&E | Customer Energy Solutions

o: 415-973-3256

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david.thayer@pge.com

From: Tagnipes, Jeorge S. [mailto:jeorge.tagnipes@cpuc.ca.gov]
Sent: Monday, November 17, 2014 4:13 PM
To: 'erik@erikpage.com' (erik@erikpage.com)
Subject: Voluntary Feedback to CPUC Laboratory Evaluation of LED Lamps

STATE OF CALIFORNIA EDMUND G. BROWN JR., *Governor*

PUBLIC UTILITIES COMMISSION

505 VAN NESS AVENUE

SAN FRANCISCO, CA 94102-3298

November 17, 2014

The California Public Utilities Commission (CPUC) plans to initiate a large-scale laboratory evaluation of LED lamps in the near future. This laboratory effort will primarily be designed to provide information to CPUC on performance and longevity on LED lamps commonly used in California and/or those promoted by California utility programs.

While the CPUC plans to finalize a sampling and experimental design that meets the goals of the CPUC and its stakeholders, we recognize that the outcomes of this test may have national significance. Thus, we invite your feedback at this early planning stage on what recommendations you might have for a large-scale laboratory evaluation of LED lamps. We welcome any feedback you might have, including your thoughts on the following:

- Are there significant "knowledge gaps" today related to LED lamp performance or longevity? If so, what are they and how could a laboratory study address them?
- Do you feel that LED lamp labeling accurately represents their expected "real world" performance and longevity? If not, how might a test be designed to better characterize expected performance and longevity?
- Are there specific laboratory results that would be useful to you and your programs?

If you do wish to provide your voluntary feedback to us, please send a response via email to CPUC contractor, Erik Page (erik@erikpage.com) by November 30, 2014. Again, the final experimental design will be focused on meeting CPUC and CPUC stakeholder objectives, but we value your opinion and hope to generate results that are more broadly applicable wherever possible.

Thank you,

Jeorge Tagnipes

CPUC Energy Division

415-703-2451

Jeorge S. Tagnipes | 415.703.2451 | jeorge.tagnipes@cpuc.ca.gov | Energy Division
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Erik Page, P.E.
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Appendix B

SCE Input on Research Objectives

SOUTHERN CALIFORNIA EDISON
An EDISON INTERNATIONAL® Company

Miriam Fischlein, Ph.D.
Southern California Edison
DSM Program Measurement and Evaluation
1515 Walnut Grove Ave.
Rosemead, CA 91770

November 26, 2014

Jeorge Tagnipes
Energy Division
California Public Utilities Commission
505 Van Ness Avenue
San Francisco, CA 94102

Erik Page
Energy Division Consultant

SCE Feedback on planned CPUC Laboratory Evaluation of LED

Dear Mr. Tagnipes, Mr. Page,

SCE appreciates the opportunity to comment on the planned CPUC laboratory test of LED. Independent lab testing of LED was a need that the Statewide Lighting Team stated and proposed to the Energy Division. We welcome addressing this request by the CPUC to provide feedback.

Just like past CFL lab tests, we fully expect that this study will provide valuable insights and findings for IOU energy efficiency programs. LED of course have some important differences to CFL, meaning that the lab test will likely include some different aspects than prior CFL studies. We have focused many of our comments on the knowledge gaps for LED, and have also provided some general comments on desirable study characteristics.

In attachment to this letter, we respectfully submit the following questions and suggestions for the planned LED lab test study. Inquiries on these comments should be directed to Miriam Fischlein via e-mail at Miriam.Fischlein@sce.com or via phone at 626.302.0633.

Thank you for your consideration,

Dr. Miriam Fischlein
DSM Program Measurement and Evaluation

SCE feedback on the LED Lab Test

SCE Comments

1. **Life cycle testing of LED**

Currently there is no industry standards for evaluating the cycle life of actual lamps or lamps in a fixture and not just the LED light engine. Yet LED can experience catastrophic failure, e.g., due to low quality components or poor connections. Some manufacturers use their own protocols to assess the life of products, but there seems to be a lack of agreement on how to assess actual lamps. The standards currently available and used by most LED manufacturers to test the life of their products, LM-80 and LM-82, are only based on the LED light engine and leaves out other important components of the system such as the driver and the optics.

Accurate assessment of lamps and lamps in fixtures is a complex issue, since the life of products will be affected by application, ambient conditions and use cycle pattern. For example, an LED lamp will likely last longer when it is operated manually or on a timer and is subjected to a fixed on-off schedule than if automatically controlled by occupancy sensor in an uncontrolled-occupancy environment.

We believe that the following should be considered to effectively assess LED lamp life cycle:

- Sample size under evaluation - there have been several discussion about this issue at major industry events such as Lightfair.
- Light output performance of LED lamps and fixtures in different applications.
- Improved power quality measurements – LM-80 and LM-82 only require basic measurements such as amps, volts, and watts. Harmonics measurements should be done to assess effects on the grid.
- Dimming effects on product life – It is our understanding that life cycle calculations are only based on full power measurements.
- LED Driver performance under accelerated life measurements – It is currently believed that the actual LED chip will outlive the useful life of the driver. However, our current standards don't look into the driver life as the main focus of performance assessment.

There are probably more areas of improvement than what we have listed above to the current industry standards used for life calculation.

2. **Impact of dimmability on life cycle**

Within the range of factors affecting the life of LED, we would like to single out dimmability as an issue of special importance to IOU lighting programs.

Little has been done to test for the effects on useful life of prolonged dimming, or the life risks associated with specific electrical parameters of the various types of sliding dimmers, 3 way switches, step dimmers, occupancy sensing, number of LED on a circuit, or other factors possibly shortening LED life.

It should be noted that the DLC has been soliciting LED product dimmability since July 2014. An increasing number of IOU incentive programs either require or will require dimmability. Therefore it is recommended that any proposed evaluation program include performance testing over each products claimed dimmable range. Part load power factor, THD, flicker, and response (speed, repeatability…) to dimming commands should be included.

If funding is ample, lab testing could provide an opportunity to look for possible threats from these areas and others, such as low or erratic power quality, socket distance on long lighting circuits, and high VAR or THD at dimmed states.

3. Electronic component testing

Even the LED products considered of high quality are not yet perfect in their technology, as has been pointed out repeatedly by lighting engineers and scientists. Lab tests can help flesh out the remaining areas needing improvement. Such areas that could result in premature lamp failure would appropriately be considered of greatest need for focus in these lab tests.

Precedents for these lab tests are the DOE and EPA third party testing, and the PEARL program coordinated by NRDC. PEARL helped identify many poorly made CFL products and resulted in numerous de-listings from the ENERGY STAR qualified products list. The currently envisioned lab testing might not be as extensive as the PEARL testing, but it can follow some of its more successful techniques to uncover quality issues. For that reason, we recommend that the ED involve Noah Horowitz of NRDC in the conceptualization of this lab testing, customized to assess LED products. The PEARL program tested off-the-shelf products for consistency with their original specifications reported to ENERGY STAR for approval. It also performed extensive rapid cycle testing and elevated temperature in-situ testing. Since many California products must meet higher specifications than nationwide, federal third party LED testing is not an appealing or viable option.

Although quality testing in a laboratory environment of LED products is hopefully a given, we also recommend physical examination of componentry and testing of internal circuit and component integrity. This would involve electronics lab testing, not mere lighting lab testing. Although a deep dive into electronics testing adds cost, it can be applied meagerly and selectively to a small number of participating products representing specific factories suspected of poorer quality, or other factories producing large volumes of LED products for our programs. Ideally, the study would develop a method to test for catastrophic failure as a component of life testing.

The reason for this recommendation is that it is commonly stated in the industry that the LED themselves are the components that last the longest. But experience has shown that the real threat to the life of LED is the quality of electronic aspects such as soldering, potting, wire gauges, reduced metal quality, improperly selected (or counterfeit) capacitors, semiconductors, cathodes, electrodes, and other components, as well as improper matching of drivers, heat sinks, and chips.

New methods for constructing LED lights with different components and designs are being developed on an ongoing basis. Lab testing will help gain understanding of these new aspects and identify possible new concerns to address in preventing premature failure.

The knowledge gap centers on a need to focus on a systems approach for the proposed evaluation (LED light engine, driver, optics, reflectors). SSL luminaires are composed of many working parts, each of which could potentially impact product reliability. Consequently, a systems approach is needed to understand failure rates in SSL devices. The DOE led Hammer Test could be a model for CPUC evaluations.

4. Lumen efficacy

Currently, LED are evaluated based on wattage equivalency. Yet it is unclear if this is the most appropriate metric of equivalency that links any given product to its baseline. LED source lumen efficacy is not quantified the same way as for fluorescents, but it is still a value that should be confirmed/validated. When comparing LED and fluorescent light sources, one major difference is the end-to end efficacy of the lamp and fixture for LED. Data that would relate metrics of equivalency based on lumen output and on wattage would be very useful. In this context, we are also interested in learning how the study will account for the constantly growing LED performance.

5. General characteristics of the study

a. Inclusion of statistical analysis

In order to make the results useful for broad application in programs, we suggest that the study include a statistical analysis to capture all ranges of application and allow for assessment of confidence in the results.

b. Types of LED to target

We assume that LED to be tested in the study will include those with higher penetration and/or high potential in the IOU lighting programs. One possibility would be to draw products from DLC categories, for example 10 samples per DLC category every 4 months for TBD years. Samples would need to have been DLC listed for at least 1 Q.

c. Use of California Labs

We highly recommend the use of California labs for this study. This would promote the use of local, qualified California labs for such public purpose long term research. In addition, there will be better control over follow-up questions for testing conditions and any subsequent data needs.

Our resources at the SCE lighting lab are perfectly suited to perform life-cycle testing of different types of LED lamp products under different application and environment settings.

d. Off-the-shelf testing

There is much opportunity for poor quality production practices even on LED products passing the most stringent initial tests. Subsequent off-the-shelf testing is essential to monitor and manage quality of LED products in the market that bear the utility's incentives and therefore our good name.

The main factor of uncertainty is build quality. This hinges on a factory's compliance to best manufacturing practices for componentry, circuit design, assembly, connections, and quality control. Here are two examples of serious concerns along these lines: (1) the use of counterfeit components of low quality that appear the same as high quality components, and (2) receiving certification with higher quality components/practices, but then switching to lower quality in production. This happened with CFLs. It is a known strategy of lighting product factories, and it jeopardizes market penetration and transformation.

To fold this lab testing into an experimental design, as suggested by the Energy Division, would be of greatest value if the focus of lab testing does not shift away from discovery and remediation, but instead uses statistical tests to validate the effectiveness of off-the-shelf testing to improve products (reduce early failures) resulting in maintenance or growth of positive awareness and customer satisfaction.

e. Data sharing

Past lighting lab tests have provided valuable data for IOU lighting programs and workpapers. Does the CPUC anticipate sharing the raw data with the IOUs. Will other photometric data be collected and also shared with IOUs?

f. TM-21 calculator

We recommend use of the TM-21 calculator for accuracy.

Appendix C

Analysis of Impact of Retail Channel on CFL Lamp Performance

In the CFL lab test study, the sample of test lamps were procured directly from retail stores using a "boots on the ground" approach, i.e. via physical purchases by field staff at retail stores. The study team chose this procurement approach based on the hypothesis that some retail channels are more likely than others to receive and sell lower-performing batches of low-price CFLs from CFL manufacturers and distributors. A major consequence of this procurement approach was that it was very expensive ($80,000 to procure 3600 lamps or $22/lamp) and time consuming to procure and assemble a large sample of CFL lamps that was representative of the distribution of CFL sales across geographies and retail channels in California.

Given the relative price premium for LED lamps (compared to CFLs), we wanted to explore opportunities to reduce procurement costs and time requirements by leveraging online procurement (with direct shipping to the testing facility) wherever possible. However, such an online procurement approach assumes that lamp failure rates do not differ significantly by retail channel, contrary to the initial hypothesis of the CFL lab test study team.[1] After consultation with the CPUC, we decided to test this hypothesis using the complete set of CFL lab test data in order to support our proposed online procurement approach for the LED lab test. Below we present the data and methods used to conduct this analysis and summarize the findings.

C.1 Preparation of CFL Test Data

CFL lamp performance data and retail channel information were tracked in two separate tables, which both required processing before they could be merged to complete the retail channel analysis. The *CFL Lab Test Results Table* contained lamp test conditions and results information for each lamp that was tested in the lab, including failure time as a percent of rated useful life which field used to analyze lamp performance. The *Procurement Tracking Table* contained retail channel information for the lamps that were procured for the CFL test.

Before these two tables could be merged and analyzed, mapping fields had to be created to match each lamp's CFL lab test results with the correct retail procurement information. To do

[1] Due to time and budget constraints, the CFL lab test team did not formally test this hypothesis as part of its final reporting.

this, we matched the Procurement Tracking Table onto the CFL Lab Test Results Table by model code, which is a code unique to each CFL model number, and retail location. The records in the Procurement Tracking Table were unique by the Category, Subcategory, Retailer, Address, City, and Zip Code, and Total Purchase Cost fields. We combined the Category and Subcategory fields to create the Model Code Field and deleted all records that were duplicates of the Model Code, Retailer, Address, City, and Zip Code fields since purchase cost information was not needed for the retail channel analysis. The CFL Lab Test Results Table included the Model Code field but did not have any retail location information. Rather, it had a SampleID field where the fourth digit of each sample ID represented a retailer code that is unique to a particular retail location.

Using the model code and retail location identifier fields, we were able to determine if each table had the same number of unique model code/retail location combinations.[2] Once the incorrect and duplicate records were removed, the two tables were combined into an analysis dataset containing retail channel information and lamp performance results.

C.2 Data Analysis

Using the final analysis dataset, we then compared the distribution of failure time results (as a percent of rated life) grouped across retail channels for each model code. The analysis dataset was divided into individual datasets for each model code that was procured in more than one retail channel. These model code datasets were then sorted by retail channel and failure time. In total, twenty-four of the lamp models that were in the CFL Lab Test Table were sold by more than one retail channel and included in the analysis presented below.

We began by first developing visual comparisons of the raw data in the form of plots of mortality curves by retail channel for each model procured through multiple channels. These plots allowed us to visually identify first order relationships (if any) between lamp performance and retail channels. We then used a statistical test (the Kolmogorov-Smirnov test) to systematically assess the statistical significance (if any) between differences in the performance of lamp models procured through multiple retail channels.

2 Note that there were several cases where the CFL Test Table had model numbers with more retail locations than the same model number had in the Procurement Tracking Table. Since a retailer code in the CFL Lab Test Results Table was being matched to an address in the Procurement Tracking Table there was no defined relationship between the retail location information in the two tables. Further examination of the data revealed patterns in the way the CFL lab test retailer code matched with the procurement address information, and which retailer codes contained clerical errors or did not have a match in the Procurement Tracking Table. All of the records in the CFL Lab Test Results Table that were found to have a model code and retailer location combination that did not have a matching model code/retailer location combination in the Procurement Tracking Table were deleted.

C.2.1 Visual Comparisons

Figures C-1 through C-24 show the distribution of failure time as a percent of rated life, referred to as mortality curves, for all CFL test models that were procured through more than one retail channel.

It should be note that many of the model codes had small samples of CFL lab test results. When these samples were broken out by retail channel, the mortality curve distributions became correspondingly less representative of the larger population of CFL lamps sold by that retail channel. Accordingly, these visual comparisons are not a reliable method of assessing the true relationship between mortality rates and retail channel. Nonetheless, for the sake of transparency and completeness, we provide the full set of visualizations in the remainder of this subsection.

Figure C-1: Mortality Curves for Model 1C Retail Channels

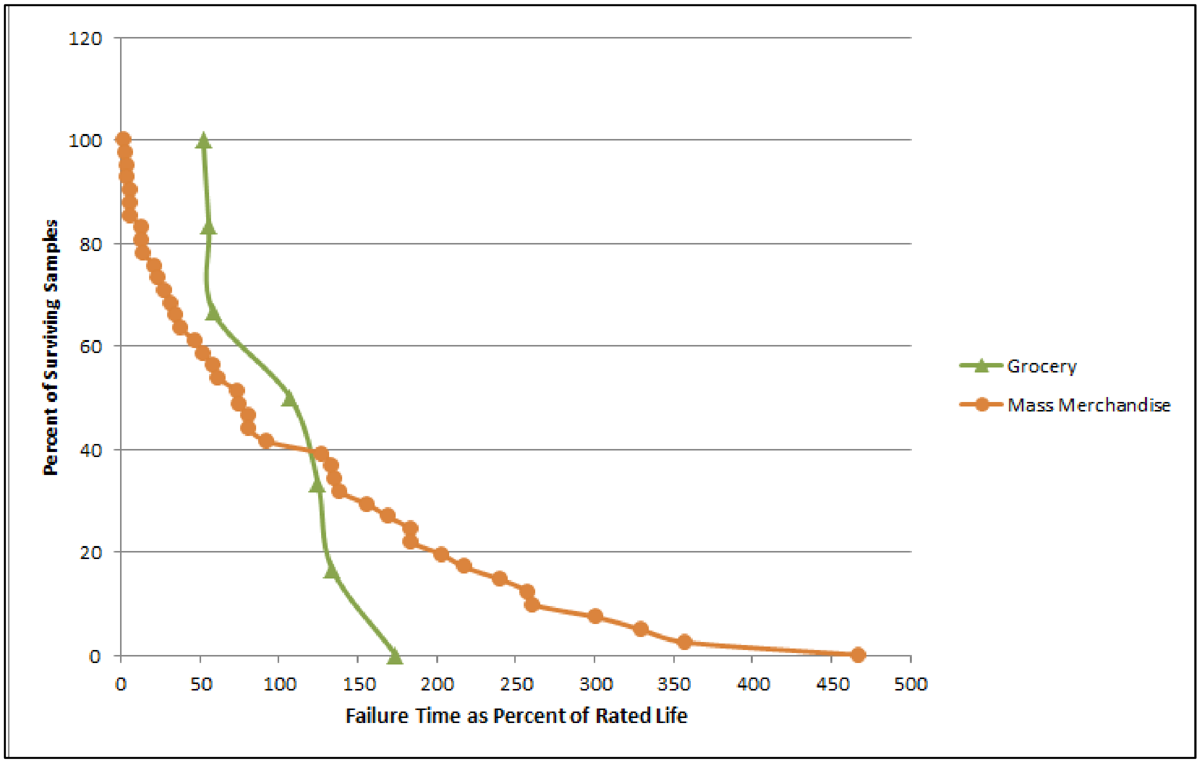


Figure C-2: Mortality Curves for Model 1D Retail Channels

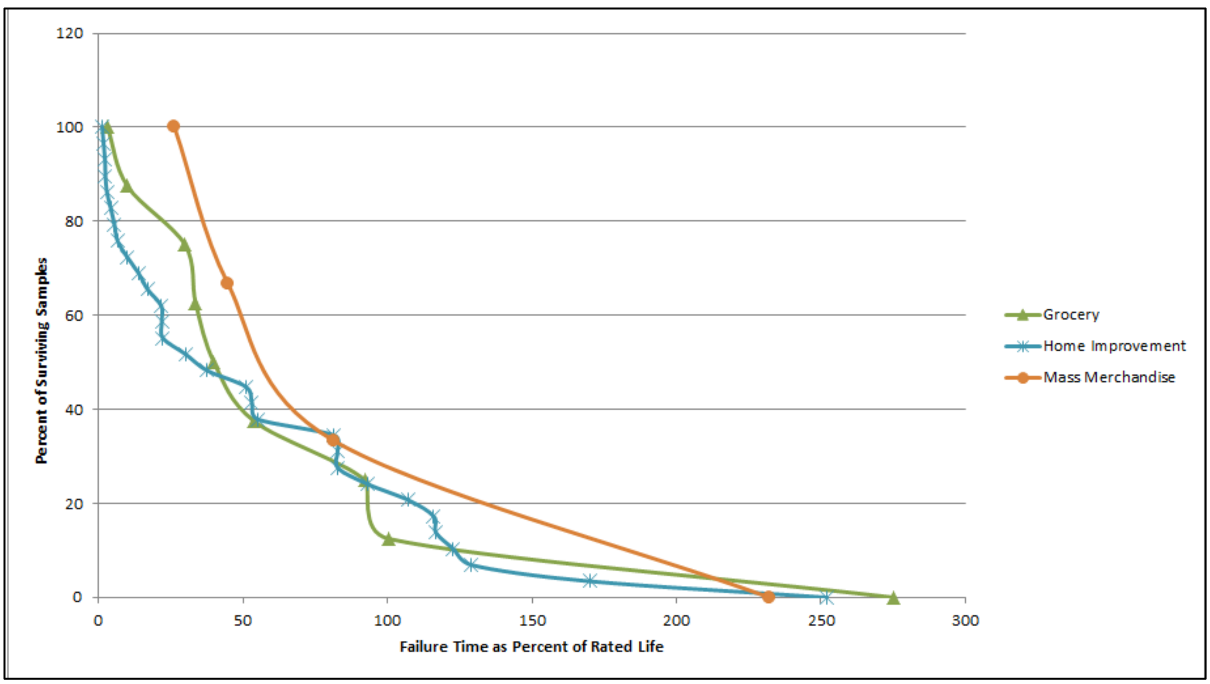


Figure C-3: Mortality Curves for Model 1F Retail Channels

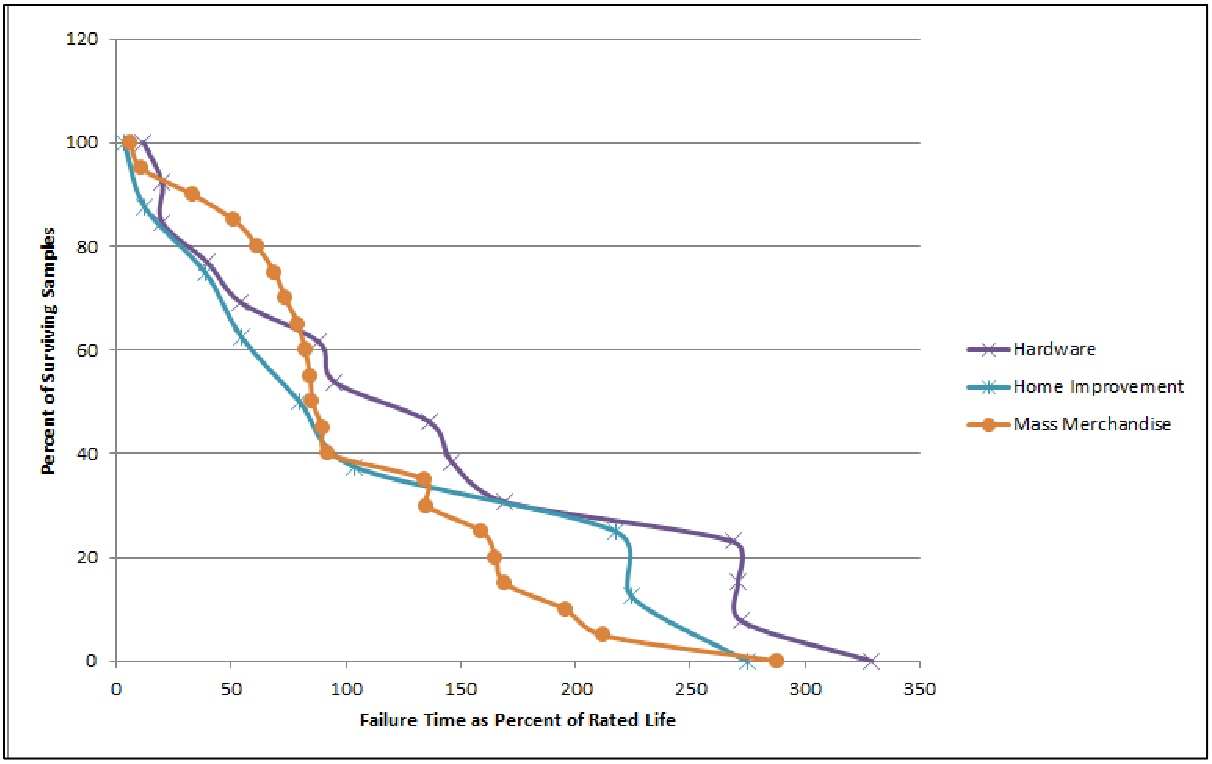


Figure C-4: Mortality Curves for Model 2B Retail Channels

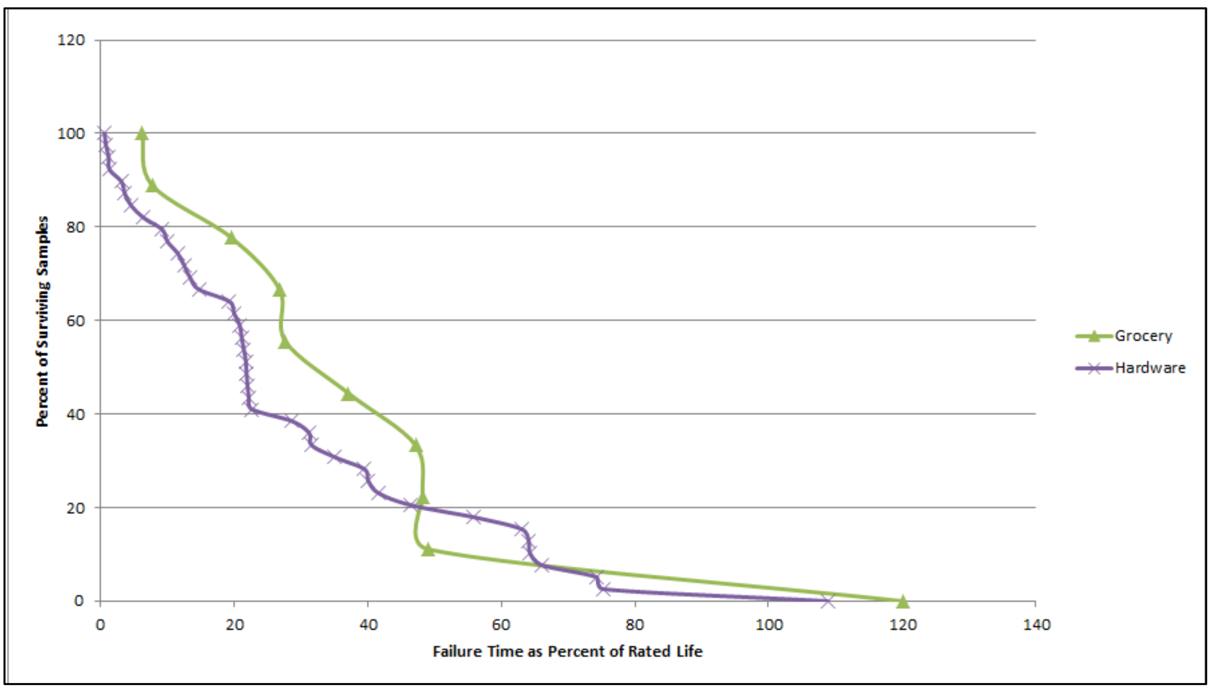


Figure C-5: Mortality Curves for Model 2E Retail Channels

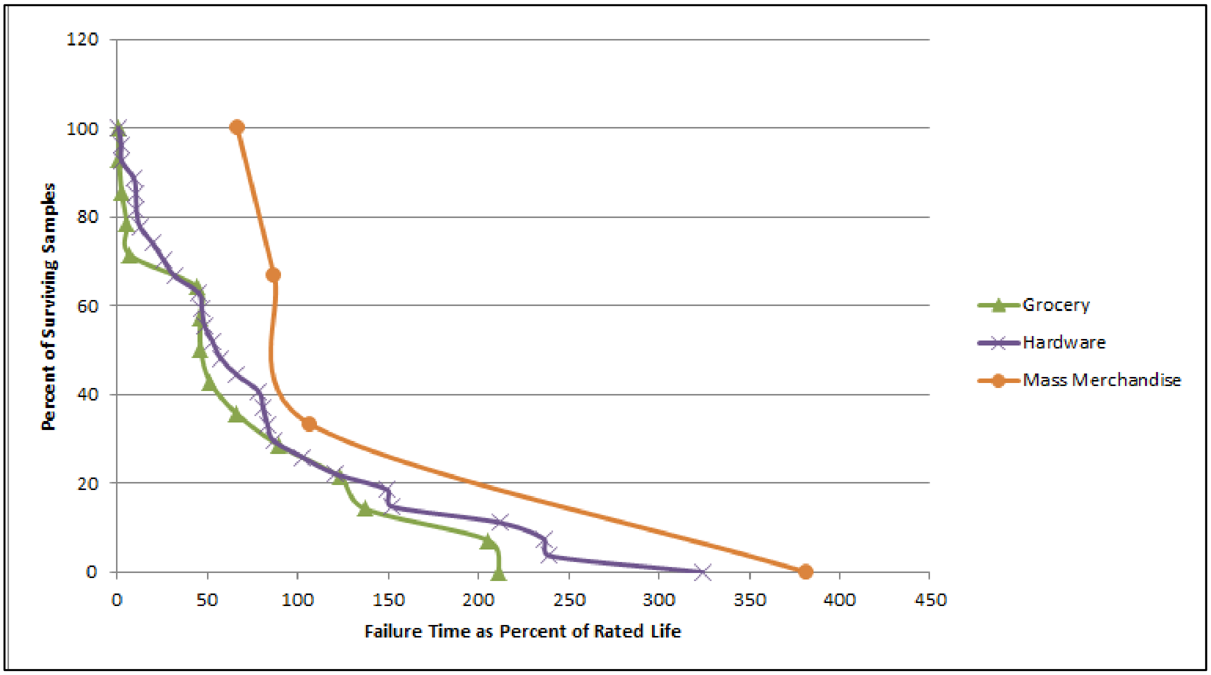


Figure C-6: Mortality Curves for Model 2F Retail Channels

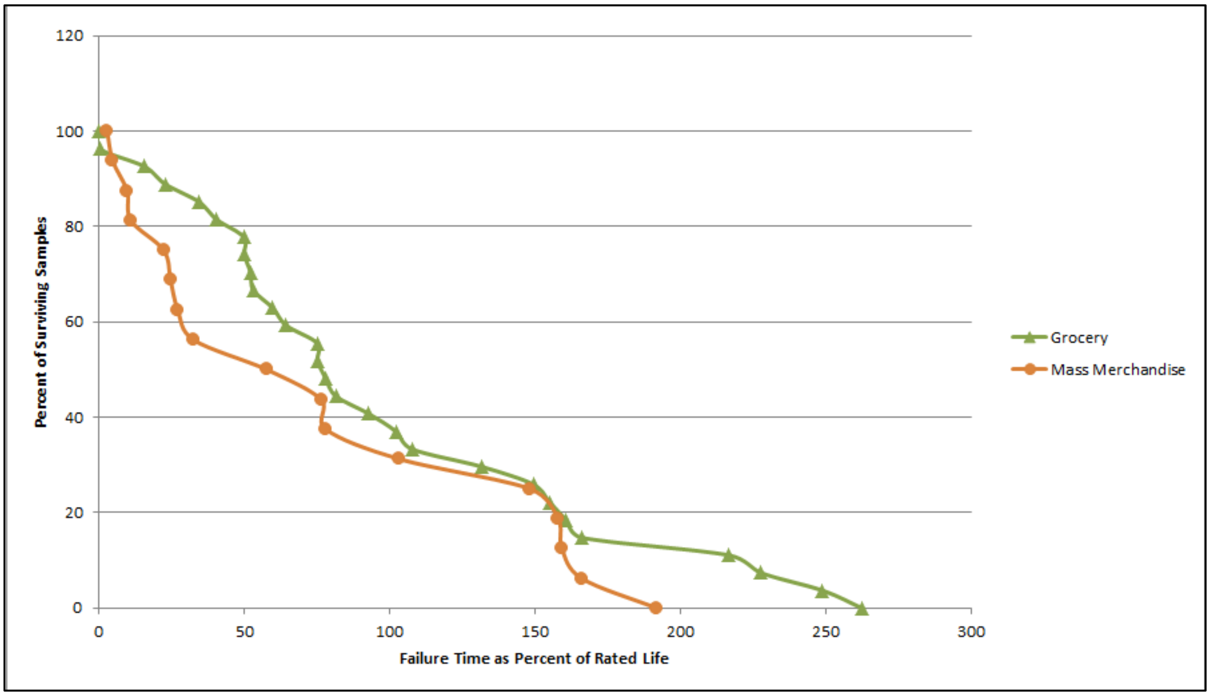


Figure C-7: Mortality Curves for Model 3B Retail Channels

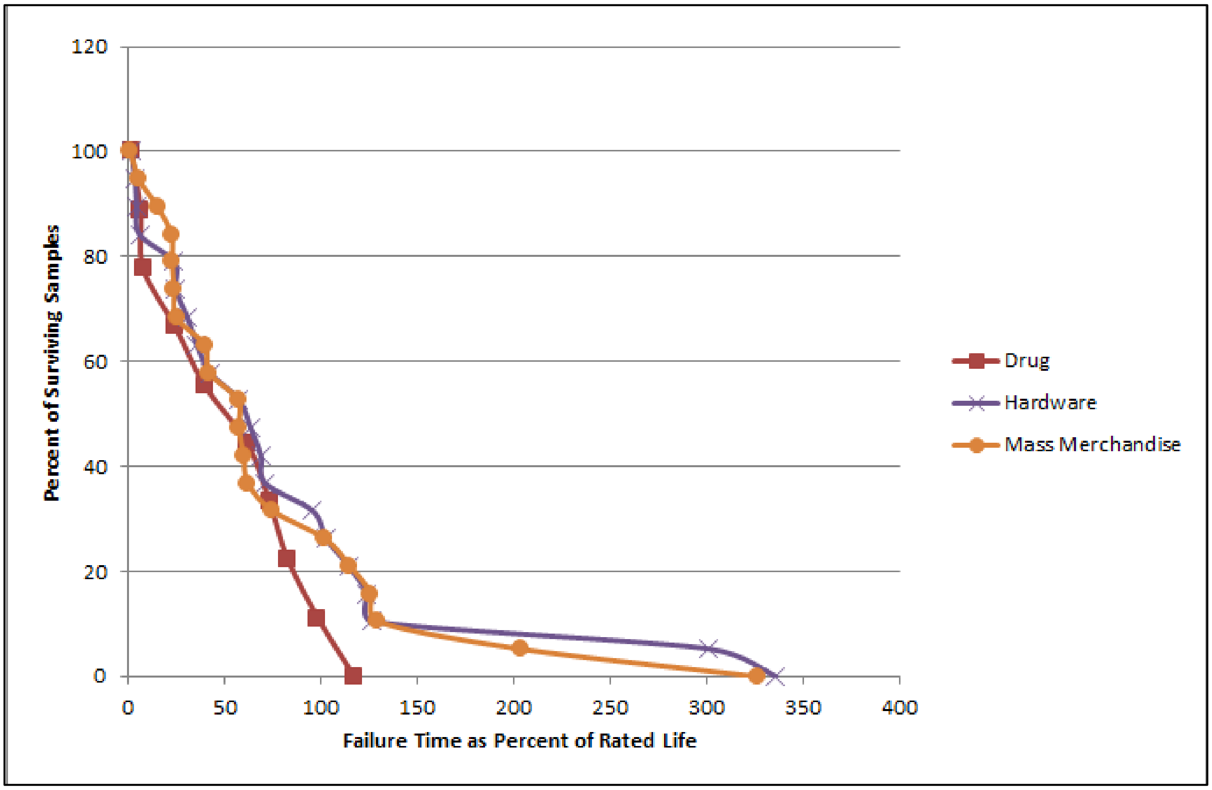


Figure C-8: Mortality Curves for Model 3C Retail Channels

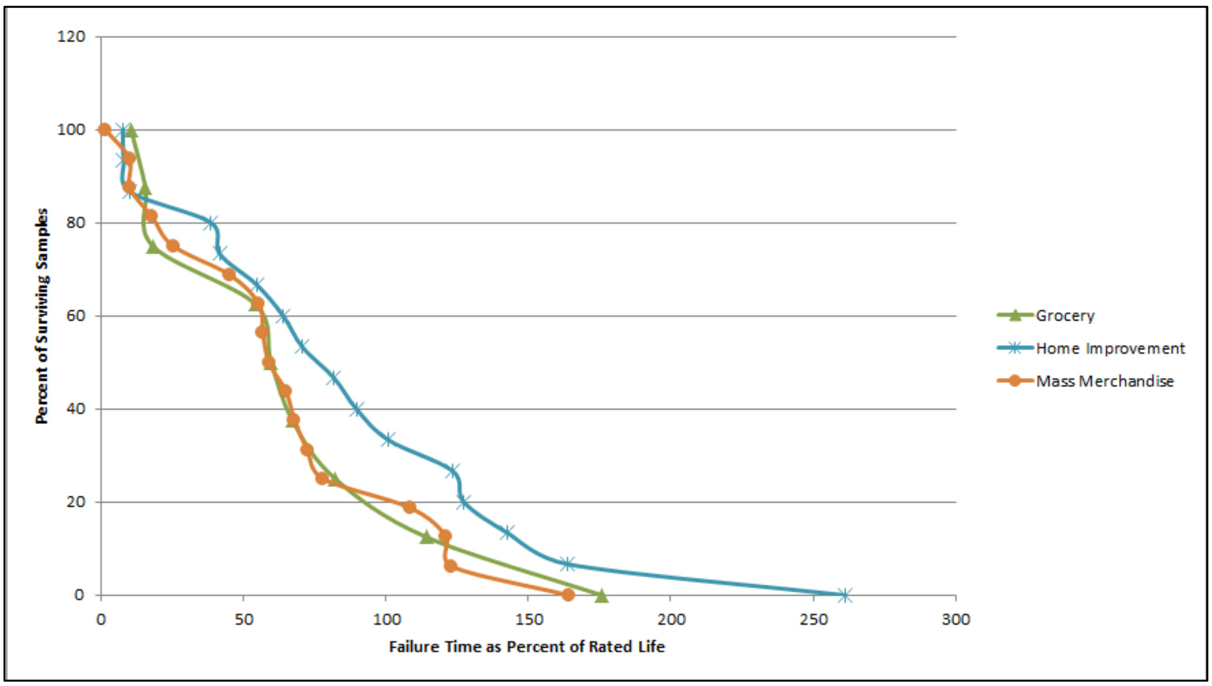


Figure C-9: Mortality Curves for Model 3F Retail Channels

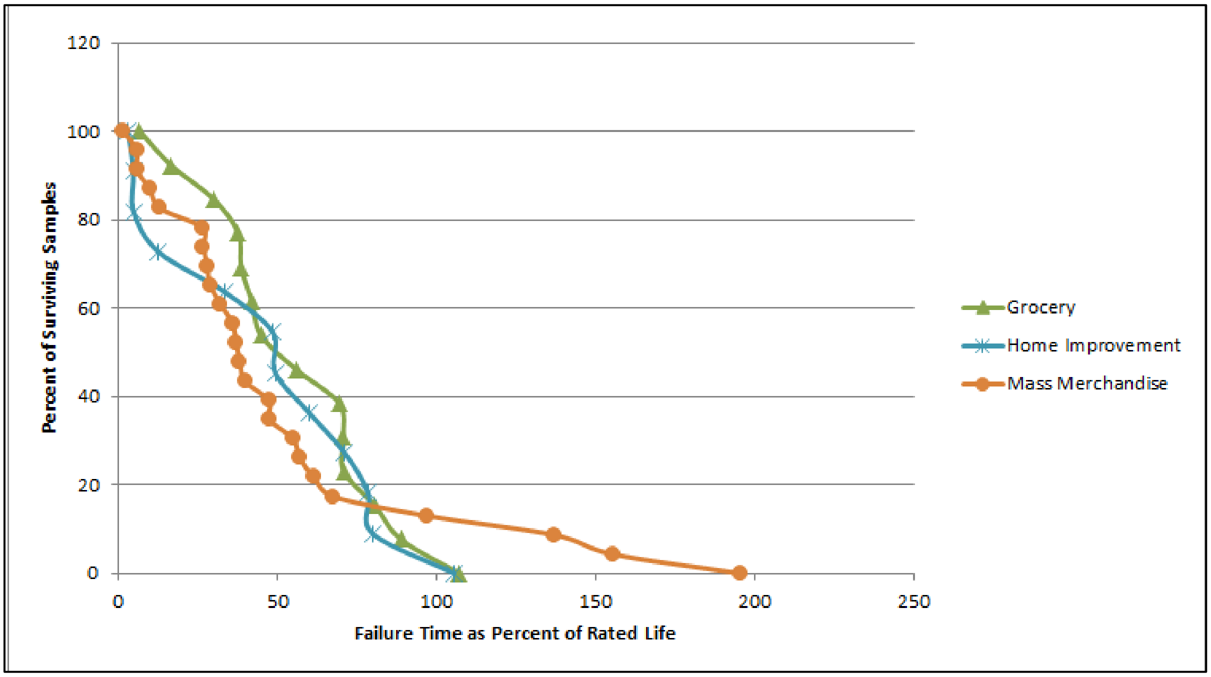


Figure C-10: Mortality Curves for Model 4B Retail Channels

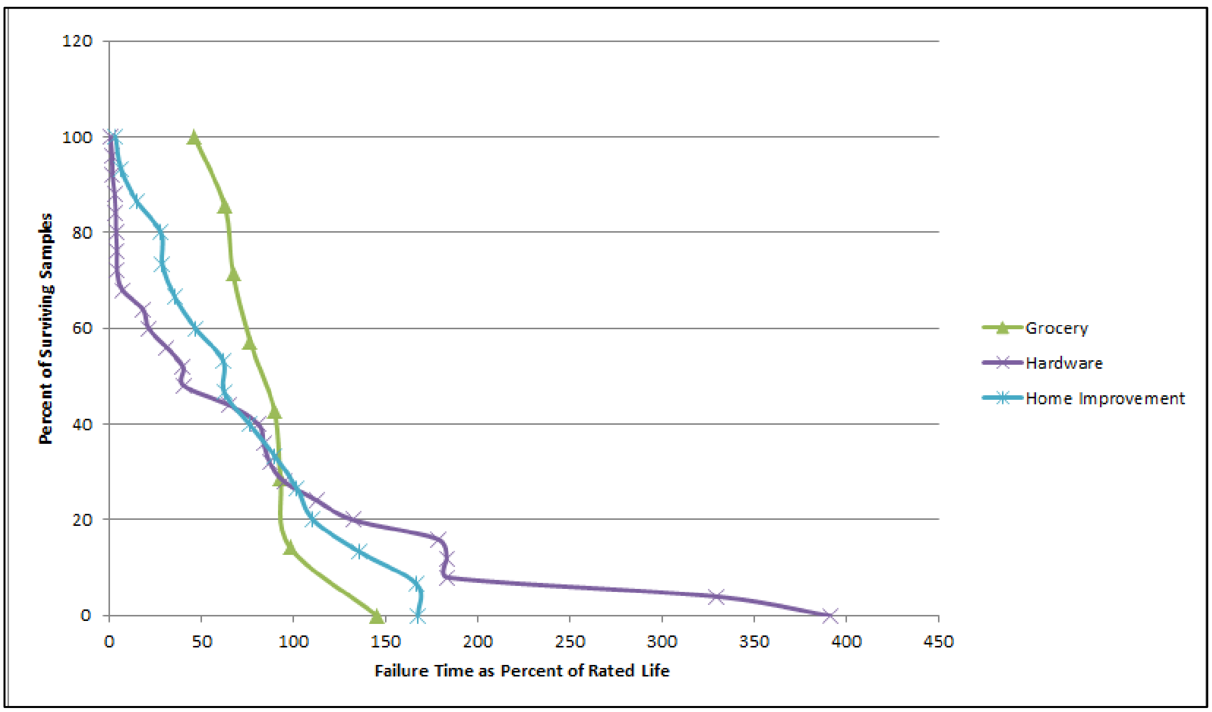


Figure C-11: Mortality Curves for Model 4D Retail Channels

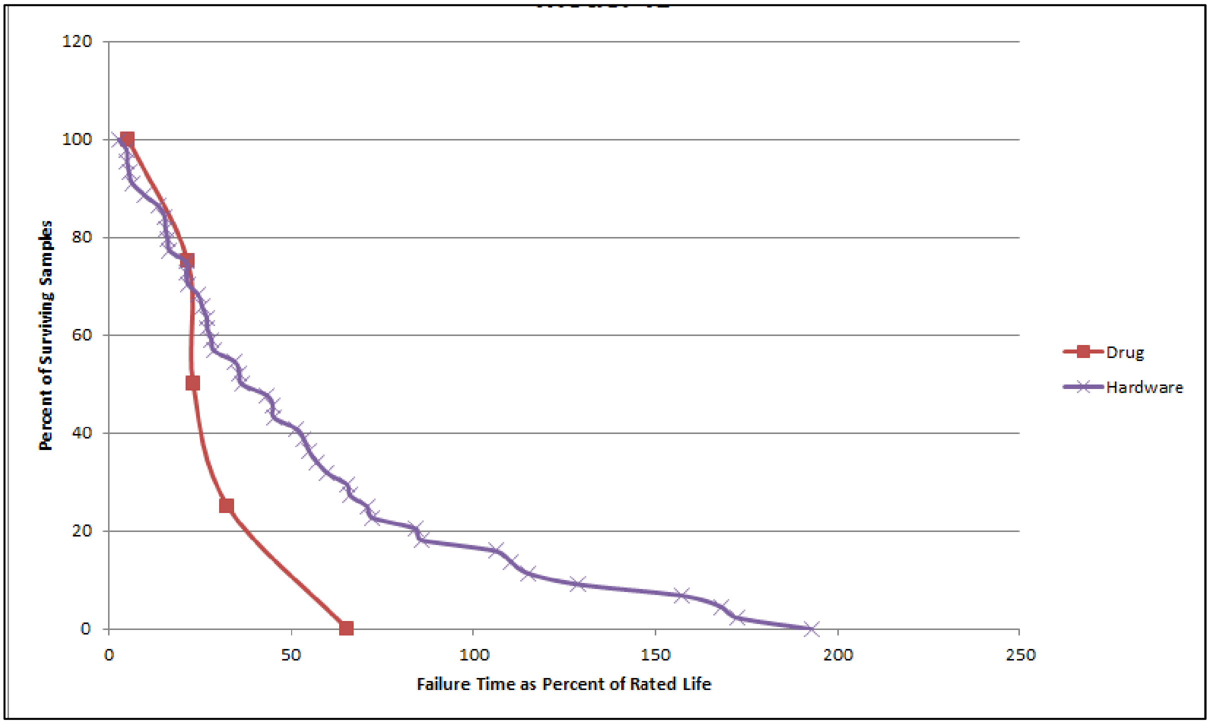


Figure C-12: Mortality Curves for Model 4E Retail Channels

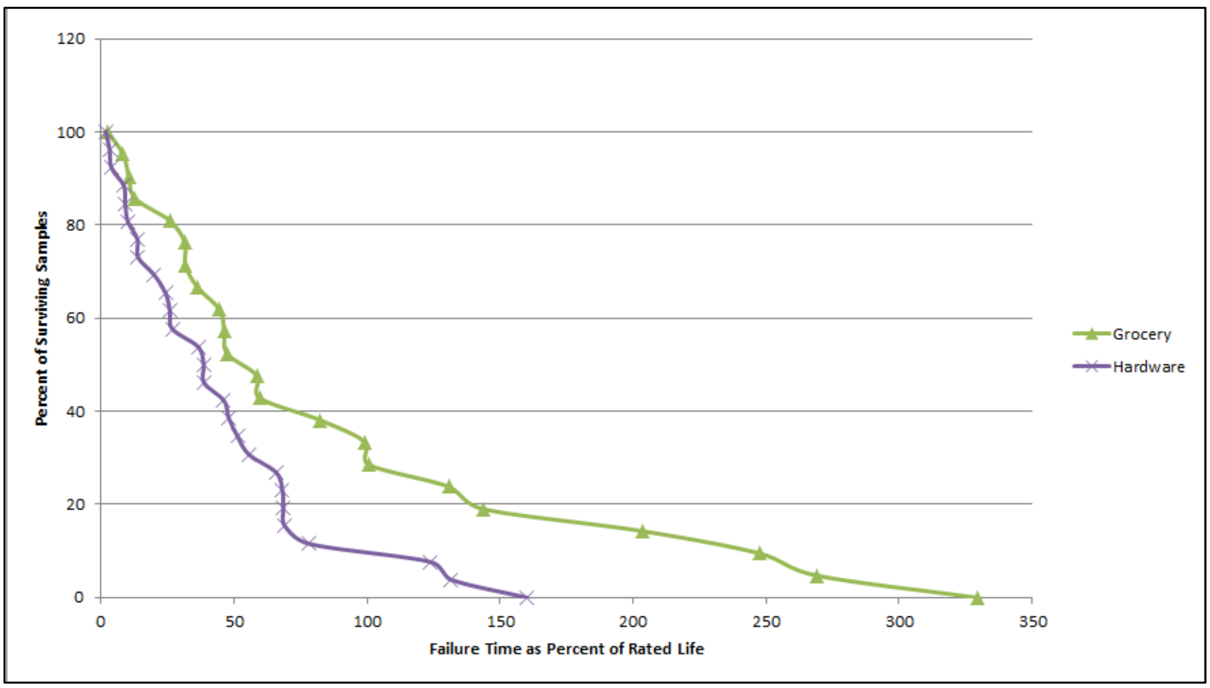


Figure C-13: Mortality Curves for Model 4F Retail Channels

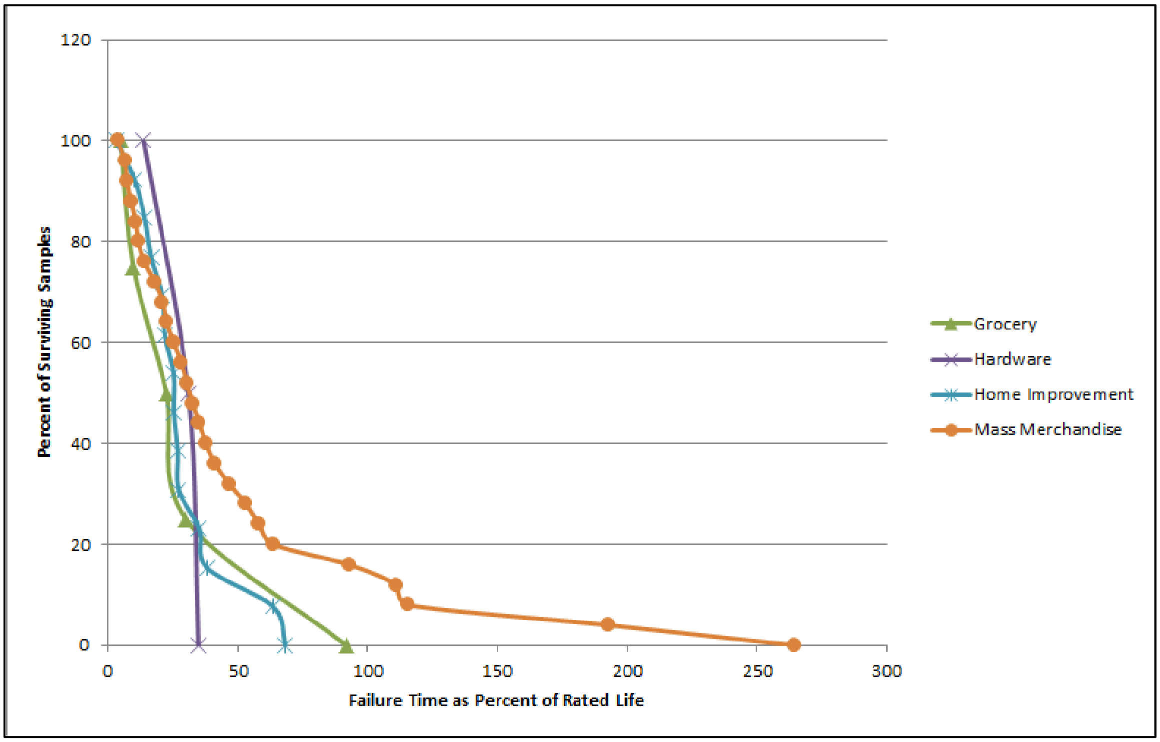


Figure C-14: Mortality Curves for Model 5D Retail Channels

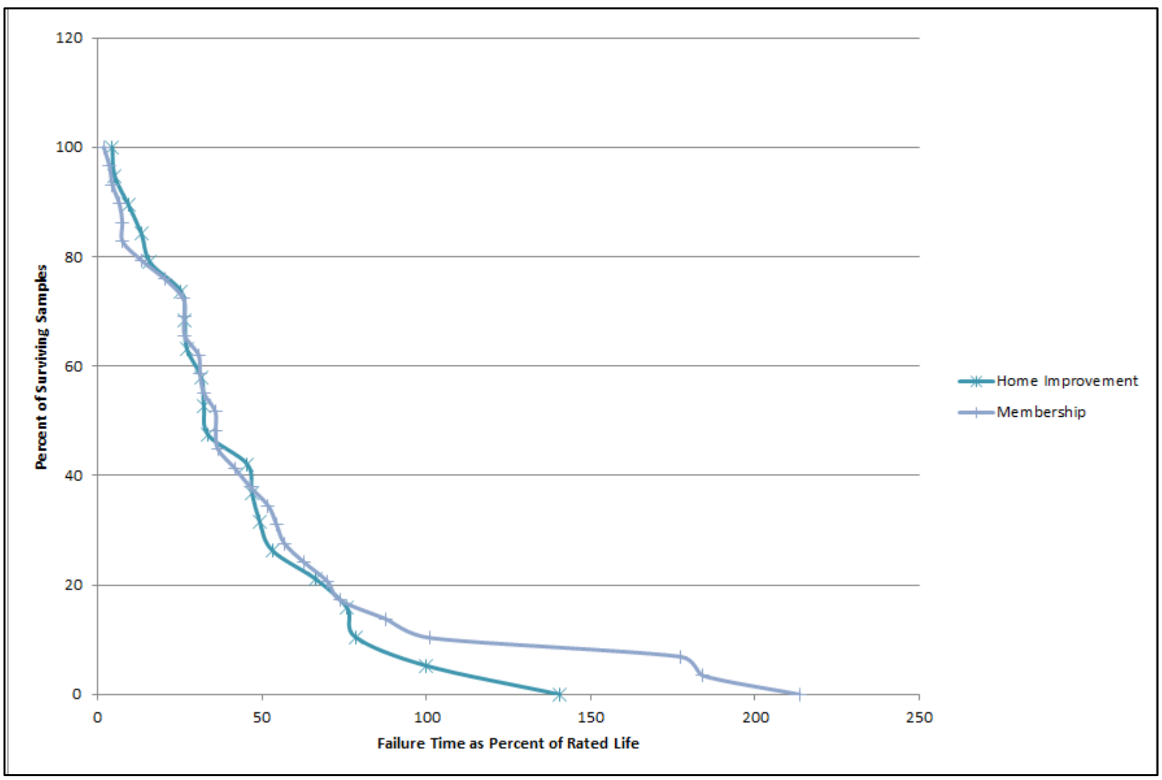


Figure C-15: Mortality Curves for Model 5H Retail Channels

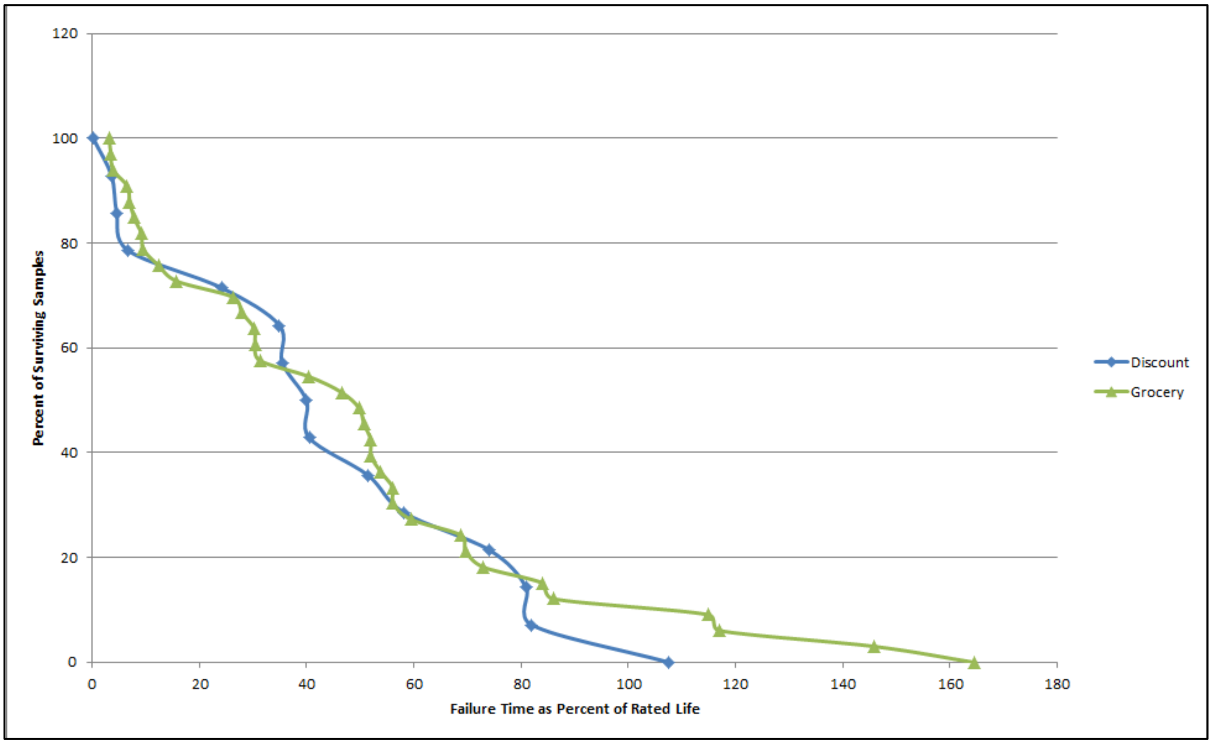


Figure C-16: Mortality Curves for Model 5I Retail Channels

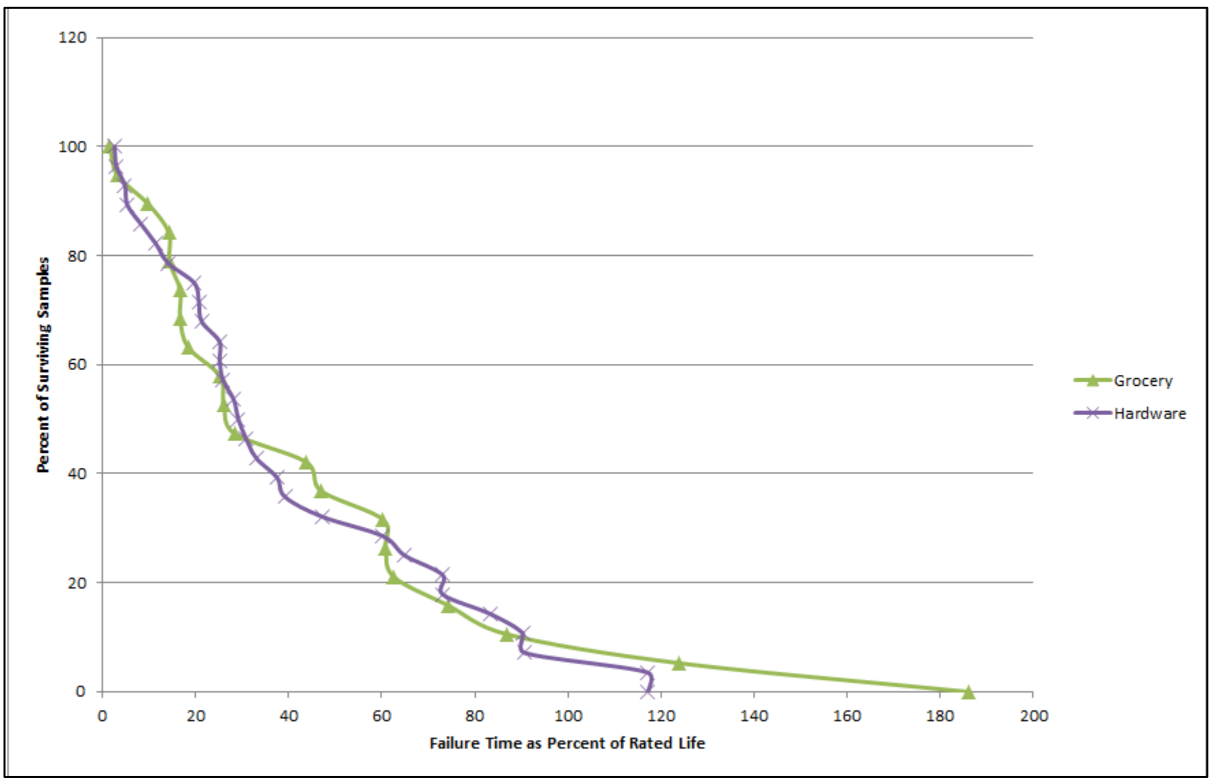


Figure C-17: Mortality Curves for Model 6C Retail Channels

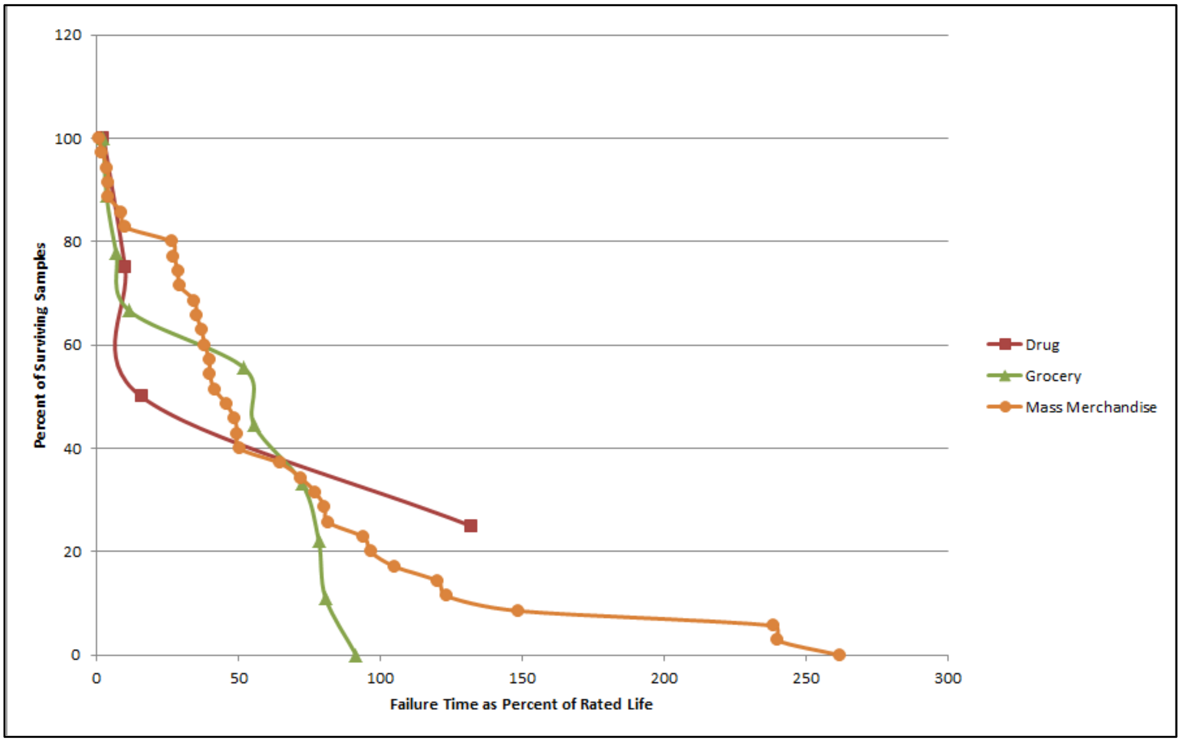


Figure C-18: Mortality Curves for Model 6D Retail Channels

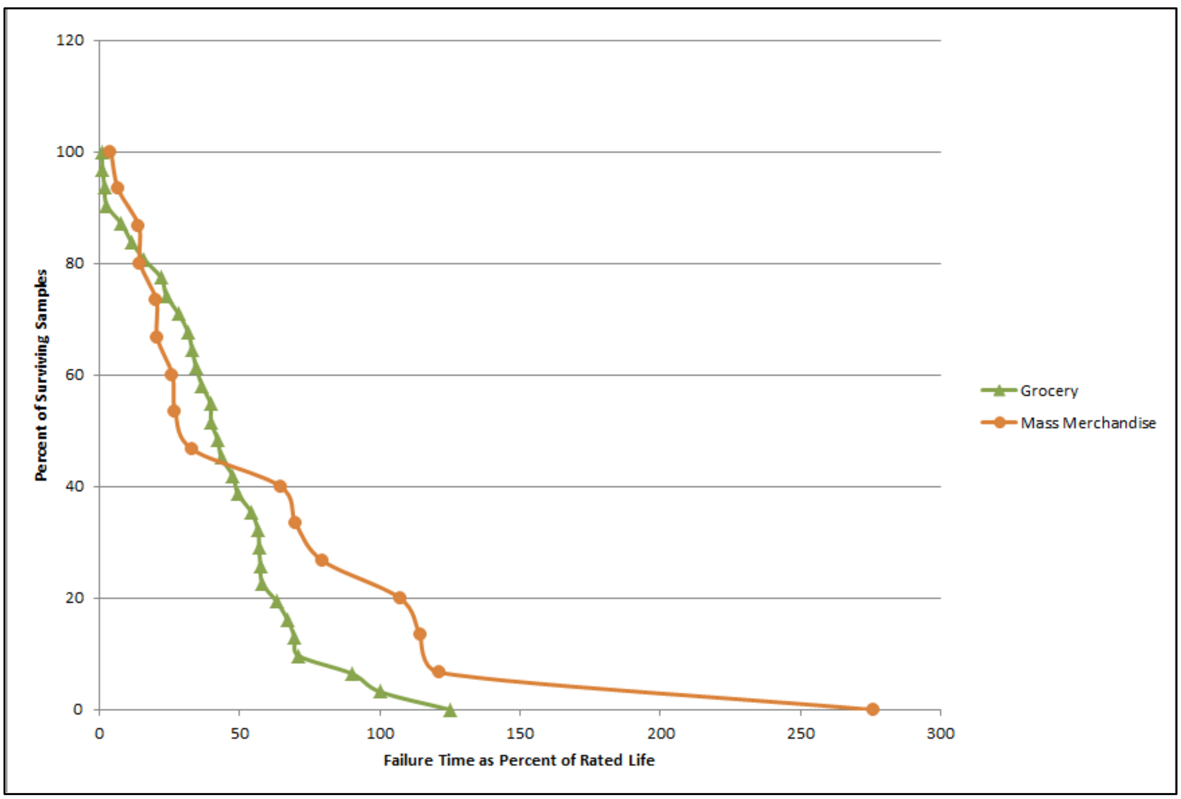


Figure C-19: Mortality Curves for Model 6F Retail Channels

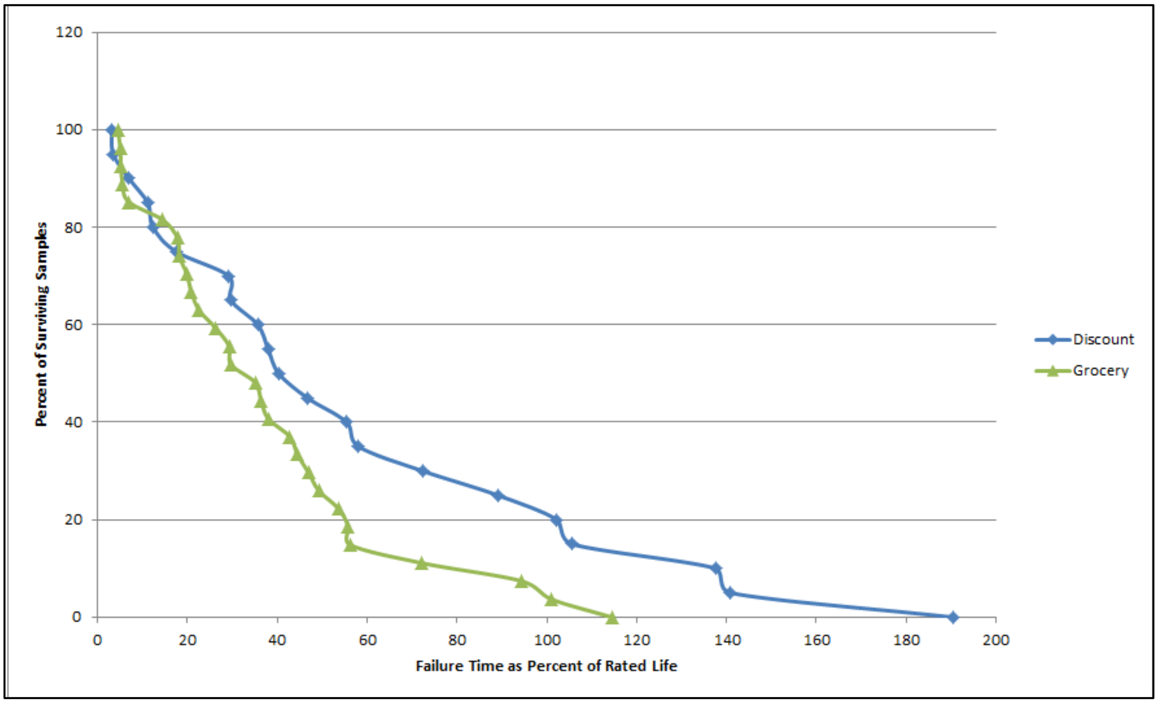


Figure C-20: Mortality Curves for Model 6G Retail Channels

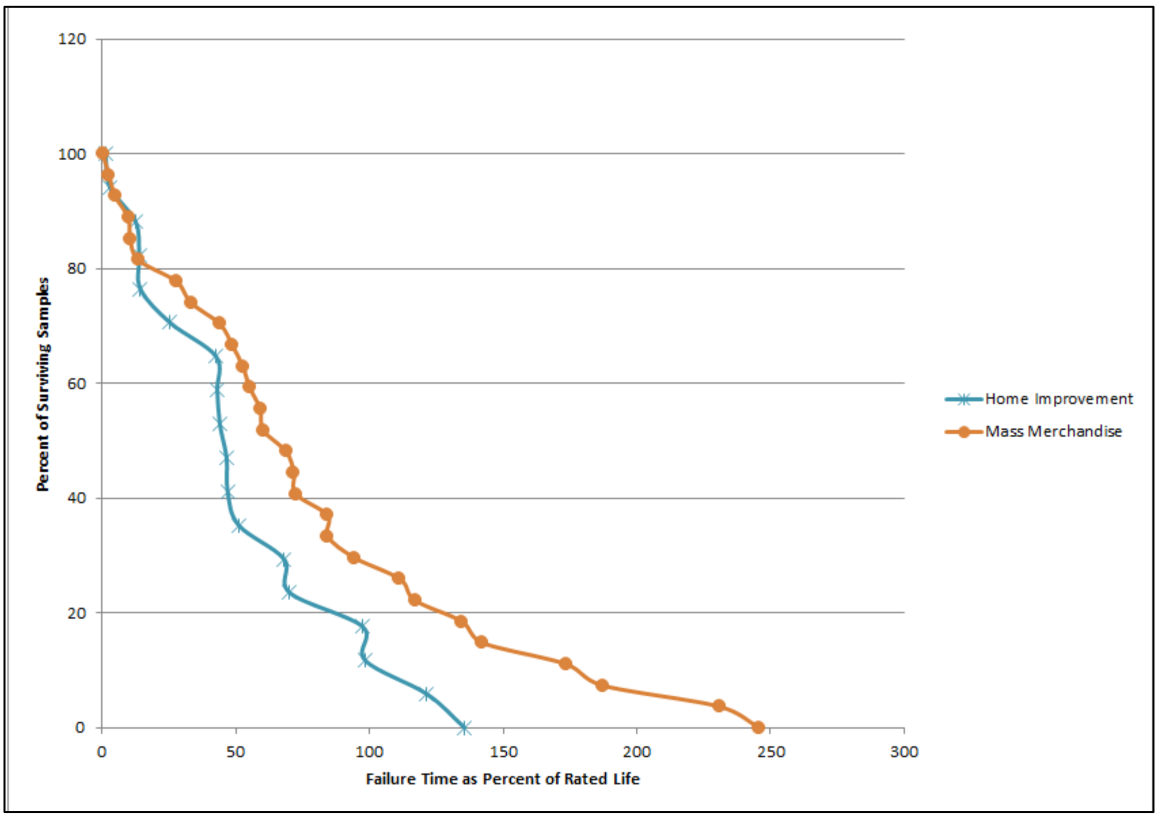


Figure C-21: Mortality Curves for Model 7B Retail Channels

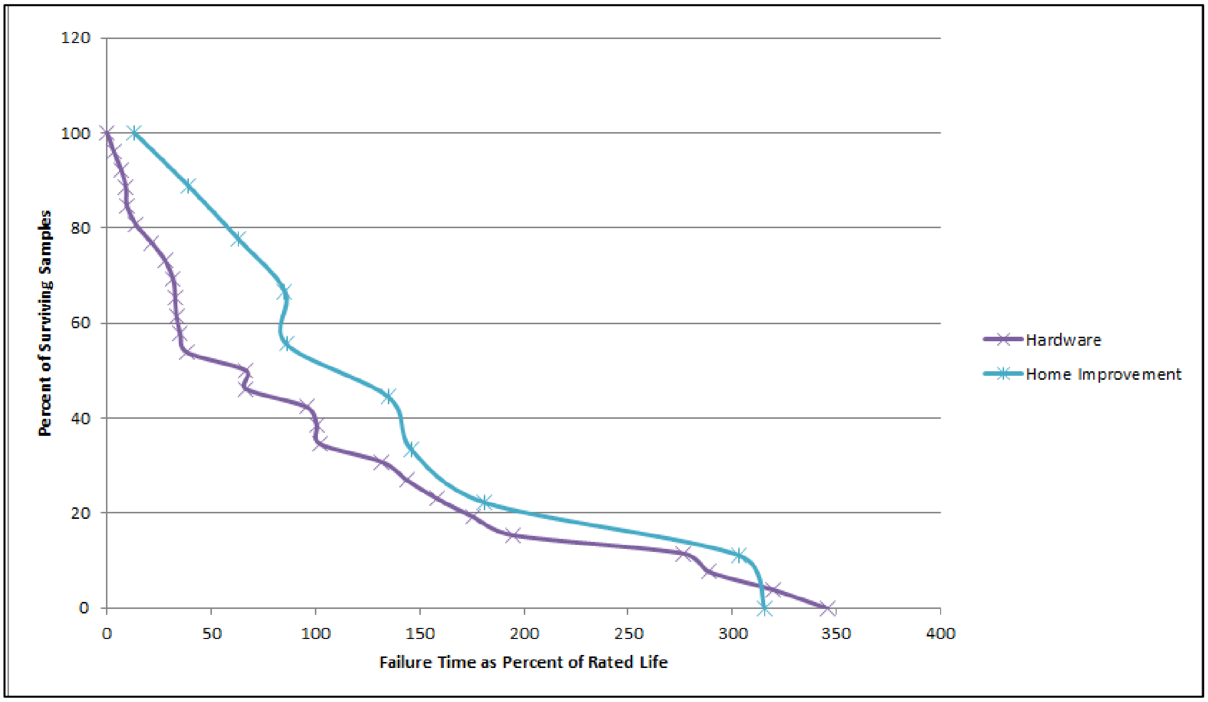


Figure C-22: Mortality Curves for Model 7C Retail Channels

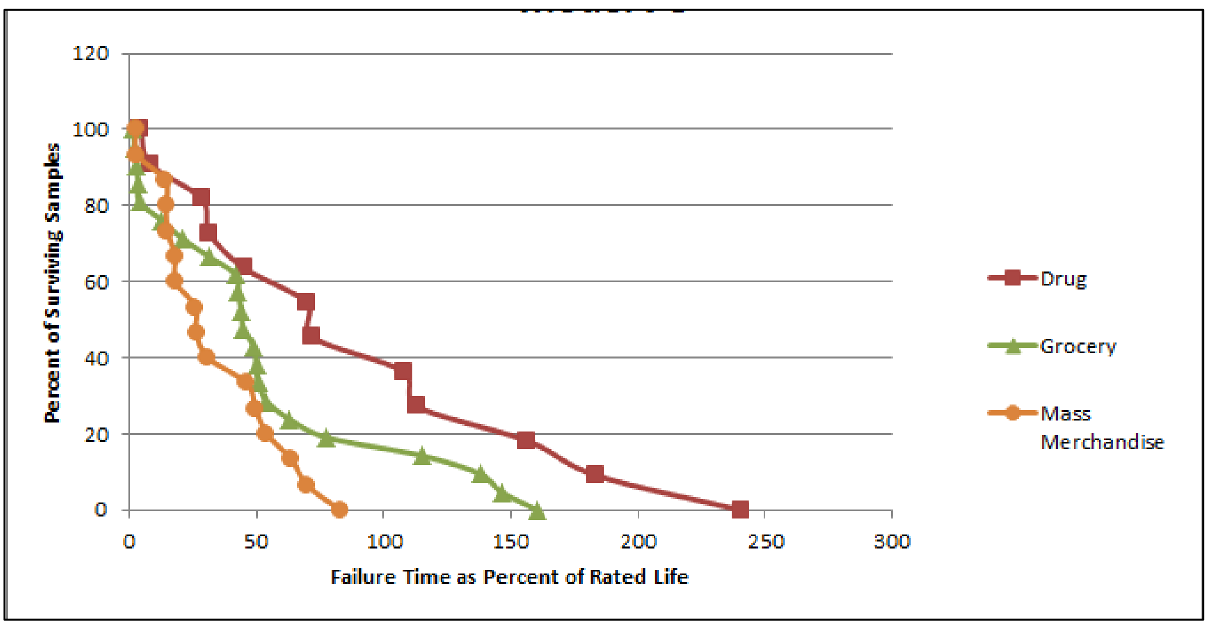


Figure C-23: Mortality Curves for Model 7D Retail Channels

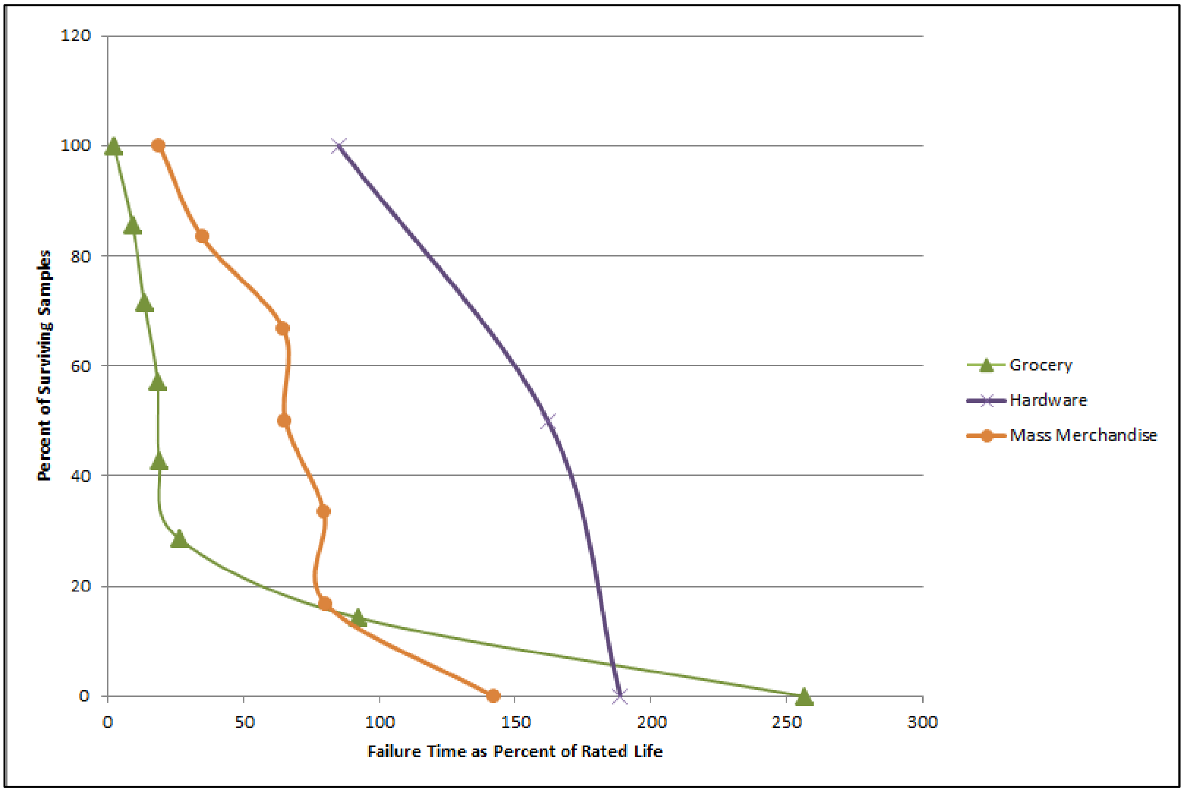
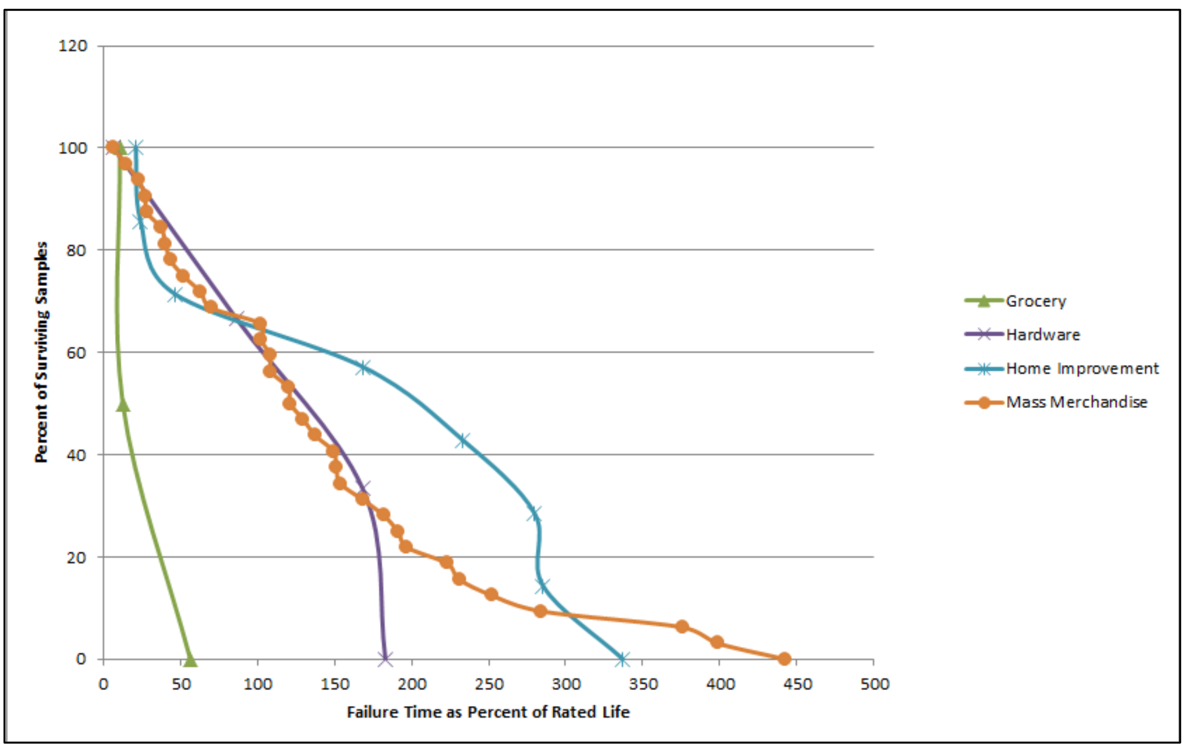


Figure C-24: Mortality Curves for Model 7H Retail Channels



C.2.2 Kolmogorov-Smirnov Test

Following the visual comparison of the retail channel mortality curves, we conducted Kolmogorov-Smirnov tests on pairs of the most disparate retail channel failure rate distributions for each model code to determine if the observed variation was statistically significant. This test was selected because the Kolmogorov-Smirnov test was the statistical test used to compare the mortality rate distributions for Energy Star versus non-Energy Star CFLs in the CFL lab test study.

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% (or 0.05), meaning that a p-value less than 5% would lead us to reject the hypothesis of no effect in favor of the hypothesis that lamp procurement from different retail channels result in significantly different failure rates.

We ran the Kolmogorov-Smirnov tests on pairs of retail channels for 24 different model codes. Twelve of the model codes had failure distributions that appeared to vary widely for more than just two retail channels, so we ran the Kolmogorov-Smirnov test on more than one pair of retail channel distributions for these model codes.

As Table C-1 shows below, the p-values resulting from the Kolmogorov-Smirnov tests on the paired retail channel failure distributions were greater than 5% for all but one retail channel pair. This suggests that the differences between the mortality curves across retail channels were not statistically significant but rather are within the range of what would be expected by chance variability. For one model code (7C), the p-value for the Kolmogorov-Smirnov tests (between mass merchandise and drug stores) was 4.8%, which indicates that the difference in the failure rate distributions between these two retail channels is significant. However, given that the statistical tests for the other 35 pairs of retail channels resulted in findings of no significance, we consider the pairing of mass merchandise and drug stores for model code 7C as an outlier. The evidence from our analysis overwhelmingly point to the conclusion that, overall, failure rate distributions across different retail channels do not have significant variation.

Table C-1: Kolmogorov-Smirnov P-Values for Retail Channel Pairs

	K-S Test Pair		
Model Code	**Retail Channel 1**	**Retail Channel 2**	**P-Value**
1C	Grocery	Mass Merchandise	0.279
1D	Grocery	Home Improvement	0.803
1D	Mass Merchandise	Home Improvement	0.426
1F	Mass Merchandise	Home Improvement	0.683
1F	Mass Merchandise	Hardware	0.728
1F	Home Improvement	Hardware	0.982
2B	Grocery	Hardware	0.468
2E	Hardware	Grocery	0.700
2E	Mass Merchandise	Grocery	0.121
2F	Grocery	Mass Merchandise	0.206
3B	Drug	Mass Merchandise	0.952
3B	Drug	Hardware	0.952
3C	Home Improvement	Mass Merchandise	0.610
3C	Home Improvement	Grocery	0.923
3F	Mass Merchandise	Grocery	0.466
3F	Mass Merchandise	Home Improvement	0.699
3F	Home Improvement	Grocery	0.767
4B	Hardware	Grocery	0.058
4B	Hardware	Home Improvement	0.591
4B	Home Improvement	Grocery	0.259
4D	Drug	Hardware	0.620
4E	Grocery	Hardware	0.232
4F	Home Improvement	Mass Merchandise	0.423
5D	Home Improvement	Membership	1.000
5H	Discount	Grocery	0.975
5I	Grocery	Hardware	0.927
6C	Grocery	Mass Merchandise	0.712
6D	Grocery	Mass Merchandise	0.518
6F	Discount	Grocery	0.504
6G	Home Improvement	Mass Merchandise	0.245
7B	Hardware	Home Improvement	0.239
7C	Mass Merchandise	Drug	0.048
7C	Mass Merchandise	Grocery	0.348
7C	Grocery	Drug	0.278
7D	Grocery	Mass Merchandise	0.108
7H	Mass Merchandise	Home Improvement	0.415

C.3 Conclusions and Caveats

The analysis described in this section concluded that there was no significant difference between the distributions of mortality rate across retail channels for all test models that were procured through more than one retail channel. Although our analysis was subject to budget, time, and sample size constraints, the results across the 24 model codes provide substantial evidence that the retail channel through which the test lamp was procured had no systematic bearing on the lamp’s failure rate.