Emerging Technologies

# Linear LED Lamps - Laboratory Performance Assessment

*ET14SCE1040 Final Report*

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# EXECUTIVE SUMMARY

SCE's Technology Labs conducted a laboratory assessment of a selective group of industry representative linear LED replacement lamps to validate this technology and gain a better understanding of previously identified concerns raised in previous studies.

## PROJECT GOALS

This project set out to validate the technology and manufacturer-provided data about linear LED replacement products. The main areas of focus were lamp performance, light output quality, power quality, safety, compatibility with existing fluorescent fixtures designed for linear fluorescent lamps, and potential installation issues. Results from this study will be analyzed to determine the technology's level of readiness for customer incentives.

## PROJECT DESCRIPTION

A selection of lamps from three different retrofit product families were tested under IES LM-79 and the Department of Energy's BLE metric to achieve a comprehensive evaluation of the lamp products and the units supplying power to them. Results are compared to the incumbent technology of fluorescent lamps. Combinations of certain products are tested in mixed or un-intended scenarios to determine the impacts on performance. Safety of the products was observed in detail to better understand possible issues the products may have.

## PROJECT FINDINGS

Products tested generally perform in accordance with manufacture's specifications with some exceptions. Ballast compatible lamps appear to be the better performing product family when the lamps are used in accordance with the manufacture's specifications.

External and internal driver product families had some inconsistencies with manufacturer provided information with some products not meeting minimum performance standards set by industry. These products also have some safety risks that need to be addressed including misleading or incorrect information provided on the product or by the manufacturer and labeling of the rewired fixtures.

## PROJECT RECOMMENDATIONS

Of the products tested, the ballast compatible family of products has the most potential for realized savings and safe installation. A long term assessment is necessary to properly assess fixture system degradation and performance. Easy to understand compatibility information needs to be developed by manufactures to assist customers in purchasing an appropriate product and customers need to

fully understand what they have installed in their buildings before selecting an appropriate replacement LED lamp.

# ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| AC | Alternating Current |
| BLE | Ballast Luminous Efficiency |
| CCT | Correlated Color Temperature |
| CRI | Color Rendering Index |
| CT | Current Transformer |
| DC | Direct Current |
| DLC | DesignLights Consortium |
| DOE | Department of Energy |
| DUT | Device Under Test |
| ET | Emerging Technologies |
| GE | General Electric |
| IES | Illuminating Engineering Society |
| IOU | Investor Owned Utility |
| LED | Light Emitting Diode |
| lm | Lumens |
| NEMA | National Electrical Manufacturers Association |
| NI | National Instruments |
| NIST | National Institute of Standards and Technology |
| OSHA | Occupational Safety and Health Administration |
| PF | Power Factor |
| QPL | Qualified Products List |
| SCE | Southern California Edison |
| SMUD | Sacramento Municipal Utility District |
| THD | Total Harmonic Distortion |
| USB | Universal Serial Bus |
| W | Watts |

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# INTRODUCTION

Linear LED lamp products have established themselves in the marketplace and become a popular option to replace fluorescent tube lamps. These products have been improving in recent years in terms of performance, and now provide light output similar to or better than linear fluorescent lamps. As the price of linear LED lamps has considerably decreased in the last few years and their power consumption is lower than comparable linear fluorescent lamps of similar light output, utilities are evaluating potential incentives to promote improved energy efficiency.

Since their introduction into the marketplace, utilities have been closely following the user acceptance, performance and price trends of linear LED lamps to determine whether they could be a viable option for fluorescent tube retrofits. A few years ago, SCE conducted laboratory testing to assess the performance of a selected group representative lamps. The testing revealed that linear LED lamps had limited compatibility with existing fluorescent ballasts. Compatibility of the LED lamps with typical ballast power wiring configurations was also noted as an issue as LED lamp product labeling and manufacturer information was not clear. Thus, safety became a major concern for utilities in their consideration for inclusion into their energy efficiency and demand response programs.

Since the study performed by SCE a few years ago, manufacturers have claimed that linear LED products have improved in many areas, including efficacy, light output quality and safety. However, there is still minimum documentation on the technology. Thus, utilities and government institutions, have become interested in assessing the current performance of lamps in laboratory and field settings. This study seeks to evaluate and verify the performance, energy savings, control options, compatibility, safety and ease of installation of linear LED lamps in fluorescent lamp retrofit applications in a lab setting. The design of this assessment was carefully designed to produce information complimentary to other studies recently performed and to assist California investor owned utilities in their evaluation of linear LED lamp products for inclusion into incentive programs.

# BACKGROUND

Linear fluorescent lamps are a popular option for illumination of large areas in offices and other types of commercial spaces. They are relatively energy efficient and are available in a variety of sizes, with the T8 4-foot lamp size being one of the most popular. In terms of power consumption, the 32W and 28W options are commonly specified with either instant-start or rapid-start electronic ballasts. The slightly smaller T5 fluorescent lamps offer similar or better performance than T8 lamps, but they are not considered direct replacements for either T8 or T12 lamps[1].

Linear LED lamps are fast becoming a popular option as T8 lamp replacements. There is a wide availability of products with some distinct configurations. While some manufacturers claim their products are considered "direct replacements", there are different lamp replacement options currently available. Recent studies conducted by Sacramento Municipal Utility District (SMUD) and the Department of Energy CALiPER program involved laboratory and field testing on these three product families in a variety of popular fluorescent fixtures. These reports yielded important observations about changes on the lighting output of some fixtures retrofitted with linear LED lamps due to the directionality of light produced by LED lamps. The installations documented in these reports also revealed the potential risk of electrical shock due to the availability of different wiring configurations. This mainly applied to the linear LED lamps with integrated and external LED drivers.

The rapid improvement observed in the last few years in terms of light output quality and efficiency of linear LED lamp technology combined with a wide range of product availability and configurations yields positive prospects for consideration of the technology into EE and DR incentive programs. This however, also represents a challenge for utilities and other entities interested in understanding the readiness of the technology for safe and reliable operation when used to retrofit existing fixtures designed around linear fluorescent lamp technology. Thus the need for continued tracking of the LED lighting technology development to properly assess their readiness for proper use in retrofitting fluorescent fixtures. Specifically, to compete with the incumbent fluorescent technology, further evaluation of linear LED lamp technology is needed to assess product quality, durability, safety and ease of installation.

This test aims to investigate whether linear LED lamp products currently available demonstrate satisfactory levels of performance and quality to be considered a safe, reliable and flexible option to operate in existing fluorescent fixtures.

## PRODUCT FAMILIES

There is no official standard available at the moment to classify the different types of LED lamps designed to retrofit existing fluorescent fixtures. However, some efforts are currently ongoing by California utilities and the DLC to offer some guidelines for the classification and performance of LED products intended as retrofits for fluorescent fixtures. The following are the most commonly agreed

[1] The "T" number on any fluorescent tube refers to the diameter of the tube only. This measurement is expressed in eighths of an inch. A T8 tube is 8/8 or 1 inch in diameter. Likewise a T12 is 12/8 or 1-1/2 inches and the T5 is 5/8 inches in diameter. All T8 and T12 bulbs have medium bi-pins on the end of the tube; the T5 has mini bi-pins.

types of linear LED lamps currently available that don’t require any modifications to existing troffer optics, and are used as the basis for this study:

- Linear LED lamps compatible with existing fluorescent lamp ballasts
- Linear LED lamps with internal LED driver
- Linear LED lamps with external LED driver

# ASSESSMENT OBJECTIVES

Conduct a laboratory test to assess the photometric and electrical performance, dimming capability, safety and appearance of market representative linear LED lamps designed to replace linear fluorescent T8 lamps. Interoperability between different manufacturer products and compatibility with fluorescent ballasts is investigated to determine whether linear LED lamps are safe and effective to use as retrofits and whether lamps of different types can be used on the same power supply.

Results from the lab tests will be used for analysis and consideration of linear LED lamp products in future SCE energy efficiency and demand response incentive program offerings. The proposed tests involve two different phases. Phase I consists of a series of laboratory tests to assess the baseline performance of three different types of LED T-8 replacement lamps. Phase II is a long-term life performance assessment to evaluate photometric and thermal degradation of selected linear LED lamps.

This study is focused on providing updated information to utility incentive programs in the following areas:

- Compatibility options with linear fluorescent lamp ballasts
- Interoperability between linear LED lamp products with fluorescent lamps
- Efficacy, light output and power quality of linear LED lamp technology
- Power and voltage supply options
- Installation requirements and safety of linear LED lamps in retrofit applications
- Long term performance of linear LED lamps powered by fluorescent ballasts in retrofit installations and effects on ballast performance

# PRODUCT EVALUATION

Selection of lamps for this evaluation, was based on the DLC Qualified Products List (QPL). SCE and other California Investor Owned Utilities (IOU) use the QPL as a bases for determining eligibility of solid state lighting products for incentives.

## PRODUCT REQUIREMENTS

TABLE 1. DLC TECHNICAL REQUIREMENTS[2]

| | MINIMUM OUTPUT | MINIMUM EFFICACY | MINIMUM WARRANTY | CCT / CRI / $L_{70}$ | POWER FACTOR / THDI |
|---|---|---|---|---|---|
| BARE LAMP | 1,600 lm | 100 lm/W | 5 Years | ≤5,000 / ≥80 / ≥50,000 | ≥0.9 / ≤20% |
| IN FIXTURE (2 LAMPS) | 3,000 lm | 85 lm/W | 5 Years | ≤5,000 / ≥80 / ≥50,000 | ≥0.9 / ≤20% |

Table 1~~Table 1~~ above shows the technical requirements for 4ft. linear replacement lamps from DLC.

## DUT CHARACTERISTICS TO CONSIDER

There are several other factors to consider when selecting a lamp, some of which are only available to LED products. When selecting products for this study, the purpose was to procure products with similar characteristics to the incumbent fluorescent lamps.

The following were important lamp characteristics considered in the final selection of linear LED lamp samples for this evaluation.

- Lens finish
- Beam angle
- Color variations
- Dimmability
- Connector type
- Lamp configuration (lamps per luminaire, per driver, etc.)
- Must meet the following minimum requirements:
    - 1800 lumen rated total output
    - 100 lm/W rated efficacy

Beam angle is important to consider in luminaire installations, as lamps with smaller beam angles tend to have higher fixture efficiency.[3] Beam angle also

[2] DesignLights Consotium, *Technical Requirements Table V3.0,* 9/1/2015, page 3; https://www.designlights.org/resources/file/TRT_V3_FULLTABLE_Final_9-1-15

[3] CALiPER, *"Report 21.1: Linear (T8) LED Lamps in a 2x4 K12-Lensed Troffer",* April 2014, page 11

tends to depend upon the lens finish, with clear finishes having generally smaller beam angles and diffuse lenses having higher beam angles. For this evaluation, beam angle was noted but not considered as a significant factor in product selection.

It has been observed that LED lamps perform more like fluorescents in luminaries when the LED lamps have a diffuse finish on the lens. This was preferred by observers who found them to be less glaring.[4] It should also be noted that on average, bare lamps with a diffuse lens have approximately 10% less efficacy than bare lamps with a clear lens.[5] For this investigation, lamps with a diffuse lens and a beam angle between 120° and 145° where prioritized due to being common in the market as well as being visually more prioritized.

Consumers are most likely to replace fluorescent lamps with LED lamps in the same color range to produce similar light output. Lamps with a Correlated Color Temperature (CCT) in the cool-white (4000K-4500K) range where selected as this is popular for linear fluorescent lamps in office spaces and commercial/industrial applications.

Due to the increasing popularity of dimming controls, both step and continuous, and their requirement as part of California Title 24,[6] it is important to evaluate products that work with these specifications. Where possible dimming products where selected over non-dimming products.

This study is interested in replacement lamps, thus lamps with a G13 connector which could be easily installed in existing fixtures with fluorescent lamps were preferred.

All lamp samples used in this evaluation were obtained from normal distribution channels. No products were taken directly from manufacturers to prevent using products with improved performance.

## SELECTED PRODUCTS

Based on the product requirements and characteristics considered as part of the project planning as explained in the DUT Characteristics to Consider section, the following lamps were selected for this test. The data reported in the Table 2 through Table 4 was obtained from product labels or manufacturer supplied brochures. It is not known whether claimed values are initial or mean.

TABLE 2. SELECTED BALLAST COMPATIBLE LAMP SPECIFICATIONS

| LAMP | LUMENS | CCT | CRI | INPUT WATTAGE | BEAM ANGLE | LENS | DIMMABLE |
|---|---|---|---|---|---|---|---|
| A | 2100 | 4000 | 90 | 21 | N/A | frosted | Yes |
| B | 2000 | 4100 | 80 | 19 | 150 | frosted | No |
| C | 2100 | 4000 | 83 | 16.5 | 160 | frosted | No |
| D | 2500 | 4100 | 80 | 22 | 110 | frosted | No |
| E | 2200 | 4100 | 82 | 22 | 110 | frosted | No |

[4] CALiPER, *"Report 21.2: Liner (T8) LED Lamp Performance in Five Types of Recessed Troffers"*, May 2014, page 27

[5] CALiPER, "*Application Summary Report 21: Linear (T8) LED Lamps"*, Match 2014, page 14

[6] California Energy Commission, *"2013 Building Energy Efficiency Standards"*, November 2013, page 145

**TABLE 3. SELECTED INTERNAL DRIVER LAMP SPECIFICATIONS**

| LAMP | LUMENS | CCT | CRI | INPUT WATTAGE | BEAM ANGLE | LENS | DIMMABLE |
|---|---|---|---|---|---|---|---|
| F | 1700 | 4100 | 80 | 17.7 | 120 | frosted | No |
| G | 1900 | 4000 | 80 | 18 | N/A | frosted | Yes |
| H | 2060 | 4000 | 83 | 20.8 | N/A | clear | Yes |
| I | 2480 | 4100 | 86 | 18 | 160 | frosted | Yes |
| J | 2123 | 4000 | 83 | 15.7 | 160 | frosted | No |

**TABLE 4. SELECTED EXTERNAL DRIVER LAMP SPECIFICATIONS**

| LAMP | LUMENS | CCT | CRI | INPUT WATTAGE | BEAM ANGLE | LENS | DIMMABLE |
|---|---|---|---|---|---|---|---|
| K | 2249 | 4100 | 80 | 22.5 | N/A | none | Yes |
| L | 2000 | 4000 | 80 | 18 | N/A | frosted | Yes |
| M | 2200 | 4000 | 80 | 22 | 110 | other | Yes |
| N | 2250 | 4000 | 80 | 22 | 150 | frosted | Yes |
| O | 2450 | 4000 | 80 | 22 | N/A | frosted | Yes |
| P | 2100 | 4000 | 80 | 18 | N/A | frosted | Yes |

All lamp samples used in this evaluation were commercially available production units obtained from normal distribution channels.

# TECHNICAL APPROACH

Laboratory tests were designed to assess the performance characteristics of different linear LED lamps and compare them to comparable linear fluorescent lamps of similar light output. The assessment were optimized to produce comparisons in terms of power, total light output (lumens), efficacy, color quality, power quality, and long term performance.

## BENCHMARK LAMPS

The following fluorescent lamps were tested and used as baselines to compare with the LED replacement lamps.

TABLE 55. SELECTED FLUORESCENT LAMP SPECIFICATIONS

| LAMP | LUMENS | CCT | CRI | INPUT WATTAGE |
|---|---|---|---|---|
| Q | 2850 | 4100 | 82 | 32 |
| R | 2950 | 4100 | 85 | 32 |
| S | 2675 | 4100 | 82 | 28 |
| T | 2725 | 4100 | 85 | 28 |

The lamps above were selected using the following pre-determined criteria:

- 32W, T8, 800 Series fluorescent linear lamp in the 4100-4500 K color temperature range with instant start, and programmed start electronic dimming ballast.
- 28W, T8, fluorescent linear lamp in the 4100-4500 K color temperature range with instant start, and programmed start electronic dimming ballast.

## BALLASTS USED FOR TESTING

The following ballasts were selected to test the ballast-compatible linear LED tubes. Selection of these was based on compatibility as specified by the linear LED tube manufacturers, and popularity of the ballasts. Some exceptions were used for testing with the Philips Programmed start ballasts. These exceptions are explained in the Discussion section.

TABLE 6. SELECTED BALLAST SPECIFICATIONS

| # | MAKE | MODEL | BALLAST TYPE | NO. OF LAMPS | DIMMING | CONTROLS |
|---|---|---|---|---|---|---|
| 1 | GE | GE132MAX-N/Ultra | Instant Start | 1 Lamp | No | None |
| 2 | GE | GE232MAXP-N/Ultra | Instant Start | 2 Lamp | No | None |
| 3 | GE | GE232MAX90-V60 | Instant Start Dimmable | 2 Lamp | Yes | 0-10V |
| 4 | GE | GE232MVPS-N | Programmed Start | 2 Lamp | No | None |
| 5 | GE | GE232MVPSN-V03 | Programmed Start Dimmable | 2 Lamp | Yes | 0-10V |
| 6 | Philips | IOP-1P32-N | Instant Start | 1 Lamp | No | None |
| 7 | Philips | IOP-2P32-N | Instant Start | 2 Lamp | No | None |

| # | Make | Model | Ballast Type | No. of Lamps | Dimming | Controls |
|---|---|---|---|---|---|---|
| 8 | Philips | IOP-2PSP32-N | Programmed Start | 2 Lamp | No | None |
| 9 | Philips | REZ-2S32-SC | Programmed Start Dimmable | 2 Lamp | Yes | Phase |

# Test Phases

The testing was broken up into two separate phases. The first test phase consisted of baseline evaluation of the lamps to determine how they perform in comparison to manufacturer specifications. The second test phase evaluated the long term performance on selected lamps and ballast combinations based on results from the first phase under a continuous cycling program.

Samples from the three linear LED product families were used in the first test phase. Different combinations of lamp and ballast were tested for ballast compatible lamps. For evaluation of linear LED lamps with external driver or directly powered from AC main, only manufacturer-approved configurations were used.

The second test phase involved long term performance evaluations of ballast-compatible linear LED lamps. Four fixtures were assemble for this evaluation using different combinations of linear LED lamps and ballasts. Additionally, one fixture using fluorescent lamps and compatible ballast was also selected for long term assessment to establish a baseline comparisons.

# Test Plan - Phase 1

For this study two different testing methods were employed to achieve a comprehensive assessment of the lamps. The first method consisted of electrical and absolute photometric measurements per appropriate IES standards while the second method consisted of electrical and relative photometric measurements based on the DOE Ballast Luminous Efficiency (BLE) metric[7]. The purpose of the IES measurement was to assess the overall performance of complete lighting systems consisting of the lamp and the ballast or driver. On the other hand, the BLE measurements were performed to assess the efficiency of ballasts or drivers in terms of input power and total output power delivered to the lamps. This phase was split into three subsections, each focused on a specific product family.

The first to be tested were the ballast compatible lamps. Each lamp was tested on a variety of ballasts in different combinations and configurations and compared with two baseline fluorescent lamps (32W and 28W lamps). Products readily available on the market at the time of testing were mainly approved by the manufacturers for use on *instant start ballasts only*, with some exceptions. Thus the majority of testing was focused on Instant start type ballasts.

Testing was conducted on both one and two lamp ballasts. For two lamp ballasts, three different installation types were evaluated:

[7] Please refer to Reference section of this report for a complete set of guidelines used for testing.

- Standard: only a single product type was fitted to the ballast
- Hybrid: a mix of technologies were installed, where appropriate, into the fixture (namely ballast compatible LEDs and fluorescent lamps together)
- De-lamping: only a single lamp was installed on the fixture designed for 2-lamp installations

These different scenarios are of interest due to consumers installing lamps in unknown configurations and limited or conflicting product compatibility information.

The second product family to be tested were the direct power lamps. Lamps were tested in both one and two lamp configurations to see if there were differences in the light output or electrical performance with paired and single lamps. The DOE BLE testing was not conducted on these lamps due to there being no ballast or driver accessible, thus eliminating any pertinent information that might have been gained from this testing.

Lastly, the external driver family of lamps were tested. Lamps were tested only with manufacturer approved drivers. All lamp and driver combinations selected were either single lamp or double lamp per driver. Lamps were tested per manufacturer's installation instructions using both IES and DOE methods detailed below. All lamps of this type were tested in both a standard and de-lamped configuration to assess what would happen in normal running operation and situations where a single lamp was either not performing or removed.

No tests were performed where LED products of any type from different manufacturers were mixed.

## Test Matrix

**Table 7. Test Matrix for Ballast Compatible and Fluorescent Lamps**

| Ballast | | LED Lamps | | | | | Fluorescent Lamps | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Make | Model | A | B | C | D | E | Q | R | S | T |
| GE | GE132MAX-N/Ultra | X | X | X | X | X | X | | X | |
| GE | GE232MAX90-V60 | X | | | | | X | | X | |
| GE | GE232MAXP-N/Ultra | X | X | X | X | X | X | | X | |
| GE | GE232MVPS-N | X | | X | | | X | | X | |
| GE | GE232MVPSN-V03 | X | | | | | X | | X | |
| Phillips | IOP-1P32-N | X | X | X | X | X | | X | | X |
| Phillips | IOP-2P32-N | X | X | X | X | X | | X | | X |
| Phillips | IOP-2PSP32-N | X | | X | | | | X | | X |
| Phillips | REZ-2S32-SC | X | | | | | | X | | X |

**Table 8. Test Matrix for External Driver Lamps**

| Test Type | K | L | M | N | O | P |
|---|---|---|---|---|---|---|
| 1-Lamp Driver | | | | X | X | X |
| 2-Lamp Driver | X | X | X | X | X | X |
| De-Lamp | X | X | X | X | X | X |
| Dimming | X | X | X | | X | |

TABLE 9. TEST MATRIX FOR INTERNAL DRIVER LAMPS

| | F | G | H | I | J |
|---|---|---|---|---|---|
| 1-Lamp | X | X | X | X | X |
| 2-Lamp | X | X | X | X | X |
| Dimming | | X | X | X | X |

## FIXTURE SETUP

DUTs were tested in a single or double lamp configuration using a standard open strip luminaire; Utopia model S4232UNVPS or equivalent were used. Luminaires were fitted with G13, un-shunted, medium base, bi-pin, slide-on, turn-type, low profile lamp holders ("tombstones"). Each pin of the tombstone was wired to a terminal block, which would be configured to the needs of an individual test (shunting was done at the terminal block). Ballasts, drivers, or direct power was wired to the terminal blocks in accordance with the manufacturers' wiring instructions and lamp requirements.

## ELECTRICAL AND PHOTOMETRIC MEASUREMENTS PER IES STANDARDS

Lamps were tested to the appropriate IES standard. IES LM-9-09 was used for Fluorescent lamps and IES LM-79-08 was used for solid state (LED) lamps. Measurements were taken at full power, and at 75%, 50% and 25% of full power input. Additionally, measurements were taken at the minimum supported dimming level.

### INSTRUMENTATION

Tests were performed in an integrating sphere with a spectroradiometer to measure total lumen output, CCT and CRI. A controlled power supply was used to provide appropriate ballast/driver input power per manufacturer specifications. A power analyzer was connected to the ballast input side for electrical measurements. Additionally, ambient temperature was recorded inside and outside the integrating sphere throughout each individual test.

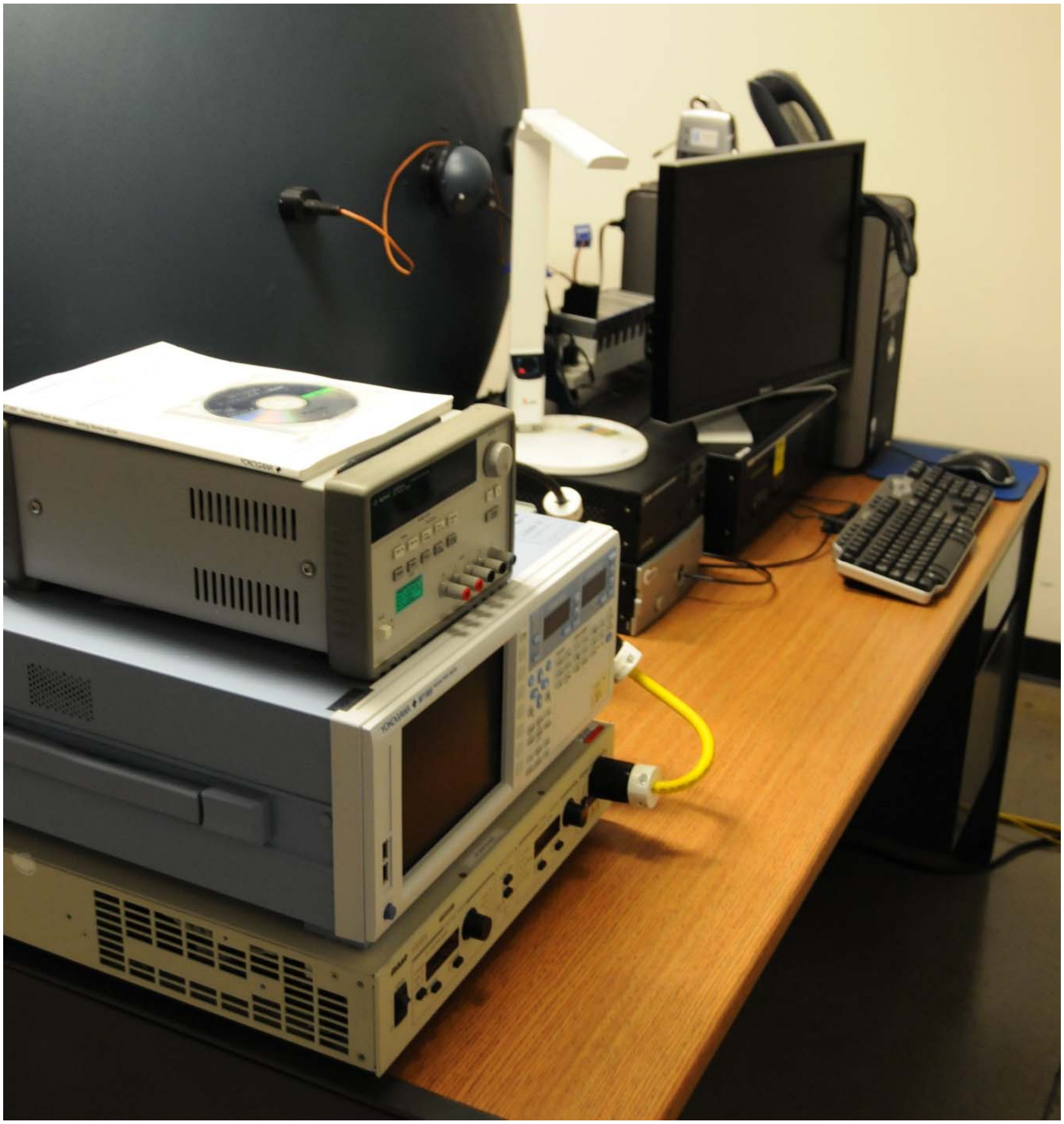


**FIGURE 1. PHASE I – INTEGRATING SPHERE INSTRUMENTATION**

## ELECTRICAL AND PHOTOMETRIC MEASUREMENTS PER DOE BLE METRIC

To obtain a more appropriate evaluation of the ballast or driver performance powering the lamps under testing, the DOE BLE test method was adopted and used separately from integrated sphere testing.

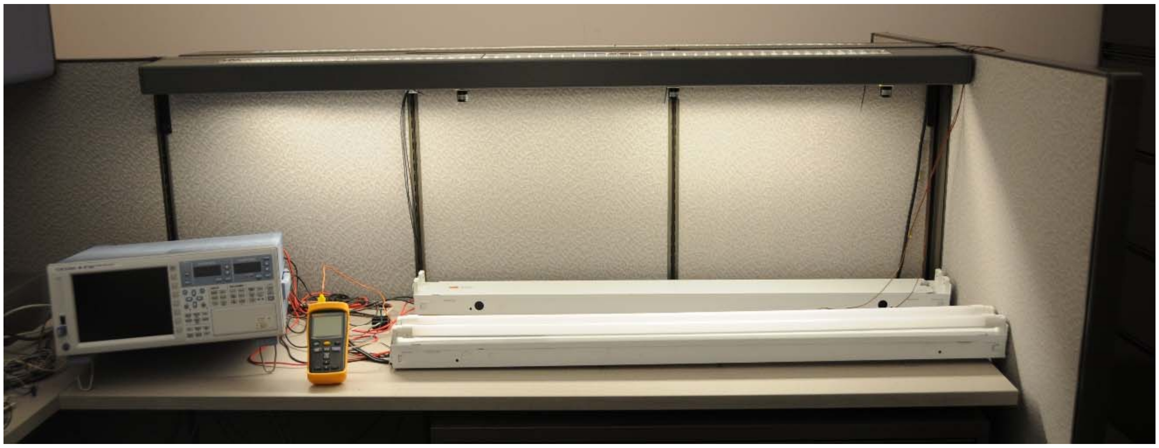


FIGURE 2. PHASE I - BALLAST EFFICIENCY TEST SETUP

#### INSTRUMENTATION

Electrical measurements were taken by a power analyzer on the input side of the ballast/driver and the output to each lamp. External current transformers (CTs) were used on the input power to each lamp. A controlled power supply was used to provide appropriate ballast/driver input power per manufacturer specifications. Relative photometric measurements (Lux), using full power lumen output as reference, were taken for each test where the lamps and ballasts supporting dimming functionality.

### DIMMING

Ballasts and drivers were tested at full power and at 75%, 50% and 25% of full power input. Additionally, measurements were taken at the minimum supported dimming level.

## TEST PLAN – PHASE 2

This phase is a long term assessment to determine degradation of the lamps or ballast in terms of both electrical energy consumption and photometric output. The testing is split into three separate evaluation schemes (see Table 10~~Table 12~~).

The first is continuous monitoring, where the lamps were monitored for electrical performance continuously for the duration of the assessment. Each fixture was instrumented to measure the energy consumption at the ballast input, and ballast and lamp surface temperatures. Ambient temperatures were also recorded throughout the test. The lamps were cycled throughout this test phase to simulate real world use of the lamps. Each day is split into three cycling segments. For one segment the lamp is off for 9 hours. This is to allow the entire fixture to cool down to room conditions and simulate off-hours office or commercial areas. The next segment is a 7-hour on period. This is to assure that the lamps achieve stabilized thermal, photometric and electrical conditions and simulate an office area with constant lighting requirements. The remaining 8-hour period is broken into four 2-hour sections where the lamp is on for 1.5 hours and off for 0.5 hours. This is to introduce more cycles and shock to the system and is intended to emulate a conference room or similar area with occupancy controls.

The second type of evaluation is a periodic dark room test. Once per week the fixture is moved into a dark room where it is monitored for 7 hours while the fixture is continuously on. Light output is measured at ten points across the lamp (5 at 0° and 5 at 90° from the horizontal plane) as shown in Figure 5~~Figure 5~~ below. The fixture is instrumented for measuring electrical performance in the same way it is for the BLE testing described in phase 1, with both ballast input and lamp input measured. At 6 hours into the test, the dark room is opened and a cover in the side of the fixture is removed to expose the ballast as shown in Figure 3~~Figure 3~~ below. A thermal image of the ballast and lamp are taken to roughly measure the surface temperatures of both. Temperature monitoring from the continuous testing continues during this test. When the test is completed, the fixture is moved from the dark room to a designated continuous monitoring station.

Results of Phase 2 tests will be reported separately in the form of an addendum report.

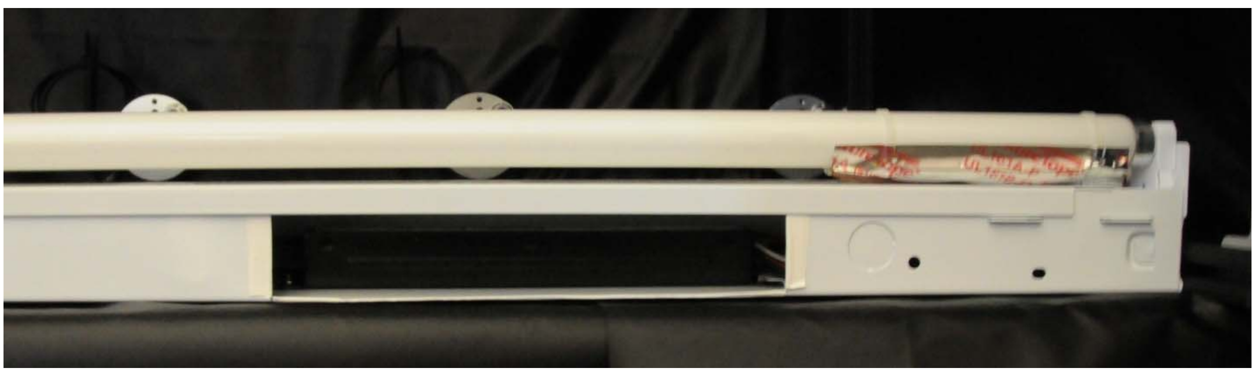


FIGURE 3. PHASE 2 – FIXTURE WITH ACCESS TO VIEW BALLAST AND THERMOCOUPLE ON LAMP

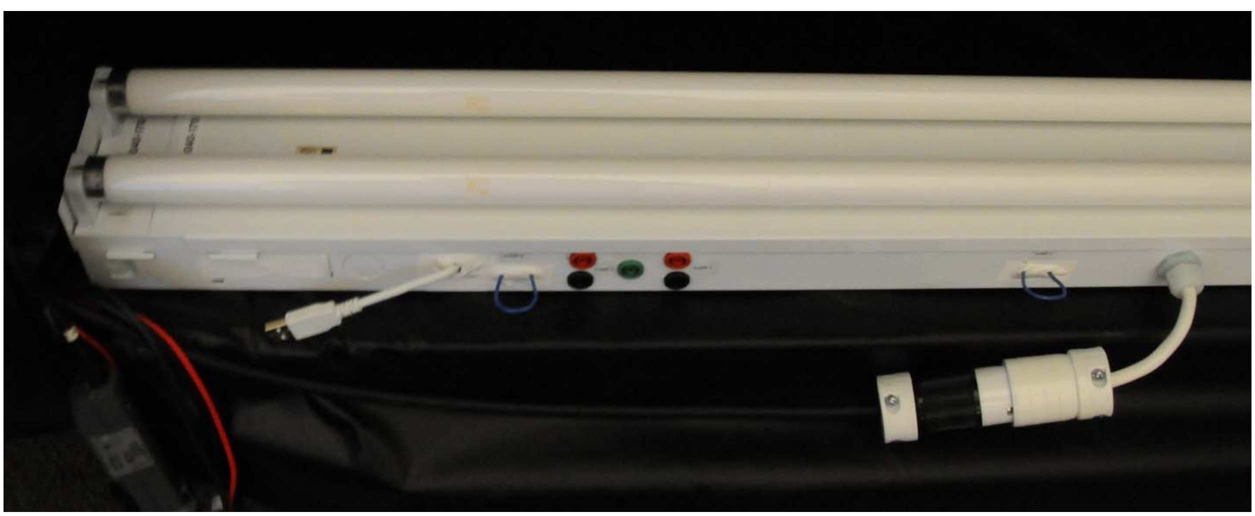


FIGURE 4. PHASE 2 – FIXTURE INSTRUMENTATION ACCESS

FIGURE 5. PHASE II – DARKROOM WITH INSTRUMENTED FIXTURE

The last type of evaluation performed on the lamps is an IES LM-79 test. This test is done once per month to monitor photometric degradation in more detail. The fixture is pulled out of service and placed inside the sphere as is, without de-instrumentation of thermocouples. Some light is known to be blocked by the thermocouple installation, so only relative measurements should be observed from these results.

TABLE 10~~12~~. PHASE II - EVALUATION SCHEMES AND MEASUREMENTS

| Measurement Type | Evaluation Scheme | | |
|---|---|---|---|
| | Power Cycling | Dark Room | LM-79 |
| Electrical | Ballast input | Ballast input and lamp input | Ballast input |
| Thermal | Ballast and lamp surfaces | Ballast and lamp surfaces | Inside and outside sphere ambient |
| Photometric | None | Illuminance at 10 different points along lamps | Total lumen output, CRI and CCT |

## PRODUCT SELECTION

From result obtained in phase 1 of the project, it was decided that ballast-compatible lamps were of most interest for long term study. Five fixtures were tested with one of the five using a baseline fluorescent lamp for comparison. Two variables were used for the setup, namely ballast type and lamp manufacturer. For a set of two tests, only one variable has changed. Three fixtures used the same, 2-lamp instant start ballast from GE (model GE232MAXP-N/Ultra) with different lamps; lamps B, C and a 32W fluorescent lamp. Lamp C was installed in the remaining two fixtures with a single lamp instant start ballast and an instant start 2-lamp ballast from a different manufacturer. All of these lamp and ballast combinations where also tested as part of phase 1 to be able to draw comparisons. Brand new lamps and ballast where used for this testing (all parts had zero run hours at the start of the test). The fluorescent lamps used for this testing were seasoned prior to cycling per IES Standard LM-54-99.

## FIXTURE SETUP

Open strip luminaires were modified such that the lamps would not need to be removed from the luminaire at any point during testing, while still allowing the fixtures to be moved into different test chambers for data collection. Each strip fixture was affixed with ports for connecting current clamps, voltage sensing leads, and USB connections to retrieve data from on-board temperature logging devices. NEMA 7-15 plugs were fitted to each fixture for power input. A section of the fixture was cut out from the side of the luminaire where the ballast resides, so that during testing the side can be opened and infrared thermal images could be taken to asses changes in ballast temperature over the course of the testing.

## MONITORING

This phase of testing is broken up into three different fixture tests. These different tests are referred to as continuous monitoring, dark room, and sphere testing. For the majority of this phase, the fixtures are undergoing continuous monitoring as they undergo their scheduled operating modes which only measures ballast input power. Dark room testing is performed once a week which is a more in depth monitoring of electrical performance while also measuring fixture relative illuminance. Sphere testing is described in the “Electrical and Photometric Measurements per IES Standards” section above and is completed once a month on each lamp to generate a detailed photometric analysis.

Dark room testing is performed inside of an enclosed chamber covered with blackout fabric to eliminate any external light source. The DOE BLE method described as part of phase one is conducted within this dark room. An illuminance sensor is positioned every one foot long the length of the lamp at a distance of 18 inches at both 0° and 90° from the horizontal plane (a total of 10 sensors).

### INSTRUMENTATION

Electrical measurements were taken by a power analyzer on the input side of the ballast/driver and the output to each lamp. External current transformers (CTs) were used on the input power to each lamp. A controlled power supply was used to provide appropriate lamp input power. Illuminance is measured using photometric sensors recorded through a data acquisition system.

# RESULTS

## PHASE I – SUMMARY RESULTS

The following tables show summary data for each product family including comparisons with manufacture's claims. Bare Lamp results are single tests using one lamp on a single lamp ballast or driver. In Fixture results are taken from 2-lamp ballast or driver tests. All results shown are from integrating sphere testing as described above in the Technical Approach section. Single lamp data is used to compare with manufacture's claims as it is the most comparable value. Double lamp test data is presented to compare with DLC in fixture information, as it is most comparable.

### BALLAST COMPATIBLE LAMPS

These tests where done on instant start ballasts with normal ballast factor, not a reference ballast.

**TABLE 11~~14~~. SINGLE LAMP – BALLAST COMPATIBLE LAMPS - MANUFACTURER'S CLAIMS VS. MEASURED**

| | Lumens (lm) | | | Input Power (W) | | | Efficacy (lm/W) | | |
|---|---|---|---|---|---|---|---|---|---|
| Lamp | Claimed | Tested | Δ | Claimed | Tested | Δ | Claimed | Tested | Δ |
| A | 2100 | 2259 | 8% | 21 | 23.5 | 12% | 100 | 96.2 | -4% |
| B | 2000 | 1420 | -29% | 19 | 13.1 | -31% | 105 | 108.5 | 3% |
| C | 2100 | 2371 | 13% | 16.5 | 23.3 | 41% | 127 | 101.6 | -20% |
| D | 2500 | 2519 | 1% | 22 | 23.3 | 6% | 114 | 108.0 | -5% |
| E | 2200 | 2600 | 18% | 22 | 24.5 | 11% | 100 | 106.0 | 6% |

**TABLE 12~~15~~. SINGLE LAMP – BALLAST COMPATIBLE LAMPS - MANUFACTURER'S CLAIMS VS. MEASURED (CONT.)**

| | CCT (°K) | | | CRI ($R_A$) | | | $THD_I$ (%) | PF |
|---|---|---|---|---|---|---|---|---|
| Lamp | Claimed | Tested | Δ | Claimed | Tested | Δ | Tested | |
| A | 4000 | 3871 | -3% | 90 | 92 | 2% | 10.0 | 0.94 |
| B | 4100 | 3955 | -4% | 80 | 83 | 4% | 13.8 | 0.85 |
| C | 4000 | 3977 | -1% | 83 | 81 | -2% | 10.2 | 0.94 |
| D | 4100 | 4024 | -2% | 80 | 81 | 1% | 10.2 | 0.94 |
| E | 4100 | 4068 | -1% | 82 | 80 | -2% | 9.8 | 0.95 |

**TABLE 13~~16~~. DOUBLE LAMP – BALLAST COMPATIBLE LAMPS – SUMMARY RESULTS**

| Lamp | Lumens | Input Power (W) | Efficacy | CCT | CRI | $THD_I$ (%) | PF |
|---|---|---|---|---|---|---|---|
| A | 3985 | 41.8 | 95.4 | 3953 | 93 | 7.0 | 0.98 |
| B | 3498 | 36.8 | 95.1 | 3967 | 83 | 7.5 | 0.97 |
| C | 4149 | 39.2 | 105.9 | 3915 | 82 | 7.3 | 0.97 |
| D | 4126 | 37.5 | 110.0 | 4025 | 81 | 7.5 | 0.97 |
| E | 4383 | 39.2 | 111.9 | 4045 | 80 | 7.3 | 0.97 |

## Internal Driver Lamps

**Table 14~~17~~. Single Lamp – Internal Driver Lamps - Manufacturer's Claims vs. Measured**

| Lamp | Lumens (lm) | | | Input Power (W) | | | Efficacy (lm/W) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Claimed | Tested | Δ | Claimed | Tested | Δ | Claimed | Tested | Δ |
| F | 1700 | 1889 | 11% | 17.7 | 17.7 | 0% | 96 | 106.6 | 11% |
| G | 1900 | 1587 | -16% | 18 | 19.7 | 9% | 106 | 80.7 | -24% |
| H | 2060 | 1926 | -7% | 20.8 | 23.1 | 11% | 99 | 83.4 | -16% |
| I | 2480 | 1971 | -21% | 18 | 25.4 | 41% | 138 | 77.7 | -44% |
| J | 2123 | 1960 | -8% | 15.7 | 18.3 | 16% | 135 | 107.4 | -21% |

**Table 15~~18~~. Single Lamp – Internal Driver Lamps - Manufacturer's Claims vs. Measured (cont.)**

| Lamp | CCT (°K) | | | CRI ($R_A$) | | | THD$_I$ (%) | PF |
|---|---|---|---|---|---|---|---|---|
| | Claimed | Tested | Δ | Claimed | Tested | Δ | Tested | |
| F | 4100 | 4040 | -1% | 80 | 81 | 2% | 10.8 | 0.91 |
| G | 4000 | 4019 | 0% | 80 | 82 | 2% | 34.8 | 0.75 |
| H | 4000 | 3988 | 0% | 83 | 83 | 1% | 35.4 | 0.76 |
| I | 4100 | 4042 | -1% | 86 | 73 | -16% | 35.6 | 0.80 |
| J | 4000 | 4018 | 0% | 83 | 81 | -2% | 39.5 | 0.72 |

**Table 16~~19~~. Double Lamp – Internal Driver Lamps – Summary Results**

| Lamp | Lumens | Input Power (W) | Efficacy | CCT | CRI | THD$_I$ (%) | PF |
|---|---|---|---|---|---|---|---|
| F | 3401 | 35.2 | 96.6 | 4122 | 83 | 61.5 | 0.80 |
| G | 3124 | 39.5 | 79.2 | 4009 | 83 | 33.5 | 0.84 |
| H | 3737 | 20.4 | 94.7 | 3990 | 84 | 33.6 | 0.84 |
| I | 3719 | 50.0 | 74.4 | 4034 | 73 | 35.3 | 0.86 |
| J | 3851 | 37.5 | 102.6 | 4020 | 81 | 35.4 | 0.81 |

## External Driver Lamps

**Table 17~~20~~. Single Lamp – External Driver Lamps – Manufacturer's Claim vs. Measured**

| Lamp | Lumens (lm) | | | Input Power (W) | | | Efficacy (lm/W) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Claimed | Tested | Δ | Claimed | Tested | Δ | Claimed | Tested | Δ |
| N | 2250 | 2033 | -10% | 22 | 21.7 | -1% | 102 | 93.7 | -8% |
| O | 2450 | 2352 | -4% | 22 | 21.8 | -1% | 111 | 107.8 | -3% |
| P | 2100 | 2379 | 13% | 18 | 22.0 | 22% | 117 | 108.2 | -7% |

**Table 18~~21~~. Single Lamp – External Driver Lamps – Manufacturer's Claim vs. Measured (cont.)**

| | CCT (°K) | | | CRI (RA) | | | THDI (%) | PF |
|---|---|---|---|---|---|---|---|---|
| Lamp | Claimed | Tested | Δ | Claimed | Tested | Δ | Tested | |
| N | 4000 | 4040 | 1% | 80 | 82 | 2% | 13.4 | 0.87 |
| O | 4000 | 4042 | 1% | 80 | 84 | 5% | 11.3 | 0.92 |
| P | 4000 | 4044 | 1% | 80 | 84 | 5% | 11.1 | 0.92 |

**Table 19~~22~~. Double Lamp – External Driver Lamps – Summary Results**

| Lamp | Lumens | Input Power (W) | Efficacy | CCT | CRI | THDI (%) | PF |
|---|---|---|---|---|---|---|---|
| K | 4266 | 43.8 | 97.4 | 4115 | 85 | 18.0 | 0.91 |
| L | 3602 | 36.4 | 98.9 | 3981 | 82 | 10.1 | 0.91 |
| M | 4704 | 42.5 | 110.6 | 3922 | 81 | 23.6 | 0.88 |
| N | 4802 | 43.9 | 109.4 | 3962 | 83 | 10.9 | 0.96 |
| O | 4400 | 47.4 | 92.7 | 4049 | 82 | 18.3 | 0.91 |
| P | 4616 | 43.3 | 106.7 | 4038 | 84 | 11.7 | 0.93 |

## Fluorescent (Benchmark) Lamps

These tests where done on normal ballast factor ballasts, not a reference ballast.

**Table 20~~23~~. Single Lamp – Fluorescent Lamps – Manufacturer's Claim vs. Measured**

| | Lumens (lm) | | | Input Power (W) | | | Efficacy (lm/W) | | |
|---|---|---|---|---|---|---|---|---|---|
| Lamp | Claimed | Tested | Δ | Claimed | Tested | Δ | Claimed | Tested | Δ |
| Q | 2850 | 2032 | -29% | 32 | 26.4 | -18% | 89 | 77.1 | -13% |
| R | 2950 | 2232 | -24% | 32 | 28.1 | -12% | 92 | 79.4 | -14% |
| S | 2675 | 1840 | -31% | 28 | 23.0 | -18% | 96 | 79.9 | -17% |
| T | 2725 | 1982 | -27% | 28 | 24.5 | -12% | 97 | 80.9 | -17% |

**Table 21~~24~~. Single Lamp – Fluorescent Lamps – Manufacturer's Claim vs. Measured (cont.)**

| | CCT (°K) | | | CRI (RA) | | | THDI (%) | PF |
|---|---|---|---|---|---|---|---|---|
| Lamp | Claimed | Tested | Δ | Claimed | Tested | Δ | Tested | |
| Q | 4100 | 3991 | -3% | 82 | 83 | 1% | 9.2 | 0.95 |
| R | 4100 | 3895 | -5% | 85 | 81 | -5% | 6.5 | 0.98 |
| S | 4100 | 3957 | -3% | 82 | 82 | 0% | 10.1 | 0.94 |
| T | 4100 | 3926 | -4% | 85 | 82 | -4% | 7.6 | 0.98 |

**Table 22~~25~~. Double Lamp - Fluorescent Lamps – Summary Results**

| Lamp | Lumens | Input Power (W) | Efficacy | CCT | CRI | THDI (%) | PF |
|---|---|---|---|---|---|---|---|
| Q | 4351 | 56.1 | 77.5 | 3962 | 83 | 6.0 | 0.98 |
| R | 4311 | 55.7 | 77.4 | 3883 | 81 | 7.0 | 0.99 |
| S | 3704 | 47.6 | 77.8 | 3942 | 82 | 6.3 | 0.98 |
| T | 4031 | 50.3 | 80.2 | 3916 | 82 | 7.6 | 0.99 |

**TABLE 23~~26~~. DE-LAMP AND HYBRID TESTS – SUMMARY RESULTS – BALLAST COMPATIBLE LAMPS**

| Lamp | Test | Lumens | Input Power (W) | Efficacy | CCT | CRI | $THD_I$ (%) | PF |
|---|---|---|---|---|---|---|---|---|
| A | 2-Lamp | 3985 | 41.8 | 95.4 | 3953 | 93 | 7.0 | 0.98 |
| | 1-Lamp | 2259 | 23.5 | 96.2 | 3871 | 92 | 10.0 | 0.94 |
| | De-Lamp | 2513 | 28.5 | 88.1 | 3960 | 92 | 8.4 | 0.95 |
| | Hybrid 32 | 4052 | 48.5 | 83.5 | 3961 | 88 | 6.4 | 0.98 |
| B | 2-Lamp | 3498 | 36.8 | 95.1 | 3967 | 83 | 7.5 | 0.97 |
| | 1-Lamp | 1420 | 13.1 | 108.5 | 3955 | 83 | 13.8 | 0.85 |
| | De-Lamp | 2315 | 26.1 | 88.6 | 3985 | 83 | 8.7 | 0.95 |
| | Hybrid 32 | 3866 | 46.0 | 84.0 | 3973 | 83 | 6.6 | 0.98 |
| C | 2-Lamp | 4149 | 39.2 | 105.9 | 3915 | 82 | 7.3 | 0.97 |
| | 1-Lamp | 2371 | 23.3 | 101.6 | 3977 | 81 | 10.2 | 0.94 |
| | De-Lamp | 2476 | 25.4 | 97.3 | 3911 | 82 | 8.9 | 0.95 |
| | Hybrid 32 | 4134 | 47.0 | 87.9 | 3943 | 82 | 6.5 | 0.98 |
| D | 2-Lamp | 4126 | 37.5 | 110.0 | 4025 | 81 | 7.5 | 0.97 |
| | 1-Lamp | 2519 | 23.3 | 108.0 | 4024 | 81 | 10.2 | 0.94 |
| | De-Lamp | 2502 | 24.4 | 102.4 | 4072 | 81 | 9.0 | 0.94 |
| | Hybrid 32 | 4040 | 46.6 | 86.8 | 4022 | 82 | 6.5 | 0.98 |
| E | 2-Lamp | 4383 | 39.2 | 111.9 | 4045 | 80 | 7.3 | 0.97 |
| | 1-Lamp | 2600 | 24.5 | 106.0 | 4068 | 80 | 9.8 | 0.95 |
| | De-Lamp | 2635 | 25.4 | 103.9 | 4040 | 80 | 8.9 | 0.95 |
| | Hybrid 32 | 4201 | 47.4 | 88.6 | 4009 | 82 | 6.5 | 0.98 |

For ballast compatible lamps, de-lamping a fixture has the effect of reducing efficacy considerably. In all cases, a de-lamped fixture will produce more lumens per lamp using the same ballast and have higher per lamp power consumption. Lamps normally rated from around 16 to 21 watts, are now being driven from 24 to 28 watts, which could lead to reduction in the life of the lamp due to over driven LEDs. THD increases and power factor decreases when de-lamping when compared to the same fixture with 2 lamps. There were no issues noted with hybrid installations. Color quality of the lamps were unchanged for these scenarios.

**TABLE 24~~27~~. DE-LAMP AND HYBRID TESTS – SUMMARY RESULTS – EXTERNAL DRIVER LAMPS**

| Lamp | Test | Lumens | Input Power (W) | Efficacy | CCT | CRI | $THD_I$ (%) | PF |
|---|---|---|---|---|---|---|---|---|
| K | 2-Lamp | 4266 | 43.8 | 97.4 | 4115 | 85 | 18.0 | 0.91 |
| | 1-Lamp | | | | | | | |
| | De-Lamp | 3966 | 46.1 | 86.0 | 4148 | 85 | 18.2 | 0.91 |
| L | 2-Lamp | 3602 | 36.4 | 98.9 | 3981 | 82 | 10.1 | 0.91 |
| | 1-Lamp | | | | | | | |
| | De-Lamp | 1856 | 19.4 | 95.5 | 3990 | 82 | 12.3 | 0.77 |
| M | 2-Lamp | 4704 | 42.5 | 110.6 | 3922 | 81 | 23.6 | 0.88 |
| | 1-Lamp | | | | | | | |
| | De-Lamp | 2349 | 22.1 | 106.3 | 3911 | 81 | 36.6 | 0.77 |
| N | 2-Lamp | 4802 | 43.9 | 109.4 | 3962 | 83 | 10.9 | 0.96 |
| | 1-Lamp | 2535 | 23.7 | 107.0 | 3967 | 82 | 56.6 | 0.71 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | De-Lamp | | | | | | | |
| O | 2-Lamp | 4400 | 47.4 | 92.7 | 4049 | 82 | 18.3 | 0.91 |
| | 1-Lamp | 2033 | 21.7 | 93.7 | 4040 | 82 | 13.4 | 0.87 |
| | De-Lamp | 2244 | 25.9 | 86.7 | 4046 | 82 | 25.0 | 0.78 |
| P | 2-Lamp | 4616 | 43.3 | 106.7 | 4038 | 84 | 11.7 | 0.93 |
| | 1-Lamp | 2379 | 22.0 | 108.2 | 4044 | 84 | 11.1 | 0.92 |
| | De-Lamp | 2352 | 21.8 | 107.8 | 4042 | 84 | 11.3 | 0.92 |

Lamp K had almost no change in light output when de-lamped and had higher power consumption. All of the power is going to a single lamp, which is being significantly overdriven. In all cases, de-lamped fixtures exhibited reductions in power factor and increases in $THD_I$. Almost all of the lamps have decreased efficacy when de-lamped but do not show significant increases in per-lamp light output, however the per-lamp power consumption is higher. Lamp N has significantly higher THD when using one lamp which could be due to its unique wiring of two line inputs, one for each lamp, and a common neutral (the one lamp test could be considered as either a de-lamp or a 1-lamp test). Color quality of the lamps are unchanged for these tests.

## TECHNOLOGY COMPARISON – FULL POWER

Figure 6~~Figure 6~~ through Figure 9~~Figure 9~~ below shows the average full-power results of all lamps in all three linear LED lamp families and fluorescent 32W and 28W lamps tested. The average was taken from tests where each lamp was tested with different ballasts or drivers per the test matrix tables found in Table 7~~Table 7~~ through

Table 9~~Table 9~~ above. This does not include tests which have hybrid or de-lamped combinations.

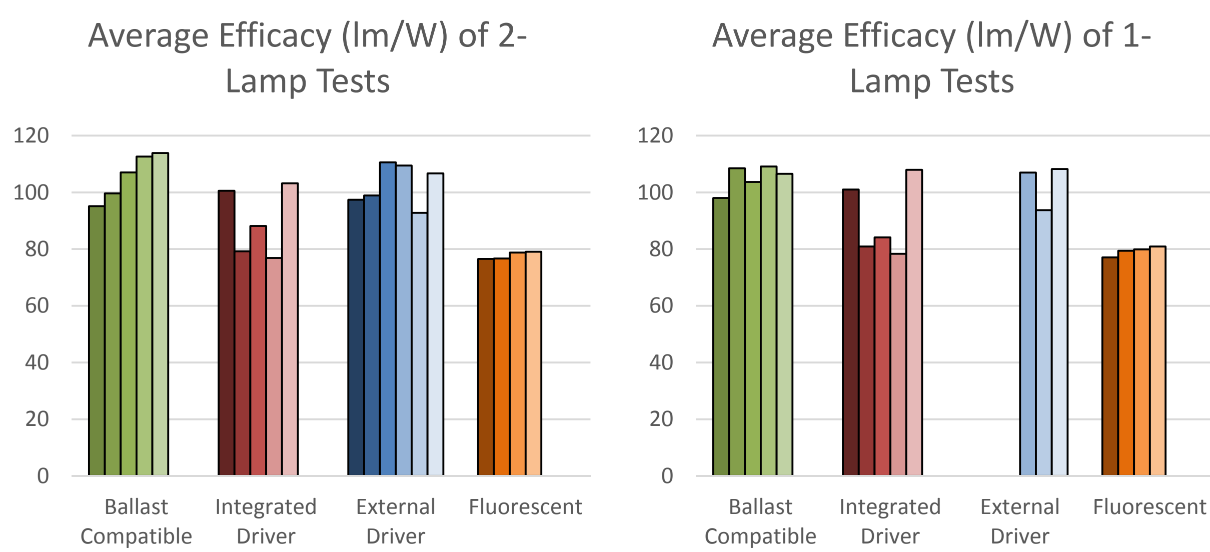
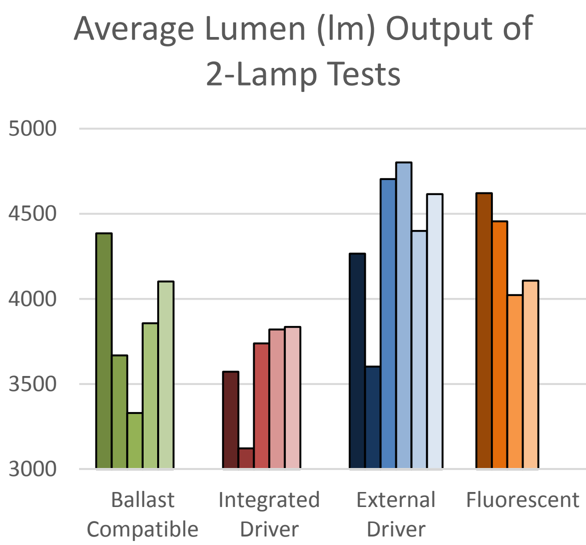



FIGURE 6. AVERAGE EFFICACY OF 2-LAMP TESTS

Average efficacy of ballast compatible and external driver lamps was consistently better than fluorescent lamps. In general, integrated driver lamps were better than fluorescents but there was a notable deviation in results for the various products.

It should be noted that efficacy test results for fluorescent lamps was consistently lower than manufacturer claims by an average of 15%. This could be mainly attributed to the fact that ballasts of normal factor of 0.87 were used in this test instead of standard reference ballasts.



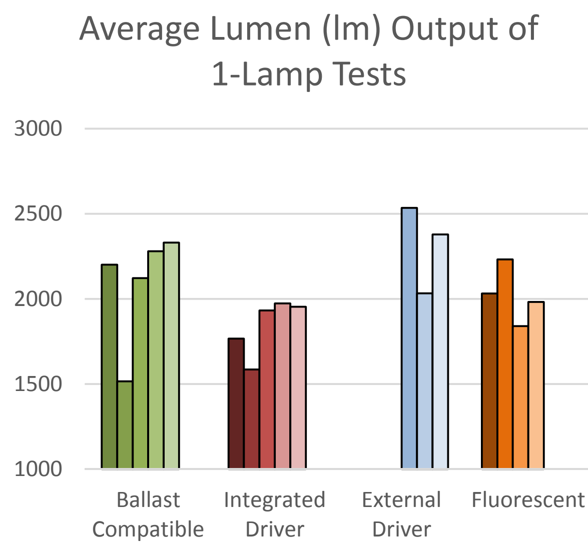
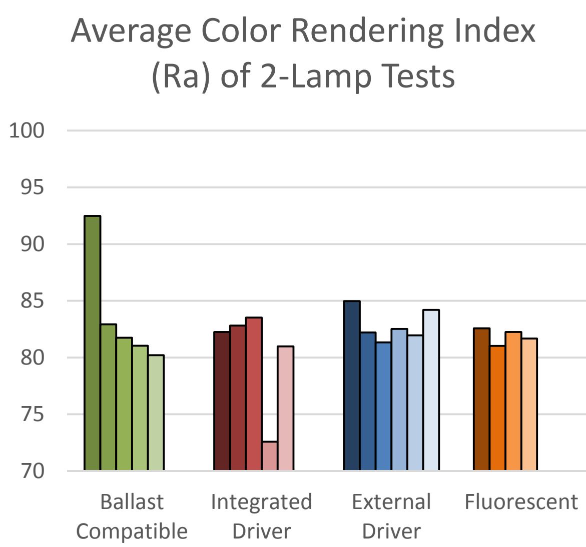




**FIGURE 7. AVERAGE LUMEN OUTPUT OF 2-LAMP TESTS**

External driver lamps in general produce lumen output comparable to 32W fluorescent lamps. Ballast compatible lamps produced similar results to 32W fluorescents when tested on single-lamp ballasts. On the other hand, when tested on double-lamp ballasts, ballast compatible lamps generally produced lumen output lower than 32W fluorescents. Integrated driver lamps consistently produced less output than fluorescents.



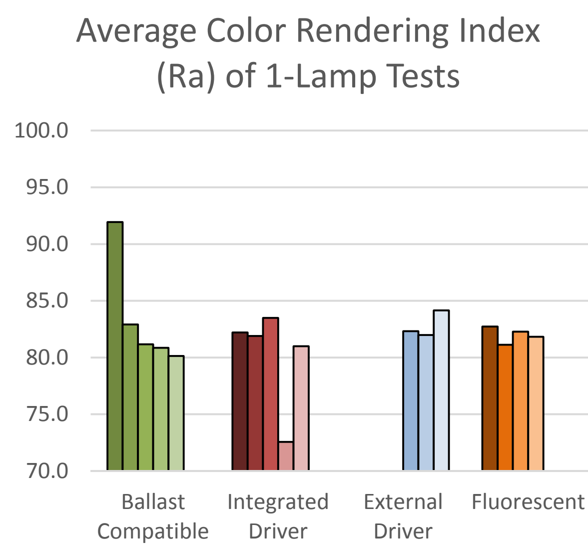



FIGURE 8. AVERAGE CRI OF 2-LAMP TESTS

All of the linear LED lamps met the DLC minimum requirement of 80 CRI except one integrated driver lamp. CRI, in general, is comparable to fluorescent lamps.

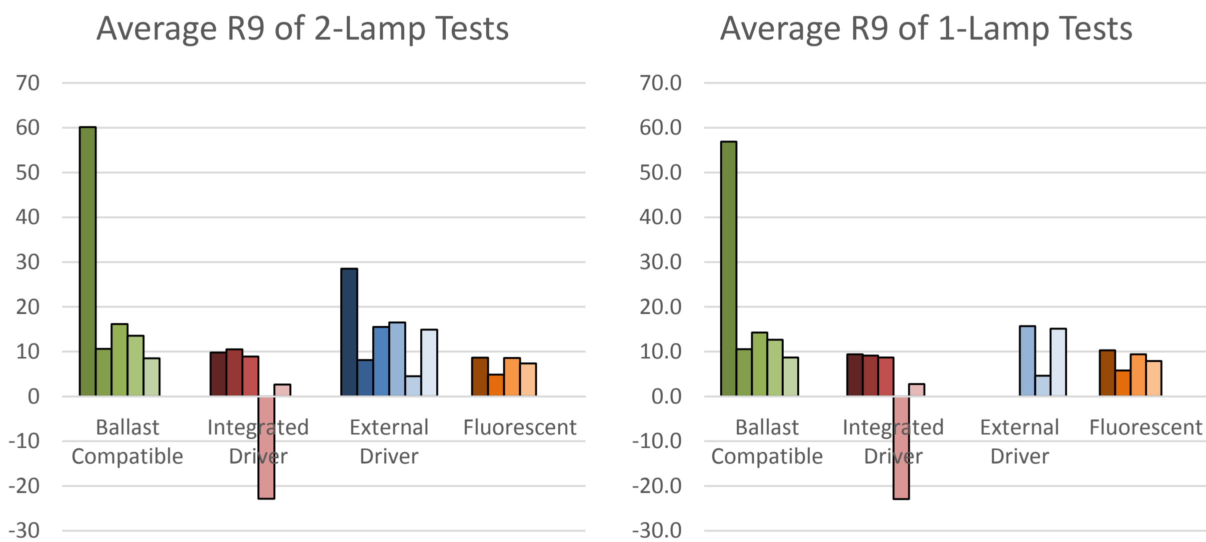



FIGURE 9. AVERAGE R9 VALUES OF 2-LAMP TESTS

One particular area of interest with LEDs has been the $R_9$ value. In general, the evaluated LED products show equivalent, or better performance when compared to fluorescents for rendering deep reds.

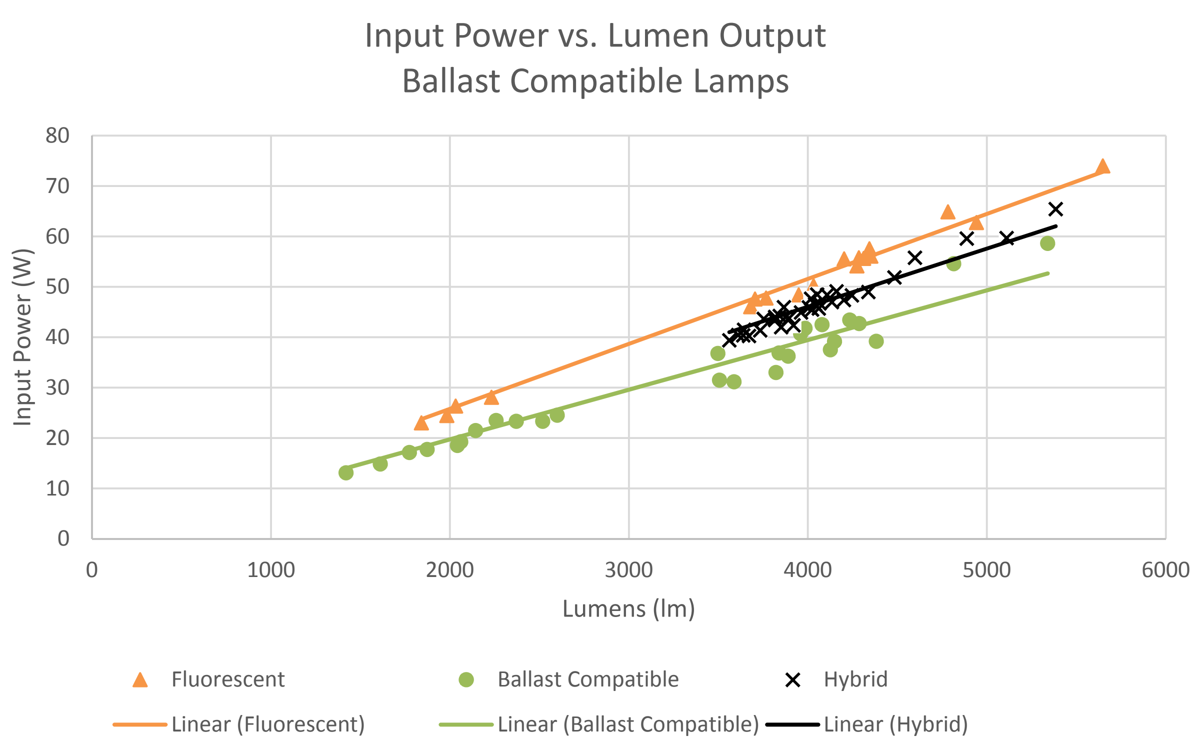


**FIGURE 10. BALLAST COMPATIBLE TEST RESULTS – BALLAST INPUT POWER VS. TOTAL FIXTURE LUMEN OUTPUT**

Figure 10~~Figure 10~~ above shows all results for Ballast Compatible, Fluorescent, and Hybrid tests regardless of manufacturer or ballast used (including de-lamping tests). The power consumption to lumen ratio, as represented by the line, is fairly linear across the entire product family. This suggests that the products perform similarly in efficacy across the entire product family. Hybrid results fall directly between Fluorescent and Ballast Compatible results, showing that on a given ballast the lamp is more of a driving factor for power consumption.

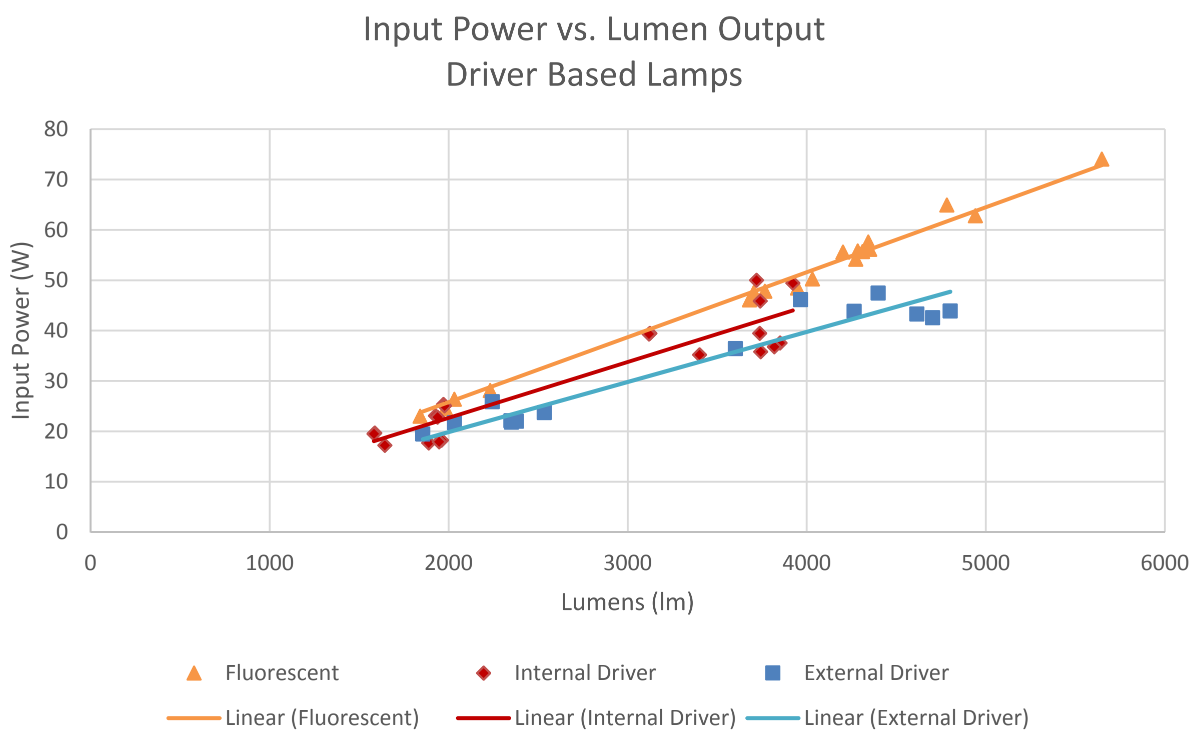



**FIGURE 11. DRIVER LAMPS TEST RESULTS – INPUT POWER VS. TOTAL FIXTURE LUMEN OUTPUT**

Figure 11~~Figure 11~~ above shows results for all internal and external driver lamps with fluorescent tests for comparison. Both of the product families tended to draw less power for the amount of lumens produced, however the spread in results is much larger than ballast compatible lamps.

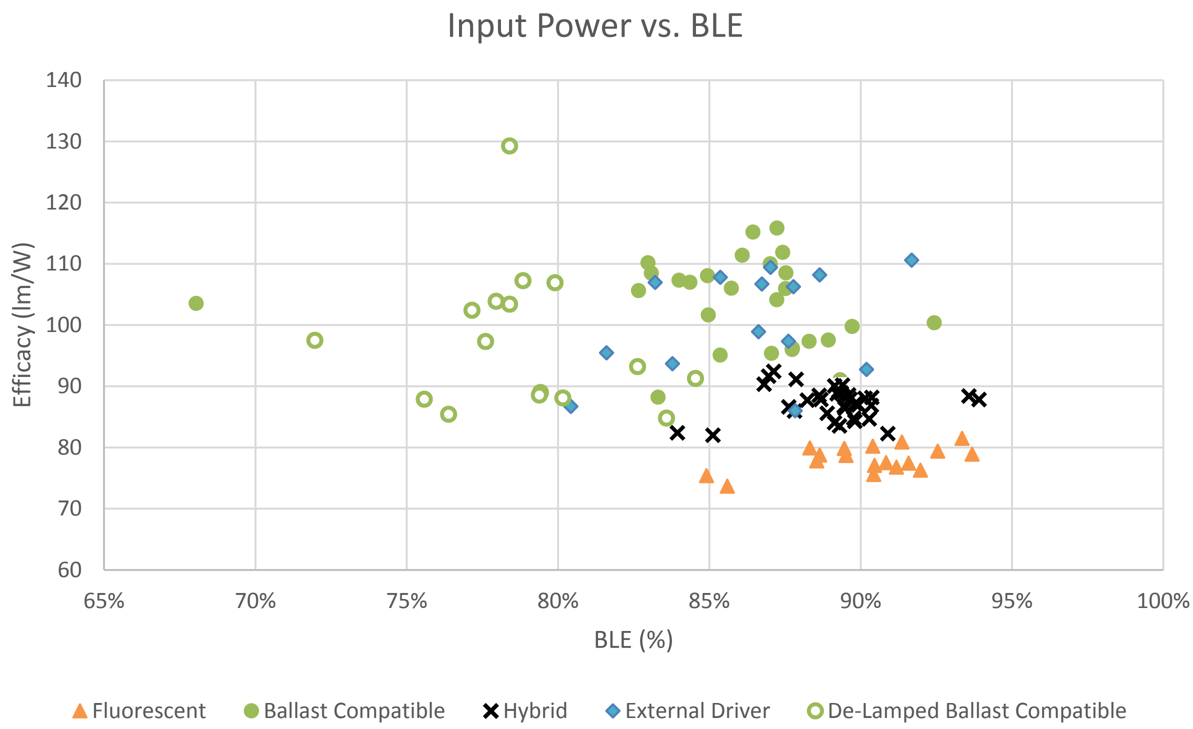



**FIGURE 12. BALLAST-COMPATIBLE LAMP TEST RESULTS – EFFICACY AND BLE**

The BLE of the different lamps with their associated lamp efficacy can be seen in Figure 12~~Figure 12~~ above. Looking at the BLE, fluorescent lamps have a higher ballast efficiency than the ballast compatible lamps. External driver lamps have a higher spread in the range of their driver efficiency, but on average are lower than the efficiency of the fluorescent ballasts tested with fluorescent lamps. De-lamping of ballast-compatible lamps has a significant effect on the efficiency of the ballast but does not have a significant difference on the lamp efficacy. On average, the efficiency of the fluorescent ballasts when used with fluorescent lamps is better than when used with led lamps, and better than the efficiency of led drivers. In terms of efficacy (lm/W), LED lamps did better than fluorescent lamps at similar levels of ballast or driver efficiency. This indicates that LED lamps produce higher lumen output than fluorescent lamps per Watt consumed.

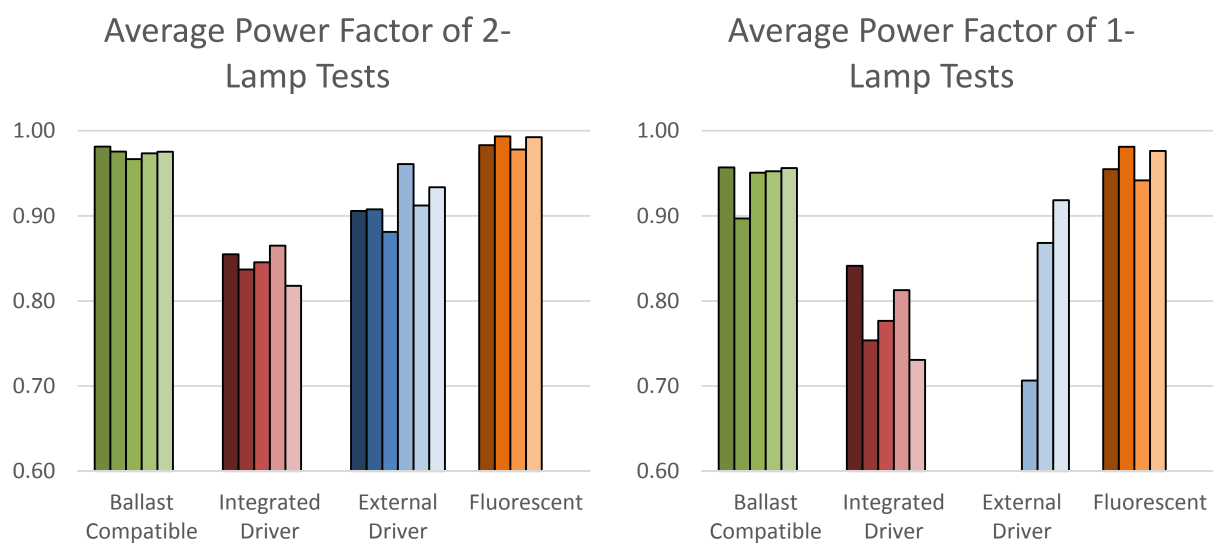



**FIGURE 13. AVERAGE POWER FACTOR OF 2-LAMP TESTS**

The power factor for the various lamp types can be seen in Figure 13~~Figure 13~~ above. Only the ballast compatible lamps perform similarly to fluorescents while external and internal driver lamps fall behind. None of the integrated driver lamps and only half of the external driver lamps we tested would pass DLC qualifications of >0.9 PF.

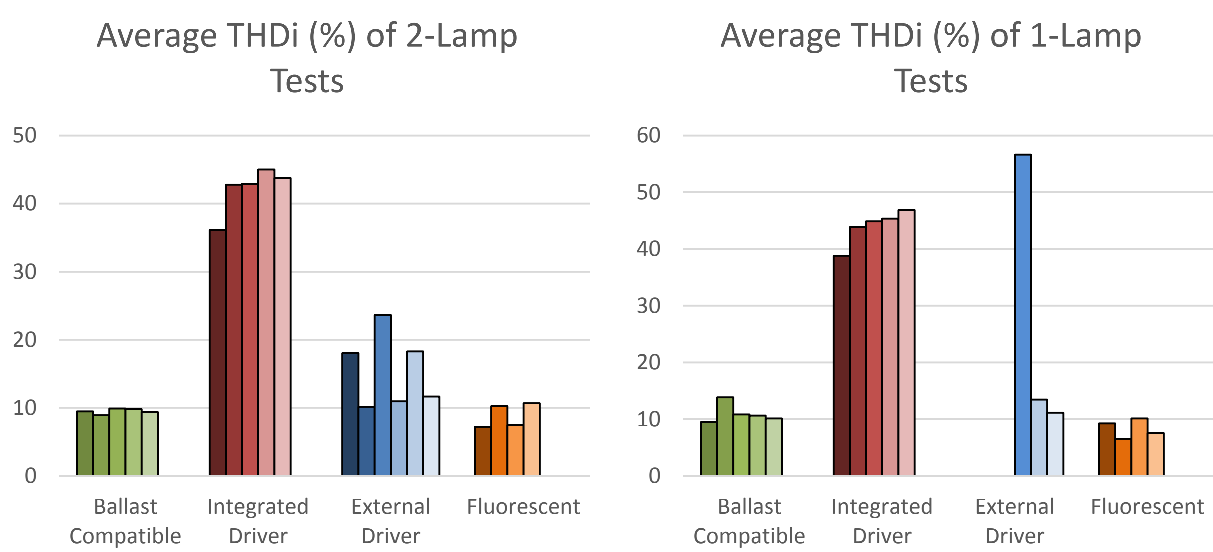



**FIGURE 14. AVERAGE THD$_I$ OF 2-LAMP TESTS**

Figure 14~~Figure 14~~ above shows the current THD caused by each of the lamps. Ballast compatible lamps performed similarly to fluorescent lamps while both external and internal driver lamps had higher levels of signal distortion. All but one of the external driver lamps meet the DLC qualification while none of the internal driver lamps meet the qualification of $THD_I \leq 20\%$.

# DIMMING

The following charts show the test results at various dimmed levels obtained from LM-79 testing in the integrating sphere. Relative power consumption is based on percentage of measured full power.

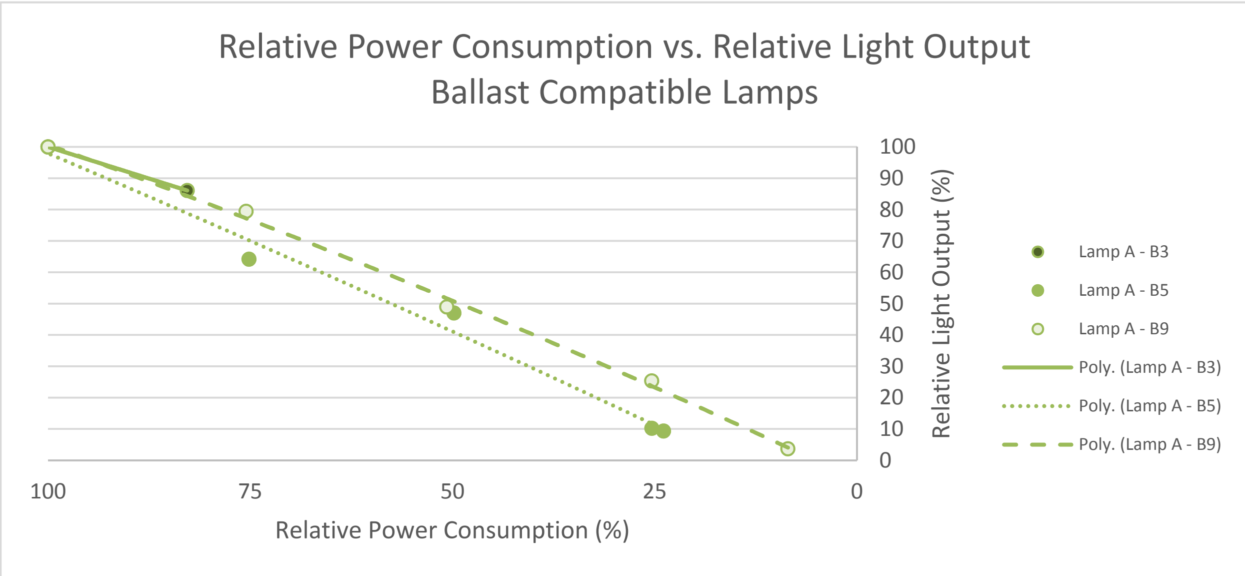



**FIGURE 15. RELATIVE POWER CONSUMPTION VS. RELATIVE LIGHT OUTPUT - BALLAST COMPATIBLE LAMPS**

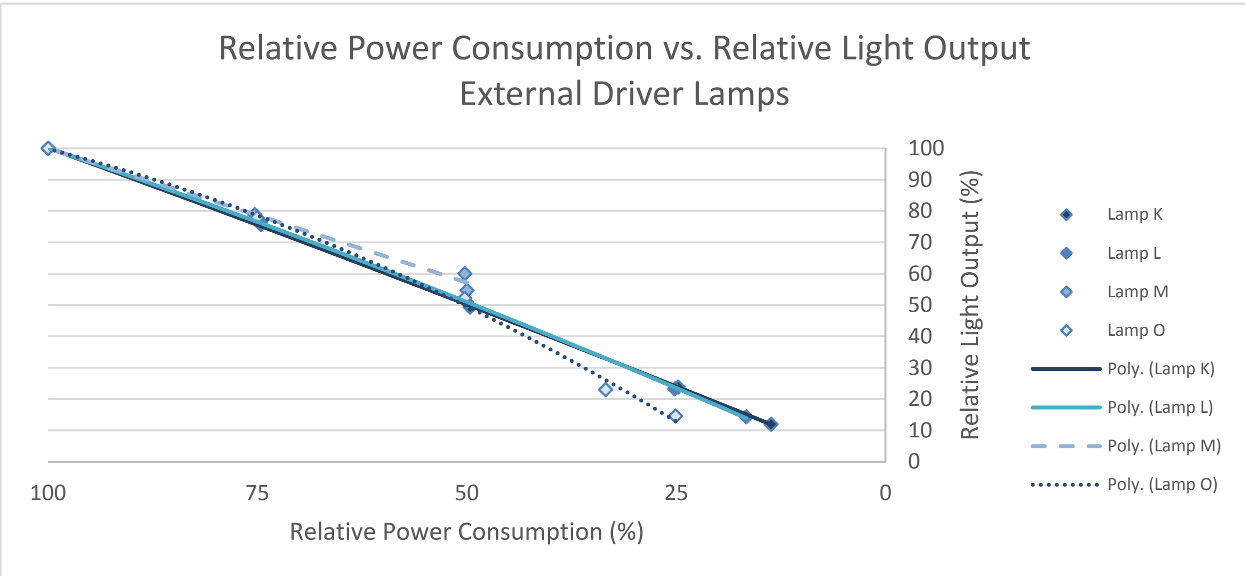



**FIGURE 16. RELATIVE POWER CONSUMPTION VS. RELATIVE LIGHT OUTPUT - EXTERNAL DRIVER LAMPS**

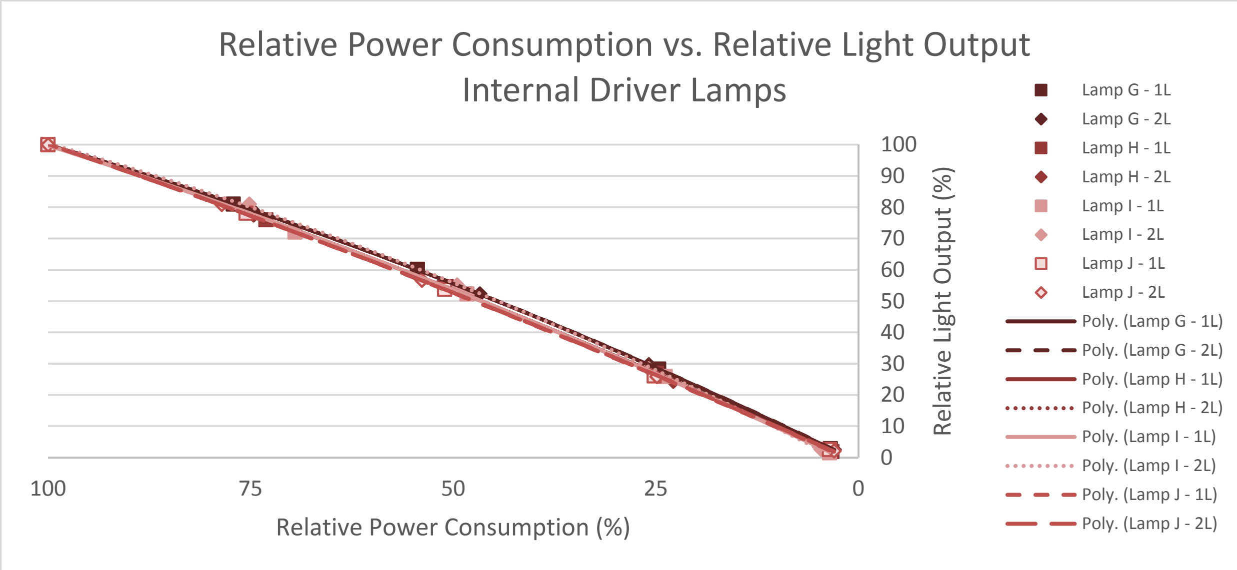



**FIGURE 17. RELATIVE POWER CONSUMPTION VS. RELATIVE LIGHT OUTPUT - INTERNAL DRIVER LAMPS**

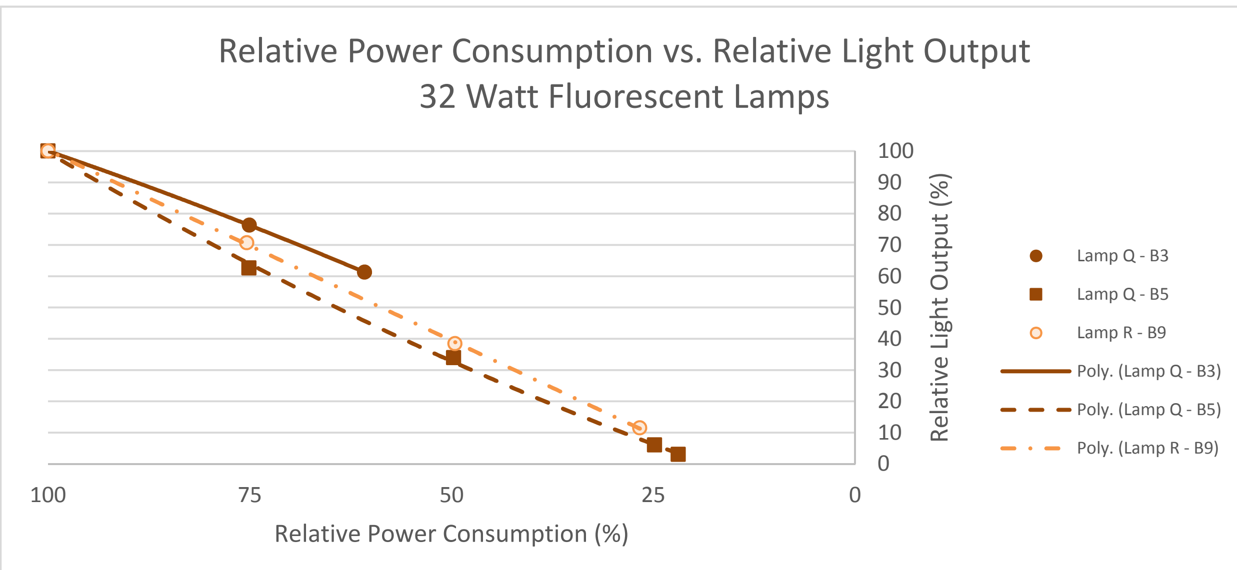



**FIGURE 18. RELATIVE POWER CONSUMPTION VS. RELATIVE LIGHT OUTPUT - 32 WATT FLUORESCENT LAMPS**

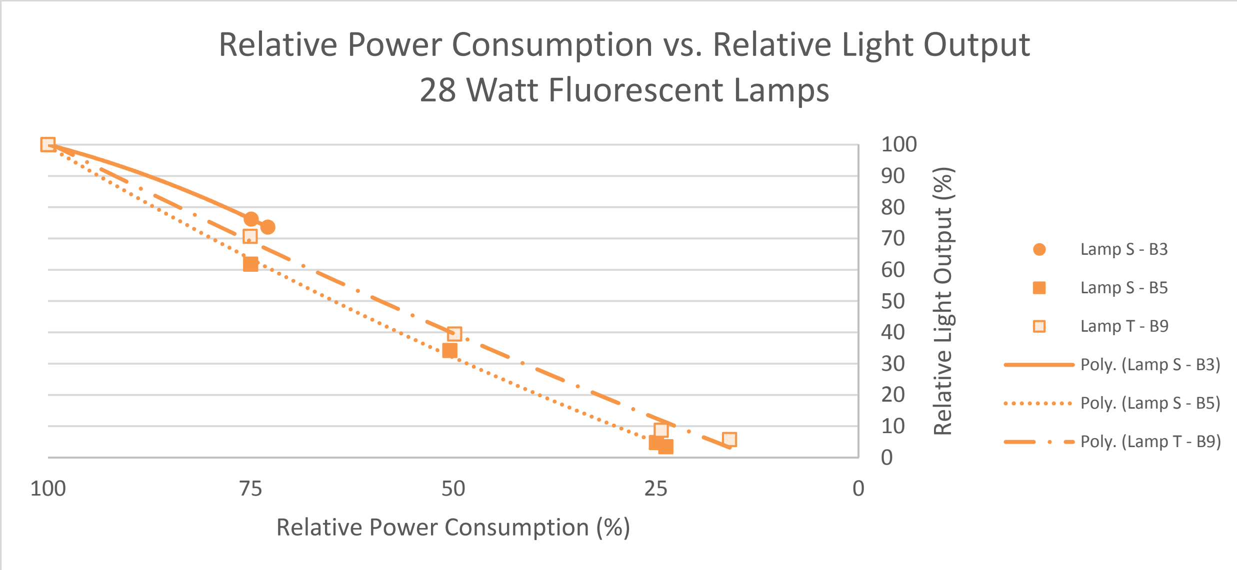



**FIGURE 19. RELATIVE POWER CONSUMPTION VS. RELATIVE LIGHT OUTPUT - 28 WATT FLUORESCENT LAMPS**

Figure 15~~Figure 15~~ through Figure 19~~Figure 19~~ above shows the dimming curves for each of the product families. The ballast compatible lamp tested is not as consistent in how it dims when compared to fluorescent. All integrated driver lamps have a smooth and more linear dimming.

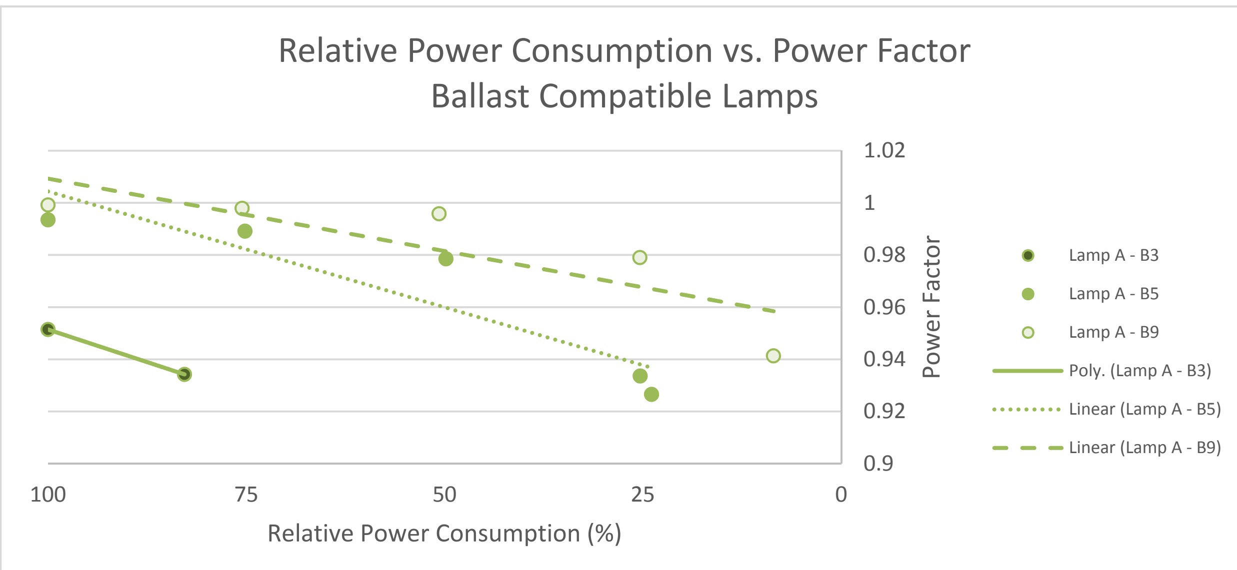



**FIGURE 20. RELATIVE POWER CONSUMPTION VS. POWER FACTOR – BALLAST COMPATIBLE LAMPS**

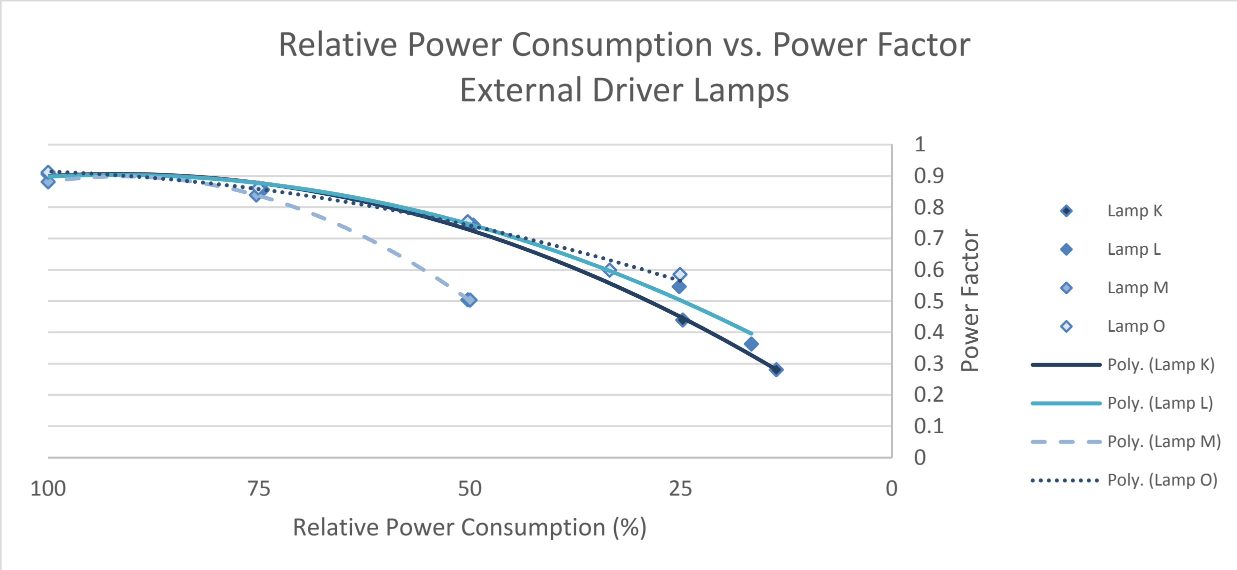



**FIGURE 21. RELATIVE POWER CONSUMPTION VS. POWER FACTOR – EXTERNAL DRIVER LAMPS**

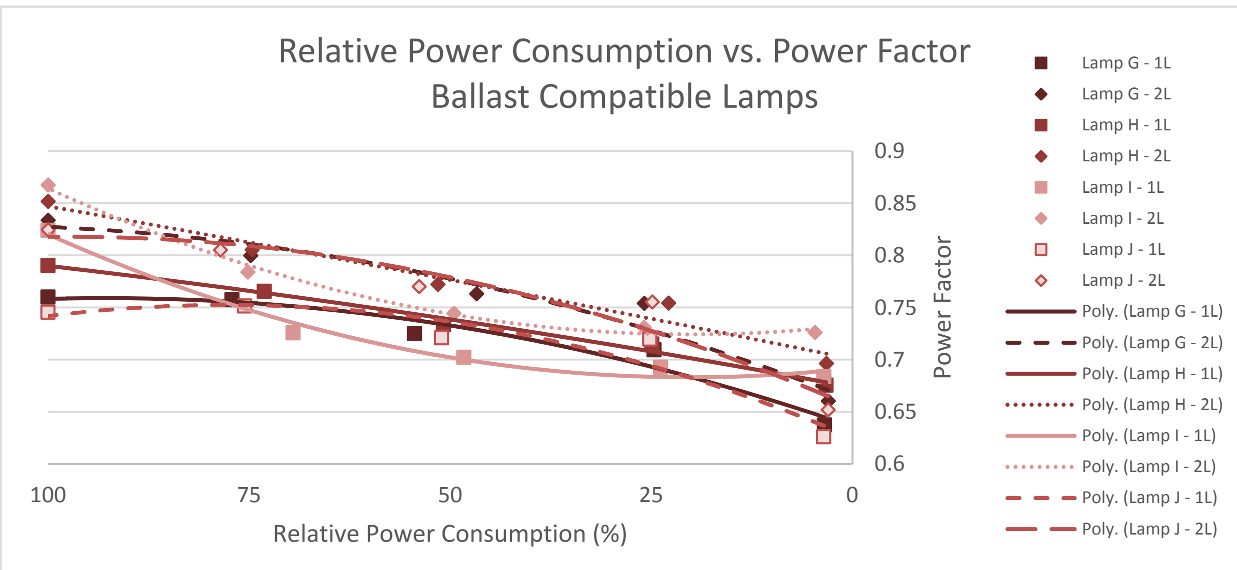



**FIGURE 22. RELATIVE POWER CONSUMPTION VS. POWER FACTOR – INTERNAL DRIVER LAMPS**

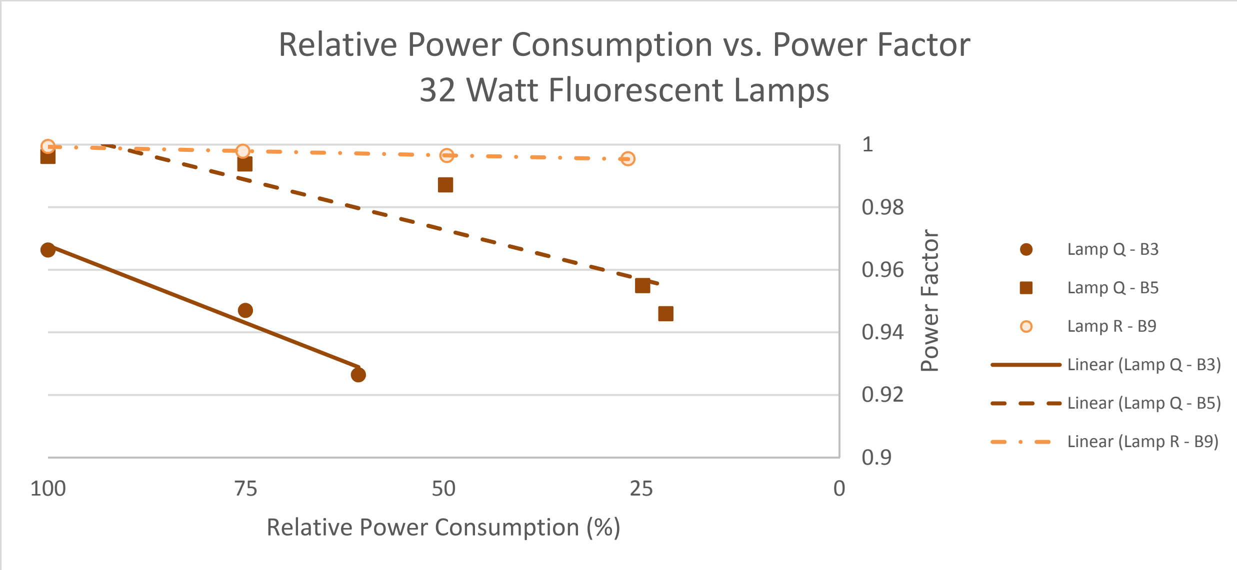



**FIGURE 23. RELATIVE POWER CONSUMPTION VS. POWER FACTOR – 32 WATT FLUORESCENT LAMPS**

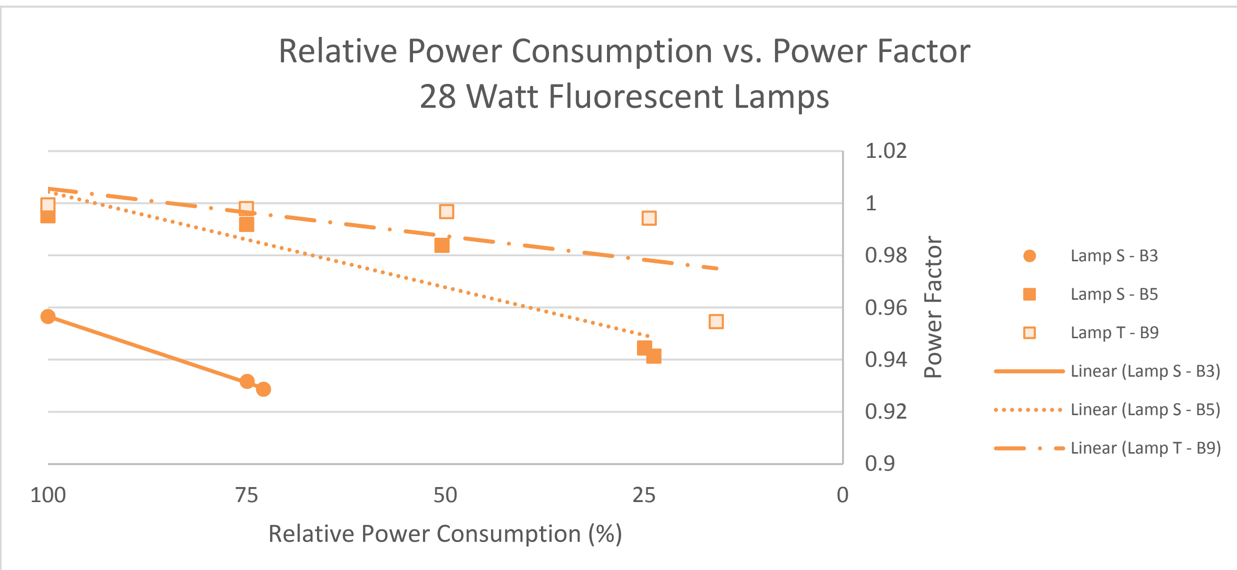



**FIGURE 24. RELATIVE POWER CONSUMPTION VS. POWER FACTOR – 28 WATT FLUORESCENT LAMPS**

It can be seen in Figure 20~~Figure 20~~ through Figure 24~~Figure 24~~ above that the power factor changes as the lamps dim. The ballast compatible lamp tested has similar power factor while dimming as fluorescent lamps. Both external and internal driver lamps have lower power factor as they dim. Internal driver lamps do not have a dramatic reduction in power factor while dimming, though they start at a lower value; whereas external driver lamps have significantly reduced power factors while they dim.

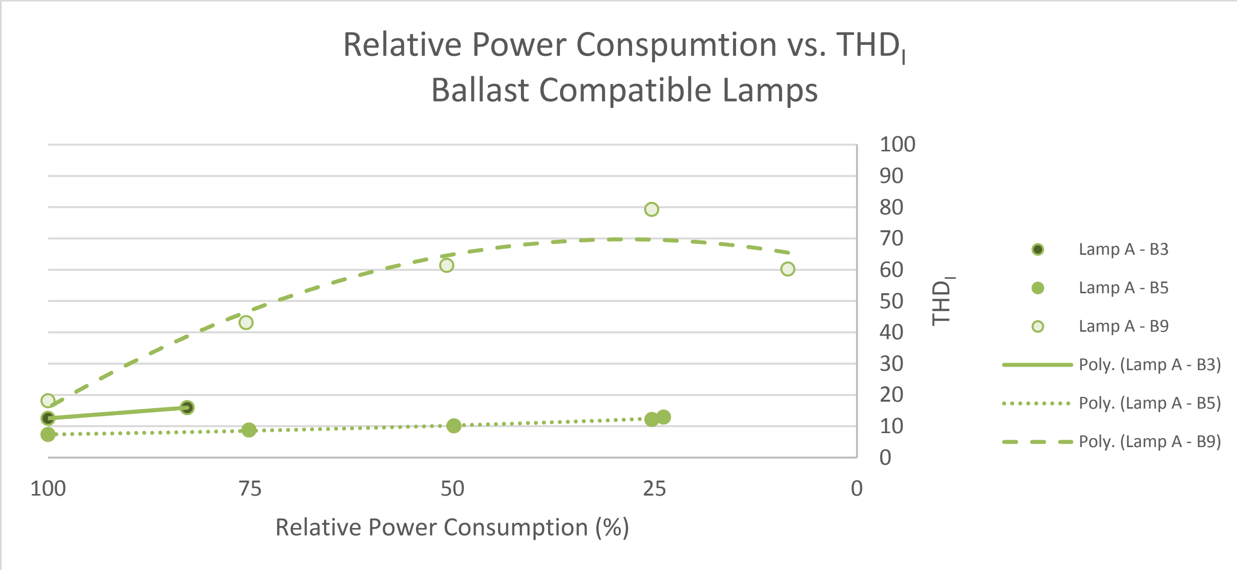



**FIGURE 25. RELATIVE POWER CONSUMPTION VS. THD$_I$ – BALLAST COMPATIBLE LAMPS**

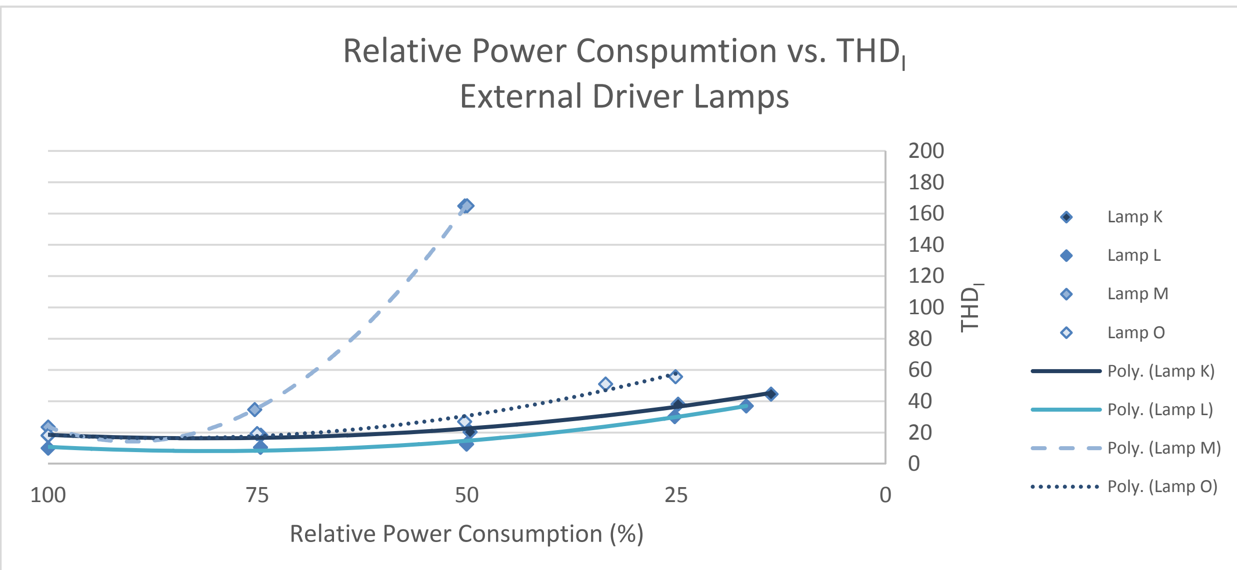



**FIGURE 26. RELATIVE POWER CONSUMPTION VS. THD$_I$ – EXTERNAL DRIVER LAMPS**

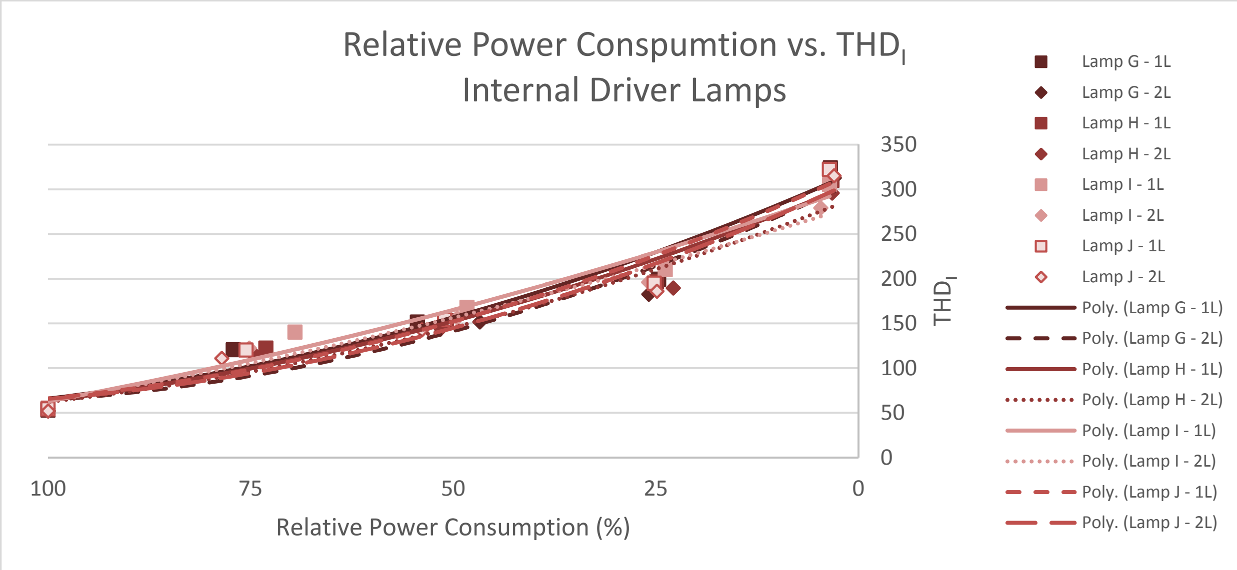



**FIGURE 27. RELATIVE POWER CONSUMPTION VS. THD$_I$ – INTERNAL DRIVER LAMPS**

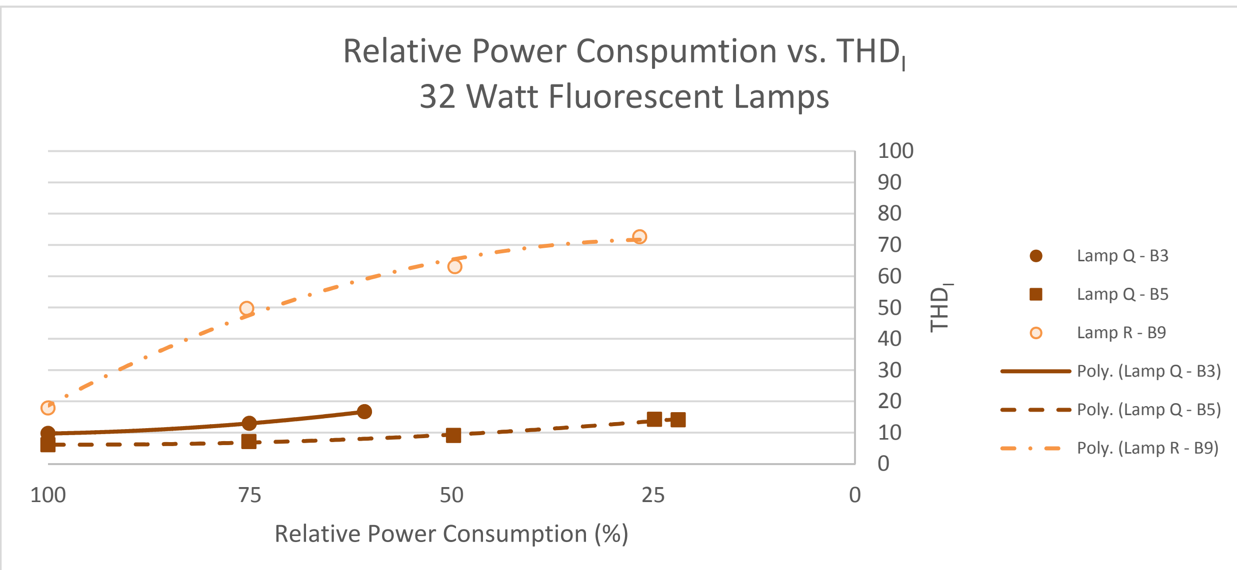



**FIGURE 28. RELATIVE POWER CONSUMPTION VS. THD$_I$ – 32 WATT FLUORESCENT LAMPS**

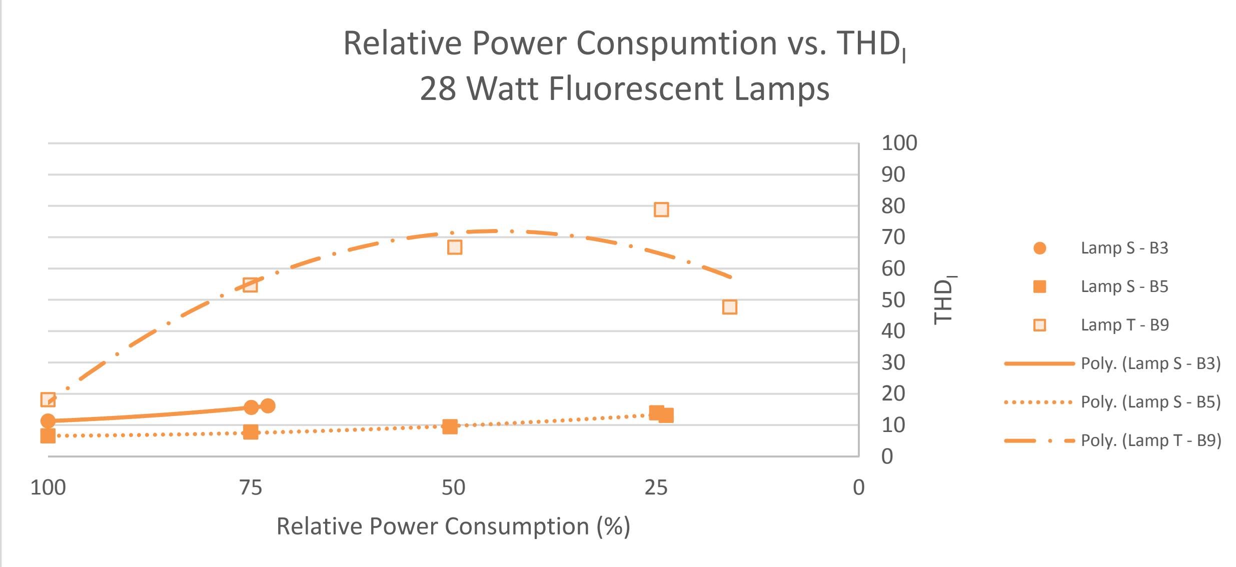



**FIGURE 29. RELATIVE POWER CONSUMPTION VS. THD$_I$ – 28 WATT FLUORESCENT LAMPS**

Figure 25~~Figure 25~~ through Figure 29~~Figure 29~~ above show the THD$_I$ at different dimming levels for all of the lamps tested. When internal driver lamps are dimmed, they have significantly increased current THD. In general, external driver lamps have lower THD at lower dimming levels than the other technologies. The tested ballast compatible lamp and fluorescent lamps perform similarly at all dimming levels.

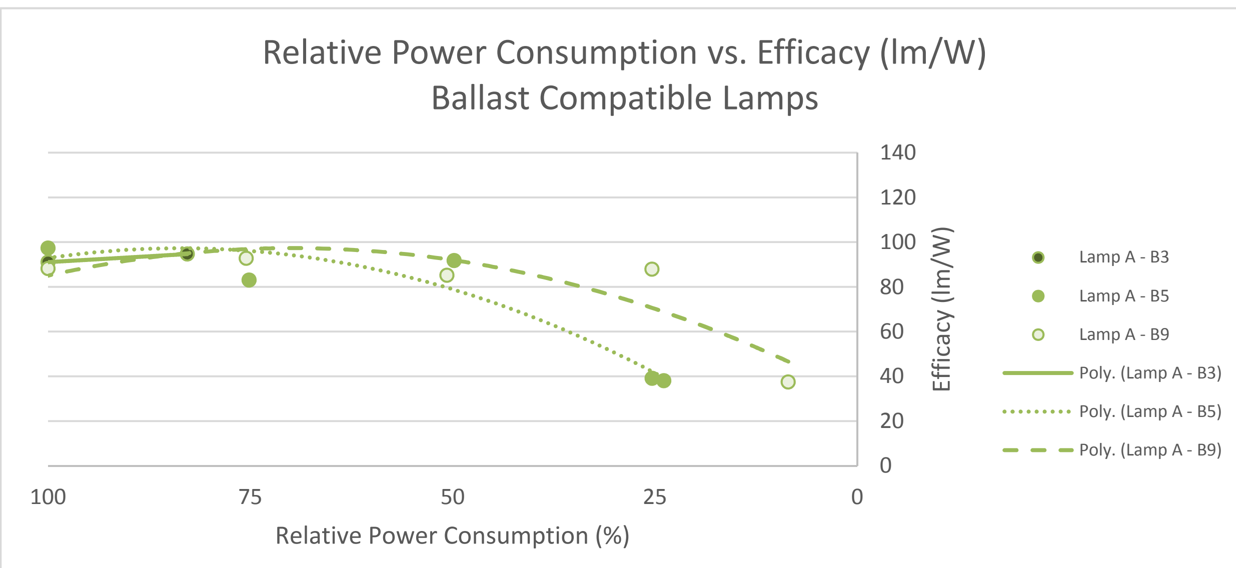



**FIGURE 30. RELATIVE POWER CONSUMPTION VS. EFFICACY – BALLAST COMPATIBLE LAMPS**

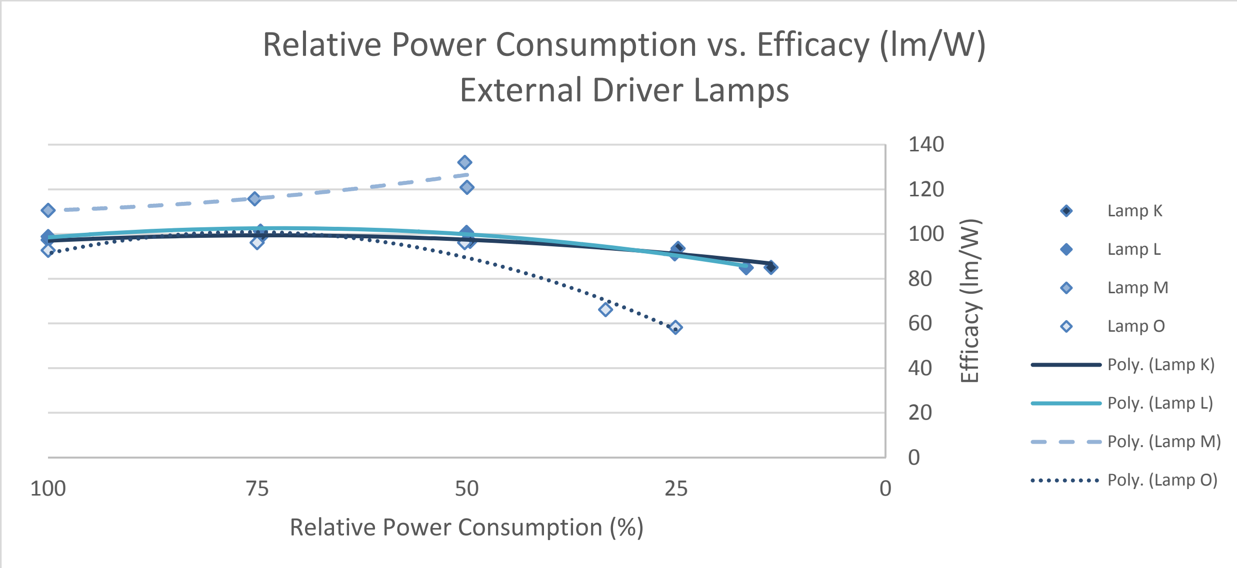



**FIGURE 31. RELATIVE POWER CONSUMPTION VS. EFFICACY – EXTERNAL DRIVER LAMPS**

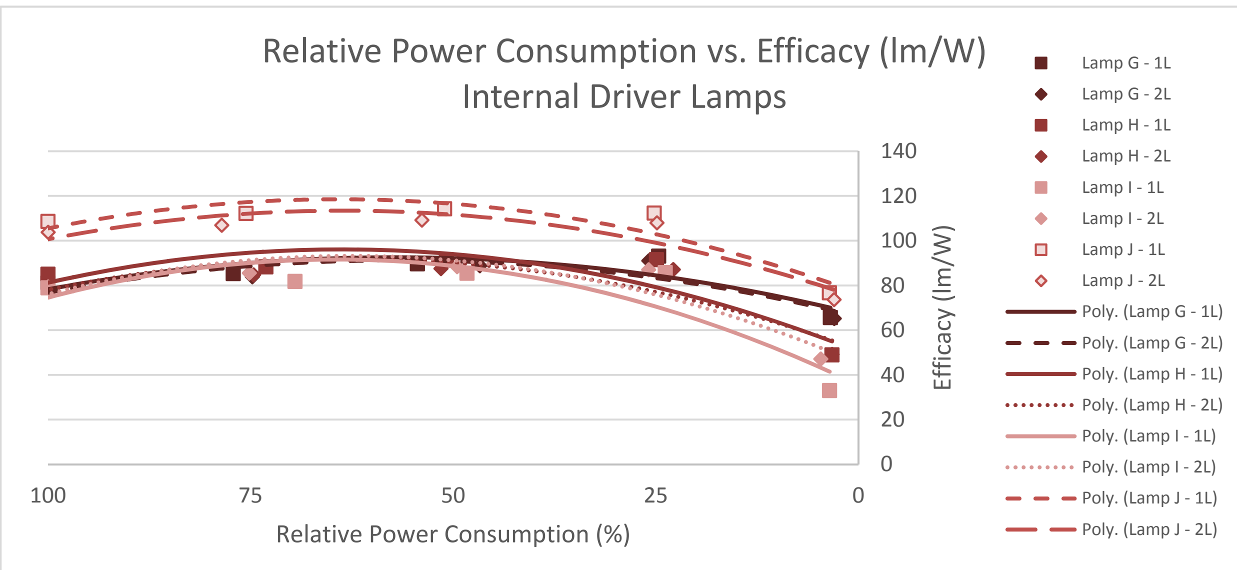



**FIGURE 32. RELATIVE POWER CONSUMPTION VS. EFFICACY – INTERNAL DRIVER LAMPS**

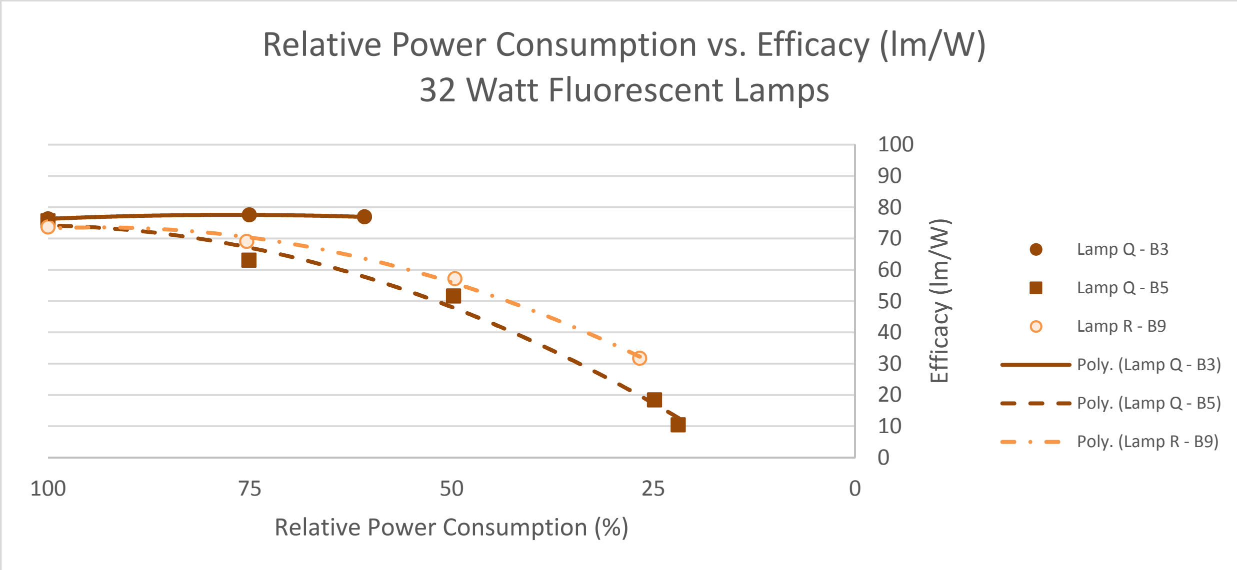



**FIGURE 33. RELATIVE POWER CONSUMPTION VS. EFFICACY – 32 WATT FLUORESCENT LAMPS**

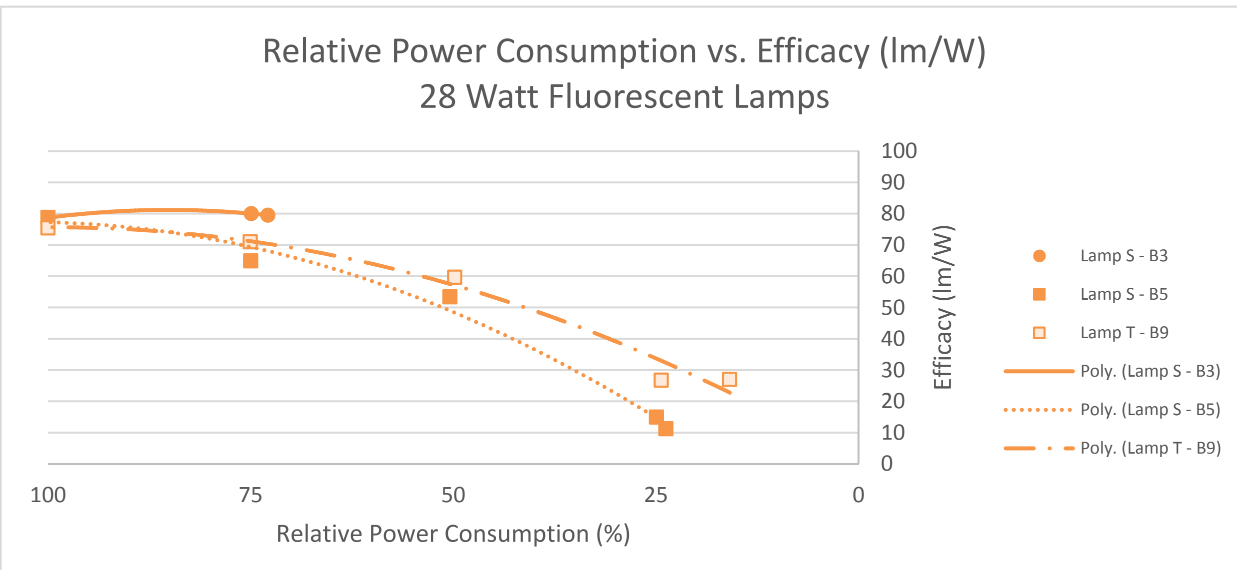



**FIGURE 34. RELATIVE POWER CONSUMPTION VS. EFFICACY – 28 WATT FLUORESCENT LAMPS**

Nearly all products tested shown in Figure 30~~Figure 30~~ through Figure 34~~Figure 34~~ above have reduced efficacy as they dim. The ballast compatible lamp tested maintains a higher efficacy at intermediate dimming levels when compared to fluorescents. External driver lamps have a more consistent efficacy at all levels of dimming than other product families. Internal driver lamps slightly increase in efficacy as they dim until low dimming levels where their efficacy drops off.

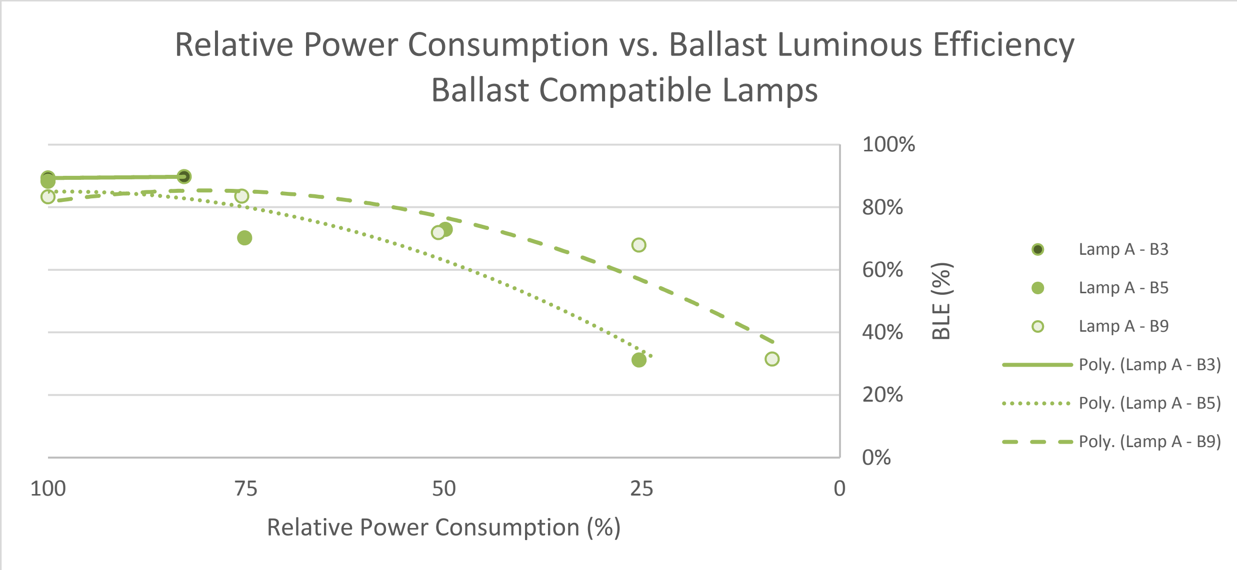



**FIGURE 35. RELATIVE POWER CONSUMPTION VS. BALLAST LUMINOUS EFFICIENCY – BALLAST COMPATIBLE LAMPS**

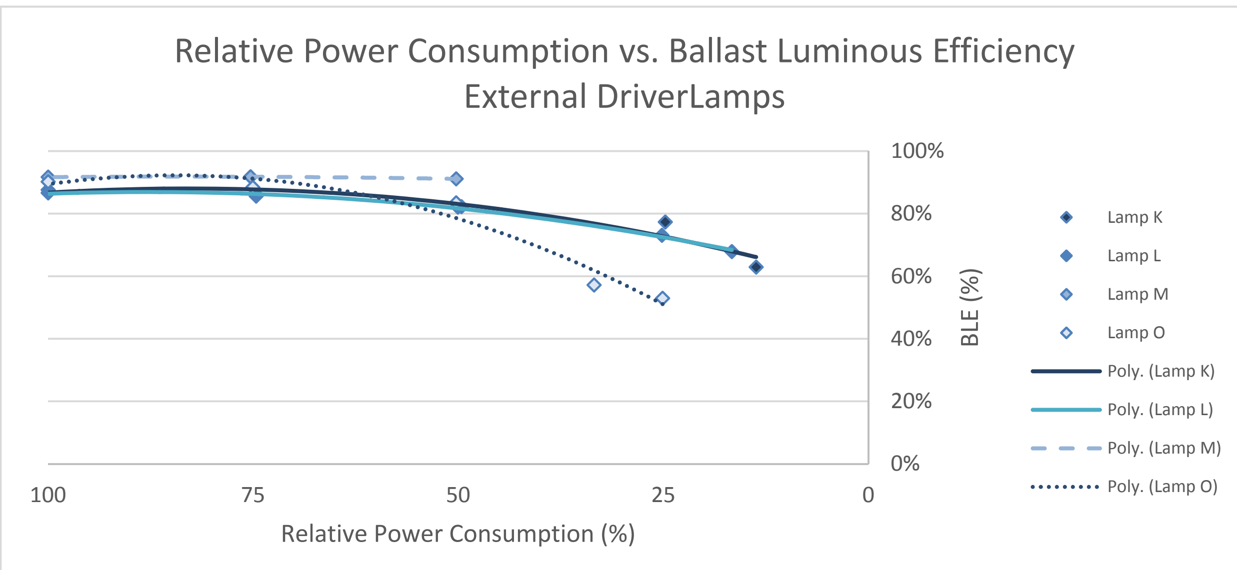



**FIGURE 36. RELATIVE POWER CONSUMPTION VS. BALLAST LUMINOUS EFFICIENCY – EXTERNAL DRIVER LAMPS**

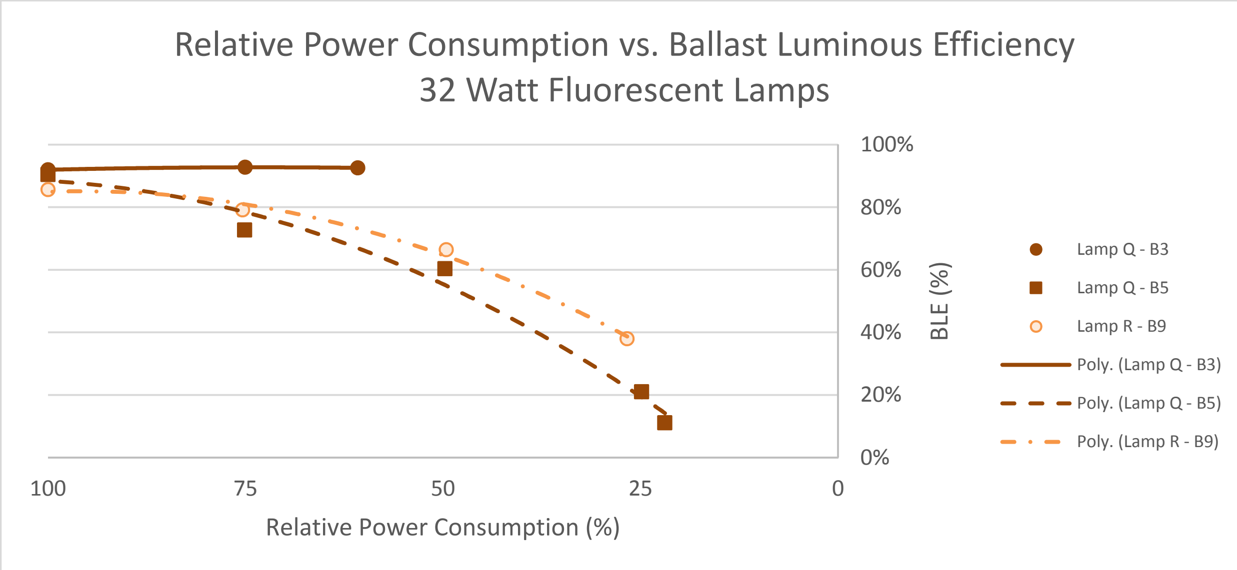



**FIGURE 37. RELATIVE POWER CONSUMPTION VS. BALLAST LUMINOUS EFFICIENCY – 32 WATT FLUORESCENT LAMPS**

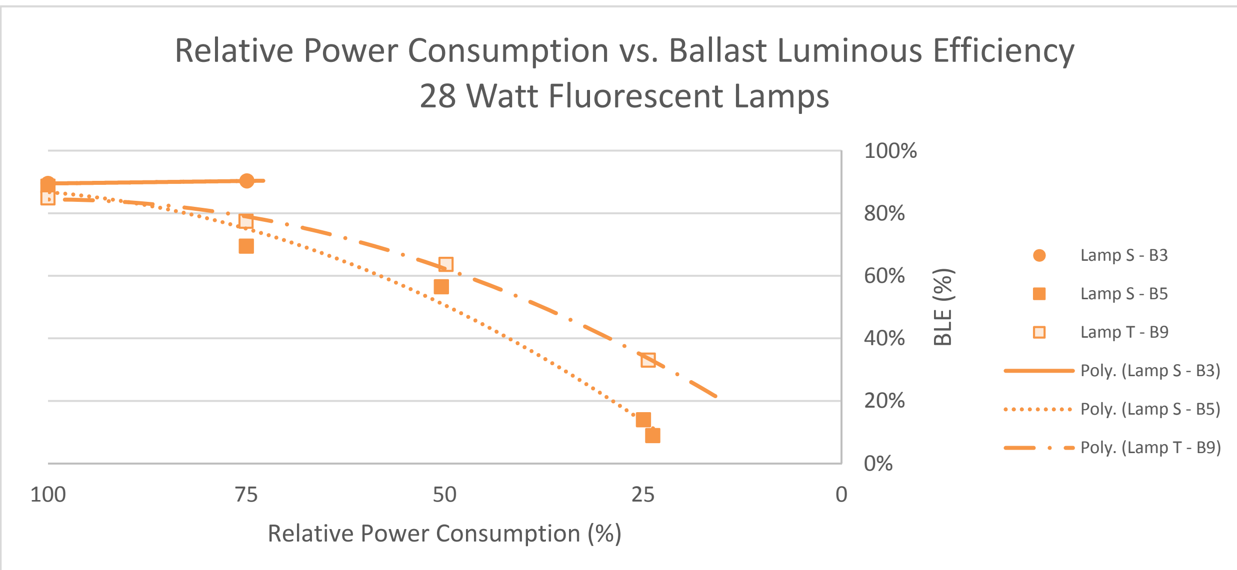



**FIGURE 38. RELATIVE POWER CONSUMPTION VS. BALLAST LUMINOUS EFFICIENCY – 28 WATT FLUORESCENT LAMPS**

Figure 35~~Figure 35~~ through Figure 38~~Figure 38~~ above shows the change in ballast or driver efficiency at different dimming levels. External drivers generally perform better in terms of efficiency throughout their dimming range as compared to fluorescent ballasts. The efficiency of fluorescent ballasts shows improvement at the lower dimming range when used with LED lamps.

# DISCUSSION

## LAMP OUTPUT QUALITY

Generally, LED lamps had similar or better efficacy than fluorescent lamps but some lamps, most notably the internal driver lamps, did not meet the DLC minimum requirement. In comparison to manufacturer claims, test results for efficacy were closely matched for ballast compatible and external driver lamps. On the other hand, internal driver lamps generally had significant lower efficacy than manufacturer claims.

It is worth noting that in terms of total lumen output, 32W fluorescent lamps generally provided more lumens per fixture (2 lamps) than LEDs. Even 28W fluorescent lamps had more total lumen output than some LED lamps. This is important when considering the type of fixtures to be retrofitted with LEDs. In terms of CRI and R9 values, LED lamps are comparable to fluorescent lamps.

Other factors that should be considered but were not part of this study is the light distribution in a space where LED lamps are installed in existing fluorescent fixtures. There is concern that light output may not be as evenly distributed with LED lamps as well as with fluorescents as existing troffer optics optimize the light output of fluorescent lamps.

## POWER QUALITY

At full power measurements, ballast compatible LED lamps had comparable values of PF and $THD_I$ to fluorescent lamps and within the DLC requirements. Internal driver lamps performed poorly as most had significantly higher values of $THD_I$ as compared to fluorescents and DLC requirements of 20%. All internal driver lamps, except for one had low values of PF as well. The external driver lamps performed better than internal driver lamps in terms of PF and $THD_I$ but a few lamps did not meet DLC requirements while most were borderline.

## DIMMING PERFORMANCE

The majority of the external driver and integrated driver lamps were dimmable. However, for ballast compatible lamps, dimming functionality was not commonality available at the time of this study and only one of the 5 lamps evaluated supporting dimming.

Dimming performance of external and internal driver lamps was more linear than fluorescent lamps. In other words, the efficacy was maintained through most of the supported dimming range, only starting to decrease significantly at around 30% of input power. In most cases, external driver and internal driver lamps had a deeper dimming range than fluorescent lamps. Ballast compatible lamps had similar or improved dimming performance as fluorescent lamps. In some cases the dimming range of ballasts was increased when using LED lamps. It is worth noting that the fluorescent lamps had the worst efficacy performance throughout the dimming range. As the power into the ballast was decreased, the efficacy of the fluorescent lamps decreased.

For the majority of LED lamps, dimming affects power quality at increasing rates as the lamp is dimmed. $THD_I$ increases dramatically for internal driver lamps as they are dimmed, reaching values around 300% of fundamental. On the other hand, power factor of external driver lamps is affected by dimming, reaching values below 0.5 at 25% of full power. Power factor of internal driver lamps was also affected, dropping below 0.8 for most of the supported dimming range but performed better than external driver.

## DE-LAMPING

During testing, it was considered possible that a customer would have an existing fixture with only one lamp, where the ballast was actually designed for two lamps. In the case of de-lamping, the impacts on performance of the LED products should be considered. Figure 39~~Figure 39~~ and Figure 40~~Figure 40~~ below compare a ballast-compatible LED lamp tested in a 1-lamp ballast against the same lamp tested in a 2-lamp ballast de-lamped configuration. These tests were performed on 1-lamp and 2-lamp GE instant start ballasts of similar performance characteristics.

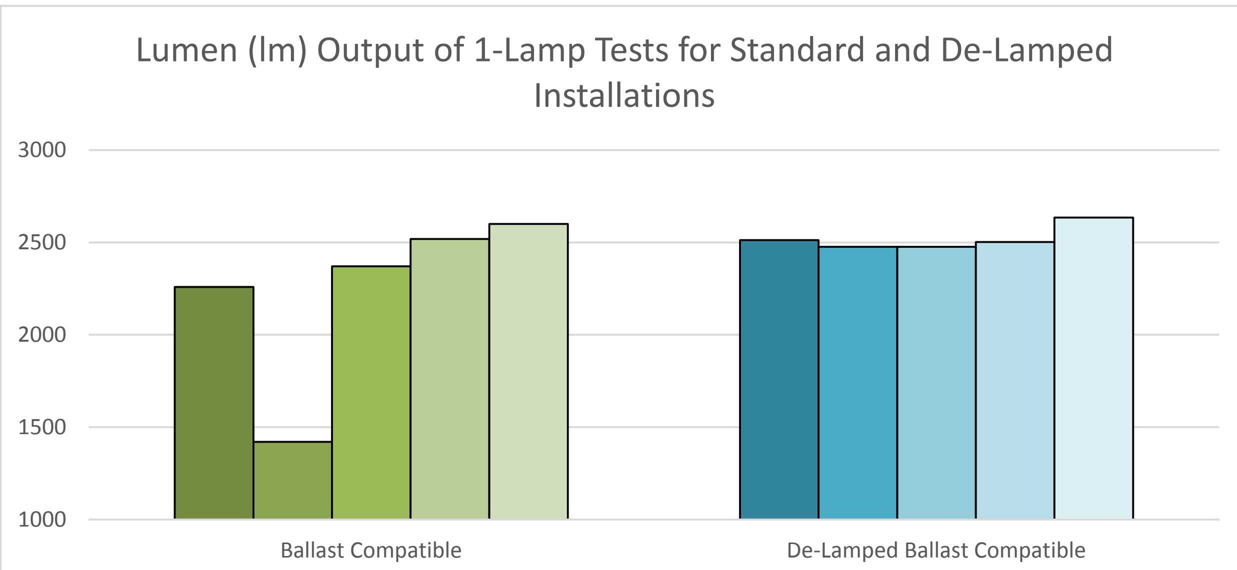



FIGURE 39.

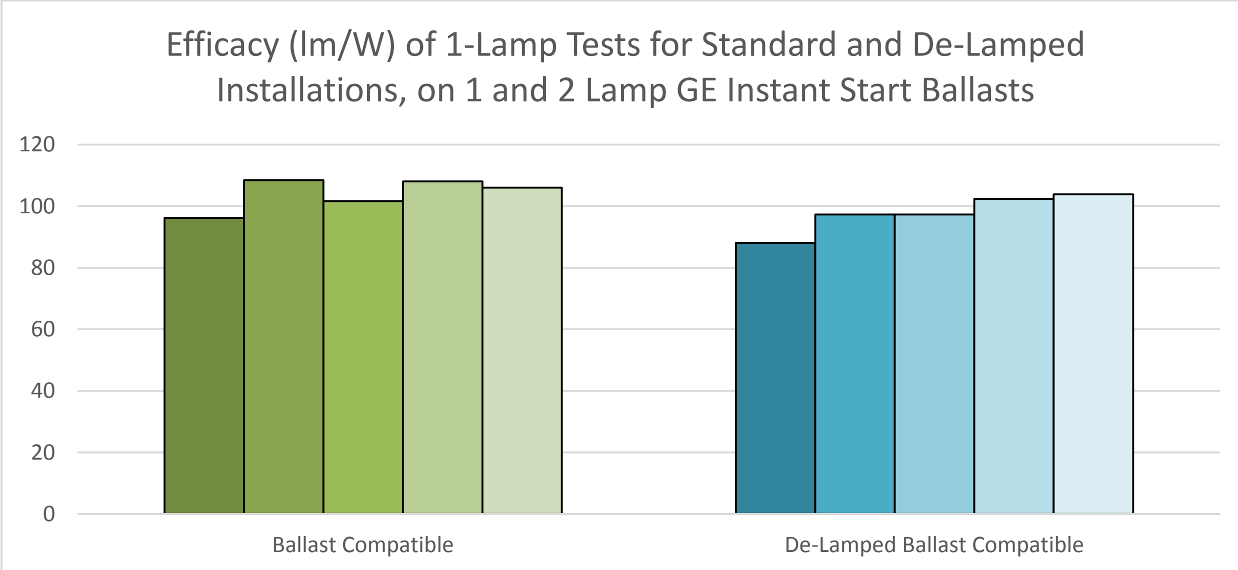



**FIGURE 40.**

No notable difference was seen in power quality for de-lamped installations, however the lamps show an increase in lumen output and a decrease in efficacy under this installation when compared with an intended installation.

## HYBRID TECHNOLOGY INSTALLATIONS

Hybrid installations are those in which both fluorescent and LED T8 lamps are installed on the same ballasts. This could result from instances where the user decides to replace existing fluorescent T8 lamps with LED lamps only upon failure. Testing was done to see the impact of hybrid installations on the same ballast. Figure 41~~Figure 41~~ and Figure 42~~Figure 42~~ below show the impacts on lumen output and efficacy of the fixture using a 32W Fluorescent lamp.

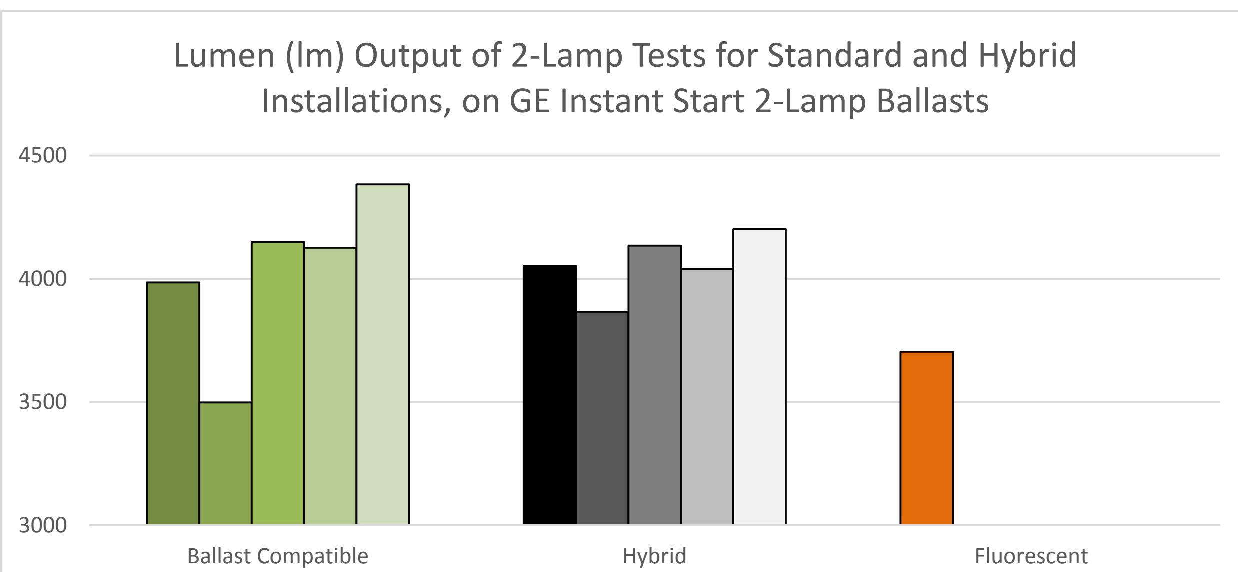


FIGURE 41.

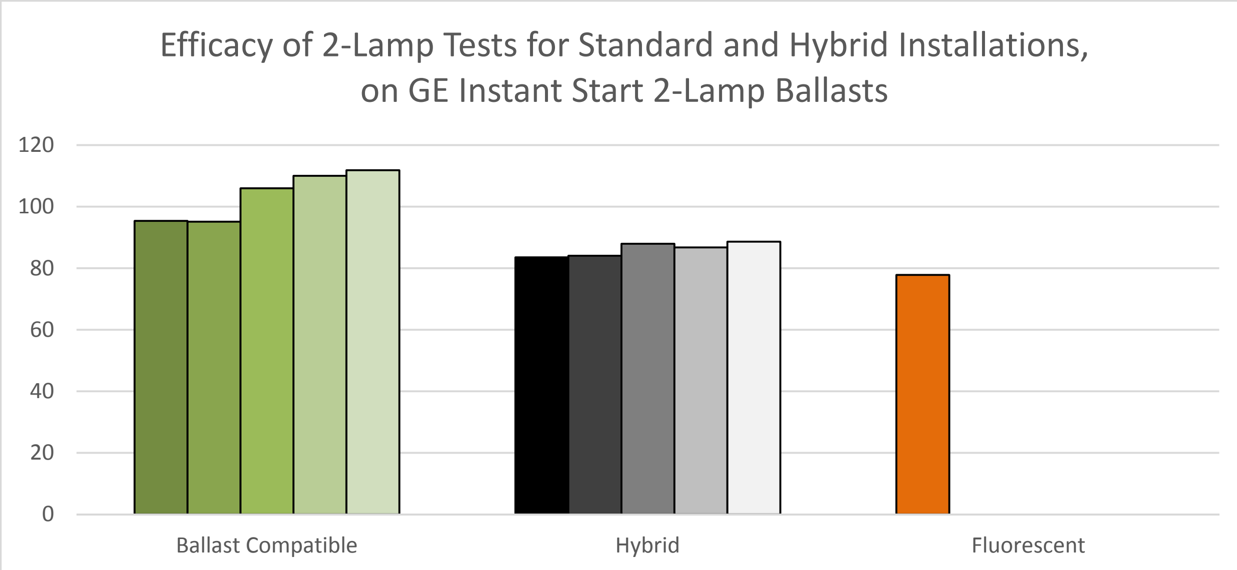



FIGURE 42.

There was no noticeable change in power quality of the fixture when a mix of technologies were installed. Total lumen output in hybrid installations either improved or remained fairly similar to that of standard Ballast Compatible LED installations. Efficacy of the fixture for Hybrid installations appears to be the average of the Ballast Compatible and Fluorescent values, indicating that the individual savings from replacing even a single lamp has a proportional effect on the fixture performance. No flickering or other issues were detected or observed under the Hybrid condition.

# INSTALLATION CONSIDERATIONS

Outside of the performance of the technology, there are other observations that were made about the products that need to be addressed. Some of these observations have potential impacts on user safety and the usability of the products with existing fixtures and controls.

## COMPATIBILITY

### DIMMING

It is important to consider if dimming or other control strategies are in place where the LED replacements are being considered.  Some products are not compatible with dimming and some families of products have very limited options for products compatible with dimmers.

### BALLAST COMPATIBLE

One of the more important things to consider when selecting an LED T8 product is the compatibility of the product with existing fixtures and ballasts. If the product is a T8 LED replacement lamp, then it is very important to know what ballasts are installed in a facility. Most manufactures provide a detailed list of ballast models the lamps are compatible with. Installers should verify which ballasts are installed in a fixture before installing any T8 LED replacement lamp.

Quick tests of lamp-ballast combinations not approved by the manufacture showed that some lamps will not work with some ballasts or will not provide adequate illumination. It is not advised to use lamps on un-approved ballasts. In general, lamps approved only for instant start ballasts will not work on programmed start ballasts (low output, or do not work at all).

### RETROFIT KITS

All of the products tested were able to use a standard open strip fixture for testing. However some of the products required special connectors and mounting to the fixture rather than using existing G13 connectors. It is not anticipated that there would be many situations where these connectors or mounting would be unfeasible, but it is something that should be considered when selecting a product.

One of the considerations to take with these products is that they will all require re-wiring of the fixture. This has possible considerations within California as doing a significant of rewiring or refitting of fixtures may trigger Title 24 considerations. This means that the installation of these lamps could require that the rest of the space be brought up to code.

All of the external driver lamps tested required drivers specified by the manufacturer. If a building were to be retrofit with a product, it would be unlikely that a different product could be used as a replacement in the future. With the quick turnaround in the market of these products and new companies entering and exiting the market, it is possible that replacement lamps may not be available for the system at some point when the lamps fail, especially considering the expected life of the lamp products and the remaining life of the existing ballasts where ballasts compatible lamps are used.

## WIRING

There are many different wiring configurations for the various lamp products. Between shunted, un-shunted, single ended, or double ended; there are many different configurations that can be required. Before installation, read through the instructions provided by the manufacturer to ensure proper installation. It is recommended that if the ballast is being removed or switched for a driver, that the connectors be replaced to ensure that the proper shunted or un-shunted connectors are in place. Rewiring should be done by qualified personnel to ensure correct and safe operation of the lamps.

## INSTRUCTIONS

It is important that when wiring or installing the lamps that the manufacturer's instructions are followed. During this evaluation, several of the products came with little, incorrect, or no installation instructions. Ballast compatible lamps did not have this issue, as they are designed to use the existing fixture and wiring.

External driver products were generally well documented, as most of the information for installation was located on the driver. However some products did not specify a polarity of the installation (this generally matters because they are DC products), pin configuration (shunting required or not), or which end of the lamp (for single end powered lamps) required power. It is recommended that manufactures note clearly all requirements for each end of a lamp, and requirements for the driver installation on the lamp, driver, and accompanying literature.

Internal driver lamps also had some missing information. Some lamps came with no installation instructions at all. In all cases where more information was needed, attempts were made to contact the manufacturer for instructions. In most cases manufacturers eventually provided sufficient information to clearly understand installation requirements, but in some cases no information ever returned by the manufacturer. To operate those lamps with the missing installation instructions other similar lamps were used as reference. This is concerning for a new product category as sufficient knowledge of the installation of the products may not be available, causing issues for customers and installers.

## LABELING

One issue noted during testing was the labeling of some products. Ballast compatible lamps did not have this issue and it was less prevalent with external driver lamps and drivers. Internal driver lamps had multiple issues with what the product was labeled as, what was ordered, and what the product actually was.

### INTERNAL DRIVER LAMPS

With the internal driver lamps, many of the products tested had very poor quality labels made of paper glued onto the lamp. The labels where often ripped or damaged. As discussed in the results section, these labels were often installed where the lamp is hottest. The main concern with this is how long the products will remain labeled, as this may be the only source of information on the product.

The information specified on some of the products was also alarming when compared to what was ordered or received. One of the products was labeled for use at 127V. When the manufacturer was asked about this, it responded by indicating that it was labeled per what was ordered (a product with 120-277Vac compatibility was ordered). Further, the manufacturer claimed that the product was actually compatible with 110-140Vac.

A similar product was ordered as 110-277V compatible, but was received as 90-140Vac compatible. When the manufacturer was contacted to inform that the wrong product was received, the manufacturer insisted that it had shipped a 110-277V product, but would look into it. The manufacturer later found that the entire batch of lamps they had was labeled as such and demonstrated confusion about the origin of the misprint. The manufacturer then contacted its supplier who confirmed that the product was indeed only 90-140V compatible and that only the non-dimming lamp was 110-277V compatible. The manufacturer then agreed to provide updated product specifications once they were created.

Another product was labeled as "dimming" on the front of the product, yet the back label stated that it was not for use with dimmers. The product was advertised as a dimming compatible lamp and was found to be compatible with dimmers. It was found that the product was compatible with dimmers.

One product of particular concern was labeled for use with 120-277 volts AC. When the lamp was tested at 277V it immediately failed. The product was purchased with these specifications as well. It was found that the lamp was only compatible with voltages between 110-140Vac.

# WARRANTY

Companies are entering and exiting the market on a regular basis for these products. Products are often sold al-la-carte and not as systems, bringing into question interoperability issues. How warranties for these products are handled is something that should be considered by specifiers and installers.

## BALLAST

It is unclear how the installation and operation of an LED product on a ballast affect the warranty on the ballast. Due to the ballasts being designed for fluorescent lamps, it is possible that manufacturers will not honor warranties for ballasts when LED T8 lamps are used on them. There is insufficient information in regards to real-life data on operation of existing fluorescent ballasts with T8 LED replacement lamps to assess durability and how ballast performance is affected over time.

## LAMPS

For ballast compatible and external driver lamps, manufactures provide a list of compatible ballasts or drivers. Some products specify types of compatible products or make more general statements of compatibility. When installed in a large space, it possible that not every ballast will be the same. If a lamp does fail, will the manufacturer require information regarding what specific ballast the lamp was used on? The performance of the lamp certainly depends on the ballast. So it is possible that unless the ballast used is on an approved compatibility list, then the product will not be able to be returned under warranty.

It is recommended that users clearly check which ballasts are installed in their facility and ensure that the products to be installed are considered compatible.

# SAFETY

## HEAT

During testing of integrated driver lamps an issue was raised regarding the temperature of the lamps. Upon the completion of a test, it was noted that when the test operator went to remove the lamps to prepare for the next test, the lamps where very hot. This was not noted for the other lamp types. Thermal images where taken of some sample lamps upon completion of their testing to determine roughly how hot they were.

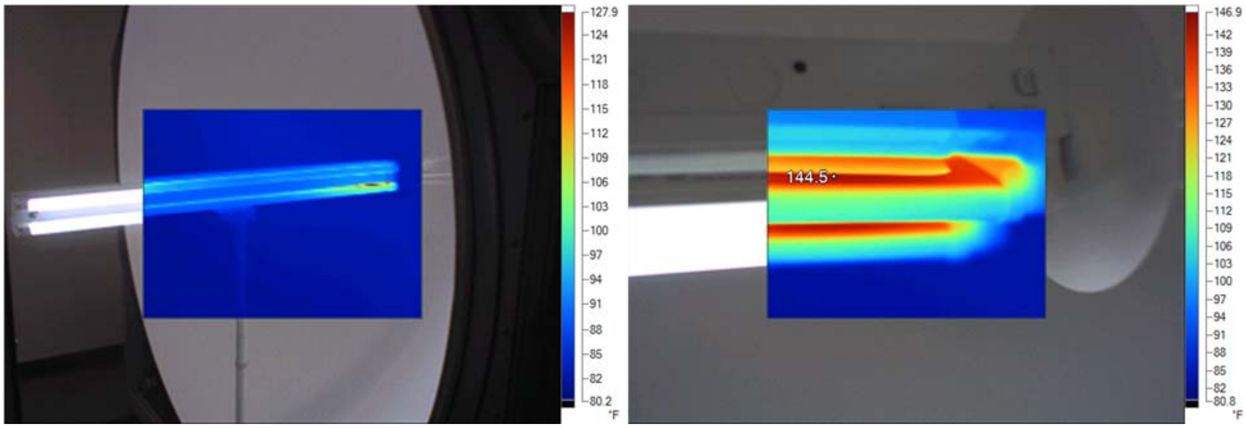



**FIGURE 43~~39~~. THERMAL IMAGE TAKEN OF INTEGRATED DRIVER LAMP UPON TEST COMPLETION**

Looking at the thermal images in Figure 43~~Figure 39~~, in the left image we can see that the heat is concentrated in a specific area of the lamp. The two lamps installed in this set-up are identical, yet only one lamp has a hot spot at that particular end. The other lamp's hot spot was at the other end. This is presumably where the internal driver resides. Other areas of the lamp have significantly lower surface temperatures. Since this was not noted until partway through testing, not all lamps have data regarding surface temperatures.

Labels on the integrated driver lamps generally tended to be in the same area as the hot spot, though this was not always the case either within the same batch of lamps or across the entire product family. None of the lamps tested came with caution or warning labels that the product may be hot. California OSHA recognizes 140°F[8] as the temperature capable of causing momentary contact burns and IEC 60950-1 also recognizes this temperature (60°C) as a safe limit for metal surfaces.[9] Since the temperature observed is higher and it is not apparent what part of the lamp will be hot, or that it will even be hot at all, it is recommended that maintenance personnel wait for the lamps to cool down before replacing them.

This also raises some concerns for long term quality of the product, as high temperatures are known to degrade the performance of LED products[10]. The high temperatures also could affect the attached labels, causing them to fall off or become unreadable over time which poses some safety concerns as the labels where often (but not always) installed on the same end as the hot spots.

A secondary set of BLE tests were performed on the ballast compatible lamps to look into surface temperatures due to the concerns raised with integrated driver lamps. From this, it was found that for ballast compatible lamps, the temperature of the lamp was highest at the ends and that the highest temperature is

[8] California OSHA, "*INITIAL STATEMENT OF REASONS; TITLE 8: Division 1, Chapter 4, Subchapter 7, Article 7, Section 3308 of the General Industry Safety Orders, Hot Surfaces and Hot Pipes*", 2/18/2010: http://www.dir.ca.gov/oshsb/hot_surfaces_isor.pdf

[9] Requirements in IEC 60950-1, 1st Edition (2001), Information Technology Equipment - Safety - Part 1: General Requirements

[10] U.S. Department of Energy Building Technologies Program, *"Lifetime of White LEDs"*, 4/12/2011: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lifetime_white_leds.pdf

significantly lower than integrated driver lamps. The temperature, as taken with a thermal camera, can be seen in the figure below.

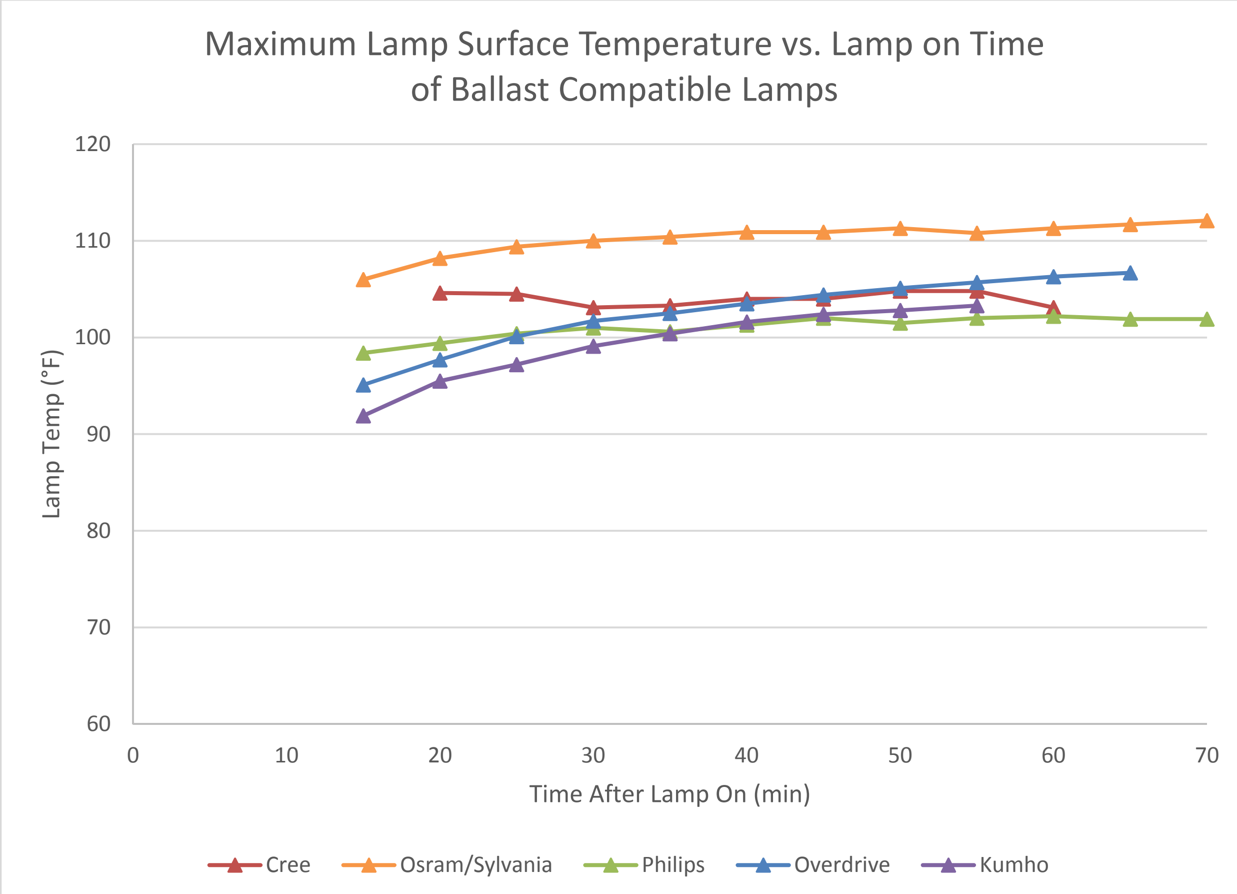



**FIGURE 44~~40~~. LAMP TEMPERATURE VS TIME FOR EACH BALLAST COMPATIBLE LAMP**

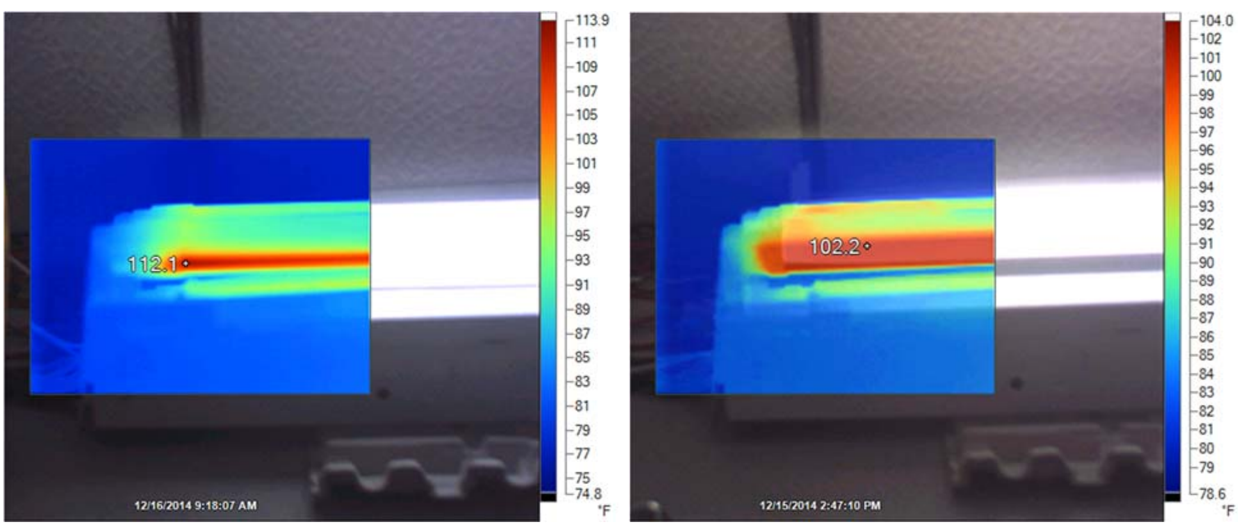



**FIGURE 45~~41~~. THERMAL IMAGE TAKEN OF LAMP B (LEFT) AND LAMP C (RIGHT) DURING SECONDARY BLE TESTING**

## SHOCK AND FIRE HAZARDS

It is recommended that for all of these products, that the fixture is de-energized before replacement of a lamp. It was noted that for internal driver lamps, an arcing sound was noted when the lamps where installed while the fixture was energized. This was not noticed on the other lamp types.

### INSTALLATION LABELING

There is concern about potential cases when the fixture is re-wired for non-ballast compatible lamps and a fluorescent or a different type of LED lamp not meant for those conditions is placed inside the fixture. Most manufacturers provided stickers or labels to place within the fixture to alert maintenance personnel that the fixture has been altered, however these stickers and labels are not large and could be easily missed by personnel. It is recommended that maintenance personnel be trained to look for modified fixtures and be familiar with the the new requirements of the retrofitted fixtures.

# CONCLUSIONS AND RECOMMENDATIONS

## CONCLUSIONS

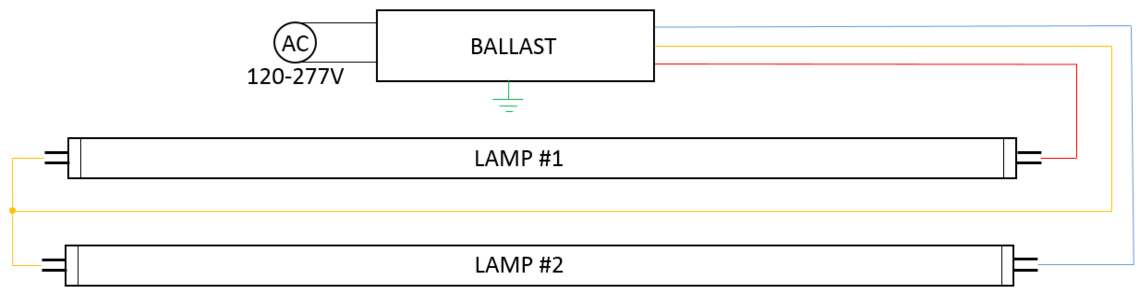
- In general, linear ballast compatible LED lamps performed in accordance to manufacturer specifications and similar to fluorescent lamps in most aspects.
- LED lamps designed to bypass existing fluorescent ballasts, either by using dedicated external or internal drivers generally did not meet DLC requirements and performed below manufacturer specifications in some cases.
- Light output quality of most LED lamps, is comparable to fluorescent lamps of similar specifications
- Measurements demonstrated better efficacy of linear LED lamps as compared to fluorescent tubes.
- Of the three linear LED lamp product categories evaluated under this laboratory study, only the ballast-compatible products could be easily used to retrofit fluorescent troffers without much effort.
- Power quality of ballast-compatible linear LED lamps was similar to fluorescent lamps, but compatibility with existing models of fluorescent ballasts is very limited.
- The majority of linear LED lamps with integrated driver evaluated under this study did not include appropriate wiring instructions or specifications either on the user guides or product labels.
- It was observed that the lack of or clarity of installation instructions, particularly for wiring, could lead to lamp damage and user injury.
- Dimming of linear LED lamps is considerably better than fluorescent lamps.
- Ballast compatible LED lamps consistently dimmed without visible flicker and considerable power quality degradation down to around 15% of full power on average.

## RECOMMENDATIONS

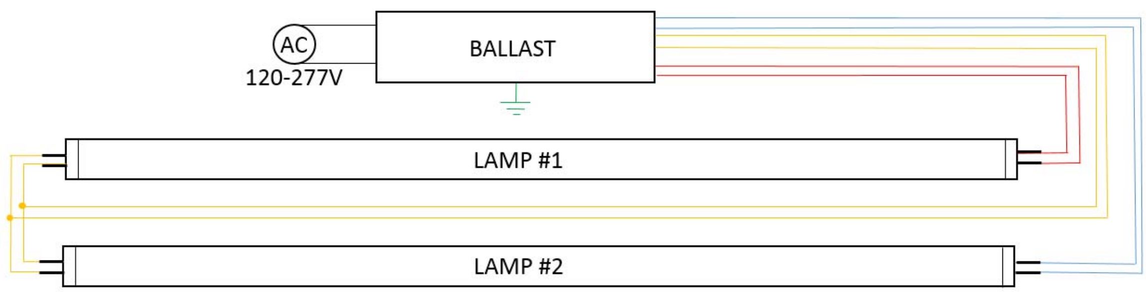
- A long term assessment would be necessary to properly assess lamp performance and rate of degradation over time, specifically those lamps meant for installation on existing ballasts.
- Proper documentation of LED lamp compatibility with fluorescent ballasts should be developed by manufacturers to help customers correctly select LED lamps to retrofit fluorescent lamps.
- Improved labeling standards should be developed to ensure manufacturers provide important product information to help customers pick the right product for their applications and minimize risk of electrical shock or fire.

# APPENDIX A: WIRING DIAGRAMS

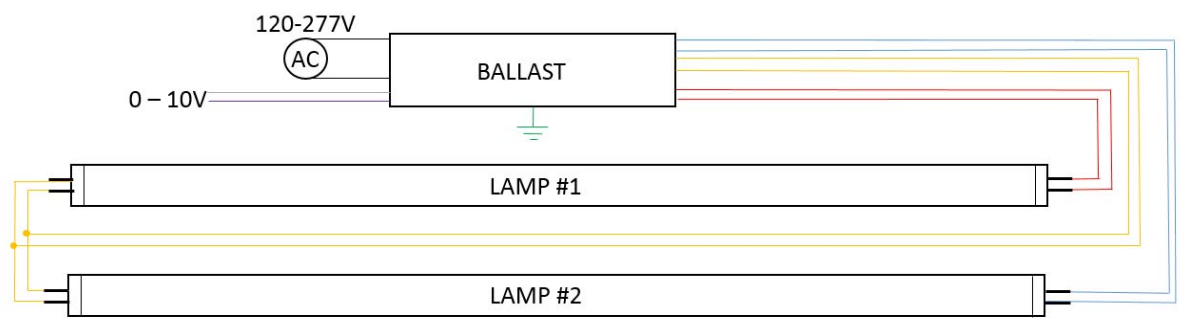
### TYPICAL WIRING FOR BALLAST COMPATIBLE LED LAMPS WITH INSTANT START BALLAST



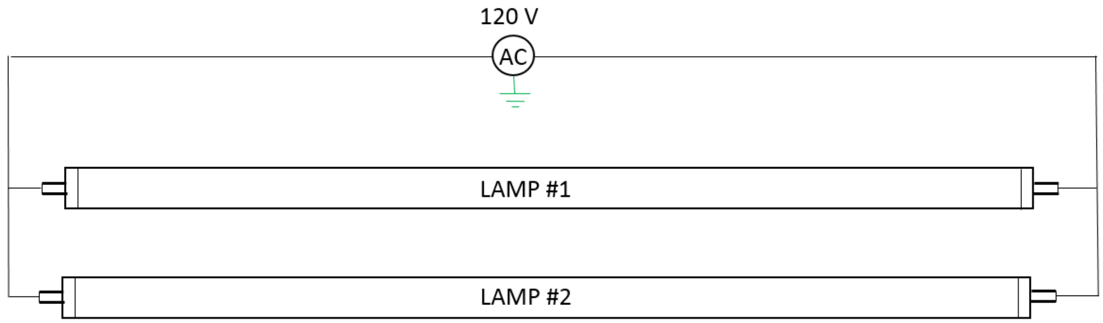

### TYPICAL WIRING FOR BALLAST COMPATIBLE LED LAMPS WITH PROGRAMMED START BALLAST



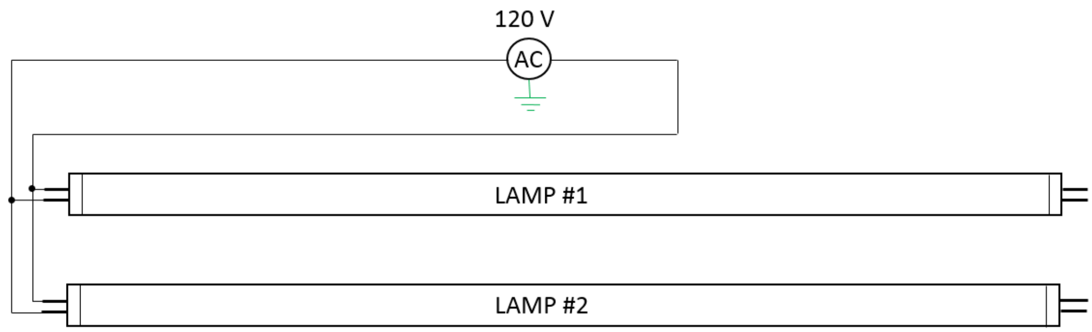

### TYPICAL WIRING FOR BALLAST COMPATIBLE LED LAMPS WITH DIMMABLE PROGRAMMED START BALLAST



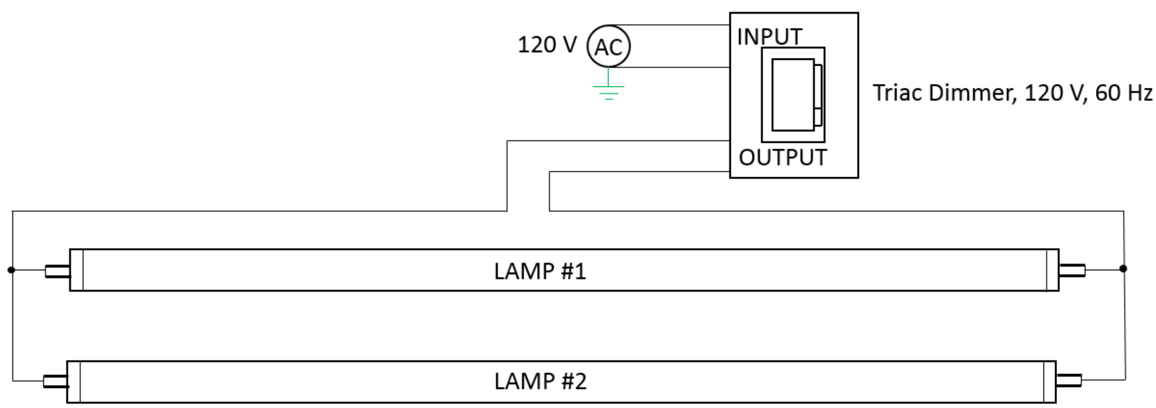
TYPICAL WIRING FOR SINGLE-ENDED LED LAMPS WITH INTEGRATED DRIVER



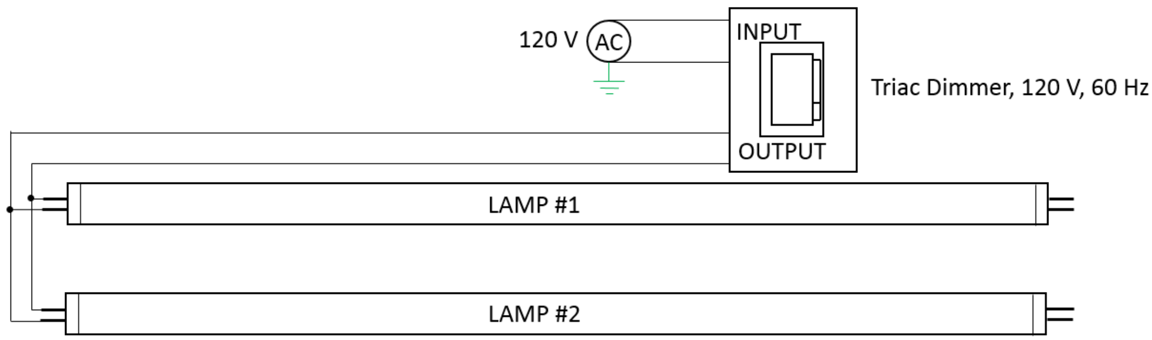

TYPICAL WIRING FOR DOUBLE-ENDED LED LAMPS WITH INTEGRATED DRIVER



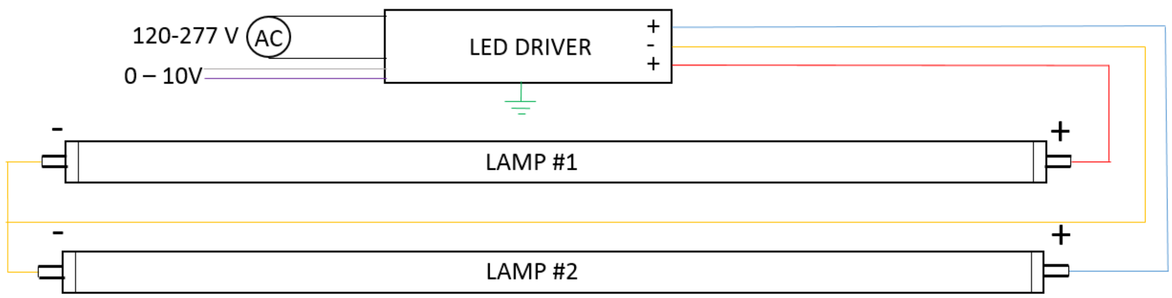

TYPICAL WIRING FOR DIMMABLE SINGLE-ENDED LED LAMPS WITH INTEGRATED DRIVER USING TRIAC DIMMER



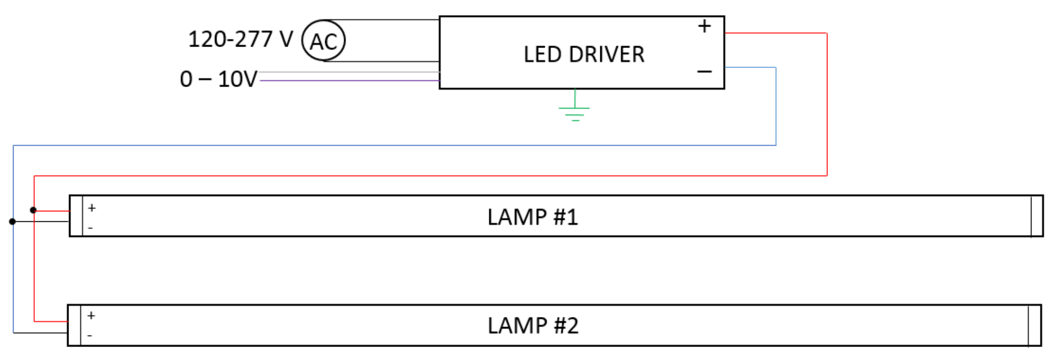
### Typical Wiring for Dimmable Double-Ended LED Lamp with Integrated Driver Using Triac Dimmer




### Typical Wiring for Double-Ended LED Lamps with External Dimmable Driver




### Typical Wiring for Single-Ended LED Lamps with External Dimmable Driver



# APPENDIX B: TEST PROPOSAL

# Linear LED T8 Lamp Performance Assessment

## 1 Project Overview

| Project Number | Name | Laboratories | Project Manager | TTC Lead |
|---|---|---|---|---|
| **NA** | Linear LED T8 Lamp Lab Performance Assessment | 2MSSL, RCRL, Dark Room Lab | Teren Abear | Al Mendoza |

### 1.1 Project Objective

Conduct a laboratory test to assess the photometric and electrical performance, dimming capability, safety and appearance of market representative linear LED lamps designed to replace linear fluorescent T8 lamps. Results from the lab tests will be provided to the Project Manager for analysis and consideration in future SCE Energy Efficiency incentive program offerings. The proposed tests involve two different phases. Phase I consists of a series of laboratory tests to assess the baseline performance of three different types of LED T-8 replacement lamps as described in Section 1.1.1. Phase II is a long-term life performance assessment to evaluate photometric and thermal degradation of the LED T-8 lamp in categories 1 and 2 in Section 1.1.1.

## 2 Phase I – Baseline Performance of T8 LED Lamps

Under this laboratory testing phase, several representative sample LED tube lamps for each of the following categories will be tested to assess their baseline performance:

1. Linear T8 LED replacements (use with existing fluorescent ballasts)
2. Linear T8 LED T8 replacements with integrated driver (use with line voltage)
3. Linear T8 LED replacements with external driver

Performance of the linear LED lamps described in items 1-3 above will be tested in following arrangement:

1. Bare Lamps (no troffer),

#### 2.1.1 Benchmark Lamps

The following fluorescent lamps will be tested and used as baselines to compare with the LED replacement lamps:

1. 32W, T8, 800 Series fluorescent linear lamp in a 2-lamp fixture in the 4100-4500 K color temperature range with instant start, and programmed start electronic dimming ballast.
2. 28W, T8, fluorescent linear lamp in a 2-lamp fixture in the 4100-4500 K color temperature range with instant start, and programmed start electronic dimming ballast.

# 3 Devices under Test

| DUT | Make | Model | Description | Quantity | Responsible |
|---|---|---|---|---|---|
| **1*** | Various | TBD | Linear LED T8 replacement lamp (EB) | Up to 5 | TTC Lead |
| **2*** | Various | TBD | Linear LED T8 replacement lamp (integrated driver) | Up to 5 | TTC Lead |
| **3*** | Various | TBD | Linear LED T8 replacement lamp (external driver) | Up to 5 | TTC Lead |
| **4*** | TBD | TBD | Linear fluorescent T8, 32W lamp and 28W lamp | 2 | TTC Lead |
| | **Total** | | | **Up to 17** | |

*Lamps are preferably dimmable.

## 3.1 DUT Selection

Selection of DUTs will be coordinated with Project Manager, and will include products from major manufacturers like Philips and Cree, DLC approved list, U.S. DOE CALiPER Series 21 Reports on Linear (T8) LED Lamps from early 2014, trade publications, EnergyStar, internet websites, national retailers and distributors. Final DUT selection criteria will be decided upon in agreement with Project Manager.

### 3.1.1 DUT Characteristics to Consider

Linear LED lamp characteristics to consider for selection of DUTs should include the following:

1. Aperture finish (clear, diffuse, etc.)
2. Aperture angle (greater than 120$^{o}$ but less than 145$^{o}$)
3. Color variations (CCT 4100$^{o}$K, CRI>80)
4. Dimmability
5. Connector type
6. Lamp configuration (lamps per luminaire, per driver, etc.)
7. Must meet the following minimum requirements:
    a. 1800 lumen rated total output
    b. 100 lm/w rated efficacy

## 3.2 DUT Ownership and Responsibility

| DUT | Ownership During Testing | Responsibility During Testing | Ownership After Testing | Destination After Testing | Destination Cost | Responsibility After Testing |
|---|---|---|---|---|---|---|
| **All** | **Project Manager** | **TTC Lead** | **Project Manager** | **TBD** | **TBD** | **Project Manager** |

DUTs are removed from TTC facilities at the completion of testing by the Project Manager, unless otherwise negotiated by the TTC Lead and Project Manager.

# 4 Configurations

## 4.1 Benchmark: Fluorescent Lamp with Fluorescent Ballast

### 4.1.1 Fluorescent Lamp Electrical and Photometric Performance

Baseline fluorescent lamps are tested per IES LM-9-09, IES Approved Method for the Electrical and Photometric Measurements of fluorescent lamps.

### 4.1.2Standards, Methods and Exceptions

| Standard | Method | Exceptions |
|---|---|---|
| **IES LM-9-09** | | None |

#### *4.1.2.1 IES LM-9-09, IES Approved Method for the Electrical and Photometric Measurement of Fluorescent Lamps*

This standard is available from IES or the TTC Lead.

### 4.1.3 Test Combinations

DUTs are tested with the following lamp-ballast combinations:

1. One fluorescent lamp with a single-lamp ballast mounted on a strip luminaire
2. Two fluorescent lamps with a double-lamp ballast mounted on a strip luminaire

### 4.1.4 Measurements and Exceptions

#### *4.1.4.1 Electrical*

| Measurement | Units | Logging Period | Instrument |
|---|---|---|---|
| **Input current** | A rms | 15 s | Power analyzer-current probe system |
| **Input current THD** | %f | 15 s | Power analyzer-current probe system |
| **Input frequency** | Hz | 15 s | Power analyzer-current probe system |
| **Input phase angle** | ° | 15 s | Power analyzer-current probe system |
| **Input power** | W | 15 s | Power analyzer-current probe system |
| **Input power factor** | PF | 15 s | Power analyzer-current probe system |
| **Input voltage** | V rms | 15 s | Power analyzer-current probe system |
| **Input voltage THD** | %f | 15 s | Power analyzer-current probe system |
| **Lamp arc current** | A rms | 15 s | Power analyzer-current probe system |
| **Lamp arc frequency** | Hz | 15 s | Power analyzer-current probe system |
| **Lamp arc power** | W | 15 s | Power analyzer-current probe system |
| **Lamp arc voltage** | V rms | 15 s | Power analyzer-current probe system |

#### *4.1.4.2 Photometric*

| Measurement | Units | Logging Period | Instrument |
|---|---|---|---|
| **Chromaticity** | u | On-demand | Sphere-spectroradiometer system |
| **Chromaticity** | v | On-demand | Sphere-spectroradiometer system |
| **Chromaticity** | x | On-demand | Sphere-spectroradiometer system |
| **Chromaticity** | y | On-demand | Sphere-spectroradiometer system |
| **Color rendering index** | Ra | On-demand | Sphere-spectroradiometer system |
| **Correlated color temperature** | °K | On-demand | Sphere-spectroradiometer system |

| | | | |
|---|---|---|---|
| **Duv** | None | On-demand | Sphere-spectroradiometer system |
| **Luminous flux** | lm | On-demand | Sphere-spectroradiometer system |

#### *4.1.4.3 Thermal*

| Measurement | Units | Logging Period | Instrument |
|---|---|---|---|
| **Sphere inside temperature** | °F | 15 s | Data acquisition-thermocouple system |
| **Sphere outside temperature** | °F | 15 s | Data acquisition-thermocouple system |

#### *4.1.4.4 Time*

| Measurement | Units | Logging Period | Instrument |
|---|---|---|---|
| **Time** | h:min:s | 15 s | Data acquisition-thermocouple system, power analyzer-current probe system |
| **Time** | h:min:s | On-demand | Sphere-spectroradiometer system |

## 4.2 Linear LED T8 Lamps

### 4.2.1 LED Lamp Electrical and Photometric Performance

DUTs are tested per IES LM-79-08, IES Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products, to measure electrical and photometric performance.

### 4.2.2 Standards, Methods and Exceptions

| Standard | Method | Exceptions |
|---|---|---|
| **IES LM-79-08** | Section 9.1, Integrating Sphere with a Spectroradiometer (Sphere-Spectroradiometer System) | 1. Air temperature may not be regulated per section 2.2.<br>2. When the DUT is dimmable and a dimming control is connected, the DUT is tested at 100%, 75%, 50%, 25%, and minimum power level.<br>3. When the DUT is dimmable, stabilization will only be done at 100% power level. For testing at dimming levels below 100% power level, no stabilization will be performed (the DUT will be assumed stable after stabilizing at 100%).<br>4. DUTs are tested in a fluorescent strip luminaire.<br>5. DUTs will be tested as single LED tube, double LED tube, and one LED tube and one fluorescent lamp combination on the same ballast.<br>6. DUTs are tested with instant start, and programmed start dimming ballasts where applicable. |

#### *4.2.2.1 IES LM-79-08, IES Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products*

This standard is available from IES or the TTC Lead.

### 4.2.3 Test Combinations

DUTs are tested with the following lamp-ballast combinations where applicable depending on compatibility of DUT under evaluation:

#### *4.2.3.1 Bare Lamp Tests*

1. One DUT [replacement (EB) LED lamp] with a single-lamp fluorescent ballast (standard)
2. One DUT [replacement (EB) LED lamp] with a double-lamp fluorescent ballast (standard)
3. Two DUT [replacement (EB) LED lamp] with a double-lamp fluorescent ballast (standard and dimmable)
4. One DUT (replacement LED lamp) and one fluorescent lamp with a double-lamp fluorescent ballast (standard and dimmable)
5. One DUT with integral driver
6. Two DUT with integral drive (with and without dimmable driver)
7. One DUT with single-lamp external driver
8. One DUT with double-lamp external driver (with and without dimmable driver)

### 4.2.4 Measurements and Exceptions

#### *4.2.4.1 Electrical*

| Measurement | Units | Logging Period | Instrument |
|---|---|---|---|
| **Current** | A rms | 15 s | Power analyzer system |
| **Current THD** | %f | " | " |
| **Frequency** | Hz | " | " |
| **Phase angle** | ° | " | " |
| **Power** | W | " | " |
| **Power factor** | PF | " | " |
| **Voltage** | V rms | " | " |
| **Voltage THD** | %f | " | " |

#### *4.2.4.2 Photometric*

| Measurement | Units | Logging Period | Instrument |
|---|---|---|---|
| **Radiant flux** | mW | On-demand | Sphere-spectroradiometer system |
| **Luminous flux** | lm | " | " |
| **Correlated color temperature** | K | " | " |
| **Color rendering index average** | Ra | " | " |
| **Chromaticity** | x | " | " |
| **Chromaticity** | y | " | " |
| **Distance from Plankian Locus** | None | " | " |
| **Color rendering index 9** | R9 | " | " |
| **Chromaticity** | u | " | " |
| **Chromaticity** | v | " | " |

#### *4.2.4.3 Thermal*

| Measurement | Units | Logging Period | Instrument |
|---|---|---|---|

| | | | |
|---|---|---|---|
| **Sphere inside temperature** | °F | 15 s | Data acquisition-thermocouple system |
| **Sphere outside temperature** | °F | " | " |

#### 4.2.4.4 Time

| Measurement | Units | Logging Period | Instrument |
|---|---|---|---|
| **Time** | h:min:s | 15 s | Data acquisition-thermocouple system, power analyzer-current probe system |
| **Time** | h:min:s | On-demand | Sphere-spectroradiometer system |

## 4.3 Ballast Efficiency

Efficiency of fluorescent ballasts with replacement linear LED T8 lamps are tested per 10 CFR Part 430 Subpart B Appendix Q1, Appendix Q1 to Subpart B of Part 430—Uniform Test Method for Measuring the Energy Consumption of Fluorescent Lamp Ballasts, to measure electrical, ballast interactivity, and lamp combination characteristics.

### 4.3.1 Standards, Methods, and Exceptions

| Standard | Method | Exceptions |
|---|---|---|
| **10 CFR Part 430 Subpart B Appendix Q1**[11] | Section 2., Active Mode Procedure | 1. Input current THD, frequency, phase angle, power factor, and voltage THD are measured.<br>2. DUTs are tested in a fluorescent strip luminaire.<br>3. When the DUT is dimmable and a dimming control is connected, the DUT is tested at 100%, 75%, 50%, 25%, and minimum power level.<br>4. When the DUT is dimmable, stabilization will only be done at 100% power level. For testing at dimming levels below 100% power level, no stabilization will be performed (the DUT will be assumed stable after stabilizing at 100%).<br>5. DUTs are tested with the following lamp combinations: 1) single LED Tube, 2) double LED tube, and 3) one fluorescent lamp combination on the same ballast. |

[11] This standard normally applies only to measuring the energy consumption of fluorescent lamp ballasts. Due to the dependence of the DUTs on fluorescent lamp ballasts and lack of a more appropriate standard, this standard is extended to apply to the DUTs, with the exceptions noted in this section.

#### *4.3.1.1 10 CFR Part 430 Subpart B Appendix Q1, Appendix Q1 to Subpart B of Part 430—Uniform Test Method for Measuring the Energy Consumption of Fluorescent Lamp Ballasts*

This standard is available from the U.S. Government Printing Office or the TTC Lead.

### 4.3.2 Measurements and Exceptions

#### *4.3.2.1 Electrical*

| Measurement | Units | Logging Period | Instrument |
|---|---|---|---|
| **Input current** | A rms | 15 s | Power analyzer-current probe system |
| **Input current THD** | %f | 15 s | Power analyzer-current probe system |
| **Input frequency** | Hz | 15 s | Power analyzer-current probe system |
| **Input phase angle** | ° | 15 s | Power analyzer-current probe system |
| **Input power** | W | 15 s | Power analyzer-current probe system |
| **Input power factor** | PF | 15 s | Power analyzer-current probe system |
| **Input voltage** | V rms | 15 s | Power analyzer-current probe system |
| **Input voltage THD** | %f | 15 s | Power analyzer-current probe system |
| **Lamp arc current 1** | A rms | 15 s | Power analyzer-current probe system |
| **Lamp arc current 2** | A rms | 15 s | Power analyzer-current probe system |
| **Lamp arc frequency 1** | Hz | 15 s | Power analyzer-current probe system |
| **Lamp arc frequency 2** | Hz | 15 s | Power analyzer-current probe system |
| **Lamp arc power 1** | W | 15 s | Power analyzer-current probe system |
| **Lamp arc power 2** | W | 15 s | Power analyzer-current probe system |
| **Lamp arc voltage 1** | V rms | 15 s | Power analyzer-current probe system |
| **Lamp arc voltage 2** | V rms | 15 s | Power analyzer-current probe system |

#### *4.3.2.2 Time*

| Measurement | Units | Logging Period | Instrument |
|---|---|---|---|
| **Time** | h:min:s | 15 s | Power analyzer-current probe system |

# 5 Phase II - Long-Term Evaluation Tests

Laboratory testing to assess the degradation of photometric and thermal performance of selected representative T8 LED lamps will be performed using the criteria listed below:

1. Lamp selection to be determined upon results generated from Phase I testing.
2. Relative Light performance to be taken in Dark Room once per week for a period of time to be determined.
3. Conduct tests in TTC's Dark Room Laboratory, or RCRL laboratory depending on available resources and test details to be confirmed upon completion of Phase I.
4. Measure the initial lumens of DUT in the integrating sphere and measure subsequent lumen output of DUT once per month.
5. Using an IR Thermal Imager, monitor the lamps and driver units temperature once per week while the lamp is stable thermally.

6. The duration of the tests will be determined in agreement with Project Manager and depending on collected test data and observations made during testing.
7. DUT Photometric and Electrical measurements will be taken as described below in Section 5.1.1.

### 5.1.1 LED Lamp Electrical and Photometric Performance

DUTs are tested per IES LM-79-08, IES Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products, to measure electrical and photometric performance. Additional measurement points and details to be determined based on information gained during Phase I of testing.

### 5.1.2 Standards, Methods and Exceptions

| Standard | Method | Exceptions |
|---|---|---|
| **IES LM-79-08** | Section 9.1, Integrating Sphere with a Spectroradiometer (Sphere-Spectroradiometer System) | 1. Air temperature may not be regulated per section 2.2.<br>2. DUTs are tested in a fluorescent strip luminaire.<br>3. Individual DUTs will be tested on single–lamp ballasts.<br>4. DUTs are tested with instant start ballasts. |

#### *5.1.2.1 IES LM-79-08, IES Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products*

This standard is available from IES or the TTC Lead.

### 5.1.3 Test Combinations

DUTs are tested with the following lamp-ballast combinations where applicable depending on compatibility of DUT under evaluation:

#### *5.1.3.1 Bare Lamp Tests*

1. One DUT [replacement (EB) LED lamp] with a single-lamp fluorescent ballast (non-dimming)
2. One DUT with integral driver

### 5.1.4 Measurements and Exceptions

#### *5.1.4.1 Electrical*

| Measurement | Units | Logging Period | Instrument |
|---|---|---|---|
| **Current** | A rms | 15 s | Power analyzer system |
| **Current THD** | %f | " | " |
| **Frequency** | Hz | " | " |
| **Phase angle** | ° | " | " |
| **Power** | W | " | " |
| **Power factor** | PF | " | " |
| **Voltage** | V rms | " | " |

| | | | |
|---|---|---|---|
| **Voltage THD** | %f | " | " |

### *5.1.4.2 Photometric*

| Measurement | Units | Logging Period | Instrument |
|---|---|---|---|
| **Radiant flux** | mW | On-demand | Sphere-spectroradiometer system |
| **Luminous flux** | lm | " | " |
| **Correlated color temperature** | K | " | " |
| **Color rendering index average** | Ra | " | " |
| **Chromaticity** | x | " | " |
| **Chromaticity** | y | " | " |
| **Distance from Plankian Locus** | None | " | " |
| **Color rendering index 9** | R9 | " | " |
| **Chromaticity** | u | " | " |
| **Chromaticity** | v | " | " |

### *5.1.4.3 Thermal*

| Measurement | Units | Logging Period | Instrument |
|---|---|---|---|
| **Sphere inside temperature** | °F | 15 s | Data acquisition-thermocouple system |
| **Sphere outside temperature** | °F | " | " |
| **Lamp back side surface temperature** | °F | " | " |
| **Luminaire surface temperatures**[12] | °F | " | " |

### *5.1.4.4 Time*

| Measurement | Units | Logging Period | Instrument |
|---|---|---|---|
| **Time** | h:min:s | 15 s | Data acquisition-thermocouple system, power analyzer-current probe system |
| **Time** | h:min:s | On-demand | Sphere-spectroradiometer system |

[12] This temperature measurement applies only in cases when the DUT is tested inside a luminaire.

# INSTRUMENTATION

**TABLE 25~~10~~. INSTRUMENTATION FOR IES-LM79-08 TESTS**

| Sensor Type | Make / Model | Description | Serial | Accuracy | Calibration Date | Corresponding Key Monitoring Points |
|---|---|---|---|---|---|---|
| **Photometric** | Labsphere/ LMS-760 | 2-meter Integrating Sphere | 9200625366 | | N/A | |
| **Photometric** | Labsphere/ CDS-1100 | Spectro-radiometer | 514102089 | ± 5% | Calibrated Internally | Luminous Intensity, and color photometric data, such as CRI and CCT |
| **Power** | Yokogawa/ WT1800 | Precision Power Analyzer | 91M622152 | ± 0.1% of reading + 0.05% of range | 4/4/2014 | Input power |
| **Temperature** | National Instrument CDAQ 9172 w/ 9211 Thermocouple Input | Data Logger | 145477F | N/A | N/A | Temperature Logging |
| **Temperature** | Type-T Thermocouples | | | ± 3.0 °F | Calibrated Internally | Ambient Temperatures, inside dark room test enclosure |
| **Supply Power** | Elgar/ CW1251P | AC Power Source | 1123A01965 | ± 0.1% of full scale at > 5 VRMS output | 10/29/2014 | N/A |

**TABLE 26~~11~~. INSTRUMENTATION FOR DOE BLE TESTS**

| Sensor Type | Make / Model | Description | Serial | Accuracy | Calibration Date | Corresponding Key Monitoring Points |
|---|---|---|---|---|---|---|
| **Photometric** | LICOR/ LI-1400 | Light meter | DLA-1233 | | N/A | Lamp relative output Illuminance (lux) |
| **Photometric** | LICOR/ PH210SA | Photometric Sensor | PH10273 | ± 5% | 6/4/2014 | |
| | | | PH10275 | ± 5% | 6/4/2014 | |
| | | | PH10274 | ± 5% | 6/4/2014 | |
| **Power** | Yokogawa/ WT1800 | Precision Power Analyzer | 91L835176 | ± 0.1% of reading + 0.05% of range | 4/8/2014 (again 4/22/2015) | |
| **Power** | Fluke i50S | CT | 20661421 | ±0.5% | 10/20/2014 | Lamp Input Current |
| | | | 20661436 | | 10/20/2014 | Lamp Input Current |
| **Supply Power** | Elgar CW1251P | AC Power Source | 1042A00776 | ± 0.1% of full scale at > 5 VRMS output | 11/17/2014 | N/A |

**TABLE 27~~13~~. INSTRUMENTATION FOR EXTENDED TEST**

| SENSOR TYPE | MAKE / MODEL | DESCRIPTION | SERIAL | ACCURACY | CALIBRATION DATE | CORRESPONDING KEY MONITORING POINTS |
|---|---|---|---|---|---|---|
| **Photometric** | National Instrument CDAQ 9172 w/ (3) 9219 4 Channel Universal Analog Input | | | ±0.18% of Reading | N/A | Lamp relative output Illuminance (lux) |
| **Photometric** | LICOR/ PH210SA | Photometric Sensor | PH7589 | ± 5% | 11/13/2014 | |
| | | | PH7590 | ± 5% | 11/13/2014 | |
| | | | PH7591 | ± 5% | 11/13/2014 | |
| | | | PH7592 | ± 5% | 11/13/2014 | |
| | | | PH7596 | ± 5% | 11/13/2014 | |
| | | | PH7597 | ± 5% | 11/13/2014 | |
| | | | PH7599 | ± 5% | 11/13/2014 | |
| | | | PH7600 | ± 5% | 11/13/2014 | |
| | | | PH8167 | ± 5% | 11/13/2014 | |
| | | | PH8168 | ± 5% | 11/13/2014 | |
| **Power** | Fluke/ i50S | CT | 20661432 | | 8/23/2015 | Lamp Input Current |
| | | CT | 20661439 | | 8/23/2015 | Lamp Input Current |
| **Power** | Yokogawa/ WT1800 | Precision Power Analyzer | 91L700522 | ± 0.1% of reading + 0.05% of range | 4/22/2015 | |
| **Temperature** | Fluke/TIR3 | Infrared Thermal Camera | 0811054 | ± 3.6 °F or ±2% full scale | 11/26/2014 | Ballast and Lamp surface temperatures |
| **Temperature** | HOBO/ UX120-014M | Temperature Logger | 10747210 | ± 2.88 °F | Calibrated Internally | Ambient Temperatures, inside RCRL |
| **Temperature** | HOBO/ UX120-014M | Temperature Logger | 10731960 | ± 2.88 °F | Calibrated Internally | Fixture Temperatures, Ballast, Lamp and fixture inside enclosure |
| **Temperature** | HOBO/ UX120-014M | Temperature Logger | 10731961 | ± 2.88 °F | Calibrated Internally | Fixture Temperatures, Ballast, Lamp and fixture inside enclosure |
| **Temperature** | HOBO/ UX120-014M | Temperature Logger | 10731962 | ± 2.88 °F | Calibrated Internally | Fixture Temperatures, Ballast, Lamp and fixture inside enclosure |
| **Temperature** | HOBO/ UX120-014M | Temperature Logger | 10731963 | ± 2.88 °F | Calibrated Internally | Fixture Temperatures, Ballast, Lamp and fixture inside enclosure |
| **Temperature** | HOBO/ UX120-014M | Temperature Logger | 10747209 | ± 2.88 °F | Calibrated Internally | Fixture Temperatures, Ballast, Lamp and fixture inside enclosure |
| **Supply Power** | Elgar/CW1251P - V | AC Power Source | 1450A00819 | ± 0.1% of full scale at | 4/10/2015 | N/A |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | > 5 VRMS output | | |
| **Supply Power** | Elgar/CW1251P - V | AC Power Source | 1450A00820 | ± 0.1% of full scale at > 5 VRMS output | 4/10/2015 | N/A |

# REFERENCES


## TECHNOLOGY REPORTS

1. U.S. Department of Energy, CALiPER Exploratory Study: Recessed Troffer Lighting, March 2013, Rev. June 2013
2. U.S. Department of Energy, CALiPER Application Summary Report 21: Linear (T8) LED Lamps, March 2014

## TEST GUIDELINES

1. Illuminating Engineering Society, IES LM-79-08, Approved Method: Electrical and Photometric Measurement of Solid-State Lighting Products
2. Illuminating Engineering Society, IES LM-9-09, Approved Method: Electrical and Photometric Measurement of Fluorescent Lamps
3. Illuminating Engineering Society, LM-54-99, IESNA Guide to Lamp Seasoning
4. U.S. Department of Energy, Code of Federal Regulations, 10 CFR Part 430, Energy Conservation Program: Test Procedures for Fluorescent Lamp Ballasts

## PRODUCT REQUIREMENTS

1. DEsignLights Consortium, Qualified Products List
2. DesignLights Consortium, Linear Replacement Lamps Policy, V3.0
3. California OSHA, "*INITIAL STATEMENT OF REASONS; TITLE 8: Division 1, Chapter 4, Subchapter 7, Article 7, Section 3308 of the General Industry Safety Orders, Hot Surfaces and Hot Pipes*", 2/18/2010: http://www.dir.ca.gov/oshsb/hot_surfaces_isor.pdf

## REGULATORY REQUIREMENTS

1. California Code of Regulations, Title 20: 2015 Appliance Efficiency Regulations, July 2015