Recessed LED Luminaire

ET10SCE1190 Report

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Southern California Edison's Design & Engineering Services (DES) group is responsible for this project. It was developed as part of Southern California Edison's Emerging Technologies Program under internal project number ET10SCE1190. DES project manager Yun Han conducted this technology evaluation with overall guidance and management from Paul Delaney. For more information on this project, contact yun.han@sce.com.

EXECUTIVE SUMMARY

Southern California Edison (SCE) conducted the Recessed Light-Emitting Diode (LED) Luminaire Emerging Technologies (ET) Assessment Project to compare the efficiency of LED technology with that of linear fluorescent (LF) technology.

Nearly five million LF fixtures are currently installed in small and large offices. These fixtures, if replaced with LED fixtures that yield a 25% efficiency gain, can result in 200 Gigawatts (GWh) in energy savings with a mere 10% market penetration in SCE territory.

LED troffers consist of an LED light engine in a traditional recessed LF luminaire form factor. Because LEDs are known for their high efficacy and long useful life, this project assessed the feasibility of replacing LF troffers that have a similar efficacy and life with their LED counterparts.

The specific objective of this project was to compare 2x2 and 2x4 LED lay-in troffers to the incumbent linear fluorescent (LF) technology. The results of this technology assessment are intended to provide sufficient data to the Energy Efficiency (EE) programs for them to determine whether Recessed LED Luminaires should be included in the itemized incentive program.

SCE tested and analyzed current LED technology relative to the LF technology in terms of lumen output, energy savings, and cost. Due to a high volume of inquiries into LED T-8 tube replacements, two LED T-8 tubes were also tested.

12 LF troffers were tested in various combinations of lamps and fixture types. Fixture types included prismatic lens, basket, non-planar, and parabolic, which are the typical fixtures used in the industry. SCE tested all the fixtures on hand at the SCE Lighting Technology Test Center (LTTC) in Irwindale, CA, using the integrating sphere and the mock-up office space. The in-house testing gave good insight into how the troffers would perform in a real-world environment. LED data not specifically tested in the lab were extracted from the Design Light Consortium's (DLC's) qualified list and from manufacturer's lab data, thereby allowing the test design to include a robust set of comparison permutations using a larger sample size.

Photometric and power data plotted on a graph showed an overlap in performance between the LF and LED technologies. Considering that there are two to four LF lamps in a fixture, with various types of lamps such as T5, T8, and high-output lamps, performance is wide spread for the incumbent technology.

The efficacy of LEDs studied in this project ranged from 60-115 lm/W, compared to the LFs' 38-84 lm/W. Although bare LF lamps are highly efficacious, some of the light is lost when installed into a fixture. Similar efficacy means similar performance, which may result in lower energy savings. Table ES-1 summarizes the energy savings, demand reduction for the LF, and LED 2x2 technologies.

TABLE ES-1. SUMMARY OF ENERGY SAVINGS AND DEMAND REDUCTION

	ANNUAL ENERGY CONSUMPTION (KWH/YR)	ANNUAL ENERGY SAVINGS (KWH/YR)	PEAK DEMAND (KW)	PEAK DEMAND REDUCTION (KW)
Incumbent Technology: Linear Fluorescent	235.67	132.32	0.07630	0.04284
Emerging Technology: LED 2x2	103.35		0.03346	

In the past, LED T8 tube replacements have failed to meet the performance of LF lamps. With DLC's minimum performance requirements, LED tubes performed approximately the same as two-lamp LF troffers tested in a lensed fixture. How well LED tubes perform in an enclosed fixture over a long period is not known; that is, insufficient information is available about the longevity of tubes with integrated drivers and about the installation of the tubes in various fixtures and configurations.

LEDs cost from $185 to $475 regardless of their sizes, with 2x4 troffers not necessarily costing twice as much as a 2x2 troffers. Typical LF fixtures cost $45 to $130. An LED's life ranges from 35,000-100,000 hours, while a LF's life ranges from 15,000-40,000 hours; therefore, using a 35,000-hour LED instead of a 40,000-hour LF lamp will not pay back unless significant energy savings are realized. When using a low-end, low-cost LED and high-end, high-cost LF, LEDs can save about $120 over a 15-year period operating 10 hours per day in a typical office.

Simple payback for a retrofit application in an office operating 10 hours per day, not factoring in maintenance, is shown in Table ES-2. High payback uses the low cost of the LED, high cost of the LF, and high-energy savings. The median payback is determined using the median of cost and energy savings. Payback is expected to be much faster for a new application, factoring in lower maintenance and longer operating hours. Payback can occur in fewer than three years when operating 8,760 hours per year.

TABLE ES-2 SIMPLE PAYBACK FOR LED OVER LF RECESSED LUMINAIRE

	INCREMENTAL COST	ENERGY SAVED	MONEY SAVED	PAYBACK
	($)	(kWh)	($ @¢15/kwh)	(Years)
Troffer – Median Payback	221.89	68.17	10.23	21.7
Troffer – High Payback	114.39	132.32	19.85	5.8
Tube Payback	56.79	77.42	11.61	4.9

Energy savings with a reasonable payback time are possible when recessed LF luminaires are replaced with LED fixtures that have a higher efficacy. However, in many instances the savings may be minimal, with long paybacks.

Most LEDs are dimmable, which can result in incremental savings. Therefore, additional study should be done, focused on dimming, so that these savings can be claimed and aligned with the system approach in the EE programs. In addition, LED tubes should be tested in other styles of fixtures than those tested, such as in non-planar, basket, and direct/indirect, because the distribution of light may be improved with different fixtures. The possibility of lumen degradation in enclosed fixtures and with integrated drivers in the tubes should also be explored.

LEDs currently cannot cover the range of the LF’s light output. Using the best LED and the worst LF troffer can save 132 Kilowatts (kWh) per year, as shown in

Table ES-1. . Although 56% in energy savings is possible, there can be as little as 2% or even no energy savings with LEDs for similar LF light levels.

LED troffers can save energy and money given the correct baseline. The customers should be aware of their existing equipment and choose the fixtures that suit their needs.

ACRONYMS

CCD	Charge-Coupled Device
CCT	Correlated Color Temperature
CLTC	California Lighting Technology Center
CPUC	California Public Utilities Commission
CRI	Color Rendering Index
DES	Design & Engineering Services
DLC	Design Lights Consortium
ED	Energy Division
EE	Energy Efficiency
ENTPE	École Nationale des Travaux Publics de l'État
ET	Emerging Technologies
fc	Foot-Candle
GWh	Gigawatt (one billion watts) hour
IES	Illuminating Engineering Society
kWh	Kilowatt (1,000 watt) hour
LCC	Lifecycle Cost
LED	Light Emitting Diode

LF	Linear Fluorescent
LTTC	Lighting Technology Test Center
RMS	Root Mean Square
SCE	Southern California Edison
SCE	Southern California Edison
SLMS	Spectral Light Measurement System
SSL	Solid State Lighting
THD	Total Harmonic Distortion
TTC	Technology Test Centers
TTTC	Thermal Technology Test Center
W	Watt

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EQUATIONS

INTRODUCTION

LED technology, also referred to as solid-state lighting (SSL) technology, has existed for over 40 years, and has been used, typically, in small indicator lamp applications, and is available only in a limited range of colors. The technology has undergone rapid advancement in the past few years and recent developments in the technology allow for a greater range of available colors, with the ability to produce white light. This advancement, along with continuing increases in performance, is enabling the technology to be used in new lighting applications.

Consumers have taken note of the advancements in this technology, resulting in increasing demand in numerous market segments, primarily because of the potential for energy savings. Other studies of the technology in various applications yield promising results, but also reveal shortcomings. The purpose of this study is to evaluate the state of LED technology and its current viability for use in 2x2 and 2x4 troffers, or recessed luminaire, applications.

BACKGROUND

LF lamps, known for their high efficiency and long life, have been available because the late 1930s and have been a viable option for many commercial as well as residential customers. LF lamps have been one of the most successful technologies in the lighting industry.

LF lamps are used widely in locations such as retail establishments, offices, and schools. With the phase-out of T12 LF lamps by July 2012, mandated by the Department of Energy, utilities have been interested in potential energy savings from replacing T8 and T5 LF lamps with LEDs. With nearly five million LF fixtures in small and large offices, recessed LED luminaires have the potential for saving more than 200 GWh[i] annually if they achieve 25% energy savings and a 10% market penetration.

Recessed LED luminaires, also known as lay-ins or troffers, are emerging technology products and feature an LED light engine in a traditional recessed luminaire form factor. The LED troffers perform the same as LF systems from the end-user perspective. The LED is designed to provide comparable light to an LF system, but also provides higher efficacy and longer lifetime hours. Higher efficacy means more output at less wattage, resulting in energy savings. Longer lifetime hours help reduce maintenance costs compared to the incumbent technology, which lowers the lifecycle cost (LCC) of the product.

ASSESSMENT OBJECTIVES

The objectives of this project were to:

- Determine potential energy reduction using current state LED technologies versus various LF lamps and fixtures
- Evaluate light distribution characteristics of LED versus LF technology of similar models in a real-world office environment, using a mock-up office
- Evaluate the performance of LED T8 tube replacements relative to LF and LED systems
- Evaluate the cost of LEDs, their LCCs, and their paybacks
- Document findings and make recommendations

PROJECT/PRODUCT EVALUATED

Testing of the LED and LF troffers was conducted in SCE's LTTC. Laboratory testing was required to determine the photometric and power data such as total lumen output and power in watts (W). LTTC provided a mock-up office space with one cubicle layout where each of the fixtures was installed to obtain real-world readings that included foot-candles (fc), luminance, and temperature. The mock-up office space allowed for consistency in readings where the troffers can be tested relative to one another without any disruption to office equipment layouts.

The assessment was performed by the project manager, with help from a professional aide on the integrating sphere testing. The professional aide was qualified to operate the integrating sphere and to test to the Illuminating Engineering Society's (IES) LM-79 test method.

TECHNICAL APPROACH/TEST METHOD

LAB TESTING OF TECHNOLOGY

The laboratory evaluations consisted of two tests: the integrating sphere test and the mock-up office space test. The integrating sphere was used to spot-check the troffers' photometric data against the manufacturer data and to determine whether the data met DLC's minimum requirements to be qualified for the energy efficiency program. The mock-up office space test consisted of three measurements: foot-candle reading, temperature, and luminance.

Testing was conducted at SCE's Technology Test Centers (TTC). See Appendix A – Technology Test Centers for additional information on these facilities.

PHOTOMETRIC TESTING

SCE conducted the photometric testing using an integrating sphere, which is described in the table in Appendix B – Equipment. Figure 1 shows the mounting system in the integrating sphere.

FIGURE 1 TROFFER SETUP IN INTEGRATING SPHERE

MOCK-UP OFFICE SPACE

Data from the mock-up office space was obtained in a one 8x8 cubicle layout in a 14x16 room with a 10 feet ceiling. Figure 2 shows the camera tripod set up for false-color luminance data measurement.

FIGURE 2 MOCK-UP OFFICE SPACE

LAB TEST PLAN

The integrating sphere testing was performed in accordance with the "IES Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting and Linear Fluorescent Lighting Products" (IES LM-79-08, LM-9-09), excluding section "2.2 Air Temperature". LM-79-08 requires ambient air temperatures be maintained at 25 centigrade (77°F), plus or minus 1 centigrade, as measured 1 meter from the product and at the same height as the product. In actual testing, ambient temperature was not maintained at 25 centigrade, but was monitored throughout the test.

Mock-up office space was utilized to take readings with one fixture installed per test. The moveable ceiling allowed quick access to the plenum side of the room for taking infrared pictures that captured thermal images of the troffers. Foot-candle measurements were taken on eight user-defined points that was compared relative to all tested troffers. The office space provided an environment with no disturbances to the layout.

VARIABLES

The variables considered in this project are defined below.

ILLUMINANCE

Illuminance is the measure of the intensity of the incident light on a surface in a given area, provided in lux (lx). For this reporting, the measurements were converted to foot-candles, which is a non-metric unit of illumination. One fc is equal to approximately 10.764 lx.

LIGHT OUTPUT

Light output is the measure of light that a source provides, measured in lumens. Lumen output data was obtained from the integrating sphere test discussed in the Instrumentation Plan section.

CONNECTED LOAD

Power requirements for all test cases are determined by measuring current and voltage. Measurements for both were taken between the driver and power source to understand alternate current power. This information was used to understand demand (kW) savings of the measure cases when compared to the baseline cases.

EFFICACY

An important indication of overall lamp performance is efficacy. This value, in lumens per watt (lm/W), is a measure of light output over power input. A higher efficacy lamp provides more lumens of light output per watt than a lower one. Though LED wattage may be lower than its fluorescent counterpart, it must do so while providing the same amount of light. A lamp with a higher efficacy has the most energy savings potential.

INSTRUMENTATION PLAN

The assessment used several pieces of equipment and each piece is described in the following sections. For additional information and technical specifications, see Appendix B – Equipment.

INTEGRATING SPHERE

The integrating sphere measured the total light output of a light source, which was either a lamp or a complete luminaire. The tested light source was placed in the center of the integrating sphere. At one side of the sphere was a light meter that measured the light output from the light source. A baffle was directly between the source and the light meter to prevent the meter from seeing any direct light from the source. This equipment was used to measure the light output of a light source, the Color Rendering Index (CRI), and Correlated Color Temperature (CCT). The temperature was regulated to approximately 77°F. Measurements were taken every 15 minutes until three consecutive measurements were within 0.5% of each other.

The entire inside of the sphere (including the baffle and mounting for the lamps) was coated with a highly reflective white paint that reflected all wavelengths equally. This allowed for accurate measurements. The calibrated power supply was connected to the lamp wiring on the outside of the sphere. Readings from the optical sensor were processed with the integrated software and were displayed on the monitor.

FIGURE 3 INTEGRATING SPHERE

LIGHT METER

Konica Minolta T-10 Illuminance Meter was used to measure the foot-candles in the mock-up office space with the fixtures installed. This meter is designed to measure the brightness and quality of a light source striking a specific location.

IR CAMERA

Fluke model TiR3 was used to capture a thermal image of the test fixture. The camera combines visible light images and infrared images together to create a single image with greatly enhanced detail. The camera allows visual comparisons of the hot surfaces between the two light sources tested.

PHOTOLUX CAMERA

Nikon Coolpix 5400 camera with an installed fisheye lens was used to measure area, total, and maximum luminance (cd/m^2) values for each fixture tested in the mock-up office space. Images were recorded using the camera’s memory card for later transfer to a computer.

Using specialized luminance software, Photolux 2.0 by the École Nationale des Travaux Publics de l'État (ENTPE), the same images taken at different apertures and shutter speeds were combined and processed, resulting in false-color luminance maps. Area, total, and maximum luminance values were then obtained from these maps. Table 3 shows the aperture and shutter speeds for each photo taken.

TABLE 3 CAMERA EXPOSURE SETTINGS

PHOTO	APERTURE	SHUTTER SPEED
1	2	2.8
2	1	3.1
3	1/2	3.5
4	1/4	4
5	1/8	4.4
6	1/15	5
7	1/30	5.6
8	1/60	6.3
9	1/125	5.6
10	1/250	5
11	1/500	5.6
12	1/1000	6.3
13	1/2000	7.1
14	1/4000	7.9

EVALUATIONS

The laboratory evaluations tested four types of LF troffer fixtures that are commonly used in the market – lensed, parabolic, basket, and non-planar in sizes 2x2 and 2x4. Within each of the LF troffers types, various lamp types were also tested, which included T5, T8, and T8 U-Tube lamps. All LF troffers were tested as a three-lamp system except for the non-planar troffer, which only contained two lamps. LF lamps can be configured to hold as many as four lamps in a fixture, depending on the fixture type. In cases where LF configurations were not used in the lab tests, the data was obtained from independent lab tests posted by the manufacturer. Figure 4 shows the four types of LF troffers.

Parabolic

Non-Planar

Basket

Lensed

FIGURE 4 TROFFER TYPES

LED troffers were not specifically picked for the fixture type. Most of them were chosen from DLC's qualified list. Some troffers that were not on DLC's qualified list were also tested. LED troffers are available in similar styles to LF troffers such as lensed and non-planar. Some troffers are custom designed and provide unique characteristics to the fixture.

Although some LF and LED troffers were tested at 3500K, other troffers were not available in the 3500K range.

PHOTOMETRIC AND POWER DATA (SPHERE TEST)

Table 4 shows a summary of measured values for the 15 LED troffers and 12 LF troffers for all sizes and lamp types tested. Dimmable LED troffers were also tested at 85% and 50% output. Information for these troffers is in Appendix C – Supporting Data.

TABLE 4 INTEGRATING SPHERE TEST RESULTS FOR TROFFERS

LED & LF TROFFERS	LUMINOUS FLUX (LUMENS)	CCT (KELVIN)	CRI	POWER (W)	EFFICACY (LM/W)
Item 1 – LED 2x2	3834	5771	73.9	53.37	71.8
Item 2 – LED 2x2	3032	5260	69.2	51.34	59.1
Item 3 – LED 2x2	3684	4041	87.6	64.92	56.7
Item 4 – LED 2x2	5094	5144	69.6	65.10	78.2
Item 5 – LED 2x2	1780	3481	86.0	30.56	58.2
Item 6 – LED 2x2	3582	3858	80.8	49.59	72.2
Item 7 – LED 2x2	3298	3529	81.2	36.72	89.8
Item 8 – LED 2x2	3204	3429	93.2	33.96	94.3
Item 9 – LED 2x2	3297	3442	87.0	44.72	73.7
Item 10 – LED 2x2	3575	3535	81.4	37.82	94.5
Item 11 – LED 2x2	3410	3578	81.3	36.55	93.3
Item 12 – LED 2x4	6786	3528	81.2	73.05	92.9
Item 13 – LED 2x4	4069	3436	92.4	42.55	95.6
Item 14 – LED 2x4	5074	3502	85.7	63.22	80.3
Item 15 – LED 2x4	4928	3513	81.6	49.55	99.5
Parabolic – (3)T5 – 2x2	2758	3373	82.6	49.45	55.8
Parabolic – (3)T8 – 2x2	2044	3262	83.9	42.84	47.7
Parabolic – (2)T8U – 2x2	3100	3229	86.1	57.81	53.6
Basket – (3)T5 – 2x2	2247	3381	82.5	47.52	47.3
Basket – (3)T8 – 2x2	1646	3190	84.1	42.33	38.9
Non-Planar (2)T5 – 2x2	2244	3379	82.5	36.44	61.6
Non-Planar (2)T8 – 2x2	1541	3203	84.6	26.86	57.4
Lensed (3)T5 – 2x2	2979	3393	82.7	51.16	58.2
Lensed (3)T8 – 2x2	2226	3284	84.0	42.22	52.7
Lensed (3)T8U – 2x2	4550	3346	86.1	74.54	61.0
Lensed (2)T8 – 2x4	3899	3324	84.4	54.79	71.2
Lensed (2)T5 – 2x4	3274	3293	84.4	55.23	59.3

Figure 3 below shows the data for 2x2 troffers. The green dots correspond to LF troffers; blue dots for DLC qualified LED troffers; and orange dots for non-DLC-qualified LED troffers. The measured data shows LF and LED troffers scattered throughout the chart. 3,000 lumens are required out of the fixture to be qualified under DLC. The qualified LEDs exceeded the light output of LF troffers tested with the exception of one LF troffer with three U-Tube T8 lamps.

Light output and efficacy varies by fixture type for LF troffers. The LED efficacy averaged 76.6 lm/W and the LF efficacy averaged 53.4 lm/W. LED with the higher efficacy would ideally save energy over the LF troffers, but due to LEDs outputting higher lumens, the energy savings is potentially reduced from the selection of troffers tested.

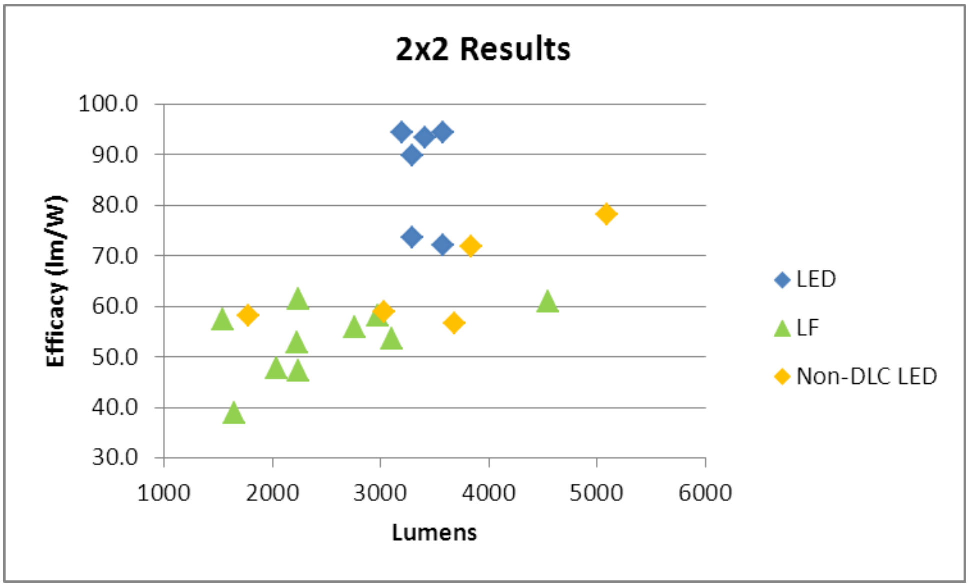


FIGURE 5 2X2 TROFFER RESULTS

A one-to-one comparison is required for LED troffers to be considered for inclusion in SCE's express efficiency incentive program. Comparing LED troffers to a single LF troffer is difficult due to the differences in light output. Given the limited light of a single lamp, a three-lamp fixture was assumed to provide sufficient light to qualify the fixture as a DLC-approved LED troffer. Note that it was not feasible to test every combination of lamps and fixtures; therefore, catalog data was obtained from a reputable LF fixture company to supplement the data collected.

LF troffer testing and catalog data indicates that LF troffers' fixture efficiency ranges from 59%-90% of the bare lamp performance; therefore, the fixture reduced the output dramatically.

Figure 6 shows tested and cataloged data for LED and LF troffers with the vertical red line representing DLC's minimum lumen output. Data includes all LF lamp types and fixture types available. A two-lamp T5 configuration in a basket fixture outputs the least amount of light at 1,639 lumens, while a three-lamp CF40 configuration in a lensed fixture outputs the most light at 8,085 lumens.

From the time LED troffers were purchased, there have been more LED troffers added to the DLC's qualified list. The chart also shows tested data and DLC's qualified fixture data. DLC's qualified fixture data comes from qualified independent test labs. LEDs currently do not output as much light as the best LF troffer. Upon close inspection of the data, it is evident that a LF troffer with 6,205 lumens draws 74W while an LED troffer with 6,180 lumens draws 75W. Therefore, in some cases there may be no energy savings by switching from LFs to LEDs.

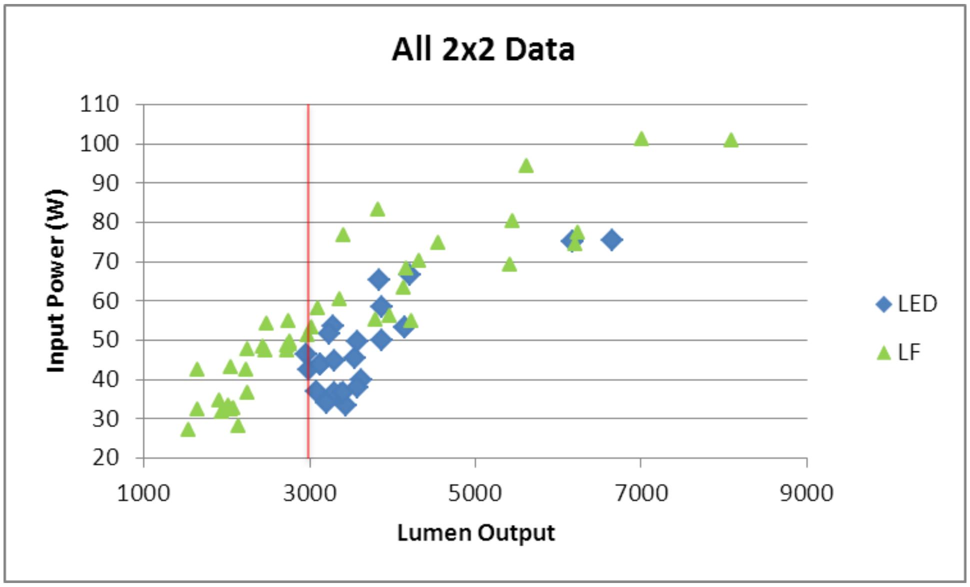


FIGURE 6 ALL 2X2 DATA

Figure 7 shows a subset of the Figure 6 data for LF troffers that perform as well as LEDs with similar output. The subset shows no clear line where the performance of LED troffers overlaps and is superior to the LF troffers for all types. The data shows some energy savings for some LED troffer styles where the lamp and fixture configurations increase efficiency. Twenty-one of 41 LF troffers do not achieve the light output of LED troffers. In cases where the LF does not output enough light, a space can be redesigned with the number of LED fixtures reduced.

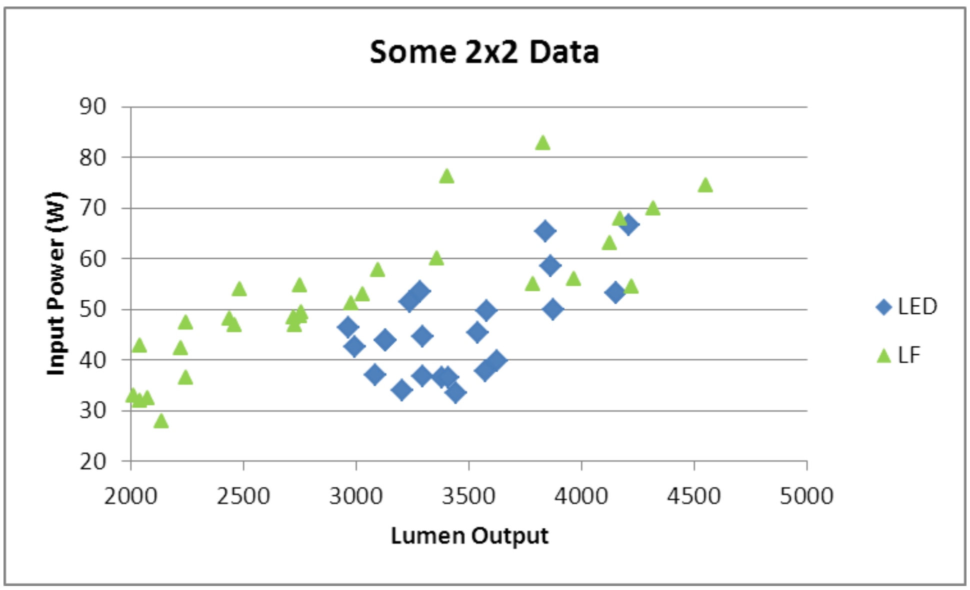


FIGURE 7 SOME 2X2 DATA

Figure 8 shows the range of wattages for both LED and LF troffers, and their performance overlaps. (Data on this chart excludes LF troffers that are under 3,000 lumens because the numbers will be biased.) The chart is not meant to represent a linear comparison where the maximum wattage of the LED would not replace maximum wattage of the LF, given that efficacy varies by product.

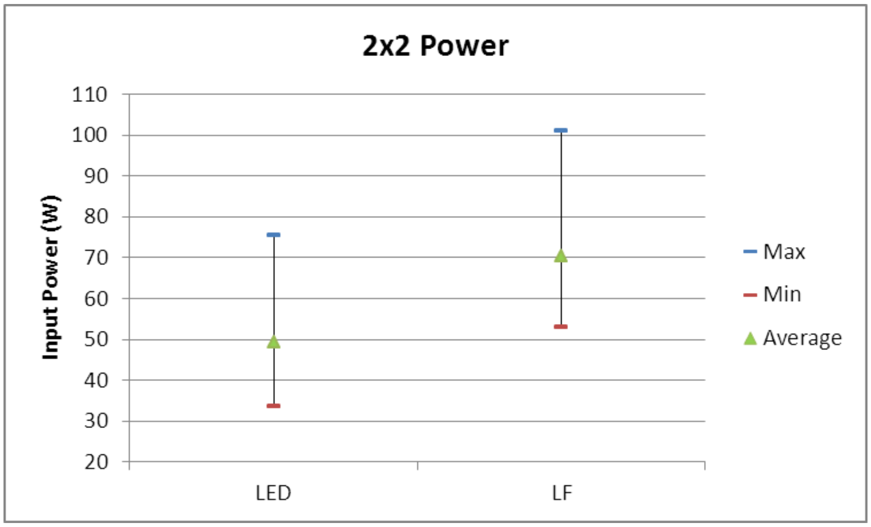


FIGURE 8 POWER DATA

The 2x4 data is similar to the 2x2 data, as shown in Figure 9, where the vertical red line represents DLC's minimum required 4,000-lumen output. LF lumens range from 3,267-13,532, while LED lumens range from 3,992-7,468. This means that LEDs do not output as much light as the best LF troffer. Within the same lumen range, where the technologies' performances overlap, there is no savings potential.

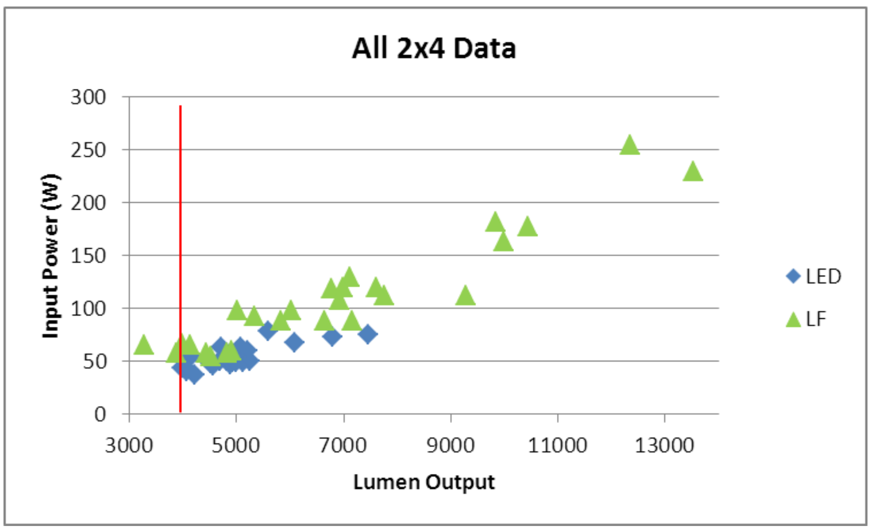


FIGURE 9 ALL 2X4 DATA

Figure 10 shows a subset of the Figure 9 data for LF troffers that perform as well as LEDs, as was shown for the 2x2 troffers. For both 2x2 and 2x4 troffers, comparing the best performing LED to the worst performing LF can show huge energy savings. Conversely, the best performing LF does show minor savings over the worst performing LED.

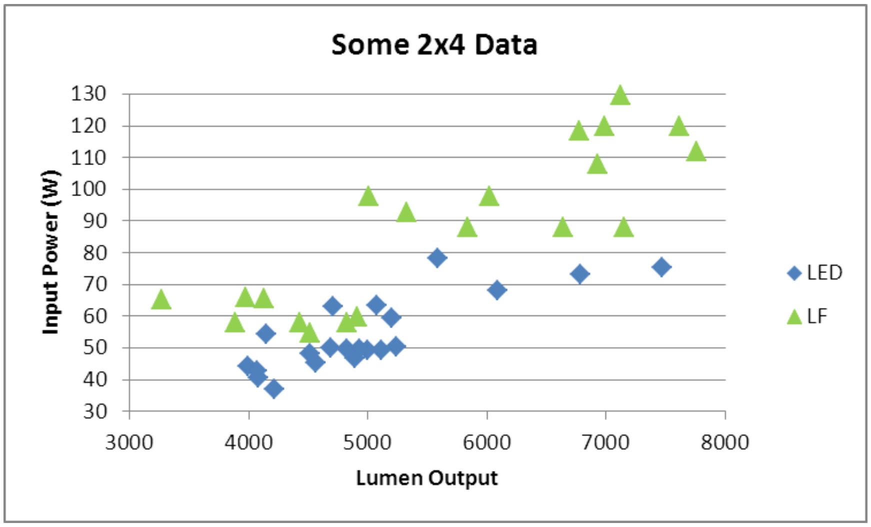


FIGURE 10 SOME 2X4 DATA

The savings for either of these technologies is based on which technologies are more efficient. Efficiency is captured in lumens per Watt, shown in Figure 11. As indicated in earlier figures, much of the LF and LED troffers' data overlap, and the overlaps represent the same light output at the same efficacy, drawing the same wattage.

The highest LF efficacy is 83.5 lm/W, while LED efficacy measures 114.69 lm/W. The LF efficacy can be as low as 39 lm/W, where there can be higher energy savings potential.

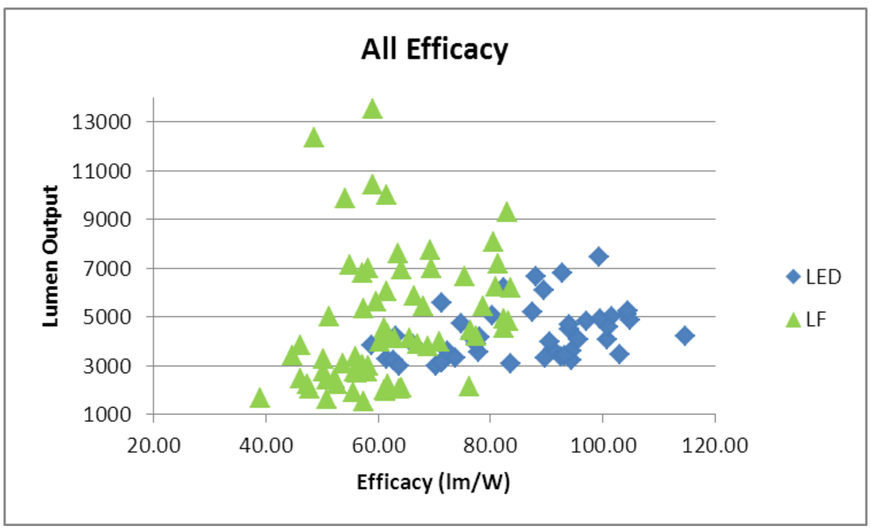


FIGURE 11 EFFICACIES OF 2X2 & 2X4

LED TUBES

DLC also qualifies LED tubes[ii] and requires 3,750 lumens from a two-lamp fixture with an efficacy of 75 lm/W. Bare-lamp minimums are 2,200 lm and 96 lm/W. This requires a fixture efficiency of at least 85%. The efficiency is very close to the 2x4 LF fixture efficiency that ranges from 62-90%.

Two different LED tubes were tested, one lamp that meets DLC specs and one lamp that has a very low light output and draws less energy. Using the same chart as Figure 10, Figure 12 shows the two LED tubes plotted to the existing graph. The tube that meets DLC specifications performs in the same pool as the qualified 2x4 LED troffers, while the non-DLC qualified tube falls short of providing enough light but has a high efficacy. The minimum light output of a LF troffer is 3,267 lumens for a lensed two-lamp F28T5 configuration.

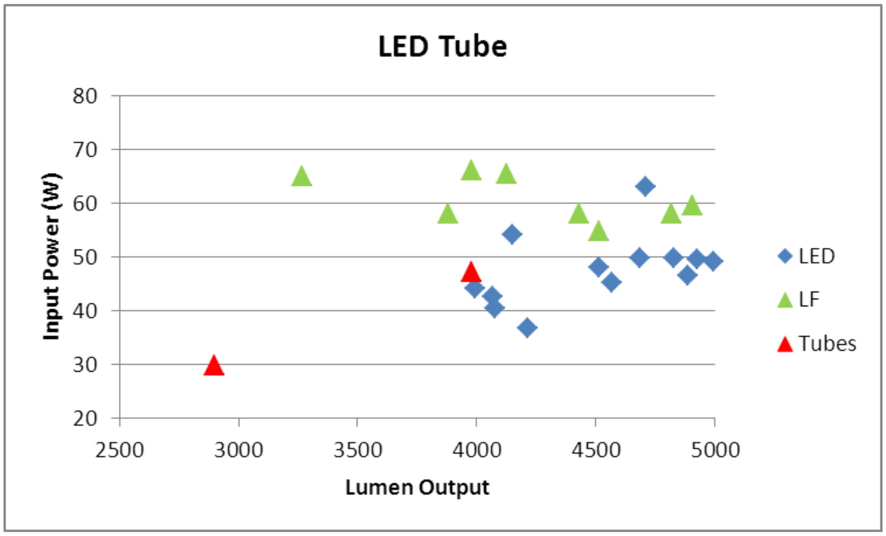
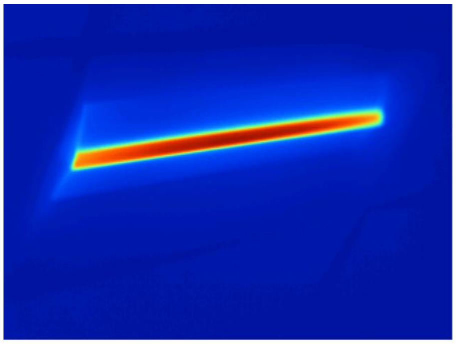


FIGURE 12 LED TUBE

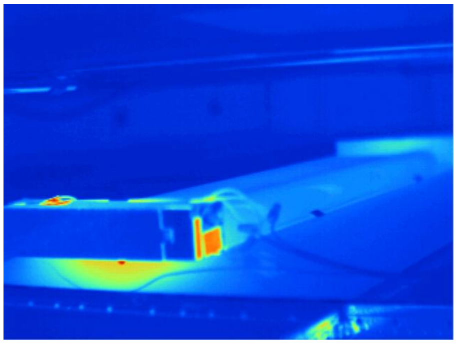
TEMPERATURE

Fixture temperatures varied based on the luminaire wattage and how well the heat sinks performed for LEDs. All the fixtures tested were kept on for one hour before capturing a thermal image with an IR camera. These images were captured to give an idea of where the fixtures warm up, not to quantify energy savings from emitting less heat.

Figure 13 shows an LED 2x4 installed. This particular fixture's heat sink is located outside, exposed to the room. The heat sink does a good job of extracting the heat from the LEDs, measuring 121°F at the heat sink while the surrounding area is approximately 85°F. The plenum side of the fixture also shows heat coming off from the driver.



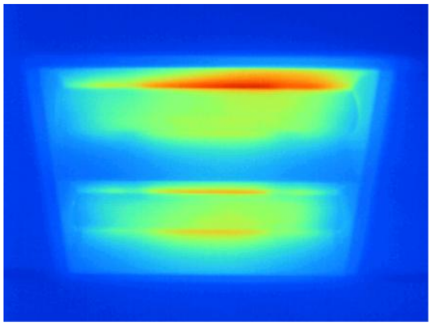
Room Side



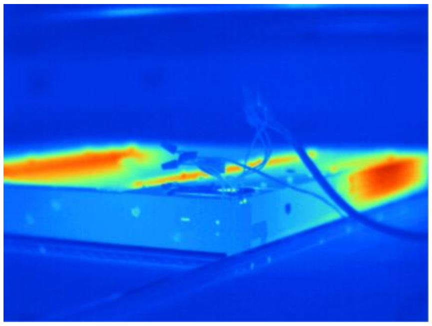
Ceiling Side

FIGURE 13 LED 2x4 – ITEM #13

Some LED troffers do not show obvious heat sinks located around the fixture. Figure 14 shows one of the non-planar style troffers with LEDs attached to the body of the fixture as a heat sink. It is easy to see where the driver of the LED is located and where the LEDs are mounted. Although the driver contributes to the heat, the LED and driver temperature both are close to 85°F.



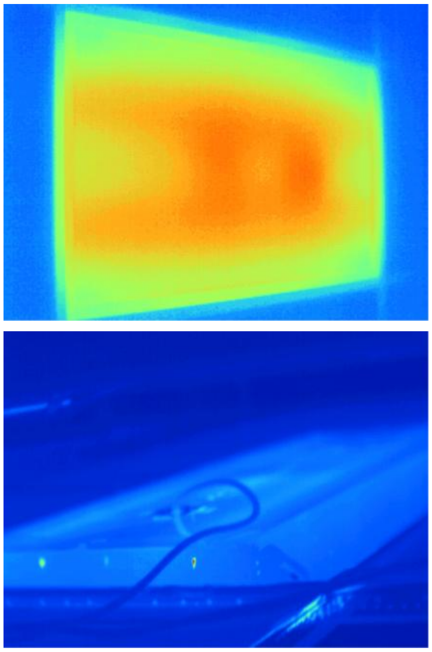
Room Side



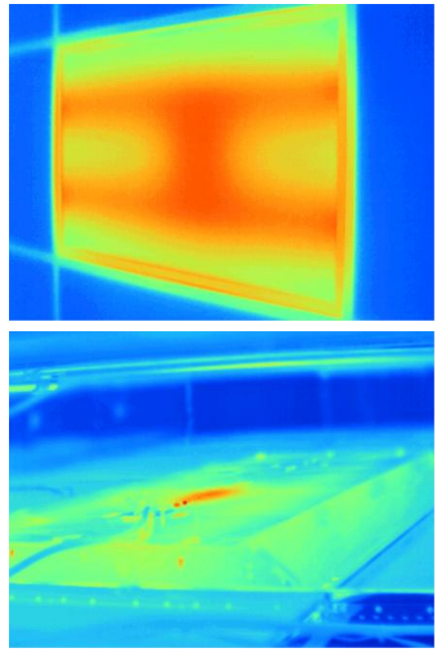
Ceiling Side

FIGURE 14 LED 2x4 – ITEM #15

Figure 15 shows a two-lamp LED Tube and two-lamp LF troffer in a lensed fixture for both the room and ceiling side. These troffers are similar in light output and wattage. A hot spot of 102°F is visible on the LF troffer where the ballast is installed. LED tubes also have a driver for each lamp but the surface temperature only reaches 85°F.



LED Tube

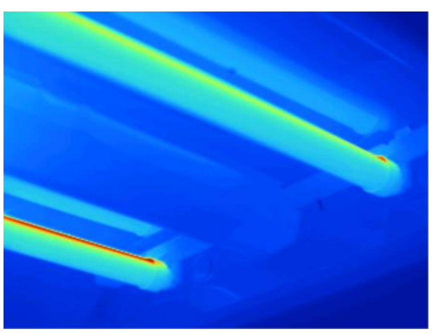


LF #11 - 2xF32T8

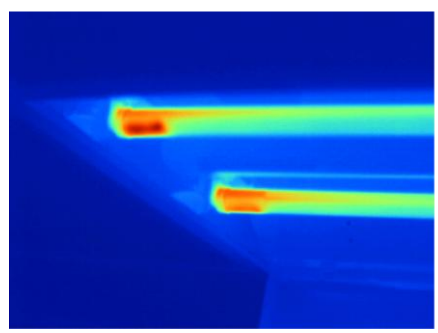
FIGURE 15 TWO-LAMP LED AND LF

The LED tubes installed inside an enclosed fixture can be harmful to the LEDs. Without proper heat sinking and/or ventilation, the heat trapped by the fixture can decrease the life of the LEDs. Figure 16 shows the LED tubes installed with the fixture open, where the tubes' heat sink is located above the tube.

The LED tube not DLC qualified, shown on the right, has an integrated driver with 120V directly going into the two pins on one side while the tube on the left has an exterior driver. The figures show that the heat is building in different locations. The internally driven LED tube has a hot spot on one side, where it is being powered; therefore, one side of the tube may degrade faster.



DLC Spec/External Driver



Non-DLC/Internal Driver

FIGURE 16 BARE LED TUBE

Foot-candle Measurements

Figure 17 shows polar curves of various 2x2 LF troffers. Basket, lensed, and non-planar have circular horizontal distributions (red lines) with similar cosine vertical distributions (blue lines). The parabolic LF troffer has an oval horizontal distribution with a bat-wing vertical distribution. A polar graph is useful in determining where the troffer will output its light. The 2x4 LF troffers have almost identical distributions to the 2x2 LF troffers.

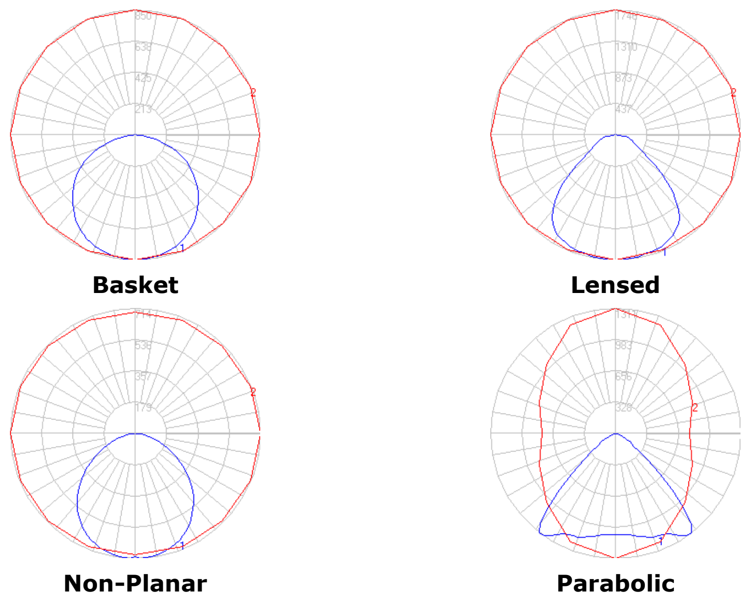


Figure 17 LF 2x2 Polar Curves

Figure 18 shows polar curves of LED troffers, which have a similar distribution to the LF troffers, with varying angles, with the exception of the parabolic LF troffer. LED troffers of the same manufacturer for 2x2 and 2x4 also show identical distributions.

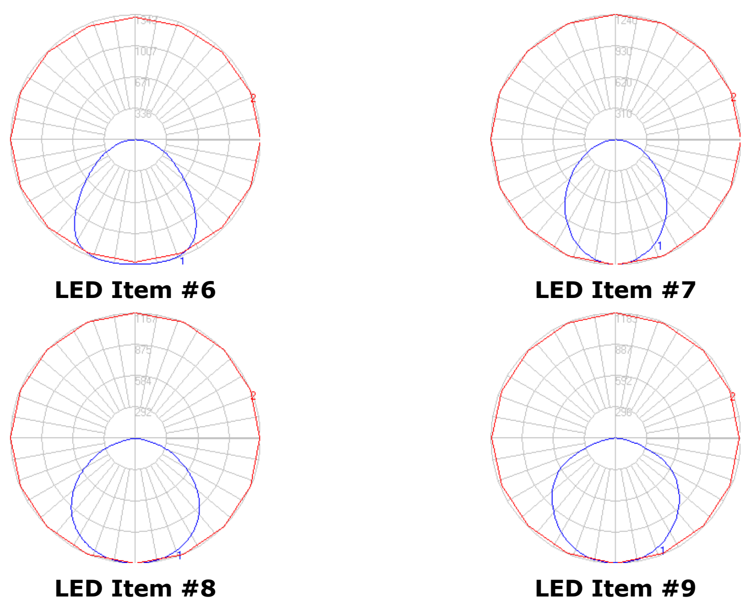


Figure 18 LED 2x2 Polar Curves

Using the 14x16 mock-up office space, eight points around the room were marked with black tape for foot-candle measurement. As shown in Figure 19 and Figure 20, the measuring points included desktop, floor, and walls. The points were used to compare the LF and LED troffers' incident light at the same locations.

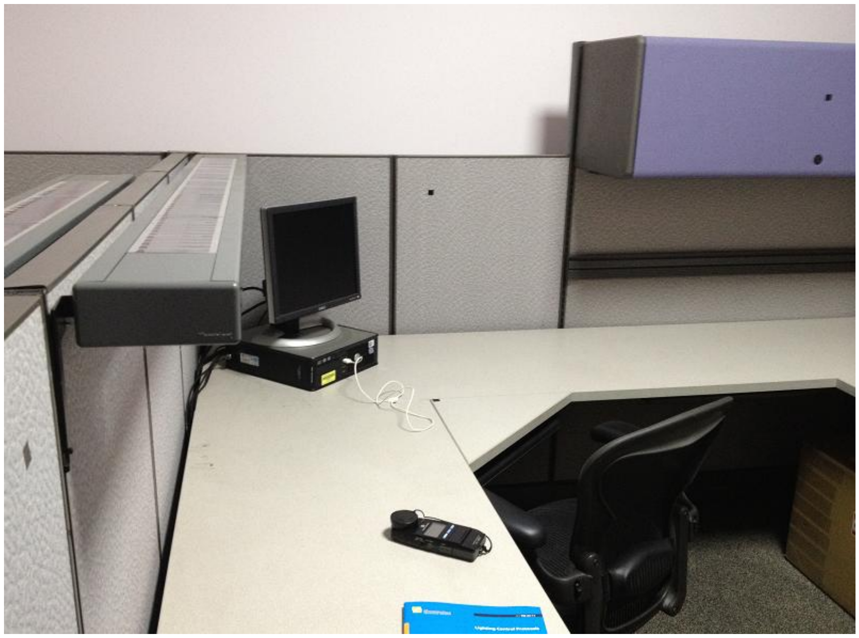


FIGURE 19 FOOT-CANDLE POINTS

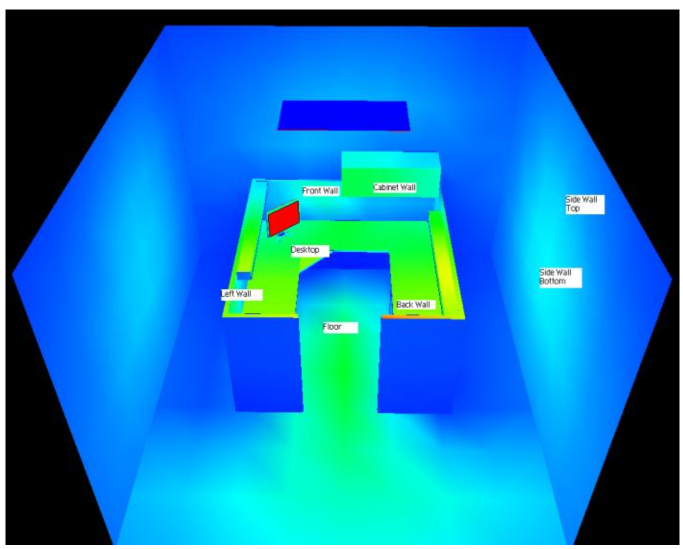
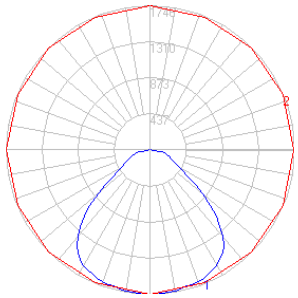
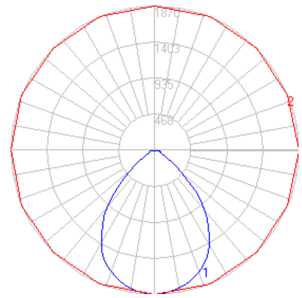


FIGURE 20 FOOT-CANDLE POINTS: GRAPHIC

Figure 21 compares LED Item #11, which is a lensed LED fixture, to an LF Item #8 lensed fixture with three F14T5 lamps that has similar light output. The LF troffer has a wider beam angle than the LED troffer. This means that the LED Item #11 would have a higher light reading immediately below the fixture, but lower light reading on the sides.



LF Item #8



LED Item #11

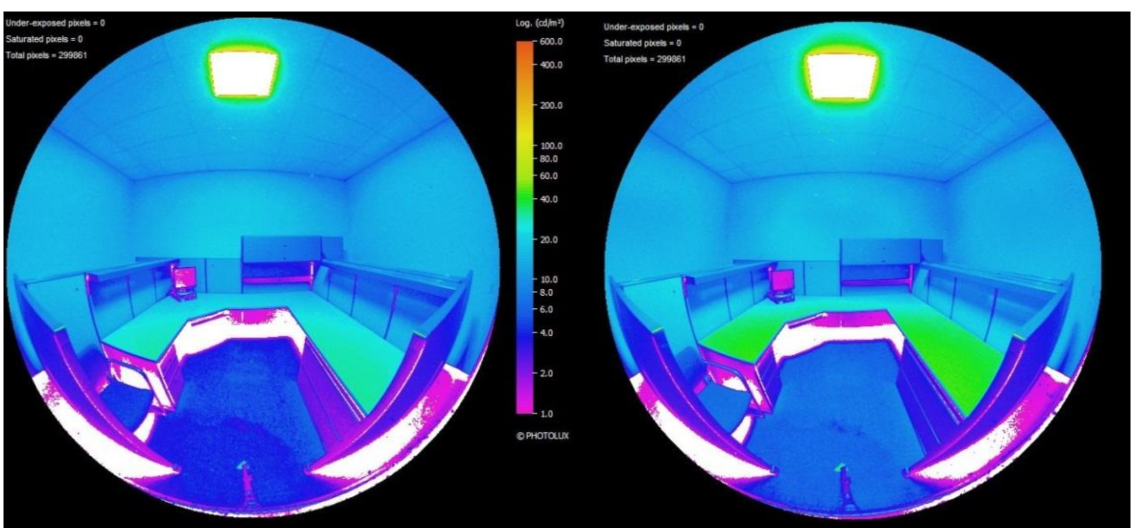
FIGURE 21 LF & LED POLAR CURVE

The readings shown in Table 5 were consistent, given that these fixtures have similar light output. LED Item #11 was dimmed to 85% to be able to compare these fixtures at similar light levels. Due to the light distribution, as seen in Figure 21, the LF has higher readings on the sidewalls, with lower readings below the fixture. A noticeable difference is apparent on the center floor where the LED measured 18 while LF measured 14. The distribution varies slightly for every LED troffer. Complete data is in Appendix C – Supporting Data.

TABLE 5 2x2 FOOT-CANDLE POINTS

ITEM #	LEFT WALL	DESKTOP	FRONT WALL	CABINET WALL	BACK WALL	FLOOR	SIDE WALL TOP	SIDE WALL BOTTOM
LED Item #11 85%	13.66	16.71	8.44	11.08	12.34	18.02	2.97	4.04
LF Item #8	12.15	15.18	9.46	12.14	10.70	14.09	4.41	4.65

Figure 22 is a visual representation of the individual foot-candle measurements taken of LED Item #11 and LF Item #8. Consistent with the foot-candle measurements and the polar curve, more light hits the desk surface below the LED fixture.



LF Item #8 **LED Item #11**

FIGURE 22 2x2 PHOTOLUX PICTURE

Foot-candle points of a lensed two-lamp LF troffer were also compared to two-lamp LED tube troffer inside the same fixture with comparable light output. The LF shown is a two-lamp F32T8 in a lensed fixture. Table 6 shows foot-candle values measured around the office cubicle. The difference between the two troffers is the horizontal distribution.

TABLE 6 2X4 FOOT-CANDLE POINTS

ITEM #	LEFT WALL	DESKTOP	FRONT WALL	CABINET WALL	BACK WALL	FLOOR	SIDE WALL TOP	SIDE WALL BOTTOM
LF Item #11	14.25	18.65	13.18	16.46	13.05	16.58	6.85	7.11
LED Tube	15.61	19.57	12.25	15.85	14.19	19.25	6.42	7.39

The LF lamp distributes further horizontally, as shown in Figure 23, with higher readings in the front and on the cabinet walls. Foot-candle measurements show that lumens to foot-candle readings are fairly linear, meaning that fewer lumens result in fewer foot-candles.

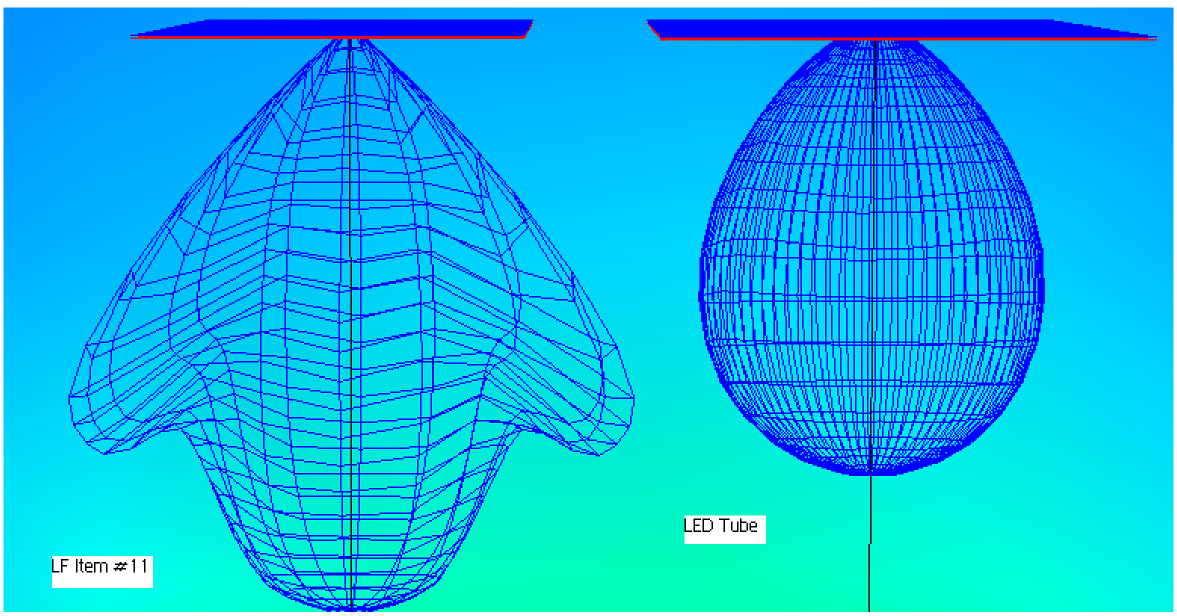
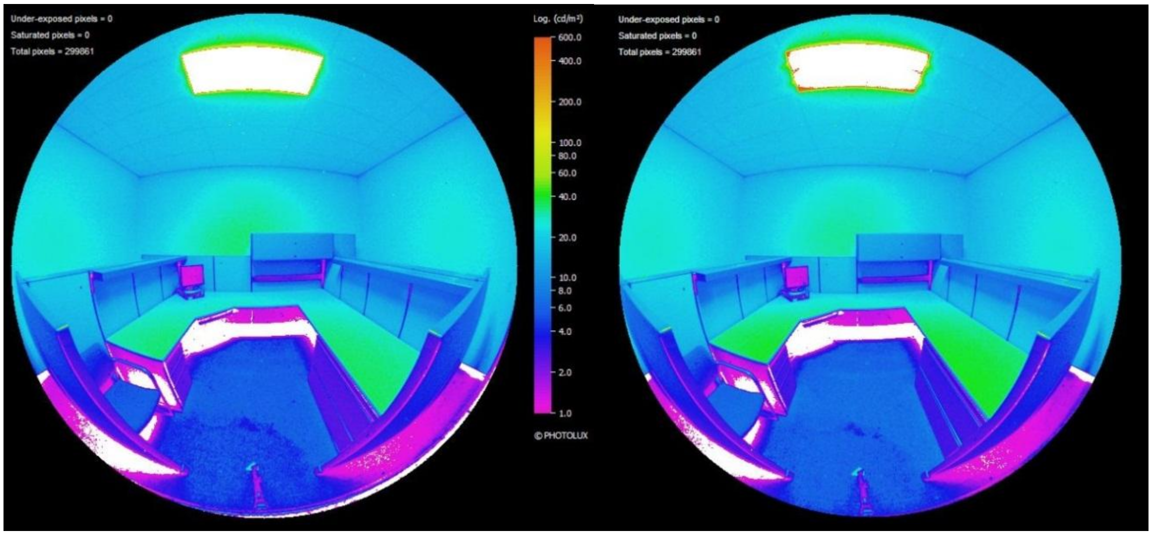


FIGURE 23 2X4 LENSED DISTRIBUTION

Consistent with the fixture's distribution, Figure 24 shows that the LED tube outputs more light directly below the fixture while the LF outputs more light against the front wall. The pictures are of the same scale.



LF Item #1 **LED Tube**

FIGURE 24 2X4 PHOTOLUX PICTURE

LUMINAIRE SPACING

DLC requires LEDs to meet the spacing criteria shown in Table 7. Spacing criteria are used when designing a space to lay out luminaires in a uniform light pattern. Luminaire spacing is calculated by multiplying the spacing criteria by the mounting height from the work plane.

TABLE 7 DLC'S SPACING CRITERIA

	0°-180°	90°-270°
2x2	1.15-1.30	1.2-1.6
2x4	1.15-1.25	1.25-1.7

Using the spacing criteria, a space is designed to have the correct number of fixtures while delivering enough uniform light into a space. In cases where arrays of low output LF troffers are used, the number of fixtures may be reduced while providing the same average foot-candles to the working plane. However, spacing criteria are not a requirement.

ENERGY SAVINGS

As discussed earlier in the Photometric and Power Data (Sphere Test) section, it is difficult to draw a clear line on where LED troffers can save energy because the data is scattered and overlaps. Comparing the best LED to the worst LF, there is a high energy savings potential. Table 8 shows energy savings of a 2x2 LED troffer operating 2,640 hours per year in a Large Office building type in Climate Zone 6. The LF troffer is a three-lamp F24T5HO.

TABLE 8 2x2 HIGH ENERGY SAVINGS

2x2	LUMENS (LM)	WATTS (W)	Δ WATTS	OPERATING HOURS	INTERACTIVE EFFECT	ENERGY SAVINGS (KWH)
LED DLC Item #14	3445.5	33.46	42.84	2640	1.17	**132.32**
LF Catalog Item #25	3406.4	76.3				

Although the highs show of up to 56% in energy savings, there can also be as little as 2% in energy savings. The example in Table 9 shows minimal savings switching to LED from a two-lamp CF40 LF troffer in a Large Office in Climate Zone 6.

TABLE 9 2x2 LOW ENERGY SAVINGS

2x2	LUMENS (LM)	WATTS (W)	Δ WATTS	OPERATING HOURS	INTERACTIVE EFFECT	ENERGY SAVINGS (KWH)
LED DLC Item #16	4210.0	66.6	1.3	2640	1.17	**4.02**
LF Catalog Item #27	4171.5	67.9				

Table 10 shows energy savings of a DLC-specified LED tube. The baseline for the LED tubes is three two-lamp LF fixtures with comparable light output averaged into a single value. The comparable LF fixtures are in the low 4,000-lumen range and the tubes show about 40% in energy savings.

TABLE 10 LED TUBE ENERGY SAVINGS

2x2	WATTS (W)	Δ WATTS	OPERATING HOURS	INTERACTIVE EFFECT	ENERGY SAVINGS (KWH)
LED Tube x 2	38.1	15.97	2640	1.17	**77.43**
LF	63.17				

The energy savings show the same data scattering, with some trending. Many types of 2x2 LED troffers cannot replace lower lumen LF troffers and many 2x4 LED troffers cannot replace higher lumen LF troffers.

Figure 25 and Figure 26 show the 2x2 and 2x4 data, separated into two groups in a lumen range and averaging them to produce more usable data. The lumen ranges were chosen based by grouping the data where there was a clear cut-off.

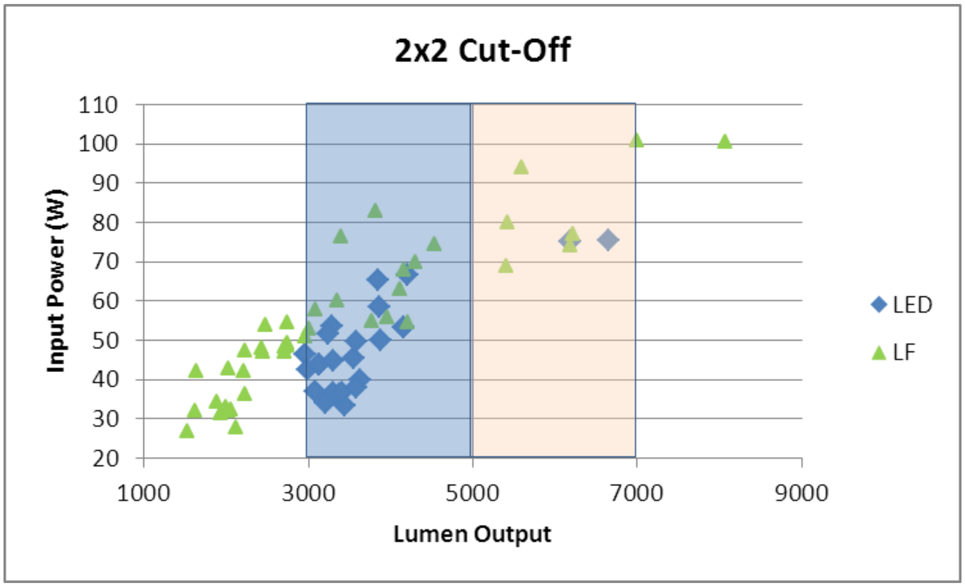


FIGURE 25 2x2 CUT-OFF

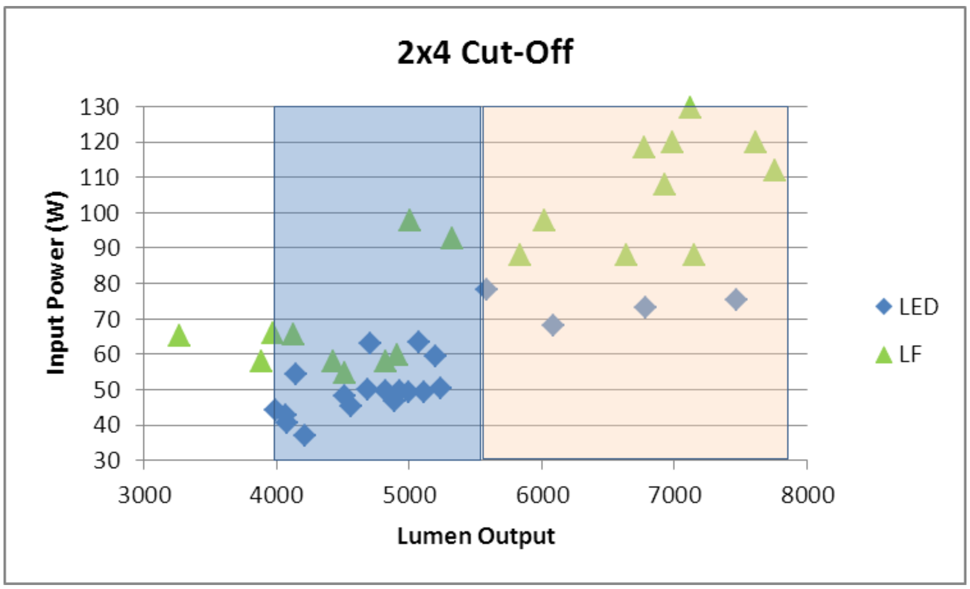


FIGURE 26 2x4 CUT-OFF

The wattage of the lumen ranges for both LF and LED troffers were averaged to obtain delta watts, shown in Table 11. Minor savings are evident for 2x2 LED troffers between 5,000 and 7,000 lumens. The savings are due to the high efficacy of the 2x2 LF troffers in the high lumen range. Table 11 shows energy savings using the operating hours and interactive effects from Table 8. The savings are expected to increase as technology improvements make the LEDs more efficient.

TABLE 11 LED TROFFER RANGE

MEASURES	LF (W)	LED (W)	Δ (W)	SAVINGS (KWH)
2x2 LED Troffers 3000-5000 Lumens	63.25	46.03	**17.22**	**53.19**
2x2 LED Troffers 5000-7000 Lumens	82.53	75.23	**7.30**	**22.55**
2x4 LED Troffers 4000-5500 Lumens	69.04	49.49	**19.55**	**60.38**
2x4 LED Troffers 5500-8000 Lumens	106.99	73.64	**33.36**	**103.03**

LIFECYCLE COSTS

The actual costs of the LED troffers were difficult to obtain due to mark-ups by the distributors and contractors. A limited number of market costs were obtained and gave a good range of troffer costs, as shown in Table 12. The 2x2 and 2x4 costs are similar, and the 2x4 troffers do not cost twice what the 2x2 troffers cost. Cost is one factor to consider when deciding to switch from LF to LED troffers. The rated lifetimes of these fixtures also play a role in determining whether LEDs are cost effective.

TABLE 12 LED TROFFER COST

MEASURES	LOW ($)	HIGH ($)
2x2 LED	185	400
2x4 LED	235	475

Using the Statewide Lighting Cost Study used in cost analysis for work papers, the ranges of LF costs were determined, as shown in Table 13. The high cost of the lamp is a single lamp cost multiplied by four to obtain the cost of a four-lamp fixture.

TABLE 13 LINEAR FLUORESCENT COST

MEASURES	LOW ($)	HIGH ($)
2x2 LF Lamp	4.21	16.84
2x2 LF Ballast	11.57	17.98
2x2 Labor	20.55	27.40
2x2 Total	**36.33**	**62.22**
2x4 LF Lamp	2.98	11.92
2x4 LF Ballast	11.03	30.08
2x4 Labor	20.55	28.61
2x4 Total	**34.56**	**70.61**

DLC's qualified list of products lists the rated lifetime of every LED troffer, which range between 35,000 and 100,000 hours. The LF lamps' lifetimes are between 15,000 and 40,000 hours, depending on which generation lamp is used. The lowest rated LED LF troffer on DLC's list is 35,000 hours, which is lower than the best LF lifetime. The cost and energy savings calculation is challenging due to varying costs without weighted averages for all available products in the market. Nonetheless, the Lifecycle Cost (LCC) is calculated as shown in Equation 1.

EQUATION 1 LIFECYCLE COST

$$LCC = \text{Capital Cost} + \begin{pmatrix}\text{Present Worth}\\ \text{of Maintenance}\end{pmatrix} + \begin{pmatrix}\text{Present Worth}\\ \text{of Energy}\end{pmatrix} - \begin{pmatrix}\text{Present Worth}\\ \text{of Salvage Value}\end{pmatrix}$$

Where:

Capital Cost = the cost of the equipment and installation

The present worth values for Maintenance, Energy and Salvage Value are calculated using Equation 2, Equation 3, and Equation 4.

EQUATION 2 PRESENT WORTH OF MAINTENANCE

$$\begin{pmatrix}\text{Present Worth}\\ \text{of Maintenance}\end{pmatrix} = \frac{MpY \times 1 - 1 + NDR^{-Y}}{NDR}$$

Where:

MpY = Yearly maintenance costs

NDR = Net Discount Rate: Expected inflation subtracted from a nominal investment rate, (for the calculations a default value of 5% is used).

Y = Number of years of equipment operation

EQUATION 3 PRESENT WORTH OF ENERGY

$$\begin{pmatrix}\text{Present Worth}\\ \text{of Maintenance}\end{pmatrix} = \frac{EpY \times 1 - 1 + NDR^{-Y}}{NDR}$$

Where:

EpY = Yearly energy costs

NDR = Net Discount Rate: Expected inflation subtracted from a nominal investment rate, (for the calculations a default value of 5% is used).

Y = Number of years of equipment operation

EQUATION 4 PRESENT WORTH OF SALVAGE VALUE

$$\begin{pmatrix}\text{Present Worth}\\ \text{of Maintenance}\end{pmatrix} = SV \times 1+NDR^{-Y}$$

Where:

SV = Salvage Value Final Year: Total worth of equipment at its end of life (for the calculations a value of $5 is used for all luminaires).

NDR = Net Discount Rate: Expected inflation subtracted from a nominal investment rate, (for the calculations a default value of 5% is used).

Y = Number of years of equipment operation

Using a 20,000[iii]-hour rated life for LEDs, Large Office operating hours of 2,640, and low energy savings, Table 14 shows the cost of operating the LED for 40,000 hours. The low-end costs of LEDs and LFs were used. The LED with a 20,000-hour life is challenging to pay back compared to the cheaper LF system, even with higher energy savings of 103kWh per fixture.

TABLE 14 LED PANEL W/20,000 HOUR LIFE OPERATING 40,000 HOURS

Linear Fluorescent	LF Cost ($)	LED Cost ($)	Years Last	$ Saved
LF 20,000 Hour	342	628	15	-287
LF 30,000 Hour	326	628	15	-303
LF 40,000 Hour	294	628	15	-334

An LED with up to a 40,000-hour life on a Large Office operating schedule starts to show lower LCCs over a 15-year period, as shown in Table 15. Using the high LF cost, low LED cost, and high energy savings, the LEDs benefit from the long operation compared to the 20,000-hour LF lamp. When compared to a 40,000-hour LF lamp, the LCC is similar.

TABLE 15 LED PANEL W/40,000 HOUR LIFE OPERATING 40,000 HOURS

Linear Fluorescent	LF Cost ($)	LED Cost ($)	Years Last	$ Saved
LF 20,000 Hour	608	487	15	121
LF 30,000 Hour	576	487	15	89
LF 40,000 Hour	511	487	15	24

LED tubes, due to their lower cost compared to the LED troffers, also show lower LCCs. Based on a two-lamp configuration, using $50/lamp with the same labor cost as an LF, Table 16 shows that the LCCs of LED tubes are similar to those of LED troffers. The challenge for LED tubes is when comparing them to three- or four-lamp configurations where the cost is multiplied by the number of lamps installed in each fixture.

TABLE 16 LED TUBE W/50,000 HOUR LIFE OPERATING 50,000 HOURS

LINEAR FLUORESCENT	LF COST ($)	LED COST ($)	YEARS LAST	$ SAVED
LF 20,000 Hour	483	307	18.9	175
LF 30,000 Hour	445	307	18.9	138
LF 40,000 Hour	427	307	18.9	119

LCC costs of other rated LED lifetime and cost of LF fixture factored in is in Appendix D – Lifecycle Costs.

RESULTS/CONCLUSION

The use of LED troffers has great energy savings potential depending on which LF troffer it is replacing. As the results show, there are many types of LF troffer systems available in the market, and they vary in performance. A LF system consists of the type of lamp, number of lamps, and fixture type, all of which determine the fixture efficiency and ultimately the lumens produced by the fixture.

LF troffers covering a wide range of performances produce a wide range of results. LEDs may save a great deal of energy, very little energy, or none at all when compared to LFs based for similar light levels. With sufficient light levels not being an issue, efficacy plays a major role in determining energy savings. Although LED’s 60-115 lm/W shows an overlap with the LFs’ 38-84 lm/W, potential energy savings can be achieved.

In addition, DLC-specified LED tubes have shown improvement over the past few years. Two-lamp performance out of the lensed fixture shows similar results to LED 2x4 fixtures. Currently, not many tubes meet DLC’s minimum requirements and those that do meet the requirements are only comparable to the lowest lumen 2x4 fixtures.

LED troffers are fixtures built for LEDs, and some follow the traditional shapes of LF troffers. While some LED troffers use a unique means of extracting the heat from LEDs, some LED boards are merely mounted to the fixture, and the fixture is used as the heat sink. The LED tube’s heat sink is located on the tube itself and is enclosed inside a fixture. The biggest difference in the tubes is where the driver is located. An integrated driver seems to have a hot spot that may degrade the life of LEDs on one side of the tube.

The light distribution of LED troffers is similar to that of LF troffers. LEDs tend to produce more light directly below the fixture, while LFs have a wider distribution. The slight variance captured is less than 3 foot-candles, which is subjectively low to make a noticeable difference, but DLC-qualified products are within the spacing criteria that allow designers to lay out the fixtures for uniform light.

Accurate energy savings are difficult to determine due to so many different LF and LED troffers varying in performance. As few as 4 kWh/year, and up to 132 kWh/year, can be achieved when selecting troffers assessed in this project. When grouping the fixtures into lumen ranges for an overall assessment, 2x2 troffers show higher savings in the lower lumen range and 2x4 troffers show higher savings in the upper lumen range. The advantage of LEDs is their long life and lower maintenance than LF troffers require.

Looking at LEDs to the extent of their rated lives, LEDs start to show lower LCC when they are rated at or greater than 40,000 hours. Over 15 years, operating 10 hours/day, LEDs can save about $120 compared to a 20,000-hour LF system. Using a low-end cost of LED and high-end cost of LF, a simple payback based only on energy savings and first cost will take more than eight years. The LEDs show more benefit over a longer operating schedule. LED tubes have similar LCC to LED troffers because the low-cost troffer was used in the study. Therefore, for some configurations, replacing LFs with LEDs will reduce cost.

RECOMMENDATIONS

The project's purpose was to determine the feasibility of replacing LF troffers with LEDs and show energy savings. By having market penetration data for LF systems that are installed in the SCE territory, energy savings can be weighted and calculated more accurately. In this report, high and low savings were shown, as was an average from the perspective of lumens.

For customers deciding to switch to LED troffers, SCE recommends that they clearly understand the performance of their existing technology and the performance of the candidate LED technology to ensure that replacement with LEDs will be more energy efficient. It is difficult to determine what light output the existing system is producing, and how much power is being drawn, merely by inspecting the fixture. Choosing the wrong LED fixture replacement can result in increased instead of reduced cost.

Because most LED troffers are dimmable with 0-10V dimming system, it is recommended that more study be conducted on the dimming aspect of lighting in troffers. This will provide incremental savings in additional to any savings already obtained from using LF troffers. Dimming studies will move widgets to a system approach in the energy efficiency program.

LED tubes tested in a lensed 2x4 fixture tested well against a comparable LF troffer. However, tubes were not tested in other style fixtures, such as non-planar, basket, and direct/indirect. The distribution may be affected with LED tubes due to LEDs being mounted in only 180° of the lamps. In addition, tubes with integrated drivers may need to be tested longer with multiple light meters below the tube to detect any degradation where the heat collects on one end and inside an enclosed fixture.

LED troffers can save energy and money given the correct baseline. This technology is an alternative to LF troffers and is recommended for inclusion in SCE's express incentive program.

REFERENCES

[i] http://www.energy.ca.gov/ceus/

[ii] SCE currently does not offer incentives for LED tubes.

[iii] The Energy Division (ED) of California Public Utilities Commission (CPUC) mandated the statewide Investor Owned Utilities (IOUs) to claim a maximum of 20,000 hours, or 12 years, for LEDs.

APPENDIX A – TECHNOLOGY TEST CENTERS

LOCATION

All laboratory tests referenced in this report were conducted at SCE's Technology Test Centers (TTC) in Irwindale, California. The TTC includes the Thermal Technology Test Center (TTTC) and the Lighting Technology Center (LTTC).

TECHNOLOGY TEST CENTERS

The mission of the TTC is to spread awareness of viable integrated demand-side management solutions to a wide range of SCE customers and EE programs. Through impartial laboratory testing and analysis of technologies, the portfolio of EE measure offerings can be expanded with quantified energy savings and alleviation of concerns about performance uncertainties. Testing in a laboratory setting allows for the performance of detailed and replicable tests that are realistic, impartial, and not influenced by unwanted variables while in a controlled environment.

THERMAL TECHNOLOGY TEST CENTER

Controlled environment testing is conducted at SCE's Thermal Technology Test Center (TTTC). This state-of-the-art research and testing facility examines refrigeration, air conditioning, cold storage, and other thermal-based technologies in support of SCE's EE programs, customers, and industry partners. The lab features walk-in controlled-environment chambers with impressive refrigeration and heating capacity, numerous types of test equipment and tools, and the ability to perform in-house calibration of many related instruments.

LIGHTING TECHNOLOGY TEST CENTER

Integrating sphere testing is conducted at SCE's LTTC. In partnership with the California Lighting Technology Center (CLTC) in Davis, California, LTTC's mission is to foster the application of EE lighting and day-lighting technologies in cooperation with the lighting industry, lighting professionals, and the design-engineering community. Unique lighting and day-lighting test equipment, EE lighting displays, and flexible blackout test areas enable the evaluation and demonstration of various lighting technologies and applications.

APPENDIX B – EQUIPMENT

Table 17 shows the key equipment used in the testing of the LED lighting discussed in this report.

TABLE 17 LED FIELD TEST EQUIPMENT

MANUFACTURER	MODEL	CALIBRATION	DESCRIPTION	USED FOR	SPECIFICATIONS
Labsphere	SLMS LED 7650	Monthly	Spectral light measurement system (integrating sphere)	Luminous flux, correlated color temperature, color rendering index	Sphere-spectroradiometer method, 76" diameter, 4pi geometry, 350-850 nm spectroradiometer bandwidth, auxiliary compensation, D65 white point
Hioki	3196	10/26/2011	Power quality analyzer	AC-side electrical logging, voltage, current, power, frequency, power factor, current Total Harmonic Distortion (THD)	Root Mean Square (RMS) voltage +/-0.2% AC, Frequency +/-10mHz, +/- 1 digit from the calculation, more specifications at www.hioki.com
Minolta	T10W	01/30/2012	Photometric Sensor, Handheld data logger	Illuminance (lux)	0.1-200,900 lux 0.001-29,990 fc +/-2%
Nikon	Coolpix 5400	NA	Digital photo camera	False color luminance mapping with Photolux software	5.2MP, 1/1.8" Charge-Coupled Device (CCD), Red, Green, Blue (RBG) color filter array 4x optical zoom, F2.8-4.6
Fluke	TiR3		Thermal imaging camera	Surface temperature	-4°F to 212°F +/- 2°C or 2%

APPENDIX C – SUPPORTING DATA

Table 18 shows the foot-candle measurements, and Table 19 shows the sphere test measurements.

TABLE 18 FOOT-CANDLE MEASUREMENT

ITEM #	LEFT WALL	DESKTOP	FRONT WALL	CABINET WALL	BACK WALL	FLOOR	SIDE WALL TOP	SIDE WALL BOTTOM
LED Item #1	173.4	202.7	131.4	171.7	150.3	208.5	81.6	84.2
LED Item #2	128.8	150.7	106.5	135.3	110.6	142.4	74.7	69.1
LED Item #3	175.3	215.5	133.4	173.5	152.7	211.5	68.1	81.4
LED Item #4	242.2	287.9	180.6	232.2	209.4	282	94.7	107.9
LED Item #5	70.6	83.7	60.3	78.2	62	74.6	38.4	39.3
LED Item #5 85%	58.8	69.2	50.1	64.8	52.2	61.6	32.2	32.8
LED Item #5 50%	33.9	40.2	28.97	37.7	30.6	35.7	18.56	19.04
LED Item #6	157.5	179.6	118.1	152.3	134	168.1	69.9	71.9
LED Item #6 85%	137	155.8	102.2	131.7	116.6	145.8	60.4	62.2
LED Item #6 50%	81.5	94	62	79.6	70.1	87.9	36.6	37.5
LED Item #7	140.6	170	110.6	141.7	125	170.2	67	71
LED Item #7 85%	121.7	146.5	95.4	121.6	106.9	146.5	58.3	61
LED Item #7 50%	76.5	91.8	59.6	76.3	68.1	91.8	36.6	38.3
LED Item #8	127.3	158.7	110.9	142	112.1	142.6	57.4	67.2
LED Item #8 85%	107.4	134.7	94.4	119.1	94.8	120.8	49.2	57.3
LED Item #8 50%	62.6	78.8	55.2	69.2	54.5	70.8	28.8	33.6
LED Item #9	122.6	158.2	115.1	143.5	112.8	146.1	65.9	65.2
LED Item #9 85%	104.5	135.4	98.7	123.3	97.3	125.7	56.8	56.1
LED Item #9 50%	62.9	81.1	59.1	73.8	57.8	75.1	33.9	33.5
LED Item #10	133.7	187.4	127.9	163.5	135.1	182.2	61.6	63.1
LED Item #10 85%	113	157.2	108.2	137	114.4	153.4	52	53.1
LED Item #10 50%	67.2	94.3	64.5	81.8	67.4	91.7	31	31.8
LED Item #11	174.9	214.4	108	143.2	158.1	231.4	38.3	52.2

Item #	Left Wall	Desktop	Front Wall	Cabinet Wall	Back Wall	Floor	Side Wall Top	Side Wall Bottom
LED Item #11 85%	147	179.9	90.8	119.3	132.8	194	32	43.5
LED Item #11 50%	87.3	106.8	54.5	71.5	79.4	115.8	19.07	25.86
LED Item #12	283.6	337	216	283	252.7	341	150.1	153.4
LED Item #12 85%	245.1	291.2	186.5	241.8	217.9	294	130.6	132.6
LED Item #12 50%	154.2	180.9	116.8	152.2	135.6	183.4	81	82.2
LED Item #13	152.1	192.7	133.9	172.8	136.5	173.8	83.2	87
LED Item #13 85%	129.4	164.1	114.1	146.7	114.3	147.1	70.9	73.9
LED Item #13 50%	75.6	95.8	66.1	85.7	67.5	86.1	41.6	43.3
LED Item #14	188.5	242.3	170.2	215.8	173.2	225	106.6	104.1
LED Item #14 85%	159.6	203.1	143.6	182.5	147.1	190.8	90.8	88.3
LED Item #14 50%	89.1	115.5	80.9	102.9	82.8	107.1	50.9	49.6
LED Item #15	181.6	245.8	167.6	214.7	178.8	240.1	89.2	87.9
LED Item #15 85%	152.3	209.7	142.5	181	150.8	203.3	75.8	75.1
LED Item #15 50%	87.9	120.3	82	104.3	87.3	116.9	44	43.3
LF #1 - 3x F14T5	114.7	155	113.4	145.5	106	131.8	31	57.8
LF #2 - 3x F17T8	86.8	120.9	75.1	100.3	82	101.2	23.19	44.1
LF #3 - 2xF32T8U	128.3	175.6	112.9	149.5	124.1	154	35	69.2
LF #4 - 3x F14T5	92.2	113.8	80.6	102.8	80.9	104.7	43.7	49
LF #5 - 3x F17T8	64.1	81.7	57.4	72.2	56.5	74.2	30.7	33.6
LF #6 - 2x F14T5	82	106.5	77.3	97.3	75.4	96.4	37.5	41.4
LF #7 - 2x F17T8	58.1	75.6	56	70.4	52.3	66.4	28	30
LF #8 - 3x F14T5	130.8	163.4	101.8	130.7	115.2	151.7	47.5	50.1
LF #9 - 3x F17T8	99.1	127	76.6	101	89.3	117	35.2	39.1
LF #10 - 2xF32T8U	202.2	261.2	159.4	206.7	185.7	245.1	74.5	80.9
LF #11 - 2x F32T8	153.4	200.7	141.9	177.2	140.5	178.5	73.7	76.5

Item #	Left Wall	Desktop	Front Wall	Cabinet Wall	Back Wall	Floor	Side Wall Top	Side Wall Bottom
LF #12 - 2x F32T8	131.2	156	121.3	152.2	115	155.5	44.6	71.9

Table 19 Sphere Test Measurements

LED & LF Troffers	Luminous Flux (Lumens)	CCT (Kelvin)	CRI	Power (W)	Efficacy (Lm/W)
LED Item #1	3834	5771	73.89	53.37	71.83811
LED Item #2	3032	5260	69.16	51.34	59.05727
LED Item #3	3684	4041	87.61	64.92	56.74677
LED Item #4	5094	5144	69.63	65.1	78.24885
LED Item #5	1780	3481	85.97	30.56	58.24607
LED Item #5 85%	1479	3485	85.89	26	56.88462
LED Item #5 50%	859.5	3493	85.85	15.28	56.25
LED Item #6	3582	3858	80.83	49.59	72.2323
LED Item #6 85%	3103	3856	80.86	42.07	73.75802
LED Item #6 50%	1887	3836	80.81	24.57	76.80098
LED Item #7	3298	3529	81.18	36.72	89.81481
LED Item #7 85%	2879	3529	81.22	31.09	92.60212
LED Item #7 50%	1802	3522	81.28	18.41	97.88159
LED Item #8	3204	3429	93.2	33.96	94.34629
LED Item # 8 85%	2705	3424	92.83	28.32	95.51554
LED Item #8 50%	1635	3438	91.56	17.04	95.9507
LED Item #9	3297	3442	86.97	44.72	73.7254
LED Item #9 85%	2874	3441	86.84	38.03	75.57192
LED Item #9 50%	1725	3438	86.58	22.32	77.28495
LED Item #10	3575	3535	81.42	37.82	94.52671
LED Item #10 85%	3022	3535	81.42	31.99	94.46702
LED Item #10 50%	1807	3531	81.43	18.86	95.81124
LED Item #11	3410	3578	81.3	36.55	93.29685
LED Item #11 85%	2887	3578	81.29	30.94	93.30963
LED Item #11 50%	1701	3574	81.29	18.08	94.08186
LED Item #12	6786	3528	81.22	73.05	92.89528
LED Item #12 85%	5955	3527	81.26	62.03	96.00193
LED Item #12 50%	3724	3520	81.31	36.56	101.86
LED Item #13	4069	3436	92.37278	42.55	95.62867
LED Item #13 85%	3462	3433	92.1542	35.92	96.38085
LED Item #13 50%	2048	3421	91.54467	21.18	96.695
LED Item #14	5074	3502	85.6988	63.22	80.25941

LED & LF Troffers	Luminous Flux (Lumens)	CCT (Kelvin)	CRI	Power (W)	Efficacy (Lm/W)
LED Item #14 85%	4336	3502	85.60804	53.56	80.95594
LED Item #14 50%	2474	3501	85.4576	31.61	78.26637
LED Item #15	4928	3513	81.63593	49.55	99.4551
LED Item #15 85%	4194	3514	81.63541	41.99	99.88092
LED Item #15 50%	2490	3511	81.63696	24.63	101.0962
LF #1 - 3x F14T5	2758	3373	82.6325	49.45	55.77351
LF #2 - 3x F17T8	2044	3262	83.89854	42.84	47.71242
LF #3 - 2xF32T8U	3100	3229	86.0976	57.81	53.62394
LF #4 - 3x F14T5	2247	3381	82.5165	47.52	47.28535
LF #5 - 3x F17T8	1646	3190	84.08088	42.33	38.88495
LF #6 - 2x F14T5	2244	3379	82.54	36.44	61.58068
LF #7 - 2x F17T8	1541	3203	84.58201	26.86	57.37156
LF #8 - 3x F14T5	2979	3393	82.67	51.16	58.22909
LF #9 - 3x F17T8	2226	3284	84.02	42.22	52.72383
LF #10 - 2xF32T8U	4550	3346	86.13573	74.54	61.04105
LF #11 - 2x F32T8	3899	3324	84.39	54.79	71.16262
LF #12 - 2x F32T8	3274	3293	84.43	55.23	59.27938

APPENDIX D – LIFECYCLE COSTS

Table 20 and Table 21 show the operating hours and LCCs for LED and LF systems with fixture cost not factored in (retrofit) and factored in (new construction), respectively.

TABLE 20 LCC: NO LF FIXTURE COST FACTORED IN (RETROFIT)

	20,000hr LED	20,000hr LF
Operating	40,000hrs, 15yrs	
LCC	608	743
	20,000hr LED	30,000hr LF
Operating	40,000hrs, 15yrs	
LCC	576	743
	20,000hr LED	40,000hr LF
Operating	40,000hrs, 15yrs	
LCC	511	743

	40,000hr LED	20,000hr LF
Operating	40,000hrs, 15yrs	
LCC	608	487
	40,000hr LED	30,000hr LF
Operating	40,000hrs, 15yrs	
LCC	576	487
	40,000hr LED	40,000hr LF
Operating	40,000hrs, 15yrs	
LCC	511	487

	60,000hr LED	20,000hr LF
Operating	60,000hrs, 22.7yrs	
LCC	762	574
	60,000hr LED	30,000hr LF
Operating	60,000hrs, 22.7yrs	
LCC	720	574
	60,000hr LED	40,000hr LF
Operating	60,000hrs, 22.7yrs	
LCC	699	574

	80,000hr LED	20,000hr LF
Operating	80,000hrs, 30.3yrs	
LCC	762	574
	80,000hr LED	30,000hr LF
Operating	80,000hrs, 30.3yrs	
LCC	720	574
	80,000hr LED	40,000hr LF
Operating	80,000hrs, 30.3yrs	
LCC	699	574

	100,000hr LED	20,000hr LF
Operating	100,000hrs, 37.8yrs	
LCC	941	676
	100,000hr LED	20,000hr LF
Operating	100,000hrs, 37.8yrs	
LCC	888	676
	100,000hr LED	20,000hr LF

	50,000hr Tube	20,000hr LF
Operating	50,000hrs, 18.9yrs	
LCC	483	307
	50,000hr Tube	30,000hr LF
Operating	50,000hrs, 18.9yrs	
LCC	445	307
	50,000hr Tube	40,000hr LF

Operating	100,000hrs, 37.8yrs	
LCC	862	676

Operating	50,000hrs, 18.9yrs	
LCC	427	307

TABLE 21 LCC: LF FIXTURE COST FACTORED IN (NEW CONSTRUCTION)

	20,000hr LED	20,000hr LF
Operating	40,000hrs, 15yrs	
LCC	665	743
	20,000hr LED	30,000hr LF
Operating	40,000hrs, 15yrs	
LCC	632	743
	20,000hr LED	40,000hr LF
Operating	40,000hrs, 15yrs	
LCC	567	743

	40,000hr LED	20,000hr LF
Operating	40,000hrs, 15yrs	
LCC	665	487
	40,000hr LED	30,000hr LF
Operating	40,000hrs, 15yrs	
LCC	632	487
	40,000hr LED	40,000hr LF
Operating	40,000hrs, 15yrs	
LCC	567	487

	60,000hr LED	20,000hr LF
Operating	60,000hrs, 22.7yrs	
LCC	818	574
	60,000hr LED	30,000hr LF
Operating	60,000hrs, 22.7yrs	
LCC	776	574
	60,000hr LED	40,000hr LF
Operating	60,000hrs, 22.7yrs	
LCC	755	574

	80,000hr LED	20,000hr LF
Operating	80,000hrs, 30.3yrs	
LCC	924	634
	80,000hr LED	30,000hr LF
Operating	80,000hrs, 30.3yrs	
LCC	876	634
	80,000hr LED	40,000hr LF
Operating	80,000hrs, 30.3yrs	
LCC	852	634

	100,000hr LED	20,000hr LF
Operating	100,000hrs, 37.8yrs	
LCC	997	676
	100,000hr LED	20,000hr LF
Operating	100,000hrs, 37.8yrs	
LCC	945	676
	100,000hr LED	20,000hr LF
Operating	100,000hrs, 37.8yrs	
LCC	862	676

	50,000hr Tube	20,000hr LF
Operating	50,000hrs, 18.9yrs	
LCC	539	307
	50,000hr Tube	30,000hr LF
Operating	50,000hrs, 18.9yrs	
LCC	502	307
	50,000hr Tube	40,000hr LF
Operating	50,000hrs, 18.9yrs	
LCC	483	307