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Linear LED Lighting Retrofit Assessment

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GPG
Green Proving Ground Program

The Green Proving Ground program leverages GSA's real estate portfolio to evaluate innovative sustainable building technologies and practices. Findings are used to support the development of GSA performance specifications and inform decision-making within GSA, other federal agencies, and the real estate industry. The program aims to drive innovation in environmental performance in federal buildings and help lead market transformation through deployment of new technologies.

Disclaimer

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Abbreviations

ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
CALiPER	Commercially Available LED Product Evaluation and Reporting
CCT	correlated color temperature
CRI	color rendering index
CRT	cathode ray tube
DLC	Design Lights Consortium™
DOE	U.S. Department of Energy
FEMP	Federal Energy Management Program
fc	foot-candle, a unit of illuminance (lumens/ft^2)
GSA	U.S. General Services Administration
GPG	Green Proving Ground
IES	Illuminating Engineering Society of North America
K	kelvin
kWh	kilowatt-hour(s)
LED	light-emitting diode
LFL	linear fluorescent lamp
lm	lumen(s)
lm/W	lumen(s) per watt
LPD	Lighting Power Density
lx	lux
MOL	mean overall length
NEMA	National Electrical Manufacturers Association
PF	power factor
PNNL	Pacific Northwest National Laboratory
SOW	scope of work
SSL	solid-state lighting
THD	total harmonic distortion
TLED	tubular light-emitting diode (a common term for linear LED replacement lamps)
V	volt(s)
W	watt(s)

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I. Executive Summary

A. RECOMMENDATIONS

This study of two linear LED retrofit products intended to replace linear fluorescent lamps (LFL) used in troffer fixtures involved the collection of energy and photometric field data, implementation of end-user surveys, and economic analysis to evaluate the overall effectiveness of these products in U.S. General Services Administration (GSA) facilities.

- The energy savings of 27% to 29% found in this study for direct one-for-one replacement is likely for most applications, with even greater savings potential where there are opportunities to reduce light levels to conform to PBS P-100 Guidelines. Actual performance depends on the existing fluorescent system installed and the delivered light and wattage of the selected linear LED retrofit product in the fixture.
- The favorable occupant acceptance of the technology documented in this report is likely relevant to most applications where the existing lighting system meets the expectations of end-users and does not significantly reduce or increase light levels or create greater glare.
- The installer responses indicate that the linear LED retrofit products have similar components and installation process as compared to fluorescent lamp and ballast systems; no special tools, techniques or electrical modifications are necessary. This product characteristic should be relevant to most applications of traditional direct lighting troffers because installation is ubiquitous to these luminaires.
- The results from this study show that the products evaluated have simple payback ranges from 6.3 to 8.9 years at the national average commercial building energy rate of $0.1062/kWh. Energy cost savings increase as the energy rate increases, but the most significant contributors to overall cost-effectiveness are the capital installation cost and the avoided maintenance cost associated with fluorescent technology. This study includes sensitivity analysis on the variables of energy cost rate, material cost and installation and maintenance cost. However, product cost and cost-effectiveness needs to be evaluated on a case-by-case basis.

The results from this singular study cannot necessarily be applied to all applications as every site is different and there continues to be wide variation in LED retrofit designs and performance. However, these results do verify the general applicability of linear LED retrofit products for typical general area lighting. Based on the favorable results of this study, we conclude that the linear LED retrofit products evaluated should be included as a viable option when considering the retrofit of existing traditional direct lighting troffers in GSA facilities. A due-diligence approach to technology and product selection is strongly advised.

B. BACKGROUND

Annually, the United States consumes approximately 700 terawatt-hours (TWh) for lighting or about 19% of total annual electricity use of the country, with the commercial indoor sector consuming fully 50% of this 700 TWh. Linear fluorescent lighting fixtures are by far the most dominant interior lighting source within commercial buildings, representing almost 70% of the lighting energy use and amounting to approximately 80% of the lamp inventory (DOE 2012).

In 2013, the U.S. Department of Energy's (DOE) Federal Energy Management Program (FEMP) conducted a study characterizing the indoor lighting market for federal facilities. This study estimates GSA has 1.53 million fluorescent troffers within its building portfolio, consuming 470 GWh of electricity per year.[1] Based on the findings from this study and current performance trends for LED technology, it is estimated GSA could save 134 GWh (≈30% of annual usage) of electricity per year with full deployment of linear LED retrofit technology in its interior lighting spaces.

In addition to the savings potential of the technology change to LED, deeper savings opportunities exist with the implementation of advanced lighting controls (ALCs) as evidenced by recent GPG and other studies. The ability of a lighting system to dynamically provide the correct quantity of light at all times and take advantage of changes in occupancy leads to maximum energy savings. To realize this opportunity, the installed lighting system must be capable of dimming and compatible with advanced control systems. This study investigates two linear LED retrofit products that challenge the linear fluorescent systems found in recessed troffers. The term "Linear LED form-factor" is used throughout to generally refer to products that are LED-based, but possess the same form, fit, and function as their fluorescent counterparts.

C. OVERVIEW OF THE TECHNOLOGY

Fluorescent Troffers

The workhorse used in today's troffer fixtures is the T8 LFL with its associated electronic ballast. Together they deliver "source" efficacies ranging from 90 to 105 lumens per watt (lm/W). These omnidirectional light sources are installed in a range of troffer fixture types that provide secondary and primary optics—in essence capturing the omnidirectional light, directing it downward and distributing it uniformly into the space. This conversion results in loss of the amount of light leaving the fixture (fixture efficiency). Lensed, louvered, and volumetric troffer fixture efficiencies range from 65 to 85 percent.[2] The term luminaire efficacy is used to describe the net amount of light leaving the fixture and is a multiplication of the light source lumens by the fixture efficiency. Using the ranges, modern fluorescent troffers perform at a rate of 65 to 85 lm/W luminaire efficacy. The rated life[3] for LFLs is a function of the ballast and lamp technology and the frequency in switching. The range in available rated life for LFL products is 24,000 to a high of over 80,000 hours depending on ballast combinations and switching cycles, but the default value for typical T8 service lamps is 30,000 or 36,000 hours. No test for ballast life exists, but most manufacturers state the ballast life of 50,000 hours/10 years, provided the ballast case temperature (t_c) remains below a prescribes level. Many permutations exist, however, the generally applied lamp life for troffers is 30,000 hours and ballast life is 10 years.

Fluorescent Troffer Types

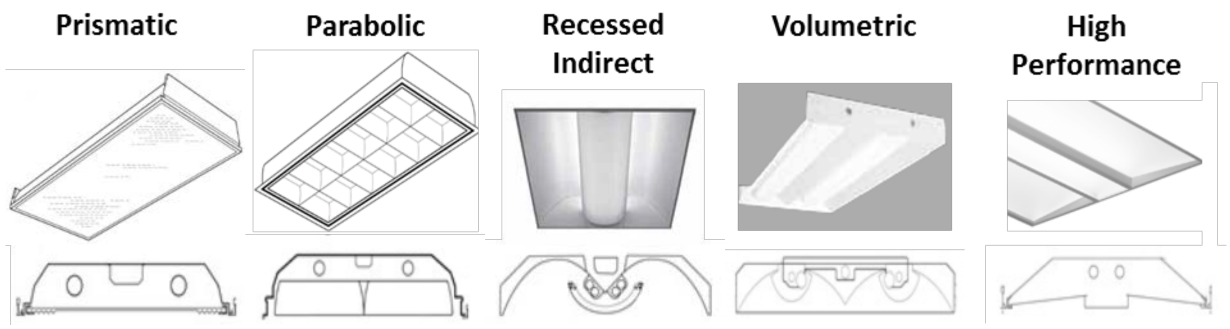
Fluorescent troffers have undergone generational changes as, in particular, the office environment has evolved. Early products needed only diffuse the light of the bare lamps and provide some level of high angle glare mitigation. **Prismatic** lensed products were the prevalent use. As personal computers began

[1] A TWh is 1000 GWh for example, GSA's lighting energy is 0.470 TWh or almost 0.5% of all lighting energy use in the United States.

[2] Fixture efficiency is the amount of light generated by the light fixture divided by the raw light from the bare lighting system. In this case, 15 – 35 percent of the light is absorbed by the fixture and never leaves.

[3] The term "rated life" refers to number of hours at which 50% of a large sample of lamps still operate.

to pervade the workspace, so did cathode ray tube (CRT) monitors with their glass screens. The highly reflective screens created a need for greater optical control to minimize user eye strain. The **parabolic** louver was introduced to control high angle glare, but the side effect was dark ceilings and upper walls creating somewhat of a “cave effect.” By the 2000s, monitor technology transitioned to LCD flat screen designs with non-glare surfaces. Additionally, energy codes began to drive down lighting power densities (LPD) and, in parallel, the Illuminating Engineering Society of North America (IES) reduced the recommended light levels for space types. Recessed designs that optimized lamp diffusion and increased uniformity began to emerge, such as **recessed indirect**, **volumetric** and **high performance**. Below are graphical representations of the various troffer types.



LED Troffer Retrofit Products

A large number of LED-based solutions are currently on the market to bring LED technology into existing fluorescent troffers. Products range from one-for-one direct lamp replacements using the existing fluorescent ballasts to retrofit kits that only use the fixture housing. The two LED products selected by GSA for this study, hereinafter referred to as “LED-A” and “LED-B,” are retrofit products that pair proprietary light bars (lamps) with matching proprietary drivers (power supplies). Both are 0-10v dimming capable and offer reduced light output options. They differ by the means by which the light bar is attached to the fixture housing. LED-A mounts the light bar to the top of the fixture housing, while LED-B utilizes the existing fluorescent lamp sockets as both the electrical and mechanical interface. Both manufacturers claim a designed lifetime of 50,000 hours for their systems, which includes the light bars and the matching drivers.

Naming Convention

GSA policy is to not specifically identify manufactures but rather, more broadly, technologies. Therefore, it is necessary to develop a nomenclature for referring to products in the body of this report. The two products investigated in this study will be referred to by the following convention:

- Linear LED Retrofit "A": LED-A
- Linear LED Retrofit "B": LED-B

D. STUDY DESIGN AND OBJECTIVES

This study evaluates the performance and applicability of specific linear LED form-factor retrofit products in fluorescent troffer and downlight installations and is focused on four critical areas: 1) energy efficiency, 2) photometric performance, 3) occupant response and acceptance, and 4) cost-effectiveness. The first three required a process of site screening and selection, followed by pre- and post- installation measurements and survey deployment. Cost-effectiveness was evaluated with the resulting measurement and verification (M&V) data coupled with projections of product cost, maintenance cost and energy price sensitivity.

The products investigated are intended to be one-for-one replacements of existing static lighting systems (although both have full dimming, step dimming, or reduced light output options), meaning, light source replacements without the interaction of controls (*e.g.*, occupancy-based sensors), dimming, or daylighting. For this reason, logging energy use was not necessary because there is neither a time nor power variability element to account for in the study. Instantaneous voltage and current readings were taken pre- and post- installation for several fixtures at each site to establish the baseline and power reduction due to the technology.

Arguably, the most critical element to the study was *in situ* photometric measurement at the sites to not only establish and verify light levels, but also capture changes in distribution and uniformity. To that end, horizontal illuminance measurements were taken over pre-established grids below luminaires unaffected by windows, walls, or variations in fixture spacing. Vertical illuminance measurements were taken along walls/partitions avoiding openings, doorways or changes in background reflectance values. In other words, the grids were selected to be representative of the typical space type and the readings directly comparable to IES recommendations and standards set by GSA's *Facilities Standards for the Public Buildings Service* (PBS P-100). P-100 prescribes 30 fc average for its office environments.

When dealing with a technology change and one that directly and visibly affects the end-user, it is not enough to rely solely on analytical measurements. It is prudent to engage the occupants about their experience, perception, and reaction to the change. Both pre- and post-installation surveys were administered at all three sites. In addition, because the technologies investigated involved professional installation and the level-of-effort could be compared and contrasted to incumbent technology replacement/maintenance, surveys also were distributed to the installers and facility staff.

AUBURN, WASHINGTON

The GSA Regional Headquarters Building is an approximately 100,000 square foot building originally constructed in 1932, with an addition in 1965, and is located south of Seattle, Washington. The study area includes two discrete office spaces within the facility's first floor: Real Estate and Design and Construction.

DALLAS, TEXAS

The Cabell Federal Building is an approximately 1,000,000 square foot building constructed in 1971 and is located in downtown Dallas. The study area includes office sections of the seventh floor: Property Management and Project Management.

PHILADELPHIA, PENNSYLVANIA

The Veterans Administration Center is an approximately 400,000 square foot building constructed in 1996 and is located just north of Philadelphia, Pennsylvania. The study area includes the entirety of a lower level daycare facility, which is comprised of classrooms, playrooms, restrooms, corridors, and associated support/common areas.

Table 1 lists key performance objectives for the study in both a quantitative and qualitative format.

Table 1. Performance Objectives

Quantitative Objectives	Metrics & Data Requirements	Success Criteria	M&V Results
Reduce Energy Usage	Lighting Energy Use, kWh/year, measured at the luminaire	Reduce kWh/year	Energy reductions of 26.7%-28.5% for LED-A and LED-B, respectively
Cost-Effectiveness Requirements	Simple payback, in years: Annual energy savings/project installation cost	Paybacks within GSA range for investment consideration	At $0.1062/kWh and RS Means installation data, simple payback is 6.5 and 6.3 years for LED-A and LED-B, respectively
Reduce Emissions	kg CO_2 equiv./year, based on per luminaire calculations	Reduce kg CO_2 equiv./year	Energy reductions proportionately reduce GHG emissions, LED-A yields 26.7% reductions and LED-B yields 28.5% reductions
Provide Recommended Light Levels	Average illuminance at the workplane for offices spaces	Average of ≥ 30 foot-candles per IES and P-100 Guidelines for offices	All locations closely met or exceeded pre-existing light levels when installed on a one-for-one basis.
Easy Installation	Questionnaire responses from installing electrical contractors	Positive responses regarding ease of installation	Installing contractors reported routine installations similar to incumbent fluorescent
Reduce Maintenance	Annual lighting energy cost, $/year, based on energy and maintenance	Reduce $/year	Not verified as part of M&V, however, projected life increases by 67% for both LED-A and LED-B
Maintain Occupant Satisfaction	Occupant responses to Satisfaction Survey	At minimum, no decrease in satisfaction, and ideally, >70% satisfaction in lighting	The vast majority of respondents said little or no decrease in satisfaction when light levels were maintained.

E. PROJECT RESULTS/FINDINGS

ENERGY EFFICIENCY

Pre- and post-retrofit electrical conditions were measured in the field by the installing contractors at several of the project sites. Measurements showed that there were varying existing installed technologies and conditions at the sites; for example, mixes of nominal and reduced wattage lamps, mixes of two- and three-lamp fixtures, mixtures of ballast technologies and manufacturers, and different contractors, meters and measurement techniques led to a wide range of values. To normalize the readings for analysis purposes, the high end of the industry accepted range in wattage for two-lamp T8 fixtures with electronic ballasts (60 W) was used for the pre-retrofit condition. Additionally, the Pacific Northwest National Laboratory Lighting Metrology Laboratory conducted independent measurement of LED-A and LED-B. Table 2 summarizes the results.

Table 2. Pre- and Post- Retrofit Savings

Properties	LED-A	LED-B
Pre-retrofit	60W	60W
Post-retrofit	44.0W	42.9W
% Savings	**26.7%**	**28.5%**

PROTOMETRIC PERFORMANCE

An important part of any lighting retrofit is achieving the correct or desired light levels. Table 3 provides a summary of the horizontal (primary task) photometric performance of the linear LED retrofit technologies in comparison to the existing LFL technology.

The measurement points in each evaluation area were generally arranged as a grid of measurements where effective measurements were possible. Because measurements could not be taken in all locations, these summary values may not represent exact numerical averages for each space, but will serve well as direct comparison of the different technologies for purposes of this evaluation. It also is important to note that in several locations there was a conscious effort to "de-lamp" from three to two lamps because of over-lighted conditions; thus, a direct comparison is not possible, but it does provide insight into the ability of the technology to address over-lighted conditions for potentially deeper energy savings. IES and, by extension, PBS P-100 provide recommended illuminance levels based on space types and activities—30 foot-candles (fc) average on the workplane (30" above the finished floor) for offices. Key metrics to establish equivalency are the maximum-to-minimum ratio and average illuminance. Lower maximum-to-minimum values generally indicate an improvement in uniformity.

Table 3. Pre- and Post- Retrofit Illuminance Data

Location	Time Frame	Light Source	# Lamps	Min. (fc)	Max. (fc)	Max : Min Ratio	Average (fc)	Target IES Average(fc)
Auburn, WA – First Floor Real Estate (LED-A)	**Pre-Retrofit**	LFL	2	49.9	57.6	1.15	**53.0**	30
Auburn, WA – First Floor Real Estate (LED-A)	**Post-Retrofit**	LED-A	2	60.8	69.9	1.15	**65.1**	30
Auburn, WA – First Floor Design & Construction (LED-B)	**Pre-Retrofit**	LFL	2	33.1	51.9	1.60	**40.4**	30
Auburn, WA – First Floor Design & Construction (LED-B)	**Post-Retrofit**	LED-B	2	45.3	70.5	1.50	**56.1**	30
Dallas, TX – Seventh Floor Internal Cubicle Offices (LED-A)	**Pre-Retrofit**	LFL	3	19.8	55.7	2.81	**36.0**	30
Dallas, TX – Seventh Floor Internal Cubicle Offices (LED-A)	**Pre-Retrofit**	LFL	2	14.0	36.9	2.64	***24.3***	30
Dallas, TX – Seventh Floor Internal Cubicle Offices (LED-A)	**Post-Retrofit**	LED-A	2	10.2	28.4	2.78	***18.2***[(a)]	30
Dallas, TX – Seventh Floor Perimeter Cubicle Offices (LED-B)	**Pre-Retrofit**	LFL	3	34.9	53.7	1.54	**42.7**	30
Dallas, TX – Seventh Floor Perimeter Cubicle Offices (LED-B)	**Pre-Retrofit**	LFL	2	24.7	36.6	1.48	***29.4***	30
Dallas, TX – Seventh Floor Perimeter Cubicle Offices (LED-B)	**Post-Retrofit**	LED-B	2	38.4	60.6	1.58	**47.3**	30
Philadelphia, PA – Daycare Classroom 460 (LED-A)	**Pre-Retrofit**	LFL	3	61.4	70.4	1.15	**64.8**	30
Philadelphia, PA – Daycare Classroom 460 (LED-A)	**Post-Retrofit**	LED-A	2	51.0	58.5	1.15	**54.6**	30
Philadelphia, PA – Daycare Playroom 405 (LED-A)	**Pre-Retrofit**	LFL	3	37.4	45.8	1.22	**42.2**	30
Philadelphia, PA – Daycare Playroom 405 (LED-A)	**Post-Retrofit**	LED-A	2	28.4	35.7	1.26	**32.7**	30
Philadelphia, PA – Daycare Playroom 413 (LED-B)(b)	**Pre-Retrofit**	LFL	3	37.4	45.8	1.22	**42.2**	30
Philadelphia, PA – Daycare Playroom 413 (LED-B)(b)	**Post-Retrofit**	LED-B	2	43.1	54.5	1.26	**50.7**	30

(a) The number of lamps in this location was reduced from 3-to-2. The existing lighting conditions and fixture type led to an inappropriate application. The problem was remedied by adding a third lamp after the fact.

(b) Playrooms 405 and 413 are identical. The pre-retrofit fluorescent measurements were used from Playroom 405.

It is important to note that these data represent specific site applications for two specific products; direct comparisons between spaces in other locations cannot be made because of variations in factors such as surface reflectance values, ceiling height, fixture spacing, and fixture type, which affect light levels and distribution. Other site applications and other similar format products could perform the same or vastly different (*i.e.*, better/worse) depending on the applications and product. These data should be considered instructive in evaluating real world application of LED products but are not intended to, nor do they, definitively determine the appropriateness of these specific applications. Final application of LED products to actual projects depends on many factors.

The results indicate that LED-A and LED-B, when installed in one-for-one applications, delivered higher initial light levels, and some sites even saw improved uniformity. Higher light levels were expected as the existing fluorescent systems were at various stages of lumen/dirt depreciation.[4] In addition, LED systems may need to have higher initial light levels to compensate for their long, exponential deprecation to L_{70} (some T8 lamps are capable of lumen maintenance greater than 95% at their rated lamp life).

OCCUPANT RESPONSE AND ACCEPTANCE

Occupant surveys administered at the three evaluation sites provide information on the relative satisfaction by the occupants of both the existing fluorescent lighting and the new installed LED lighting. The primary focus of the survey was to determine if there were any specific issues with either the existing fluorescent or retrofit LED systems and if they were any significant differences with the change to LED technology.

In general, the occupants' responses to the pre-retrofit survey at all three sites indicate the existing fluorescent system was acceptable. This result is expected as the occupants are accustomed to working under this system and any significant issues would likely have been addressed.

In analyzing the data for statistically significant responses that showed differences between the fluorescent and retrofit LED systems, the following results are noted related to light levels and glare:

- In the Auburn Real Estate area, the occupants thought the LED lighting system was too bright. This can be attributed simply to higher light levels, but also could be a result of the clean new system that can often present a brighter appearance.
- In the Auburn Real Estate area, the occupants also thought the LED lighting system presented a slightly higher glare potential on work surfaces, both from lighting overhead and viewing from a distance, but not on the computer screens. Again, this can be attributed simply to higher light levels.
- In the Dallas Property Management area with LED-A lamps installed, the occupants thought the LED lighting system presented a slightly higher glare potential on computer screens, but slightly less glare on both work surfaces and from overhead lighting.
- In the Dallas Project Management area with LED-B LED lamps installed, the occupants thought the LED lighting system presented a slightly higher glare potential on computer screens, but slightly less glare on work surfaces.

[4] Lumen depreciation is the ratio of light at a point in time compared to initial light values. All light sources degrade at different rates. Fluorescent depreciation is very limited and is about 90-95% of the initial values at the end of life.

- In the Philadelphia daycare areas, the occupants thought the LED lighting system presented a slightly higher glare potential with viewing from a distance.

All of these differences for both light levels and glare potential were found, on average, to be slight with no major issues identified. However, there can always be individual issues with specific occupants. In one case, there were complaints at the Dallas site of low light levels in one area. The light levels in the area are significantly lower with the LED technology, but it simply was a difference in the light output of the installed lamps. A different lamp output product (*i.e.*, a higher wattage lamp) would likely have resolved this issue.

COST-EFFECTIVENESS

The decision process for energy efficiency measures (EEMs) requires a thorough understanding of the existing condition (*i.e.*, the base case), cost of energy, and costs and periods for maintenance and replacement. In addition, the time value of money for the evaluation period must be considered. To that end, life-cycle costing (LCC) is used to account for the cash flows over the evaluation period and calculate present (or net present) values for competing EEMs. In the federal sector, it is common practice to use a software package named Building Life-Cycle Cost[5] (BLCC) developed by the National Institute of Standards and Technology. Below are the assumptions used in the BLCC models developed for the project:

- Energy rates: $0.06 to $0.24 kWh, plus $0.1062 kWh (national commercial average for February 2015)
- Annual operating hours: 4000
- "Base-case" for troffers: 2 x F32T8 with 1 generic electronic ballast operating at 60W. Lamp replacement at 25,000 hours (6.25 years).
- LED-A = 44.0W and 176.0 kWh per year
- LED-B = 42.9W and 171.6 kWh per year
- No demand or power factor charges
- No heating, ventilation, and air conditioning impact (*i.e.*, reduced cooling, increased heating)
- Life-cycle period: 12 years, 6 months selected for the following reasons:
  - Manufacturer claimed LED product life: 50,000 hours
  - Typical rated life for modern electronic ballasts: 50,000 hours
  - Period is long enough for at least one fluorescent lamp replacement to account for LED maintenance savings.
- Models include assumed bare equipment costs of $50, $60, and $70 for the LED-A and LED-B products. Installation costs are based on RS Means Data[6] with specific application of GSA procurement lists.
- For purposes of comparative economic analysis, it is assumed the base-case and associated costs are installed at time = 0.
- Nominal discount rate: 3.1%.

[5] http://energy.gov/eere/femp/building-life-cycle-cost-programs

[6] The Gordian Group, "RS Means Construction Cost Data Book," 2015

Table 4 summarizes the results for the national average energy rate of $0.1062/kWh and mid-range bare material costs for LED-A and LED-B of $60. Both products are seen to be cost-effective under the given conditions, with simple paybacks (SPB) for LED-A of between 7.3 and 8.2 years and LED-B of between 7.1 and 8.0 years, with savings-to-investment ratios (SIR) of approximately 1.0 to 2.0, and present values (PV) less than the base case fluorescent.

Table 4. Retrofit Economic Assessment

Properties	Light Source Baseline 2-lamp T8 + Electronic Ballast	Light Source LED-A	Light Source LED-B
Equipment Cost[(a)]	Not Applicable	$50, $60 and $70	$50, $60 and $70
Installation[(b)]	Not Applicable	$34.19 and 68.38	$34.19 and 68.38
Maintenance[(c)]	$110.14	$0	$0
Energy Rate[(d)]	$0.1062/kWh	$0.1062/kWh	$0.1062/kWh
Energy Consumption Before[(e)]	240 kWh/yr	Not Applicable	Not Applicable
Energy Consumption After	Not Applicable	176 kWh/yr	172 kWh/yr
Energy Consumption Savings	Not Applicable	64 kWh/yr	68 kWh/yr
Energy Cost Before	$25.49/yr	Not Applicable	Not Applicable
Energy Cost After	Not Applicable	$18.69/yr	$18.27/yr
Energy Cost Savings	Not Applicable	$6.80/yr	$7.22/yr
Simple Payback	Not Applicable	6.5 to 8.9 yrs	6.3 to 8.6 yrs
Net-Present Value[(f)]	Not Applicable	$62 to $8	$67 to $13
Savings-to-Investment Ratio	Not Applicable	2.3 to 1.4	2.4 to 1.5

(a) Assumed $50, $60, and $70 equipment cost
(b) 50% and 100% RS Means derived labor estimates
(c) Assumes 50,000 hour period; 2 lamp and 1 ballast replacement
(d) National average energy rate in Feb. 2015
(e) Assumed 4000 hour per year operation
(f) Discount rate is 3.1%

Figure 1 and Figure 2 represent sensitivity analyses for energy rates ranging from $0.06 to $0.24/kWh, bare material costs for LED-A and LED-B of $50, $60 and $70 and two assumptions of installation cost; 50% and 100% of RS Means derived estimates. Results indicate LED-A and LED-B are marginally cost-effective at low energy rates, with installation labor cost being the greatest contributor to overall cost-effectiveness.

Figure 1. LED-A Simple Payback, Savings-to-Investment-Ratio, and Present Value Results with 50% RS Means Labor Assumption

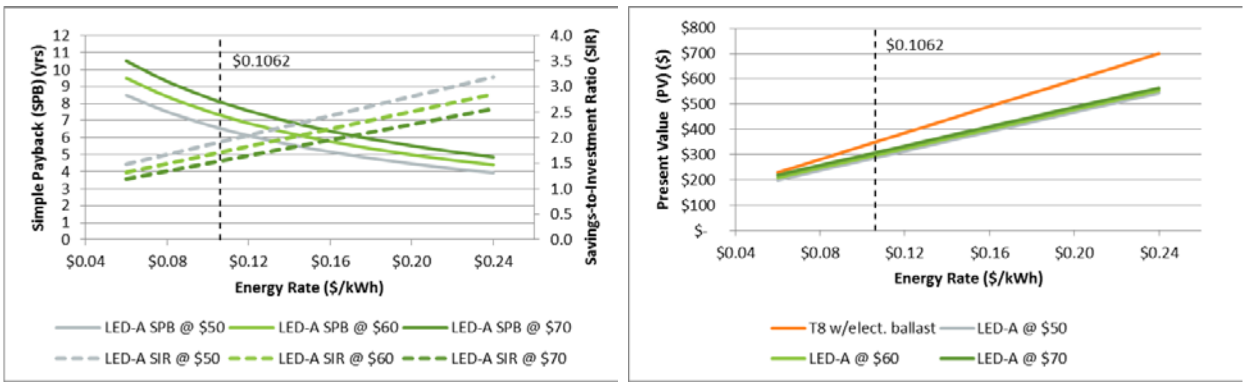


Figure 2. LED-A Simple Payback, Savings-to-Investment-Ratio, and Present Value Results with 100% RS Means Labor Assumption

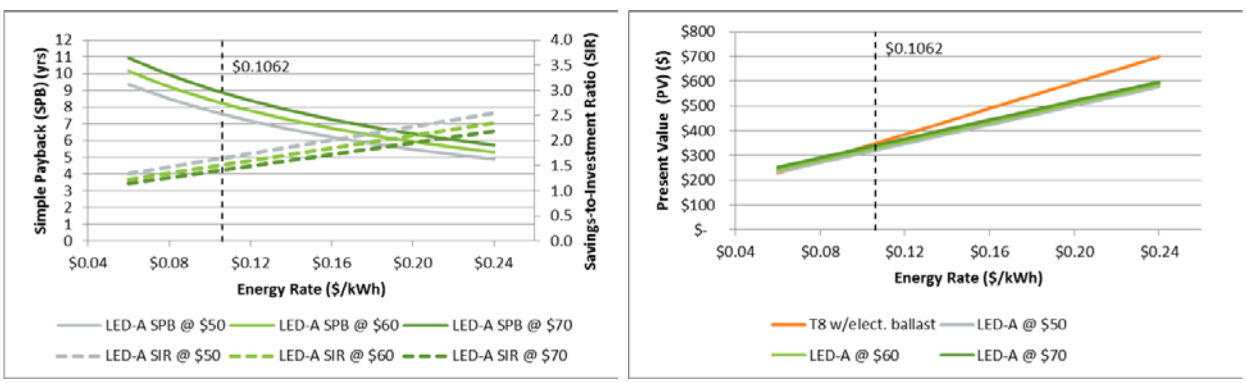


Figure 3. LED-B Simple Payback, Savings-to-Investment-Ratio, and Present Value Results with 50% RS Means Labor Assumption

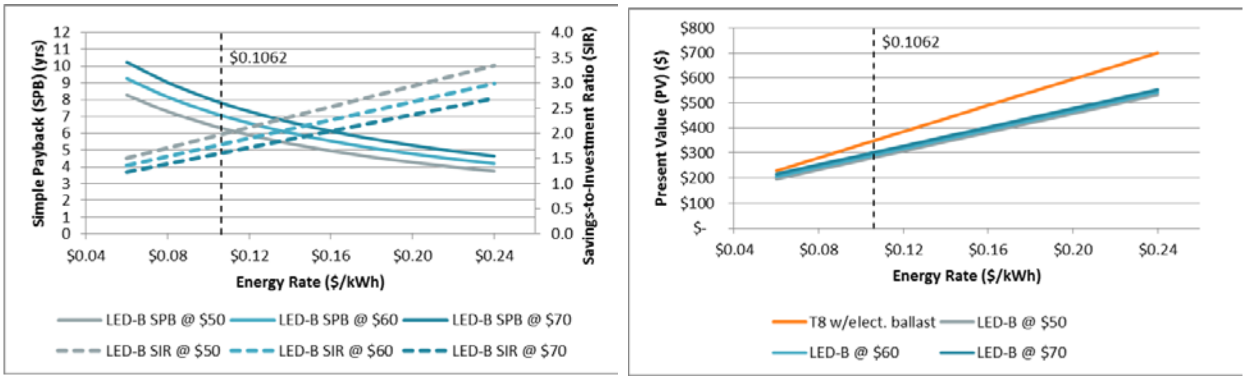
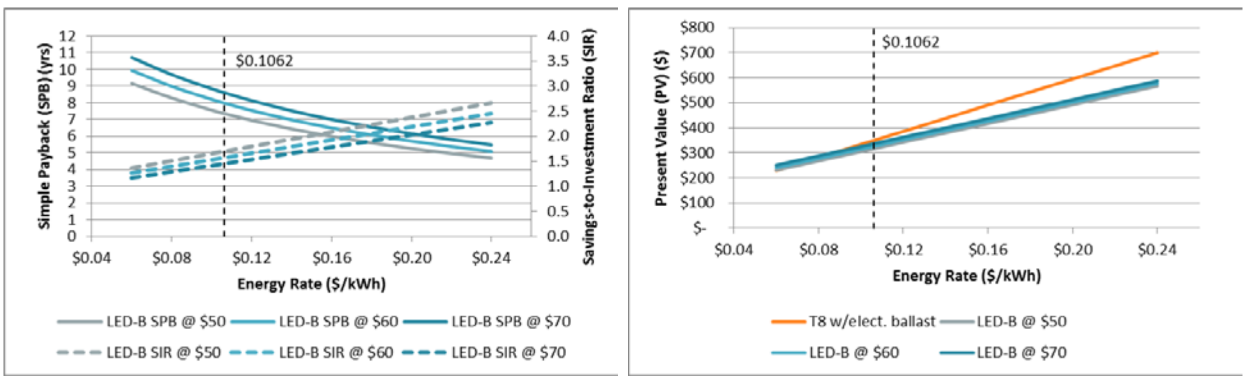


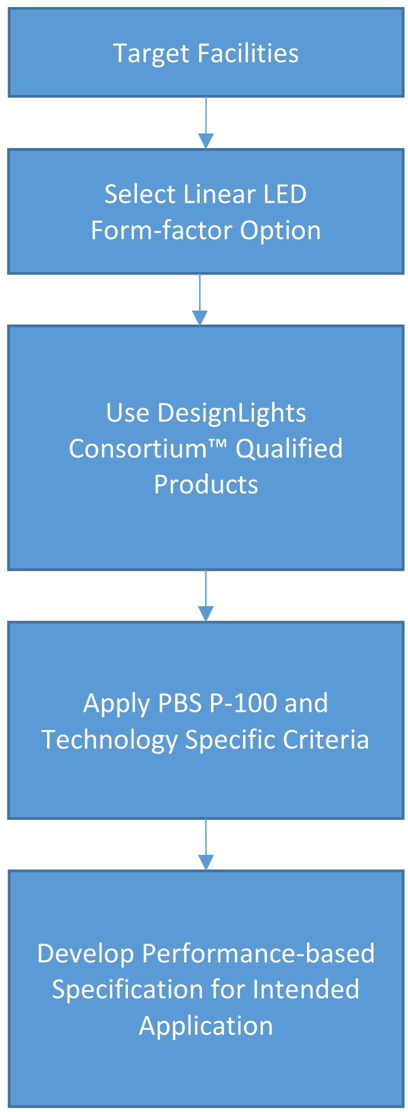
Figure 4. LED-B Simple Payback, Savings-to-Investment-Ratio, and Present Value Results with 100% RS Means Labor Assumption



F. DEPLOYMENT RECOMMENDATIONS

The favorable results of the study conclude that the linear LED form-factor products evaluated in this study should be included as a viable option when considering retrofitting or re-lamping existing fluorescent fixtures in GSA facilities. Although this can be stated for the specific products evaluated, the confluence of many factors, not the least of which is the current diversity of LED products in the market, requires a due-diligence approach to technology and product selection.

The five-step decision process described below is recommended for GSA in selecting facilities and pairing them with the best products for specific applications.



Targeting begins with an evaluation of the existing lighting technology and lighting design coupled with strategic decisions on cost-effectiveness thresholds. Clearly, regions with the highest energy costs will yield the greatest returns; however, the results of this study indicate cost-effectiveness even at relatively low energy rates.

There are many LED form-factor options competing in the existing fluorescent troffer space. These options range from a simple lamp replacement using the existing fluorescent ballast all the way up to a free-form retrofit installed in a bare fixture housing or even a new luminaire altogether. A form-factor decision must be made that considers the existing lighting system configuration, LCC and expected system useful life, and provides segue to any future lighting control strategies.

Products under consideration should be required to meet the appropriate category under DesignLights Consortium™ (DLC) standards and be listed on their qualified product list. Federal users are required to purchase products that meet ENERGY STAR standards. In cases where ENERGY STAR (or other federally approved body [*e.g.*, FEMP]) does not provide a covered category, end-users are left to exercise due diligence. Fortunately, as is the case with LED-A and LED-B, DLC standards act as *de facto* ENERGY STAR standards for commercial luminaires.

GSA maintains its own *Facilities Standards for the Public Buildings Service* (P-100), which establishes criteria for lighting performance requirements, performance attributes, prescriptive requirements, and electrical performance requirements. These criteria govern all facets of lighting and lighting equipment installed within GSA facilities and, although P-100 does not directly specify LED form-factor products (in fact the current [*i.e.*, 2016] version expressly prohibits them), it does provide guidance on illumination requirements and target performance levels. In addition to P-100, technology-specific LED form-factor criteria (see Basic Product Specification) should be included in the solicitation package.

The final step is to develop performance-based specifications that are site/application specific. These are application-based criteria that convey to the manufacturer or energy service companies how the LED solution should preform and under what conditions. Such things as the type of fixture in which the product will be installed, initial illuminance levels, spacing criteria, room surface reflectance values, and ceiling height must be clearly defined. With this information, manufacturers or energy service companies are able to perform the necessary calculations, modelling, or demonstrations needed to select the appropriate product to meet the application.

II. Introduction

GSA is a leader among federal agencies in actively pursuing energy- and water-efficiency opportunities for its facilities. Its Green Proving Ground program identifies emerging technologies and leverages its expansive building portfolio to conduct measurement, verification, and validation. This study examines the emergence of solid state lighting (SSL) as a direct competitor to incumbent fluorescent lighting systems, specifically LFLs used in troffers.

A. PROBLEM STATEMENT

The ubiquitous fluorescent lamp is widely used in commercial buildings and has been the mainstay of interior lighting design since the 1960s. As technology has progressed, there have been incremental improvements in efficiency (efficacy) resulting in today's LFL T8/T5 systems, which routinely deliver between 90 and 105 lm/W. However, fluorescent lighting is not without its shortcomings. There are the well-known problems of disposal and environmental concerns with mercury, global limitations on phosphor supply that impact lamp cost, and marginal dimming performance to take full advantage of today's sophisticated daylighting and adaptive control systems, just to name a few.

Over the last 10 years, SSL went from a technology that was able to compete only in a limited number of niche applications—directional and relatively low light output—to the point today where it can compete and prevail in just about all applications. Steady reductions in cost and increases in efficacy, coupled with the enormous installed base of fluorescent lighting, has led manufacturers to develop new products to compete for sockets once reserved for only fluorescent lamps.

The rapid development and expansion of SSL has forced building owners to make major purchasing decisions based on limited, and often imperfect, information with varying results. Further exacerbating the situation is the lack of standards and wide range in performance for products competing in the same space. This study investigates two retrofit products in the linear fluorescent troffer space.

B. OPPORTUNITY

In 2013, FEMP conducted a study to characterize the indoor lighting market for federal facilities.[7] The study estimated that GSA has 1.53 million fluorescent troffers within its building portfolio, consuming 470 GWh of electricity per year. Linear fluorescent lighting fixtures are by far the most dominant interior lighting source within commercial buildings, representing almost 70% of the lighting energy use and accounting for approximately 80% of the lamp inventory (DOE 2012a).

Based on the findings from this study and current performance trends for SSL technology, it is estimated GSA could save 134 GWh of electricity per year with full deployment of SSL in its interior lighting spaces.

[7] DOE FEMP, "Interior Commercial Lighting Market Characterization for the Federal Sector," September 2013

C. TECHNOLOGY DESCRIPTION

SOURCE EFFICIENCY (EFFICACY)

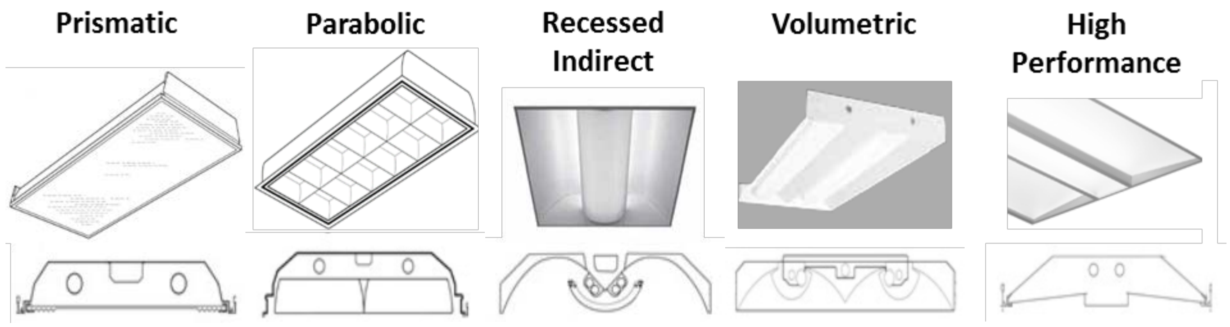
Light sources have traditionally been characterized by how efficiently the light source converts power into light. The metric, known as luminous efficacy (or just efficacy), is expressed in light output in lumens (lm) divided by their input power in watts (W). The best analogy to luminous efficacy is the car metric of miles per gallon, which indicates how far the car will travel per gallon of fuel. For fluorescent systems, ballasts are a necessary component to drive the lamp, so any ballast losses are included in the efficacy calculation. A typical T8 lamp/electronic ballast combination provides between 90 and 105 lm/W. LEDs exhibit a wide range in performance at their source, and multiple parameters such as drive current, thermal management, correlated color temperature (CCT), and epitaxial technology, affects both light output and input power. Generally speaking, the 2015 range in LED source efficacy at the package level is 100 to 160 lm/W.

FIXTURE EFFICIENCY

All light sources prior to LEDs emit light in all directions (*i.e.*, they were omnidirectional); however, once packaged in a lamp, some could be directional (*e.g.*, flood lamps). To direct and distribute the light for the task or application, fixture manufacturers designed luminaires with reflective surfaces, geometric reflectors, and optics to direct light out of the fixture in a useful pattern. In addition to getting light out of their fixtures, manufacturers also needed to mitigate occupant glare for everyday tasks and workstation functions. Various types of lenses were developed to diffuse the light and provide "cut-offs" for high angle glare. The result of manipulating an omnidirectional light source comes at the expense of fixture efficiency. For example, the typical fluorescent troffer is only about 60 to 70% efficient, meaning only 65 to 85% of the light created by the lamp/ballast combination actually leaves the fixture. The inherent directionality of LEDs means that a significant portion of the light that would otherwise be lost within the fixture is directed downward and negates some needs of the secondary optic. The inclusion of a directional light source in a fixture originally designed for an omnidirectional light source nets an increase in overall fixture efficiency, thus fewer light source lumens are needed to accomplish the same light levels.

TROFFER TYPES

Fluorescent troffers have undergone generational changes as, in particular, the office environment has evolved. Early products needed only to diffuse the light of the bare lamps and provide some level of high angle glare mitigation. **Prismatic** lensed products were the prevalent use. As personal computers began to pervade the workspace, so did cathode ray tube (CRT) monitors with their glass screens. The highly reflective screens created a need for greater optical control to minimize user eye strain. The **parabolic** louver was introduced to control high angle glare, but the side effect was dark ceilings and upper walls creating somewhat of a "cave effect." By the 2000s, monitor technology transitioned to LCD flat screen designs with non-glare surfaces. Additionally, energy codes began to drive down lighting power densities (LPD) and, in parallel, the IES reduced the recommended light levels for space types. Recessed designs that optimized lamp diffusion and increased uniformity began to emerge, such as **recessed indirect**, **volumetric** and **high performance**. Below are graphical representations of the various troffer types.



LUMINAIRE EFFICACY (LE) AND LUMINAIRE EFFICACY RATING (LER)

One of the fundamental differences between LEDs and incumbent lighting technologies is how they are measured. To make direct comparisons in performance, it is necessary to understand how and where they are measured and how to make direct comparisons at the fixture level.

Fluorescent technologies (and all omnidirectional technologies for that matter) use a measurement technique called relative photometry. With relative photometry, it is assumed that the distribution of light from the lamp is uniform (omnidirectional) and that the light output is scalable based on wattage. A reference lamp (and ballast) is measured to determine total lamp lumens. The lamp is then installed in the fixture and measured to determine total net lumens. The difference between the two values yields luminaire efficiency. Once fixture efficiency is known, the net fixture light output for any lamp is simply a multiplication of the nominal lamp lumens times the fixture efficiency. This approach works well when there is standardization of light sources across manufacturers. With this relative approach, the industry has developed a metric that allows the end-user to determine the efficacy of a system or the luminaire efficacy rating (LER) using the following equation:

$$LER = (EFF \times TLL \times BF) \div \text{luminaire input watts}$$

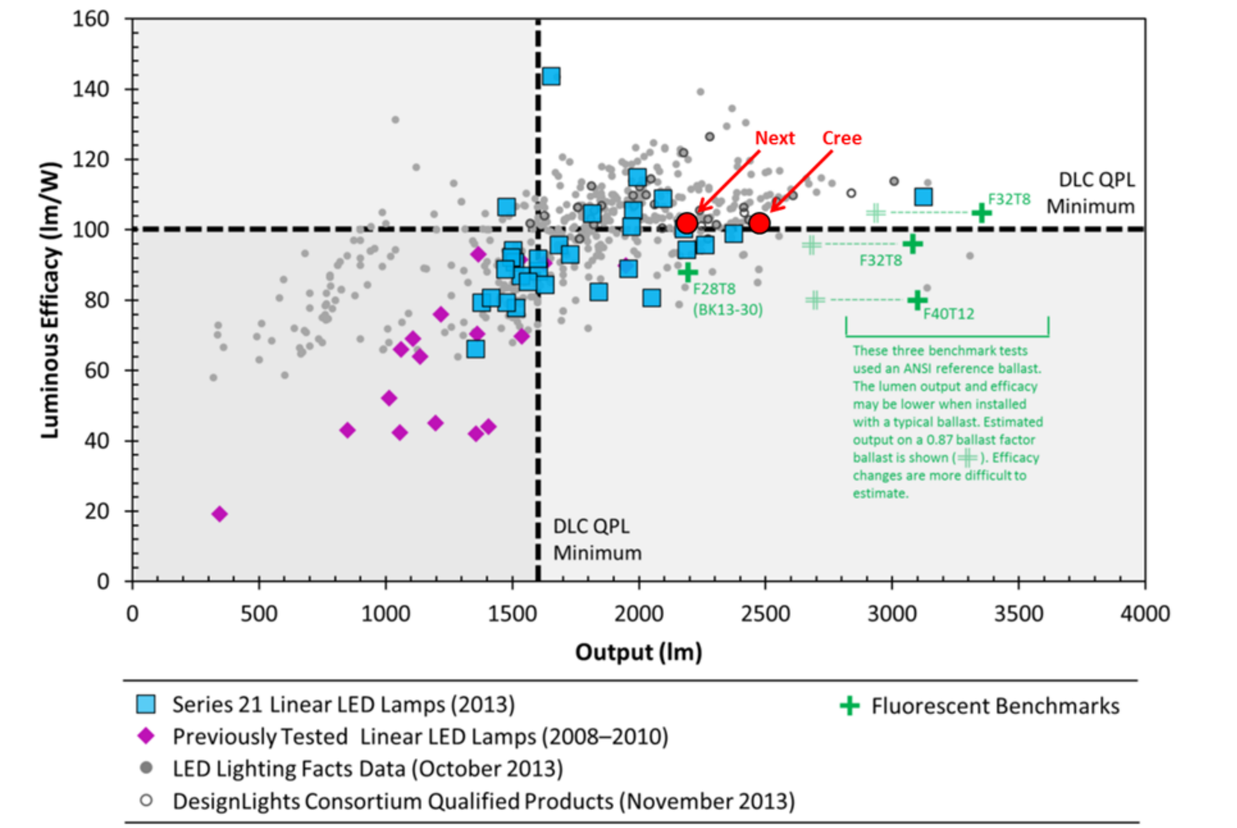
where:

- LER = luminaire efficacy rating
- EFF = luminaire efficiency
- TLL = total lamp lumens (nominal lamp lumens x number of lamps)
- BF = ballast factor.

LEDs, because of their directionality and the lack of standard interchangeable light engines among manufacturers, must be measured using a technique called absolute photometry. With this technique, the entire luminaire is measured instantaneously, and the result is net fixture lumens and luminaire efficacy (LE). Although it is possible to measure a fluorescent luminaire with absolute photometry, it is uncommon to do so. LE and LER provide the end-user with a means to reasonably compare luminaires of different technologies to determine how well the fixture converts power into light.

Figure 5 shows the relative performance of past and currently available linear tubular LED (TLED) lamps and fluorescent benchmarks.

Figure 5. Existing Market Luminous Efficacy vs. Light Output



LUMEN DEPRECIATION, RATED LIFE AND L_{70}

All light sources exhibit lumen depreciation; however, they do not depreciate by the same amount or at the same rate. Furthermore, the failure mode and end-of-life determinations must be clearly understood when comparing the technologies. Incumbent light sources exhibit catastrophic failure at some point in time and define rated-life to be the number hours at which 50% of a large sample are still operating. In contrast, it is unlikely for LED packages or modules to fail catastrophically (although it is possible), but rather to depreciate to a point at which their light output no longer meets the needs of the application. The industry defines this point as 70% of the initial light output or L_{70}. For a well-designed luminaire, this point can be upwards of 50,000 hours. It must also be recognized that the LEDs themselves are part of a system and other components (such as the driver) can cause failure.

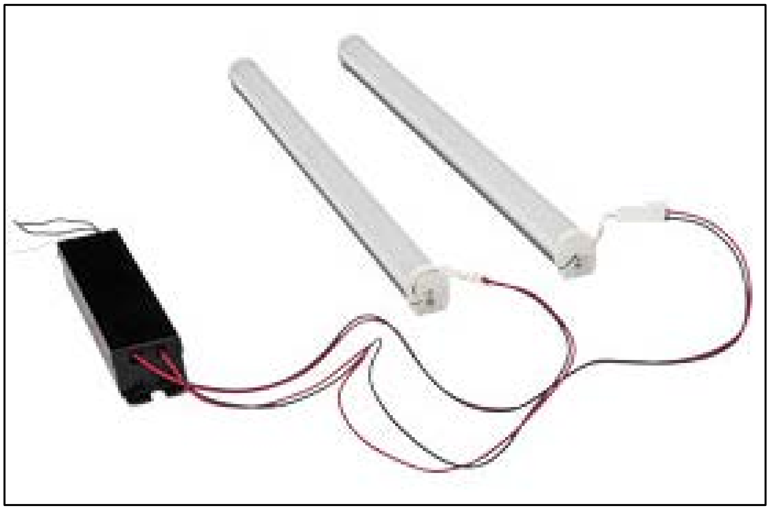
The typical T8 fluorescent lamp can maintain 90 to 95% lumen maintenance to its rated life of 24,000 to 36,000 hours for a standard lamp. LED L_{70} values vary, but for the products evaluated in this study, values up to the 50,000 hour range are claimed by manufacturers.

DESCRIPTIONS

LINEAR LED RETROFIT – "LED-A"

The LED-A retrofit kit is a paring of two or three LED lamps with a dedicated driver (see Figure 6). The retrofit bypasses existing fluorescent connection sockets and installs directly to the inside (top) of the existing fixture housing. The existing fluorescent ballast is replaced with the dedicated LED driver matched to the lamps.

Figure 6. Linear LED Retrofit "LED-A" Product Image



LED-A Manufacturer Claims of Product Features (not verified as part of this study)

- Efficacy: Up to 102 lm/W at source level
- Delivered Light Output: 3600 or 4500 lumens
- Input Power: 36 or 44 W
- CRI: 80
- CCT: 3500K, 4000K
- Input Voltage: 347 V, 120 to 277 VAC
- Controls: Step level to 50% or 0-10 V dimming to 5%
- Accessories: Emergency backup options available
- Mounting: Existing fluorescent fixtures
- Lifetime: Designed to last 50,000 hours
- Qualifications: Qualified for DLC Qualified Products List
- Warranty: LED-A offers industry-leading limited product warranties.

LED-A Manufacturer Installation Instructions

1. Locate latches on the lens frame and release them allowing lens frame to swing open. Carefully let lens frame hang.
2. Remove existing linear fluorescent tubes and properly dispose of them.
3. To remove the wiring compartment, squeeze the sides in and pull down and set aside.
4. Locate the existing ballast and remove the screw holding the ballast to the housing. Properly dispose of the screw.
5. To remove the ballast from housing, cut the leads from the ballast to the socket housing on both ends of the luminaire and cap socket leads. NOTE: When cutting leads, leave the smallest amount of wire attached to luminaire.
6. Cut the leads from the ballast to the input power ensuring to leave as much length as possible for electrical connections. Remove ballast from housing and properly dispose of.
7. Push exposed socket leads back into socket housing on each side of the luminaire or cap any exposed accessible leads.
8. Prepare input power by stripping input power leads 1/4".
9. Bring new driver into housing using mounting holes from old ballast and secure it using supplied #8-32 screw. Ensure that the existing luminaire housing is properly grounded to ensure proper driver grounding. NOTE: If housing has multiple locations for power supply, new driver can be secured in any of these locations.
10. Make electrical connection per "Electrical Connections" section. NOTE: Ensure that the driver is properly grounded to luminaire using supplied screw from Step 9.
11. Bring wiring compartment previously removed in Step 3 into the housing. Carefully tuck all leads and wire connectors into the wire compartment. Reattach wire compartment by snapping into place over driver insuring no wires are pinched. NOTE: Route the driver outgoing leads through the wiring compartment allowing leads to be exposed through the end of the wiring compartment.
12. Snap (3) supplied mounting clips onto each LED lightbar.
13. Bring LED lightbar into housing and reposition clips on LED lightbar as needed. For temporary placement of LED lightbar the clips have magnets located on the bottom of the clip. Repeat this step for each LED lightbar supplied in kit.
14. Once all LED lightbars are in desired position, permanently secure them to housing by inserting two supplied self-tapping screws into each end of the LED lightbar. NOTE: The middle bracket on the LED lightbar DOES NOT need to be secured.
15. Connect the power supply leads connector, which is exposed at the end of the wiring compartment with the LED lightbar connector. NOTE: Place the relamp label, provided in the kit, on the lighting compartment. Make sure that the label is visible.
16. Close the lens door and secure the latches.

LINEAR LED RETROFIT – "LED-B"

The LED-B retrofit kit is also a system with multiple lamps driven by a dedicated LED driver (see Figure 7). This product installs directly into the existing fluorescent medium bi-pin connection base, but is driven by a dedicated LED driver.

Figure 7. Linear LED Retrofit "LED-B" Product Image

LED-B Manufacturer Claims of Product Features (not verified as part of this study)

- Product Features: Glare-free soft light
- Lamps Made in U.S.A
- Universal socket compatibility (shunted and non-shunted)
- Two light levels (standard mode and energy saver mode)
- 0-10V Dimming
- Long lifetime (L_{70} >50,000 hours)
- Mercury free
- Durable construction: Made from shatterproof materials
- High reliability external driver architecture
- Identical installation to existing fluorescent lamps and ballasts
- UL Approved LED Retrofit Kit: 1598C, LED Driver: 8750 & 1310

LED-B Manufacturer Installation Instructions (One or Two Lamp Luminaire)

1. Switch off the power to the luminaire or verify that it is disconnected before beginning the installation.
2. Open luminaire diffuser and lens, if applicable and remove the existing fluorescent lamp(s).
3. Open or remove the cover for the ballast and wiring channel.
4. Cut all wires connected to the ballast. Cut wire within 12 inches of the existing ballast. The input line voltage wires and wires providing power to the tombstones will be re-used during installation of the Driver.
5. Remove or bypass the starter (if present). STARTER MUST BE REMOVED BEFORE LAMP INSTALLATION.
6. Remove any fastening devices used to mount the ballast to the luminaire (save the fastening devices for installation of the Driver). Slide the ballast out from any mounting clips and remove the ballast.
7. Mount the Driver to the luminaire using the same holes and fasteners as were previously used to mount the fluorescent ballast.
8. On the output side of the Driver, connect the yellow common V- return wire to the yellow (or red) common line(s) of the luminaire.
9. Connect the blue V+ wire from the Driver output to the blue wire for the luminaire tombstones. If there are two lamps, connect both blue V+ wires to the blue wires of the luminaire, one to each tombstone. If there is only one lamp being connected, cap the second blue V+ output wire from the Driver with a wire nut.
10. On the input side of the Driver, connect the black wire to the live wire that supplies power from the AC Mains (108-305V compatible). Connect the white wire on the input side of the Driver to the mains neutral.
11. Affix the Luminaire Retrofit Kit Label (included in the lamp packaging) on the luminaire near the positive end (the end to which the blue wires are connected). The label will provide directional guidance when installing the Lamps.
12. If EnergySaver mode is desired, connect the orange output wire to the grey common wire from the 0-10V dimming output with a wire nut. Cap the purple 0-10V wire with a wire nut.
13. Close the wiring and Driver/Ballast compartment cover on the luminaire.
14. Install either one or two Lamps, as appropriate, for your luminaire using the same method used for conventional fluorescent tubes. The Lamps have positive and negative polarity indicators on each end of the lamp. The end with the positive, plus sign, should be inserted into the tombstone that is connected to the blue positive output wires from the Driver. This end should be indicated by the Luminaire Retrofit Kit Label that was previously installed.
15. If applicable, close or replace the lens or louvers per luminaire manufacturer's instructions.

III. Methodology

A. TECHNICAL OBJECTIVES

This project evaluated two linear LED retrofit technologies for use in GSA facilities to help identify and provide guidance for effective energy savings changes to lighting. The evaluation involves the following actions:

- Identify appropriate technology options;
- Demonstrate the technologies in existing GSA facilities;
- Measure and verify the energy savings, performance, and power-related characteristics of the retrofit products; and
- Develop specification and guidance material for the widespread application of LED technologies where and as appropriate and cost effective.

Particular attention was paid to developing guidance for different LED product types, facility space types, and applications to make the evaluation as generic as possible across GSA sites. The resulting evaluation documentation should provide clear application guidance and cautions that can be used in future retrofit and new construction decisions.

B. CRITERIA FOR SITE SELECTION

Identification of sites for the demonstration and evaluation was made based on specific criteria important in ensuring that useful and applicable data was collected. A survey of the existing lighting fixture types and quantities also was conducted to make sure the site would have the appropriate existing lighting technologies for a successful and useful demonstration and evaluation (see Appendix C for the survey).

The site selection criteria are described below:

1. Strong project advocate. Identify a strong advocate for the project or space or a specific assigned contact with access to the space and operations. This facilitated addressing potential issues with both the space and its operation and occupants.
2. Stable space. Identify spaces or areas with permanent function and not under consideration for discontinued use or change of use, unless this is a specific condition needed for the test. Typically, the demonstration project needs a consistent test environment for useful pre- and post-retrofit data collection.
3. Appropriate space conditions for anticipated technology:
    a. Do spaces or areas exist where the conditions and functions are similar to the expected application of the product?
    b. Is the ceiling type appropriate for the product and for ease of retrofit and metering? Avoid solid (non-drop ceiling grid), unless this is one of the demonstration variables.
    c. Are existing controls contrary to the test criteria? If so, can they be removed or reconfigured? If they can, determine how this might affect any occupant opinions of the retrofit.
4. Reasonable day and nighttime access:

    a. Identify spaces with available nighttime access, when needed. Most non-control lighting measurements typically need to be taken without the variable of daylight, making nighttime access important.
    b. Avoid facilities with additional security constraints. These may come in the form of building access or restrictions associated with the nature of the work in the space.
5. Typical but clean electrical layout:
    a. Avoid spaces or areas where there have been electrical modifications, as this may make clean measurements difficult.
    b. Avoid spaces or areas with configurations that may not be typical.
6. Stable occupants. For retrofit demonstrations in worker environments, avoid interior spaces where occupants are transient or relocate often, as this will severely affect the quality of occupant input.
7. Stable space operation and function. Avoid spaces where operations may be changing during the demonstration period, as this may introduce additional variables to the responses to surveys.

IV. Measurement and Verification Evaluation Plan

A. TECHNOLOGY SPECIFICATION

GSA has an extensive and diverse portfolio of buildings and their requisite lighting systems. The types of luminaires utilized are driven by multiple factors, including building vintage, prevailing energy code at the time of construction, cost-effective lighting technology during procurement, interior design details, floor plan, and remodels. We assumed that the prevailing linear fluorescent technology is T8 lamps with electronic ballasts in lensed troffers. Common practice until the early 2000s was to use enclosed prismatic lenses and open parabolic louvers with two, three, or four lamps. Since then, the installed fixtures trend toward volumetric, high efficiency, and non-planer designs[8] in an effort to mitigate glare and provide a more indirect form of lighting with lower illuminance levels, but with improved uniformity. Because of the directional nature of the TLEDs which are the focus of this study, pre-2000 lensed troffers were selected.

B. FACILITY DESCRIPTION

After extensive evaluation, three sites were identified as appropriate for the LED technology demonstrations. These sites, each of which included specific locations for evaluating both the selected LED technologies, are described in this section.

[8] Volumetric, high efficiency and non-planer designs refer to lensed troffers where the lens is curved or angled around each lamp within the fixture which increases the efficiency of the fixture. The optics of the lens direct light to higher on the wall, which is often characterized as providing a volume of light compared to a “cave effect” of older technologies that tend to light down and light less vertical surfaces.

GSA REGIONAL HEADQUARTERS BUILDING – AUBURN, WASHINGTON

The GSA Regional Headquarters Building is located approximately 30 miles south of Seattle. The building was constructed in 1932 with an addition completed in 1965, and has a footprint of approximately 100,000 ft^2. The study area includes two discrete offices within the facility—Real Estate and Design and Construction, both of which are on the first floor. Both areas are typical open office spaces with partitions (cubical) with some enclosed perimeter offices. General area lighting is provided by prismatic lensed 2’ x 4’ recessed troffers spaced 8’ x 10’ on-center containing two-T8 lamps with electronic ballasts. Existing lighting controls consist of “on”/“off” wall switches. Visual inspection yielded no evidence of de-lamped fixtures, failed lamps or ballasts. Operating hours are typical of an office building with Monday through Friday from 8 AM to 6 PM, although some lighting is energized outside that time period for maintenance purposes.

Figure 8. Exterior photo of GSA Regional Headquarters Building

CABELL FEDERAL BUILDING – DALLAS, TEXAS

The Earle Cabell Federal Building is a 16-story high-rise building located in downtown Dallas that houses various court and other federal agencies. It was constructed in 1971 and has a footprint encompassing approximately 1,000,000 ft2. The study area includes two sections of the seventh floor—Property Management and Project Management. Both spaces include open and private offices and common areas/corridors. General illumination is provided by prismatic lensed 2' x 4' two- and three-T8 lamp electronically ballasted recessed troffers spaced 8' x 10' on-center. Lighting controls consist of "on"/"off" wall switches in all spaces. A visual inspection yielded no evidence of de-lamped fixtures, failed lamps or ballasts. Operating hours are typical of an office building with Monday through Friday operation from 8 AM to 6 PM, although some lighting is energized outside that time period.

Figure 9. Exterior Photo of Cabell Federal Building

VETERANS ADMINISTRATION CENTER – PHILADELPHIA, PENNSYLVANIA

The Veterans Administration (VA) Center is a multi-story complex located north of Philadelphia. It was constructed in 1996 and has a footprint of approximately 400,000 ft^2. The study area comprises the entirety of a lower level daycare facility that includes classrooms, playrooms, restrooms, corridors, and associated support/common areas. The predominant general area luminaires are drop-lens semi-opaque 2' x 4' three-T8 lamp electronically ballasted recessed troffers spaced 8' x 8' on-center. Visual inspection indicated several failed lamps or ballasts. Lighting controls consist of "on"/"off" wall switches in all spaces. Operating hours are atypical of an office building to accommodate early drop-off of children. Typical hours of operation are Monday through Friday from 7 AM to 6 PM, although some lighting is energized outside that time period for daily maintenance.

Figure 10. Exterior Photo of Philadelphia VA Facility

C. TEST PLAN

Specific M&V tasks to support the evaluation included:

1. Develop and administer a pre- and post-retrofit survey to identify occupant issues and general acceptance of the retrofit lighting conditions. The survey was administered to occupants of test areas. Survey questions were crafted to capture both existing condition issues (to assist with future retrofit planning) and any post-retrofit technology/application issues that might apply across various GSA sites and building types.
2. Identify spaces or areas within facilities that meet project evaluation needs. Areas should be large enough to accommodate both reasonable measurement grids and occupant numbers for meaningful survey input. Where possible, areas should be separated from other existing or retrofit areas to avoid mixing of occupant reactions and lighting applications.
3. Develop and administer a product performance measurement plan to collect all useful data for each technology both before and after technology installation.
    a. Pre- and post-retrofit light levels will be measured using handheld illuminance meters over a uniform horizontal grid or specific point measurement system depending on the technology and area configuration. The same measurement system will be applied for before-and-after measurements in each area.
    b. Light-level and luminous intensity measurements in vertical orientations or other planes will be made as needed based on application needs.
    c. Electrical measurements of pre- and post-retrofit LED fixtures will be made to confirm the energy saving potential of the retrofit products.

Other objectives of the evaluation included:

1. Develop applicable cost-effectiveness calculation methods to determine the conditions under which various technology options may be cost-effective.
2. Prepare specification and guidance information that will be useful to facilities and project personnel in making product and application decisions.

D. INSTRUMENTATION PLAN

The instrumentation described below was used to capture photometric performance data, as well as electrical power data, on both pre- and post-retrofit products and their application:

1. Minolta illuminance meter. This instrument was used to measure the illuminance provided by the pre- and post-retrofit lighting products on horizontal and vertical surfaces. These data are used to compare light levels and potential lighting uniformity throughout the space.
2. Photo Research luminance meter. This instrument was used to evaluate the relative luminous intensity of pre- and post-retrofit fixtures as a way of comparing lighting glare in the space from different products.
3. Contractor electrical measurement equipment. The installation contractors supplied their own equipment to measure the power (*e.g.*, amps and volts) draw of the pre- and post-retrofit products. These data were used to confirm the potential energy savings from application of the LED technology.

V. Results

The following sections present the results of the data analysis and other evaluations of the product installations and an overview of the LED market and current technology status.

A. ILLUMINATION (LIGHT-LEVEL) COMPARISONS

An important part of any lighting retrofit is achieving the correct or desired light levels and maintaining, or improving the original lighting design. A large part of this project was an evaluation of how well LED technologies could match existing florescent lighting system light levels and uniformity. The following charts provide a view of the photometric performance of the LED technologies in comparison with the original LFLs. Charts are provided showing comparisons of:

- Horizontal illuminance (light levels and distribution on floor or desk top surfaces). These data relate to the primary purpose of the lighting to illuminate tasks and general areas.
- Vertical illuminance (light levels and distribution on wall surfaces). These data help identify how well each technology provides vertical light for surfaces and faces.
- Normalized percent change (the percent change from the normalized base case fluorescent to the normalized LED-A or LED-B). Normalizing consists of taking the ratio of the absolute illuminance measurements to the average of all measurements taken in the given space. Normalizing both the base case fluorescent and LED-A and LED-B effectively removes the variation in light levels between technologies and existing states of lumen depreciation, thereby allowing for comparisons of light distribution and uniformity. Note that there are instances where the normalized percent change (either positive or negative) and magnitude are contrary to the absolute measurements shown. The data are correct as the process of normalizing removes absolute comparison.

The measurement points in each evaluation area were generally arranged as a grid of measurements. However, the data is presented as a direct comparison of individual measurement points in a given space, that is to say, obstacles such as furniture, partitions, and building structural elements, are included in measurement points that may not be in the same plane as the other measurements taken. Thus the measurements provide a space specific comparison between the base case fluorescent and LED-A and LED-B, respectively.

It is important to note that these data represent specific site applications of the specific products. Other site applications and other similar format products could perform the same or vastly different (better or worse) depending on the situation and product. These data should be considered to be instructive in evaluating real world applications of LED products but are not intended to, nor do they definitively, determine the appropriateness of these specific applications. Final application of LED products to actual projects depends on many factors.

AUBURN

AUBURN REAL ESTATE (LED-A)

Figure 11 are photographs of the Auburn Real State office showing the location of horizontal and vertical measurement points. Figure 12 is a sketch indicating the fixture layout, room geometry and horizontal measurement points that correspond to the data represented in Figure 13.

Figure 11. Photographs of the Auburn Facility Real Estate Area

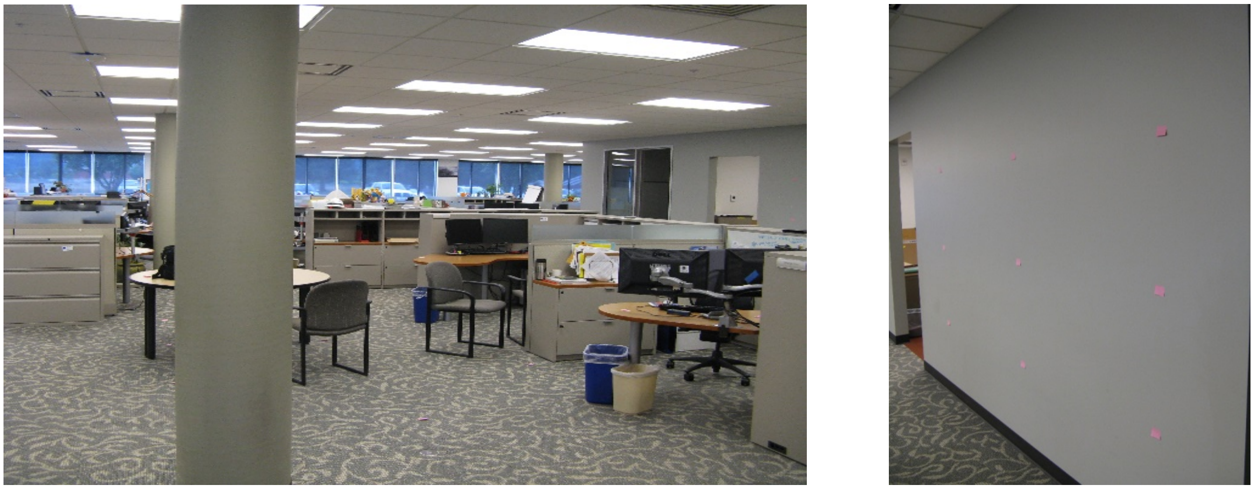


Figure 12. Sketch of Auburn Real Estate Horizontal Measurement Points (LED-A)

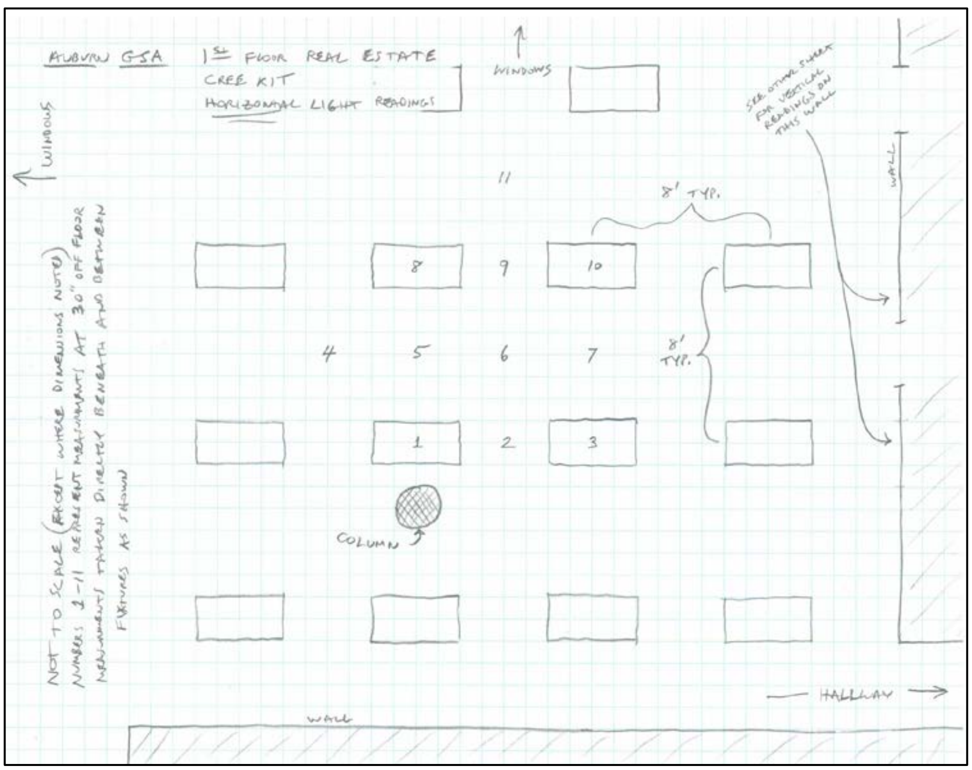


Figure 13 shows the measured horizontal illuminance for both the base case fluorescent and LED-A with values on the primary axis. The solid colored lines represent the average of all data taken for each technology, and generally represent the system lighting condition. The black line is the design condition set forth in PBS P-100 (*e.g.,* 300 lux). The data indicate LED-A delivers ~15 percent higher light levels than the depreciated base case fluorescent and both significantly exceed the P-100 threshold, indicating the space is currently over lighted. The data further indicates the distribution and associated uniformity of LED-A closely mirrors the base case fluorescent with very little variation as evidenced by the normalized percent change of less than 5 percent over all measurement points.

Figure 13. Auburn Real Estate (LED-A). Horizontal Illuminance and Normalized Percent Change

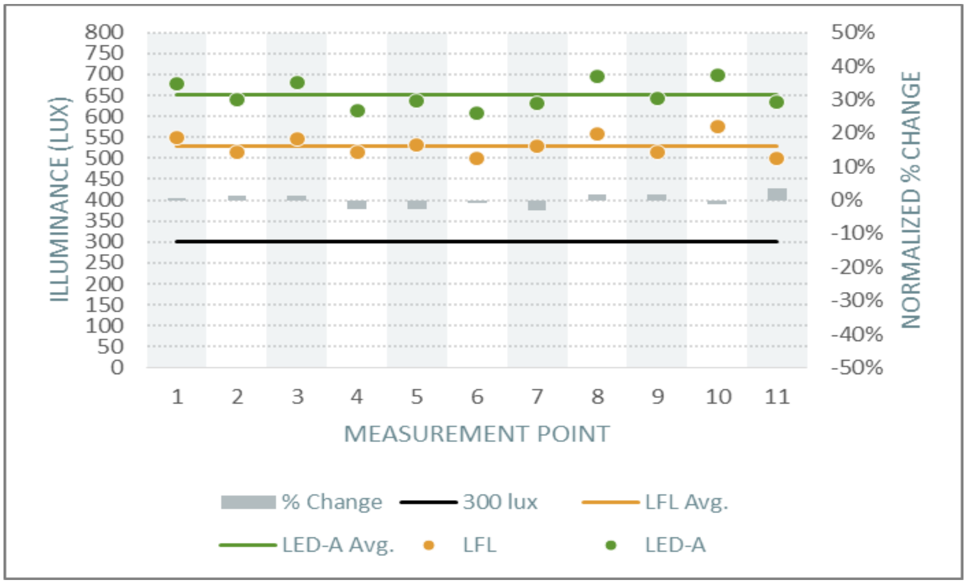


Figure 14 is a sketch indicating the fixture layout, room geometry and vertical measurement points that correspond to the data represented in Figure 15.

Figure 14. Sketch of Auburn Real Estate Vertical Measurement Points (LED-A)

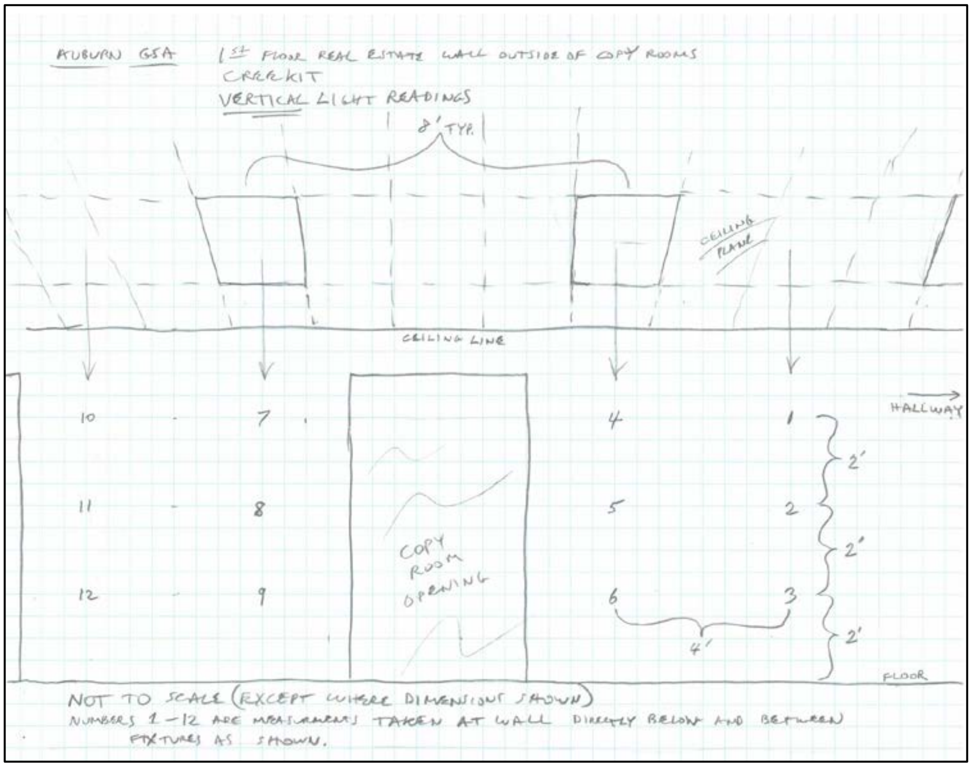
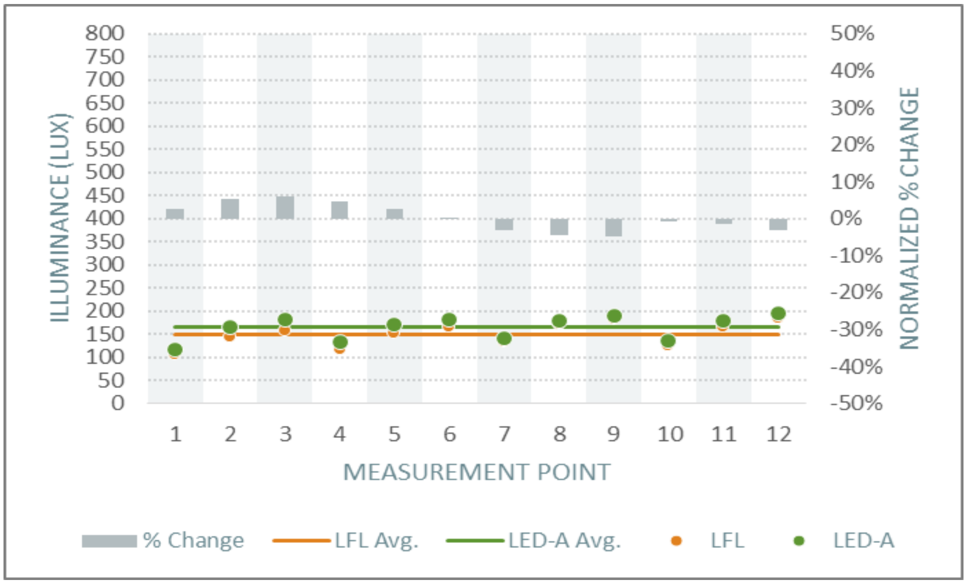


Figure 15 shows the measured vertical illuminance for both the base case fluorescent and LED-A with values on the primary axis. The solid colored lines represent the average of all data taken for each technology, and generally represent the system lighting condition. The data indicate LED-A delivers near-identical light levels compared to the depreciated base case fluorescent. The data further indicates the distribution and associated uniformity of LED-A closely mirrors the base case fluorescent with very little variation as evidenced by the normalized percent change of less than 10 percent over all measurement points.

Figure 15. Auburn Real Estate (LED-A). Vertical Illuminance and Normalized Percent Change



AUBURN DESIGN AND CONSTRUCTION (LED-B)

Figure 16 are photographs of the Auburn Design and Construction office showing the location of horizontal and vertical measurement points. Figure 17 is a sketch indicating the fixture layout, room geometry and horizontal measurement points that correspond to the data represented in Figure 18.

Figure 16. Photos of Auburn Design and Construction

Figure 17. Sketch of Auburn Design and Construction Horizontal Measurement Points (LED-B)

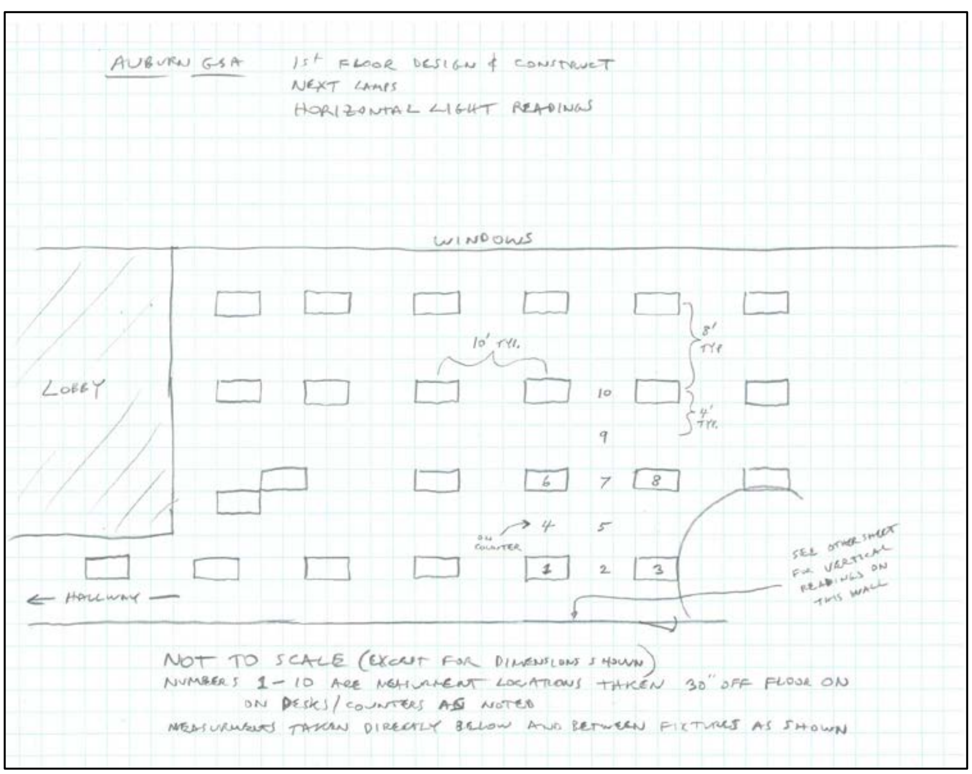


Figure 18 shows the measured horizontal illuminance for both the base case fluorescent and LED-B with values on the primary axis. The solid colored lines represent the average of all data taken for each technology, and generally represent the system lighting condition. The black line is the design condition set forth in PBS P-100 (*e.g.*, 300 lux). The data indicate LED-B delivers ~30% higher light levels than the depreciated base case fluorescent and both significantly exceed the P-100 threshold, indicating the space is currently over lighted. The data further indicates the distribution and associated uniformity of LED-B mirrors the base case fluorescent with peak variation below 15 percent and the majority of points in single digits.

Figure 18. Auburn Design and Construction (LED-B). Horizontal Illuminance and Normalized Percent Change

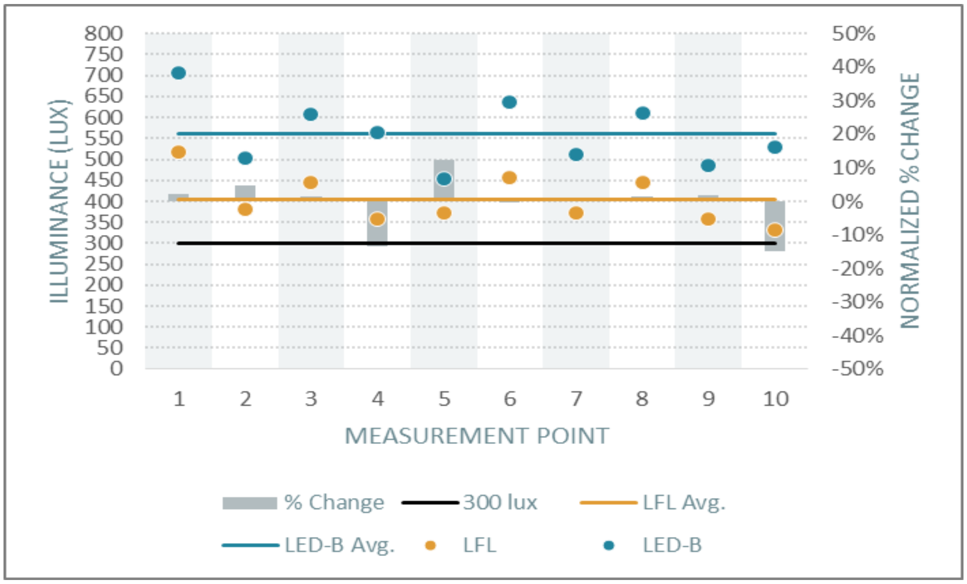


Figure 19 is a sketch indicating the fixture layout, room geometry and vertical measurement points that correspond to the data represented in Figure 20.

Figure 19. Sketch of Auburn Design and Construction Vertical Measurement Points (LED-B)

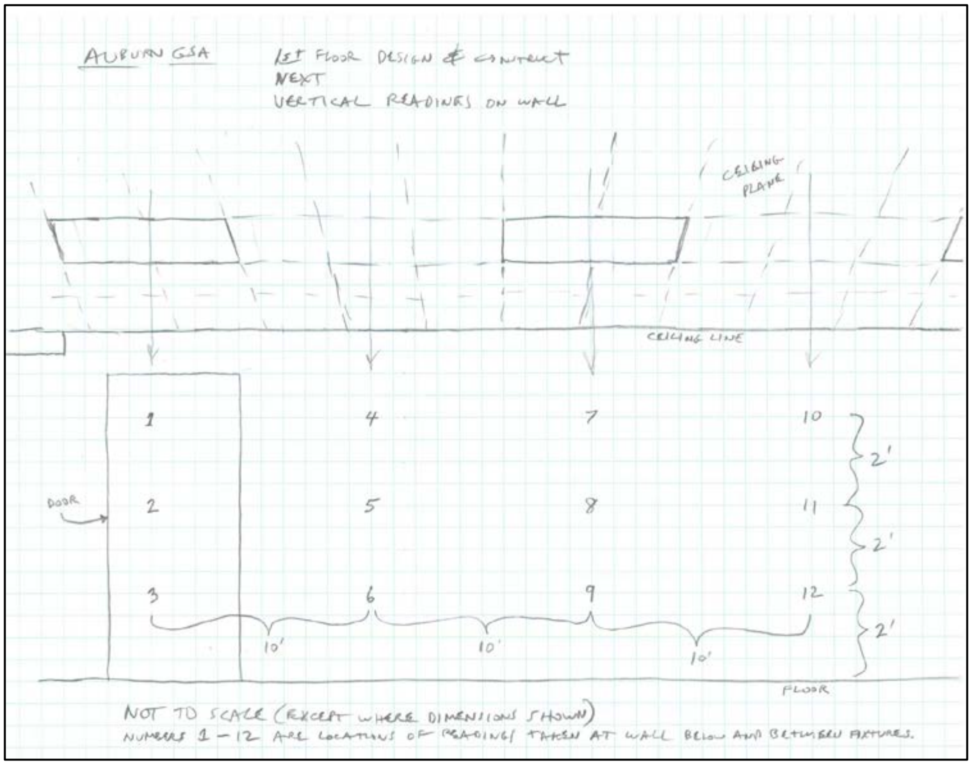
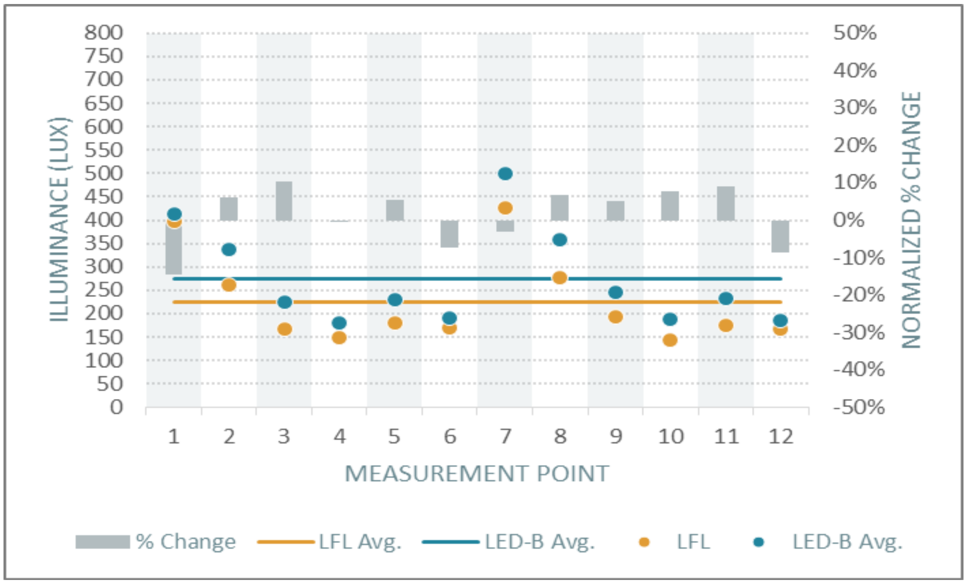


Figure 20 shows the measured vertical illuminance for both the base case fluorescent and LED-B with values on the primary axis. The solid colored lines represent the average of all data taken for each technology, and generally represent the system lighting condition. The data indicate LED-B delivers near-identical light levels compared to the depreciated base case fluorescent. The data further indicates the distribution and associated uniformity of LED-B mirrors the base case fluorescent with minimal variation as evidenced by the normalized percent change of 15 percent or less over all measurement points.

Figure 20. Auburn Design and Construction (LED-B) – Vertical Illuminance and Normalized Percent Change



DALLAS

DALLAS PROPERTY MANAGEMENT (LED-A)

Figure 21 are photographs of the Dallas Property Management showing the location of horizontal and vertical measurement points. Figure 22 is a sketch indicating the fixture layout, room geometry and horizontal measurement points that correspond to the data represented in Figure 23. The existing fixtures in Property Management were three-lamp fluorescent and GSA chose to install the two-lamp version of LED-A.

Figure 21. Photos of Dallas Property Management

Figure 22. Sketch of Dallas Property Management Horizontal Measurement Points (LED-A)

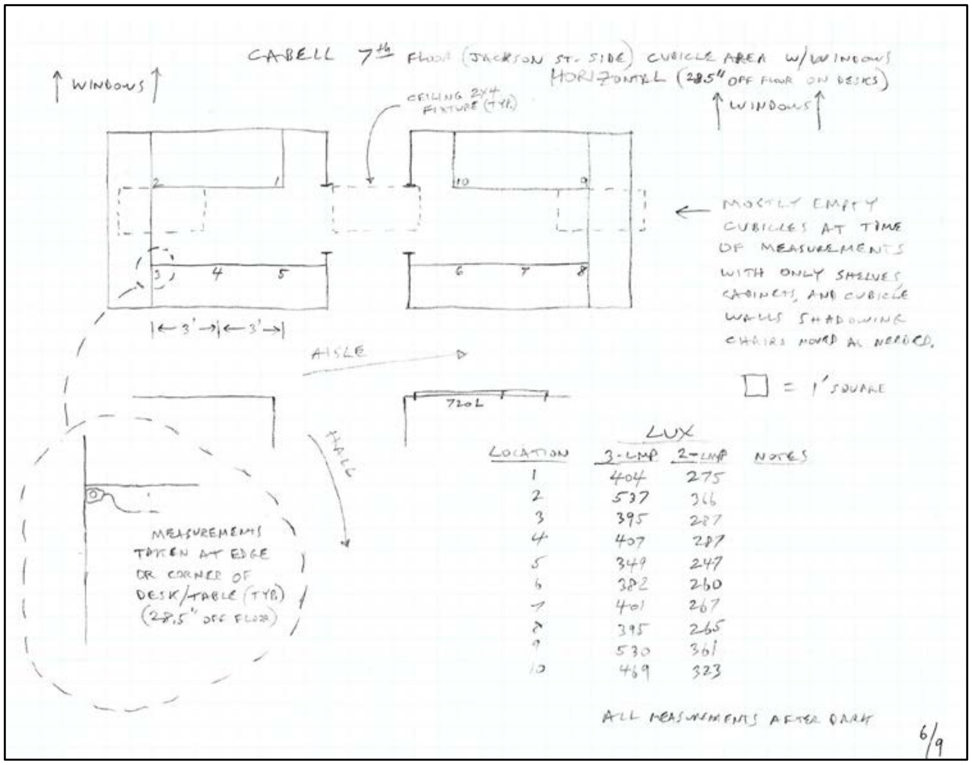


Figure 23 shows the measured horizontal illuminance for both the base case fluorescent and LED-A with values on the primary axis. The solid colored lines represent the average of all data taken for each technology, and generally represent the system lighting condition. The black line is the design condition set forth in PBS P-100 (*e.g.,* 300 lux). The data indicate that the existing three-lamp fluorescent system meets the P-100 threshold, while the two-lamp LED-A delivers ~42 percent less; significantly under lighting the space. Clearly, a three-lamp version of LED-A would have provided a more comparable light level. That said, the data further indicates the distribution and associated uniformity of LED-A closely mirrors that of the base case fluorescent with very little variation, as evidenced by the normalized percent change of less than 5 percent over all measurement points.

Figure 23. Dallas Property Management Horizontal Illuminance and Normalized Percent Change (LED-A)

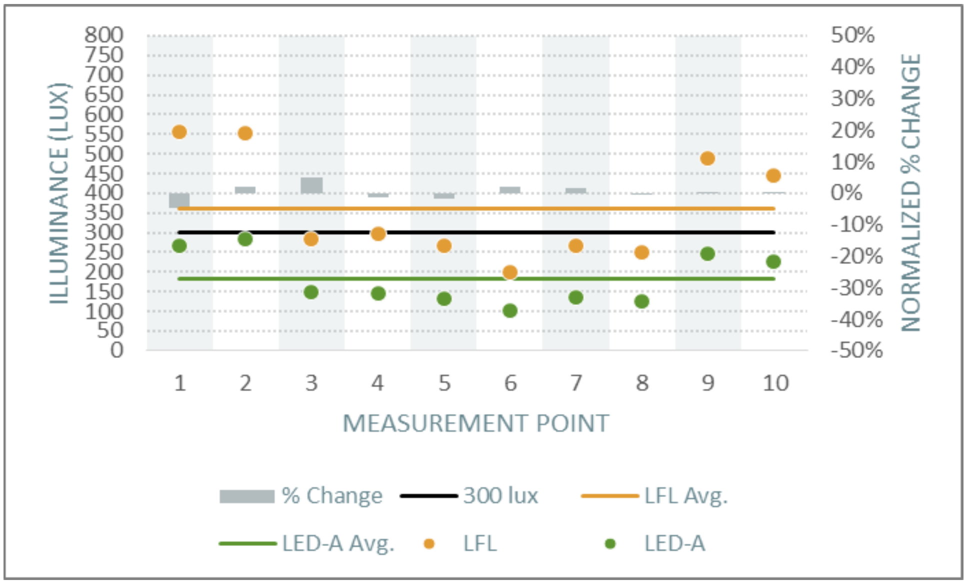


Figure 24 is a sketch indicating the fixture layout, room geometry and vertical measurement points that correspond to the data represented in Figure 25.

Figure 24. Sketch of Dallas Property Management Vertical Measurement Points (LED-A)

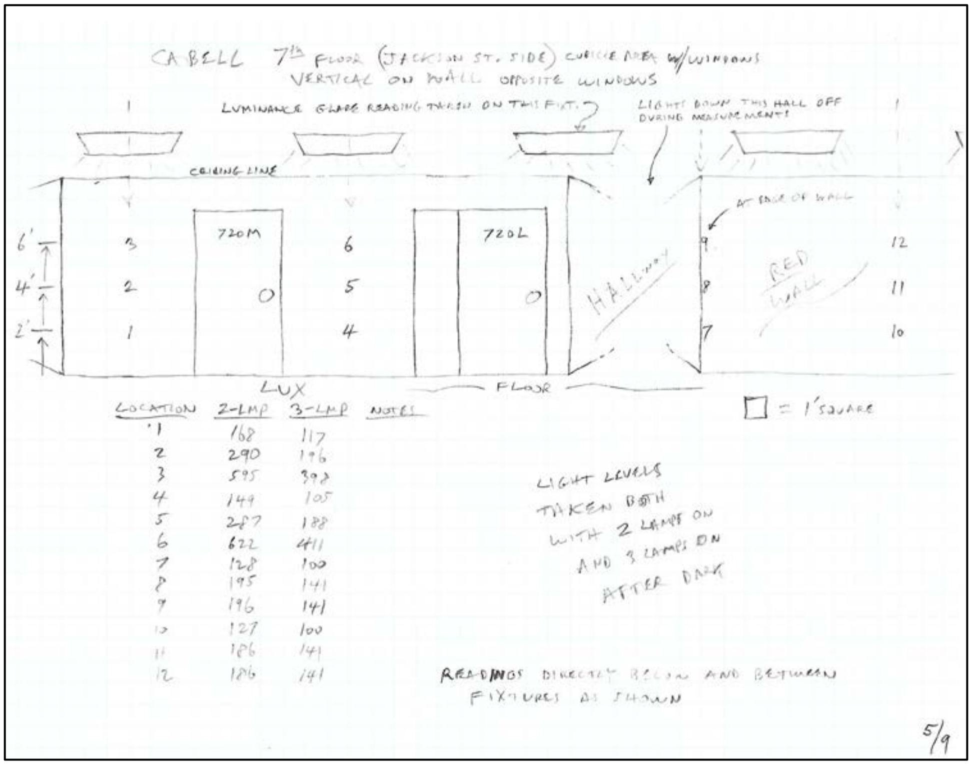
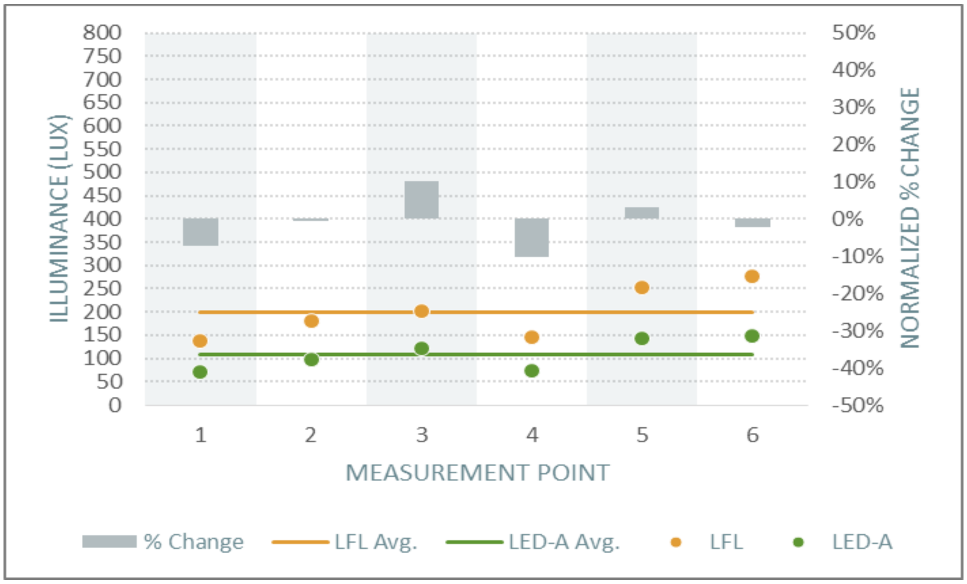


Figure 25 shows the measured vertical illuminance for both the base case fluorescent and LED-A with values on the primary axis. The solid colored lines represent the average of all data taken for each technology, and generally represent the system lighting condition. As was seen with the horizontal measurements, the reduced light output of the two-lamp LED-A delivers lower vertical illuminance. The data indicates the distribution and associated uniformity of LED-A is similar to the base case fluorescent with little variation, as evidenced by the normalized percent change of less than 10 percent over all measurement points. However, it is likely that the lower vertical illuminance levels contributed more to the overall variation because there is less light contribution from adjacent fixtures in vertical wall measurements.

Figure 25. Dallas Property Management Vertical Illuminance and Normalized Percent Change (LED-A)



DALLAS PROJECT MANAGEMENT (LED-B)

Figure 26 are photographs of the Auburn Design and Construction office showing the location of horizontal and vertical measurement points. Figure 27 is a sketch indicating the fixture layout, room geometry and horizontal measurement points that correspond to the data represented in Figure 28. The existing fixtures in Project Management were three-lamp fluorescent and GSA chose to install the two-lamp version of LED-B.

Figure 26. Photos of Dallas Project Management

Figure 27. Sketch of Dallas Project Management Horizontal Measurement Points (LED-B)

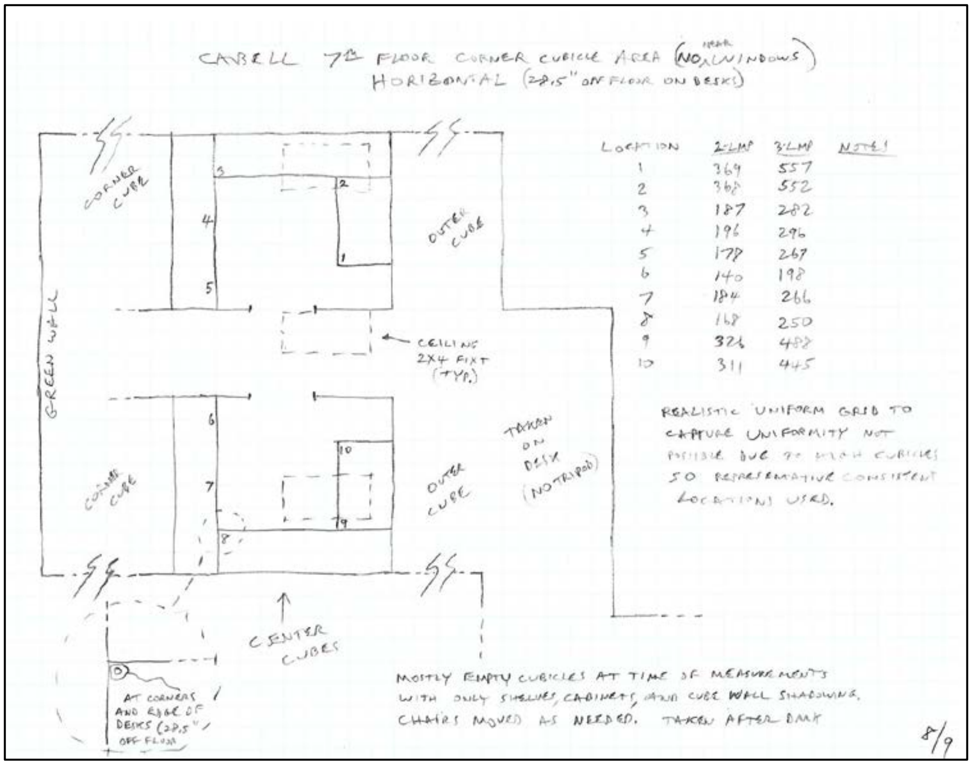


Figure 28 shows the measured horizontal illuminance for both the three-lamp base case fluorescent and two-lamp LED-B with values on the primary axis. The solid colored lines represent the average of all data taken for each technology, and generally represent the system lighting condition. The black line is the design condition set forth in PBS P-100 (*e.g.,* 300 lux). The data indicate the two-lamp LED-B delivers nearly identical light levels compared to the depreciated three-lamp base case fluorescent with both exceeding the P-100 threshold by approximately 30 percent, indicating the space is currently over lighted. The data further indicates the distribution and associated uniformity of LED-B mirrors the base case fluorescent, with peak variation below 10 percent and the majority of points in single digits.

Figure 28. Dallas Project Management Horizontal Illuminance and Normalized Percent Change (LED-B)

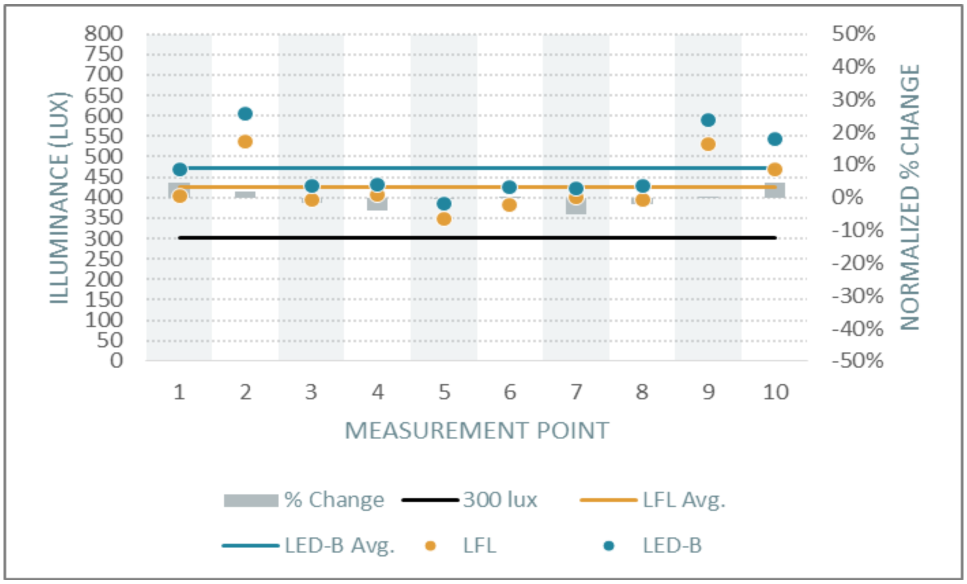
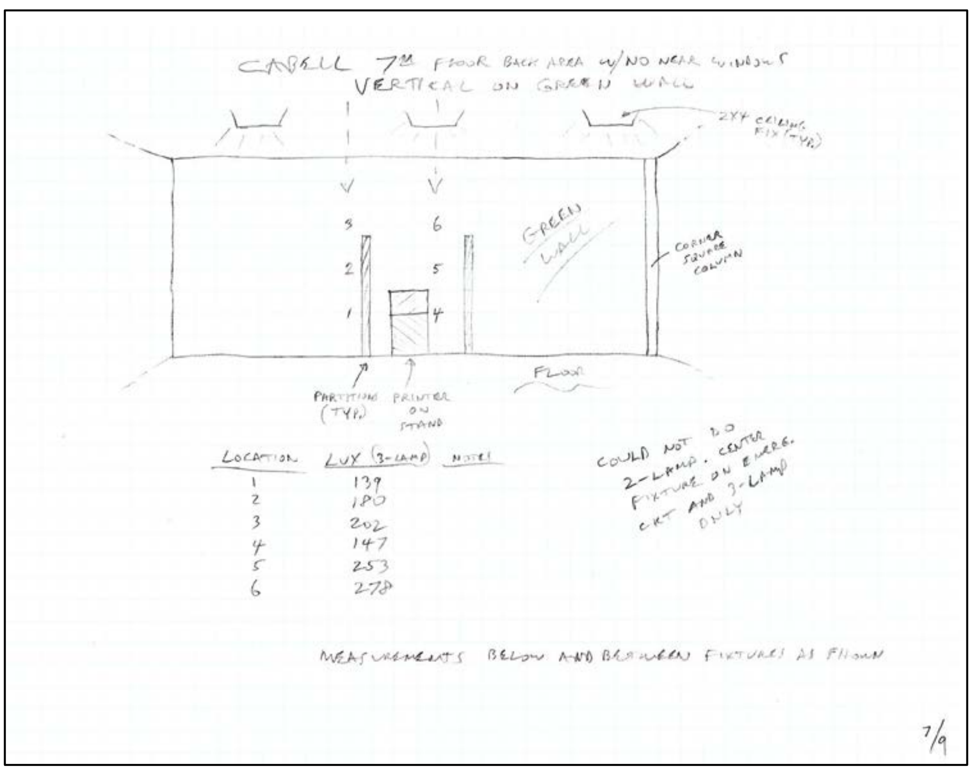


Figure 29 is a sketch indicating the fixture layout, room geometry and vertical measurement points that correspond to the data represented in Figure 30.

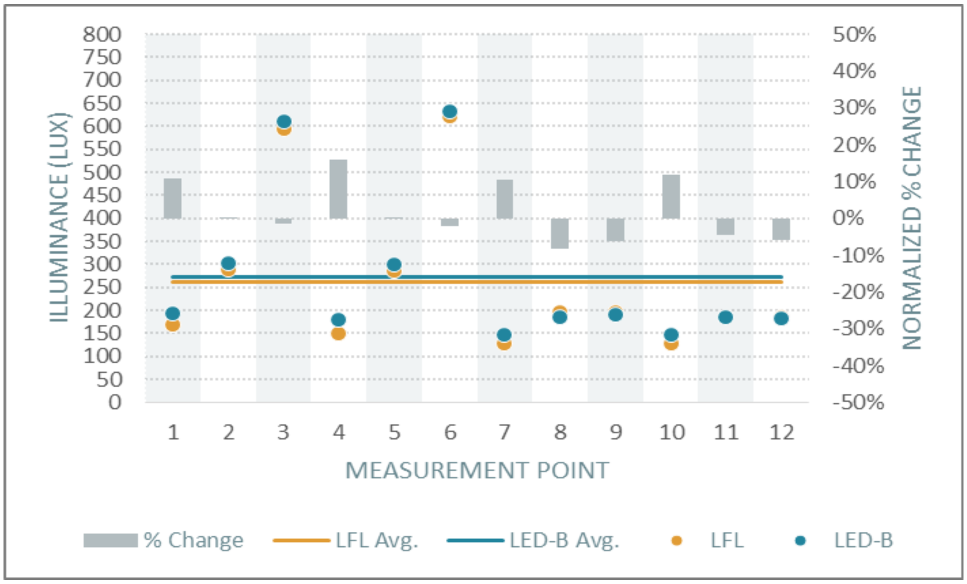
Figure 29. Sketch of Dallas Project Management Vertical Measurement Points (LED-B)



The vertical (wall) comparison shows almost identical distribution, with LED-B product light levels comparable to the original fluorescent system with all three lamps on.

Figure 30 shows the measured vertical illuminance for both the base case three-lamp fluorescent and two-lamp LED-A with values on the primary axis. The solid colored lines represent the average of all data taken for each technology, and generally represent the system lighting condition. The data indicate LED-A delivers near-identical light levels compared to the depreciated base case fluorescent. The data further indicates the distribution and associated uniformity of LED-A closely matches the base case fluorescent, with only slight variation as evidenced by the normalized percent change being less than 15 percent over all measurement points.

Figure 30. Dallas Project Management Vertical Illuminance and Normalized Percent Change (LED-B)



PHILADELPHIA

PHILADELPHIA CLASSROOM 460 (LED-A)

Figure 31 is a photograph of Philadelphia Daycare Classroom 460 showing the location of the horizontal measurement points (vertical measurements were not taken due to obstacles in the environment). Figure 32 is a sketch indicating the fixture layout, room geometry and horizontal measurement points that correspond to the data represented in Figure 33. The existing fixtures in Classroom 460 were three-lamp fluorescent and GSA chose to install the two-lamp version of LED-A.

Figure 31. Photo of Philadelphia Daycare Classroom 460

Figure 32. Sketch of Philadelphia Daycare Classroom 460 Horizontal Measurement Points (LED-A)

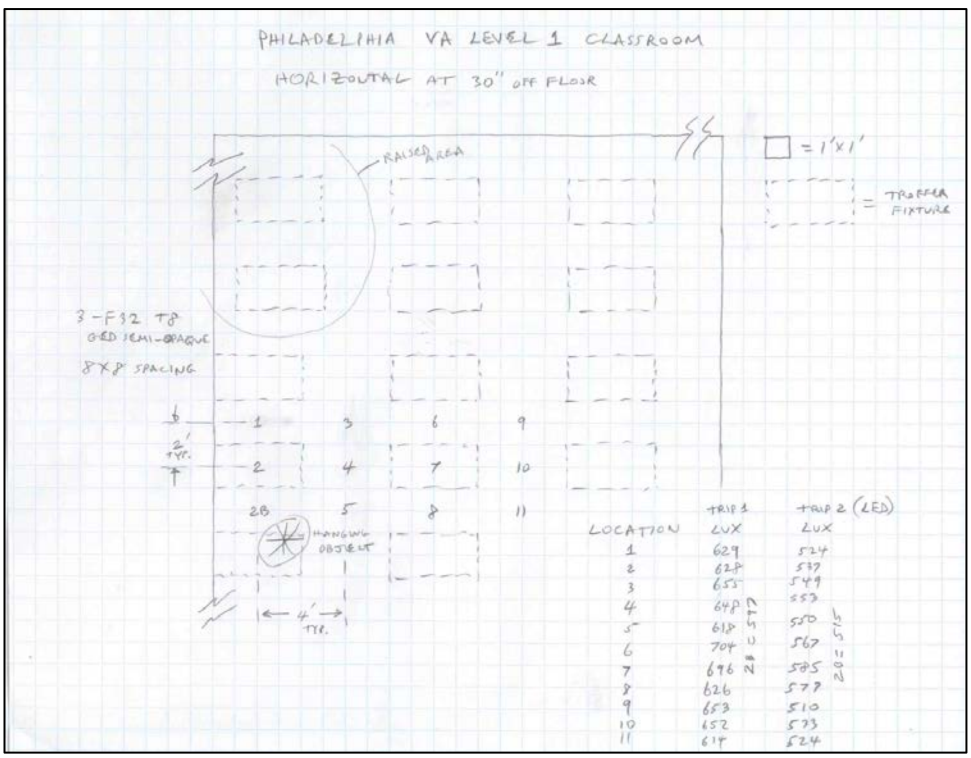
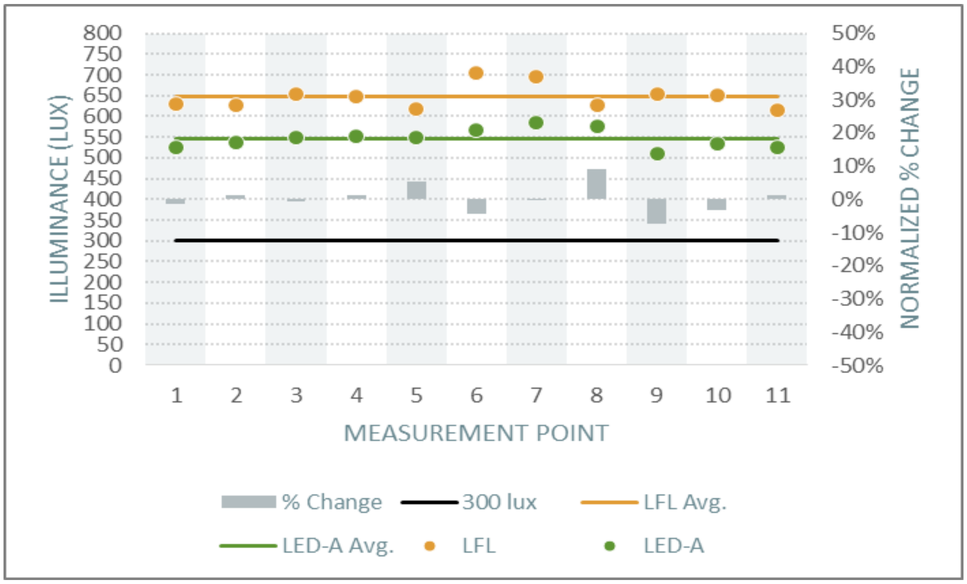


Figure 33 shows the measured horizontal illuminance for both the three-lamp base case fluorescent and two-lamp LED-A with values on the primary axis. The solid colored lines represent the average of all data taken for each technology, and generally represent the system lighting condition. The black line is the design condition set forth in PBS P-100 (*e.g.,* 300 lux). The data indicate LED-A delivers ~15 percent lower light levels than the depreciated base case fluorescent and both significantly exceed the P-100 threshold, indicating the space is currently over lighted. The data further indicates the distribution and associated uniformity of LED-A closely mirrors the base case fluorescent with very little variation, as evidenced by the normalized percent change of less than 10 percent over all measurement points.

Figure 33. Philadelphia Daycare Classroom 460 Horizontal Illuminance and Normalized Percent Change (LED-A)



PHILADELPHIA PLAYROOM 405 (LED-A)

Figure 34 is a photograph of Philadelphia Daycare Playroom 405 showing the location of the horizontal measurement points (vertical measurements were not taken due to obstacles in the environment). Figure 35 is a sketch indicating the fixture layout, room geometry and horizontal measurement points that correspond to the data represented in Figure 36. The existing fixtures in Playroom 405 were three-lamp fluorescent and GSA chose to install the two-lamp version of LED-A.

Figure 34. Photo of Philadelphia Daycare Playroom 405

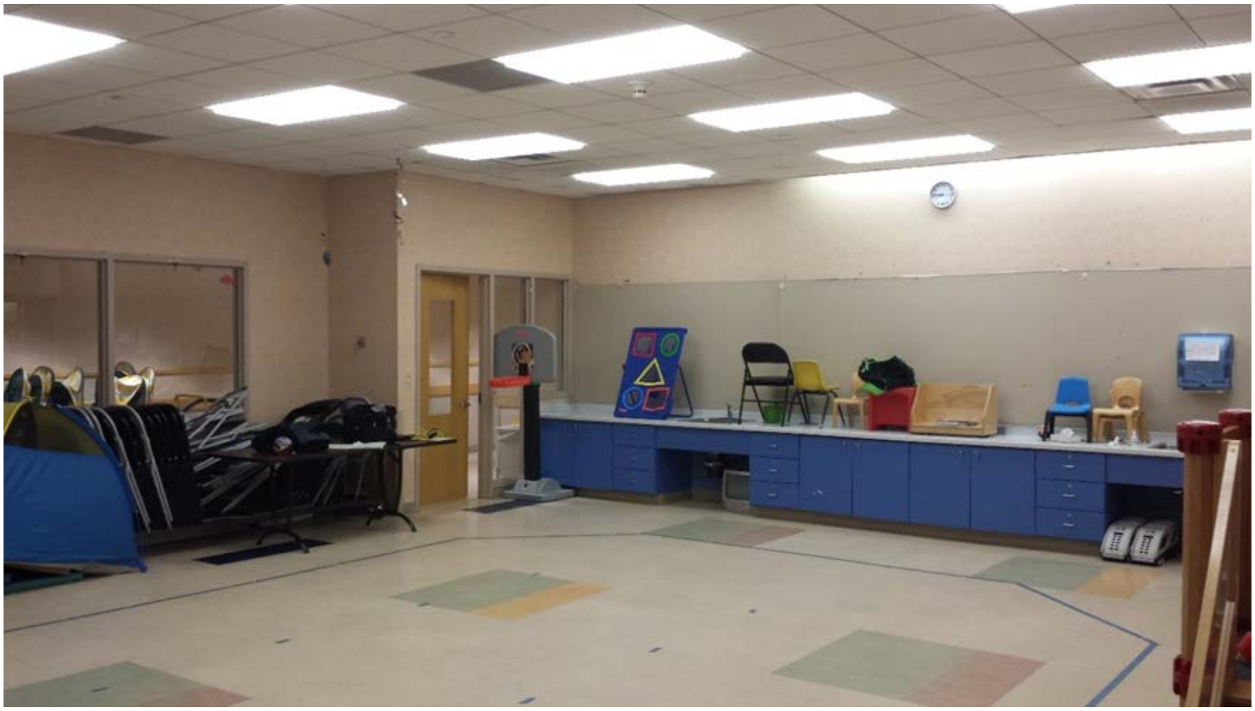


Figure 35. Sketch of Philadelphia Daycare Playroom 405 Horizontal Measurement Points (LED-A)

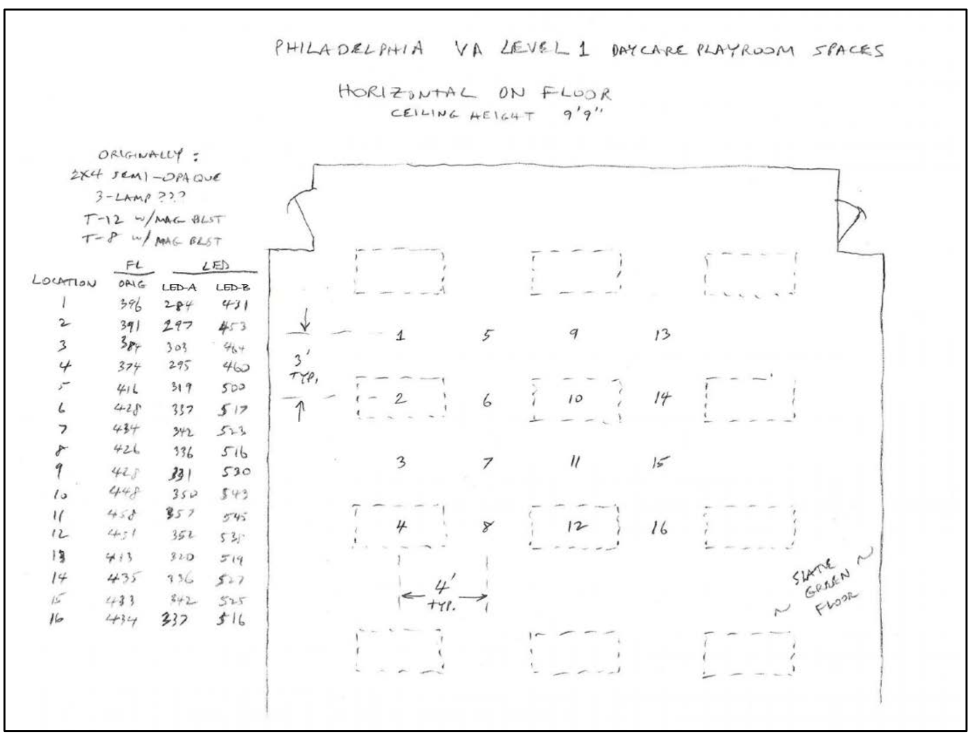
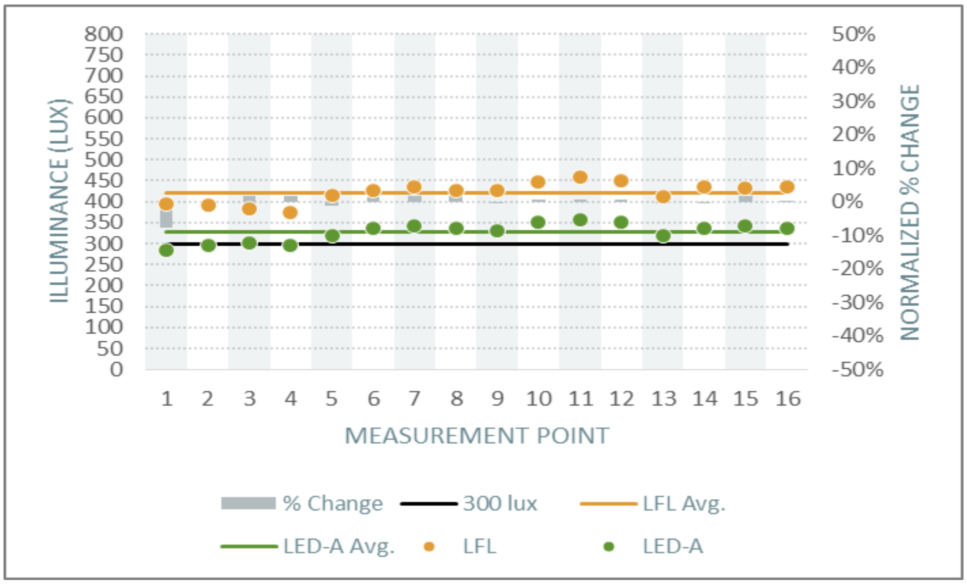


Figure 36 shows the measured horizontal illuminance for both the three-lamp base case fluorescent and two-lamp LED-A with values on the primary axis. The solid colored lines represent the average of all data taken for each technology, and generally represent the system lighting condition. The black line is the design condition set forth in PBS P-100 (*e.g.,* 300 lux). The data indicate LED-A delivers ~15 percent lower light levels than the depreciated base case fluorescent, but still meeting the P-100 threshold. The data further indicates the distribution and associated uniformity of LED-A very closely mirrors the base case fluorescent with only slight variation, as evidenced by the normalized percent change of less than 5 percent over all measurement points.

Figure 36. Philadelphia Daycare Playroom 405 Horizontal Illuminance and Normalized Percent Change (LED-A)



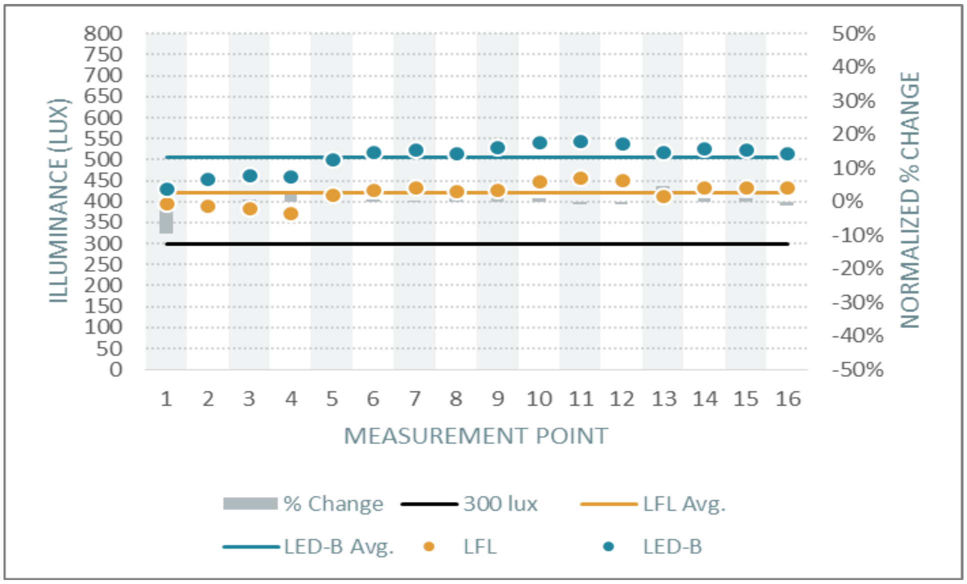
PHILADELPHIA PLAYROOM 413 (LED-B)

Figure 37 is a photograph of Philadelphia Playroom 413 showing the location of the horizontal measurement points (vertical measurements were not taken due to obstacles in the environment). Figure 35 (Playrooms 405 and 413 are identical) is a sketch indicating the fixture layout, room geometry and horizontal measurement points that correspond to the data represented in Figure 38. The existing fixtures in Playroom 413 were three-lamp fluorescent and GSA chose to install the two-lamp version of LED-B.

Figure 37. Photo of Philadelphia Daycare Playroom 413

Figure 38 shows the measured horizontal illuminance for both the three-lamp base case fluorescent and two-lamp LED-B with values on the primary axis. The solid colored lines represent the average of all data taken for each technology, and generally represent the system lighting condition. The black line is the design condition set forth in PBS P-100 (*e.g.,* 300 lux). The data indicate LED-B delivers ~15 percent higher light levels than the depreciated base case fluorescent and significantly exceeds the P-100 threshold. The data further indicates the distribution and associated uniformity of LED-B very closely mirrors the base case fluorescent with very little variation, as evidenced by the normalized percent change of less than 5 percent over all measurement points.

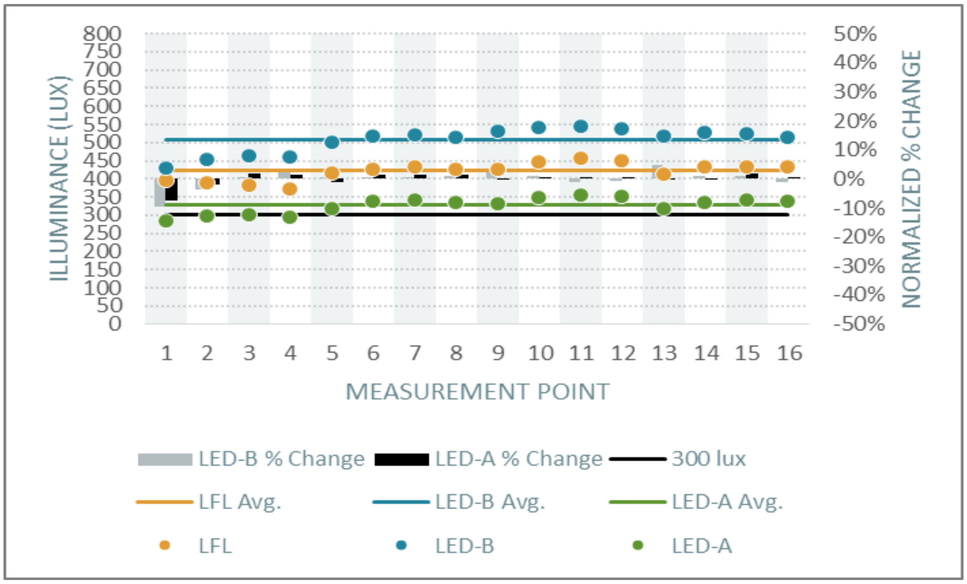
Figure 38. Philadelphia Daycare Playroom 413 Horizontal Illuminance and Normalized Percent Change (LED-B)



PHILADEPLHIA PLAYROOMS DIRECT COMPARISON (LED-A AND LED-B)

Figure 39 represents the only direct comparison of LED-A and LED-B in identical installations. The figure shows the measured horizontal illuminance for the three-lamp base case fluorescent, two- lamp LED-A and two-lamp LED-B with values on the primary axis. The solid colored lines represent the average of all data taken for each technology, and generally represent the system lighting condition. The black line is the design condition set forth in PBS P-100 (*e.g.,* 300 lux). The data indicate LED-B delivers ~15 percent higher light levels compared to the depreciated base case fluorescent and LED-A delivers ~15 lower light levels than the depreciated base case fluorescent, but still meets the P-100 threshold. The data further indicates the distribution and associated uniformity of both LED-A and LED-B very closely mirrors the base case fluorescent with very little variation, as evidenced by the normalized percent change of less than 5 percent over all measurement points.

Figure 39. Philadelphia Daycare Playrooms 405 and 413 Combined Horizontal Illuminance and Normalized Percent Change (LED-A and LED-B)



B. LIGHTING INTENSITY COMPARISONS (GLARE POTENTIAL)

Luminous intensity is a measure of brightness when viewing an object such as a lighting fixture. This intensity can be related to various forms of glare and it is important to assess if and how there may be increased glare issues with any new technology. As part of this project, data were collected to help evaluate the potential for problematic glare for various fixtures and technologies.

These charts provide a relative comparison of the brightness the human eye may see when looking directly at a lighting fixture. These values can be very high when looking up at a fixture from directly below or at steep angles. However, occupants typically view fixtures in the room at a much shallower angle related to fixtures in a typical field of view of the office environment. Typical viewing distances from fixtures in an office environment will be eight feet or more. For comparisons of potential changes in glare, each chart below shows the intensity from the viewpoint of an occupant starting at approximately 8 feet away to as far as 20 feet away.

Troffers have distinct long and short axis orientations; therefore, intensity measurements are taken across both axes to represent a majority of viewing possibilities. Also, the view of a larger fixture can encompass variations in brightness based on the brightness of the actual lamp versus spaces between lamps in fixtures. Therefore, measurements were made at points on the fixture that seemed to represent a maximum and minimum intensity value. However, as the viewing distance got larger, minimum and maximum intensities tended to disappear and, therefore, only single values were taken.

LED-B TROFFER RETROFITS

Figure 40 and Figure 41 show the LED-B product intensity data compared with the same pre-retrofit fluorescent troffer taken at the Dallas site. The values have been normalized such that they represent the intensities that would exist if the replaced fluorescent lamp had the exact same output as the LED lamps. The intensity levels show that, viewing directly from the long axis, the LED product has much more variability of intensity within the viewing area with potentially much brighter maximum intensity. This could indicate the potential for increased glare to occupants depending on their viewing angle. Taking the brightest spot on the fixtures, the intensities represent possible contrast ratios (bright spot on fixture to surrounding ceiling) of less than 10:1 and 18:1 (with typical 50 lux ceiling illuminance) depending on how far away the viewer is located (8 to 20 feet). The same values for the fluorescent fixture are approximately 8:1 (little variance across the fixture). The LED contrast ratios would be considered high when looking at uniformity on a work surface for performing tasks on that surface. However, the viewing of bright spots at a distance is a different situation and some studies on glare have noted that contrast ratios between 10:1 and 100:1 can be acceptable, with ratios above 100:1 causing glare. Another study suggests that lighting intensity above 1500 cd/m^2 is likely to cause glare. Neither condition exists in this case.

Another calculated measure of glare that is the Unified Glare Rating (UGR). This glare rating, as well as others, depends heavily on the position of the viewer. Glare ratings are subjective with respect to the viewer and their surroundings, so it is difficult to assign a specific or single glare metric to a fixture for all applications. For the installations in this study, a UGR rating was calculated based on the location of the intensity measurements taken and estimates of surrounding conditions. In the case of the LED-B long axis in the Dallas facility, the UGR values range from 15.3 to 11.7 depending on the distance from the fixture in the field of view. These are in the less than perceptible range and well below where glare becomes “just acceptable” (UGR of 19).

The short axis data shows similar contrast ratios of 8:1 for the fluorescent product but lower contrast ratios of 11:1 to 7:1 for the LED product with corresponding lower UGR ratings ranging from 12.1 to 8.5. The values for both long and short axes indicate that the LED product does present more variability in brightness within the fixture and, based on calculations, may present more potential for glare. However, compared to established metrics, the LED product does not show values that exceed established glare metric levels. It is important to note that even with good or bad number ratings available, actual glare issues are often best determined from actual occupant input. See the occupant survey results provided in this report for more glare evaluation.

Figure 40. Dallas Project Management Luminous Intensity – Long Axis (LED-B)

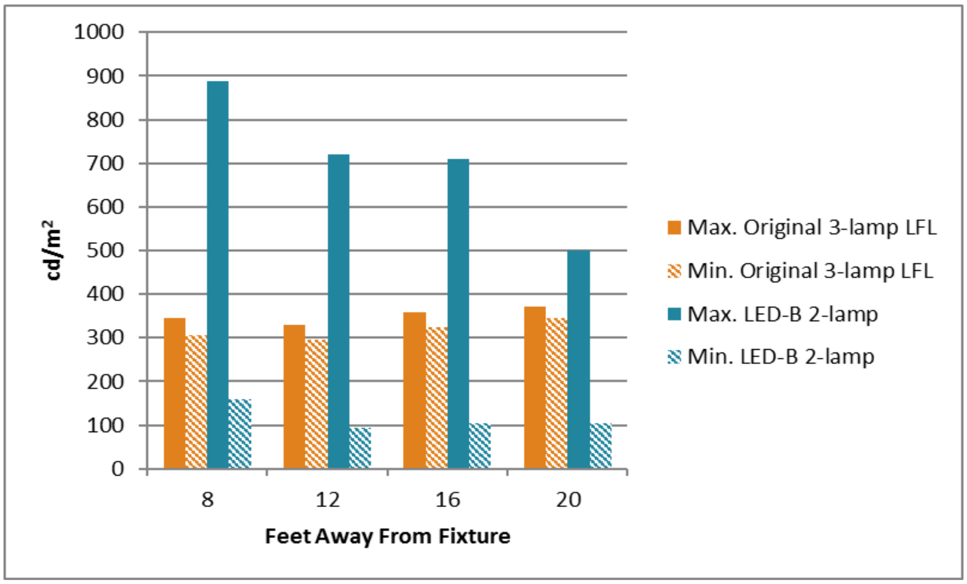


Figure 41. Dallas Project Management Luminous Intensity – Short Axis (LED-B)

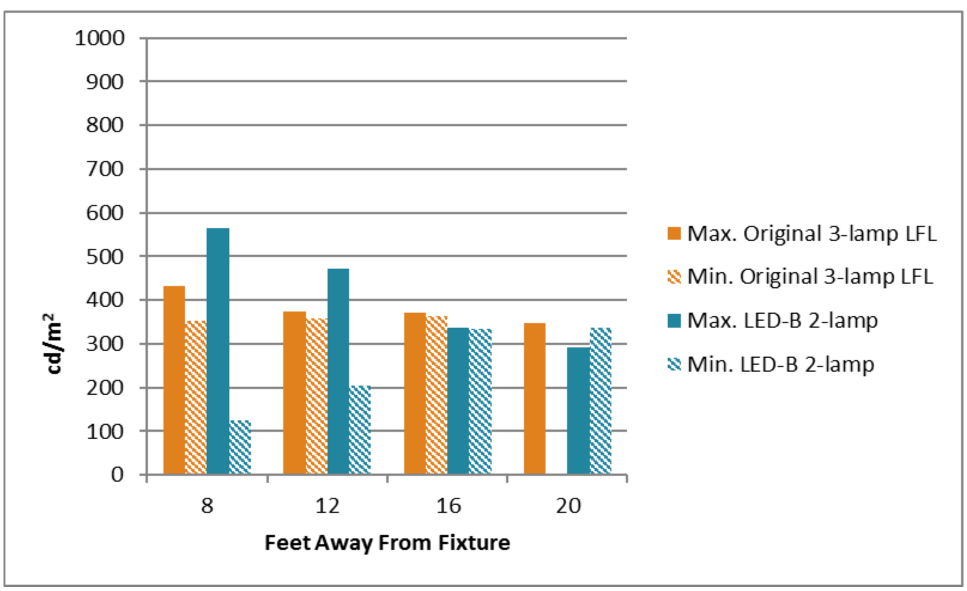


Figure 42. Auburn Design and Construction Luminous Intensity – Long Axis (LED-B)

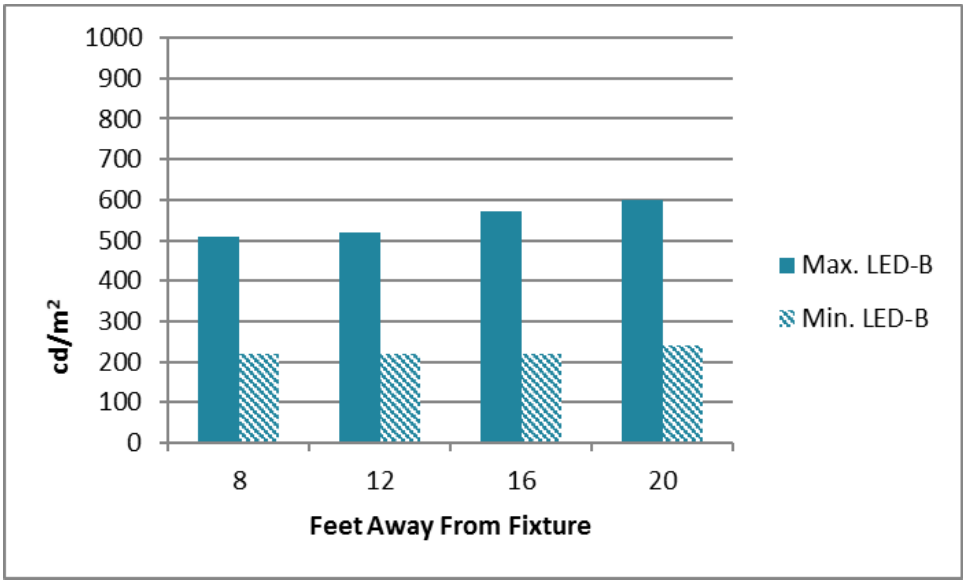
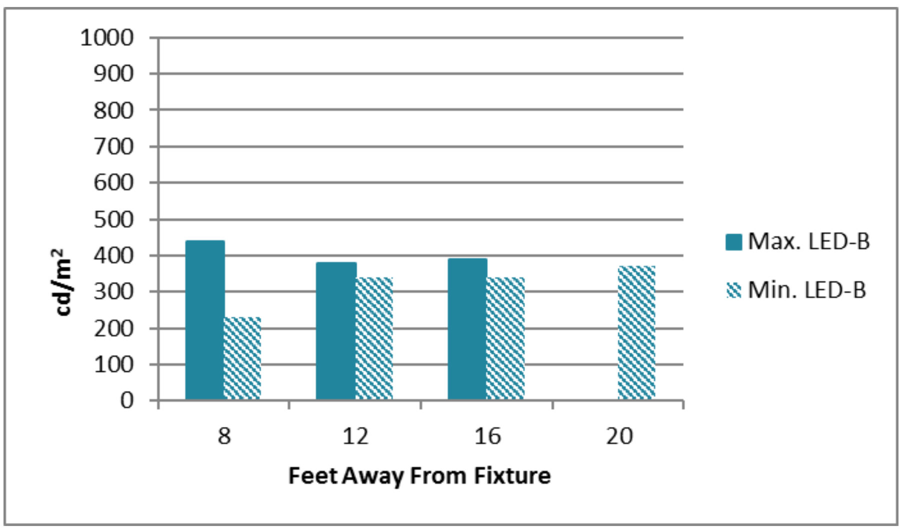


Figure 43. Auburn Design and Construction Luminous Intensity – Short Axis (LED-B)



LED-A TROFFER RETROFITS

A similar set of brightness data was taken on the LED-A retrofit troffer product at the Auburn site. These data also show that the intensity is similar to that of the LED-B product (approximately 200 to 600 cd/m^2) and there are no obvious indications of increased glare issues.

Figure 44. Auburn Real Estate Luminous Intensity – Long Axis (LED-A)

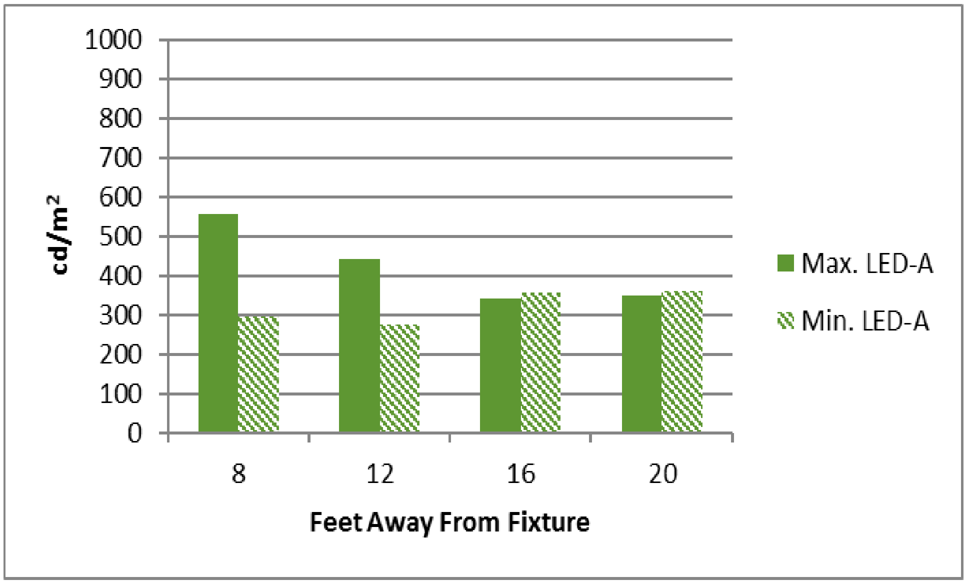
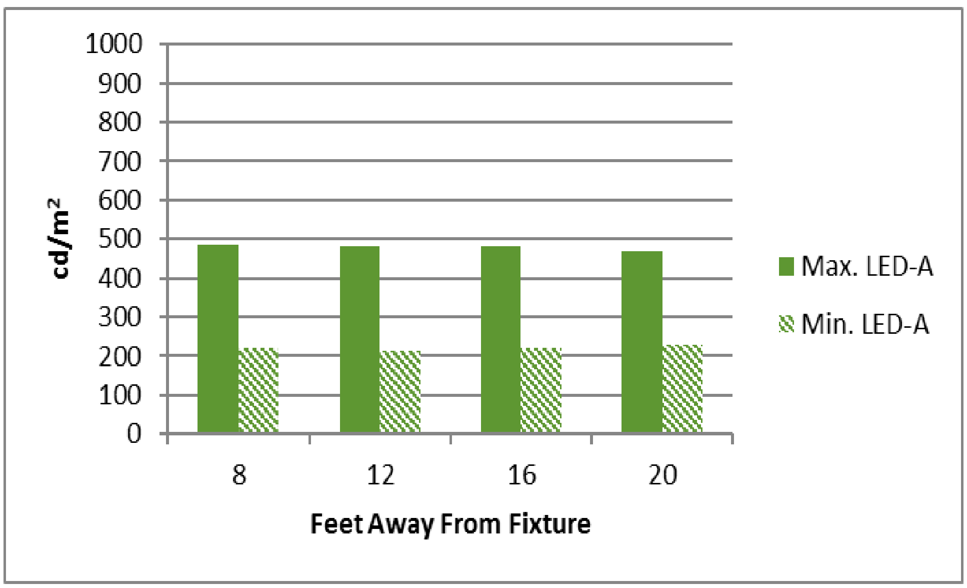


Figure 45. Auburn Real Estate Luminous Intensity – Short Axis (LED-A)



C. ELECTRICAL POWER AND POWER QUALITY COMPARISONS

POWER MEASUREMENTS

These data collected onsite by the installation crews were requested to provide electrical characteristics on both the existing and retrofitted LED lighting systems to help confirm estimates of potential energy savings. Data were received from the Auburn and Dallas installation crews and are shown below in Table 5 and Table 6.

Table 5. Auburn Pre- and Post-Retrofit Lighting Electrical Characteristics

Troffer #	Pre-Retrofit LFL 1	Pre-Retrofit LFL 1	Pre-Retrofit LFL 1	Post-Retrofit LED-A 1	Post-Retrofit LED-A 2	Post-Retrofit LED-A 3	Post-Retrofit LED-B 1	Post-Retrofit LED-B 2	Post-Retrofit LED-B 3
# Lamps	2	2	2	2	2	2	2	2	2
Volts (V_{ac})	277	277	277	277	277	277	277	277	277
Amps (A)	0.19	0.18	0.16	0.12	0.13	0.13	0.12	0.11	0.12
Watts (W)	52.6	49.9	44.3	33.2	36.0	36.0	33.2	30.5	33.2
Average (W)	48.9	48.9	48.9	35.1	35.1	35.1	32.3	32.3	32.3
% Reduction	N/A	N/A	N/A	28%	28%	28%	34%	34%	34%

Table 6. Dallas Pre- and Post-Retrofit Lighting Electrical Characteristics

Properties	Pre-Retrofit LFL	Post-Retrofit LED-A	Post-Retrofit LED-B
Troffer #	1	1	1
# Lamps	2	2	2
Volts (V_{ac})	277	277	277
Amps (A)	0.19	0.09	0.16
Watts (W)	52.6	24.9	44.3
Average (W)	52.6	24.9	44.3
% Reduction	N/A	53%	16%

It is important to note that each application of new technology, such as LED lighting, will provide different energy savings depending on the lighting system that it replaces and any other changes to the space such as light levels, controls or operations.

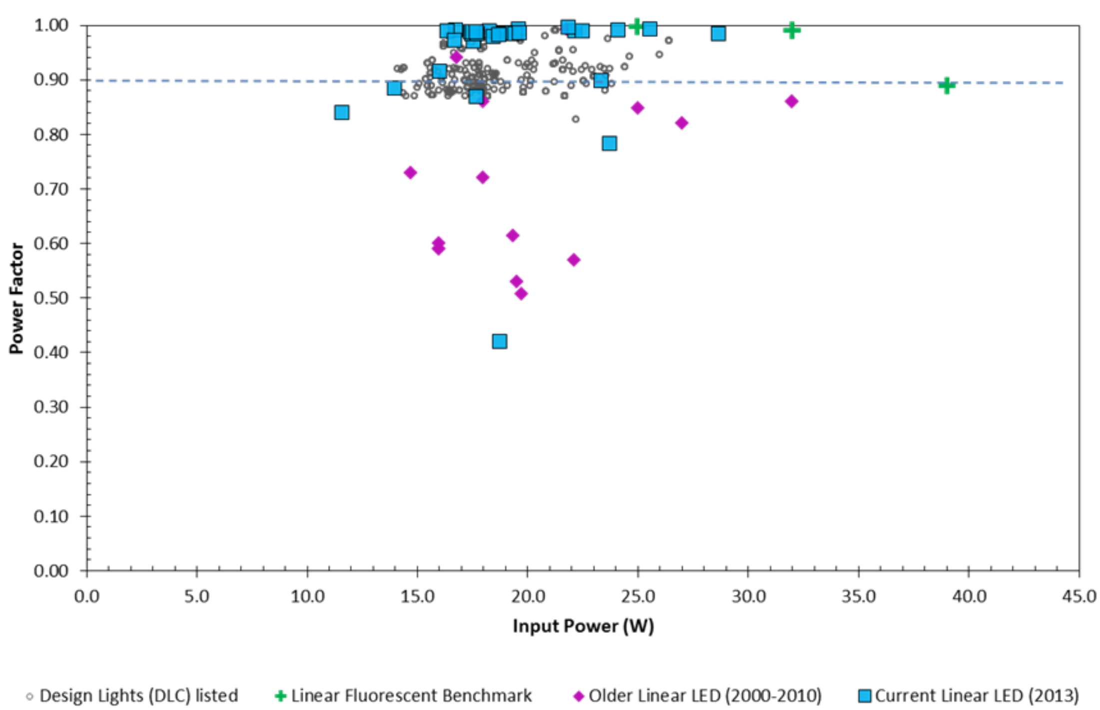
In reviewing the data, it is also clear that the collection was not consistent with well-established industry knowledge for lighting fixture energy usage. In the case of the Dallas LED data, only one sample was measured and the results were not as anticipated. Without other sample measurements to corroborate, these data were not used. However, where multiple samples were taken, and the data were recorded consistently, the relative percentage change is considered useful and is included. It is believed that the meters used in the field did not have the capability to accurately measure the fixtures. To normalize the readings for analysis purposes, the high end of the industry accepted range in wattage for two-lamp standard T8 fixtures with electronic ballasts (60 W) was used for the pre-retrofit condition. Additionally, the Pacific Northwest National Laboratory Lighting Metrology Laboratory conducted independent measurement of both LED-A and LED-B and found them to draw 44.0 W and 42.9 W, respectively. The results demonstrate that LED-A reduces power by 26.7% and LED-B reduces power by 28.5% over the existing fluorescent technology. However, this will not always be the expected savings in any or all applications. Actual savings will be different for all applications and will depend on the existing technology, as well as what wattage LED lamp is chosen to provide the light levels needed for the space.

POWER FACTOR

Power factor (PF) is a measure of how efficiently electrical devices use power. For lighting ballasts or drivers, this is the ratio of the power actually made available to the lamp to power input to the ballast or driver. For electrical devices, if the current draw is in-phase with the voltage, the power utilization is maximized, but when they are out of phase, part of the input power cannot be converted to produce light. Low PF registered at a building electrical service can be charged additional fees by the servicing utility. However, individual electrical products with low power factors are only individual contributors to a buildings PF rating. High power factor products are considered to have PF values greater than 0.9. Some rating or listing systems have limits for PF for products on their lists that relate a measure of quality for those products. This does not mean that products with lower PF are not good or are detrimental to a lighting system or building. Like many product or system characteristics, it is a relative value that must be considered along with others when choosing equipment.

The following chart displays various linear LED products (TLED) along with several linear fluorescent products for comparison. For reference, the current DLC threshold for PF is 0.9, which is considered an industry standard level representing quality and a level that should not affect building PF levels and, therefore, not impact utility billing charges. It is clear from the data that most current linear LED products have PFs above 0.9 and are as good as, if not better than, comparable linear fluorescent products they replace.

Figure 46. Linear LED and Fluorescent Lighting Product Power Factors



The LED-A and LED-B products were tested over their dimming range for both PF and total harmonic distortion (THD). The test data found in Table 7 show the PF values to be reasonable and close to or above industry accepted standards of greater than or equal to 0.9 at full load, which is expected to be the typical design condition. However, results from LED-A indicate that, if controls are implemented that dim the light output to below 25%, the PF will drop below the 0.9 threshold to an extreme low of 0.64. Note however, that low dimming positions such as the 1% level are unlikely to occur in real building operation.

Table 7. Measured Power Factor over Dimming Range

Product	100%	75%	50%	25%	1%
LED-A	0.99	0.99	0.97	0.87	0.64
LED-B	0.99	0.99	0.99	0.97	0.93

As noted, individual product PF does not directly equate to the PF for a building. For reference, a separate GSA study from December 2011[9] involved the replacement of over 90% of an existing lighting system with LED products. The chosen LED products had relatively poor PF values of around 0.61. However, analysis of the average 15-minute measured PF from the utility billing data for June through July both before and after the retrofit shows effectively no change in overall building PF (2010 = 0.8614, 2011 = 0.8603).

TOTAL HARMONIC DISTORTION

THD is a measure of the distortion of the input current expressed as a percentage of the fundamental frequency current of 60 Hz. Significant harmonics can be introduced back onto electrical lines when the electrical device load type is not linear. This can include lighting ballasts and drivers. Total THD on an electrical circuit or system can be an important consideration for detrimental effects on other electrical equipment or electrical safety.

The extent to which THD affects lighting products depends on several factors.

- It is path dependent (*i.e.*, it does not necessarily affect the entire system).
- It does not adversely affect all equipment or systems.
- It depends on the percent of total load that lighting or other equipment represents in a building.

The two products being evaluated in this study were also tested for THD at varying dimmed load levels, where capable. The test data found in the Table 8 shows the THD values to be well within the industry accepted and regulation standards of 20% or lower at full load. For the LED-A and LED-B products that are dimmable, the THD does increase with lower loads. However, the THD only goes above the 20% threshold at the low 25% and 1% dimming levels for LED-A. Similar to the PF section above, these are dimming levels that are unlikely to be seen in real building operation for extended periods of time.

[9] General Services Administration (GSA) (December 2011), Aberdeen Federal Building Lighting Retrofit Evaluation, PNNL-21070, Pacific Northwest National Laboratory, Richland, WA.

Table 8. Measured Total Harmonic Distortion over Dimming Range

Product	THD (current) at 100%	THD (current) at 75%	THD (current) at 50%	THD (current) at 25%	THD (current) at 1%
LED-A	5%	6%	10%	44%	79%
LED-B	3%	5%	9%	13%	17%

D. ECONOMIC ANALYSIS

The decision process for energy conservation measures requires a thorough understanding of the existing condition (base case), costs for energy, maintenance and replacement, and the time value of money for the evaluation period. To that end, LCC is used to account for the cash flows over the evaluation period and calculate present (or net present) values for competing energy conservation measures. In the federal sector, it is common practice to use a software package called Building Life-Cycle Cost (BLCC) developed by the National Institute of Standards and Technology.

GSA buildings are subject to a wide range of utility rates and rate structures, prevailing labor rates and a diverse building portfolio in terms of vintage and installed technology. For these reasons, it is appropriate to conduct multi-variable sensitivity analysis to provide GSA with both a means to identify and target facilities, but also quantify the relationship between material and installation costs. The three variables to be analyzed are:

- Energy rates from $0.06 to $0.24/kWh in $0.02/kWh increments and including the national average of $0.1062/kWh.
- LED-A and LED-B material cost of $50, $60 and $70. Venders were not asked to provide budget numbers, but the values selected are representative of current costs for their products.
- Labor rates of 50% and 100% of RS Means[10]. RS Means is a database of labor costs used by the construction industry to provide accurate estimates and projections for projects. The rationale for including two different labor rates is the fact that GSA is likely to implement technologies en masse (*e.g.,* ESPC, by region, or building-wide) and therefore gain economies of scale and preferential pricing.

Assumptions fed into the BLCC models developed for the project are shown in Table 9, Table 10, and Table 11.

Table 9. BLCC Model Parameters with 50% and 100% RS Means Labor

Parameter	Economic Model Input	Notes

[10] The Gordian Group, "RS Means Construction Cost Data Book," 2015

Parameter	Economic Model Input	Notes
Analysis Period	12.5 yrs/50,000 hrs.	Accounts for one ballast and two lamp replacements
Annual Operating Hours	4000	Typical Office Space
Energy Rates	\$0.06 – \$0.24/kWh, plus \$0.1062 kWh	\$0.1062/kWh (national commercial average)
Nominal Discount Rate	3.1%	

Notes: No demand or power factor charges included. No heating, ventilation, and air conditioning impact (*i.e.*, reduced cooling, increased heating)

Table 10. BLCC Baseline Assumptions with 50% and 100% RS Means Labor

Baseline Assumptions	T8 Lamp + Electronic Ballast	Notes
T8 System Consumption	240.0 kWh/yr.	Assumes 60 W load
T8 Lamp Replacement	25,000 hrs.	30,000 hour rated life but replacement at 25,000 hours
T8 Lamp Cost	\$4.90	From GSA Schedule (2 lamps)
Electronic Ballast Cost	\$15.00	Estimated Average Cost
T8 Lamp + Ballast Labor Cost	\$34.19 and \$68.38	Lamp and ballast replacement at time = 0. 50% and 100% RS Means[(a)] labor costs
T8 Re-Lamp Labor Cost	\$21.86	Re-lamp at time =25,000 hrs.

(a) The Gordian Group, "RS Means Construction Cost Data Book," 2015

Notes: No demand or power factor charges included. No heating, ventilation, and air conditioning impact (*i.e.*, reduced cooling, increased heating)

Table 11. BLCC LED Assumptions with 50% and 100% RS Means Labor

LED Assumptions	LED	Notes
LED-A Consumption	176.0 kWh/yr.	Measured 44.0 W load
LED-B Consumption	171.6 kWh/yr.	Measured 42.9 W load
Material Cost (LED-A and LED-B)	\$50, \$60 and \$70	Anticipated material cost range for sensitivity analysis
Installation Labor Cost (LED-A and LED-B)	\$34.19 and \$68.38	Similar cost to lamp + ballast replacement

Notes: No demand or power factor charges included. No heating, ventilation, and air conditioning impact (*i.e.*, reduced cooling, increased heating)

ADJUSTED INTERNAL RATE OF RETURN

Adjusted internal rate of return is a measure of the annual percentage yield from an alternative over the investment period and is usually compared to the discount rate used in the LCC analysis (3.1%). Higher values equal greater cost-effectiveness.

SIMPLE PAYBACK

Simple payback (SPB) is a commonly used metric for cost-effectiveness and return on investment by reporting the number of years to recover the initial investment accounting for energy and maintenance savings. Care should be taken in its use and interpretation as it is easy to focus on just energy and O&M savings without considering the time value of money when cash flows occur over the evaluation period. Both LED-A and LED-B have SPB of less than the 12.5 year term of the evaluation period.

SAVINGS-TO-INVESTMENT RATIO

Savings-to-investment ratio (SIR) compares the operational savings of the alternative to the additional investment cost of the alternative. Both values are put into PV. An investment is considered cost-effective if the SIR is greater than 1.0; higher values indicate greater cost-effectiveness. Another way to think about SIR is that an investment will return the SIR valve for every dollar invested over the discount rate. For both technologies investigated, the SIR is greater than 1.0; however, it should be noted that at higher first costs and lower energy rates, the LED-A and LED-B solutions are only marginally cost-effective. This reality is driven by the relatively high material and labor costs to implement the solutions over the base case and lower energy cost savings with lower energy rates.

Figure 47 presents the results for LED-A with 50% of RS Means labor assumptions and Figure 48 presents the results for LED-A with 100% of RS Means labor assumptions. Figure 49 presents the results for LED-B with 50% of RS Means labor assumptions and Figure 50 presents the results for LED-B with 100% of RS Means labor assumptions.

Figure 47. LED-A Simple Payback and Savings-to-Investment-Ratio with 50% of RS Means Labor Assumption

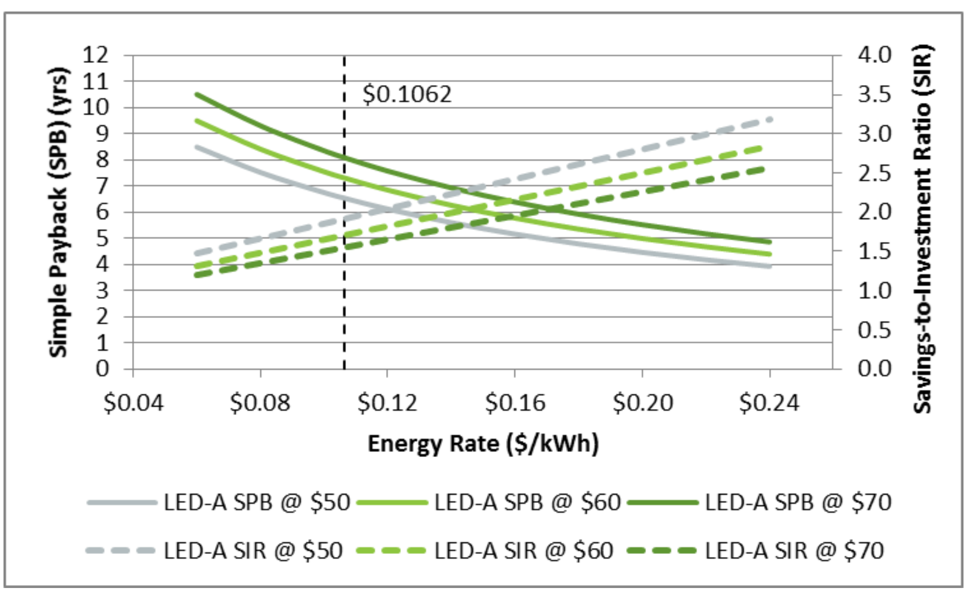


Figure 48. LED-A Simple Payback and Savings-to-Investment-Ratio with 100% of RS Means Labor Assumption

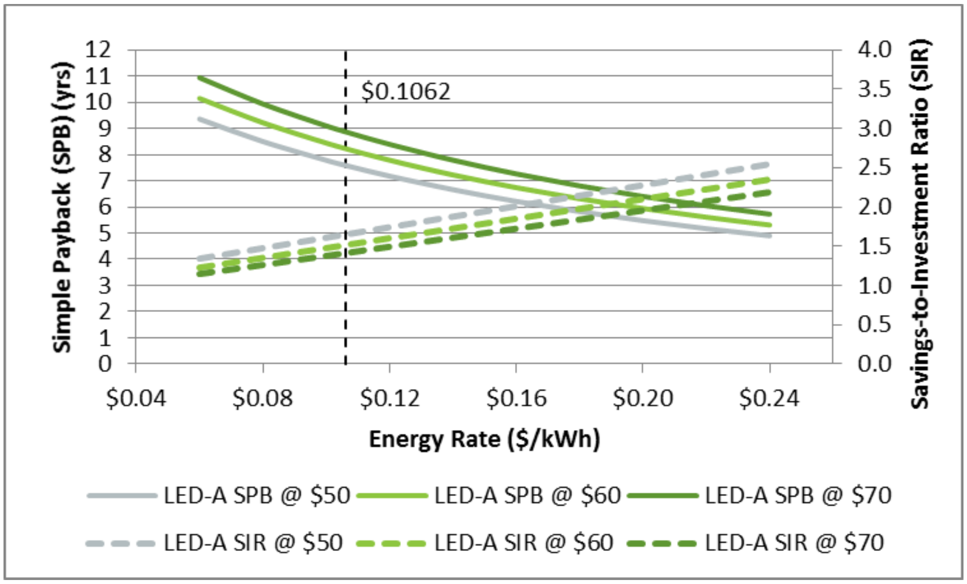


Figure 49. LED-B Simple Payback and Savings-to-Investment-Ratio with 50% of RS Means Labor Assumption

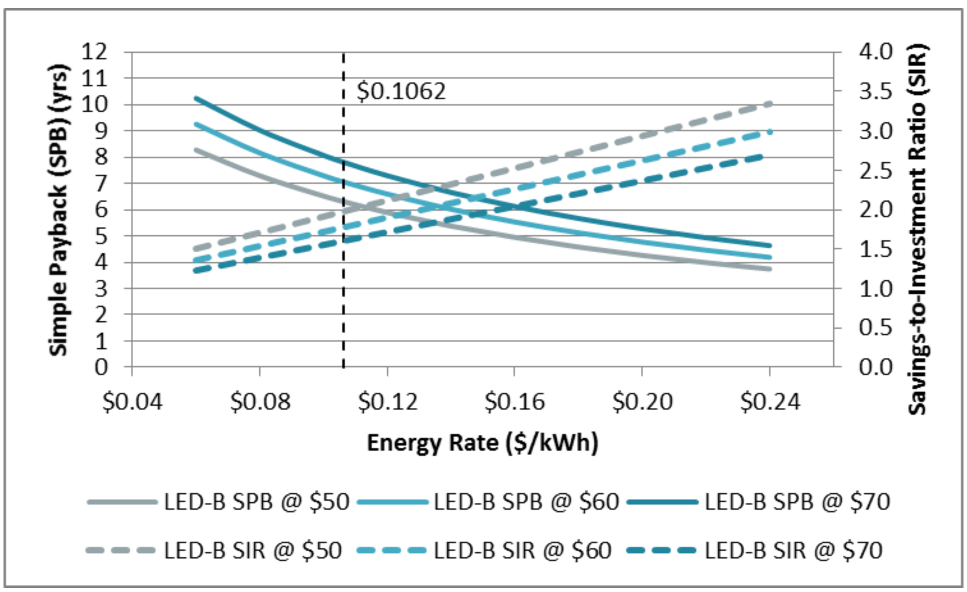
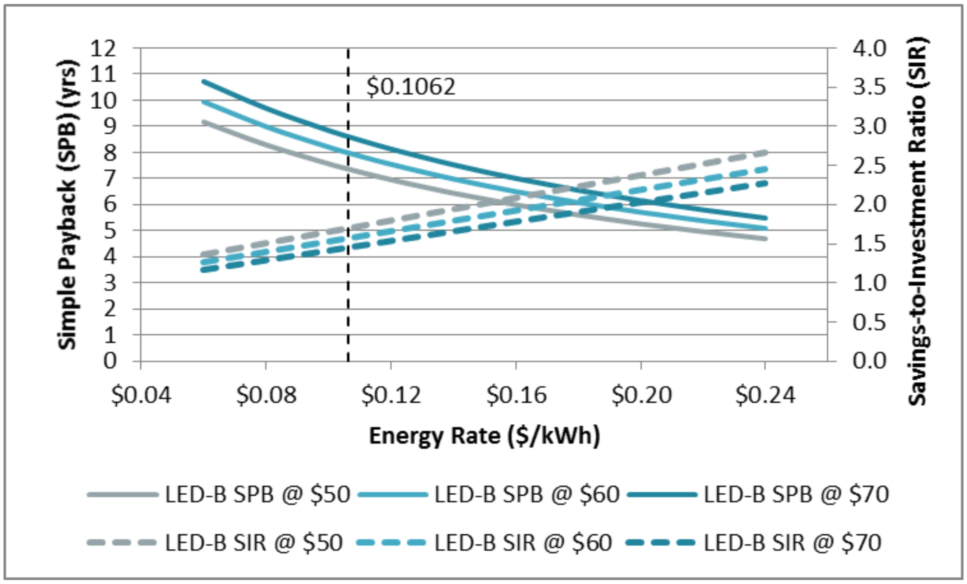


Figure 50. LED-B Simple Payback and Savings-to-Investment-Ratio with 100% of RS Means Labor Assumption



PRESENT/NET PRESENT VALUE

Present value (PV) takes a stream of cash inflows and outflows and applies discounting and price inflation to convert the sum of those cash flows into "today's" (*i.e.*, present) dollars. The lowest PV between competing alternatives is considered the more cost-effective. NPV is simply the difference between the base case PV and the alternative PV. When evaluating results, the alternative with the highest NPV is generally considered the most cost-effective. While energy savings are important, the most significant contribution to the NPV is the avoided maintenance costs for the fluorescent systems. With the 50% of RS Means labor, both LED-A and LED-B have a lower PV compared to the base case, albeit slight at the lowest energy rates. However, with the 100% of RS Means scenario, it is clear that the increased installation labor cost increases the PV to the point where it is not cost effective until energy cost savings can compensate.

Figure 51 presents the results for LED-A with 50% of RS Means labor assumptions and Figure 52 presents the results for LED-A with 100% of RS Means labor assumptions.

Figure 53 presents the results for LED-B with 50% of RS Means labor assumptions and Figure 54 presents the results for LED-B with 100% of RS Means labor assumptions.

Figure 51. LED-A Present Value Results with 50% of RS Means Labor Assumption

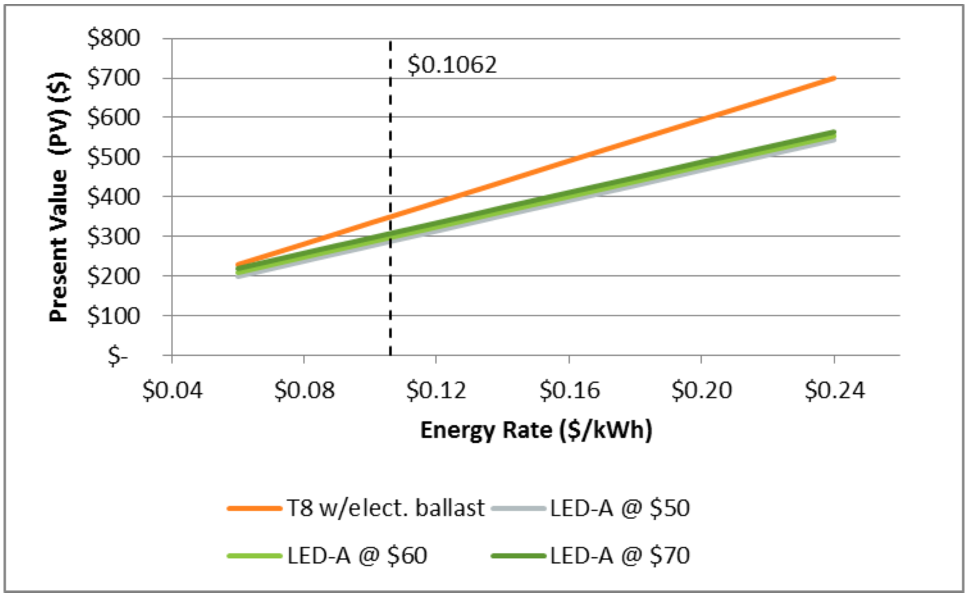


Figure 52. LED-A Present Value Results with 100% of RS Means Labor Assumption

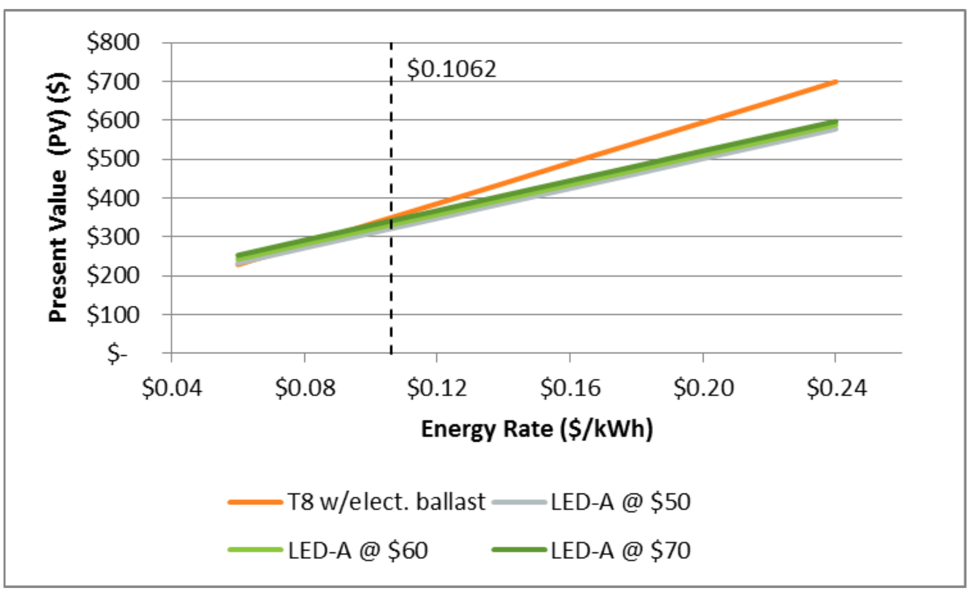


Figure 53. LED-B Present Value Results with 50% of RS Means Labor Assumption

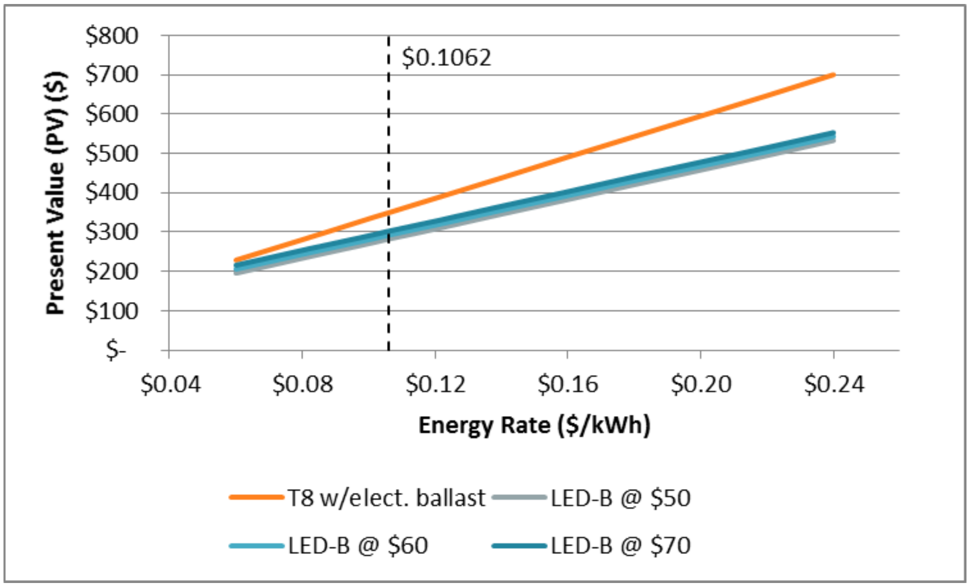
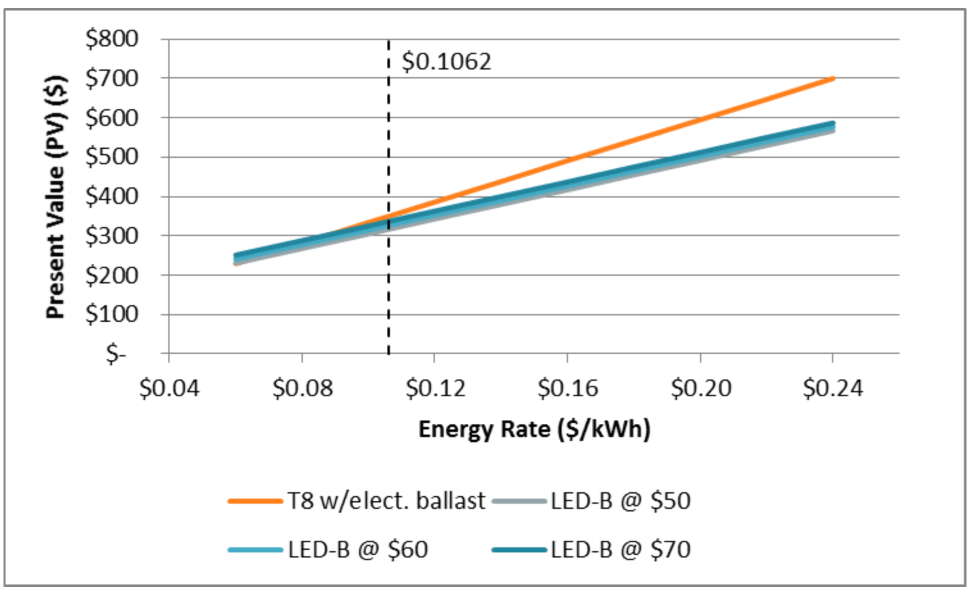


Figure 54. LED-B Present Value Results with 100% RS of Means Labor Assumption



E. OCCUPANT SURVEY RESULTS

Occupant surveys administered at the three evaluation sites provide information on the relative satisfaction by the occupants of both the existing fluorescent lighting and the new installed LED lighting. The following observations of the data are based on a statistical significance analysis of the various responses and provide some general indication of the noticed differences between the pre- and post-retrofit LED systems.

The primary focus of the analysis was to determine if there were any specific issues with either the existing fluorescent or retrofit LED systems and if there were any significant differences with the change to LED technology.

In general, the occupants' responses to the pre-retrofit survey at all three sites indicate that the existing fluorescent system was acceptable. This result is expected as the occupants have been accustomed to working under these systems and any significant issues would likely have been addressed.

In analyzing the data for significant responses that showed differences between the fluorescent and new LED systems, the following results are noted related to light levels.

AUBURN

In the Auburn Real Estate office area, the occupants thought the LED lighting system was too bright. Again, this can be attributed simply to higher light levels, but also could be a result of the clean newly installed system that can often present a brighter look.

In addition, in the Auburn Real Estate office area, the occupants thought the LED lighting system presented a slightly higher glare potential on work surfaces, from lighting overhead and far away but not on the computer screens. Again, this can be attributed simply to higher light levels.

Figure 55. Auburn Real Estate (LED-A) Task Light Level Survey

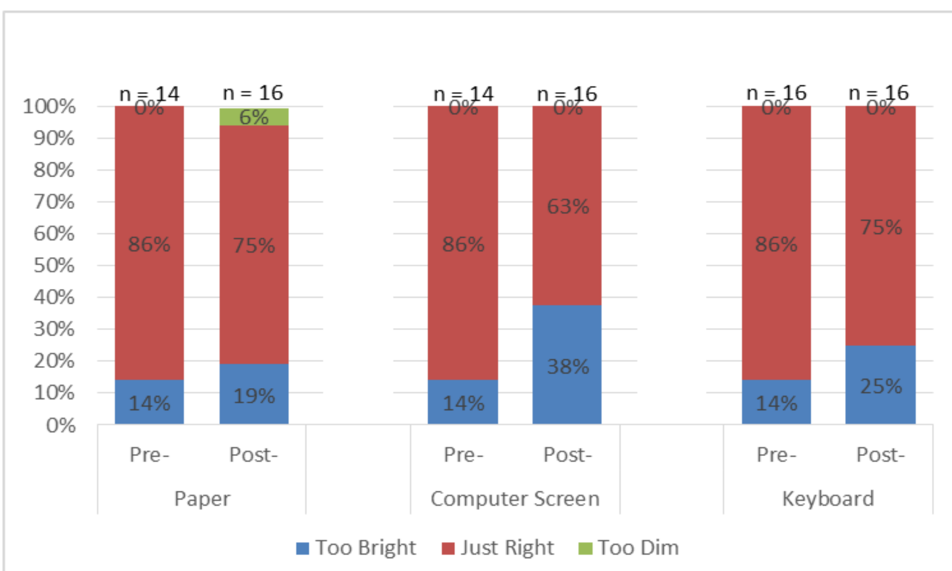
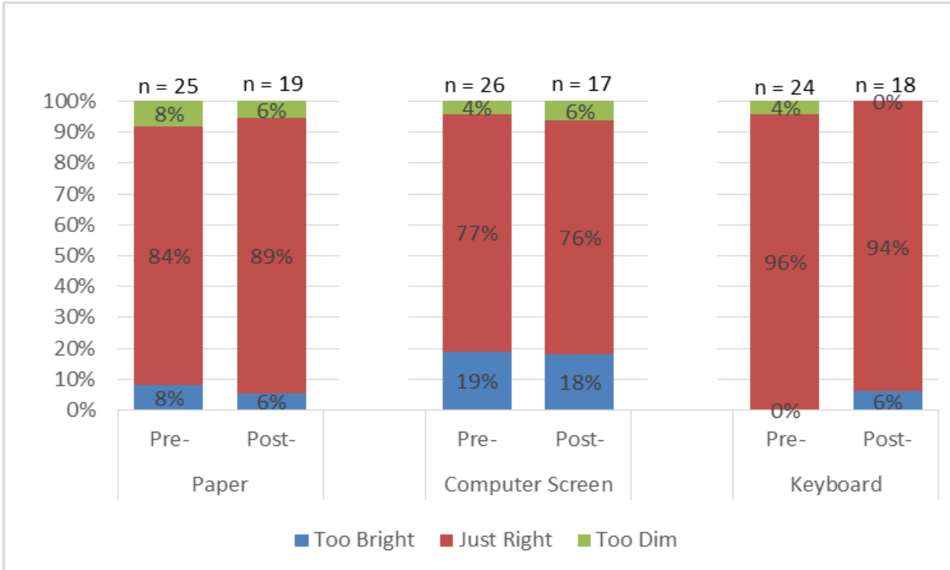


Figure 56. Auburn Design and Construction (LED-B) Task Light Level Survey



DALLAS

In the Dallas office area with LED-B LED lamps installed, the occupants thought the LED lighting system presented a slightly higher glare potential on computer screens, but slightly less glare on work surfaces.

In the Dallas office area with LED-A lamps installed, the occupants also thought the LED lighting system presented a slightly higher glare potential on computer screens, but slightly less glare on both work surfaces and from overhead lighting.

Figure 57. Dallas Property Management (LED-A) Task Light Level Survey

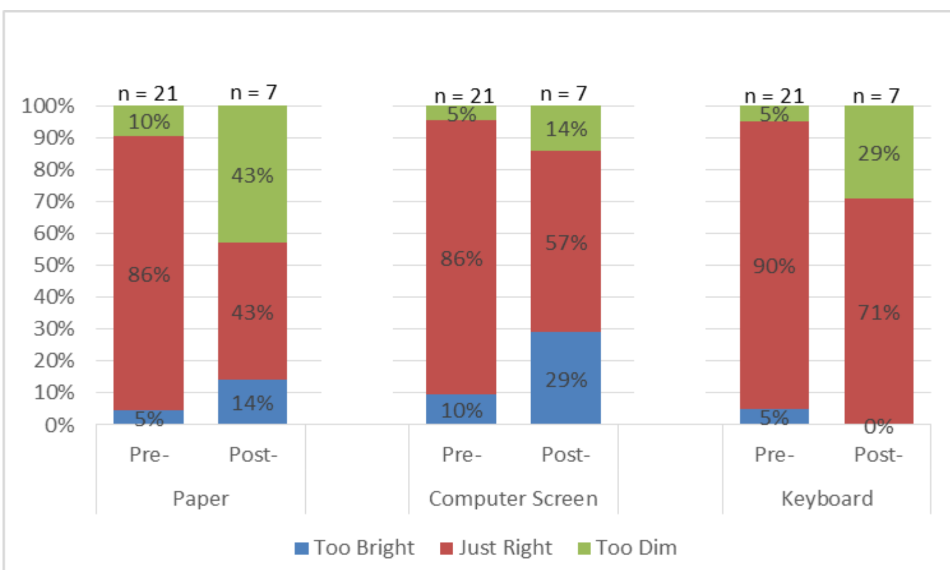
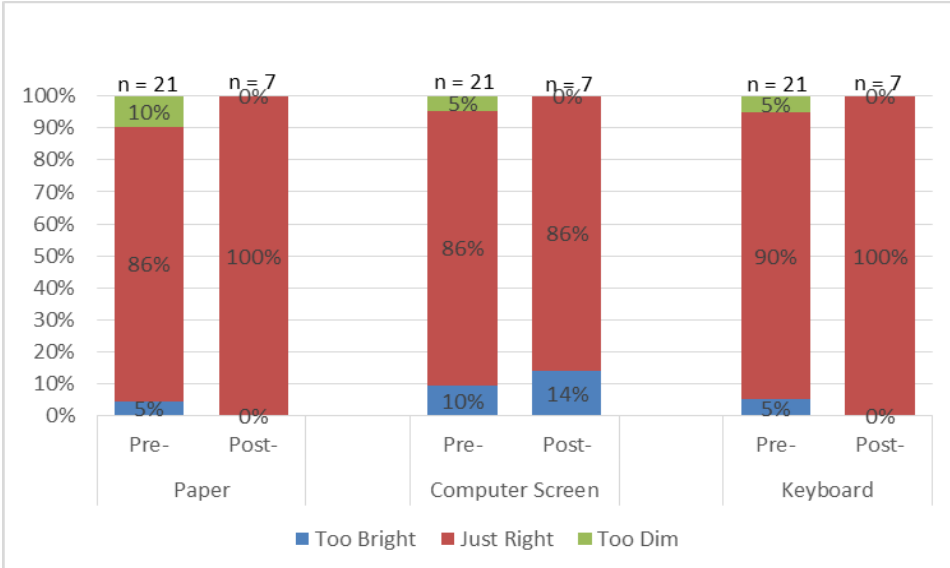


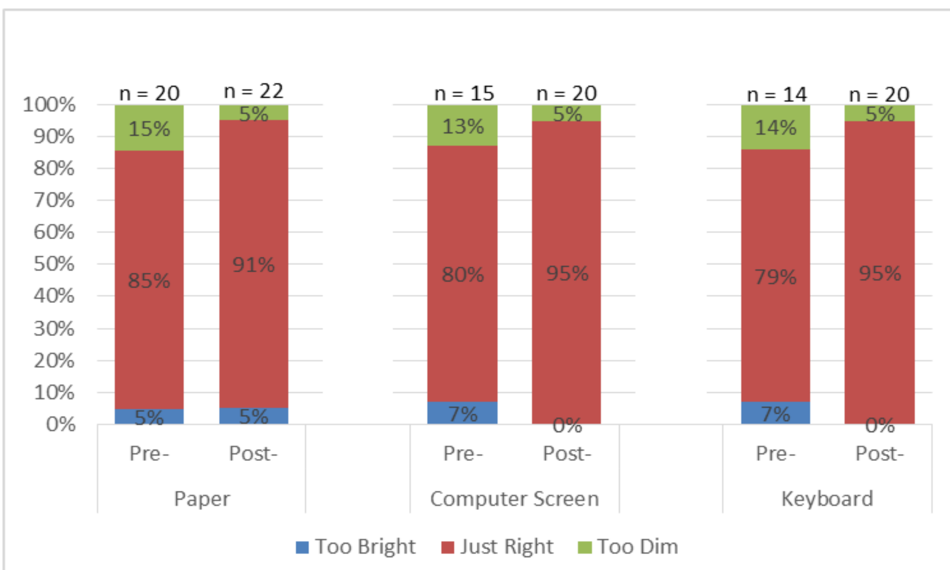
Figure 58. Dallas Project Management (LED-B) Task Light Level Survey



PHILADELPHIA

In the Philadelphia daycare areas, the occupants thought the LED lighting system presented a slightly higher glare potential for far-away lighting only.

Figure 59. Philadelphia Daycare (LED-A and LED-B) Task Light Level Survey



VI. Summary Findings and Conclusions

A. OVERALL TECHNOLOGY ASSESSMENT AT DEMONSTRATION FACILITIES

ENERGY SAVINGS

The LED-A and LED-B technologies, when installed on a one-for-one basis, demonstrated the potential to save 64.0 to 68.4 kWh per year, or 27 to 29%, of the energy compared to the baseline two-lamp T8 fluorescent lamp (2800 lm) with a generic electronic ballast (0.87 ballast factor).

PHOTOMETRIC PERFORMANCE

An important part of any lighting retrofit is achieving the correct or desired light levels and every project will be different because of existing conditions and specific task needs. Therefore, matching or creating appropriate light levels will require specific considerations of each site or area.

The results of this evaluation at three sites can provide an idea of what can be done with retrofits to new technology, but these results may not be typical or applicable to every project.

In general, we came to the following conclusions regarding photometric performance:

- The uniformity of lighting throughout the retrofit spaces provided by linear LED technology (LED-A and LED-B) appears to be similar to what existed with the original fluorescent technology.
- Light levels with the new LED products are generally higher than that provided by the fluorescent lamps, but in some cases lower. This outcome is directly related to a choice of products and the number of lamps, and not an issue with product efficacy or performance.

OCCUPANT SATISFACTION

Occupant satisfaction with existing and retrofit lighting is important for worker stability and to avoid workplace issues. In general, little change was noticed between the existing fluorescent and replacement LED technology. We came to the following conclusions regarding occupant satisfaction:

- In most office spaces, the occupants did not find significant differences in the light level or quality between the fluorescent and LED lighting systems.
- The occupants thought the fluorescent and LED lighting in the common hallway areas was generally too dim, but somewhat better with the LED system at the Auburn and Dallas study sites, and slightly dimmer with the LED technology at the Philadelphia study site.
- In some areas at all three sites, the occupants felt that the LED retrofit technology was more likely to produce glare on surfaces, but none of the occupants noticed any severe issues.

All of these differences for both light levels and glare potential were found, on average, to be slight with no major issues identified. However, there can always be individual issues with specific occupants. In one case, there were complaints at the Dallas study site of low light levels in one area. Light levels in the area are significantly lower with the LED technology, but this difference simply is in the light output of the installed lamps, and a different lamp output product would likely have eliminated this issue.

COST-EFFECTIVENESS

The LED-A and LED-B are both cost-effective over the 12.5 year economic period selected for the study, even at the lowest energy rate of $0.06/kWh. Over the 12.5 year economic study period, the greatest contribution to cost-effectiveness is labor savings due to avoided lamp replacement, which would be one replacement for a LFL.

LED-A

At $0.1062/kWh, LED-A saves approximately $6.80 in energy costs per year over a typical linear fluorescent system. Assuming installations at a rate of 50% and 100% of RS Means, simple paybacks are listed below:

- 6.5 to 7.6 year simple payback if the material cost is $50
- 7.3 to 8.2 year simple payback if the material cost is $60
- 8.1 to 8.9 year simple payback if the material cost is $70.

LED-B

At $0.1062/kWh, LED-B saves approximately $7.26 in energy costs per year over a typical linear fluorescent system. Assuming installations at a rate of 50% and 100% of RS Means, simple paybacks are listed below:

- 6.3 to 7.4 year simple payback if the material cost is $50
- 7.1 to 8.0 year simple payback if the material cost is $60
- 7.8 to 8.6 year simple payback if the material cost is $70.

B. LIGHTING RETROFIT IMPACTS ON HEATING/COOLING SYSTEMS

Lighting energy introduced into a building equates to heating load that affects heating, ventilation, and air-conditioning operation and, therefore, building energy use. When lighting energy is reduced, heating load also is reduced, and cooling systems in a building can generally use less energy. However, when lighting energy is reduced, additional compensatory heating in colder climates may be required. To determine the net effects that lighting energy reduction can have on a project, the total kWh savings of the lighting project along with cooling and heating season fractions described by Runquist *et al.* (1993) can be used. Cooling and heating fractions are that portion of the year in weeks when cooling or heating, respectively, is needed and provided to the building.

Other factors that affect the calculation of additional heating and reduced cooling are described below:

- Electric Cooling Equipment Coefficient of Performance. This is a measure of the efficiency of heat pump type cooling equipment. It helps determine how much energy is saved from reduced cooling load. For most typical facilities, it is estimated to be approximately 3.0.
- Gas/Oil Equipment Seasonal Efficiency. This is a measure of the efficiency of gas or oil to heat a building. A value of 0.8 is considered typical for a mix of existing buildings, which is used as the commonly found system. Typically, this is 0.8 for a mix of gas/oil systems. If the current system efficiency or coefficient of performance is known, that value should be used.

- Building Heating Area. This is the estimated percentage factor of a building that is actively heated in cold weather. For buildings with perimeter heating zones, such as larger and multi-story buildings, this is often found to be between 0.4 and 0.9. For smaller buildings where there is only single zone or random zoning (not perimeter zoning) and the entire building is actively heated, this may be 1.0.

By applying the correct factors and site data, the effect of lighting retrofits on building heating and cooling energy use can be estimated as described below.

ADDITIONAL YEARLY KWH COOLING SAVINGS FROM LIGHTING KWH REDUCTION

Additional Yearly Cooling Savings (AYCS) = ((C-FAC/52)/C-COP) × SAV

where:

- C-FAC is the cooling fraction that relates the portion of the year in weeks when cooling is required for a building's location.
- 52 is the number of weeks in the year.
- C-COP is the efficiency for cooling equipment. The value is considered to be 3.0 for typical systems.
- SAV is the calculated or estimated yearly kWh savings from the lighting retrofit project.

ADDITIONAL YEARLY KWH OF HEATING LOSS CAUSED BY LIGHTING KWH REDUCTION

Additional Yearly Heating Loss (AYHL) = ((H-FAC/52) × (HEAT %/EFF)) × SAV × 3414

where:

- H-FAC is the heating fraction that relates the portion of the year in weeks when heating is required for a building's location.
- 52 is the number of weeks in the year.
- HEAT % is a percentage factor estimate of the perimeter area of a typical building where heating is required (0.5 is the values suggested by Rundquist et al. 1993).
- EFF is the measure of efficiency of the heating system. This is considered to 0.8 for typical gas/oil systems, or 3.0 for typical heat pump heating systems.
- SAV is the calculated or estimated yearly kWh savings from the lighting retrofit project.
- 3414 converts kWh to BTU when needed for costing purposes.

With these values calculated, the total overall expected energy savings from a project can be generated:

Total project energy savings = SAV + AYCS – AYHL

For actual project energy costs, these values can be converted to fuel costs based on prevailing rates.

C. BEST PRACTICE APPLICATION GUIDANCE

This section provides information on the various options available for re-lamping or retrofitting 2' x 4' (or 1' x 4') fluorescent troffers. It also offers important guidance on the issues to consider in evaluating the best option for particular applications.

Many options exist for this form factor retrofit, each with its own advantages and challenges, as shown in the following table and described in detail below.

Target Facilities. Given GSA's expansive portfolio (in terms of age, volume and location), wide range of technologies serving similar space-type applications, and variations in the cost of energy, we recommended that GSA adopt a targeted approach to systematic installation. In general, older facilities tend to be over-lighted relative to current IES illuminance recommendations. These facilities also tend to use older technologies (*e.g.*, T12 and "first-generation" T8 troffers)." The cost of energy, and thus operating cost, should also be a significant factor in the decision process as return on investment will be maximized.

Select LED Form-factor Option. There are multiple product offerings available to the end-user, and each will have its strengths and weaknesses from a performance, ease of installation, cost, maintenance, risk, and segue for controls, standpoint. No one solution will meet the needs of all buildings and all users. Therefore, a diligent evaluation of available options that sets priorities for near-term as well as long-term objectives is necessary. At this point, the end-user must choose a form-factor option. Table 12 summarizes the available options and characterizes their various attributes.

Apply "Above Code" Performance Criteria and Approved Product Lists. As a federal agency, GSA is required to procure products that meet ENERGY STAR criteria, or in the case where a product class is not covered, FEMP will develop "FEMP-designated" performance criteria. However, at the time of this report, neither ENERGY STAR nor FEMP have developed performance criteria for linear LED replacement lamps or retrofits.

In the case of troffer lighting, DLC is a default "ENERGY STAR" organization operated by the Northeast Energy Efficiency Partnerships, which includes member utilities and market transformation groups from across the United States and Canada. Although the DLC is not formally recognized by statute as an acceptable substitute for ENERGY STAR or FEMP-designated products, it meets the intent of those programs to identify highest level performance in the marketplace and promote LED-based commercial lighting solutions. To that end, DLC performance criteria and its associated qualified product list should be used as an additional resource in the selection process.

Apply Additional GSA Criteria. At this stage, GSA may wish to apply its own specification/criteria (see section on Basic Product Specification in Section E) not addressed in the prior step. GSA should also apply any baseline and High Performance Tier requirements from its P-100 standard.

Develop Performance-Based Specification for Intended Application. The final step in the process is to develop a performance-based specification for the space type(s) in question and require the manufacturer to demonstrate that its solution, when installed in the defined GSA application, will meet the requirement, thereby effectively shifting the burden of performance onto the manufacturer. As an example, the specification my look something like the following:

- Installed in a prismatic lensed 2’ x 4’ troffer
- Deliver 35 fc initially assuming ceiling/wall/floor reflectance values of 80/50/20, respectively, and a spacing criteria of 1.0 to 2.0
- Mounted in a 9’ to 11’ ceiling
- Luminaire spacing of 8’ x 10’ on-center

With the above information the manufacturer would be able to model or test its solution in the prescribed environment to demonstrate compliance.

Table 12. LED Form-factor Options for Fluorescent to LED Retrofits

Category	Power Supply	Light Source Mounting	Dimming	Controls	Risk	Total Cost	Attributes	Unknowns	Useful application where:
1. LED Replacement Lamp (Ballast)	Existing fluorescent ballast	Existing fluorescent socket	Unlikely	Shut-off only (switch or occupancy sensor)	•	$	LED or LFL option, No electrician, matches lens configuration, need for future ballast replacement	Performance on various ballasts and over time	Cost is critical, existing FL ballasts are healthy, and advanced control is not useful
2. LED Replacement Lamp (Mains)	"Mains" voltage	Existing fluorescent socket	Yes, with matching 0-10V system	Shut-off only (switch or occupancy sensor)	••	$$	Matches existing lens configuration	Performance over time	Cost is important and advanced control is not useful
3. LED Replacement Lamp (Hybrid)	"Mains" voltage or existing fluorescent ballast	Existing fluorescent socket	Only likely if FL ballast removed	Shut-off only (switch or occupancy sensor)	•/••	$$	Matches existing lens configuration	Performance on various ballasts and over time	Cost is important, advanced control is not useful, and fluorescent ballasts may have limited life
4. LED Retrofit Kit (Lamp Socket)	Proprietary power supply	Existing fluorescent socket	Yes, with matching 0-10V system	Yes, with matching driver/control	••	$$$	Matches existing lens configuration	Product availability and performance over time	Advanced control may be useful
5. LED Retrofit Kit (Free-form)	Proprietary power supply	Free-form	Yes, with matching 0-10V system	Yes, with matching driver/control	•••	$$$	Allows for light source relocation/re-alignment	Product availability and performance over time	Advanced control may be useful

1. **LED Replacement Lamp using the fluorescent socket and ballast**

This option involves directly replacing the existing LFL with a similar form factor LED lamp product and does not require any fixture rewiring. The replacement LED is designed to operate on the existing fluorescent ballasts. These replacement LED lamp products are currently available from many manufacturers and more manufacturers are offering these products. Advantages and disadvantages of this type of lamp replacement are listed below:

- Advantages
  - Ease of installation – no electrician required
  - Lamp only – no need to purchase ballasts, drivers, or other accessories
- Disadvantages
  - May not work on all existing ballasts
  - Does not address potentially limited remaining ballast life or actual performance on all ballast types
  - Extends the need for continued availability/production for a dwindling technology.
  - All power conversion takes place within the lamp and in proximity to the heat-generating LEDs, which potentially could affect LED lumen maintenance and system life
  - Fluorescent ballast might become inefficient and energy savings labeled might be negated.

2. **LED Replacement Lamp using the fluorescent socket and "mains" voltage**

This option involves directly replacing the existing LFL with a similar form factor LED lamp product, but requires rewiring the fluorescent sockets to accommodate "mains" voltage (typically 120 or 277 V). These replacement LED lamp products are currently available from many manufacturers and more manufacturers are offering these products. Advantages and disadvantages of this type of lamp replacement are listed below:

- Advantages
  - Eliminates the potential for ballast incompatibilities
  - Eliminates the need to replace the ballast at some future date
  - Lamp includes all power conversion only – no need to purchase ballasts, drivers, or other accessories
- Disadvantages
  - Requires an electrician
  - Potential safety issue
  - All power conversion takes place within the lamp and in proximity to the heat generating LEDs, potentially impacting LED lumen maintenance and system life

3. **Hybrid replacement lamp capable of operating on the fluorescent ballast or mains voltage**

- Same advantages and disadvantages identified in 1 and 2 above, save for needing a ballast replacement. However, once the ballast fails, an electrician will be required to re-wire for "main's" voltage.

4. **LED replacement kit (hardwire) using the fluorescent socket configuration.**

These kits are generally lamps that utilize the tubular form-factor of LFLs and are designed to fit inside troffers without modifying the housing. This option requires that the fluorescent ballast be removed (to prevent it from being re-wired in the future), and will require some modification of the electrical wiring. Depending on the existing sockets (shunted or un-shunted) and the electrical requirement of the LED products, the re-wiring could be anywhere from very simple to a full replacement of the sockets. Using these types of products provides a potentially easier and less costly option compared with a new LED fixture. Depending on the optics of the troffer, the system performance characteristics, such as light output, distribution, and application effectiveness should be considered. Advantages and disadvantages of this type of replacement are listed below:

- Advantages
  - Potential energy savings compared to fluorescent lamps
  - Less costly than new LED fixture
- Disadvantages:
  - Light output might not provide sufficient illumination, depending on the application and current light levels.
  - Performance may not be optimal, depending on the optics and lensing of fluorescent troffer.

5. **LED replacement kit (hardwire) using alternative mounting hardware.**

These kits often utilize the tubular form-factor of linear fluorescents, but can be designed in any shape that could be accommodated by a fluorescent troffer. This option usually requires that the fluorescent ballast be removed (to prevent it from being re-wired in the future), and will require direct wiring to the power source. The fixture manufacturer will provide some method of attaching the light kit to the fixture housing, such as self-tapping screws. Using these types of products provides a potentially easier and less costly option compared with a new LED fixture. Depending on the optics of the troffer, the system performance characteristics, such as light output, distribution, and application effectiveness should be considered. Advantages and disadvantages of this type of replacement are listed below:

- Advantages of this option include:
  - Potential energy savings compared to fluorescent lamps
  - Less costly than new LED fixture
  - Products could have superior optics as compared to kits that are limited to utilizing the form factor of LFLs.
- Potential disadvantages include:

   - Light output might not provide sufficient illumination, depending on the application and current light levels.
   - Performance may not be optimal, depending on the optics and lensing of fluorescent troffer.
   - Self-tapping screws could cause electrical problems when being installed in fixtures-in-place if they penetrate existing wiring in the building.

6. **New LED troffer fixture**

A new fixture will eliminate any issues with UL listing and decreases in optical efficiency and can provide the same or better light for the space and its tasks. Advantages and disadvantages of this option are listed below:

- Advantages
  - Expected energy savings compared to retrofit kits
  - New clean install avoiding most socket and wiring issues
  - Potential integration of sensors for advanced lighting controls
- Disadvantages
  - New fixture and installation cost
  - LED array may not be replaceable requiring new fixture when the LED needs to be replaced.

USE CASE SCENAROS

The following Use Cases are intended to guide the decision process:

Use Case:	2-Lamp 2'x4' (or 1'x4') Fluorescent "Lensed" Troffer – Light Levels ≈ P-100
Description:	Existing lighting system consists of 2x4 (or 1x4) troffers with fluorescent technology with a semi-opaque lens currently delivering light levels consistent with P-100.
Actors:	Facility Manager, Building Owner, ESCO, Contractor
Pre-conditions:	1. 2'x4' (or 1'x4') troffer 2. 2-lamp T12 or T8 fluorescent 3. Pre-light levels within 10% of P-100 (*e.g.*, 30 fc) 4. Existing lamps have rated life of ≤ 30,000 hrs.* 5. Lensed fixture (*e.g.*, K-12 prismatic, semi-opaque or similar diffusing lens) 6. Existing Lighting Power Density (LPD) ≥ 0.75 W/ft^2 7. Lighting system is operated ≥ 3500 hrs/yr
Post-conditions:	1. Post-light levels 10-20% greater than P-100 (*e.g.*, 30 fc)** 2. 2-lamp LED retrofit system 3. Reduce LPD by ≥ 25% 4. Increase lamp life L_{70} ≥ 50,000 hours 5. Meets GSA cost-effectiveness threshold (*e.g.*, simple payback < 7 yrs.)
Notes:	*Nominal 30,000 hr. rated lamp life (25,000 yr replacement cycle) requires 2 lamp replacements over 50,000 hr period. Avoided lamp replacement cost is a significant contributor to cost-effectiveness. **Linear fluorescent lamps can maintain 90-96% of their initial light output all the way to rated life. An LED system is allowed to depreciate to 70% of its

Use Case:	2-Lamp 2'x4' (or 1'x4') Fluorescent "Lensed" Troffer – Light Levels ≈ P-100
	initial life. To compensate for the extended period of time where the LED system is delivering less light than fluorescent, the LED system must begin with higher initial light levels. Ideally, the LED system would be capable of dimming (trim) so as to meet P-100 at all times and save additional energy.

Use Case:	2-Lamp 2'x4' (or 1'x4') Fluorescent "Lensed" Troffer – Light Levels ≥ 30% P-100
Description:	Existing lighting system consists of 2x4 (or 1x4) troffers with fluorescent technology with a semi-opaque lens currently delivering light levels exceeding P-100 greater than 30%.
Actors:	Facility Manager, Building Owner, ESCO, Contractor
Pre-conditions:	1. 2'x4' (or 1'x4') troffer 2. 2-lamp T12 or T8 fluorescent 3. Pre-light levels ≥ 30% P-100 (*e.g.*, 30 fc) 4. Existing lamps have rated life of ≤ 30,000 hrs.* 5. Lensed fixture (*e.g.*, K-12 prismatic, semi-opaque or similar diffusing lens) 6. Existing Lighting Power Density (LPD) ≥ 0.75 W/ft^2 7. Lighting system is operated ≥ 3500 hrs/yr
Post-conditions:	1. Post-light levels 10-20% greater than P-100 (*e.g.*, 30 fc)** 2. 2-lamp LED retrofit system 3. Reduce LPD by ≥ 25% 4. Increase lamp life L_{70} ≥ 50,000 hours 6. Meets GSA cost-effectiveness threshold (*e.g.*, simple payback < 7 yrs.)
Notes:	*Nominal 30,000 hr. rated lamp life (25,000 yr replacement cycle) requires 2 lamp replacements over 50,000 hr period. Avoided lamp replacement cost is a significant contributor to cost-effectiveness. **Linear fluorescent lamps can maintain 90-96% of their initial light output all the way to rated life. An LED system is allowed to depreciate to 70% of its initial life. To compensate for the extended period of time where the LED system is delivering less light than fluorescent, the LED system must begin with higher initial light levels. Ideally, the LED system would be capable of dimming (trim) so as to meet P-100 at all times and save additional energy.

Use Case:	3-Lamp 2'x4' Fluorescent "Lensed" Troffer – Light Levels ≥ 30% P-100
Description:	Existing lighting system consists of 2'x4' troffer with fluorescent technology with a semi-opaque lens currently delivering light levels exceeding P-100 greater than 30%.
Actors:	Facility Manager, Building Owner, ESCO, Contractor
Pre-conditions:	1. 2'x4' troffer 2. 3-lamp T12 or T8 fluorescent 3. Pre-light levels ≥ 30% P-100 (*e.g.*, 30 fc) 4. Existing lamps have rated life of ≤ 30,000 hrs. 5. Lensed fixture (*e.g.*, K-12 prismatic, semi-opaque or similar diffusing lens) 6. Existing Lighting Power Density (LPD) ≥ 0.75 W/ft^2

Use Case:	3-Lamp 2'x4' Fluorescent "Lensed" Troffer – Light Levels ≥ 30% P-100
	7. Lighting system is operated ≥ 3500 hrs/yr
Post-conditions:	1. Post-light levels 10-20% greater than P-100 (*e.g.*, 30 fc)** 2. 2-lamp LED retrofit system 3. Reduce LPD by ≥ 25% 4. Increase lamp life L_{70} ≥ 50,000 hours 5. Meets GSA cost-effectiveness threshold (*e.g.*, simple payback < 7 yrs.)
Notes:	*Nominal 30,000 hr. rated lamp life (25,000 yr replacement cycle) requires 2 lamp replacements over 50,000 hr period. Avoided lamp replacement cost is a significant contributor to cost-effectiveness. **Linear fluorescent lamps can maintain 90-96% of their initial light output all the way to rated life. An LED system is allowed to depreciate to 70% of its initial life. To compensate for the extended period of time where the LED system is delivering less light than fluorescent, the LED system must begin with higher initial light levels. Ideally, the LED system would be capable of dimming (trim) so as to meet P-100 at all times and save additional energy).

Use Case:	2-Lamp 2'x4' (or 1'x4') Fluorescent "Parabolic" Troffer – Light Levels ≈ P-100
Description:	Existing office lighting system consists of 2'x4' fluorescent technology with a parabolic lens that currently delivers light levels consistent with P-100.
Actors:	Facility Manager, Building Owner, ESCO, Contractor
Pre-conditions:	1. 2'x4' (or 1'x4') troffer 2. 2-lamp T12 or T8 fluorescent 3. Pre-light levels within 10% of P-100 (*e.g.*, 30 fc) 4. Existing lamps have rated life of ≤ 30,000 hrs.* 5. Parabolic louver 6. Existing Lighting Power Density (LPD) ≥ 0.75 W/ft^2 7. Lighting system is operated ≥ 3500 hrs/yr
Post-conditions:	1. Post-light levels 10-20% greater than P-100 (*e.g.*, 30 fc)** 2. 2-lamp LED retrofit system 3. Reduce LPD by ≥ 25% 4. Increase lamp life L_{70} ≥ 50,000 hours 5. Meets GSA cost-effectiveness threshold (*e.g.*, simple payback < 7 yrs.)
Notes:	*Nominal 30,000 hr. rated lamp life (25,000 yr replacement cycle) requires 2 lamp replacements over 50,000 hr period. Avoided lamp replacement cost is a significant contributor to cost-effectiveness. **Linear fluorescent lamps can maintain 90-96% of their initial light output all the way to rated life. An LED system is allowed to depreciate to 70% of its initial life. To compensate for the extended period of time where the LED system is delivering less light than fluorescent, the LED system must begin with higher initial light levels. Ideally, the LED system would be capable of dimming (trim) so as to meet P-100 at all times and save additional energy).
Caution:	Be aware that parabolic louvers were designed to reduce glare on CRT computer screens by blocking light emission at high angles from the fixture. LED retrofit systems can be employed successfully in these fixture types.

Use Case:	2-Lamp 2’x4’ (or 1’x4’) Fluorescent “Parabolic” Troffer – Light Levels ≈ P-100
	However, because the LED systems are directional and circumvent the secondary optics (top) of the fixture, there is a risk of altering the distribution of light from the fixture. Additionally, there can be aesthetic concerns with contrast when looking up at the fixture. It is recommended that mock-ups be conducted to determine the existence of any problems before wide-scale implementation.

Use Case:	3-Lamp 2’x4’ (or 1’x4’) Fluorescent “Parabolic” Troffer – Light Levels ≈ P-100
Description:	Existing office lighting system consists of 2x4 fluorescent technology that currently delivers light levels consistent with P-100.
Actors:	Facility Manager, Building Owner, ESCO, Contractor
Pre-conditions:	1. 2’x4’ troffer 2. 3-lamp T12 or T8 fluorescent 3. Pre-light levels ≥ 30% P-100 (*e.g.*, 30 fc) 4. Existing lamps have rated life of ≤ 30,000 hrs.* 5. Parabolic louver with 3-cells across the short (2’) dimension. 6. Existing Lighting Power Density (LPD) ≥ 0.75 W/ft^2 7. Lighting system is operated ≥ 3500 hrs/yr
Post-conditions:	1. Post-light levels 10-20% greater than P-100 (*e.g.*, 30 fc)** 2. 2-lamp or 3-lamp LED retrofit system 3. Reduce LPD by ≥ 25% 4. Increase lamp life L_{70} ≥ 50,000 hours 5. Meets GSA cost-effectiveness threshold (*e.g.*, simple payback < 7 yrs.)
Notes:	*Nominal 30,000 hr. rated lamp life (25,000 yr replacement cycle) requires 2 lamp replacements over 50,000 hr period. Avoided lamp replacement cost is a significant contributor to cost-effectiveness. **Linear fluorescent lamps can maintain 90-96% of their initial light output all the way to rated life. An LED system is allowed to depreciate to 70% of its initial life. To compensate for the extended period of time where the LED system is delivering less light than fluorescent, the LED system must begin with higher initial light levels. Ideally, the LED system would be capable of dimming (trim) so as to meet P-100 at all times and save additional energy).
Caution:	1. Be aware that parabolic louvers were designed to reduce glare on CRT computer screens by blocking light emission at high angles from the fixture. LED retrofit systems can be employed successfully in these fixture types. However, because the LED systems are directional and circumvent the secondary optics (top) of the fixture, there is a risk of altering the distribution of light from the fixture. Additionally, there can be aesthetic concerns with contrast when looking directly up at the fixture. It is recommended that mock-ups be conducted to determine the existence of any problems before wide-scale implementation. 2. 3-lamp to 2-lamp retrofits can be problematic as the inboard lamp space is vacated. The parabolic lens coupled with the directional LED system effectively limits the light that would otherwise be emitted from the inboard lamp space. The increased contrast can be more noticeable.

ISSUES TO CONSIDER WHEN EVALUATING OPTIONS

a Product Efficacy

Product Efficacy – the efficacy of a lighting source is important for energy savings and should meet a reasonable minimum. LED products across the market have greatly varying efficacies depending on product type and manufacturer. For simplicity in determining a minimum efficiency for a project, it can be useful to refer to existing lighting program requirements for setting minimum criteria and searching for product options.

Table 13. Programs with Developed Lighting Performance Criteria

Property	CFL Lamps	LED Lamps	FL Linear Lamps	LED Linear Lamps	FL Troffer/Grid Ceilings	LED Troffer/Grid Ceilings	LED-Retrofit Troffer/Grid Ceilings	FL Downlights	LED Downlights	LED-Retrofit Downlights	FL Linear Suspended	LED Linear Suspended	LED-Retrofit Linear Suspended	FL Industrial High Bay/Low Bay	HID Industrial High Bay/Low Bay	LED Industrial High Bay/Low Bay	LED Retrofit Industrial High Bay/Low Bay
Energy Star	●	●						●	●	●							
DLC				●		●	●					●	●			●	●
LED Lighting Facts																	
FEMP-designation			●		●	●					●	●		●	●	●	
BBA					●	●											
CEE			●														
● = Existing																	

b Light delivery to the task

Will the replacement provide the same or appropriate lighting for the tasks in the space? Evaluate the light output of various options and ensure reasonable light distribution. This may require measurements of the existing conditions or modeling to ensure that post-retrofit light levels are appropriate. It is important to manage light levels to meet established industry recommendations.[11]

c Light distribution

LED lamps and kits designed to replace LFLs do not emit light at 360 degrees as do the incumbent fluorescent lamps. This change in light delivery from the light source leads to a substantial difference in total light delivery from the luminaire, and the light distribution and visual comfort level of the occupants in the space. With fluorescent lamps, the internal reflectance of the fixture housing plays a large role in the efficiency and distribution of the luminaire, while with LED replacement products, the inherent directionality of the LEDs results in light leaving the luminaire directly. This difference can provide increases in the fixture efficiency by reducing light loss in the luminaire, but it also changes the overall light distribution, which might lead to unpleasant and uneven patterns in the space.

d Product useful life

Will the replacement last as long as or longer than the existing lamp? Will the project make use of the long life of potential replacement options? LEDs have the potential to last longer than fluorescent lamps, especially in an application where the lamps might be turned on and off frequently. However, LEDs do degrade over time and will eventually degrade past their usefulness for the lighting task. Many LEDs are rated for 35,000 to 50,000 hours at 70% of initial light output compared to LFLs with common lifetimes of 25,000 to as high as 80,000 hours before failure. A good LED can provide five times or more life compared to an LFL. However, the project must consider if that long life will be used and, therefore, cost-effective. If the space has low lighting use time or may be reconfigured in the near future, then a very long life product may not be practical or cost-effective.

e Lighting Color

Can the same or more appropriate color be acquired with the replacement? LED products are available in the same general color choices as fluorescent lamps from warm white (*i.e.*, 2700K) to cool white (*i.e.*, 5000K). If the current color in the space is appropriate, choose an LED lamp with the same color temperature. In general, people-occupied spaces are commonly lighted with warmer color temperatures (3000K to 4100K) because skin tones are rendered better at those color temperatures.

f Installation time and cost

Which option that meets performance needs will create the least installation hassles and cost for the value? LED direct lamp replacements will cost more than fluorescent lamps, and labor costs for replacements may vary widely, depending on LED replacement kit wiring requirements and the wiring configuration of the existing fluorescent luminaire. Depending on the complexity of the re-wiring required, a new LED fixture might not be the highest installation cost and should be compared carefully with replacement kit needs. It may be prudent to consult with a contractor with details of replacement kits and new fixtures in hand to get an estimate of the difference in installation cost.

[11] IES maintains the industry accepted information of light level recommendations for various indoor and outdoor tasks and areas. www.ies.org.

g Installation Compatibility

For replacement LED lamps that operate on existing ballasts, it is important to verify that the existing fluorescent luminaires have the appropriate ballast type to operate the LED products. Generally, these types of products require electronic instant-start ballasts. If a magnetic, rapid-start, or programmed rapid start ballast is installed, the ballast would have to be replaced, and these types of products would not be the best option.

All LEDs require a driver to operate, and kits either have drivers integral to the lamp or externally, essentially taking the place of the ballast. The driver location is not as indicative of a time consuming retrofit as is the wiring required by the LED replacement product. Depending on the existing type of ballast in the existing fluorescent troffer, wiring to the tombstones (or sockets, that hold the lamps in place and provide the electrical current) varies. The different wiring configurations in the existing luminaire as well as the wiring required by the LED product should align to reduce the burden of the installation.

The best way to determine if your current lighting system would be a good candidate for a linear LED retrofit is to perform a mock retrofit to answer the following questions:

1. Does the optical system (lens or louver) come off easily?
2. How difficult is it to access the ballast? Is it attached with screws or by other means that allow easy removal?
3. What type of ballast is required?
4. How many sockets are installed?

h Maintenance

Will any option create extra or lower maintenance in the future? Will this create additional or reduced cost given existing budget and costing structures?

With the longer useful life of LED technology, there can be significant maintenance savings from reduced fluorescent lamp replacement. However, in some organizational budget structures, lighting maintenance may not be an adjustable budget item; therefore, cost savings may not be actually realized. Verify that reduced maintenance can be realistically identified in costing and budgeting before applying maintenance cost savings to any project decision analysis.

i Sustainability

In terms of energy, the LED options should always be more sustainable than fluorescent technology. In terms of environmental responsibility, again LED products have been considered more environmentally friendly, which is generally confirmed by DOE studies.[12]

D. BASIC PRODUCT SPECIFICATION

TROFFER RETROFIT KITS

A. General Description: Linear LED retrofit replacing T8 or T12 recessed or surface-mounted 1’ x 4’ or 2’ x 4’- troffer:

[12] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_led_lca-pt2.pdf

- Linear LED retrofit utilizing existing fluorescent sockets and operating on dedicated LED driver
- Linear LED retrofit mounted directly to luminaire housing and operating on dedicated LED driver

B. Luminaire Application
- Lensed (*e.g.*, K12 prismatic, semi-opaque, etc.)
- Volumetric
- High Performance
- Parabolic Louver
- Recessed Indirect (depends on mounting)

C. Electrical
- Operating voltage: 120 to 277 V
- Power Factor: 0.90 at full light output
- Total Harmonic Distortion: <20% at full light output
- Source Efficacy: 100 lm/W at full light output

D. Photometric Performance
- Light Output: minimum 1600 lumens
- Beam Angle: >120° (greater beam angle may be desirable for open (*e.g.,* parabolic) fixtures

E. Chromaticity
- CCT: 3000K, 3500K, 4000K or as specified by site
- CRI: 80, R9>0

F. Approved Product List
- Product(s) shall be listed in the most current iteration of the DesignLights Consortium™ Qualified Products List (see: https://www.designlights.org/QPL). Only currently "Qualified" products are acceptable.

G. Controls
- Look for "dimmable" products if considering daylight harvesting or task tuning controls methods

H. Lumen Maintenance: Minimum 70% light output at 50,000 hours derived from LM-80 and TM-21 reportable rating

I. Warranty: Minimum 5 years

J. Access Through Other Networks or Systems
- Wired and wireless control systems must not be accessible, networked or otherwise tied to external systems, unless specified by the GSA.

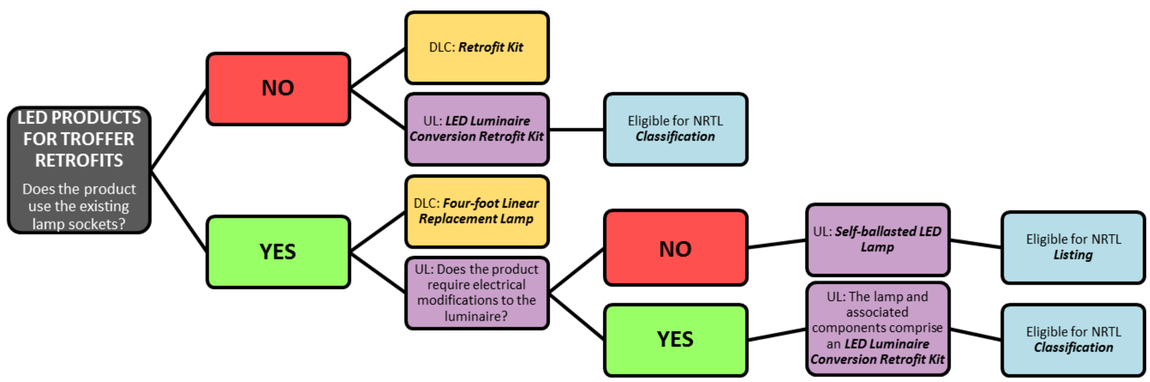
E. RECOMMENDATIONS FOR INSTALLATION, COMMISSIONING, TRAINING AND MAINTENANCE MANAGEMENT

SAFETY RELATED INSTALLATION CONSIDERATIONS

Any retrofitting of lighting fixtures typically involves some modification of the fixture or wiring, which may present safety issues. TLEDs that are considered plug-and-play technology for LFLs also present possible safety issues with often required rewiring of fixtures.

Manufacturers typically have their luminaires certified for electrical safety by a Nationally Recognized Testing Laboratory (NRTL), such as Underwriters Laboratories Inc. (UL), Canadian Standards Association (CSA), or ETL. LED replacement lamps that replace a fluorescent lamp without making any modifications to the luminaire are eligible for safety listing as "Self-Ballasted LED Lamps" including those that do not have an integral driver but operate on the fluorescent lamp ballast (*i.e.*, TLED). Products in this category can be used in a listed luminaire without requiring further investigation. When the electrical or thermal characteristics of a listed luminaire are modified in the field, it is uncertain whether the modified luminaire continues to meet the relevant safety requirements unless the field modifications are investigated by an NRTL. Many tube-style LED replacement lamps require modifications such as installation of a driver, rewiring of the lamp sockets, or both. The lamps and other components used in these cases are commonly categorized by UL as "LED Luminaire Conversion Retrofit Kits" and are eligible for NRTL Classification. When a luminaire modification is performed using an NRTL Classified LED Conversion Retrofit Kit, the modified luminaire is considered to meet the same level of safety that was present prior to retrofit, without requiring an infield investigation.

Figure 60. Luminaire Retrofit Classifications



As part of the retrofit using an NRTL Classified LED luminaire conversion retrofit kit, the luminaire must be labeled indicating that the luminaire has been modified from its original condition and that it will no longer support operation from a light source other than the specific tube-style LED replacement lamp with which it has been fitted. The label must be prominent and the information on the label must match corresponding information on the installation instructions and other documents. When evaluating LED upgrades to fluorescent lamp troffers, use the following equipment to avoid any possible need for post-install field safety investigation:

- A replacement lamp that requires no further electrical modifications to the luminaire and is NRTL listed

- A replacement lamp that requires electrical modifications to the luminaire, such as installing a driver, and that is part of an NRTL Classified LED luminaire conversion retrofit kit
- A properly installed retrofit kit that is NRTL Classified.

VII. Appendices

A. OCCUPANT PRE- AND POST- RETROFIT SURVEY DATA

Occupant Survey Data with Statistical Significance Notations

Auburn, WA – GSA Regional: 1st Floor Design and Construction

Property	Description	Pre-Retrofit Total Responses	Pre-Retrofit Percentage	Post-Retrofit Total Responses	Post-Retrofit Percentage
Job Description	Accounting/financial professional	1	4%	0	0%
Job Description	Administrative	4	14%	1	5%
Job Description	Engineering/Technical	5	18%	6	32%
Job Description	Project or program management	8	29%	5	26%
Job Description	Supervisor/team management	2	7%	1	5%
Job Description	Other	8	29%	6	32%
Age	30 or under	1	4%	0	0%
Age	31 to 50	11	44%	9	56%
Age	Over 50	13	52%	7	44%
Workspace	Enclosed Private Office	0	0%	0	0%
Workspace	Cubicles with partitions	26	100%	16	89%
Workspace	Other -please specify	0	0%	2	11%
Workspace	Please specify	0	0%	0	0%
Computer Screen	Laptop	6	21%	4	22%
Computer Screen	Flat panel	21	72%	14	78%
Computer Screen	Other-please specify	2	7%	0	0%
Computer Screen	Please specify	0	0%	0	0%
Window	Yes	25	93%	17	94%
Window	No	2	7%	1	6%
Task Lighting	Under cabinet	1	4%	0	0%
Task Lighting	Desktop	24	89%	13	72%
Task Lighting	None	2	7%	5	28%
Workspace Lighting	Yes	23	92%	17	94%
Workspace Lighting	No	2	8%	1	6%
Rate Lighting[a]	25	2	8%	1	5%
Rate Lighting[a]	Paper Task Just Right	21	84%	17	89%
Rate Lighting[a]	Paper Task Too Dim	2	8%	1	5%
Rate Lighting[a]	Reading Computer Screen Too Bright	5	19%[b]	3	18%[c]
Rate Lighting[a]	Reading Computer Screen Just Right	20	77%	13	76%
Rate Lighting[a]	Reading Computer Screen Too	1	4%	1	6%

Property	Description	Pre-Retrofit Total Responses	Pre-Retrofit Percentage	Post-Retrofit Total Responses	Post-Retrofit Percentage
	Dim				
Rate Lighting[a]	Keyboard Typing Too Bright	0	0%	1	6%[c]
Rate Lighting[a]	Keyboard Typing Just Right	23	96%	17	94%
Rate Lighting[a]	Keyboard Typing Too Dim	1	4%	0	0%
Glare[a]	Work Surface Often	3	12%	3	18%
Glare[a]	Work Surface Sometimes	5	20%	5	29%
Glare[a]	Work Surface Rarely/Never	17	68%[c]	9	53%[c]
Glare[a]	Computer Screen Often	4	16%	6	33%
Glare[a]	Computer Screen Sometimes	9	36%	8	44%
Glare[a]	Computer Screen Rarely/Never	12	48%[c]	4	22%
Glare[a]	Lighting Overhead Often	1	4%	4	22%
Glare[a]	Lighting Overhead Sometimes	5	20%	2	11%
Glare[a]	Lighting Overhead Rarely/Never	19	76%[c]	12	67%[c]
Glare[a]	Far Away Lighting Often	1	4%	3	17%
Glare[a]	Far Away Lighting Sometimes	5	20%	2	11%
Glare[a]	Far Away Lighting Rarely/Never	19	76%[c]	13	72%[c]
Color	Space Now Warm	5	20%	3	17%
Color	Space Now Neutral	11	44%	5	28%
Color	Space Now Cool	2	8%	4	22%
Color	Space Now Don't Know	7	28%	6	33%
Color	Prefer Warm	7	28%	3	18%
Color	Prefer Neutral	12	48%	6	35%
Color	Prefer Cool	2	8%	2	12%
Color	Prefer Don't Know	4	16%	6	35%

(a) Statistical Analysis Performed

(b) Statistical Significance Level 90%

(c) Statistical Significance Level 95%

Auburn, WA – GSA Regional: 1st Floor Real Estate

Property	Description	Pre-Retrofit Total Responses	Pre-Retrofit Percentage	Post-Retrofit Total Responses	Post-Retrofit Percentage
Job Description	Accounting/financial professional	0	0%	0	0%
Job Description	Administrative	1	8%	0	0%
Job Description	Engineering/Technical	0	0%	0	0%
Job Description	Project or program management	7	54%	8	53%
Job Description	Supervisor/team management	3	23%	4	27%

Property	Description	Pre-Retrofit Total Responses	Pre-Retrofit Percentage	Post-Retrofit Total Responses	Post-Retrofit Percentage
Job Description	Other	2	15%	3	20%
Age	30 or under	2	17%	2	15%
Age	31 to 50	7	58%	6	46%
Age	Over 50	3	25%	5	38%
Workspace	Enclosed Private Office	0	0%	0	0%
Workspace	Cubicles with partitions	13	93%	15	94%
Workspace	Other -please specify	0	0%	1	6%
Workspace	Please specify	1	7%	0	0%
Computer Screen	Laptop	2	15%	4	27%
Computer Screen	Flat panel	11	85%	11	73%
Computer Screen	Other-please specify	0	0%	0	0%
Computer Screen	Please specify	0	0%	0	0%
Window	Yes	11	79%	13	81%
Window	No	3	21%	3	19%
Task Lighting	Under cabinet	0	0%	0	0%
Task Lighting	Desktop	8	57%	10	63%
Task Lighting	None	6	43%	6	38%
Workspace Lighting	Yes	12	86%	11	69%
Workspace Lighting	No	2	14%	5	31%
Rate Lighting[(a)]	Paper Task Too Bright	2	14%	3	19%
Rate Lighting[(a)]	Paper Task Just Right	12	86%	12	75%
Rate Lighting[(a)]	Paper Task Too Dim	0	0%	1	6%
Rate Lighting[(a)]	Reading Computer Screen Too Bright	2	14%2	6	38%3
Rate Lighting[(a)]	Reading Computer Screen Just Right	12	86%	10	63%
Rate Lighting[(a)]	Reading Computer Screen Too Dim	0	0%	0	0%
Rate Lighting[(a)]	Keyboard Typing Too Bright	2	14%	4	25% 3
Rate Lighting[(a)]	Keyboard Typing Just Right	12	86%	12	75%
Rate Lighting[(a)]	Keyboard Typing Too Dim	0	0%	0	0%
Glare[(a)]	Work Surface Often	0	0%	4	27%
Glare[(a)]	Work Surface Sometimes	5	38%	2	13%
Glare[(a)]	Work Surface Rarely/Never	8	62%3	9	60%3
Glare[(a)]	Computer Screen Often	2	15%	3	19%
Glare[(a)]	Computer Screen Sometimes	4	31%	5	31%
Glare[(a)]	Computer Screen Rarely/Never	7	54%3	8	50%3
Glare[(a)]	Lighting Overhead Often	1	8%	5	31%

Property	Description	Pre-Retrofit Total Responses	Pre-Retrofit Percentage	Post-Retrofit Total Responses	Post-Retrofit Percentage
Glare[(a)]	Lighting Overhead Sometimes	2	15%	2	13%
Glare[(a)]	Lighting Overhead Rarely/Never	10	77%3	9	56%3
Glare[(a)]	Far Away Lighting Often	0	0%	1	7%
Glare[(a)]	Far Away Lighting Sometimes	2	15%	5	33%
Glare[(a)]	Far Away Lighting Rarely/Never	11	85%3	9	60%3
Color	Space Now Warm	4	29%	4	27%
Color	Space Now Neutral	3	21%	6	40%
Color	Space Now Cool	5	36%	4	27%
Color	Space Now Don't Know	2	14%	1	7%
Color	Prefer Warm	5	36%	2	13%
Color	Prefer Neutral	5	36%	6	40%
Color	Prefer Cool	1	7%	3	20%
Color	Prefer Don't Know	3	21%	4	27%

(a) Statistical Analysis Performed

(b) Statistical Significance Level 90%

(c) Statistical Significance Level 95%

Dallas, TX – Project Management-Supervisors (near Jackson street windows)

Property	Description	Pre-Retrofit Total Responses	Pre-Retrofit Percentage	Post-Retrofit Total Responses	Post-Retrofit Percentage
Job Description	Accounting/financial professional	1	4%	1	14%
Job Description	Administrative	5	21%	0	0%
Job Description	Engineering/Technical	2	8%	0	0%
Job Description	Project or program management	7	29%	2	29%
Job Description	Supervisor/team management	7	29%	4	57%
Job Description	Other	2	8%	0	0%
Age	30 or under	0	0%	0	0%
Age	31 to 50	9	50%	6	86%
Age	Over 50	9	50%	1	14%
Workspace	Enclosed Private Office	8	40%	4	57%
Workspace	Cubicles with partitions	12	60%	3	43%
Workspace	Other -please specify	0	0%	0	0%
Workspace	Please specify	0	0%	0	0%
Computer Screen	Laptop	4	19%	1	14%
Computer Screen	Flat panel	15	71%	6	86%
Computer Screen	Other-please specify	2	10%	0	0%
Computer Screen	Please specify	0	0%	0	0%
Window	Yes	8	38%	6	86%
Window	No	13	62%	1	14%
Task Lighting	Under cabinet	17	81%	7	100%
Task Lighting	Desktop	1	5%	0	0%
Task Lighting	None	3	14%	0	0%
Workspace Lighting	Yes	20	95%	7	100%
Workspace Lighting	No	1	5%	0	0%
Rate Lighting[a]	Paper Task Too Bright	1	5%	0	0%
Rate Lighting[a]	Paper Task Just Right	18	86%	7	100%
Rate Lighting[a]	Paper Task Too Dim	2	10%	0	0%
Rate Lighting[a]	Reading Computer Screen Too Bright	2	10%	1	14%
Rate Lighting[a]	Reading Computer Screen Just Right	18	86%	6	86%
Rate Lighting[a]	Reading Computer Screen Too Dim	1	5%	0	0%
Rate Lighting[a]	Keyboard Typing Too Bright	1	5%	0	0%
Rate Lighting[a]	Keyboard Typing Just Right	19	90%	7	100%

Property	Description	Pre-Retrofit Total Responses	Pre-Retrofit Percentage	Post-Retrofit Total Responses	Post-Retrofit Percentage
Rate Lighting[(a)]	Keyboard Typing Too Dim	1	5%	0	0%
Glare[(a)]	Work Surface Often	1	5%	0	0%
Glare[(a)]	Work Surface Sometimes	4	20%	2	29%
Glare[(a)]	Work Surface Rarely/Never	15	75%3	5	71%3
Glare[(a)]	Computer Screen Often	3	15%	1	14%
Glare[(a)]	Computer Screen Sometimes	4	20%	3	43%
Glare[(a)]	Computer Screen Rarely/Never	13	65%3	3	43%3
Glare[(a)]	Lighting Overhead Often	2	10%	0	0%
Glare[(a)]	Lighting Overhead Sometimes	4	19%	0	0%
Glare[(a)]	Lighting Overhead Rarely/Never	15	71%3	7	100%3
Glare[(a)]	Far Away Lighting Often	0	0%	0	0%
Glare[(a)]	Far Away Lighting Sometimes	2	10%	0	0%
Glare[(a)]	Far Away Lighting Rarely/Never	18	90%3	7	100%3
Color	Space Now Warm	1	5%	1	14%
Color	Space Now Neutral	9	43%	4	57%
Color	Space Now Cool	6	29%	2	29%
Color	Space Now Don't Know	5	24%	0	0%
Color	Prefer Warm	6	29%	0	0%
Color	Prefer Neutral	6	29%	4	57%
Color	Prefer Cool	7	33%	3	43%
Color	Prefer Don't Know	2	10%	0	0%

(a) Statistical Analysis Performed

(b) Statistical Significance Level 90%

(c) Statistical Significance Level 95%

Dallas, TX – GSA Cabell: 7th floor GSA area(s) behind the GSA lobby Property MGNT/ Contracting No windows

Property	Description	Pre-Retrofit Total Responses	Pre-Retrofit Percentage	Post-Retrofit Total Responses	Post-Retrofit Percentage
Job Description	Accounting/financial professional	1	4%	0	0%
Job Description	Administrative	5	21%	1	14%
Job Description	Engineering/Technical	2	8%	0	0%
Job Description	Project or program management	7	29%	2	29%
Job Description	Supervisor/team management	7	29%	0	0%
Job Description	Other	2	8%	4	57%
Age	30 or under	0	0%	0	0%
Age	31 to 50	9	50%	1	14%
Age	Over 50	9	50%	6	86%
Workspace	Enclosed Private Office	8	40%	1	14%
Workspace	Cubicles with partitions	12	60%	6	86%
Workspace	Other -please specify	0	0%	0	0%
Workspace	Please specify	0	0%	0	0%
Computer Screen	Laptop	4	19%	1	14%
Computer Screen	Flat panel	15	71%	6	86%
Computer Screen	Other-please specify	2	10%	0	0%
Computer Screen	Please specify	0	0%	0	0%
Window	Yes	8	38%	2	29%
Window	No	13	62%	5	71%
Task Lighting	Under cabinet	17	81%	7	100%
Task Lighting	Desktop	1	5%	0	0%
Task Lighting	None	3	14%	0	0%
Workspace Lighting	Yes	20	95%	4	57%
Workspace Lighting	No	1	5%	3	43%
Rate Lighting[(a)]	Paper Task Too Bright	1	5%	1	14%
Rate Lighting[(a)]	Paper Task Just Right	18	86%	3	43%
Rate Lighting[(a)]	Paper Task Too Dim	2	10%	3	43%
Rate Lighting[(a)]	Reading Computer Screen Too Bright	2	10%	2	29%
Rate Lighting[(a)]	Reading Computer Screen Just Right	18	86%	4	57%
Rate Lighting[(a)]	Reading Computer Screen Too Dim	1	5%	1	14%
Rate Lighting[(a)]	Keyboard Typing Too Bright	1	5%	0	0%
Rate Lighting[(a)]	Keyboard Typing Just Right	19	90%	5	71%

Property	Description	Pre-Retrofit Total Responses	Pre-Retrofit Percentage	Post-Retrofit Total Responses	Post-Retrofit Percentage
Rate Lighting[(a)]	Keyboard Typing Too Dim	1	5%	2	29%
Glare[(a)]	Work Surface Often	1	5%	0	0%
Glare[(a)]	Work Surface Sometimes	4	20%	2	29%
Glare[(a)]	Work Surface Rarely/Never	15	75%3	5	71%3
Glare[(a)]	Computer Screen Often	3	15%	2	29%
Glare[(a)]	Computer Screen Sometimes	4	20%	1	14%
Glare[(a)]	Computer Screen Rarely/Never	13	65%3	4	57%3
Glare[(a)]	Lighting Overhead Often	2	10%	1	14%
Glare[(a)]	Lighting Overhead Sometimes	4	19%	2	29%
Glare[(a)]	Lighting Overhead Rarely/Never	15	71%3	4	57%3
Glare[(a)]	Far Away Lighting Often	0	0%	0	0%
Glare[(a)]	Far Away Lighting Sometimes	2	10%	2	33%
Glare[(a)]	Far Away Lighting Rarely/Never	18	90%3	4	67%3
Color	Space Now Warm	1	5%	2	33%
Color	Space Now Neutral	9	43%	1	17%
Color	Space Now Cool	6	29%	2	33%
Color	Space Now Don't Know	5	24%	1	17%
Color	Prefer Warm	6	29%	3	43%
Color	Prefer Neutral	6	29%	2	29%
Color	Prefer Cool	7	33%	2	29%
Color	Prefer Don't Know	2	10%	0	0%

(a) Statistical Analysis Performed

(b) Statistical Significance Level 90%

(c) Statistical Significance Level 95%

Philadelphia, PA – GSA VA: Daycare Center

Property	Description	Pre-Retrofit Total Responses	Pre-Retrofit Percentage	Post-Retrofit Total Responses	Post-Retrofit Percentage
Job Description	Accounting/financial professional	0	0%	0	0%
Job Description	Administrative	0	0%	0	0%
Job Description	Engineering/Technical	0	0%	0	0%
Job Description	Project or program management	0	0%	0	0%
Job Description	Supervisor/team management	1	6%	0	0%
Job Description	Other	16	94%	17	100%
Age	30 or under	6	32%	5	25%
Age	31 to 50	6	32%	9	45%
Age	Over 50	7	37%	6	30%
Workspace	Enclosed Private Office	1	5%	1	6%
Workspace	Cubicles with partitions	0	0%	0	0%
Workspace	Other -please specify	18	95%	15	94%
Workspace	Please specify	0	0%	0	0%
Computer Screen	Laptop	1	20%	1	8%
Computer Screen	Flat panel	4	80%	12	92%
Computer Screen	Other-please specify	0	0%	0	0%
Computer Screen	Please specify	0	0%	0	0%
Window	Yes	18	95%	21	95%
Window	No	1	5%	1	5%
Task Lighting	Under cabinet	0	0%	0	0%
Task Lighting	Desktop	0	0%	3	15%
Task Lighting	None	15	100%	17	85%
Workspace Lighting	Yes	18	100%	21	95%
Workspace Lighting	No	0	0%	1	5%
Rate Lighting[(a)]	Paper Task Too Bright	1	5%	1	5%
Rate Lighting[(a)]	Paper Task Just Right	16	80%	20	91%
Rate Lighting[(a)]	Paper Task Too Dim	3	15%	1	5%
Rate Lighting[(a)]	Reading Computer Screen Too Bright	1	7%	0	0%
Rate Lighting[(a)]	Reading Computer Screen Just Right	12	80%	19	95%
Rate Lighting[(a)]	Reading Computer Screen Too Dim	2	13%	1	5%
Rate Lighting[(a)]	Keyboard Typing Too Bright	1	7%	0	0%
Rate Lighting[(a)]	Keyboard Typing Just Right	11	79%	19	95%
Rate Lighting[(a)]	Keyboard Typing Too Dim	2	14%	1	5%

Property	Description	Pre-Retrofit Total Responses	Pre-Retrofit Percentage	Post-Retrofit Total Responses	Post-Retrofit Percentage
Glare[a]	Work Surface Often	0	0%	0	0%
Glare[a]	Work Surface Sometimes	4	24%	5	23%
Glare[a]	Work Surface Rarely/Never	13	76%3	17	77%3
Glare[a]	Computer Screen Often	0	0%	0	0%
Glare[a]	Computer Screen Sometimes	6	35%	6	29%
Glare[a]	Computer Screen Rarely/Never	11	64%3	15	71%3
Glare[a]	Lighting Overhead Often	0	0%	0	0%
Glare[a]	Lighting Overhead Sometimes	2	12%	3	14%
Glare[a]	Lighting Overhead Rarely/Never	15	88%3	19	86%3
Glare[a]	Far Away Lighting Often	0	0%	0	0%
Glare[a]	Far Away Lighting Sometimes	2	11%	5	23%
Glare[a]	Far Away Lighting Rarely/Never	16	89%3	17	77%3
Color	Space Now Warm	5	31%	9	41%
Color	Space Now Neutral	5	31%	6	27%
Color	Space Now Cool	3	19%	4	18%
Color	Space Now Don't Know	3	19%	3	14%
Color	Prefer Warm	4	29%	10	45%
Color	Prefer Neutral	5	36%	5	23%
Color	Prefer Cool	3	21%	4	18%
Color	Prefer Don't Know	2	14%	3	14%

(a) Statistical Analysis Performed

(b) Statistical Significance Level 90%

(c) Statistical Significance Level 95%

B. INSTALLER RETROFIT SURVEY DATA

LED-A

Question	Auburn	Dallas	Philadelphia
Was it clear from the product or package how or where the product was to be installed?	Yes	Yes	Yes
Were instructions needed to complete the installation? If so, were they complete and effective?	Yes	Yes	Yes
Were there any potential safety issues identified with this system or the process for replacing it? Describe.	Yes, eye protection recommended because you have to drill screws in to metal top of troffer to hold lamps in place	No	No
Was there any difference in time or effort involved in installing this LED fixture retrofit system compared to the standard Fluorescent lamp/ballast or complete fixture replacement? Describe.	Yes, more time consuming. Need drill with ¼" nut driver bit to install brackets that hold lamps in fixture.	No	Yes, had to take "runny" thing out of fixture to make work
Do you see anything about this product or its installation that would affect future maintenance costs or process? Please describe.	Yes, replacing lamps might be difficult because of plastic clip that holds in the lamp. Brackets might break.	No	No
Anything else you would like to note about this product or the process for installing it?	Less time making up wires because driver has quick connectors that clip in to lamp. But more time consuming installing with screwing in brackets	No	I would not use in fixtures that LEDs you can see threw

LED-B

Question	Auburn	Dallas	Philadelphia
Was it clear from the product or package how or where the product was to be installed?	Yes	Yes	Yes
Were instructions needed to complete the installation? If so, were they complete and effective?	Yes, wish they would have explained better lamps were polarity sensitive	Yes	Yes
Were there any potential safety issues identified with this tube/driver product or the process for installing it? Please describe.	No	No	No
Was there any difference in time or effort involved in installing this new LED tube/driver product compared to the standard Fluorescent lamp/ballast replacement? Describe.	No, installed same way as regular ballast and lamp change (Besides polarity)	No	No
Do you see anything about this product or its installation that would affect future maintenance costs or process? Please describe.	No, installed same way as regular ballast and lamp change (Besides polarity)	No	No
Anything else you would like to note about this product or the process for installing it?	Just making sure both lamps are facing same way and that the "+" positive side of lamps are installed on the side where the blue wires come out of tombstones.	No	No

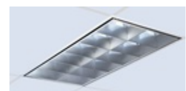
C. SITE SELECTION FIXTURE SURVEY

The following site survey was used to identify sites with appropriate facility lighting for the technology evaluations:

Does your facility have significant 2x4 ceiling lighting fixtures (check YES or NO)? ___YES ___NO

If YES, please indicate the approximate percentage (%) of each of the 3 major types throughout the facility.

_____% – 2x4 lensed



_____% – 2x4 (12-cell) parabolic (2 rows of cells)

_____% – 2x4 (18-cell) parabolic (3 rows of cells)

_____% – 1X4 or 2x4 ceiling-mounted lensed

_____% – Open louver (older)

_____% – Other

Does your facility have significant recessed ceiling lighting fixtures (can lights)? ___YES ___NO

If, YES, please indicate the approximate percentage (%) of each of the 3 major types throughout the facility.

_____% – open

_____% – lensed

_____% – louvered

_____% – Other

D. COSTING ASSUMPTIONS FOR ECONOMIC ANALYSIS

Replace 2x LFL, 32W T8	10	1 Elec	Ea.							
Remove fluor. lamps in fixture				0.078		$ 4.27		$ 4.27	$ 5.28	$ 6.39
2x LFL				0.232	$ 4.90	$ 12.69		$ 17.59	$ 21.10	$ 25.14
Total				**0.31**	**$ 4.90**	**$ 16.96**		**$ 21.86**	**$ 26.38**	**$ 31.53**
Replace LFL Ballast	10	1 Elec	Ea.							
Remove indoor fluor., ballast				0.333		$ 18.22		$ 18.22	$ 22.55	$ 27.29
LFL, electronic ballast				0.667	$ 15.00	$ 36.48		$ 51.48	$ 61.67	$ 73.40
Test fixture				0.018		$ 0.98		$ 0.98	$ 1.22	$ 1.47
Total				**1.018**	**$ 15.00**	**$ 55.68**		**$ 70.68**	**$ 85.44**	**$102.17**
Replace 2x LFL and Ballast, 32W T8	10	1 Elec	Ea.							
Remove indoor fluor., ballast				0.333		$ 18.22		$ 18.22	$ 22.55	$ 27.29
2x LFL				0.232	$ 4.90	$ 12.69		$ 17.59	$ 21.10	$ 25.14
LFL, electronic ballast				0.667	$ 15.00	$ 36.48		$ 51.48	$ 61.67	$ 73.40
Test fixture				0.018		$ 0.98		$ 0.98	$ 1.22	$ 1.47
Total				**1.25**	**$ 19.90**	**$ 68.38**		**$ 88.28**	**$106.54**	**$127.30**
LED-A/B Retrfofit @ $50	12.5	1 Elec	Ea.							
Remove indoor fluor., ballast				0.333		$ 18.22		$ 18.22	$ 22.55	$ 27.29
LED A/B Lamp Install				0.232		$ 12.69		$ 12.69	$ 15.71	$ 19.01
LED-A/B Driver Install				0.667	$ 50.00	$ 36.48		$ 86.48	$100.17	$117.15
Test fixture				0.018		$ 0.98		$ 0.98	$ 1.22	$ 1.47
Total				**1.25**	**$ 50.00**	**$ 68.38**		**$118.38**	**$139.65**	**$164.93**
LED A/B Retrfofit @ $60	12.5	1 Elec	Ea.							
Remove indoor fluor., ballast				0.333		$ 18.22		$ 18.22	$ 22.55	$ 27.29
LED A/B Lamp Install				0.232		$ 12.69		$ 12.69	$ 15.71	$ 19.01
LED-A/B Driver Install				0.667	$ 60.00	$ 36.48		$ 96.48	$111.17	$129.65
Test fixture				0.018		$ 0.98		$ 0.98	$ 1.22	$ 1.47
Total				**1.25**	**$ 60.00**	**$ 68.38**		**$128.38**	**$150.65**	**$177.43**
LED A/B Retrfofit @ $70	12.5	1 Elec	Ea.							
Remove indoor fluor., ballast				0.333		$ 18.22		$ 18.22	$ 22.55	$ 27.29
LED A/B Lamp Install				0.232		$ 12.69		$ 12.69	$ 15.71	$ 19.01
LED-A/B Driver Install				0.667	$ 70.00	$ 36.48		$106.48	$122.17	$142.15
Test fixture				0.018		$ 0.98		$ 0.98	$ 1.22	$ 1.47
Total				**1.25**	**$ 70.00**	**$ 68.38**		**$138.38**	**$161.65**	**$189.93**
Replace fixture, lay-in, recess mtd., 2' x 4' LED @$100	20	1 Elec	Ea.							
Turn branch circuit off and on				0.018		$ 0.98		$ 0.98	$ 1.22	$ 1.47
Remove fluor. lighting fixture				0.533		$ 29.16		$ 29.16	$ 36.09	$ 43.67
Fluor, lay-in, recess mtd., 2' x 4', four 32 W				1.702	$100.00	$ 93.10		$193.10	$225.26	$264.46
Total				**2.253**	**$100.00**	**$123.24**		**$223.24**	**$262.57**	**$309.61**
Replace fixture, lay-in, recess mtd., 2' x 4' LED @ $150	20	1 Elec	Ea.							
Turn branch circuit off and on				0.018		$ 0.98		$ 0.98	$ 1.22	$ 1.47
Remove fluor. lighting fixture				0.533		$ 29.16		$ 29.16	$ 36.09	$ 43.67
Fluor, lay-in, recess mtd., 2' x 4', four 32 W				1.702	$150.00	$ 93.10		$243.10	$280.26	$326.96
Total				**2.253**	**$150.00**	**$123.24**		**$273.24**	**$317.57**	**$372.11**

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LED Retrofit Luminaire Conversion Kits, UL 1598C, http://ulstandardsinfonet.ul.com/outscope/outscope.asp?fn=1598C.html

F. VENDOR SPECIFICATION

UR Series

UR2-48™ and UR3-48™ LED Upgrade Kit – 4'

Product Description

The UR Series 4ft (1219mm) LED upgrade kit delivers 4500 lumens of enhanced spectrum 80 CRI light while achieving over 100 lumens per watt at the system level. This innovative kit is designed for upgrading existing 1'x4' (305mm x 1219mm) or 2'x4' (610mm x 1219mm) fixtures to energy saving LED. The UR Series is available in neutral or cool color temperatures and with step dimming or 0-10V dimming. The UR Series upgrade kit is easy to install and fits into almost any existing linear fluorescent fixture making it a perfect upgrade option where energy savings and long life are critical.

Performance Summary

- Upgrade Existing 1'x4' (305mm x 1219mm) & 2'x4' (610mm x 1219mm) fixtures
- **Efficacy:** 102 LPW at source level
- **System Delivered Light Output:** 4500 lumens
- **Target Fixture Delivered Light Output:** 4000 lumens*
- **Input Power:** 44 watts
- **CRI:** 80
- **CCT:** 3500K, 4000K
- **Input Voltage:** 120-277 VAC or 347 VAC
- **Limited Warranty†:** 7 years
- **Lifetime:** Designed to last 50,000 hours
- **Controls:** Step Level to 50% or 0-10V Dimming to 5%
- **Mounting:** Existing dry or damp rated linear fluorescent fixtures including troffers, parabolics, strips, wraps, volumetric/baskets and industrials; not intended for use in vaportights

4' (1219mm) LED Lightbar
MOL- 44" (1118mm)

The UR Series upgrade kit ships as two components: lightbars and driver. Each component must be ordered separately.

Accessories

Field-Installed
Emergency Backup UR-EB10W - 10W

Ordering Information

Fully assembled kit is composed of two components that must be ordered separately:
Example: **Lightbar:** UR 48 35K FD LB 2 + **Driver:** UR2 48 45L 10V FD DR

Lightbar (Driver must be ordered separately)

UR	48		FD	LB	
Series	**Length**	**CCT**	**Options**	**Lightbar**	**Number of Lightbars**
UR	**48**	**35K** 3500 Kelvin **40K** 4000 Kelvin	**FD** 80 CRI	**LB** Lightbar	**2** 2 Lightbar Kit **3** 3 Lightbar Kit **6** 6 Lightbar Bulk Pack

Driver (Lightbar must be ordered separately)

	48	45L			FD	DR
Product	**Length**	**Lumen Output**	**Voltage**	**Control**	**Options**	**Driver**
UR2 2 Lightbar **UR3** 3 Lightbar	**48**	**45L** 44W, 4500 lumens - 102 LPW	**Blank** 120-277 Volt (Standard) **34** 347 Volt (Optional) - Available with 10V control option only	**S** Step Dimming to 50% **10V** 0-10V Dimming to 5%	**FD**	**DR** Driver

* Varies by fixture
† See www.cree.com/lighting/products/warranty for warranty terms

Rev. Date: V3 01/13/2015

US: www.cree.com/lighting T (800) 236-6800 F (262) 504-5415 Canada: www.cree.com/canada T (800) 473-1234 F (800) 890-7507

NEXTLamp™ Series

4' Linear LED Lamp

Product Description

The NEXTLamp provides lasting, dimmable, high-quality LED light while delivering an attractive ROI. The unique indirect design reflects light off of a specially-coated surface, eliminating glare. Lamps are installed in existing fixtures with NEXTDrivers™ to deliver a long-lasting solution that is fully compatible with dimming and lighting automation. These products are made in the USA using only the highest quality LED components available on the market. The NEXTLamp Series is a perfect solution for commercial, municipal and industrial spaces where energy savings, appearance and long life are of the utmost importance.

4' LED Lamp (1200 mm)
Glare-free, indirect design

Performance Summary

Efficiency:	>100 lumens per Watt
Light Output:	2200 lumens in Standard mode; 1800 lumens in Energy Saving mode
Input Power:	21.5 Watts in Standard mode; 17.5 watts in Energy Saving mode
CRI:	80+
CCT:	3500K, 4000K and 5000K
Input Voltage:	120 – 277 Volts
Lifetime:	50,000 L70
Controls:	Dimmable, compatible with lighting control systems; 0 – 10V standard input
Mounting:	Existing linear fluorescent fixtures
Warranty:	5 years

Features:
- Glare-free indirect design
- Aluminum housing provides durability
- Dimmable
- Compatible with sensors and lighting automation
- Designed to be used with NEXTDrivers for long life
- UL 1598C
- Made in the USA

Applications:
- Office
- Retail and grocery
- Industrial/high bay
- Schools
- Parking garages
- Stairwells
- Tunnels
- Cooler/freezer cases
- Displays

MADE IN USA

www.nextlighting.com T: (415) 821-6000

G. GLOSSARY

Ballast	A device that regulates the current and voltage supplied to a gaseous discharge lamp(s) (*e.g.*, a fluorescent lamp).
Daylight Harvesting	A control strategy that reduces electric light levels in the presence of available daylight, "harvesting" the daylight to save electrical lighting energy.
Dimmable Ballast	A ballast that responds to external control signals by adjusting current flowing through the lamp(s), raising and lowering light output.
Life-Cycle Cost (LCC)	The total discounted dollar costs of owning, operating, maintaining, and disposing of a building or building system over the Study Period (see Life-Cycle Cost Analysis).
Life-Cycle Cost Analysis (LCCA)	A method of economic evaluation that sums discounted dollar costs of initial investment (less Resale, Retention, or Salvage Value), replacements, operations (including energy and water usage), and maintenance and repair of a building or building system over the Study Period (see Life-Cycle Cost). Also, as used in this project, LCCA is a general approach to economic evaluation encompassing several related economic evaluation measures, including Life-Cycle Cost (LCC), Net Benefits (NB) or Net Savings (NS), Savings-to-Investment Ratio (SIR), and Adjusted Internal Rate of Return, all of which take into account long-term dollar impacts of a project.
Savings-to-Investment Ratio (SIR)	A ratio computed from a numerator of discounted energy and/or water savings, plus (less) savings (increases) in Nonfuel Operation and Maintenance Costs, and a denominator of increased Investment Costs plus (less) increases (decreased) Replacement Costs, net of Residual Value (all in present-value terms), for an Alternative Building System as compared with a Base Case.
Simple Payback (SPB)	A measure of the length of time required for the cumulative savings from a project to recover the Investment Cost and other accrued costs, without taking into account the Time Value of Money.
Discounted Payback	The time required for the cumulative savings from an investment to pay back the Investment Costs and other accrued costs, taking into account the Time Value of Money.
Adjusted Internal Rate of Return	The annual yield from a project over the Study Period, taking into account investment of interim amounts.

4-Step Guide: Converting Fluorescent Troffers to LED

Step 1

TARGET facilities where conversion will be most cost-effective

Facilities with higher energy costs (national average commercial rate is $0.11/kWh) and comparatively inefficient existing fixtures, such as T12s or T8s with standard efficiency lamps (32W), will be more cost-effective. Locations that have light levels that are above what is needed, or required by the P-100 or other standards, are also good candidates.

Step 2

SELECT LED replacement option

When making a selection, consider the condition of the existing system, the replacement system's installed cost, the system's ability to provide adequate light levels, current need for advanced lighting controls (ALC), and whether the new system will provide a transition to future lighting control strategies.

	LED OPTIONS	PROS	CONS	USEFUL WHERE:	COST*
REPLACEMENT LAMP	**Uses existing socket & ballast**	• No electrician required	• No dimming or ALC • May not work on all ballasts; need for future ballast replacement • Performance depends on optics & lens of existing fixture	• Cost is critical • Existing FL ballast is healthy • ALC not required	$20–$40 + $17
REPLACEMENT LAMP	**Uses existing socket, "main AC" voltage**	• Eliminates ballast incompatibilities & need for ballast replacement	• Possible safety issues • Not likely capable of dimming or ALC • Performance depends on optics & lens of existing fixture	• FL ballast is suspect or in poor condition • Cost is important	$20–$40 + $50
RETROFIT KIT	**Replacement lamp, uses alternative mounting, LED driver**	• Lamps can be repositioned in the fixture process • Dimming & ALC possible	• Performance depends on optics & lens of existing fixture • Self-tapping screws could cause electrical problems	• ALC may be useful	$40–$70 + $68
RETROFIT KIT	**Replacement lamp, uses existing socket, LED driver**	• Familiar installation • Dimming & ALC possible	• Performance depends on optics & lens of existing fixture	• ALC may be useful	$40–$70 + $68
RETROFIT KIT	**Bare fixture housing**	• Optics optimized for LED • Dimming & ALC possible	• Performance might depend on geometry of existing fixture	• FL ballast is in poor condition • Ceiling access is limited	$60–$70 + $68
NEW	**New light fixture**	• Optics optimized for LED • Integrated ALC sensors • Energy savings compared to retrofit kits	• Might require ceiling access	• FL ballast is in poor condition • No issue with ceiling access	$100–$200 + $123

* Installed cost: materials + installation using RSMeans derived labor estimates

Step 3

DEFINE site-specific specifications

Determine the necessary system performance (e.g., lumen output and distribution) and desired appearance (e.g., color temperature). Any chosen system should meet the following minimum and GSA-specific criteria. Site-specific criteria, such as those listed below, should also be met.

MINIMUM	SITE SPECIFIC	GSA SPECIFIC
A. Use DesignLights Consortium™ qualified products (https://www.designlights.org/QPL) **B. Electrical** • Operating voltage: 120V to 277V • Power Factor: 0.90 at full light output • Total Harmonic Distortion: <20% at full light output • Source Efficacy: 100 lm/W at full light output **C. Photometric performance** • Light Output: minimum 1600 lumens or as needed to meet required light levels • Beam Angle: >120° Greater beam angle may be desirable for open (e.g. parabolic) fixtures **D. Chromaticity** • CCT: 3000K, 3500K, 4000K or as specified by site • CRI: 80, R9 >0 **E. Controls**: Look for "dimmable" products if considering daylight harvesting or task tuning controls methods **F. Lumen maintenance:** Minimum 70% light output at 50,000 hours derived from LM-80 and TM-21 reportable rating **G. Warranty:** Minimum 5 years	**A. Type of existing fixture** • For example: prismatic lensed 2 x 4 troffer, 3-lamp T8 **B. Initial illuminance levels** • For example: 35 fc, assuming ceiling/wall/floor reflectance of 80/50/20 and spacing criteria of 1.0 to 2.0 **C. Ceiling height** • For example: 9' ceiling **D. Luminaire spacing** • For example: 8' x 10' on center **E. Ballast** • For example: electronic instant-start; magnetic rapid-start; programmed rapid-start • Most LED lamp replacements require electronic instant-start ballasts **F. Sockets** • For example: shunted vs. unshunted; not all retrofit solutions are compatible with shunted lamp holders **G. Wiring** • For example: master/remote • Not all retrofit solutions are compatible with master/remote setups	**A. Initial light-levels** • 10 to 20% greater than P-100 (e.g., P-100 calls for 30 fc for work surfaces, so initial light levels should be 33 fc to 36 fc.) • In order to maintain P-100 light levels while benefiting from long-lasting LED lamps, the LED system must begin with higher initial light levels. • Ideally, the LED system would be capable of dimming so as to meet P-100 at all times and save additional energy. **B. Network/system access** • Wired and/or wireless control systems shall not be accessible, networked or otherwise tied to external systems unless specified by GSA.

Step 4

TEST retrofit kits in place

Require the manufacturer to demonstrate that their solution meets the established specifications. Install the solution in at least four fixtures that have the predominant spacing (e.g., 8'x10'); get feedback from the installer on the amount of time and effort required. Also, get feedback from occupants on the appearance of the modified luminaires. (Note: inspect parabolic louvered fixtures carefully. They can alter the intended distribution of light, and sometimes create unappealing contrast when viewed from below. This is especially true when the retrofit involves delamping from three LFL lamps to two LEDs.)