# Demystifying LED Lighting

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TRI-STATE LED

## Introduction

The ultimate goal of any lighting installation is to provide ample illumination at the lowest cost. Achieving this objective, however, depends entirely on the space being lighted, because every space is unique. Ceiling height, wall color, floor area and reflectance, window placements, even the activities and objects in a room all affect illumination requirements.

A properly lighted space, therefore, is one that efficiently meets both the functional and aesthetic needs of its occupants. In other words, lighting design is both a science and an art in which form, function, and cost must all be thoughtfully considered.

When lighting a space, designers typically choose from three conventional lamp technologies: 1) *Incandescent*, 2) *Fluorescent* (FL), and 3) *High Intensity Discharge* (HID).[1] All three of these technologies are well established and used extensively. In recent years, however, a new lighting technology has become generally available: *Light-Emitting Diodes*, or *LEDs* for short. This technology is developing so rapidly that many designers and architects are unaware of how competitive and interchangeable LEDs now are with conventional lamps. Moreover, the technology continues to improve at an astounding pace, with brighter, cheaper, more efficient LEDs coming to market nearly every month.

What makes LED technology so alluring is its efficiency and durability. Not only do these low-power solid-state devices deliver more visible light with less electricity than most conventional lamps, they have useful lifetimes of 50,000 hours or more, which is about three or four times the typical lifetime of a fluorescent lamp and 25 to 50 times the rated lifetime of an incandescent.

Because of their high *luminous efficacy*, LEDs routinely reduce energy consumption by 40% to 84% in actual lighting installations.  Over the course of a 50,000-hour lifetime, this translates into significant savings, including lower heat loads on the HVAC systems of large buildings. LED lamps are also available in a broad range of *correlated color temperatures* (CCT) from warm white (3000K) to day white (5500K to 6000K) and even up to 9000K (*Ref*: The Lighting Handbook, p 13.13). Their *color rendition index* (CRI) can reach as high as 95. Furthermore, LEDs can be ordered as self-contained retrofit “lamps” that are installed directly into existing luminaires.

Of course, LEDs are not always the best and only solution for every lighting application. Nevertheless, for many installations LEDs offer competitive and even superior performance over conventional lamps.

Determining the economics and performance of LED lamping should be done on a case-by-case basis using real-world photometric data and realistic assumptions that take into account initial costs, energy costs, maintenance and life-cycle costs, and the specific illumination needs of the installation. However, lighting designers typically analyze a lamp’s luminous performance using manufacturer photometric data that is then entered into a program such as Lithonia Visual or AGi32 and used to calculate the expected illuminance for a given space. This calculated data is then used, along with general economic assumptions, to analyze the life-cycle costs of an installation. The results are entirely computed, so the conclusions are only as good as the data and assumptions used to reach them. Consequently, it is critical to ensure that the data and assumptions are accurate; otherwise, it would be a classic case of GIGO (Garbage In, Garbage Out).

[1] Please refer to Technical Terms and Background for a fuller explanation of the italicized terms used in this report.

The purpose of this report is to present real-world photometric and economic data taken from actual Revolution Lighting, Inc. LED installations to demonstrate the performance, life-cycle costs, and ROI of these installations. This approach reveals how effective LEDs can be at delivering light where it is needed and serves as a cautionary tale for lighting designers who might be tempted to make design decisions based mostly on photometric calculations and assumptions.

## Deconstructing Real-World LED Lighting Installations

When laying out a properly lighted space, the designer usually creates a drawing or lighting plan that specifies the type of luminaires and lamps to be used and their locations. Many factors must be taken into account to ensure proper selection and placement of lamps and luminaires. The physical environment, building layout, daylight conditions, environmental impact, maintenance costs, HVAC loads, tasks being performed, and even the age and psychological needs of the occupants all affect the lighting design. With so many aspects to consider, a good lighting design can be a daunting task and usually involves tradeoffs between competing influences.

To help sort through these factors and evaluate appropriate illumination for virtually any installation, the *Illuminating Engineering Society (IES)* publishes an exhaustive collection of lighting standards and recommendations in its seminal book The Lighting Handbook (*Ref*: The Lighting Handbook). The IES is a recognized authority on lighting practices and applications, having established a variety of specific photometric guidelines for lighting designers and manufacturers over the years. For example, nearly half of The Lighting Handbook is exclusively devoted to recommended illumination levels for everything from correctional facilities to houses of worship.

The IES also regularly publishes recommendations for the proper measurement and classification of light sources. IES publication LM-9, for instance, establishes recommended photometric measurement methods for linear fluorescent lamps. IES LM-45 covers incandescent lamps, while IES LM-79 and LM-80 describe photometric testing of LED light sources.

The standards and practices set forth by the IES—as well as by its European cousin the *International Commission on Illumination* (CIE)—help to regulate the design, fabrication, and specification of efficient lighting solutions. When it comes to LED lighting, however, IES standards can sometimes cause confusion, because LEDs are tested and specified differently than conventional lamps. This is because an LED normally cannot be separated from its fixture and tested in the same manner that the IES prescribes for conventional lighting systems (*Ref*: Approved Method: Electrical and Photometric Measurements, p 15).

For conventional lighting systems, the lamps and luminaires are tested independently using different testing techniques. Luminaires are tested by a *goniophotometer* to determine their *luminous intensity distribution* and efficiency, and lamps are usually tested using an *integrating sphere* to measure their *luminous flux* and *chromaticity*. Separate photometric testing for conventional lamps and luminaires is called *relative photometry*, which evolved from the different operating conditions and standards that were developed for each.

When LEDs first appeared on the scene, they required a whole new set of operating conditions. Also, LED light sources are nearly always constructed as an integrated unit combining *heat sinking* and beam-shaping optics. Heat sinking is employed to control the temperature of the LED semiconductor junction where the light is created because junction temperature affects the light output. LEDs use beam-shaping optics because unlike the *omnidirectional* output of conventional lamps the light from an LED is more directional.

For all of these reasons, the IES classifies LEDs as a kind of lamp-luminaire hybrid and recommends that they be tested using *absolute photometry*. The confusion arises because many architects and designers still think of lamps and luminaires in the conventional sense. Consequently, when specifying LEDs in their lighting designs, they sometimes assume that LED “lamps” and “luminaires” must be installed as integrated units. In redesign installations this would mean removing the existing luminaires/lamps and installing new LED luminaires. Some LEDs are, in fact, manufactured and sold as complete luminaire units, thus compounding the confusion.

But many LEDs are available as retrofit replacements that install directly into existing conventional luminaires. The power supply, heat sinking, optics and LEDs are all included as a complete retrofit installation. About 80% of the LEDs manufactured by Revolution Lighting are retrofits, for example.

Given the unique nature of LEDs, then, one should avoid drawing conclusions based solely on photometric calculations when considering them for a lighting application. LEDs simply perform differently from conventional lamps. They are not even tested in the same way. The best approach, therefore, is to look at real illumination data taken from real LED installations in order to put other lighting projects into proper perspective.

## Actual LED Lighting Installations

The lighting calculations, illumination data, and life-cycle cost analysis that follow describe actual LED installations at a college in Pasadena, Calif. Each space was lighted using Revolution Lighting retrofit LED tube lights installed in existing *T8 fluorescent lamp* luminaires. Shown here is a dental lab at the college lamped with 78 LED tube lights.

## Illuminance Calculations, Assumptions, and Measurements

***Classroom #213***: Figs. 1-3 below show three separate lighting layouts of a classroom containing 42, 1' x 4' fluorescent-style luminaires, each retrofitted with two Revolution Lighting natural-white, 15-W LED tube lights. The layouts were created in Lithonia Visual using three *light loss factors* (LLFs) to simulate the light levels of new LED lamps (LLF = 1.0), the same LEDs at 17,000 hours (LLF = 0.92), and the LEDs at the end of their useful life (LLF = 0.70).

At 17,000 hours, the light output of LEDs has declined by about 8% (*Ref*: Benya, p 13), which is typically when the first relamping of a fluorescent installation has already taken place; whereas 70% of initial *lumen* output (LLF = 0.70) represents the useful lifetime of LEDs, as defined by the Alliance for Solid State Illumination Systems and Technologies (ASSIST) and the IES (*Ref*: Approved Method: Measuring Lumen Maintenance, p 2). This definition of useful lifetime differs from the rated lifetime of conventional lamps because LEDs don't usually fail catastrophically like conventional lamps do. Consequently, LED lifetime is based on useful light output. The lighting layouts, therefore, signify three snapshots of illuminance for a real LED installation (Classroom #213) using extrapolated data spanning more than 10 years.

The layouts of Figs. 1-3 were calculated at a normal desk height of 30 in. using the actual classroom dimensions of 30' x 43' x 10' and standard room reflectances of 80% ceiling, 50% walls, and 20% floors. Luminaire placements (depicted as blue rectangles) also were accurately depicted in the layouts. Actual lamp performance was measured using absolute photometry and quantified in the IES files used to create the lighting layouts. Each of the 84 natural-white LED tube lights has a total *luminous flux* of 1,298 lm, a CCT of 4000K to 4500K, CRI of 76, and *wall-plug efficacy* of 86.5.

Table 1 on page 11 summarizes the calculated illuminances for the classroom. It shows that throughout the useful lifetime of 50,000 hrs, average *foot-candles (fc)* meet or exceed the IES recommendation for classrooms of 40-50 fc (*Ref*: The Lighting Handbook, p 24.12). To verify these calculated light levels, a light meter was used to measure actual illuminances at three locations across the middle of the classroom immediately after installation. Measured results reveal initial illuminances of 88 fc directly below the central luminaire, 99 fc between luminaires, and 57 fc at the edge of the room, all well above the IES recommended level. One important factor to note is that the luminaires of the installation employ prismatic lenses that scatter the light more, which was not accounted for in the calculated layouts.

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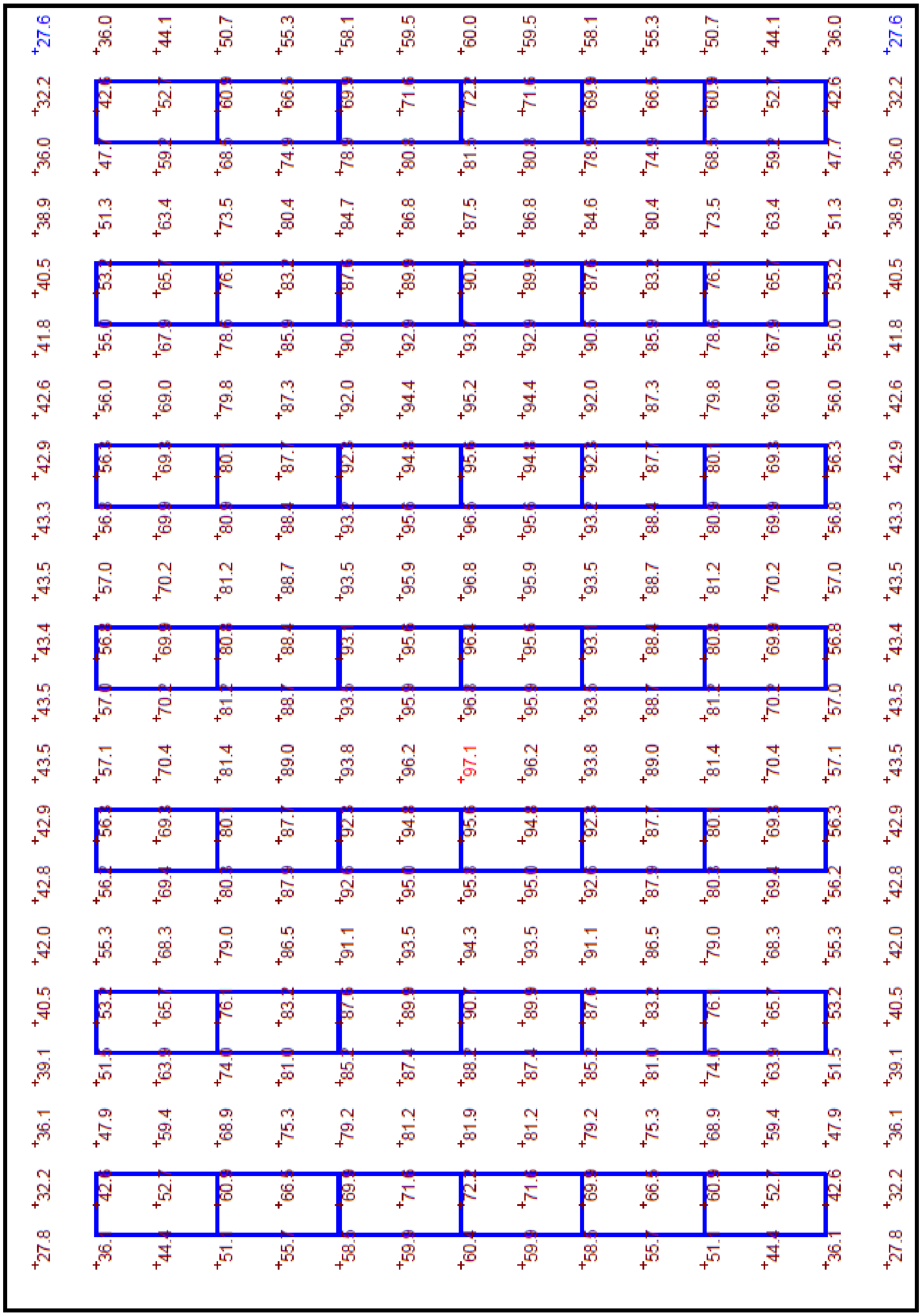


**Figure 1: Classroom #213 Illuminances (in foot-candles) using Revolution Lighting T8 Tube Lights (SKU 200011), LLF = 1.00**

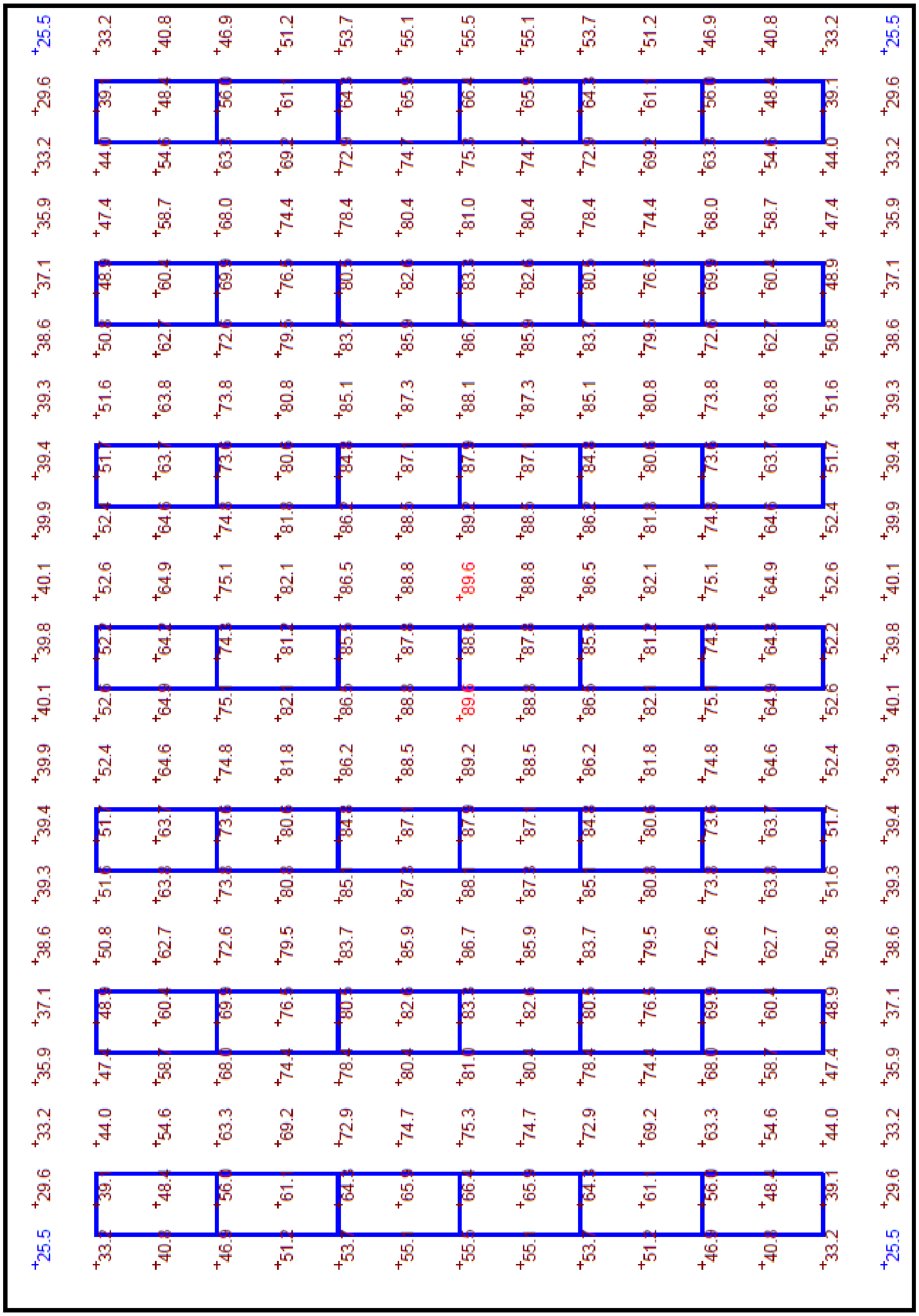


**Figure 2: Classroom #213 Illuminances (in foot-candles) using Revolution Lighting T8 Tube Lights (SKU 200011), LLF = 0.92**

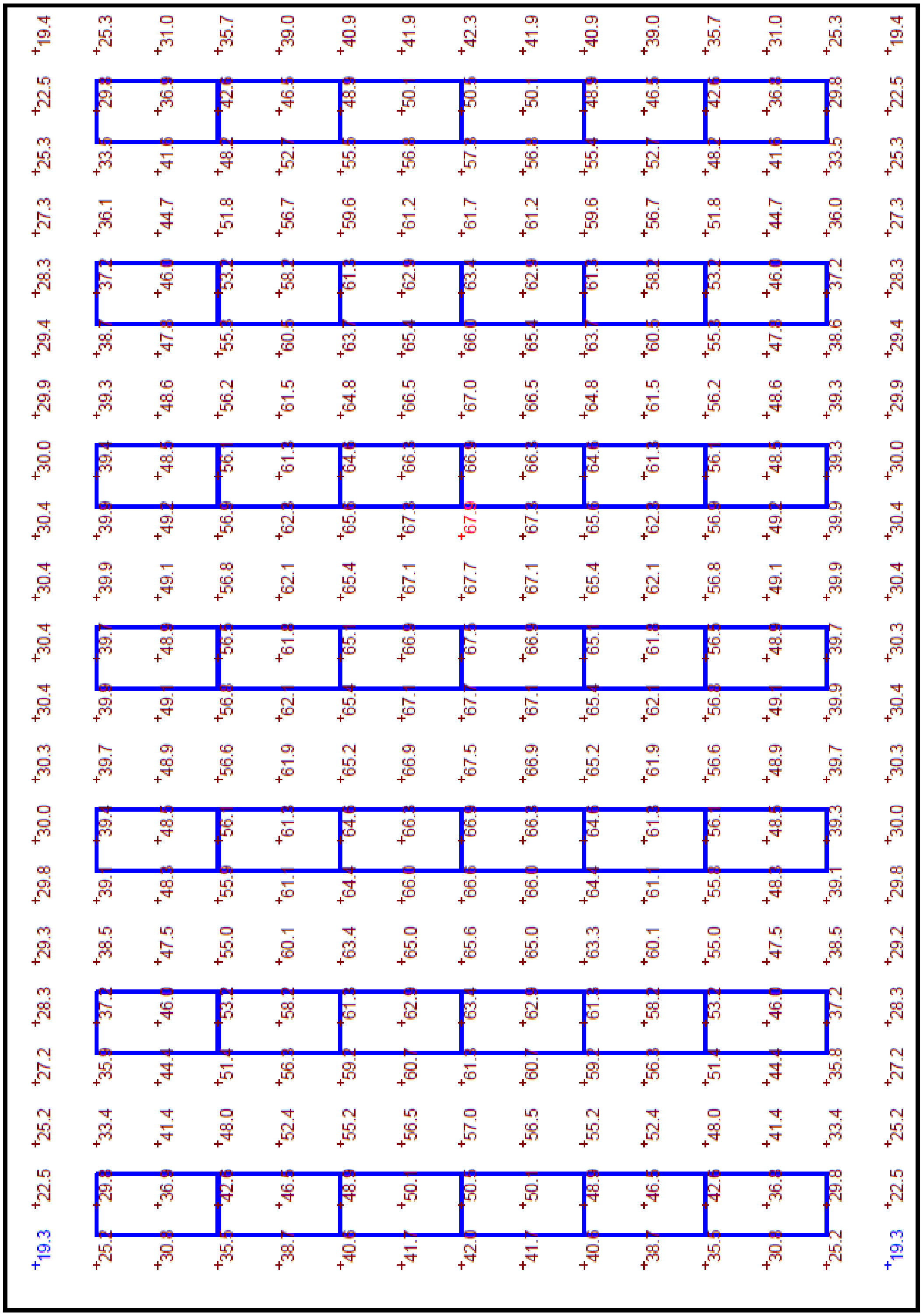


**Figure 3: Classroom #213 Illuminances (in foot-candles) using Revolution Lighting T8 Tube Lights (SKU 200011), LLF = 0.70**

## STATISTICS

| Description | Symbol | Avg | Max | Min | Max/Min | Avg/Min |
|---|---|---|---|---|---|---|
| CLASSROOM LLF 1 | + | 69.8 fc | 97.1 fc | 27.6 fc | 3.5:1 | 2.5:1 |
| CLASSROOM LLF .7 | + | 48.8 fc | 67.9 fc | 19.3 fc | 3.5:1 | 2.5:1 |
| CLASSROOM LLF .92 | + | 64.3 fc | 89.6 fc | 25.5 fc | 3.5:1 | 2.5:1 |

## LUMINAIRE SCHEDULE

| Symbol | Label | Qty | Catalog Number | Description | Lamp | File | Lumens | LLF | Watts |
|---|---|---|---|---|---|---|---|---|---|
| ▯ | LM-3 | 84 | 200011 | WITH WHITE INTERIOR AND CLEAR PLASTIC CURVED LENS | 300 LED ARRAY. LUMINAIRE OUTPUT = 1298 LMS | Seesmart IES_200011.IES | Absolute | 0.70 | 16 |
| ▯ | LM-4 | 84 | 200011 | WITH WHITE INTERIOR AND CLEAR PLASTIC CURVED LENS | 300 LED ARRAY. LUMINAIRE OUTPUT = 1298 LMS | Seesmart IES_200011.IES | Absolute | 0.92 | 16 |
| ▯ | LM-5 | 84 | 200011 | WITH WHITE INTERIOR AND CLEAR PLASTIC CURVED LENS | 300 LED ARRAY. LUMINAIRE OUTPUT = 1298 LMS | Seesmart IES_200011.IES | Absolute | 1.00 | 16 |

**Table 1: Classroom #213 Lighting Statistics**

***Dental Lab #504***: Figs. 4-6 below illustrate three calculated layouts of a dental lab lighted with 26, 2' x 4' fluorescent-style luminaires, each retrofitted with three Revolution Lighting day-white 15-W LED tube lights. (See page 6 for photo of dental lab LED installation.) The layouts were done in the same manner as the classroom above, using Lithonia Visual with the same three LLFs: 1.0, 0.92, and 0.70. As before, the lighting layouts signify three snapshots of illuminance for the school's dental lab spanning more than 10 years.

The three dental lab layouts were calculated at the IES-recommended bench height of 36 in., with room dimensions of 20' x 40' x 10'. The following standard reflectances were applied: 80% ceiling, 50% walls, and 20% floors. Colored rectangles indicate actual luminaire placements. Each of the 78 day-white LED tube lights has a total luminous flux of 1,254 lm, a CCT of 5500K to 6000K, a CRI of 76, and wall-plug efficacy of 83.6. The IES files for these light sources were obtained using absolute photometry.

The calculated illuminances for the dental lab are summarized in Table 2 on page 16. It demonstrates average light levels that exceed the recommended IES target of 50 fc (*Ref*: The Lighting Handbook, p 27.10) throughout the 50,000-hr LED lifetime. Note that because of the L-shaped room, the luminaire schedule breaks into two contiguous rectangular spaces containing 48 and 30 LED tube lights, respectively, and three LLFs for each space.

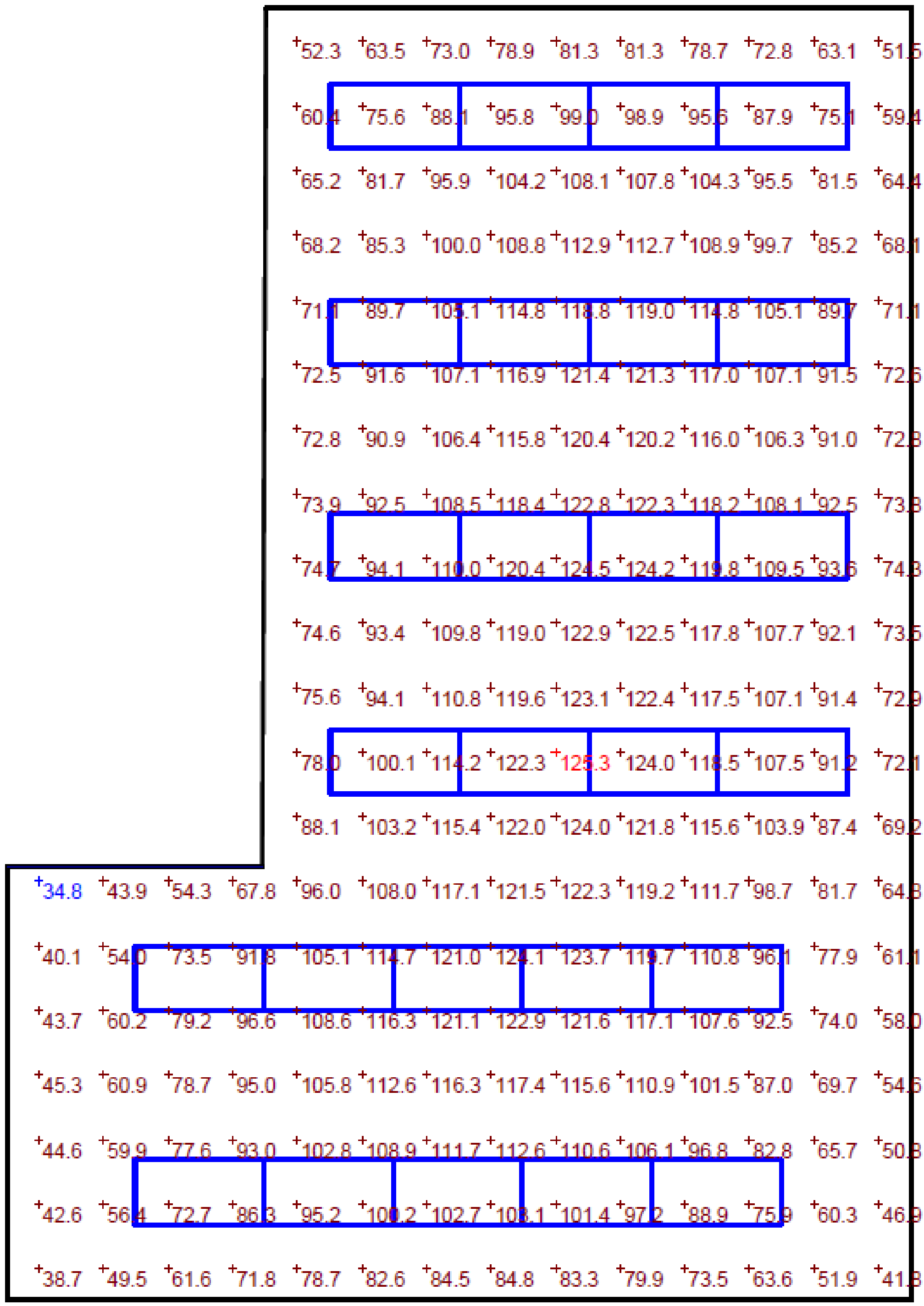



**Figure 4: Dental Lab Illuminances (in foot-candles) using Revolution Lighting T8 Tube Lights (SKU 200009), LLF = 1.00**

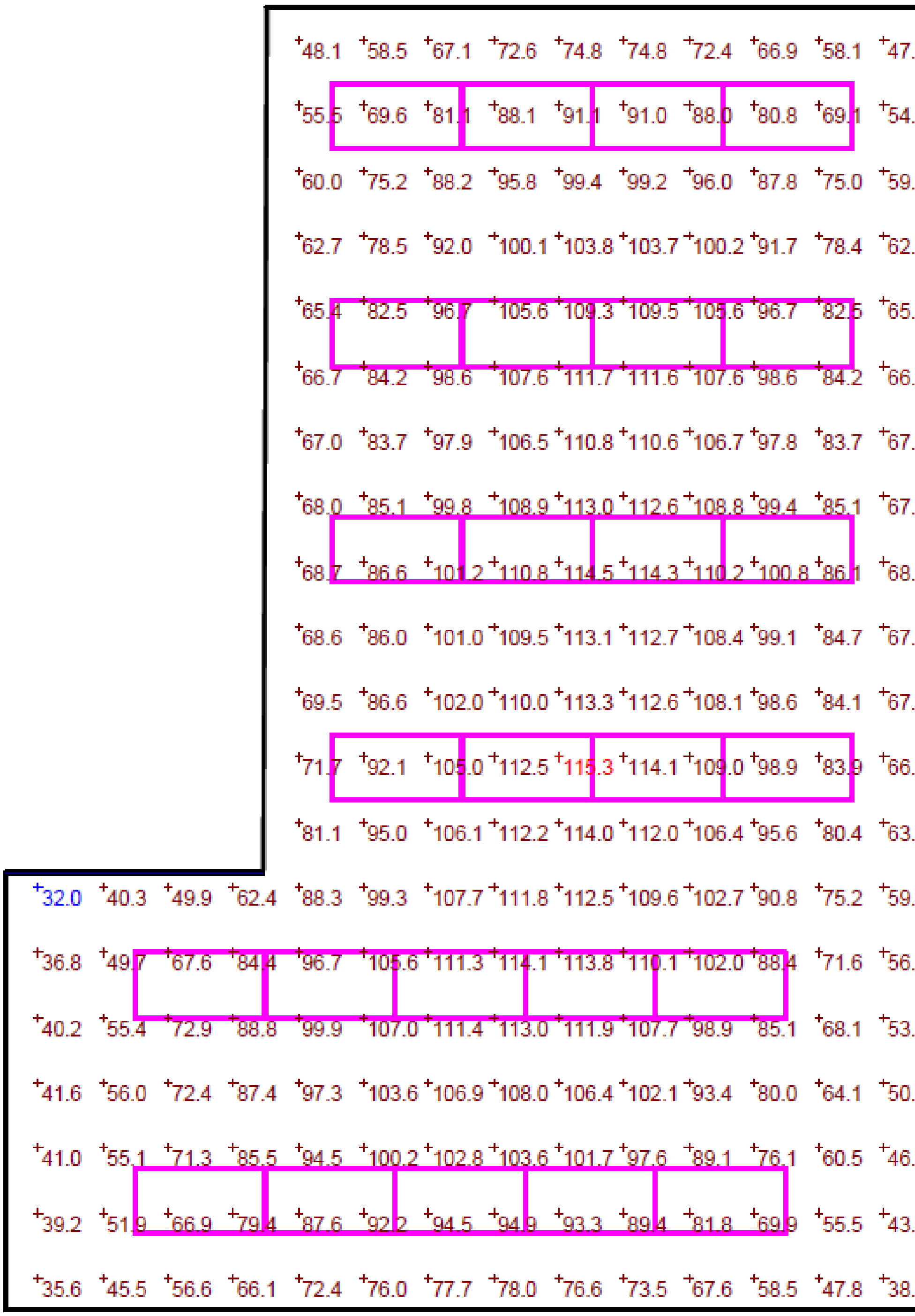
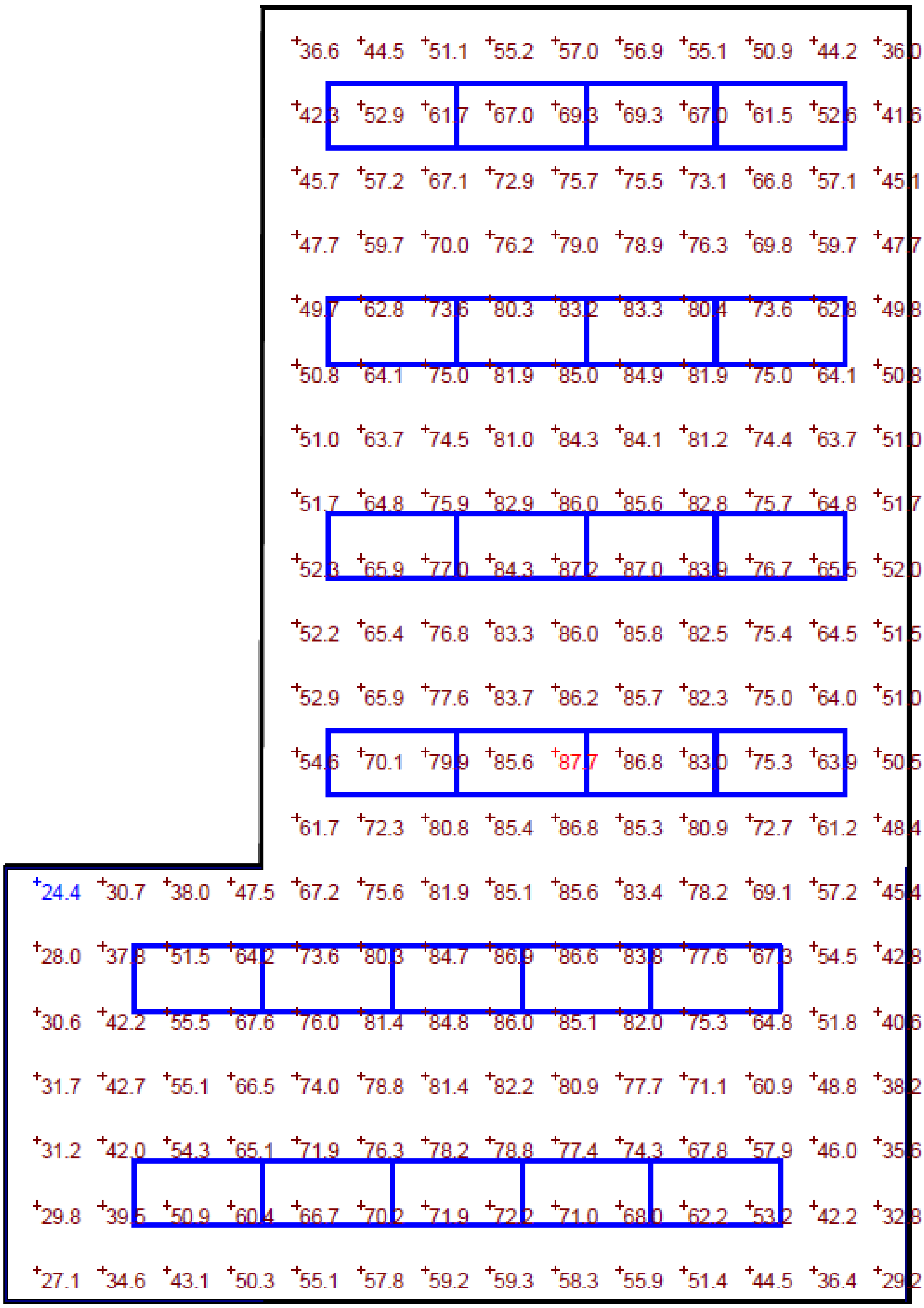



**Figure 5: Dental Lab Illuminances (in foot-candles) using Revolution Lighting T8 Tube Lights (SKU 200009), LLF = 0.92**




**Revolution Lighting T8 Tube Lights (SKU 200009), LLF = 0.70**

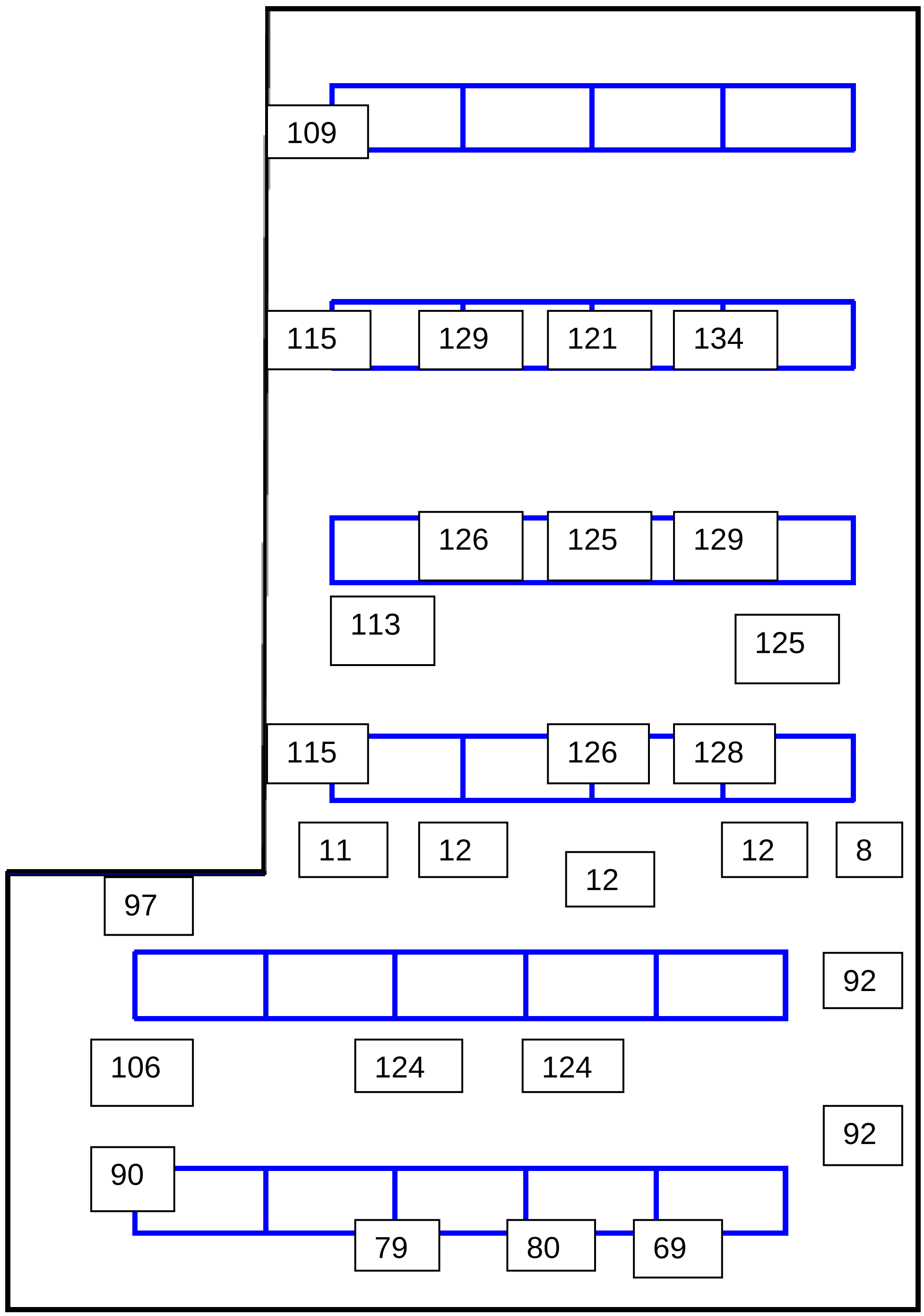


Figure 7: Measured Illuminances of Dental Lab (in foot-candles), LLF = 1.00

| LUMINAIRE SCHEDULE | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Symbol | Label | Qty | Catalog Number | Description | Lamp | File | Lumens | LLF | Watts |
| | LM-1 | 48 | 200009 | WITH WHITE INTERIOR AND CLEAR PLASTIC TUBE LENS | 300 LEDS. LUMINAIRE OUTPUT = 1254 LMS | Seesmart IES_200009.IES | Absolute | 0.70 | 15 |
| | LM-2 | 48 | 200009 | WITH WHITE INTERIOR AND CLEAR PLASTIC TUBE LENS | 300 LEDS. LUMINAIRE OUTPUT = 1254 LMS | Seesmart IES_200009.IES | Absolute | 0.92 | 15 |
| | LM-3 | 48 | 200009 | WITH WHITE INTERIOR AND CLEAR PLASTIC TUBE LENS | 300 LEDS. LUMINAIRE OUTPUT = 1254 LMS | Seesmart IES_200009.IES | Absolute | 1.00 | 15 |
| | LM-4 | 30 | 200009 | WITH WHITE INTERIOR AND CLEAR PLASTIC TUBE LENS | 300 LEDS. LUMINAIRE OUTPUT = 1254 LMS | Seesmart IES_200009.IES | Absolute | 1.00 | 15 |
| | LM-5 | 30 | 200009 | WITH WHITE INTERIOR AND CLEAR PLASTIC TUBE LENS | 300 LEDS. LUMINAIRE OUTPUT = 1254 LMS | Seesmart IES_200009.IES | Absolute | 0.92 | 15 |
| | LM-6 | 30 | 200009 | WITH WHITE INTERIOR AND CLEAR PLASTIC TUBE LENS | 300 LEDS. LUMINAIRE OUTPUT = 1254 LMS | Seesmart IES_200009.IES | Absolute | 0.70 | 15 |

| STATISTICS | | | | | | |
|---|---|---|---|---|---|---|
| Description | Symbol | Avg | Max | Min | Max/Min | Avg/Min |
| Dental Exam Rm 1 | + | 92.6 fc | 125.3 fc | 34.8 fc | 3.6:1 | 2.7:1 |
| Dental Exam Rm .7 | + | 64.8 fc | 87.7 fc | 24.4 fc | 3.6:1 | 2.7:1 |
| Dental Exam Rm .92 | + | 85.2 fc | 115.3 fc | 32.0 fc | 3.6:1 | 2.7:1 |

**Table 2: Dental Lab Lighting Statistics**

Actual illuminances in the dental lab were measured at 28 points throughout the room using a light meter. Fig. 7 above maps these measurements, which show good agreement with the calculated levels depicted in Fig. 4 (LLF = 1.00). All readings are well above IES recommended illuminance levels. It should be noted that the meter readings were taken at a height of 30 in. above the floor, implying higher actual illuminances at the IES-recommended height of 36 in. Also, as before, the luminaires contain prismatic lenses that were not accounted for in the lighting layouts.

## Life Cycle Cost Analysis

Table 3 below analyzes the life cycle costs of LEDs when compared to the tangible costs of conventional fluorescent lamps over a period of ten years. The spreadsheet includes data for two of the college's classrooms and the dental lab.

| Space (illumination Level) Conventional or LED Lighting Technology | Luminaire Description | Luminaire to meet Specified Illumination Levels | Luminaire Price | Lamps per Luminaire | Lamp Price | System Input watts per Luminaire | Weekly Hours of Operation Annual KWh | Hours of Operation 10 years | KWh in 10 years | Number of lamp changes in 10 yrs | Initial Costs | | Operation Costs | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Lamps | Labor | Lamp replacement cost (present value) | Ballast replacement cost (present value) @ 2 over 10 years | Labor for replacements of Lamps | Labor for replacements of Ballasts | Energy Cost (present value) | Lamp Disposal Cost (present value) | 10 Year Total Cost |
| Bldg V Classroom # 102 | | 40-50 fc | | | | | 90 | | | | | | | | | | | | |
| Fluorscent Lighting | 1X4 Fluorscent Fixture with Prismatic lens | 28 | $0.00 | 2 | $3.25 | 64 | 8387 | 46800 | 83866 | 3 | $182 | $1,190 | $546 | $1,960 | $1,428 | $1,190 | $9,225 | $168 | $15,889 |
| LED Lighting | 1X4 Fluorscent Fixture with Prismatic lens | 28 | $0.00 | 2 | $58.28 | 30 | 3931 | 46800 | 39312 | 0 | $3,264 | $1,190 | $0 | $0 | $0 | $0 | $4,324 | $0 | $8,778 |
| | | | | | | | | | | | | | | | | | | | |
| Bldg V Classroom # 213 FC | | 40-50 fc | | | | | 90 | | | | | | | | | | | | |
| Fluorscent Lighting | 1X4 Fluorscent Fixture with Prismatic lens | 42 | $0.00 | 2 | $3.25 | 64 | 12580 | 46800 | 125798 | 3 | $273 | $1,785 | $819 | $2,940 | $2,142 | $1,785 | $13,838 | $252 | $23,834 |
| LED lighting | 1X4 Fluorscent Fixture with Prismatic lens | 42 | $0.00 | 2 | $58.28 | 30 | 5897 | 46800 | 58968 | 0 | $4,896 | $1,785 | $0 | $0 | $0 | $0 | $6,486 | $0 | $13,167 |
| Bldg R Dental Lab #504 | | 50 fc | | | | | 126 | | | | | | | | | | | | |
| Fluorscent Lighting | 2X4 Fluorscent Fixture with Prismatic lens | 26 | $0.00 | 3 | $3.25 | 96 | 16354 | 46800 | 163538 | 3 | $254 | $1,105 | $761 | $1,820 | $1,326 | $1,105 | $17,989 | $234 | $24,593 |
| LED Lighting | 2X4 Fluorscent Fixture with Prismatic lens | 26 | $0.00 | 3 | $58.28 | 45 | 7666 | 46800 | 76658 | 0 | $4,546 | $1,105 | $0 | $0 | $0 | $0 | $8,432 | $0 | $14,083 |

**Table 3: Ten-Year Life Cycle Cost Analysis**

Using costs typically encountered with real-world lighting installations, the analysis shows that LEDs save money over the course of their long useful life. For this particular installation, the total related costs of LED retrofit lighting are nearly half those of conventional fluorescents after ten years. In fact, despite their higher initial costs, the LEDs used in this installation will pay for themselves in 26 months.

Some of the assumptions used to arrive at these numbers include:

- $0.11/kWh for electricity
- $85/hr for labor
- $35 for ballasts
- Classroom light usage: 90 hrs/wk
- Dental lab light usage: 126 hrs/wk
- FL lamps changed 3x in 10 yrs
- FL ballasts changed 2x in 10 yrs
- FL disposal cost: $1/lamp

## Conclusion

The lighting installations presented in this report demonstrate just how cost-effective LED retrofit lighting can be. Nevertheless, there are some studies that still recommend against using LED retrofits as replacements for existing FLs, claiming that the luminous flux is too low to provide cost-effective lighting for applications requiring more than 30 fc (see, for example: *Ref*: Department of Veterans Affairs, p 4 and p 33). Yet the real-world LED retrofit installations detailed here clearly demonstrate sustained illuminances well over 50 fc and a maximum measured illuminance of 134 fc. Moreover, these same retrofit LEDs will pay for themselves in 26 months and cost nearly half as much as FLs over ten years.

When planning an installation, therefore, lighting designers and architects should carefully consider all of the technologies available, but it is important to also be mindful of the unique capabilities and features of LEDs. As always, the prevailing goal is to provide the best illumination at the lowest cost.

## Technical Terms and Background

**Absolute photometry**: Calibrated measurements made of a lamp's light output. (Compare with *relative photometry* below.)

**Application efficiency**: A generic term that refers to a sufficient quantity and quality of light for a given application delivered with the least energy consumption.

**Ballast**: An electronic device used to regulate the current passing through an FL. Energy lost through the ballast must be included when determining the *wall-plug efficacy* of an FL.

**Blackbody emitter**: An idealized energy source in which 100% of the thermodynamic energy is emitted as radiant energy. A blackbody emitter is a thermodynamic device, meaning it gives off radiant energy that is uniquely determined by its temperature. The higher the temperature of a blackbody, the bluer or "cooler" the light appears. Engineers use blackbody emitters to compare the spectral output of artificial light sources. It is the standard used for specifying *correlated color temperature* (CCT), in which the lamp's spectral output is compared to a blackbody emitter raised to a specific temperature measured in Kelvin (K).

**Chromaticity**: A specification of the perceived color saturation and hue of a light source independent of its luminance. Chromaticity is quantified by the CIE *chromaticity diagram*.

**Chromaticity Diagram**: A graphical representation of color hue and saturation as perceived by the human eye. The diagram is most often used to specify the *correlated color temperature* and *color rendering index* of a light source.

**Colorimetry**: The science of quantifying human color perception.

**Color Rendering Index (CRI)**: A measure of the fidelity with which an artificial light source reproduces the color of objects it illuminates. The higher the index, the more faithful the color rendition is. Perfect color rendition has a CRI of 100.

**Correlated Color Temperature (CCT)**: A measure of the apparent color of a light source relative to the color of an ideal reference source (*blackbody emitter*) heated to a given temperature. Color temperature is specified in Kelvin (K) and is a general indicator of the "warmth" or "coolness" of a lamp's appearance. The higher the color temperature, the "cooler" or bluer the light seems.

**Driver**: An electronic device that provides constant current or constant voltage to an LED in order to maintain a constant luminous output. Energy lost through the electronic components of a driver must be included when determining the *wall-plug efficacy* of an LED.

**Efficacy**: (See *wall-plug efficacy*.)

**Fluorescent Lamp (FL)**: A gas-discharge lamp in which mercury vapor is electrically excited inside a phosphor-coated tube. The spectrum of an FL differs from that of an *incandescent lamp* because of how the light is created. The excited mercury vapor inside the lamp emits much of its radiant energy in discrete colors, mostly in the green, blue and ultraviolet. These higher-energy photons are then absorbed by the phosphor coating, which reemits the energy in a more continuous spectrum of light at longer wavelengths. The associated conversion losses (due to the *Stokes shift*) reduce the overall efficacy of the device. The final output of the lamp results mostly from the fluorescent emission of the phosphor, hence the name. Light is emitted from the lamp in all directions (omnidirectional).

**Foot-candle (fc)**: A measurement of illumination equal to 1 lumen per square foot (or 1 lm/ft$^2$).

**Goniophotometer**: A device for measuring the *luminous intensity distribution* of a light source. The instrument is typically used to determine the light dispersal of a luminaire.

**Heat sinking**: Any method used to transport excess thermal energy from one place to another.

**High-Intensity Discharge (HID)**: A type of arc lamp in which a high-voltage arc between two electrodes excites a gas containing evaporated metal salts. HIDs take some time to start when turned on because the high-voltage arc must first melt the metal salts, which solidify at normal temperatures. Once the metal salts evaporate they form a plasma, which increases the light output and reduces the power consumption. Because of the requisite startup time, however, HIDs are not recommended for use with occupancy sensors, but they can be dimmed, provided the voltage doesn't drop below 50%. Dimming an HID does reduce its efficacy significantly, though. The light from these lamps is *omnidirectional*.

**Illuminance**: A measure of the amount of visible light striking an area, usually measured in *lumens* per square foot (lm/ft$^2$) or *lux* (lm/m$^2$).

**Illuminating Engineering Society (IES)**: An organization of lighting manufacturers, designers, architects, consultants, and building contractors dedicated to improving and standardizing the lighting industry. IES committees help develop many of the standards that regulate lighting design and manufacture.

**Incandescent lamp**: The oldest and most established electric lighting technology, in which a filament (usually made of tungsten) is heated to a high temperature by an electric current. At high temperatures the filament acts like a *blackbody emitter*, generating a broad, continuous spectrum of light from the ultraviolet into the infrared. Incandescent lamps have the lowest *wall-plug efficacy*, since approximately 95% of the energy is released as heat. Light exits the lamp in all directions (*omnidirectional*).

**Integrating Sphere**: A photometric device used for measuring the total *luminous flux* of a light source. Integrating spheres can also be equipped with a *spectroradiometer* to measure the source's *colorimetry*, too.

**International Commission on Illumination (CIE)**: The initials CIE stand for the Commission Internationale de l'éclairage, or International Commission on Illumination. It is an international organization, based in Vienna, Austria, responsible for setting photometric standards, similar to the *IES*. For example, the CIE created the *chromaticity diagram*, which classifies the color of light sources.

**Light-Emitting Diode (LED)**: A solid-state electro-optical device that emits light when an electric current is applied across a junction formed between two adjoining (contiguous) semiconductor layers on a silicon chip. Unlike conventional light sources, LEDs are typically designed to be directional, emitting light into one hemisphere instead of in all directions. The dark side of the LED is frequently used for *heat sinking*.

The light emitted from a simple LED is comparatively monochromatic (one color); however, multicolor or white-light LEDs can be fabricated by either combining LEDs of different colors (usually red, green and blue), or by coating a blue LED with a phosphor compound. White-light LEDs made with the latter method function much like an FL, in which light from the blue LED is absorbed and reemitted by the phosphor at longer wavelengths via fluorescence.

LEDs can have very high *luminous efficacy*. As LED efficacies continue to improve, more energy is converted into light and less is lost as heat. Current commercially available LEDs have typical luminous efficacies of about 100 lm/W or more. That translates into a *wall-plug efficacy* of about 85 lm/W when driver efficiencies are included.

**Light Loss Factor (LLF)**: A multiplier applied to lighting calculations that accounts for changes in the luminous flux of a light source over time. LLFs are usually less than 1.0, but can be more than 1.0 in certain circumstances. An LLF of 0.70 would indicate a decline of 70% from initial light levels.

**Lumen (lm)**: A unit of *luminous flux*.

**Luminous efficacy**: The ratio of *luminous flux* to *radiant flux*, defined as lumens/watt. It gauges the amount of radiation from a source that is visible to the human eye. This is not the same as *wall-plug efficacy* or *overall luminous efficacy*, which are the ratio of luminous flux to the total electric power consumed by a light source. Efficacy is an important measure of lamp performance. For comparison, the efficacy of an *incandescent lamp* is about 15 lm/W. Typical white-light LEDs used for illumination have efficacies of 85 lm/W or more.

**Luminous flux**: A measure of the total perceived power of a light source. It is a weighted sum taken across the entire visible spectrum, therefore it accounts for the human eye's nonlinear sensitivity to different colors. A unit of luminous flux is called a *lumen*.

**Luminous Intensity Distribution**: A measure of how evenly a light source illuminates an area. It is usually measured geometrically by a *goniophotometer*.

**Lux**: A metric measure of *illuminance* defined in units of *lumens* per square meter ($lm/m^2$).

**Omnidirectional**: Flowing in all directions (defined mathematically as a solid angle of $4\pi$ steradians).

**Overall luminous efficacy**: (See *wall-plug efficacy* and *luminous efficacy.*)

**Photometry**: The science of measuring radiant energy as perceived by the human eye.

**Radiant Flux**: A measure of the total radiant power emitted from a light source. It is defined in units of watts.

**Radiometry**: The science of measuring radiant energy.

**Relative photometry**: Calibrated measurements that compare the light output of a lamp with the output of the same lamp mounted in a fixture or luminaire. (See also *absolute photometry* above.) The *IES* recommends that LED lamps not be measured using relative photometry because their photometric performance depends on the *heat sinking* and optics that are functionally integrated into the fixtures that house them. This special classification of LEDs, however, can cause confusion regarding LED compatibility with conventional luminaires, leading some designers to believe that LEDs require the installation of custom luminaires. In fact, many LEDs are designed to be installed in existing conventional luminaires as a retrofit option.

**Spectroradiometer**: A device for measuring how the radiant energy of a light source is distributed across the spectrum. The result is a spectral power distribution (SPD) that plots radiant power versus wavelength. An incandescent lamp has a very smooth SPD across the visible spectrum, while FLs have a smooth fluorescent spectral distribution punctuated by high power spikes in the ultraviolet, blue and green from the excited mercury vapor. SPDs of white-light LEDs, reveal a high emission spike in the blue, accompanied by a smooth fluorescence at longer wavelengths from the phosphor.

**Stokes shift**: In the quantum process of fluorescence, Stokes shift measures the difference between the peak wavelength (or frequency) of the absorbed photons and the peak wavelength (or frequency) of the reemitted photons. When a fluorescent light source undergoes a Stokes shift, the reemitted light always has less energy than the absorbed light. The energy difference is lost as heat, lowering the efficacy of the source.

**T8 fluorescent lamp**: A low-wattage type of fluorescent tube lamp designed for energy efficiency. A 4-ft tube usually consumes about 32W of electricity.

**Wall-plug efficacy**: Also called *overall luminous efficacy* or just *efficacy*, it is the ratio of the total visible light emitted from a source to the total electric power used. It is measured in units of lumens/watt (abbreviated as lm/W).

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