Approaching the Conventional Light Bulb with a Solid State of Mind

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ABSTRACT

The 60-watt incandescent light bulb, or A19 lamp, is one of the most recognizable and widely used technologies ever invented. For well over 100 years, tried and true incandescent technology has provided us with a simple means to light up our homes, as well as anywhere else you can screw in a light bulb. Herein, we are presented with opportunities and challenges to fuel energy efficiency by surpassing this common technology with newer generations, without sacrificing function or performance. One approach is solid-state lighting (SSL): specifically, A19 replacement lamps that use LEDs.

This paper presents findings from two projects conducted in the laboratories of Southern California Edison's Technology Test Centers. These lab assessments analyzed the performance and efficiency of various incandescent, CFL (dimmable and non-dimmable), and LED A19 replacement lamps, as well as one prototype high-efficiency, high-performance LED A19 replacement lamp. Performance was analyzed by comparing power and energy use, correlated color temperature (CCT), color rendering index (CRI), luminous flux, and efficacy. Dimmed performance at multiple prescribed steps was also analyzed for the prototype LED replacement lamp, and compared with its CFL and incandescent counterparts. Test results indicated that LED replacement lamps are able to achieve comparable performance, with up to 80 percent energy savings compared to incandescent lamps.

Introduction

We, as an increasingly globalized society, face countless challenges on the grounds of electricity and climate change. As industry professionals, it is imperative to use our abilities to continually seek out opportunities for the mutual benefits of humankind. In this new era, we have identified energy efficiency as an effective resource for minimizing our dependence on fossil fuels and mitigating the environmental impacts from their use. Here in California, the Statewide Emerging Technologies (ET) program exists as a crucial mechanism that aims to accelerate the introduction of innovative energy efficient technologies, applications and analytical tools that are not widely adopted in California.

California homes account for around 85 billion kWh annually (RECS 2005). Of this, an estimated 22% is attributed to lighting (CEC 2009). Herein, we are presented with opportunities and challenges to fuel energy efficiency by surpassing a common technology with newer generations, without sacrificing function or performance: the light bulb. At Southern California Edison (SCE), through the ET program, two efforts were conducted to investigate the current state of Light-emitting diodes (LEDs) as suitable replacement technologies. Specifically, laboratory efforts focused on evaluating products from the common family of light bulbs classified as A-19 incandescent lamps. The A19 incandescent lamp is one of the most recognizable and widely used technologies ever invented. For well over 100 years, tried and true incandescent technology has provided us with a simple means to light up our homes, as well as anywhere else you can screw in a light bulb.

The A-19 Incandescent Lamp

The A-19 incandescent lamp is a typical household lamp with a standard Edison screw base. The "A" shaped lamp, shown in Figure 1, is most commonly used for its omnidirectional light characteristic in light fixtures such as table and floor lamps. These lamps offer a wide range of wattages, 25 Watts (W) - 150 W, and a variety of lighting market segments use them. For the purposes of this paper, focus will be given to 60W incandescent A-19 lamps. LED technologies are investigated for their suitability as A-19 incandescent lamp replacements. They are also compared alongside their compact fluorescent lamp (CFL) counterparts.

Figure 1. A-19 Incandescent Lamp[1]

Incandescent Lamps

Incandescent lamps consist of sealed glass bulbs containing an electric circuit (a wound wire filament, typically tungsten) and an inert gas (typically argon) to extend the life of the filament. As electricity passes through the filament, it encounters resistance due to the filament's small diameter. The tungsten atoms undergo excitation, and the filament heats up. Excitation occurs through collisions between the flowing electrons and tungsten atoms. In this excitation process, the tungsten atoms' electrons momentarily jump into higher orbitals/energy levels. Once they fall back into their original orbitals/energy levels, they release energy in the form of photons (electromagnetic radiation). These photons are released at varying wavelengths. Only 10% of the energy is released as useful light in the visible spectrum.

Compact Fluorescent Lamps

CFLs consist of sealed glass tubes containing an inside coating of phosphor powders, an inert gas fill (typically argon), mercury, and an electrode at each end of the tube. When electricity is delivered to the electrodes, the inert gas becomes ionized, allowing current to flow

[1] http://en.wikipedia.org/wiki/Incandescent_light_bulb

through the tube. The resulting energy transfer causes the mercury to vaporize. Collisions occur between the vaporized mercury and other electrons and ions. These collisions excite the mercury atoms, causing their electrons to jump momentarily into higher orbitals/energy levels. When these electrons fall back into their original orbitals/energy levels, they release excess energy in the form of photons in the ultraviolet spectrum.

The ultraviolet photons collide with the atoms in the phosphor powder coating, causing a second excitation process. This process causes the phosphor's electrons to jump and fall, releasing light in the visible spectrum. Different wavelengths of light are achieved with the use of different phosphors. While there are minor losses associated with an intermediate step to producing visible light, CFLs are able to convert more of their energy to the release of photons in the visible spectrum when compared to incandescent.

Light-emitting Diodes

Also referred to as solid state lighting (SSL), LEDs are forms of semiconductor electronics. Two dissimilar, doped semiconductor materials are mated together. One doped semiconductor contains extra free electrons (negative, N-layer) while the other has spaces for free electrons to fill (positive, P-layer). When these two are mated together, a positive-negative (P-N) junction exists at the point of connection. Local to this junction, free electrons fill the available spaces and create a neutral zone.

When direct current (DC) voltage is applied across the P-N junction, electrons flow from the N-layer to the P-layer. This flow continually pushes electrons out of their original positions in the neutral zone as new electrons fall into the free spaces. Electrons falling into lower states release energy in the form of photons in a range of wavelengths narrower than that of incandescent lamps or CFLs, the range of wavelengths is narrower. As a result, less energy is lost to emission of photons in the non-visible portions of the spectrum. Different colors may be achieved by using different semiconductor doping processes, as well as coating the lens of the LED with phosphors.

Objective

The objective of this paper is to compare the general performance and dimming performance characteristics of incandescent, CFL, and LED technologies for the 60W incandescent equivalent A-19 lamp class. The intent is to focus on evaluating LED technologies as a viable option.

Approach

The overall approach for this paper is to aggregate and analyze available data from the DOE's SSL Lighting Facts program, as well as from laboratory assessments conducted for the ET program, at SCE's Technology Test Centers (TTC). The TTC's integrating sphere and calibrated power supplies were leveraged for testing, with test methodologies influenced by the following standards: LM-54-99: IESNA Guide to Lamp Seasoning, LM-45-00: IESNA Approved Method for the Electrical and Photometric Measurements of General Service Incandescent Filament Lamps, LM-66-00: IESNA Approved Method for the Electrical and

Photometric Measurements of Single-Ended Compact Fluorescent Lamps, and LM-79-08: Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products.

Metrics

Luminous flux. Luminous flux is a measurement of the perceived power of light. It takes the radiant flux, the total power of light, and adjusts it to account for the human eye's varying perception of intensity for different wavelengths. The unit of measurement is the lumen (lm).

Power. This refers to the instantaneous rate at which electrical energy is transferred to enable a device to operate. The unit of measurement is the Watt (W).

Efficacy. An important indication of overall lamp performance is efficacy. This value, in lumens per watt (lm/W), is a measure of light output over power input. New technologies would ideally have high efficacy: use less power for per amount of light given.

Correlated Color Temperature. Correlated color temperature (CCT) indicates whether a white light source appears more yellow/gold or blue, in terms of the range of available shades of white. CCT is derived by a theoretical object in physics: a "black body" that absorbs all electromagnetic radiation. This object emits different colors of light based on its exact temperature. Hence, the CCT of a light source is the temperature (in Kelvin) of the "black body" needed to match the color of the light source in question. Higher temperatures (3600K – 5500K) correspond to a "cool" or blue appearance; lower temperatures (2700K – 3500K) correspond to a "warm" or red appearance.

Color Rendering Index. Color rending index (CRI) describes how well a light source renders color compared to a reference light source of similar CCT. This index is scaled from 0 to 100. CRI affects visual perception. The CRI is directly related to the colors or spectral characteristics that the lamp produces.

Test Products

Test products were selected to explore various A-lamp products that are commercially available to consumers. The scope of analyzed products includes incandescent, CFL, and LED technologies. The intent of the product scope is to focus on capturing more of the LED products (the "newcomer" of the three technologies) to better gage their performance variations across different manufacturers. Additionally, a prototype LED was included for comparison to represent the "high end" of LED products. General performance data was aggregated from TTC testing and DOE LED Lighting Facts and reported. The following products were tested, and are hence referred to in the nomenclature detailed as follows:

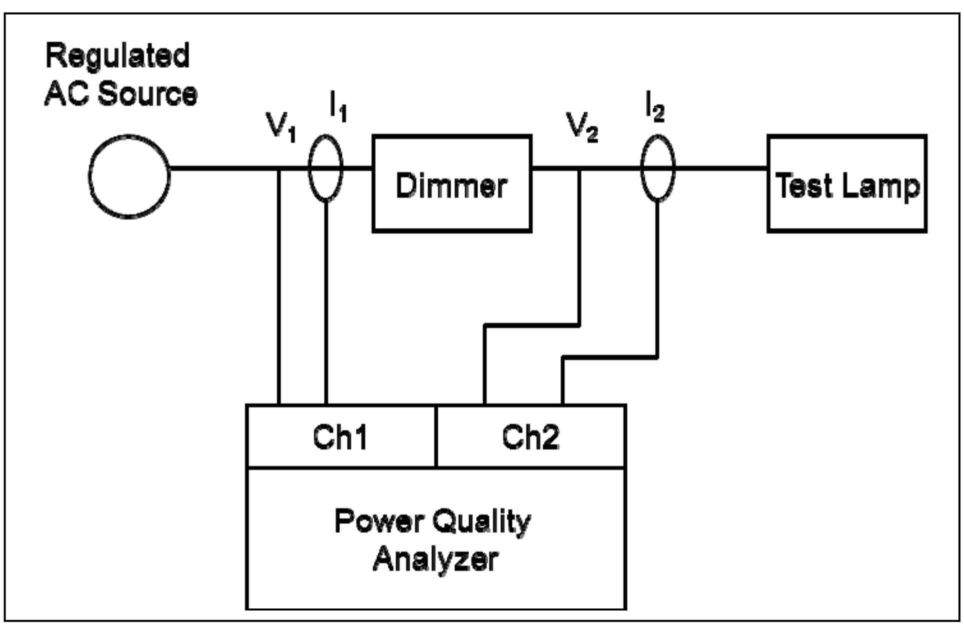
- (6) Incandescent Lamps: 3 selected manufacturers, two of the same lamp from each, tested at SCE TTC
    - "Inc_1" through "Inc_6"

- (6) Non-dimmable CFL's: 3 selected manufacturers, two of the same lamp from each, tested at SCE TTC
    - "CFL_1" through "CFL_6"
- (1) dimmable CFL, tested at SCE TTC
    - "CFL_7"
- (31) LED 60-Watt A-19 Incandescent Lamp Replacements, Several Manufacturers, data provided by DOE LED lighting facts
    - "LED_1" through "LED_31"
- (25) High-Efficiency, High-Performance LED Prototypes, 1 manufacturer, tested at SCE TTC
    - "P_LED_1" through "P_LED_25"

Dimming performance was tested at the SCE TTC on the Inc_5, CFL_7, and P_LED_14 lamps. Inc_5 and CFL_7 were paired with a standard rotary-knob line dimmer. The prototype LED manufacturer specifications however, required P_LED_14 to be paired with an electronic low voltage (ELV) dimmer. P_LED_14 was accordingly paired to a commercially available slide-knob ELV dimmer. Both dimmers had a maximum and minimum position. Dimming tests took place at several prescribed thresholds, defined on a percent-of-maximum-position basis.

Figure 2 illustrates the configuration for taking electrical measurements for dimming performance testing. Voltage (V) and current (I) are directly measured. The power quality analyzer uses these measurements to calculate power. This power is used with luminous flux measurements (obtained with the integrating sphere) to calculate efficacy. Electrical measurements are taken at points before the dimmer and after the dimmer. "System" measurements are considered those that use measurements taken before the dimmer. "System" measurements are designated with subscripts V_1 and I_1. "Lamp" measurements are considered those that use measurements taken after the dimmer. "Lamp" measurements are designated with subscripts V_2 and I_2.

Figure 2. Dimming Performance Testing: Electrical Measurement Configuration



Results and Discussion

Table 1 and Figures 3 through 5 present the general performance data for various A-19 incandescent lamps, CFLs, and LEDs. In each figure, data scatter is depicted, along with the average of each technology. Averages are indicated in the figures in the following format: (Technology), (Metric X), (Metric Y). The following trends are observed:

- All CFL and LED lamps are able to achieve comparable, and in many cases, higher luminous flux output, than incandescent technologies, for significantly less power. When comparing the data averages for LEDs and CFLs, with incandescent as a baseline:
  - LEDs used 79% less power, with 16% more luminous flux
  - The prototype LEDs used 83% less power, with 27% more luminous flux
  - CFLs used 77% less power, with 17% more luminous flux
- LEDs showed a wider range of CCT (warm and cool), but the majority are able to achieve values comparable with incandescent lamps. CFLs are also able to achieve CCTs comparable to incandescent lamps. CFLs and LEDs were able to achieve CRI values comparable with incandescent lamps, but the prototype LEDs and a handful of other LEDs were able to achieve CRI values closer to those of incandescent lamps. When comparing the data averages for LEDs and CFLs, with incandescent as a baseline:
  - LED CCT was 22% higher, CRI was 17% lower
  - The prototype LED CCT was effectively equal, CRI was 6% lower
  - CFL CCT was 1% higher (effectively equal), CRI was 18% lower
- CFLs and LEDs were able to achieve significantly higher values of efficacy. When comparing the data averages for LEDs and CFLs, with incandescent as a baseline:
  - LED efficacy was 456% higher
  - The prototype LED efficacy 649% higher
  - CFL efficacy was 413% higher

Table 1. Lamp General Performance Averages

Lamp	Luminous Flux (lm)	CCT (K)	CRI (%)	Power (W)	Efficacy (lm/W)
Incandescent	704	2715	99.3	57.0	12.3
CFL	825	2737	81.7	13.0	63.4
LED	818	3314	82.4	12.09	68.6
Prototype LED	895	2719	93.1	9.68	92.4

Figure 3. General Performance: Luminous Flux and Power

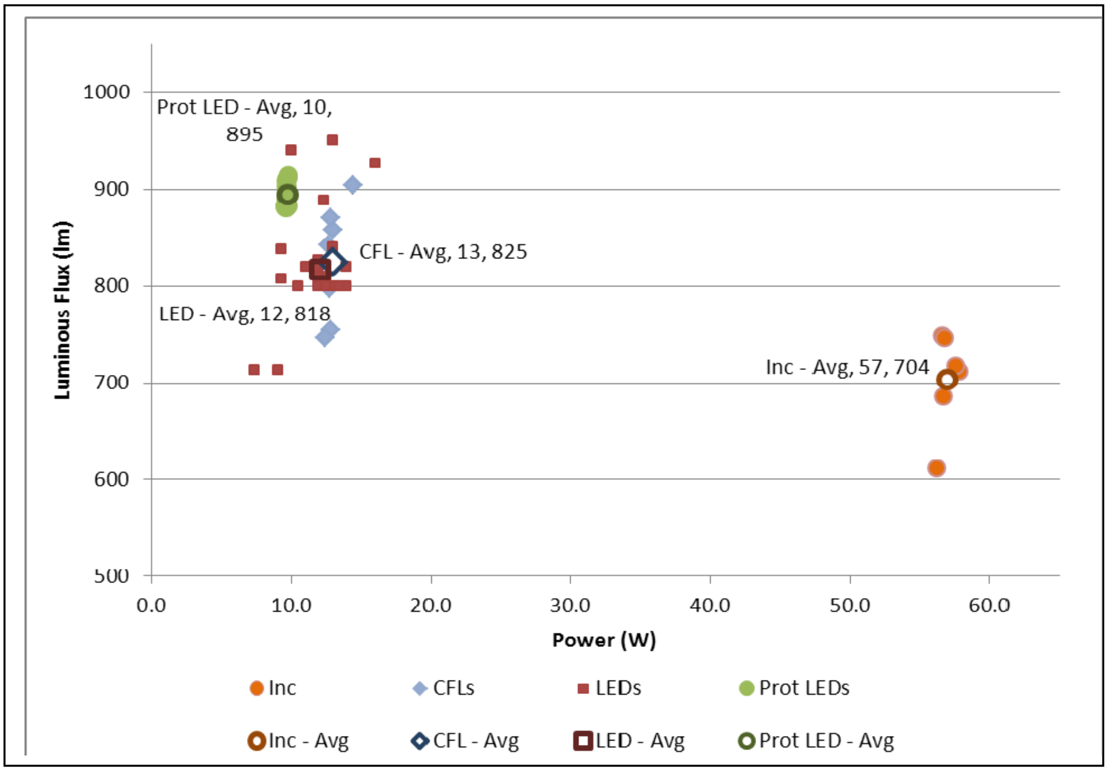


Figure 4. General Performance: CRI and CCT

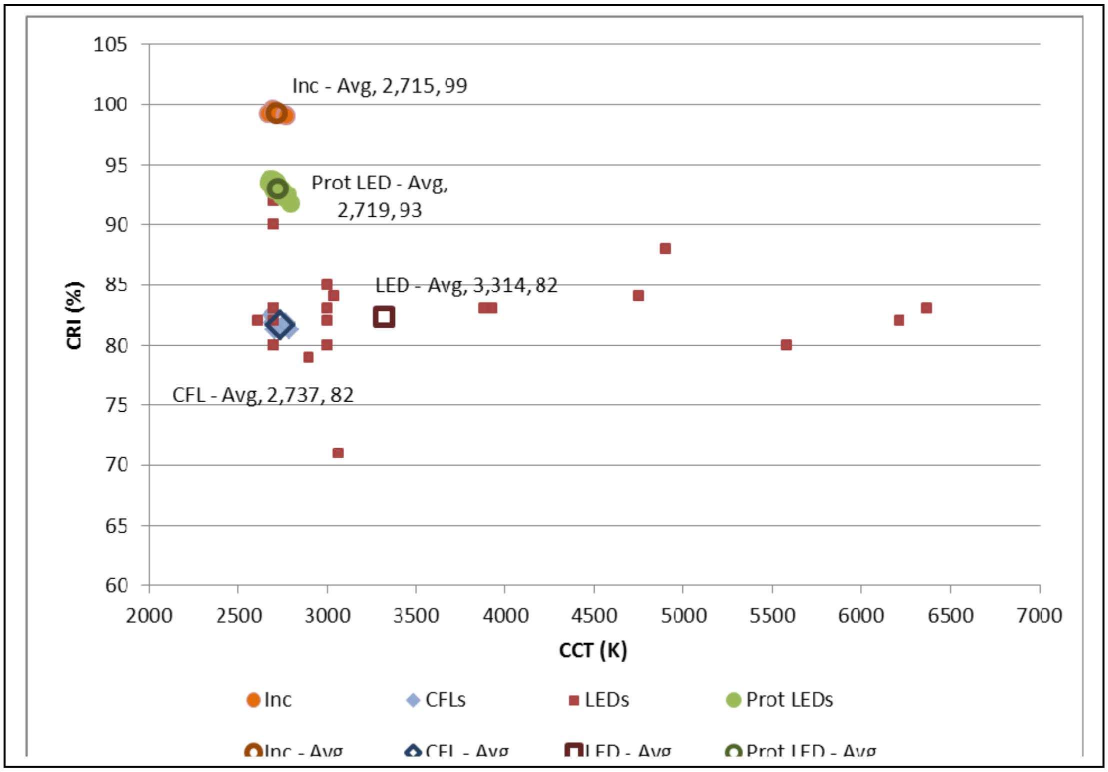
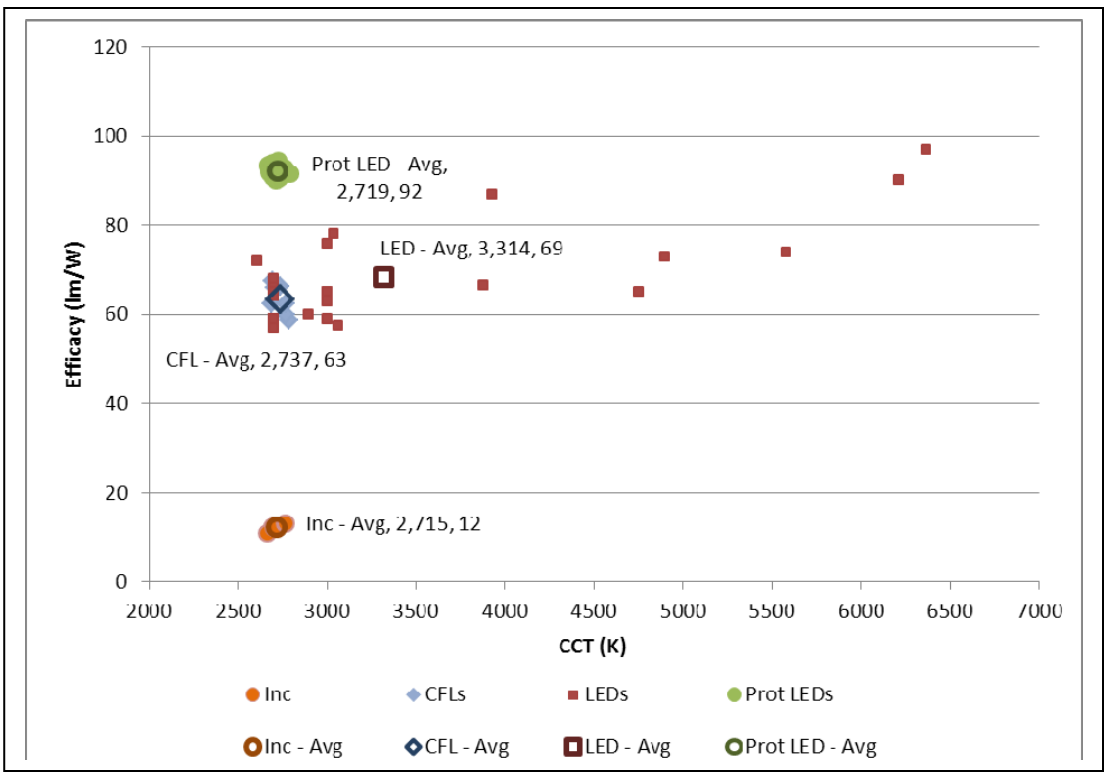


Figure 5. General Performance: Efficacy and CCT



Figures 6 through 10 present the dimming performance data for the dimming test lamps (Inc_5, CFL_7, and P_LED_14). All three technologies were observed to be continuously dimmable. P_LED_14 was the only technology to stay lit when at a 0% (minimum) dimmer position. Notably, P_LED_14 was also the only lamp unable to be shut off through toggling of the integrated dimmer ON/OFF switch.

Inc_5 and CFL_7 turned off at the 0% position; no measurements were taken at the 0% position. It was observed that CFL_7 required warming up before dimming could be properly performed. Without proper warm up, the CFL did not dim properly; it would shut off at roughly 50% of dimmer travel. Regardless of warm up, once the CFL turned off, the dimmer would have to be cranked back up to nearly the 100% position to re-start.

The following trends are observed from the figures:

- Marginal differences are seem between “system” versus “lamp” efficacy for CFL_7 and Inc_5, whereas, they are more pronounced for P_LED_14, especially at the 0% dimmer position.
- Efficacy drops off in a more pronounced fashion for Inc_5 and CFL_7 with decreasing dimmer position. P_LED_14 efficacy is affected marginally, until the 0% dimmer position is reached
- Luminous flux becomes zero for Inc_5 and CFL_7 at the 0% dimmer position
- CCT changes minimally for Inc_5, CFL_7, and P_LED_14 with decreasing dimmer position. P_LED_14 CCT increases (green color shift) at the 0% dimmer position.
- CRI changes minimally for Inc_5, CFL_7, and P_LED_14 with decreasing dimmer position. P_LED_14 CRI decreases at the 0% dimmer position.

Figure 6. Dimming Performance: Efficacy

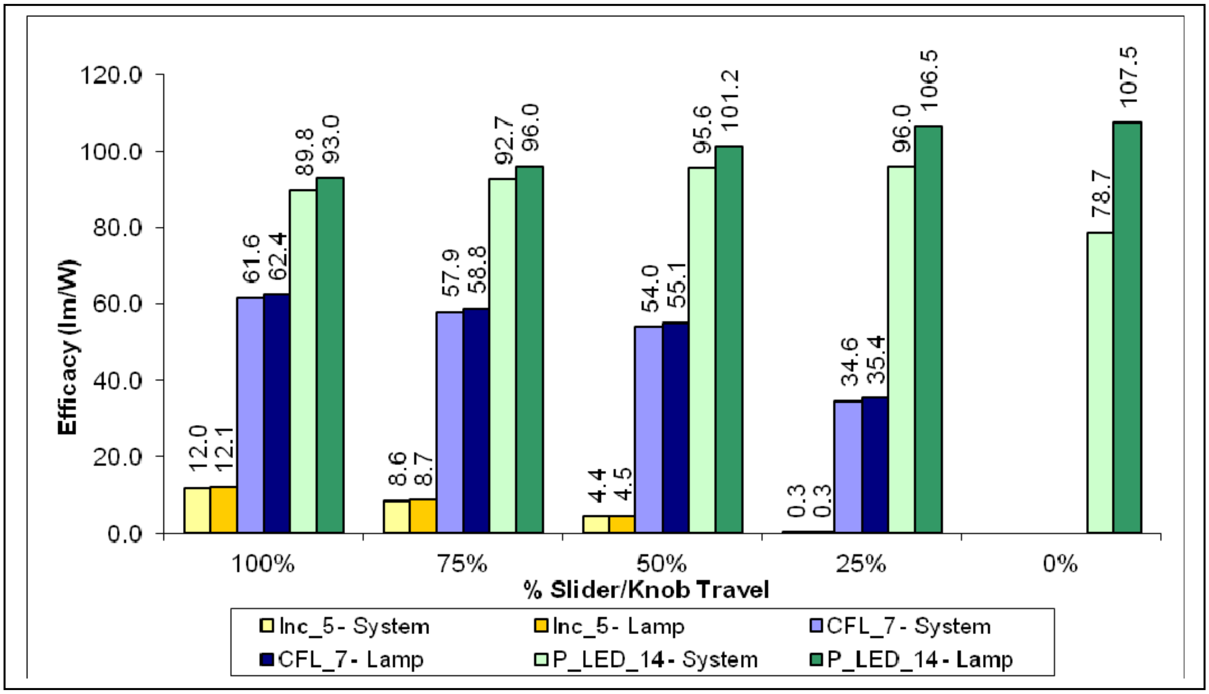


Figure 7. Dimming Performance: Luminous Flux

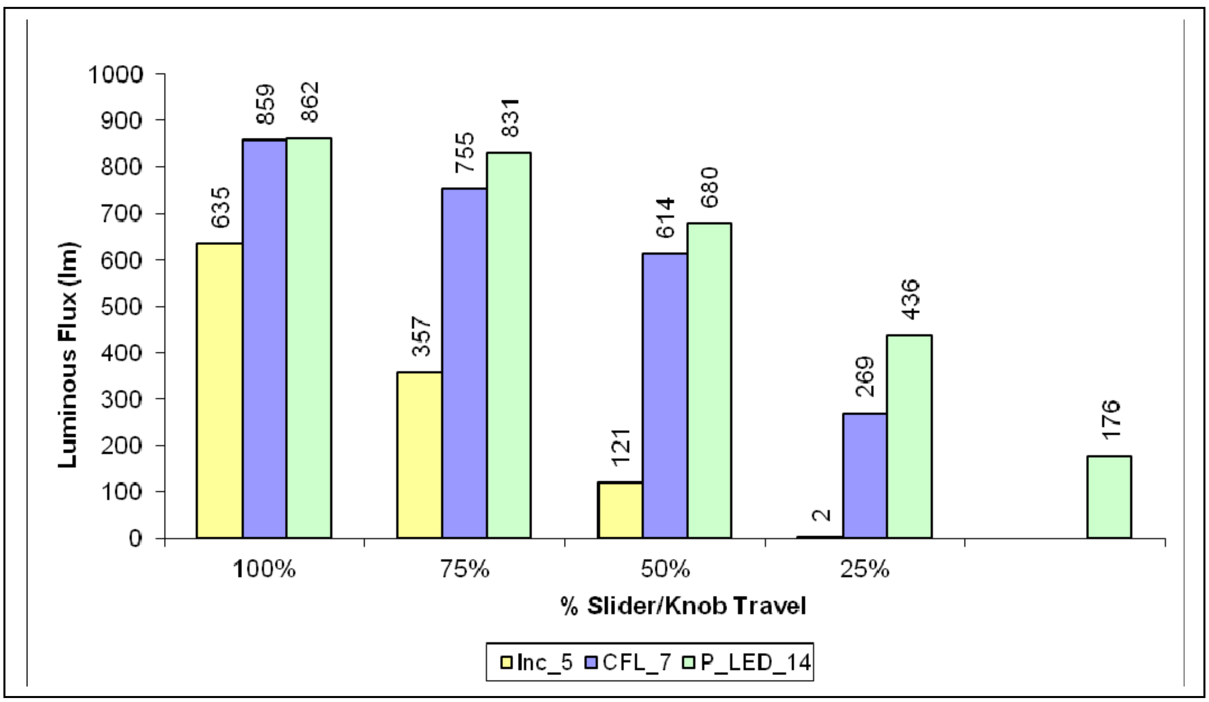


Figure 8. Dimming Performance: Power

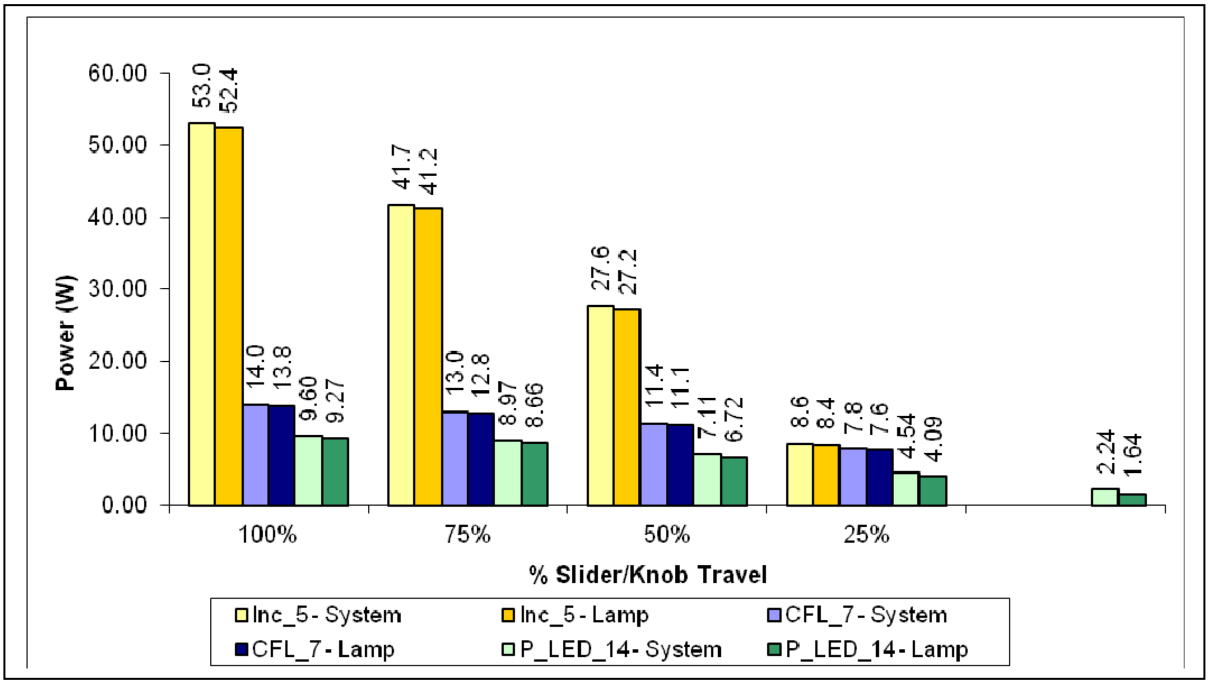


Figure 9. Dimming Performance: CCT

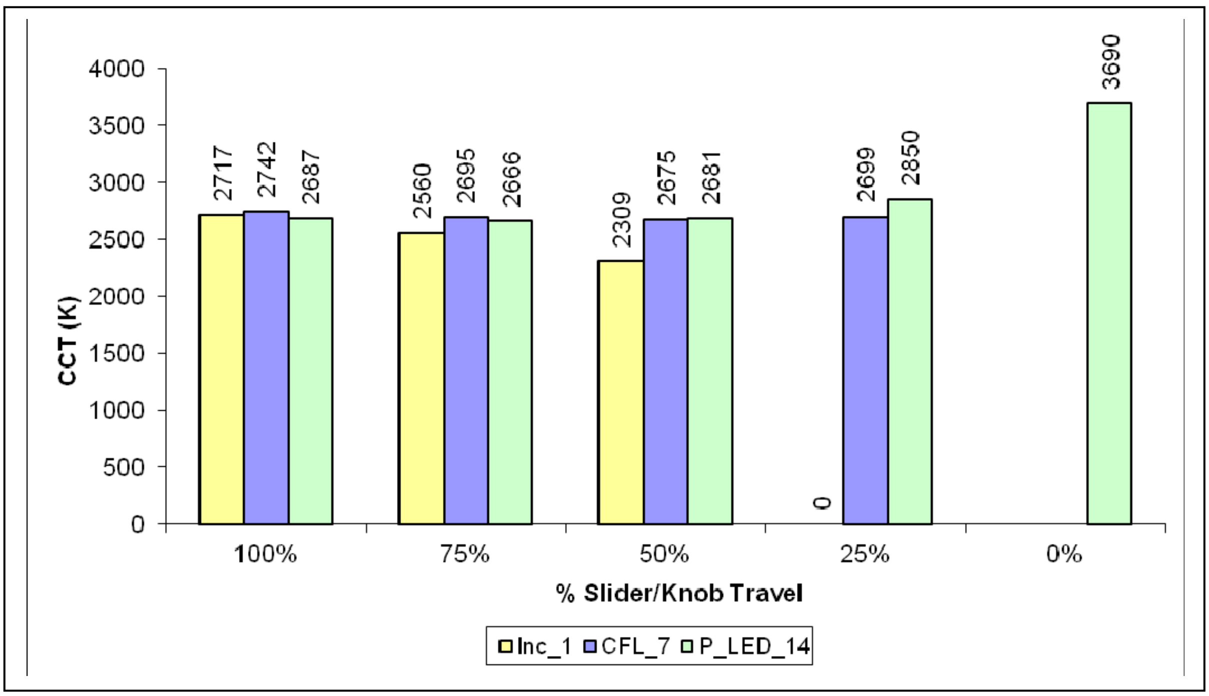
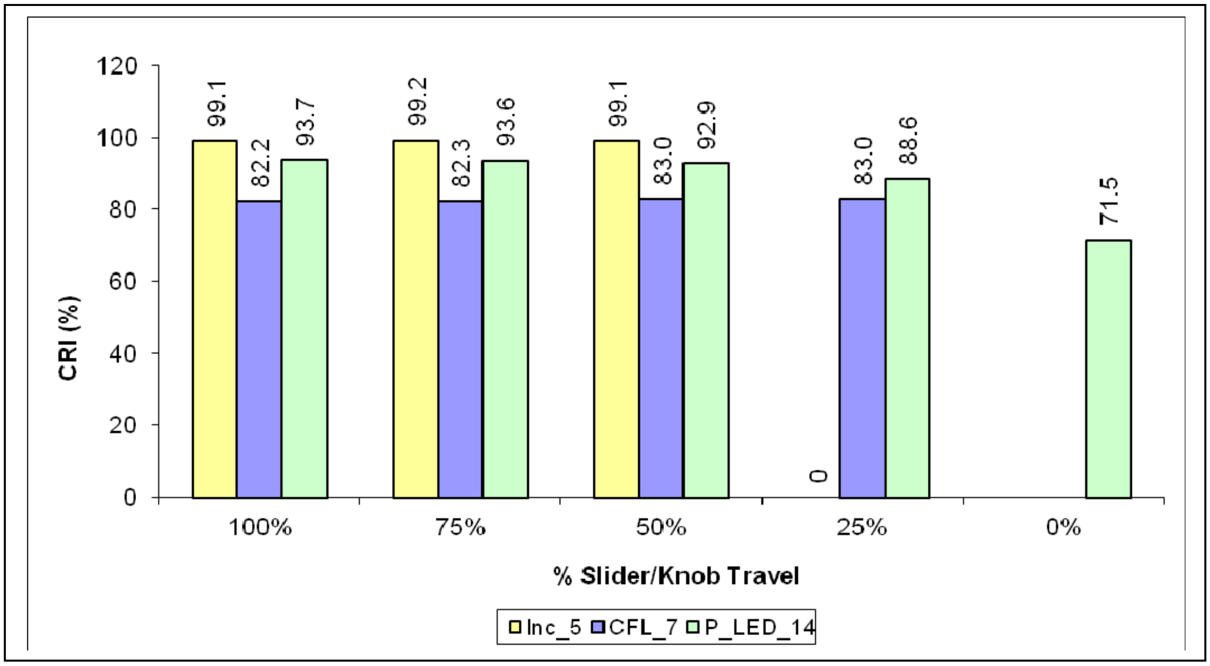


Figure 10. Dimming Performance: CRI



Conclusions and Recommendations

It is of great importance to continue to monitor and promote suitable energy-efficient technologies through venues such as the American Council for an Energy-Efficient Economy (ACEEE) and California statewide utility programs. LED technology generally shows promise in terms of becoming a suitable high-efficiency A-19 incandescent lamp replacement. The LED products analyzed had the lowest power draw, and the highest luminous flux and efficacy values. Although the selected LEDs showed a wider range of CCT, the majority of products were able to achieve comparable "warm" CCTs. LEDs were able to reach CRI values closer to incandescent lamps. LEDs also do not require warm-up periods similar to CFLs to operate. Additionally, at dimmed performance, the prototype LED showed higher efficacy and better CRI than the dimmable CFL. However, the prototype LED also showed green color shift at the lowest dimmed point, and special consideration was needed to find an appropriate LED dimmer. Ultimately, at this time further investigation is still recommended for this technology/application in the following areas:

Cost: At the time of the SCE study in 2010, LED products were observed to retail for roughly \$80 per lamp. A May 2011 LED Product Snapshot indicated that LED product costs reduced to around \$40 per lamp. This results in an approximate payback of around six years. In order to be geared as more reasonable alternatives, when compared to cheaper CFLs, around a one year payback is preferable. This would mean LEDs would need to retail for around \$5 per lamp: by DOE's projections, this is achievable within the next decade.

Lifetime testing: These results do not analyze performance variation throughout the lifetime of each unit. Longer lifetimes are a significant advantage and should be better understood.

Dimming: Manufacturer specifications for the prototype LED lamp require use of an ELV dimmer. These results do not analyze how different dimmers would affect unit performance. Also, ELV dimmer costs are not trivial; the cost of the ELV dimmer selected for this project retails for $30[2]. When paired to the selected dimmer, green color shift occurred at the lowest dimming positions, and the lamp was unable to toggle off using the ELV dimmer's controls. Dimming is a significant advantage of SSL technologies; any dimming-related issues should be better understood and addressed.

Thermal effects: The prototype LED lamps were specified to be used in dry locations, and not within totally enclosed fixtures. The quantified effects of ambient temperatures/humidities on this technology's performance and lifetime are not well understood at this point. The conditions in the lab assessment were within a fairly narrow range, when taking into consideration the various climate zones/applications these general-purpose devices may see.

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