LED Screw-in Directional Lamps

ET07.12

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ABBREVIATIONS AND ACRONYMS

CCT	Correlated Color Temperature
CRI	Color Rendering Index
kWh	Kilowatt Hour
LED	Light Emitting Diode
MR	Multifaceted Reflector
PQL	Power Quality Logger
SCE	Southern California Edison
SCLTC	Southern California Lighting Technology Center
W	Watt

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EXECUTIVE SUMMARY

TECHNOLOGY DESCRIPTION

Screw-in Directional lighting, or Screw-In Directional Lamps (SDL), refer to lamps with halogen, fluorescent, or light-emitting diode light sources that provide even illumination across a wide area. Typical halogen and fluorescent SDL lamps have a reflector to direct the light within a certain degree angle. SDL lamps are typically used in applications where the light needs to be directional, such as down lights. LED SDL lamps are designed to replace standard halogen and fluorescent SDL lamps. LED SDL lamps are screw-in replacements for existing fixtures and lighting systems.

FIGURE 1: COMMERCIALLY AVAILABLE LED SDL LAMPS (PHOTO CREDIT: GBL ON CYBERGUYS.COM)

Advances in LED technology have made them brighter and more efficient, thereby expanding the application of LED to other markets.

The operation of the LED Screw-in Directional Lamp is the same as that of the halogen and fluorescent versions from the perspective of the end-user.

PROJECT OBJECTIVE

The objective of the project is to assess the incremental energy savings and demand reductions of using LED SDLs over incandescent and fluorescent PAR30 floodlight lamps. Photometric tests conducted in the Southern California Lighting Technology Center (SCLTC) demonstrate the differences and similarities of the incandescent and LED SDL lamps. Fluorescent SDLs were not tested. Short-term durability tests will assess potential immediate defects, failure mechanisms, and feasibility of manufacturer lifetime ratings.

TEST EQUIPMENT

All testing was conducted at the Southern California Lighting Technology Center (SCLTC) in Irwindale, California. The lab allowed for a consistent environment to measure the performance of the lamps.

The measurements taken at the SCLTC laboratory verified the energy and demand reduction and compared other lighting characteristics of the LED and halogen SDLs. Additionally, tests were conducted to qualify performance. The qualitative tests were designed to determine how the LED SDL lamps would perform as compared to the halogen SDL lamps.

SUMMARY OF RESULTS

LAMP LUMENS

A total of twenty-two LED SDL lamps of varying luminosity were tested in the Integrating Sphere to examine their performance over the first 25 minutes of operation. For comparison purposes, three halogen Par30 lamps were also tested.

The lumen results of the Sphere test are reported in Figure 2 for all LED SDL products. The tested products had a wide range of initial lumens (lm) recorded at 30 seconds of operation. Initial lumens ranged from a minimum of 107 lm to 850 lm. The Figure also shows the drop in lumens over the course of the Sphere test.

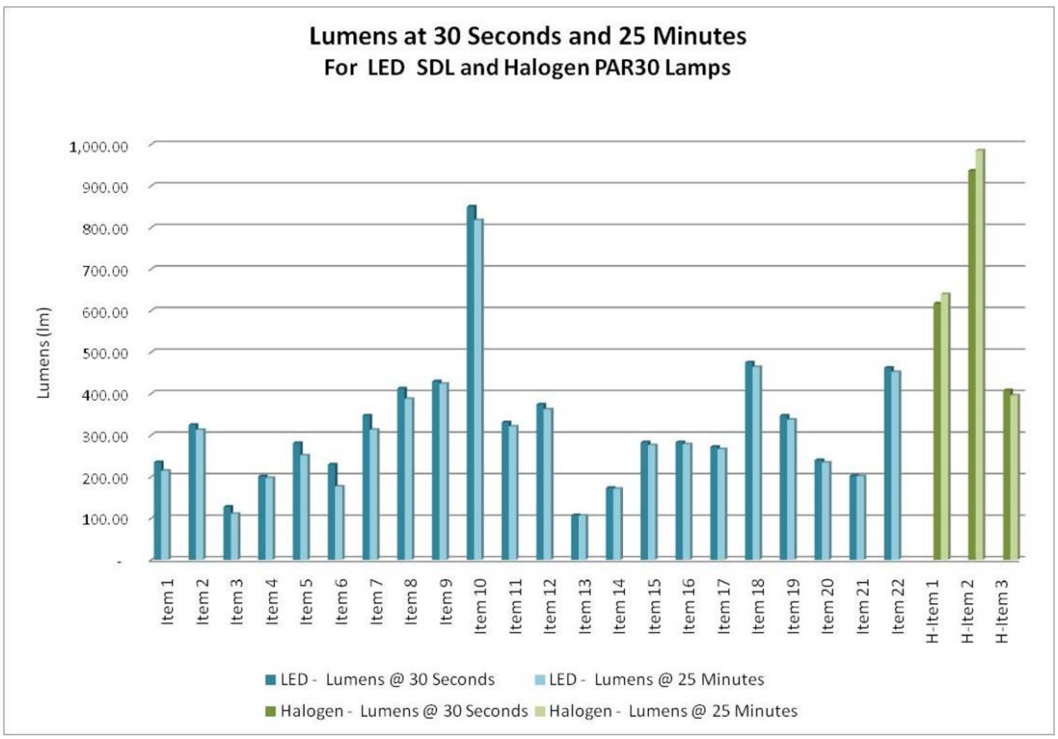

FIGURE 2: AVERAGE LUMENS AT 30 SECONDS AND 25 MINUTES FOR LED AND HALOGEN PAR30 LAMPS

All LED products did experience at least some reduction from initial lumens during the first 25 minutes of operation.

Most LED products tested did not have the same luminosity as the halogen products after 25 minutes of run time. However, there are a number of LED products that are comparable to or better than two of the halogen items. A number of LED items can adequately replace some of the halogen items tested. Of the twenty LED products that included manufacturer rated lumens, six items had measured lumens at 25 minutes that exceeded the manufacturer rating; however, twelve items had measured lumens at 25 minutes that were significantly lower than the manufacturer rating.

POWER MEASUREMENTS

One of the main advantages of the LED SDL products over the halogen PAR30 products is their lower rated energy use. Demand measurements were taken during the Integrating Sphere test to compare actual wattage consumption of the LED and halogen lamps.

In general, the measured power is consistent with the manufacturer rated power for both LED and halogen products.

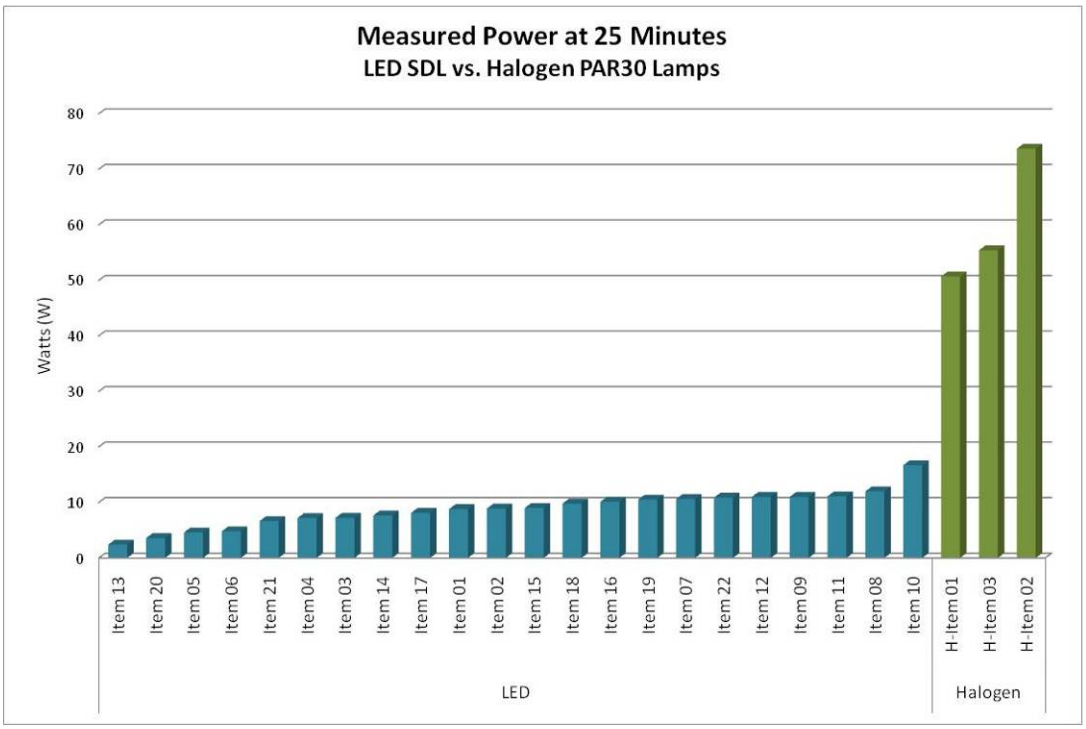

FIGURE 3: MEASURED POWER FOR LED SDL AND HALOGEN PAR30

Without exception, the LED products consume considerably less energy than the halogen products. The *maximum* energy consumption for the LED SDLs is just fewer than 17 watts, while the *minimum* energy consumption for the halogen PAR30s is just over 50 watts.

EFFICACY

The power data was measured and recorded during the Sphere test. The power data was then combined with the Sphere lumen data at 25 minutes to determine if the lower energy consumption of the LED products translated to an overall more efficacious lamp.

The LED lamps were, on average, significantly more efficacious than the halogen lamps. The average LED SDL produced just over 35 lumens per watt, while the average halogen produced just 11 lumens per watt.

Figure 4 shows the efficacy of the individual SDL and PAR30 lamps. Because of the number of lamps tested, they have been arranged in increasing order of efficacy to aid comparison. It is clear that all LED SDL lamps tested were more efficacious than the Halogen lamps after 25 minutes of run time.

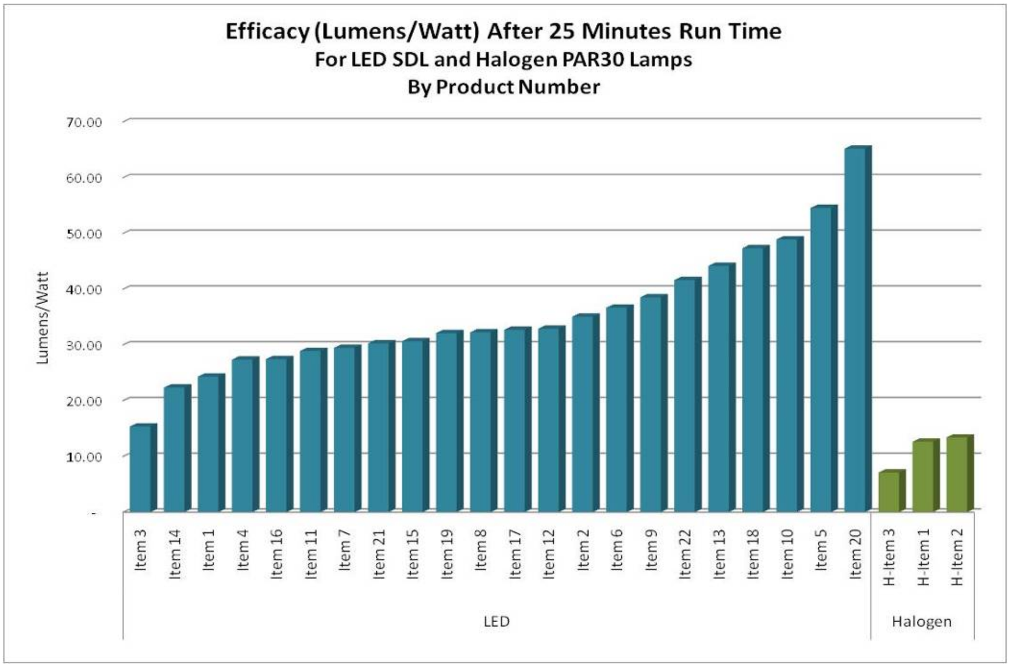

FIGURE 4: INDIVIDUAL LAMP EFFICACY AFTER 25 MINUTES BURN TIME

The lamps were examined by the manufacturer's designation of cool (blue) and warm (yellow) color categories to determine if one category was more efficacious than the other. In general, the Cool White (blue, higher CCT) LED SDLs were more efficacious than the Warm White (yellow, lower CCT) LEDs, though there was overlap between the two categories.

CORRELATED COLOR TEMPERATURE

There is no "correct" CCT for lighting use. Depending on the purpose of the lighting, some applications may benefit from a higher CCT while others will benefit from a lower CCT.

On average the Cool White LED products have a much higher CCT than the Warm White LED and halogen products, resulting in a light source that is bluer, or "cooler", than the yellow "warm" lamps. Examination of the individual LED and halogen products showed the manufacturer CCT rating was consistently in accordance with the measured CCT at 25 minutes.

COLOR RENDERING INDEX

Most products did not have manufacturer ratings for CRI, therefore no comparison could be made between rated and measured CRI. The following figure compares measured CRI between LED and halogen lamps.

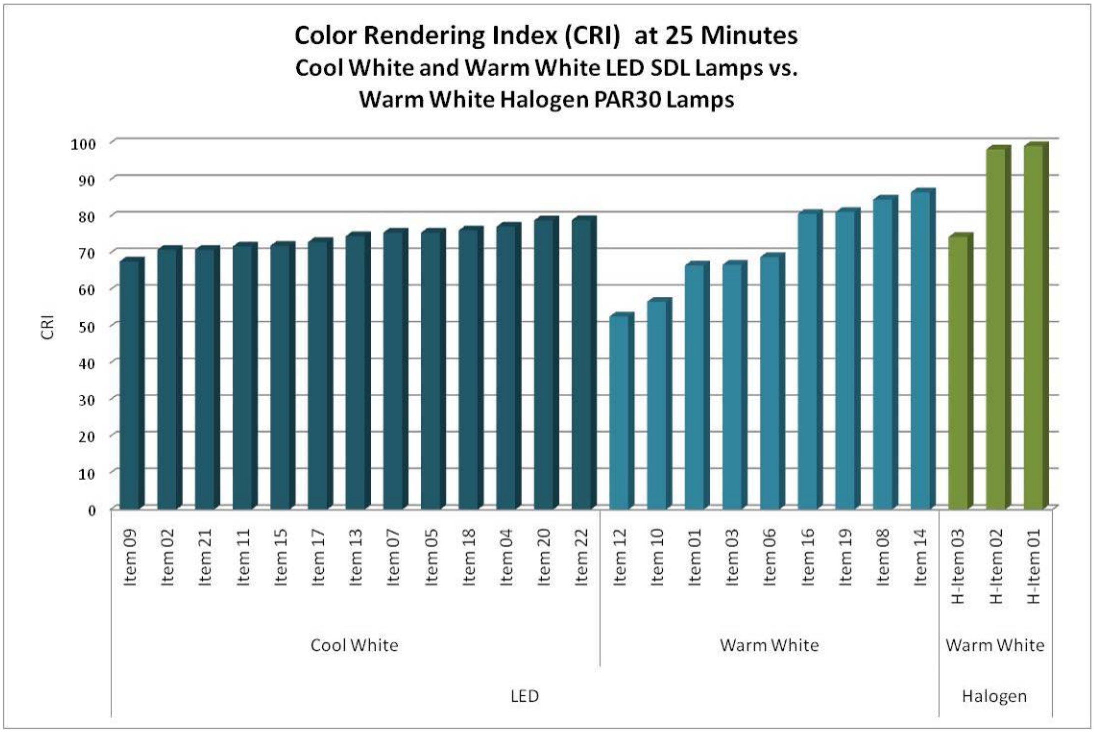

FIGURE 5: INDIVIDUAL CRI

In comparing the Warm White LED and halogen products, on average the halogen PAR30s tend to have a higher CRI; however, some of the individual LED products had CRIs of approximately 85 to 87, which approached the CRI of the halogen PAR30 products.

BURN-IN TEST

A short-term Burn-In test is being performed to determine lumen persistence and to record overall performance within the first couple months. At the end of the testing period, this data can help determine the feasibility of the rated lifetime hours.

All lamps were installed on a track fixture for the Burn-In test. All the lamps are turned on 24 hours a day, 7 days a week, and are sampled approximately every 2 weeks. During this bi-weekly sampling, the lamps are tested in the Integrating Sphere to obtain lumen, CCT, and CRI data.

Interestingly, as shown in Figure 6, not all the LED products experienced a continued drop in lumens after the Sphere test. It is apparent that a few lamps did have a significant drop, many had a minimal drop, and others appear to have stabilized. Some products, however, experienced a small spike in lumens during week 2 of testing (e.g. Item 12).

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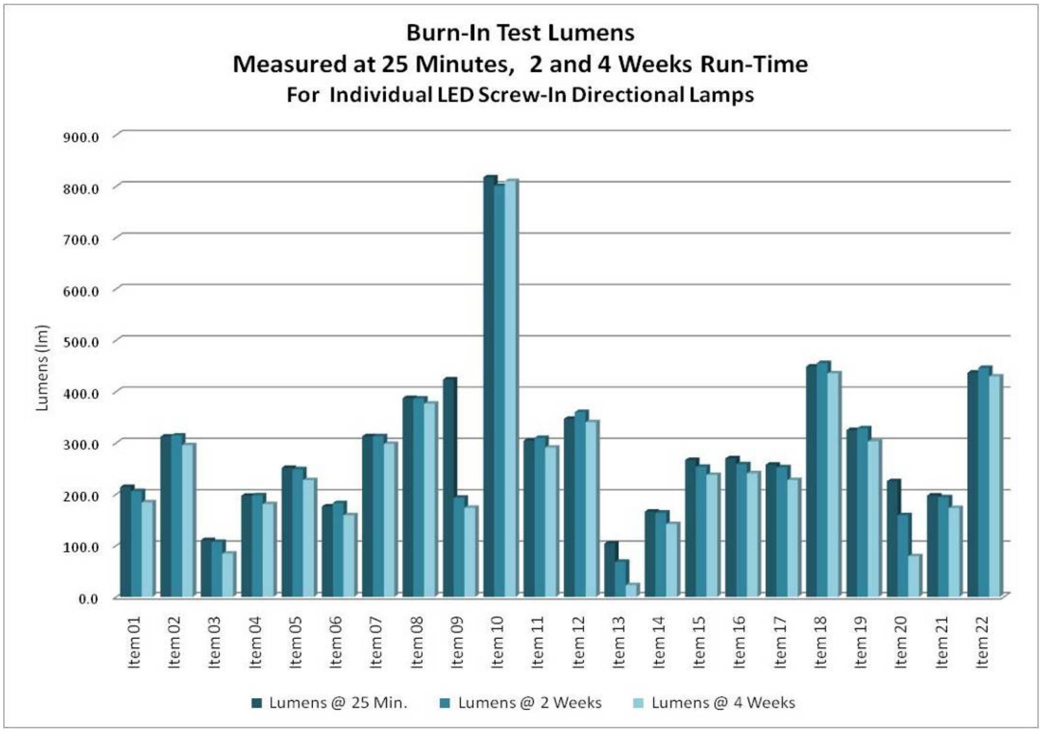

FIGURE 6: BURN-IN TEST LUMENS FOR INDIVIDUAL LED SDLS

This strange fluctuation in lumens may be due to an unexpected decrease in indoor temperature which can result in an increase in lumen output. Additional bi-weekly testing during the remainder of the Burn-In test will better determine the lumen trend in these lamps.

The biweekly luminosity values were combined with energy consumption to determine average lamp efficacy.

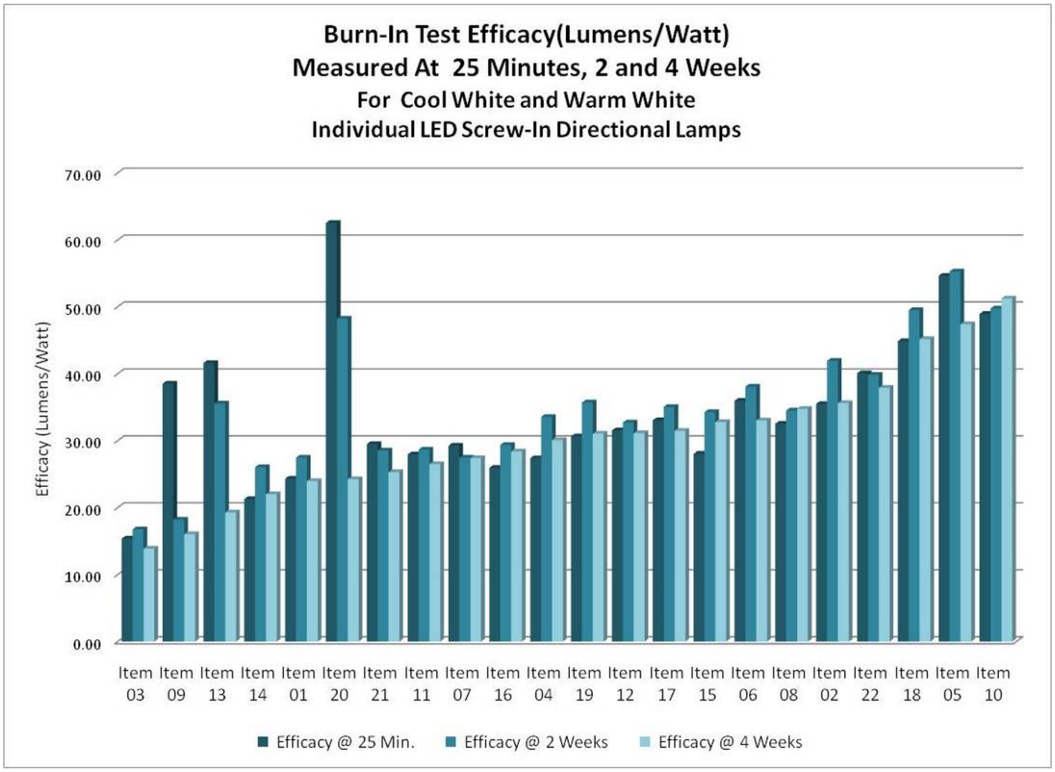

FIGURE 7: BURN-IN TEST INDIVIDUAL EFFICACY, COOL WHITE VS. WARM WHITE

In Figure 7 the LED SDL products were sorted from lowest to highest efficacy using week 4 of the Burn-In test. The efficacy values at week 2 appear to be reflecting the increase in lumens that was noted in Figure 6.

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The CCT data showed changes during the test period. The data showed a greater Kelvin increase for the average Cool White LED SDL in week 4. The Cool White LEDs had an average CCT of 7700K by week 4, an increase of over 1600K from week 2. The Warm White LED SDL products had only a slight increase in CCT.

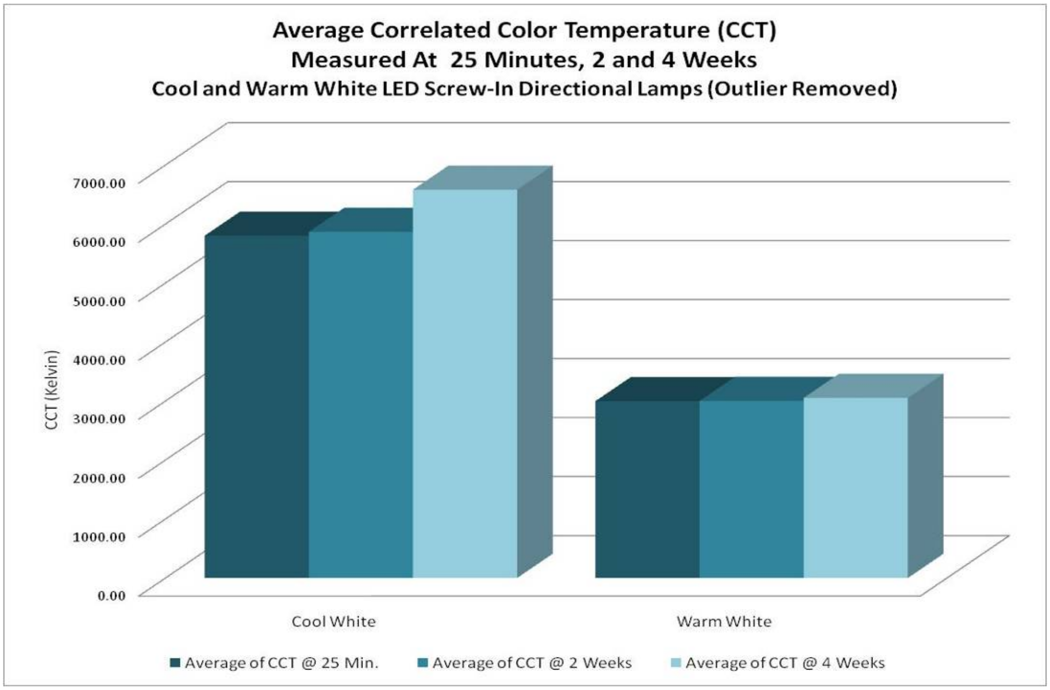


FIGURE 8: BURN-IN TEST AVERAGE CCT, COOL WHITE VS. WARM WHITE, COOL WHITE OUTLIER REMOVED

The measurement of the CRI during the bi-weekly Burn-In testing revealed a surprising trend for both the Cool White and Warm White LED lamps. Both experienced an increase in the CRI during the 2 week testing, followed by a significant decrease in week 4.

LIGHT DISTRIBUTION

Images for each lamp were downloaded from the camera's memory card, and imported into Adobe Photoshop software for processing. The Photoshop images were used to reveal and highlight inconsistencies in light distribution as well as any patterns and shadows caused by the optics. It may also help to identify characteristics of the SDLs that may impact performance.

Most of the LED SDLs had even light distribution as shown in Figure 9; however, some had uneven color distribution, streaks or hot spots as shown in Figure 10.

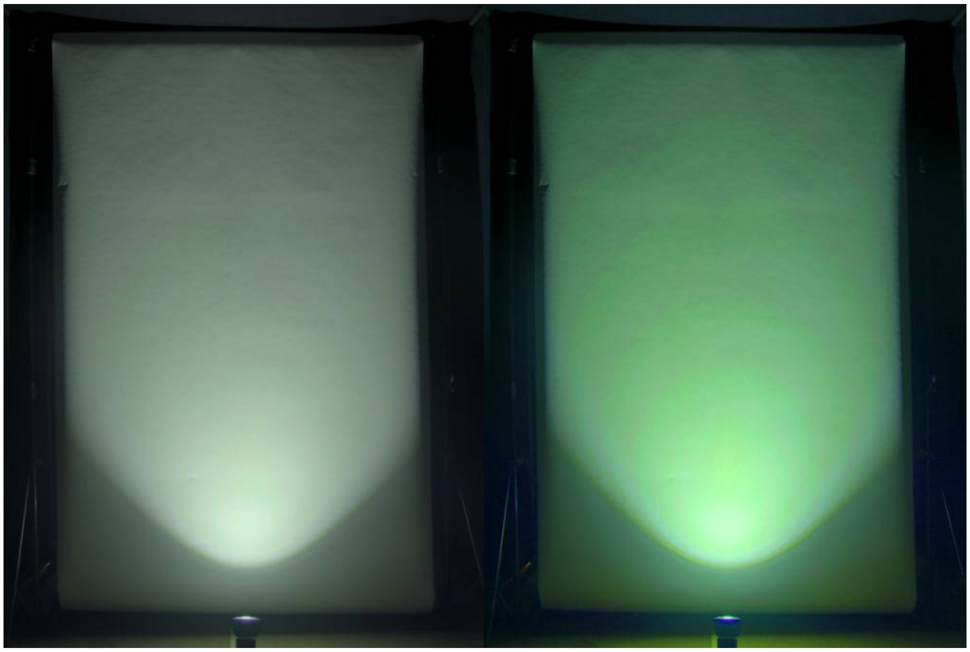


FIGURE 9: ITEM 11: PROCESSED PHOTOSHOP IMAGE (LEFT) AND SATURATED PHOTOSHOP IMAGE (RIGHT)

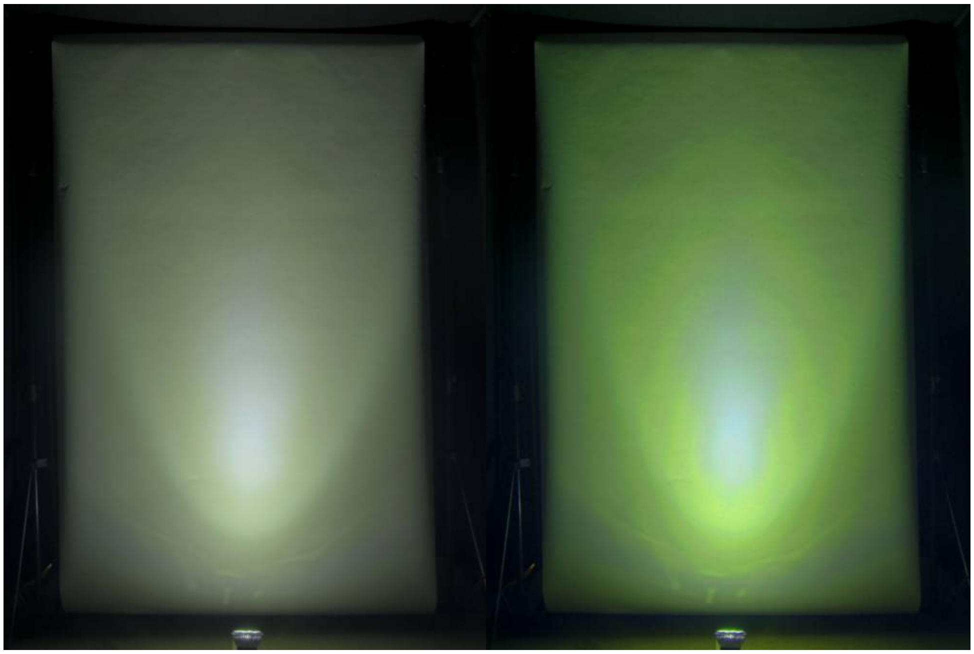


FIGURE 10: ITEM 17: LED SDL PRODUCT WITH UNEVEN LIGHT DISTRIBUTION

ENERGY SAVINGS

Annual energy savings is directly dependent on the lamps' annual operating hours. In some cases, operating hours will follow those of retail operating hours, especially in applications where merchandise is highlighted. The California utilities' Energy Efficiency Programs estimate average retail operating hours to be 12 hours per day, 365 days a year. For indoor residential use, the operating hours will be much less than commercial applications. Residential CFL operating hours of 2.34 hours can be used to estimate likely hours of use for the LED SDL lamps. In many cases, the SDL lighting may run 24 hours a day. This would be true in cases where highlighted merchandise or architecture is continually on display. Therefore, energy savings was calculated using 2.34, 12 and 24 hours per day to provide a savings range.

Table 1 reports the energy savings that a consumer can expect when replacing a halogen PAR30 of approximately 400 lumens with an LED SDL of approximately 425 lumens.

TABLE 1: ESTIMATED ANNUAL ENERGY SAVINGS WITH VARYING OPERATING HOURS

Daily Hours of Use	Annual Hours of Use	Estimated Energy Savings (kWh)
2.34	854.1	37.9
12	4380	194.5
24	8760	388.9

CONCLUSIONS

Halogen PAR30s, on average, are brighter than the LED SDL counterparts. However, when comparing individual lumen output from the lamps, some of the LED SDL lamps did produce comparable or greater lumens than the halogen lamps.

Many LED SDL products had a percentage lumen drop of less than 5% during the first 25 minutes of operation. This was comparable to one of the halogen PAR30 lamps tested. The remaining halogen PAR30 lamps had an increase in lumen output during the first 25 minutes of operation.

Manufacturers of LED SDLs are inconsistent in labeling the products true lumen output. The majority of tested LED SDLs had manufacturer rated lumens higher than the lumen output measured at 25 minutes of operation. On the other hand, some manufacturers had lumen ratings that were lower than the measured lumen output at 25 minutes. These manufacturers may be accounting for the eventual degradation of the LED's lumens. In addition to the inconsistent manufacturer lumen rating, many manufacturers do not include a recommendation for the appropriate Halogen equivalency. The combination of these two limitations makes it difficult to choose the appropriate LED replacement for a halogen light source.

The lumen data shows there are good LED replacements for some halogen PAR30s. Unfortunately, there is significant variation between manufacturers in the lumen output of the LED SDLs, adding to the difficulty in choosing an appropriate LED replacement for Halogen PAR30s.

The LED technology consumed considerable less energy than the halogen technology. When comparing efficacy values, the LED SDLs produced, on average, nearly three times the lumens per Watt. On an individual basis, even LED SDLs with the lowest efficacy have greater performance than the halogen PAR30s with the highest efficacy. The LED SDLs marketed as "cool white" lamps had, on average, higher efficacy values than those marketed as "warm white" lamps.

The initial results from the Burn-In test indicate variable lumen depreciation in the first four weeks of operation. This will continue to be monitored and the results from the full year of tests are planned to be included as an addition to this report.

The quality of the light is very important for many applications where SDLs are used. In these applications, consumers may be more sensitive to changes in CCT and CRI. Unfortunately there is no quantitative "right" CCT and CRI as it varies with application and consumer preference. For this reason, consistent performance of the lamps is preferable.

The LED SDL products come in a wide range of color temperatures, from 2600K (warm white) to 7700K (cool white). This wide range of CCT allows consumers to select the appropriate color temperature according to preference and/or application.

The CRI, or color quality, affects visual perception of the color output from the lamp. A higher CRI can improve the perception of the light. In some cases, increased CRI may reduce needed luminous flux. On average, LED products had lower CRI values than the halogen products. However, some individual products had CRI values that exceed the CRI of the lowest performing halogen product.

The sample of lights tested included a variety of beam angles and intended applications. The analysis provided by the light distribution tests allows a qualitative assessment of how the LED SDL will illuminate objects. While certain characteristics are "bad" such as poor light distribution across the surface other characteristics truly depend on the intended application, such as spot lighting or merchandising. As with many lighting applications, these are personal preferences and may only be assessed after the lamp is installed.

Several LEDs could be energy efficient replacements for halogen lamps, however, inconsistencies in lamp quality, color temperature and lumen output may lead to unsatisfactory consumer experiences until the technology matures.

Introduction

Technology Description

Screw-in Directional lighting, or Screw-In Directional Lamps, (SDL) refer to lamps with halogen, fluorescent, or light-emitting diode light sources that provide even illumination across a wide area. Typical halogen and fluorescent SDL lamps have a reflector to direct the light within a certain degree angle. The reflector in the SDL lamp allows the light to be aimed from the source in a general directed beam. SDL lamps are typically used in applications where the light needs to be directional, such as down lights. LED SDL lamps are designed to replace standard halogen and fluorescent SDL lamps. LED SDL lamps are screw-in replacements for existing fixtures and lighting systems. Many LED SDL manufacturers use the incandescent names, such as R30, BR30, or PAR30. The ‘R’ in each name refers to ‘reflector,’ however, the LED counterpart may not have a reflector as the name suggests. This is due to the inherent property of LED to be directional. Maintaining the naming convention for the LED SDLs, although not necessarily precise, is useful for consumers who are looking for lighting products with similar function or applicability.

Figure 11: Commercially Available LED SDL Lamps (Photo Credit: GBL on Cyberguys.com)

An LED is a semiconductor that is completely covered in epoxy. It emits light when there is a proper amount of current in the LED. Often used as little indicator lights on everything from large appliances to portable electronics, the small, low-output LED is a fairly mature technology. However, advances in LED technology have made them brighter and more efficient, thereby expanding the application of LED to other markets.

The operation of the LED Screw-in Directional Lamp is the same as that of the halogen and fluorescent versions from the perspective of the end-user.

Objective

The objective of the project is to assess the incremental energy savings and demand reductions of using LED SDLs over incandescent and fluorescent PAR30 floodlight lamps. The project will verify claimed energy savings and demand reductions through lab assessments. Photometric tests conducted in the Southern California Lighting Technology Center (SCLTC) demonstrate the differences and similarities of the incandescent and LED SDL lamps. Fluorescent SDLs were not tested. If the LED SDL is comparable to the halogen counterpart, then it will be comparable to fluorescent lamps as well. Short term durability tests will assess potential immediate defects, failure mechanisms, and feasibility of manufacturer lifetime ratings. Long-term durability tests will require too much time, and are outside the scope of these tests.

BACKGROUND

LED technology, sometimes referred to as Solid State Lighting, differs from traditional light sources in the way light is produced. The historical light sources are incandescent and fluorescent. In an incandescent lamp, a tungsten filament is heated by electric current until it glows or emits light. In a fluorescent lamp, an electric arc excites mercury atoms, which in turn emits ultraviolet (UV) radiation. The UV radiation strikes the phosphor coating on the inside of glass tubes, and is converted to visible light.

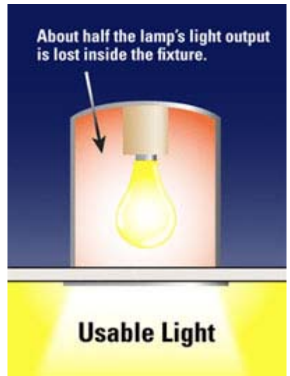
An LED, in contrast, is a semiconductor diode. The LED consists of a chip of semiconducting material treated to create a structure called a p-n (positive-negative) junction. When connected to a power source, current flows from the p-side or anode to the n-side, or cathode, but not in the reverse direction. Charge-carriers (electrons and electron holes) flow into the junction from electrodes. When an electron meets a hole, it falls into a lower energy level, and releases energy in the form of a photon (light).[1]

The specific color produced by LED lights depends on the materials used in manufacturing. LEDs are manufactured to produce many colors. There are a few popular ways to produce white light. One method is to combine red, green, and blue LEDs (referred to as RBG light), but this can be expensive. A less expensive method is to coat blue LED chip with yellow phosphor, but this can result in a low quality product. For a better quality product, blue LED chips can be coated with high quality phosphors, a method used by many high quality LED manufacturers.

Fluorescent light sources require a ballast to function, providing a starting voltage and then limiting electrical current to the lamp. LEDs also require additional electronics, called drivers. The driver converts line power to the appropriate voltage and current.

LED’s are directional in nature and have potentially higher application efficiency than other light sources in specific lighting applications. Because fluorescent and standard "bulb" shaped incandescent lamps emit light in all directions, much of the light produced by the lamp is lost within the fixture, reabsorbed by the lamp, or escapes from the fixture in a direction that is not useful for the intended application. For many fixture types it is not uncommon for 40-50% of the total light output of the lamp(s) to be wasted in a direction not intended for the purpose of the light. LEDs emit light in a specific direction and do not require reflectors or diffusers.

The directional nature of LEDs make them an ideal light source for SDL lamps.



Graphic from DOE, EERE

FIGURE 12: TRADITIONAL INCANDESCENT OR NEON LIGHT OUTPUT LOSS

APPLICATIONS

Screw in directional lighting is commonly used in general lighting, spotlighting, floodlighting, landscape lighting, architectural lighting, artwork lighting, and display lighting. With these different applications, lamps with different beam angles will be used. Figure 13 shows some of the common beam angles for SDL lamps.

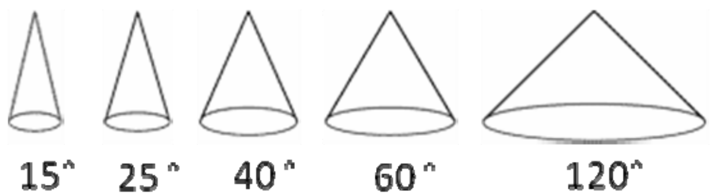


FIGURE 13: COMMON BEAM ANGLES FOR SDLS

Not all of the LED lamps can be used for outdoor applications. Indoor or outdoor use is indicated on the packaging.

MARKET SIZE AND BARRIERS

LED SDL lamps are readily available for purchase online; however they are difficult to find in stores. One big box home improvement store has them available online only; another large chain does not carry them online or in-store. LED SDL lamps were found from a variety of manufacturers for prices between $19.95 and $113.40.

CODES AND STANDARDS

The codes and standards impacting the use of SDL lamps vary with the use. Outdoor use is covered by one part of title 24, while high-lighting products in a store are covered under another. Below is a brief summary of the applicable codes and standards.

Title 24 section 5.13 addresses the codes and standards for high-efficacy luminaires. Some LED SDL products qualify as high-efficacy according to the criterion provided in Title 24 Table 5-10. The following high-efficacy text is excerpted from Title 24.[2]

5.13 High Efficacy Luminaires

High efficacy luminaires are defined by §150(k) for residential buildings. However, high efficacy luminaires that are installed in nonresidential buildings must also meet the definition of §150(k) for high efficacy. These luminaires must meet the following requirements:

- Ballasts for lamps rated 13 watts or greater shall be electronic and shall have an output frequency no less than 20 kHz.
- Luminaires shall not contain medium screw base sockets

EXCEPTION: Outdoor high intensity discharge (HID) luminaires with HID rated medium screw base sockets and factory-installed hardwired HID ballast which meet the minimum lumens per watt in Table 150-C. HID Ballasts for this application may be electromagnetic (magnetic).

- Luminaires must contain only lamps with the following minimum efficacies

Table 5-10 – Standards Table 150-C

Lamp Power Rating Minimum Lamp Efficacy	**Efficacy**
15 watts or less	40 lumens per watt
Over 15 watts to 40 watts	50 lumens per watt
Over 40 watts	60 lumens per watt

To determine minimum lamp efficacy category only the watts of the lamp (not the ballast) are to be considered.

The following text on outdoor lighting is excerpted from Title 24.[3] These codes and standards address lighting that is used for applications such as façade lighting.

6.1.3 Summary of Requirements

§119, §130, §132, §147 and §148

Mandatory Measures

The Standards require that outdoor lighting be automatically controlled so that it is turned off during daytime hours and during other times when it is not needed. The mandatory measures also require that most of these controls be certified by the manufacturer and listed in the Energy Commission directories. Luminaires with lamps larger than 175 watts must be classified as cutoff so that the majority of the light is directed toward the ground. Luminaires with lamps larger than 60 watts must also be high efficacy or controlled by a motion sensor. More detail on the mandatory measures is provided in Section 6.2.

Lighting Power

The 2005 Standards limit the lighting power for general site illumination and for specific outdoor lighting applications.

- General site illumination includes parking lots, driveways, walkways, building entrances, sales lots, and other paved areas of the site (see column one of Table 6-1). The Standards provide a separate allowance for each of these general site lighting applications, but tradeoffs are permitted among these applications. Essentially, one outdoor lighting budget can be calculated for all these general site applications together. Section 6.4 has more information on general site illumination.
- Specific outdoor lighting applications include building facades, canopies, ornamental lighting, and the front row of car lots (outdoor

sales frontage) [see column two of Table 6-1 for a complete list]). Trade-offs are not permitted for specific lighting applications. Each application must comply on its own. Section 6.5.3 has more information on specific lighting applications.

The allowable lighting power for both general site illumination and specific applications are based on four separate outdoor Lighting Zones. The Lighting Zones characterize ambient lighting in the surrounding areas. Sites with higher ambient lighting levels (Zones 3 or 4) have a larger allowance than sites with lower ambient lighting levels (Zones 1 or 2). Section 6.3 has more information on Lighting Zones.

6.6 Specific Lighting Applications

§147(a)
Table 147-B

The allowance for specific lighting applications are given in Standards Table 147-B. These include

- Building facades.
- Outdoor sales street frontage.
- Vehicle service stations with or without canopies.
- Vehicle service station hardscape.
- All other sales canopies.
- Non-sales canopies.
- Ornamental lighting.
- Drive up windows.
- Guarded facilities.
- Outdoor dining.

Each of these specific lighting applications shall comply with the standard on their own. Tradeoffs are not permitted between specific lighting applications or with general site illumination.

The allowed lighting power for specific lighting applications is the smaller of the product of the area of the each lighting application and the allowed lighting power density foot from Standards Table 147-B, or the actual power used to illuminate this area. Luminaires qualifying for these allowances shall not be used to determine allowed lighting power for general site illumination or any other specific application.

6.6.1 Building Facades

§147(c)2.A.

A building façade is the exterior surfaces of a building, not including horizontal roofing, signs, and surfaces not visible from any reasonable viewing location. Building facades and architectural features may be illuminated by flood lights, sconces or other lighting attached to the building. Building façade lighting is not permitted in Lighting Zone 1. Only the illuminated façade area may be counted when calculating the allowance for façade lighting. Façade orientations that are not illuminated and façade areas that are not illuminated because the lighting is obstructed shall not be included. General site illumination and/or lighting for other specific applications can be attached to the side of a building and not be considered façade lighting. However, every luminaire must be assigned to only one specific lighting application. Unshielded wallpacks mounted on sides of the buildings are not considered façade lighting, since most of the light exiting these fixtures lands on areas other than the building façade.

6.6.2 Sales Frontage

§147(c)2.B.

While outdoor sales areas in the category of general site illumination, the portion of the lot along the street may qualify for additional lighting power. This additional allowance is intended to accommodate the retailers need to highlight merchandise to motorists who drive by their lot. Outdoor sales frontage includes car lots, but can also include any sales activity. The allowed lighting power for outdoor sales frontage is the smaller of the product of the frontage (in feet) and the allowed lighting power density per foot from Standards Table 147-B, or the actual power used to illuminate the frontage. Sales frontage is immediately adjacent to the principal viewing location and unobstructed for its viewing length. A corner sales lot may include both sides provided that a different principal viewing location exists for each side. Measured in plan view, only sections of the outdoor sales area that are along the frontage and are within a 3 mounting heights of frontage luminaires are eligible for this power allowance. The area within three mounting heights may not be counted as part of the outdoor sales lot. Luminaires qualifying for this allowance must be located in plain view between the principal viewing location and the frontage outdoor sales area.

The following text addresses lighting for floor display, including very valuable display lighting, and is excerpted from Title 24.[4]

Allowed Floor Display Power

Some of the primary functions listed in Table 146-D in the Standards are allowed additional lighting power for floor displays. The allowance is determined by multiplying the power allowance in Standards Table 146-D (w/ft²) by the total area of the space. This is a use-it-or-lose-it allowance so the allowance is the lesser of the allowed power or the installed power.
The floor display allowance may be adjusted for luminaire mounting heights that are greater than 13 ft above the finished floor (see Table 146-E in the Standards).

Qualifying floor display lighting systems shall be mounted no closer than 6 ft to a wall and shall be a lighting system type such as track lighting, adjustable or fixed luminaires with PAR, R, MR, AR, or other projector lamp types or employing optics providing directional display light from non-directional lamps. Except for lighting for very valuable merchandise as defined below, lighting mounted inside of display cases shall also be considered floor display lighting.

Allowed Very Valuable Display Power (W/ft^2)

Some of the primary functions listed in Table 146-D in the Standards are allowed additional lighting power for the display of very valuable merchandise. Typical spaces are in museums, religious facilities and retail stores. The allowance is the smaller of the product of power allowance in Standards Table 146-D (w/ft²) and the area of the space, or multiplying the area of the display case by 20 w/ft². This is a use-it-or-lose-it allowance so the allowance is the lesser of the allowed power or the installed power.

Qualifying lighting includes internal display case lighting or external lighting employing highly directional luminaires specifically designed to illuminate the case without spill light. To qualify for this allowance, cases shall contain jewelry, coins, fine china or crystal, precious stones, silver, small art objects and artifacts, and/or valuable collections the selling of which involves customer inspection of very fine detail from outside of a locked case.

Mounting Height Adjustment
When a space requires that luminaires for wall or floor display lighting be mounted at a height of 13 ft or higher, additional lighting power is permitted. Table 146-E in the Standards lists mounting height adjustments for various mounting heights. The appropriate multiplier is applied to the power allowance for wall or floor display lighting shown in Standards Table 146-D. When there is more than one mounting height condition, they should be separated into different task areas for purposes of applying the mounting height adjustments. The boundaries of these separate areas should be clearly shown on the plans, and the mounting height in each should also be shown with a section diagram.

Determining Area of a Task
In order to determine the allowed lighting power, the task areas need to be identified. For illuminance categories A, B, C D, E, F, and G, the task areas are the areas of each task space that has a separate illuminance requirement. If the task area in bounded by walls or partitions, then the area of each task space is determined by measuring the dimensions from inside the bounding partitions.
The area is calculated by multiplying the width times the depth, as measured from the inside of the bounding partitions. The floor area occupied by the interior partitions is not included in the floor area of the function area. However, if the task area is not bounded by walls and partitions, then the actual area of the task may be used to determine the allowable power.
Determining Allowed Watts
After the LPD and task area assigned to each space or task is established, the allowed watts may be calculated. There are two cases:

- For illuminance categories A through D and for the gross sales floor area, the allowed watts are calculated simply by multiplying the LPD (w/ft^2) by the area of the space (ft^2).
- For illuminance categories E through I, gross sales wall areas and feature displays, the allowed watts are the lesser of: the LPD (w/ft^2) multiplied by the area of the task (ft^2) to obtain allotted watts, or the design watts of the luminaires assigned to the task.

The sum of the allowed watts for all spaces and tasks is the building allowed lighting power, in watts, as determined by the tailored method.

METHODOLOGY

Screw-in directional lighting is used for general lighting, spotlighting, floodlighting, landscape lighting, architectural lighting, artwork lighting, and display lighting. Table 2 below shows the seven performance characteristics of traditional MR16 lamps[5]. While SDLs are not generally used for the same applications as MR16 lighting, the performance characteristics are applicable to SDLs. In addition to the characteristics, the table shows the testing done to compare the LED SDL lamps to their halogen counterparts.

TABLE 2: MR16 PERFORMANCE CHARACTERISTICS AND APPLICABLE TESTS FOR SDL

PERFORMANCE CHARACTERISTIC	ANALYSIS RESULT	APPLICABLE TEST
Lamp Life	Quantitative	Burn-In Test
Correlated Color Temperature	Quantitative	Integrating Sphere
Color Rendering Index	Quantitative	Integrating Sphere
Lumen Maintenance	Quantitative	Integrating Sphere
Light Distribution	Qualitative	Photoshop Enhanced Images
Lumen Output	Quantitative	Integrating Sphere
Luminous Efficacy.	Quantitative	Integrating Sphere

All testing was conducted at Southern California Lighting Technology Center (SCLTC) in Irwindale, California. The lab allowed for a consistent environment to measure the performance of the signs. The ambient temperature was not consistent for the entire test period because the fixture was near the windows. The ambient temperature around the fixture averaged 76.6° Fahrenheit during the test period. The facility featured an internal, light-isolated dark room lined with black stage curtains. The test area was 10 feet deep, 5 feet wide and 8 feet high. This environment provided a near-black area to photograph the lamps while operating with negligible interference from external sources.

The measurements taken at the SCLTC laboratory verified the energy and demand reduction and compared other lighting characteristics of the halogen PAR30 and LED SDL lamps. Additionally, tests were conducted to qualify performance. The qualitative tests were designed to compare how the LED SDL lamps would perform as opposed to the halogen PAR30 lamps.

INDEPENDENT VARIABLES

LAMP TECHNOLOGY

A total of 22 LED SDL lamps from a variety of manufacturers were tested. A list of lamps tested can be found in the appendix. Test results for each lamp are not associated with the manufacturer; each lamp was assigned a number for reporting results.

DEPENDANT VARIABLES

LUMINOUS FLUX

Luminous flux data is obtained from the Integrating Sphere test, discussed in detail, below. The luminous flux data is used to make comparisons between the LED and halogen technologies, as well as to compare the state of different LED SDL products. The Integrating Sphere luminous flux data also allows for short-term degradation testing. Longer-term lumen persistence and lamp life will be tested with Burn-In testing with bi-weekly sampling. At the time of the test launch, industry accepted testing standards for lifetime have not been fully developed.

COLOR RENDERING INDEX

The color quality, measured as Color Rendering Index (CRI), affects visual perception of the color output from the lamp. A higher CRI can improve the perception of the light. In some cases, increased CRI may reduce needed luminous flux. CRI data was obtained from the Integrating Sphere test, discussed below.

CRI is an indication of how well a specific light source renders color compared to a reference light source of similar color temperature. The test scores the light source on a scale of 0-100.

The International Commission on Illumination (CIE) provides standards for measuring the appearance of eight standard color samples under a given light source and comparing it to the reference source. Figure 14 shows the color samples used in the test.

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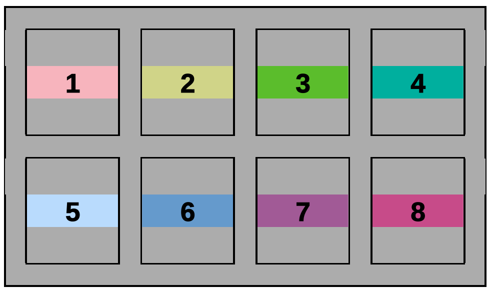

Eight standard color samples used in the test-color method for measuring and specifying the color rendering properties of light sources. Adapted from IESNA Handbook.

Reprinted courtesy of the Illuminating Engineering Society of North America.

FIGURE 14: CIE STANDARD COLOR SAMPLES FOR CRI TEST

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 refers to the color a theoretical black body heated to high temperatures would appear. The CCT of a light source is the temperature (in Kelvin) at which the heated black body matches the color of the light source in question. The "hotter" (higher Kelvin) the more blue in appearance, the "cooler" (lower Kelvin) the more red in appearance.[6] CCT data is obtained from the Integrating Sphere test, discussed below, and was compared to manufacturer CCT ratings.

Consumers usually refer to light with a yellow hue as "warm" and light with a blue hue as "cool," therefore manufacturer's classifications of lamps as "cool white" and "warm white" do not directly refer to the CCT, but rather the appearance of the light.

Connected Load

The power is measured with the Power Quality Logger and recorded during performance testing. Power data is used for both direct comparisons between the technologies (LED consumption versus halogen consumption), and efficacy comparisons (LED efficacy versus halogen efficacy).

Efficacy

The lamp power data is combined with the lamp lumens to provide an efficacy value of lumens per watt, a common unit for comparison across products. It is well known that LED wattage is significantly lower than halogen sources. However, lower wattage is only of value if the luminosity requirements are still met. Therefore, the lumen/watt value allows an "apples to apples" comparison across the two product types.

Light Distribution

In addition to the quantitative data collected, qualitative light distribution data was collected for each SDL tested. Light distribution data includes intensity distribution and chromaticity differences within the beam. These qualitative tests give insight into the beam angle and uniformity of light within the beam.

Equipment

Luminous flux, CRI, and CCT Measurements

Integrating Sphere

The integrating sphere measures the total light output of a lamp. The lamp being tested is placed in the center of the integrating sphere. At one side of the sphere is a light meter which measures the light output of the lamp. A baffle is directly between the lamp and the light meter to prevent the meter from seeing any direct light from the lamp.

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

FIGURE 15. INTEGRATING SPHERE

DEMAND DATA

POWER QUALITY LOGGER (PQL)

Demand values for each SDL lamp were measured using an Aemc Instruments PQL 120 power meter with integrated logging capability. Values were recorded using the internal memory for later transfer to a computer for analysis. Figure 16 shows the PQL 120.

FIGURE 16. POWER QUALITY LOGGER

BURN-IN DATA

TRACK FIXTURE

All LED SDL lamps were installed on the SDL track fixture for the Burn-In test. The lamps are turned on 24 hours a day, 7 days a week, and are sampled about every 2 weeks. During this approximate bi-weekly sampling, the lamps are tested in the Integrating Sphere to obtain lumen, CCT, and CRI data. During the burn-in test, lamps that cease working are recorded. A total of four (4) HOBO temperature loggers were used. Three (3) were used to record the ambient temperature around the fixture. One was used to measure the ambient temperature of the lab away from the fixture during the tests.

LIGHT DISTRIBUTION DATA

DIGITAL CAMERA

Photos of each product were taken using a tripod-mounted Nikon Coolpix 5400 camera. Images were recorded using the camera's memory card to allow for later transfer to a computer for analysis. Figure 17 shows the camera.

FIGURE 17: DIGITAL CAMERA

This measurement technique utilized the camera's image sensor as an array of light sensors. Similar images taken at different apertures and shutter speeds were combined and processed using Adobe Photoshop software to reveal and highlight inconsistencies in light distribution as well as patterns and shadows caused by the optics.

PHOTOSHOP

The Photoshop software produces a single image from one or more photos (with different exposures). This image is then saturated to enhance color and intensity inconsistencies for easier comparison. Figure 18 shows both an unsaturated and saturated image from the test.

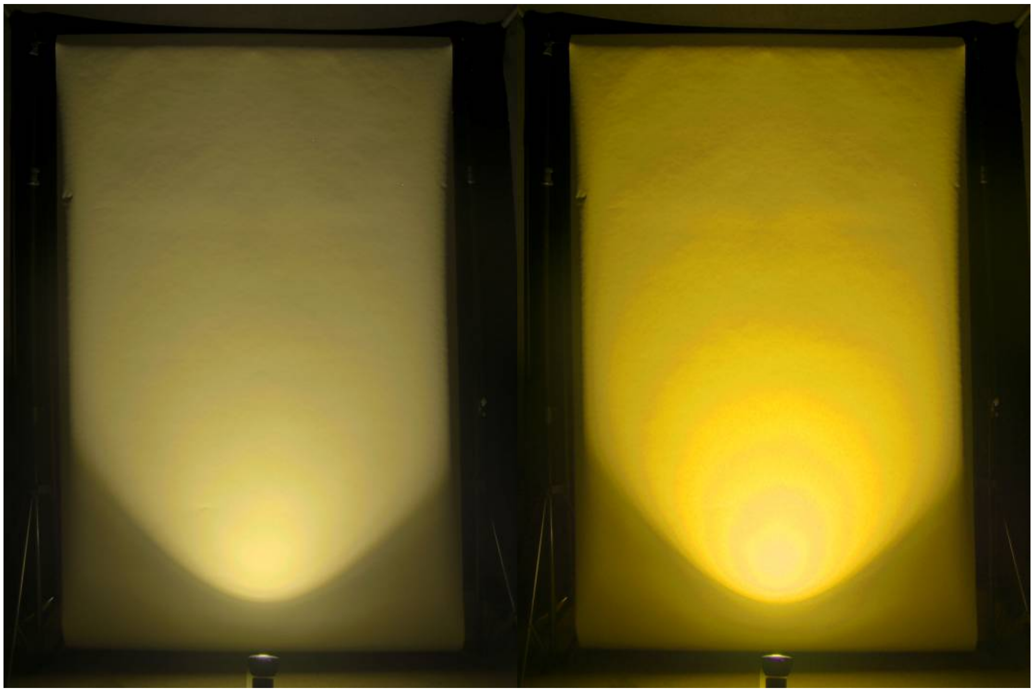

FIGURE 18: PHOTOSHOP ENHANCED IMAGE (ITEM 12)

For this test a series of fourteen photos were taken and processed to produce the single image on the left. This image was then saturated with color, to produce the image on the right, to highlight any inconsistencies in the light distribution. The aperture and shutter speed for each photo are shown in Table 3.

TABLE 3: CAMERA EXPOSURE SETTINGS

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

DETAILED PROCEDURES

Each of the LED SDL lamps was measured using the same basic routine. For the Sphere test the SDL was installed in the Integrating Sphere and a series of 10 measurements were taken at various intervals. Table 4 below shows the measurement intervals.

TABLE 4: MEASUREMENT INTERVALS FOR SDL SPHERE TESTS

MEASUREMENT	TIME FROM START
1	.5 min.
2	1 min.
3	1.5 min.
4	2 min.
5	2.5 min.
6	5 min.
7	10 min.
8	15 min
9	20 min
10	25 min

Power measurements for these tests were taken from the PQL.

After the Sphere test, the lamps were stored for approximately 2 weeks before the Light Distribution testing began. The SDL was set up against a white backdrop and aimed at a near 45° angle. This setup enabled a qualitative analysis of the light distribution of each lamp. The tri-pod mounted camera was positioned to capture the entire spill from the light source. While the camera was positioned, the lamps were on for approximately 1 minute before the testing began. Then, the fourteen photos at various apertures and shutter speeds were taken for later processing.

The lamps were then installed on a track fixture to begin the Burn-In testing. At 2 week intervals, the lamps were taken from the track fixture and placed in the Integrating Sphere. This Integrating Sphere data is used for longer-term performance and lifetime feasibility testing.

RESULTS

OVERVIEW

Data was downloaded from equipment memory and imported into appropriate software for processing and analyzing luminous flux, demand, and performance characteristics.

The results are reported by the three tests that were performed: Integrating Sphere, Burn-In, and Light Distribution tests.

INTEGRATING SPHERE

LAMP LUMENS

A total of twenty-two LED SDL lamps of varying luminosity were tested in the Integrating Sphere to examine their performance over the first 25 minutes of operation. For comparison purposes, three halogen Par30 lamps were also tested.

The lumens for each lamp were recorded at the intervals reported in Table 4. This allowed for comparison of not only luminosity, but lumen depreciation and efficacy changes over the first 25 minutes of use.

After the Integrating Sphere test, the LED lamps were tested at approximately biweekly intervals for the Burn-In test. The Burn-In test examines lumen depreciation and efficacy over a longer period of time. The initial results of this long-term testing are discussed in detail in the Burn-In Test section, below.

LUMENS RESULTS

The lumen results of the Sphere test are reported in Figure 19 for all LED SDL products. The tested products had a wide range of initial lumens (lm) recorded at 30 seconds of operation. Initial lumens ranged from a minimum of 107 lm to 850 lm.

One feature that was tested for the LED SDL products was the drop in lumens over time. The Sphere test intervals allowed for comparison of lumen measurements across the first 25 minutes of operation. Figure 19 also shows the drop in lumens over the course of the Sphere test, as seen in the difference between the first interval (at 30 seconds) and the last interval (at 25 minutes) for all tested products.

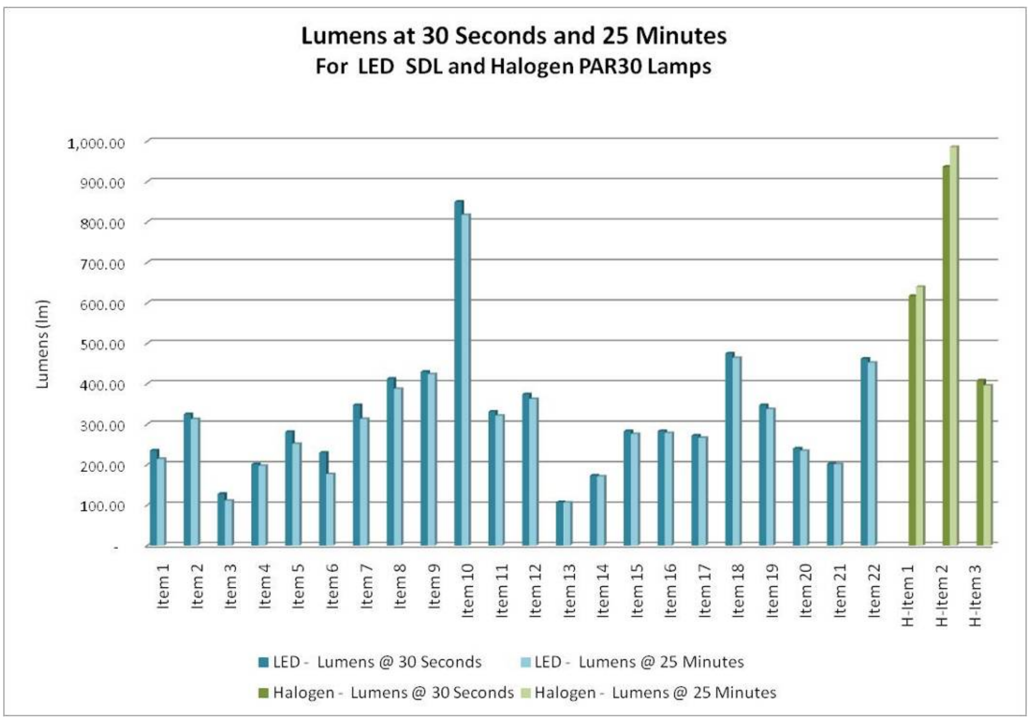

FIGURE 19: AVERAGE LUMENS AT 30 SECONDS AND 25 MINUTES FOR LED AND HALOGEN PAR30 LAMPS

All LED products did experience at least some reduction from initial lumens during the first 25 minutes of operation. The smallest drop in lumens was 1 lm, for Items 13 and 21, and the greatest drop was 53 lm for Item 6. Two out of the three halogen Par30 lamps increased in luminosity as they warmed up over the first 25 minutes of operation.

Figure 20, below, reports the drop in lumens over the course of the Sphere test as a percentage of the initial lumens.

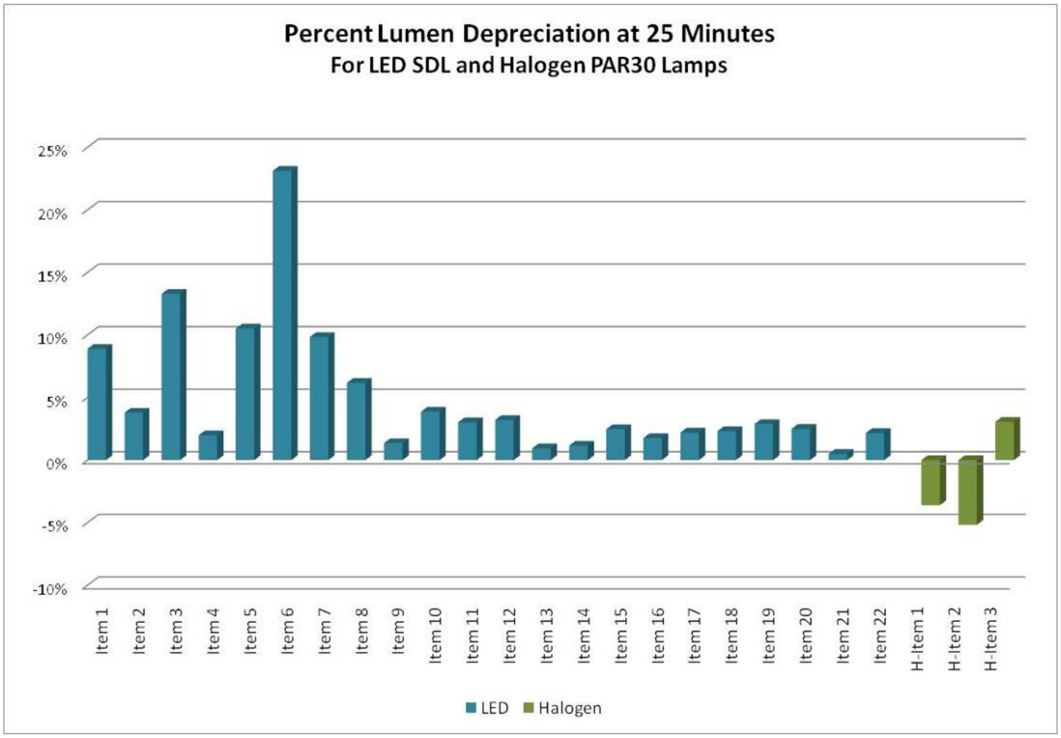

FIGURE 20: PERCENTAGE DROP IN LUMENS AT 25 MINUTES

The percentage drop in lumens during the Sphere test for the LED SDL lamps ranged from a low of 1% for Items 9, 13, and 14, to a high of 23% for Item 6. Two halogen Par30 lamps had a negative percentage change due to their increase in lumens over the 25 minute test period. The remaining halogen product, Halogen Item 3, had 3% lumen depreciation over the 25 minute Sphere test.

Some manufacturers account for this initial drop in lumens with a lower lumen rating. To determine if this was the true for the tested LED SDL products Figure 21 compares lumens at 25 minutes to the manufacturer rated lumens.

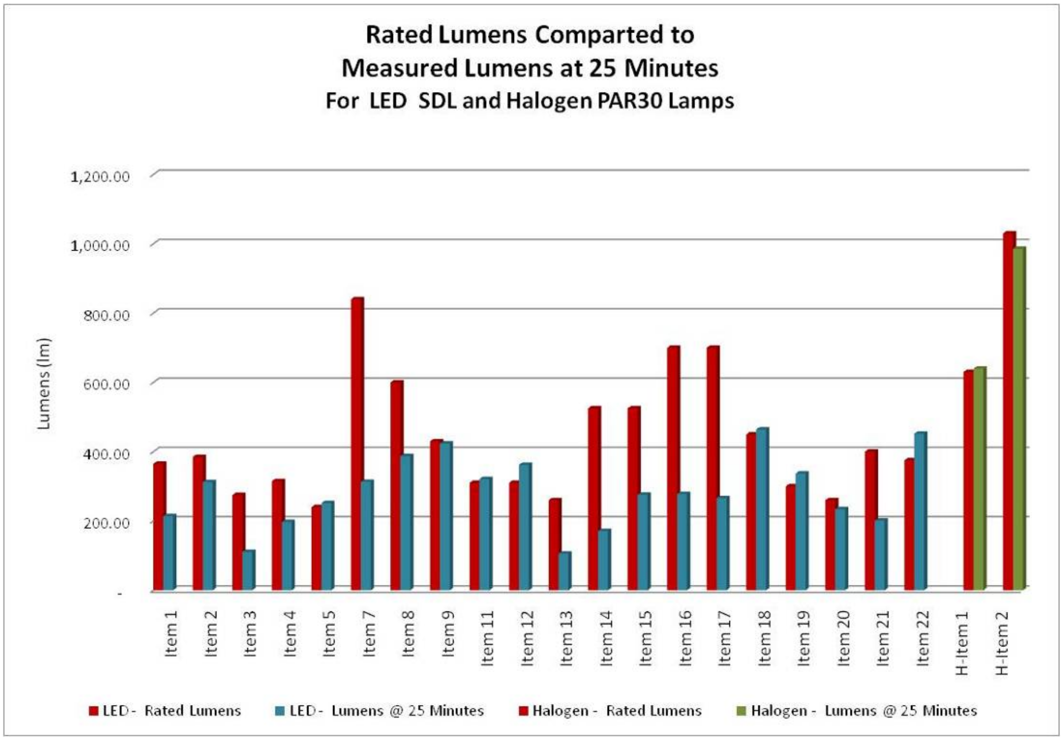

FIGURE 21: MANUFACTURER RATED LUMENS COMPARED TO MEASURED LUMENS, LED PAR30

Of the twenty LED products that included manufacturer rated lumens, six items (30%) had rated lumens lower than the lumens measured at 25 minutes (LED Items 5, 11, 12, 18, 19, and 22). However, of these, five were within 50 lumens of the actual lumen measurement. One, Item 22, had a lumen measurement 77 lumens above the rated lumens. As with all the LED items, the lumens for these six items dropped during the 25 minute test, and may continue depreciating over time until the lumens match the manufacture rated lumens. The Burn-In test will reveal if the lumens eventually stabilize at the manufacture rated lumens or if they continue to depreciate. The remaining fourteen items, (70%) had rated lumens higher than the measured lumens at 25 minutes. Two of these items (Item 9 and Item 20) had measurements that were considered comparable to the rated lumens, as they were within 30 lm of the rating. Twelve items (Items 1-4, 7-8, 13-17, and 21) had rated lumens that were significantly higher than the measured lumens at 25 minutes. The Burn-In test will again reveal if the depreciating trend has stabilized at 25 minutes.

The lumens measured for each product at 25 minutes run time are displayed in Figure 22. The items are grouped by technology (LED versus halogen) and then sorted from lowest to highest lumens for easy comparison between the technologies.

As shown, there is a wide range of LED SDL products available. The data show that in terms of lumen output, some individual LED SDL products out-perform, or are comparable to, halogen Par30 products.

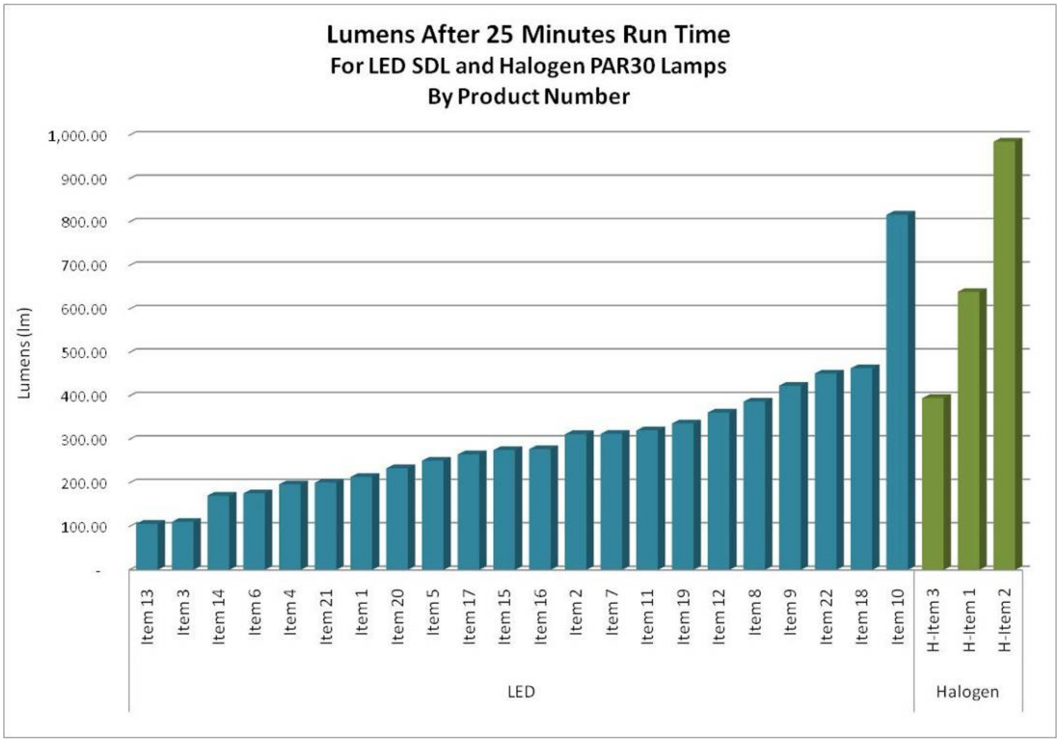

FIGURE 22: LED SDLS AND HALOGEN PAR30S LUMENS COMPARISON AFTER 25 MINUTES BURN TIME

Most LED products tested did not have the same luminosity as the halogen products after 25 minutes of run time. However, there are a number of LED products that are comparable to or better than halogen Items 1 and 3. LED Items 12, 8, 9, 22, and 18 can adequately replace halogen Item 3 in terms of luminosity at 25 minutes. With luminosity that exceeds that of the halogen, LED Item 10 can more than adequately replace halogen Item 1.

The halogen products tested were between 50W and75W lamps. Thus, many of the LED SDL products tested may be suitable replacements for lower wattage halogen lamps.

Additional performance testing results are discussed in the Burn-In Test section, below.

POWER MEASUREMENTS

One of the main advantages of the LED SDL products over the halogen PAR30 products is their lower rated energy use. Demand measurements were taken during the Integrating Sphere test to compare actual wattage consumption of the LED and halogen lamps.

POWER RESULTS

Figure 23 shows the rated and measured power (in Watts) for the LED SDL; Figure 24 shows the same data for the halogen PAR30 products. In general, the measured power is consistent with the manufacturer rated power for both LED and halogen products. LED Item 10 is an exception, with rated power significantly *higher* than the measured power.

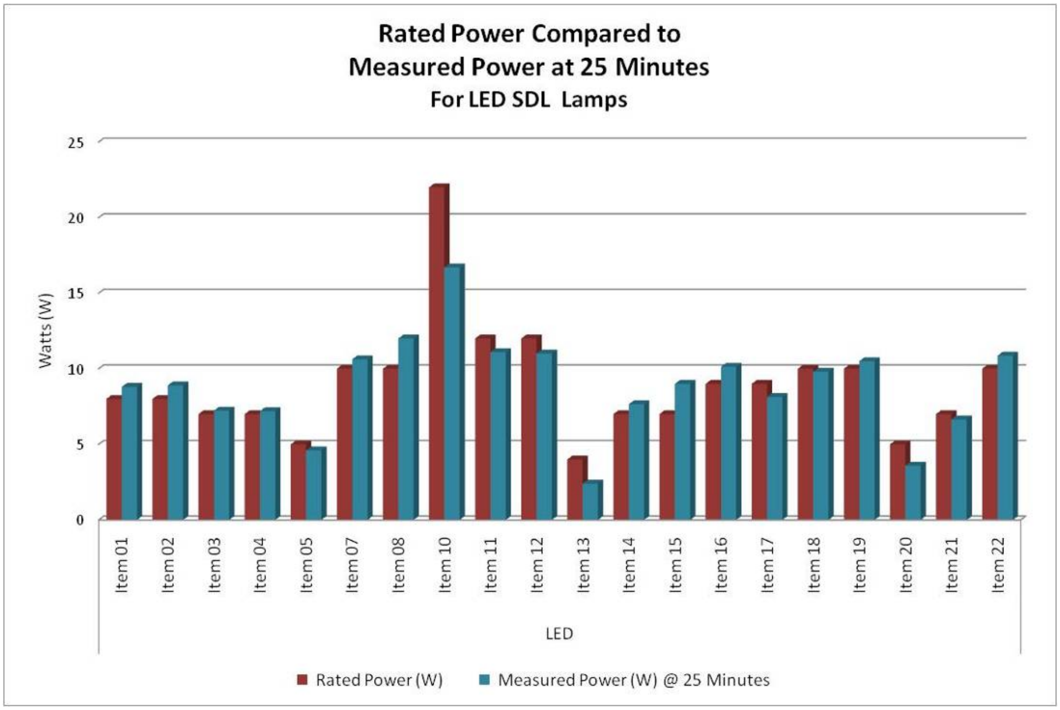

FIGURE 23: RATED VS. MEASURED POWER FOR LED SDLS

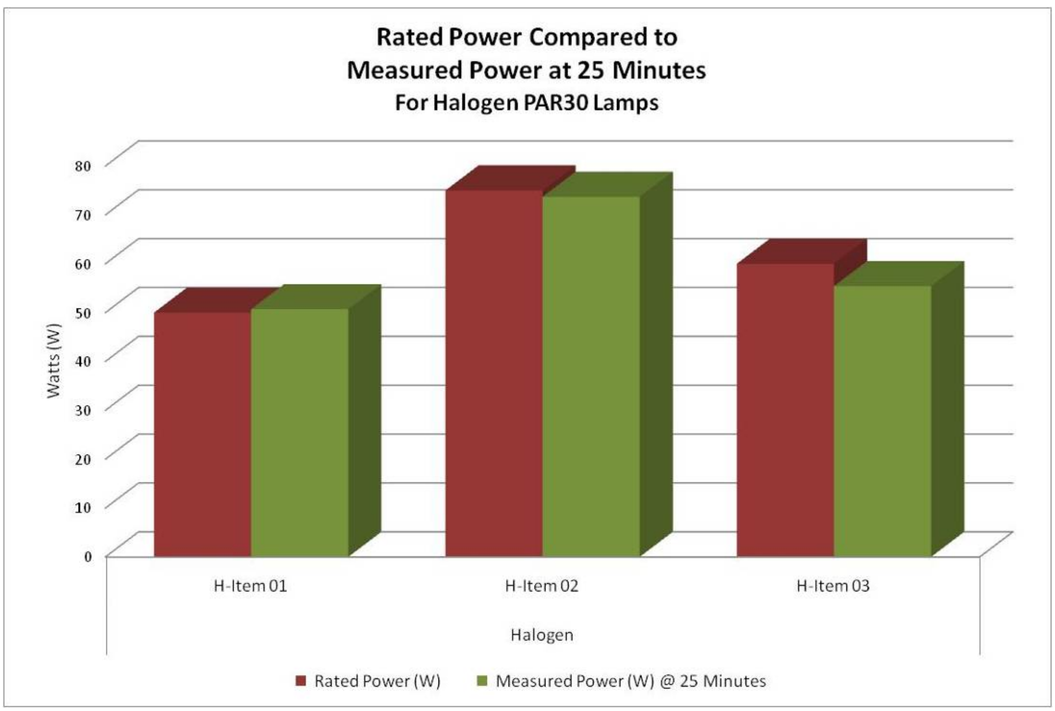

FIGURE 24: RATED VS. MEASURED POWER FOR HALOGEN PAR30S

The following chart compares the measured wattage of the LED SDL and halogen PAR30 lamps.

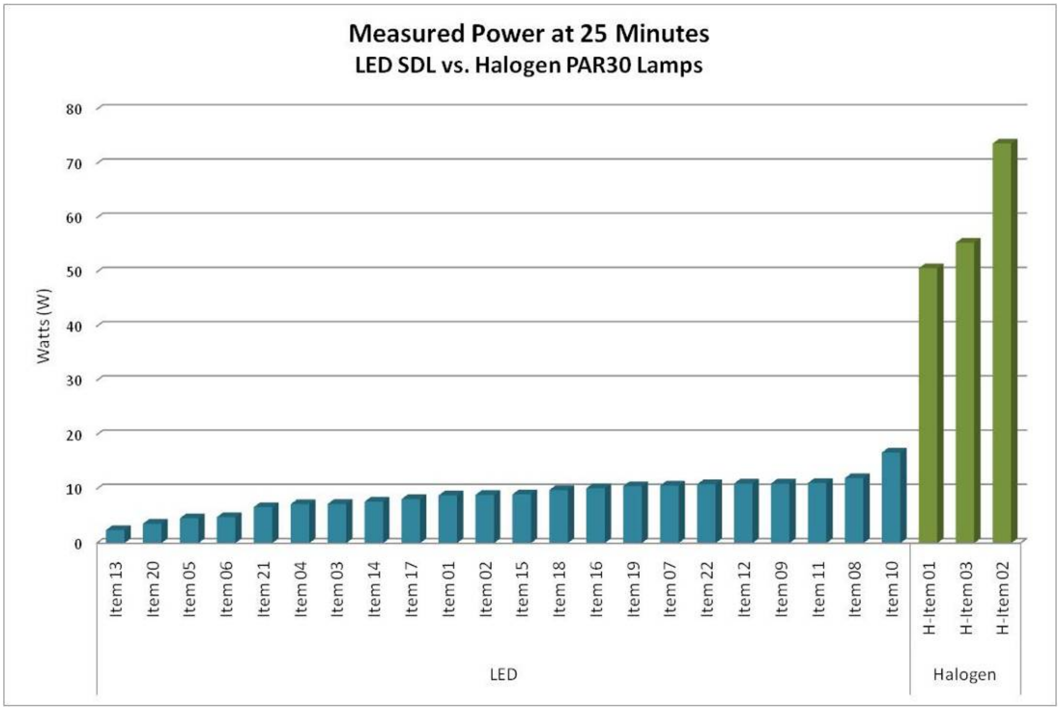

FIGURE 25: MEASURED POWER FOR LED SDL AND HALOGEN PAR30

Without exception, the LED products consume considerably less energy than the halogen products. The *maximum* energy consumption for the LED SDLs is just fewer than 17 watts, while the *minimum* energy consumption for the halogen PAR30s is just over 50 watts, a significant difference. On average, the tested LED products consume 8.8 watts. The three halogen products consume, on average, 60.0 watts, a nearly 7 fold increase in energy consumption.

EFFICACY

One of the objectives of the LED SDL tests was to determine if replacing halogen PAR30 lamps with LED SDL lamps would result in energy savings without compromising light quality. The efficacy comparison provides information that helps to answer this question.

Efficacy is defined as the lumen output per watt of power, and provides a common unit for comparison between products. The power data was measured and recorded during the Sphere test. The power data was then combined with the Sphere lumen data at 25 minutes to determine if the lower energy consumption of the LED products translated to an overall more efficacious lamp.

EFFICACY RESULTS

Figure 26 shows the average efficacy values, reported in lumens/Watt (lm/W), for the LED and halogen lamps.

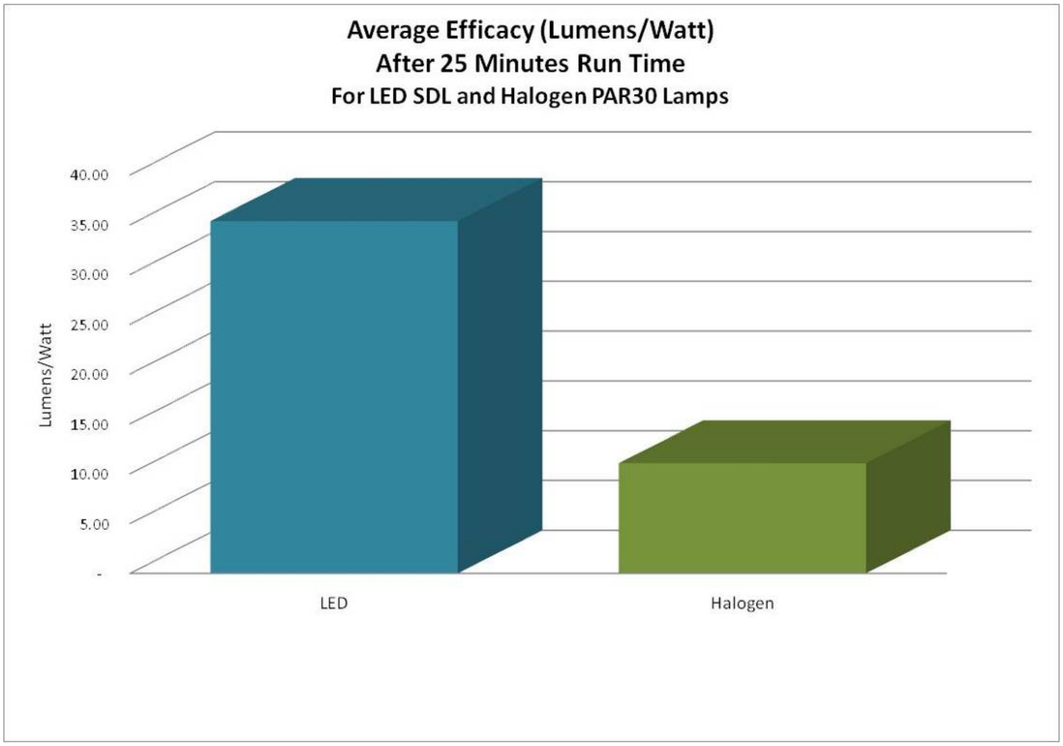

FIGURE 26: AVERAGE EFFICACY AFTER 25 MINUTES RUN TIME

The LED lamps were, on average, significantly more efficacious than the halogen lamps. The average LED SDL produced just over 35 lumens per watt, while the average halogen produced just 11 lumens per watt.

The products were also examined individually. Figure 27 shows the efficacy of the individual SDL and PAR30 lamps. Because of the number of lamps tested, they have been arranged in increasing order of efficacy to aid comparison. It is clear that all LED SDL lamps tested were more efficacious than the Halogen lamps after 25 minutes of run time.

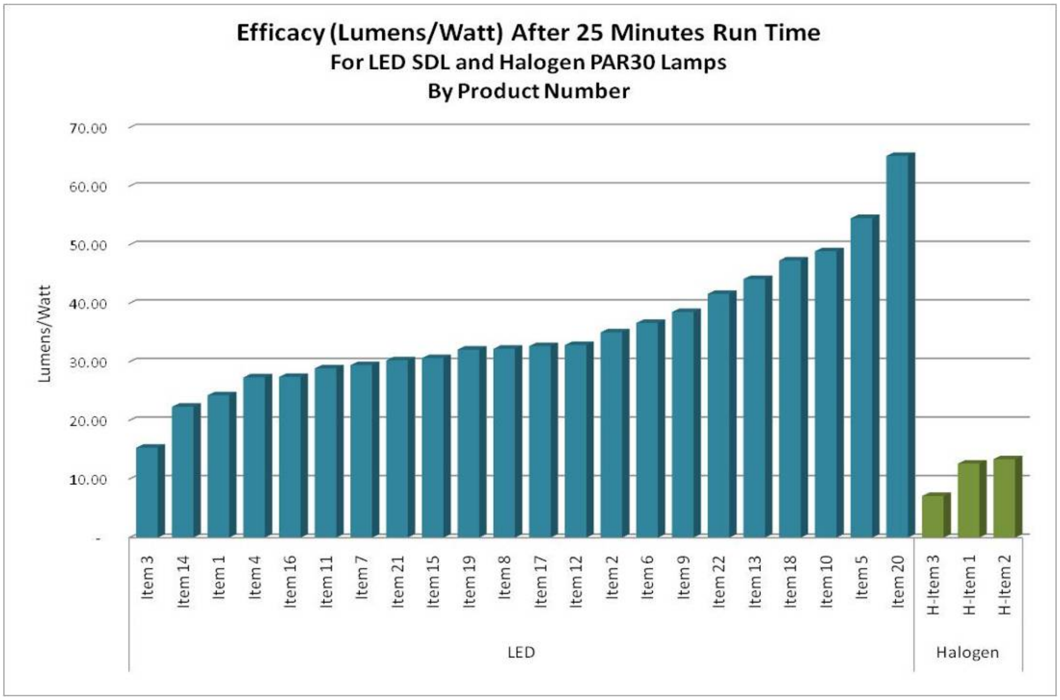

FIGURE 27: INDIVIDUAL LAMP EFFICACY AFTER 25 MINUTES BURN TIME

The lamps were examined by the manufacturer's designation of cool (blue) and warm (yellow) color categories to determine if one category was more efficacious than the other. Figure 28 displays this comparison.

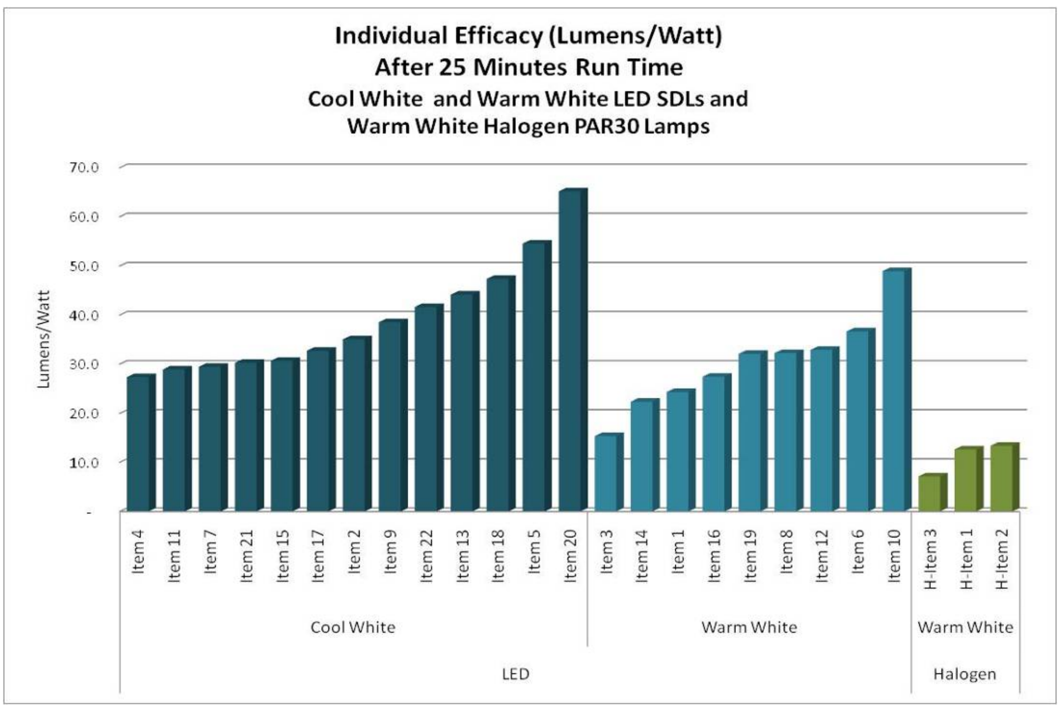

FIGURE 28: COMPARING EFFICACY OF COOL AND WARM WHITE SDL AND PAR30 PRODUCTS

In general, the Cool White (blue, higher CCT) LED SDLs were more efficacious than the Warm White (yellow, lower CCT) LEDs, though there was overlap between the two categories. On average, the Cool White LEDs had an efficacy value of 39 lm/W, the Warm White LEDs had a value of 30 lm/W, and the Warm White halogens had a value of just 11 lm/W.

CORRELATED COLOR TEMPERATURE

There is no "correct" CCT for lighting use. Depending on the purpose of the lighting, some applications may benefit from a higher CCT while others will benefit from a lower CCT.

Results are displayed be color categories (cool versus warm). Cool white, sometimes referred to as "natural" or "daylight" white, is expected to be on the more blue end of the Kelvin scale, while the warm white is expected to be on the more yellow end of the spectrum.

CORRELATED COLOR TEMPERATURE RESULTS

The following chart displays the rated CCT to the measured CCT at 25 minutes. On average, the rated CCT is consistent with the measured CCT.

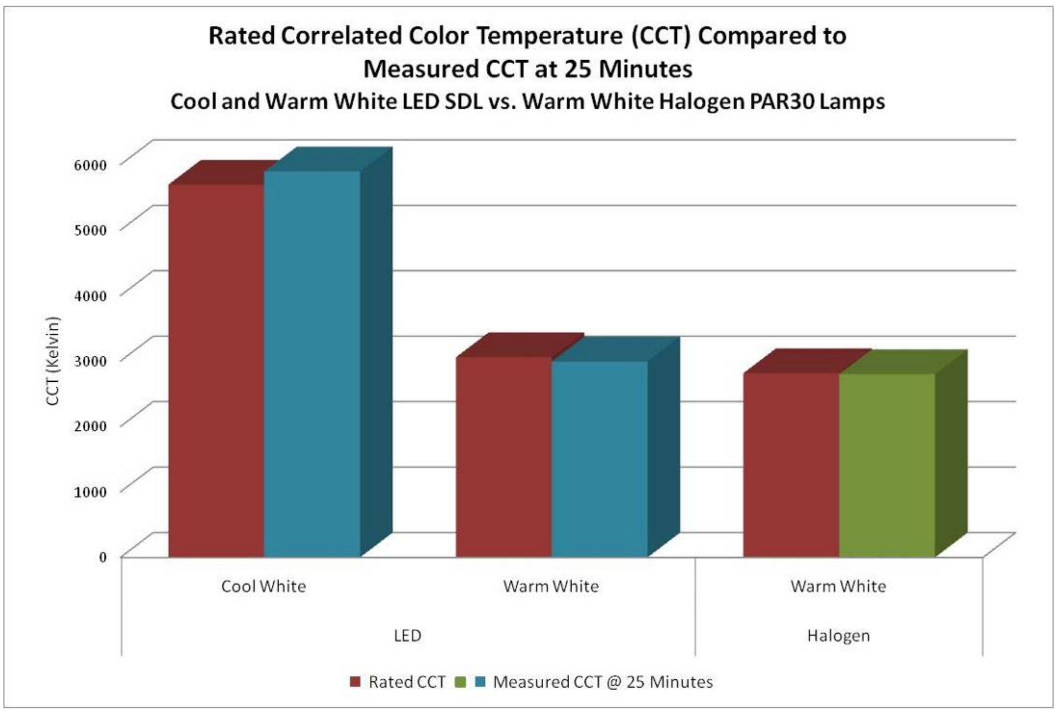

FIGURE 29: AVERAGE RATED VS. MEASURED CCT

Examination of the individual LED and halogen products showed the same results; the manufacturer CCT rating was consistently in accordance with the measured CCT at 25 minutes.

On average the Cool White LED products shown in Figure 29 have a much higher CCT than the Warm White LED and halogen products, resulting in a light source that is bluer, or "cooler", than the yellow "warm" lamps.

The measured CCT of the individual LED and halogen lamps is compared in Figure 30, to assess the range of CCT availability.

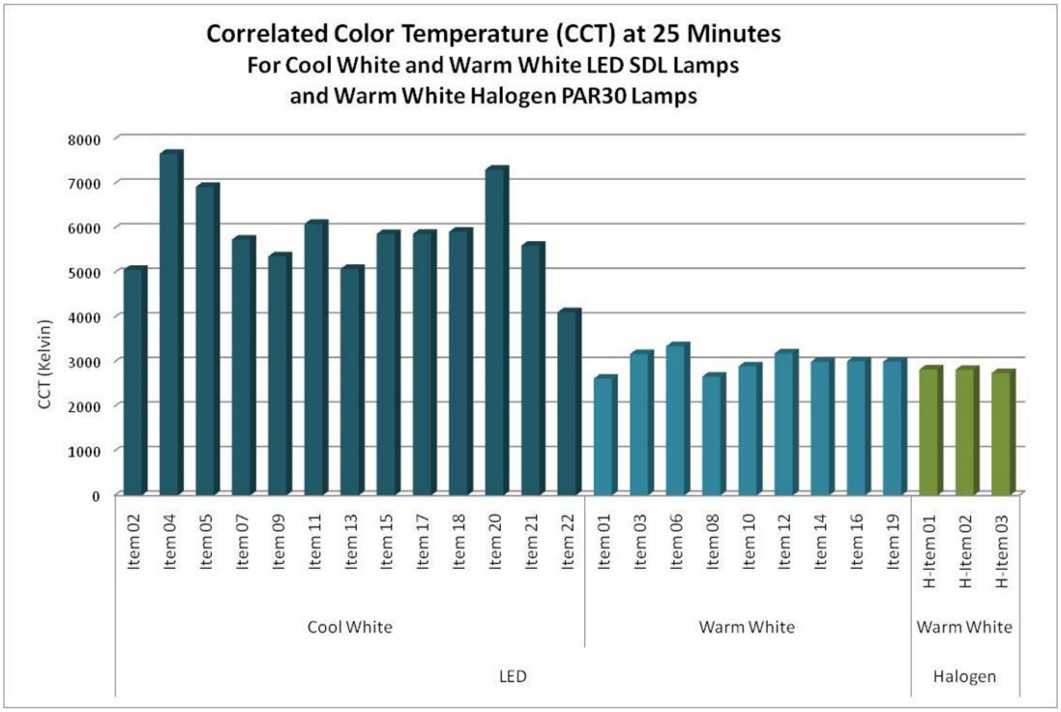

FIGURE 30: MEASURED CCT OF LED SDLS AND HALOGEN PAR30S

As seen with the averaged data, the individual Cool White LED SDL products have a higher CCT than both the Warm White LED SDL and the Warm White halogen PAR30 products. The Cool White LEDs range between 4100K and 7700K, which falls in the cool white (blue) end of the CCT scale. The Warm White LED SDLs range between 2600K and about 3400K, falling in the warm white (yellow) end of the CCT scale. The halogens are also a Warm White and all measured approximately 2800K on the CCT scale.

COLOR RENDERING INDEX RESULTS

The CRI was measured for each product at 30 seconds and then again at 25 minutes during the Integrating Sphere Test. Most products did not have manufacturer ratings for CRI, therefore no comparison could be made between rated and measured CRI. Figure 31 shows the initial CRI compared to the CRI at 25 minutes.

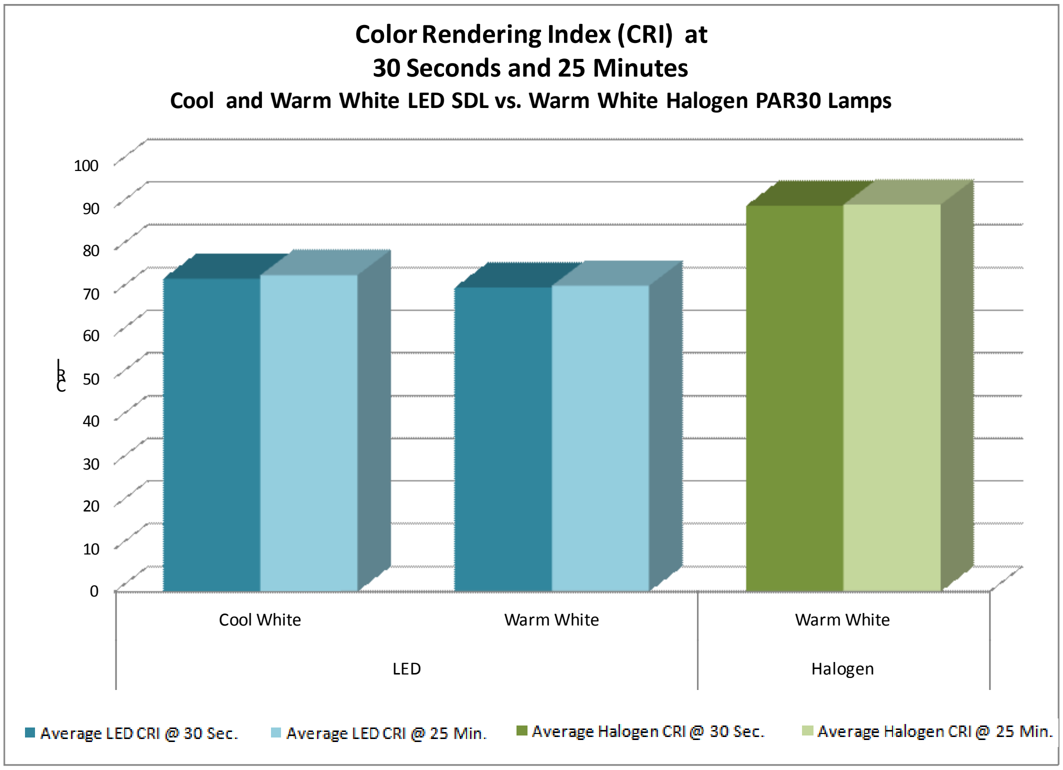

FIGURE 31: AVERAGE INITIAL AND 25 MINUTE CRI FOR LED AND HALOGEN SDLS

On average, all the products maintain their CRI over the first 25 minutes of operation. In comparing the Warm White LED and halogen products, the halogen PAR30s tend to have a higher CRI.

Examination of the individual products showed the same trends. However, some of the individual LED products had CRIs of approximately 85 to 87, which approached the CRI of the halogen PAR30 products.

Figure 32 compares the measured CRI at 25 minutes for individual LED and halogen lamps, assessing the range of CRI availability. It is apparent that the cooler white LED lamps have a less variable CRI, while the warm white lamps have a greater range.

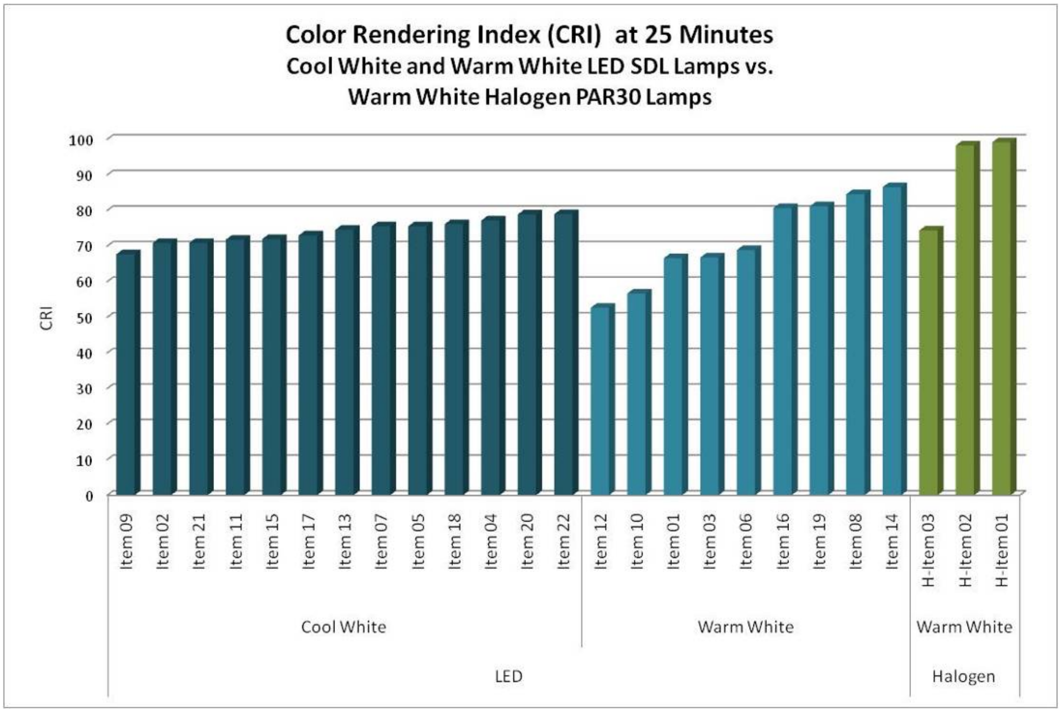

FIGURE 32: INDIVIDUAL CRI

BURN-IN TEST

PROCESSING

The LED SDL products that were tested have rated lifetimes of between 20,000 hours and 100,000 hours. At the time of the test initiation, industry accepted testing standards for lifetime testing have not been fully developed. Actual lifetime performance testing, which would take between 2.3 and 11.4 years to complete, is not being conducted for this report. However, a short-term Burn-In test is being performed to determine lumen persistence and to record overall performance within the first couple of months. At the end of the testing period, this data can help determine the feasibility of the rated lifetime hours.

All lamps were installed on a track fixture for the Burn-In test. The lamps are turned on 24 hours a day, 7 days a week, and are sampled approximately every 2 weeks. During this bi-weekly sampling, the lamps are tested in the Integrating Sphere to obtain lumen, power, CCT, and CRI data. During the burn-in test, lamps that cease working are recorded. Data is collected and downloaded to Excel for processing.

The Burn-In data is used to measure any additional drop in lumens after the initial Integrating Sphere test, and to calculate updated efficacy values.

ANALYSIS

LUMENS

On average, the LED SDL lamps continued to drop in lumens over the Burn-In testing. By week 2, the average lamp had a drop of 16 lumens and by week 4, the drop increased to 38 lumens. The average drop in lumens is shown in Figure 33.

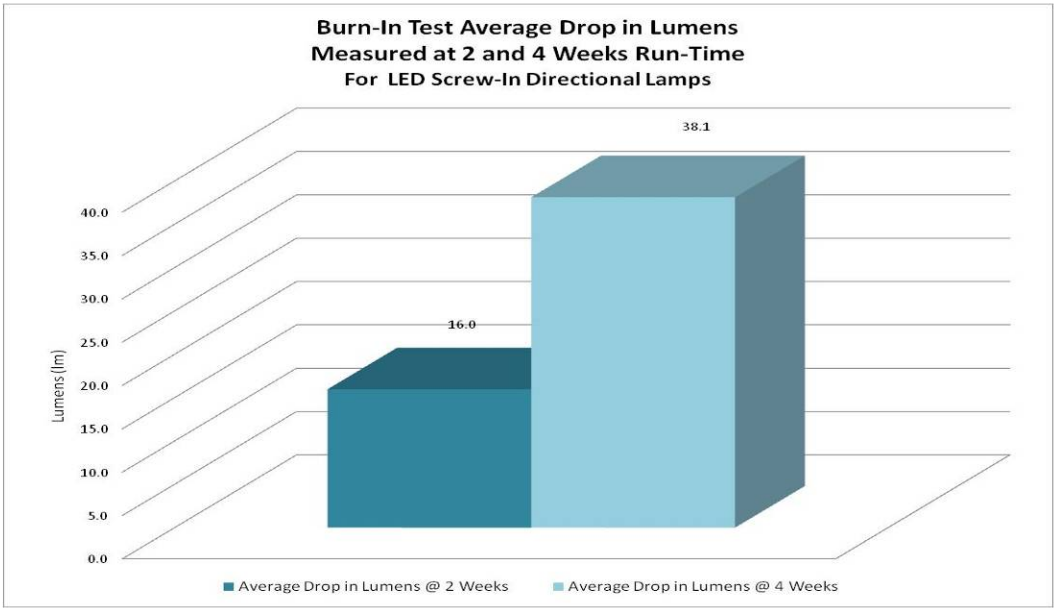

FIGURE 33: AVERAGE LUMEN DEPRECIATION AFTER 2 AND 4 WEEKS RUN TIME

The following figure examines the change in lumens for the individual LED SDLs. Interestingly, not all the LED products experienced a continued drop in lumens after the Sphere test. It is apparent that a few lamps did have a significant drop, many had a minimal drop, and others appear to have stabilized. Some products, however, experienced a small spike in lumens during week 2 of testing (e.g. Item 12).

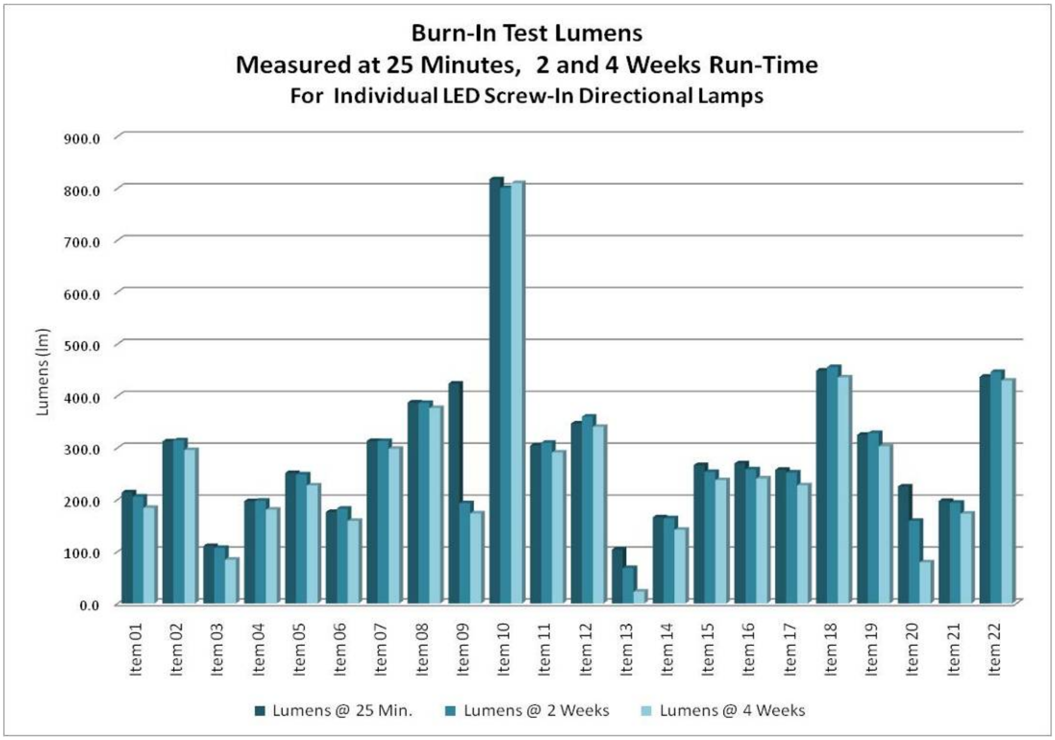

FIGURE 34: BURN-IN TEST LUMENS FOR INDIVIDUAL LED SDLS

Because all lamps experienced a drop in lumens during the Sphere test, it is surprising that some lamps experienced an increase in lumens at the 2 week Burn-In test, followed by a decrease at the 4 week test. This strange fluctuation in lumens may be due to an unexpected change in indoor temperature. A decrease in temperature can result in an increase in lumen output. Additional bi-weekly testing during the remainder of the Burn-In test will better determine the lumen trend in these lamps.

Figure 35 reports the 4 week lumen depreciation as a percentage of luminosity measured at 25 minutes burn time.

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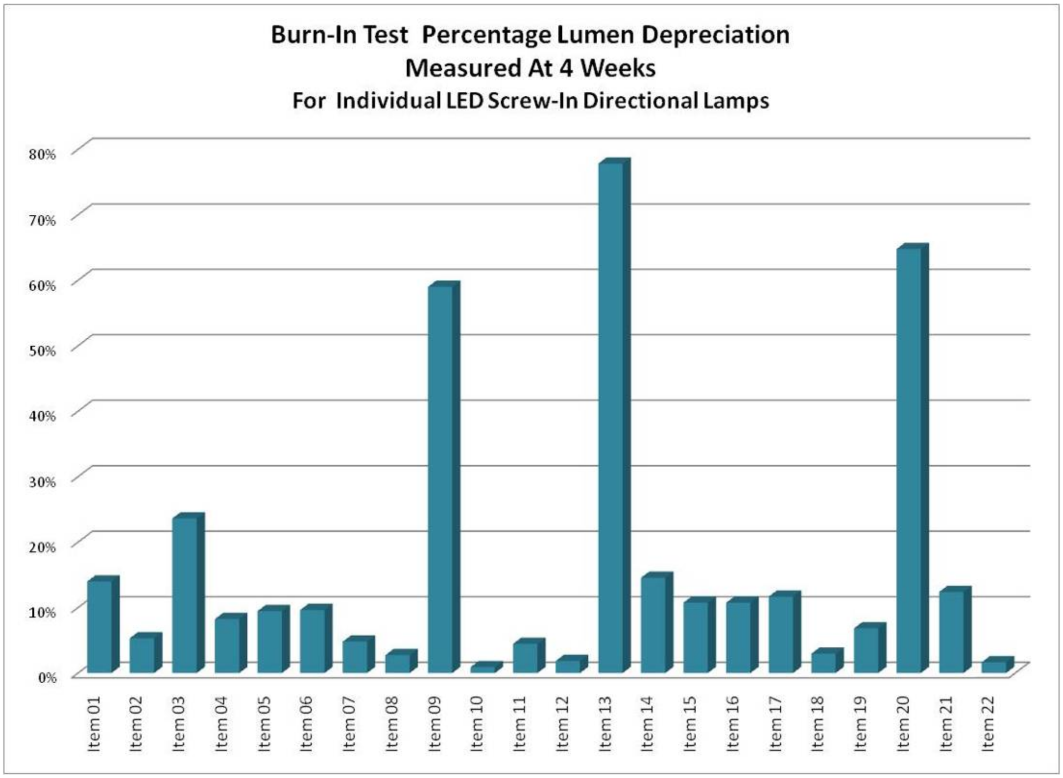

FIGURE 35: BURN-IN TEST LED SDLS PERCENTAGE LUMEN DROP

The majority of the lamps experienced less than a 15% reduction, with most less than 10%. Four lamps experienced greater than 20% reduction in lumens, with the highest three experiencing 59%, 65% and 78% reduction (Item 09, Item 20, and Item 13, respectively). Industry standard for "end of life" of an LED is when it has reached a 30% reduction in light output and is emitting 70% of its initial light output. By this definition, those three lamps have reached their end of life.

LAMP EFFICACY

The biweekly luminosity values were combined with the bi-weekly energy consumption to determine average lamp efficacy. Figure 36 examines the average efficacy values at 25 minutes, 2 weeks, and 4 weeks.

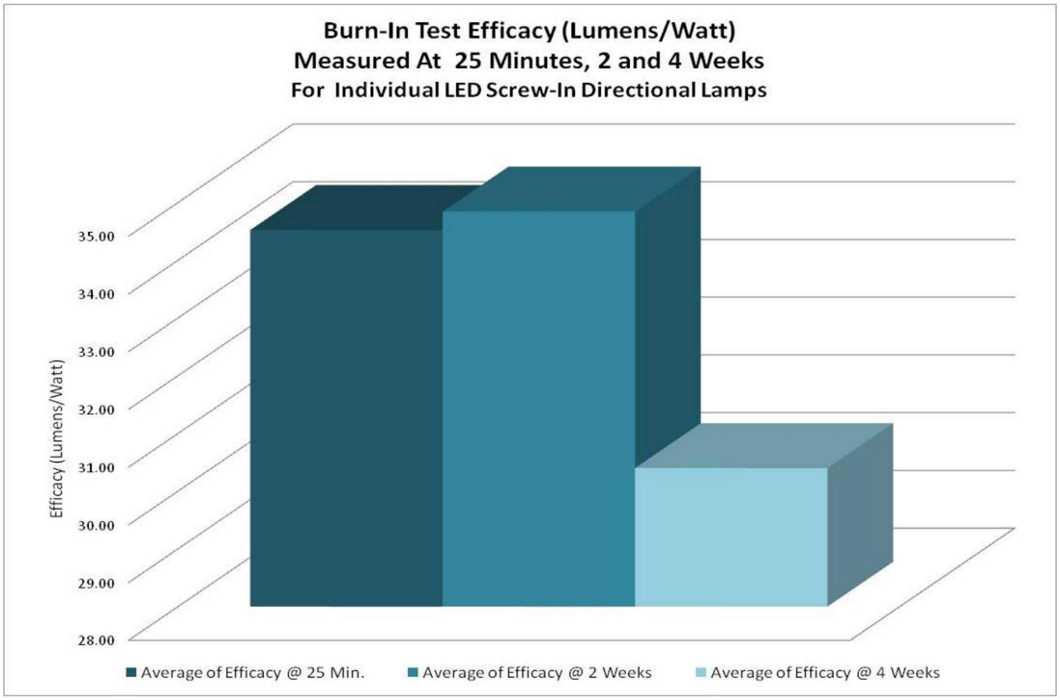

FIGURE 36: BURN-IN TEST AVERAGE EFFICACY

To determine if the increase in efficacy that is apparent during week 2 was true for both Cool White and Warm White bulbs, the following chart examines efficacy by color category.

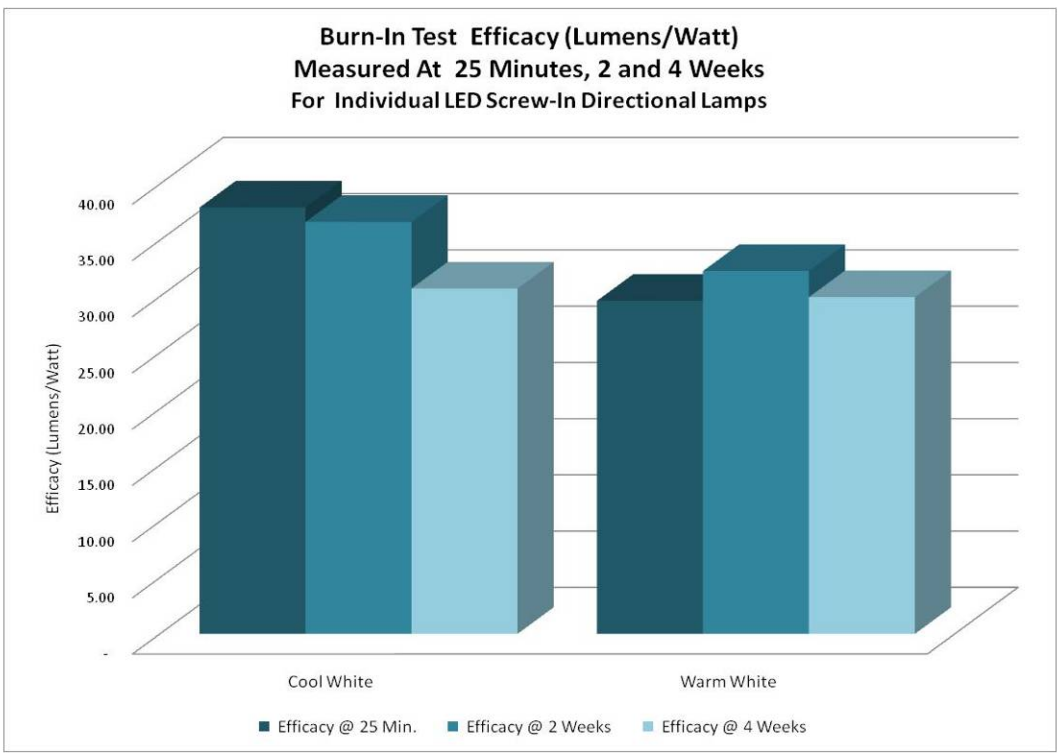

FIGURE 37: BURN-IN TEST AVERAGE EFFICACY FOR COOL WHITE VS. WARM WHITE LED SDLS

The efficacy values at week 2 appear to be reflecting the increase in lumens that was noted in Figure 34. The increase in lumens combined with fairly steady power consumption would result in the increased efficacy values for week 2.

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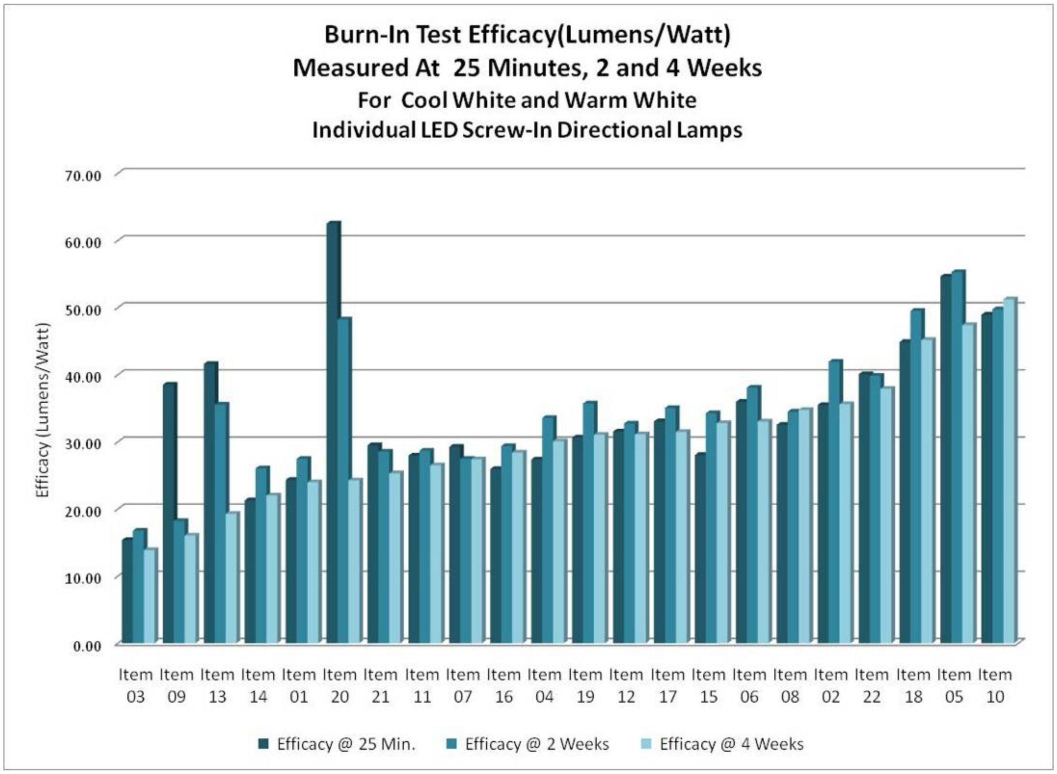

FIGURE 38: BURN-IN TEST INDIVIDUAL EFFICACY, COOL WHITE VS. WARM WHITE

The LED SDL products were sorted from lowest to highest efficacy using week 4 of the Burn-In test. There is a wide range in efficacy values, ranging from a minimum of 14 lm/W for Item 03 to a maximum of 51 lm/W for Item 10. Most items did not experience dramatic changes in efficacy from the initial Sphere test, with the exception of Items 09, 13, and 20, which had significant drops in efficacy.

CORRELATED COLOR TEMPERATURE

The phosphors that coat an LED chip will degrade over time. The rate of degradation depends on many factors, including the color and quality of the phosphor used. The phosphor degradation can be captured with CCT measurements. Due to the logarithmic nature of the CCT scale, one would expect to see more dramatic Kelvin increases in the Cool White lamps than the Warm White lamps for the same relative change in color. Refer to the image of the Planckian locus or curve in Figure 39. This is a visual representation of the CCT scale embedded within a chromaticity diagram. It is clear that the bluer (higher Kelvin) end of the scale has increasingly narrower distances between tick marks.

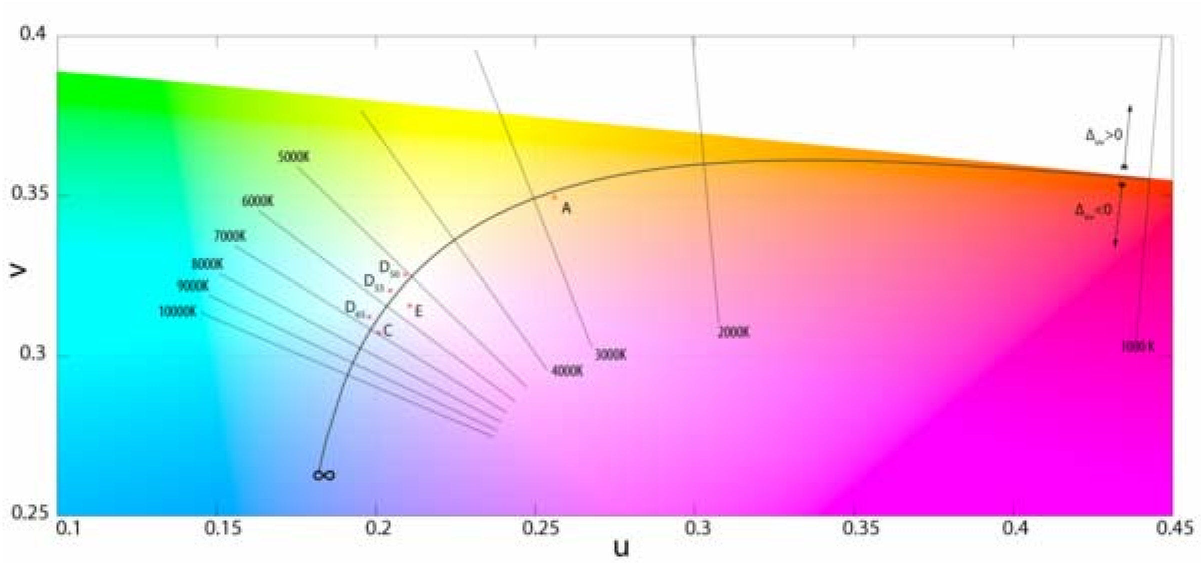

FIGURE 39: PLANCKIAN LOCUS EMBEDDED IN A CHROMATICITY DIAGRAM (IMAGE FROM WIKIMEDIA COMMONS)

The data did in fact show a greater Kelvin increase for the average Cool White LED SDL in week 4. The Cool White LEDs had an average CCT of 7700K by week 4, an increase of over 1600K from week 2. The Warm White LED SDL products had only a slight increase in CCT.

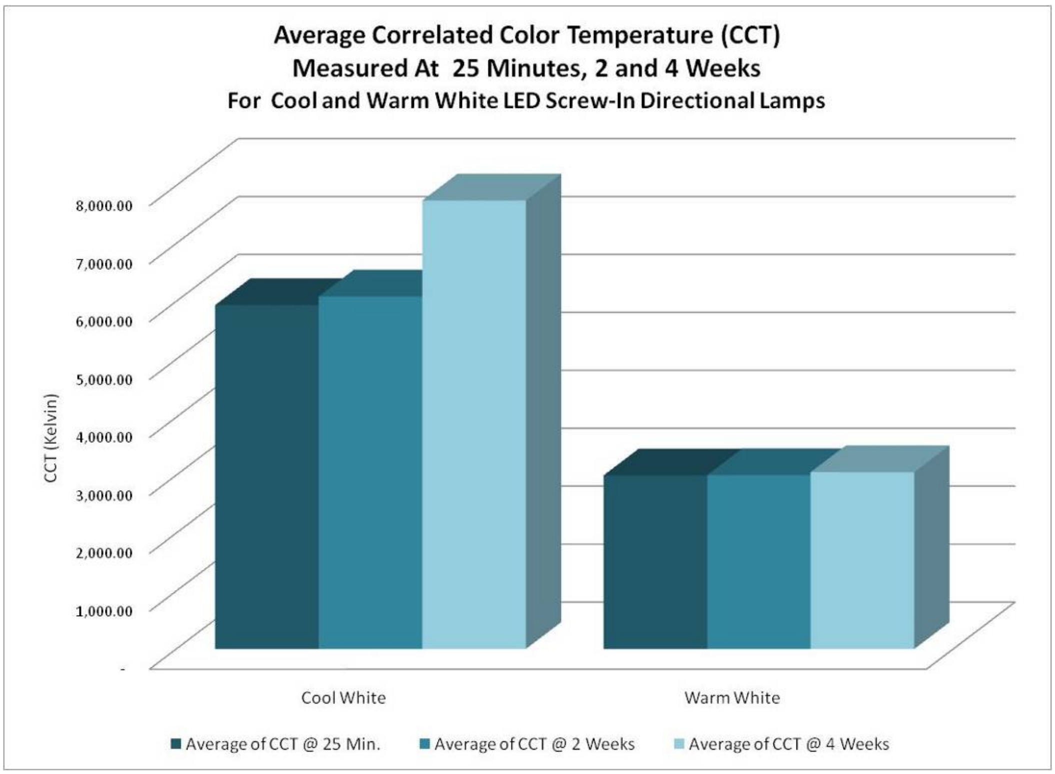

FIGURE 40: BURN-IN TEST AVERAGE CCT, COOL WHITE VS. WARM WHITE

Despite the fact that the Cool White and Warm White LED SDLs follow the expected trend, the Cool White products have a more dramatic increase from week 2 to week 4 than from the initial Sphere test to week 2. Figure 41, below, examines the individual Cool White LED SDLs, to determine if the trend seen with the averaged data was a true trend, or if it was due to outliers in the tested lamps.

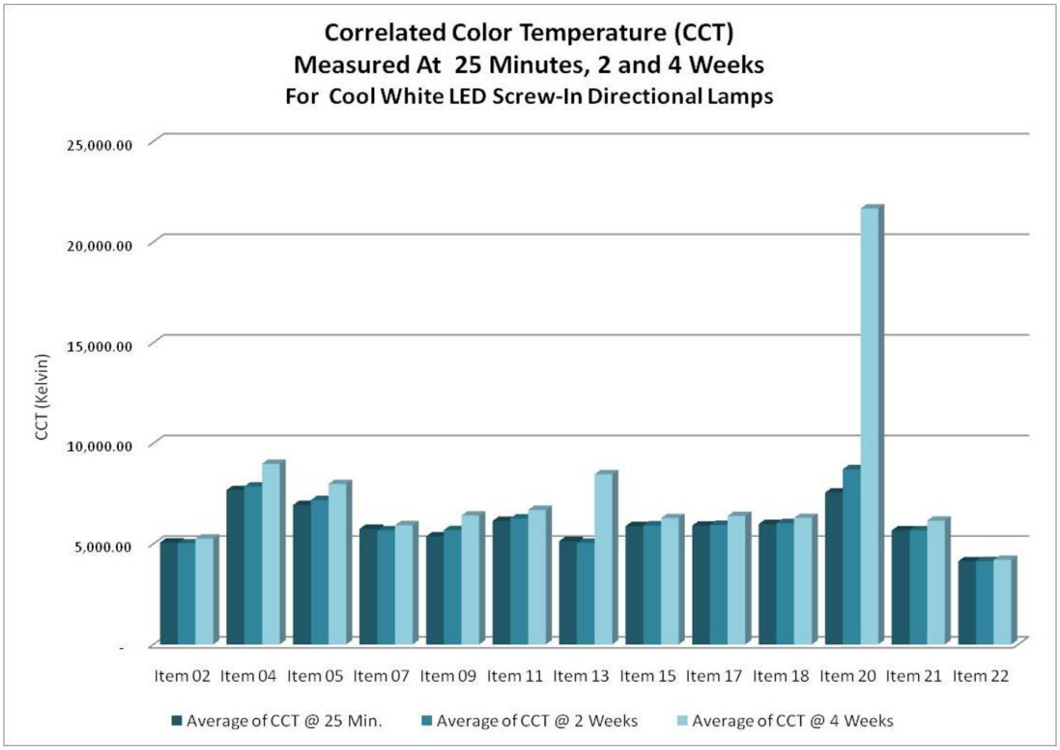

FIGURE 41: BURN-IN TEST INDIVIDUAL CCT FOR COOL WHITE LED SDLS

One lamp is an outlier, Item 20, and skews the average results. By removing this item, the average data follows a more expected trend.

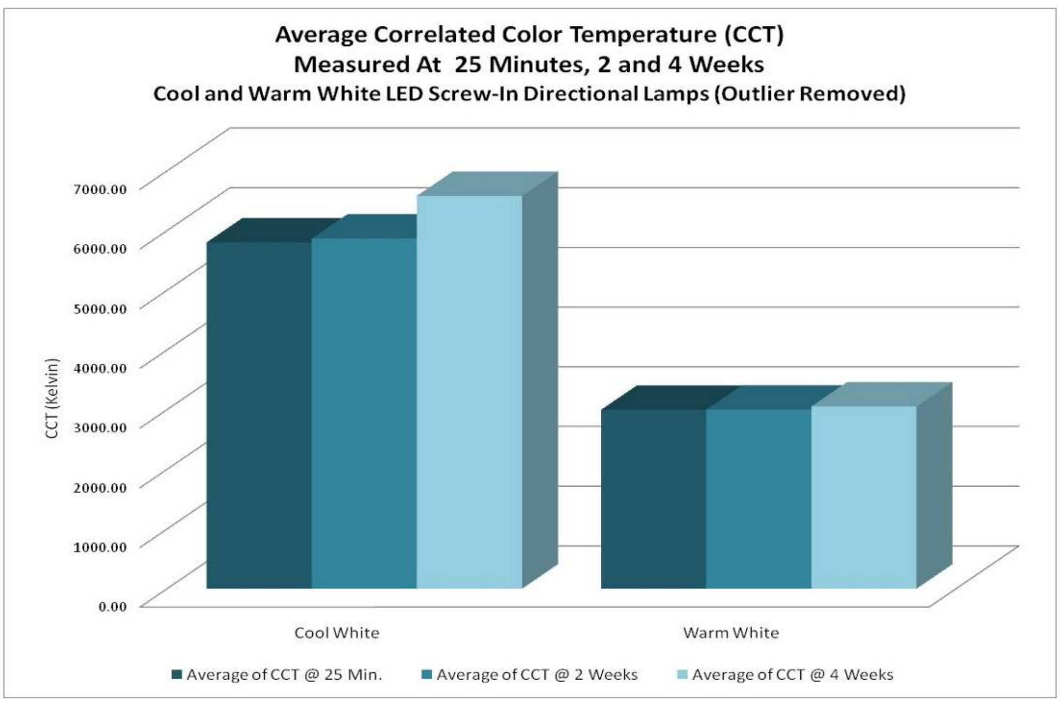

FIGURE 42: BURN-IN TEST AVERAGE CCT, COOL WHITE VS. WARM WHITE, COOL WHITE OUTLIER REMOVED

The following chart examines the individual changes to CCT for the Warm White LED SDL products.

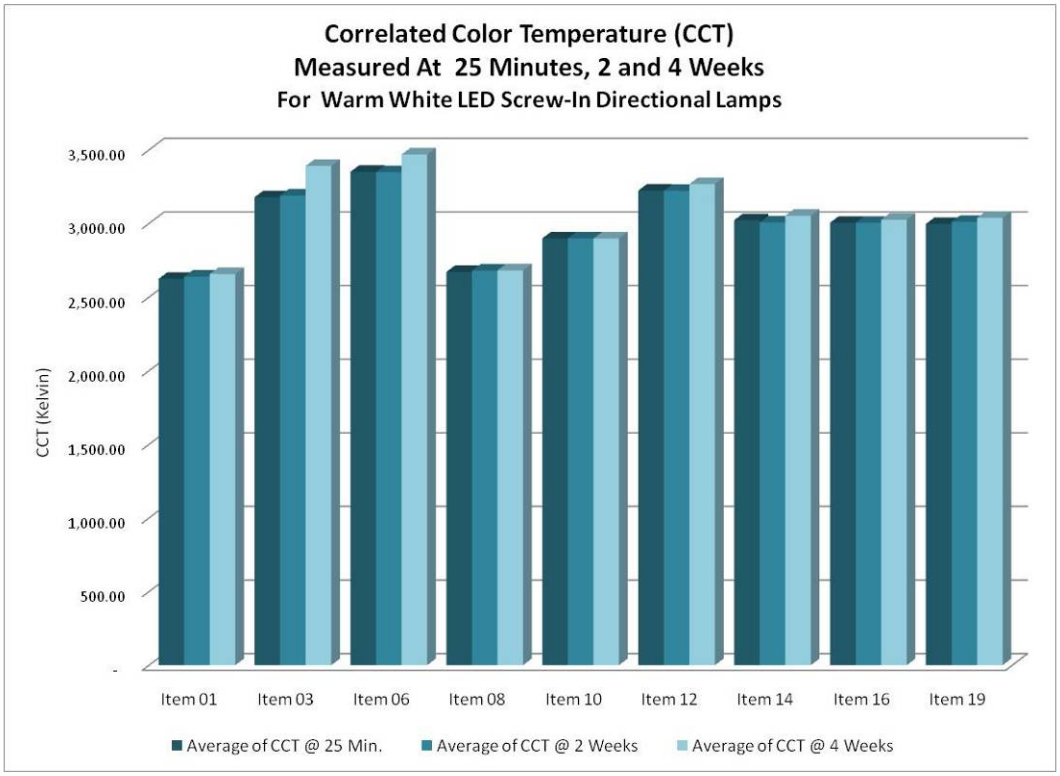

FIGURE 43: BURN-IN TEST INDIVIDUAL CCT FOR WARM WHITE LED SDLS

The individual Warm White LED SDLs followed the expected trend of maintaining CCT over time, as seen with the averaged data in Figure 40. The majority of the lamps experienced very minimal increases in CCT, with only a couple (Items 03 and 06) experiencing a slightly greater increase in CCT.

Over time, all lamps appear to experience at least minimal increases in CCT, resulting in a trend toward the bluer end of the CCT spectrum.

COLOR RENDERING INDEX

The measurement of the CRI during the bi-weekly Burn-In testing revealed a surprising trend for both the Cool White and Warm White LED lamps. Both experienced an increase in the CRI during the 2 week testing, followed by a significant decrease in week 4.

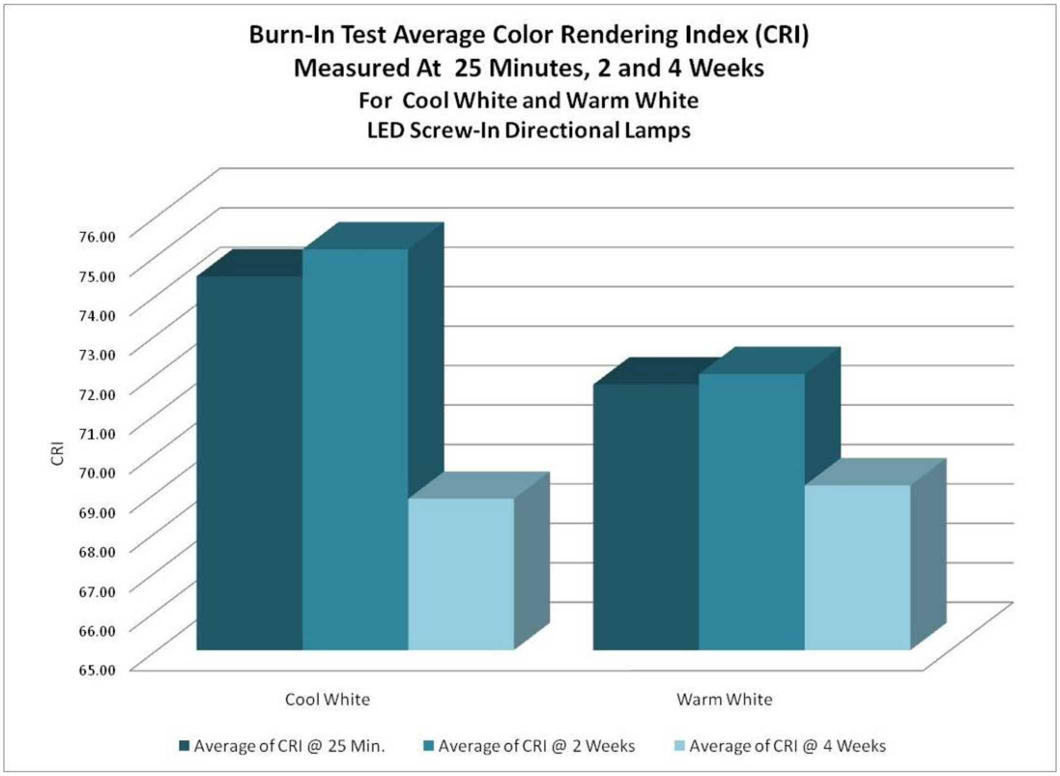

FIGURE 44: BURN-IN TEST CRI FOR LED SDLS

It is apparent that, on average, the Cool White SDLs have a slightly higher CRI during the first 2 weeks, with the 4 week measurements being approximately 69 CRI for both Cool White and Warm White LED SDLs.

When comparing individual products, there does not appear to be significant differences between the Cool and Warm White groups. Two of the Cool White LEDs (Item 13 and Item 20), did experience a significant drop of over 10 CRI over the 4 week period, but the remainder experienced only a small drop.

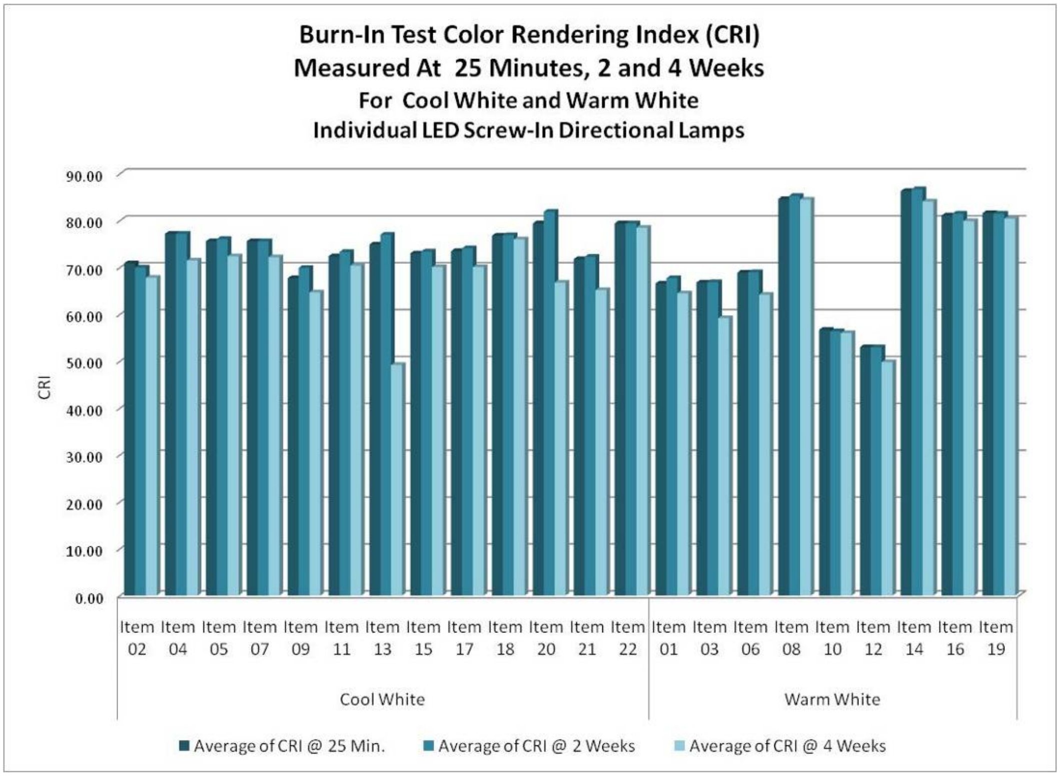

FIGURE 45: BURN-IN TEST INDIVIDUAL CRI

LIGHT DISTRIBUTION RESULTS

PROCESSING

Images for each lamp were downloaded from the camera's memory card, and imported into Adobe Photoshop software for processing. The Photoshop images were used reveal and highlight inconsistencies in light distribution as well as any patterns and shadows caused by the optics. It may also help to identify characteristics of the SDL that may impact performance.

ANALYSIS

LIGHT DISTRIBUTION

Figure 46 shows an example of an LED SDL (Item 11) that had even light distribution across the spill of light, with little to no feathered shadows created by the heat sink.

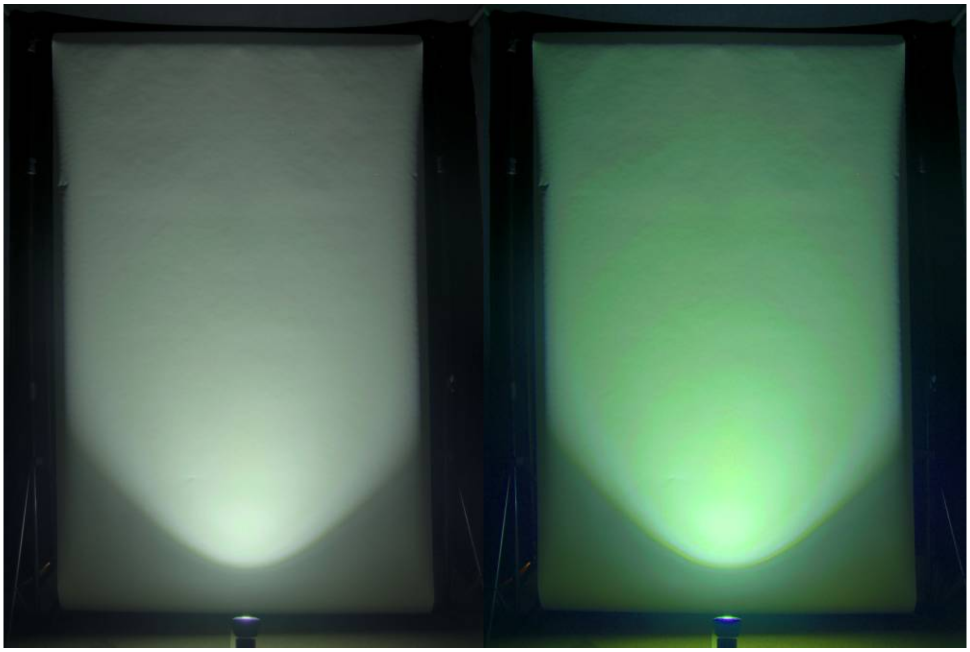

FIGURE 46: ITEM 11: PROCESSED PHOTOSHOP IMAGE (LEFT) AND SATURATED PHOTOSHOP IMAGE (RIGHT)

Most tested products had fairly even light distribution across the spill of light. However, some products did have uneven or spotty light distribution. The following figures show examples of some of these products. Figure 47 is an example of an LED SDL with a hot spot of light in the middle of the light spill.

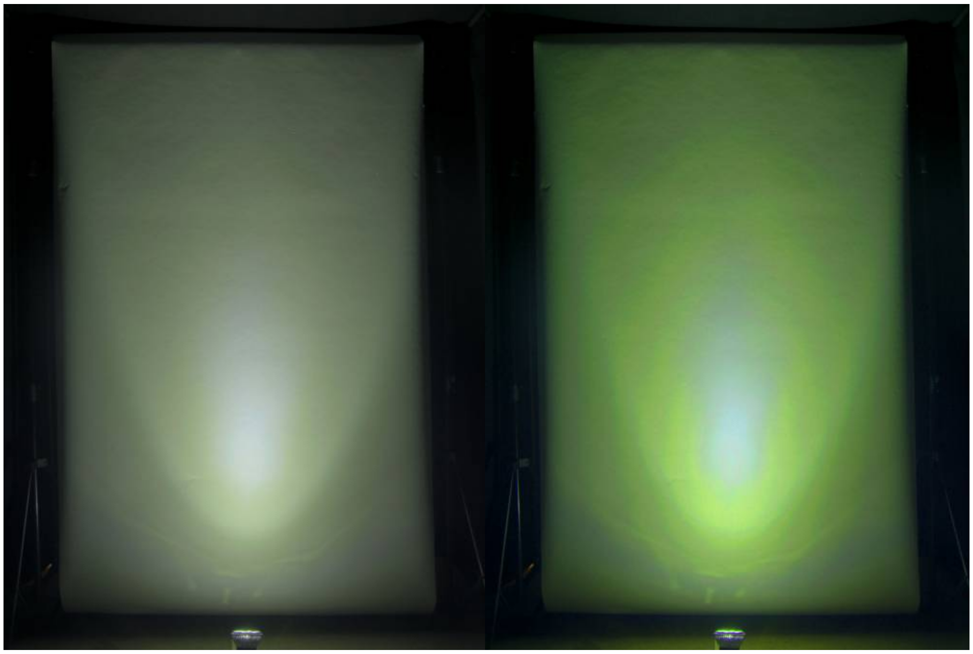

FIGURE 47: ITEM 17: LED SDL PRODUCT WITH UNEVEN LIGHT DISTRIBUTION

Figure 48 shows another LED SDL that had uneven light distribution. The color distribution is uneven, with yellow streaking visible on the sides of the light spill.

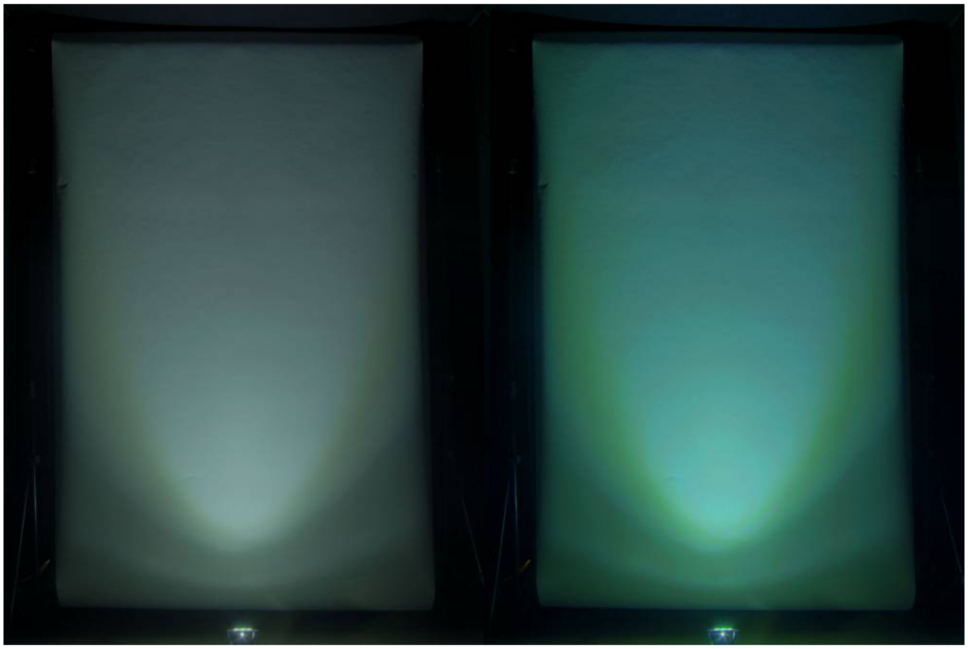

FIGURE 48: LED SDL WITH UNEVEN COLOR DISTRIBUTION (ITEM 04)

Figure 49 is an additional example of uneven light distribution. In the saturated image, the uneven light distribution is visible as blue steaks throughout the light spill.

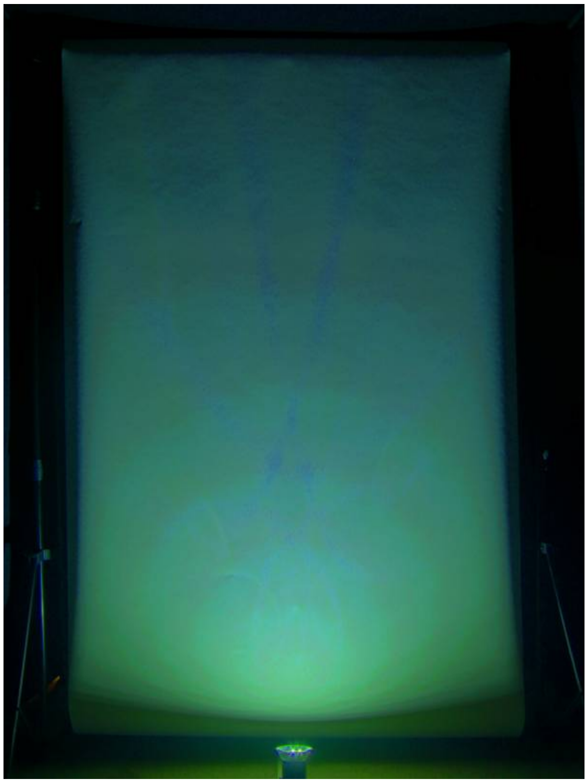

FIGURE 49: ITEM 5: LED SDL WITH UNEVEN LIGHT DISTRIBUTION

ENERGY SAVINGS

To understand the energy savings a consumer may expect, a sample energy savings calculation is provided. This is only a sample since it is difficult to match lamps consumers are currently using with possible LED replacements. These calculations assume the light quality of the replacement LED is sufficient for the intended purpose.

Annual energy savings is directly dependent on the lamps' annual operating hours. In some cases, operating hours will follow those of retail operating hours, especially in applications where merchandise is highlighted. The California utilities' Energy Efficiency Programs estimate average retail operating hours to be 12 hours per day, 365 days a year. Restaurant and retail compact fluorescent lamp (CFL) operating hours can be used to estimate store open hours, with a reasonable assumption that CFLs are turned off when stores close. Using Restaurant and Retail market sectors in California's Database for Energy Efficiency Resources (DEER),[2] the average hours is also 12 hours per day. For indoor residential use, the operating hours will be much less than commercial applications. Residential CFL operating hours of 2.34 hours can be used to estimate likely hours of use for the LED SDL lamps.

In cases where architecture is highlighted, an assumption of 12 hours per day is a fair assumption for the average nighttime hours in which such lighting would be desired.

In many cases, the SDL lighting may run 24 hours a day. This would be true in cases where highlighted merchandise or architecture is continually on display. Therefore, energy savings was calculated using 2.34, 12 and 24 hours per day to provide a savings range.

Using 12 hours per day, the energy savings is calculated as shown in Equation 1.

EQUATION 1: ANNUAL ENERGY SAVINGS

$$Annual\ Energy\ Savings = (Halogen\ Annual\ Energy\ Use) - (LED\ Annual\ Energy\ Use)$$

Where:

$$Halogen\ Annual\ Energy\ Use = \frac{(Halogen\ Measured\ Demand) \times (Annual\ Hours)}{(1000W/kW)}$$

$$LED\ Annual\ Energy\ Use = \frac{(LED\ Measured\ Demand) \times (Annual\ Hours)}{(1000W/kW)}$$

The following example calculates the energy savings when replacing a 75W halogen PAR30 with a 22W rated LED SDL.

$$Halogen\ Annual\ Energy\ Use_{20W} = \frac{(73.7W) \times (4380\ Hours)}{(1000W/kW)} = 322.8\,kWh$$

$$LED\ Annual\ Energy\,Use_{5W} = \frac{(16.7W)\times(4380\,Hours)}{(1000W/kW)} = 73.1kWh$$

$$Annual\ Energy\ Savings = (322.8\,kWh)-(73.1\,kWh) = 249.7\,kWh$$

The following example calculates the energy savings when using an LED SDL that is comparable in *measured* luminosity at 25 minutes to a halogen PAR30. The LED SDL chosen for the calculation is Item 09, a lamp with 424 lm at 25 minutes burn time. The comparable Halogen Item 03 is a lamp with 396 lm at 25 minutes burn time. Using Equation 1, the annual savings for 12 hours of daily operation are as follows:

$$Halogen\ Annual\ Energy\,Use_{20W} = \frac{(55.4W)\times(4380\,Hours)}{(1000W/kW)} = 242.7\,kWh$$

$$LED\ Annual\ Energy\,Use_{5W} = \frac{(11.0W)\times(4380\,Hours)}{(1000W/kW)} = 48.2\,kWh$$

$$Energy\ Savings = (242.7\,kWh)-(48.2\,kWh) = 194.5\,kWh$$

Table 5 reports the energy savings that a consumer can expect when replacing a halogen PAR30 of approximately 400 lumens with an LED SDL of approximately 425 lumens.

TABLE 5: ESTIMATED ANNUAL ENERGY SAVINGS WITH VARYING OPERATING HOURS

DAILY HOURS OF USE	ANNUAL HOURS OF USE	ESTIMATED ENERGY SAVINGS (KWH)
2.34	854.1	37.9
12	4380	194.5
24	8760	388.9

The LED SDL Item 09 has a manufacturer rated lifetime of 20,000 hours. Halogen Item 03 did not have a manufacturer rated lifetime, but similar halogen PAR30s have a rated lifetime of 3,000 hours. This means that by installing LED SDL Item 09, the consumer is replacing nearly 7 halogen Item 03 lamps over the lifetime of the LED, as follows:

$$Number\,of\ Replacements = \frac{(20{,}000\,hours/lamp)}{(3{,}000\,hours/lamp)} = 7\,replacements$$

Assuming the LED SDL continues to replace an equivalent halogen for its entire lifetime, the calculation for lifetime savings is shown in Equation 2.

EQUATION 2: LIFETIME ENERGY SAVINGS

$$Lifetime\ Energy\ Savings = (Halogen\ Lifetime\ Energy\ Use) - (LED\ Lifetime\ Energy\ Use)$$

Where:

$$Halogen\ Lifetime\ Energy\ Use = \frac{(Halogen\ Measured\ Demand) \times (LED\ Lifetime\ Hours)}{(1000W/kW)}$$

$$LED\ Lifetime\ Energy\ Use = \frac{(LED\ Measured\ Demand) \times (LED\ Lifetime\ Hours)}{(1000W/kW)}$$

Note that the Halogen demand is multiplied by the LED lifetime hours. This is to account for the multiple halogen replacement required during the lifetime of one LED SDL. The expected lifetime saving using Equation 2 is shown below.

$$Halogen\ Energy\ Use = \frac{(55.4W) \times (20{,}000\ hours)}{(1000W/kW)} = 1{,}108.0\ kWh$$

$$LED\ Lifetime\ Energy\ Use = \frac{(11.0W) \times (20{,}000\ hours)}{(1000W/kW)} = 220.0\ kWh$$

$$Lifetime\ Energy\ Savings = (1{,}108.0) - (220.0) = 888.0\ kWh$$

The halogen PAR30 consumes over five times the kWh energy during the lifetime of a lumen-equivalent LED SDL.

In many cases, it is possible to install an LED SDL with higher lumen output than the halogen being replaced, and still save energy annually, and over the lifetime of the lamp.

CONCLUSION

Halogen PAR30s, on average, are brighter than the LED SDL counterparts. However, when comparing individual lumen output from the lamps, some of the LED SDL lamps did produce comparable or greater lumens than the halogen lamps.

Many LED SDL products had a percentage lumen drop of less than 5% during the first 25 minutes of operation. This was comparable to one of the halogen PAR30 lamps tested. The remaining halogen PAR30 lamps had an increase in lumen output during the first 25 minutes of operation.

Manufacturers of LED SDLs are inconsistent in labeling the products true lumen output. The majority of tested LED SDLs had manufacturer rated lumens higher than the lumen output measured at 25 minutes of operation. On the other hand, some manufacturers had lumen ratings that were lower than the measured lumen output at 25 minutes. These manufacturers may be accounting for the eventual degradation of the LED's lumens. In addition to the inconsistent manufacturer lumen rating, many manufacturers do not include a recommendation for the appropriate Halogen equivalency. The combination of these two limitations makes it difficult to choose the appropriate LED replacement for a halogen light source.

The lumen data shows there are good LED replacements for some halogen PAR30s. Unfortunately, there is significant variation between manufacturers in the lumen output of the LED SDLs, adding to the difficulty in choosing an appropriate LED replacement for Halogen PAR30s.

The LED technology consumed considerable less energy than the halogen technology. When comparing efficacy values, the LED SDLs produced, on average, nearly three times the lumens per Watt. On an individual basis, even LED SDLs with the lowest efficacy have greater performance than the halogen PAR30s with the highest efficacy. The LED SDLs marketed as "cool white" lamps had, on average, higher efficacy values than those marketed as "warm white" lamps.

The initial results from the Burn-In test indicate variable lumen depreciation in the first four weeks of operation. This will continue to be monitored and the results from the full year of tests are planned to be included as an addition to this report.

The quality of the light is very important for many applications where SDLs are used. In these applications, consumers may be more sensitive to changes in CCT and CRI. Unfortunately there is no quantitative "right" CCT and CRI as it varies with application and consumer preference. For this reason, consistent performance of the lamps is preferable.

The LED SDL products come in a wide range of color temperatures, from 2600K (warm white) to 7700K (cool white). This wide range of CCT allows consumers to select the appropriate color temperature according to preference and/or application.

The CRI, or color quality, affects visual perception of the color output from the lamp. A higher CRI can improve the perception of the light. In some cases, increased CRI may reduce needed luminous flux. On average, LED products had lower CRI values than the halogen products. However, some individual products had CRI values that exceed the CRI of the lowest performing halogen product.

The sample of lights tested included a variety of beam angles and intended applications. The analysis provided by the light distribution tests allows a qualitative assessment of how the LED SDL will illuminate objects. While certain characteristics are “bad” such as poor light distribution across the surface other characteristics truly depend on the intended application, such as spot lighting or merchandising. As with many lighting applications, these are personal preferences and may only be assessed after the lamp is installed.

Several LEDs could be energy efficient replacements for halogen lamps, however, inconsistencies in lamp quality, color temperature and lumen output may lead to unsatisfactory consumer experiences until the technology matures.

REFERENCES

[1] US Department of Energy, Energy Efficiency and Renewable Energy, *LED Basics* *http://www.netl.doe.gov/ssl/usingLeds/general_illumination_basics_how.htm*

[2] Title 24 Nonresidential Compliance Manual, 2005, p. 5-30

[3] Ibid p. 6-3 and p. 6-28

[4] Ibid, p. 5-47

[5] Rensselaer Polytechnic Institute, Lighting Research Center National Lighting Product Information Program. http://www.lrc.rpi.edu/programs/nlpip/lightingAnswers/mr16/performance.asp

[6] Color Quality of White LEDs, U.S. Department of Energy, Energy Efficiency and Renewable Energy, Building Technologies Program, www.netl.doe.gov/ssl/PDFs/ColorQualityofWhiteLEDs.pdf