DOE Solid-State Lighting
Commercial Product Testing Program

Summary of Results:
Round 1 of Product Testing

U.S. Department of Energy

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Summary of Results: Round 1 of Product Testing

Round 1, the first complete round of testing for the DOE Solid-State Lighting (SSL) Commercial Product Testing Program (CPTP), was conducted from December 2006 – February 2007. In CPTP Round 1, eight products were selected for testing, representing a range of applications, designs, and manufacturers, continuing and extending testing based on insight from the pilot round of testing. [1] All luminaires were tested with both spectroradiometry and goniophotometry, along with temperature measurements (taken at the hottest accessible spots on the luminaire) and off-state power consumption.

The lighting testing laboratory was instructed to follow test procedures specified in LM-79 (IESNA Guide for Electrical and Photometric Measurement of Solid-State Lighting Products) which tests the luminaire as a whole—as opposed to traditional testing methods that separate lamp ratings and fixture efficiency.[2] There are two main reasons for this: 1) there is no industry standard test procedure for rating the luminous flux of LED devices or arrays; and 2) because LED performance is temperature sensitive, luminaire design has a material impact on the performance of LEDs used in the luminaire. For these reasons, luminaire efficacy (efficacy of the whole luminaire) is the measure of interest for assessing energy efficiency of SSL products, as specified in LM-79.

Table 1 summarizes results for energy performance and color metrics (including light output, luminaire efficacy, correlated color temperature (CCT), and color rendering index (CRI)) for all products tested under CPTP in the pilot round and Round 1.

The first four luminaires—identified as 06-01, 06-02, 06-03, and 06-04—were initially tested during pilot testing; additional testing was conducted on 06-02 and 06-04 during Round 1 to complete the assessments of these two luminaires. Test results from the pilot round are compiled along with Round 1 results in Table 1.

The selection of products for Round 1 was in part designed to provide initial insight into variability across units and to provide benchmarking data with respect to other light source technologies and LED thermal management. To enable observation of variability across units, two samples, A & B, of each product were tested for products 06-06 and 06-07. To provide benchmarking data, products 06-11, 07-02, and 07-03 were all selected from the same line of products. Products 07-02 and 07-03 are the same luminaire design, the first using a compact fluorescent lamp (CFL) for its light source and the second using LEDs for its light source. Products 06-11 and 07-03 demonstrate two luminaire designs which each use the same type of LED engine and driver, but different thermal management systems.

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[1] The DOE Solid-State Lighting Commercial Product Testing Program Summary of Results: Pilot Round of Product Testing, December, 2006. Available online at http://www.netl.doe.gov/ssl/comm_testing.htm.

[2] The draft document entitled "IESNA Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products," designated LM-79, is currently under review by a joint IESNA-ANSI committee on SSL.

Table 1. Summary of DOE SSL CPTP Round 1 Results Energy Performance and Color Metrics					
Photometrics based on LM-79 for • Complete luminaires • 25º C ambient temperature		**Light Output (lumens)**	**Luminaire Efficacy (lm/W)**	**Correlated Color Temperature (K)**	**Color Rendering Index**
CPTP 06-01 Downlight (manufacturer published LED luminous efficacy = 40 lm/W)		193	12.8	3012	70
CPTP 06-02 Undercabinet (manufacturer published LED luminous efficacy = 55 lm/W)		166	16.1	3483	78.2
CPTP 06-03 Downlight (manufacturer published LED luminous efficacy = 45 lm/W)		298	19.4	2724	67.3
CPTP 06-04 Task Light (manufacturer published LED luminous efficacy = 36 lm/W)		114	11.6 [7.1]	6392	76
CPTP 06-05 Outdoor Area (manufacturer published luminaire efficacy = 24 lm/W)		2638	23.9	4661	20
CPTP 06-06A Surface Mount (manufacturer published LED luminous efficacy = 55 lm/W)	A	960	23.5	3405	75
	B	967	23.8	3414	75
CPTP 06-07A Wall/Step	A	23.8	4.0	2833	70.3
	B	25.9	4.3	2874	69.8
CPTP 06-08 Undercabinet		375	21.6	7003	72.3
CPTP 06-09 Task/Desk		327.5	15.3 [11.6]	3841	84.9
CPTP 06-10 Undercabinet		166	32.8] [21.9]	4103	77.3
CPTP 06-11 Task/Desk		215	17.0 [8.2]	5973	74
CPTP 07-02 Task/Desk	***CFL***	236	24.2 [13.3]	3432	79
CPTP 07-03 Task/Desk	LED	226	18.4 [8.6]	5939	74
Adjusted efficacy values in brackets [] include the effect of measured off-state power consumption assuming 3 hours on-time per day. See below for discussion of the impact of off-state power consumption on average yearly efficacy.					

All products in Round 1 which incorporate an on/off switch were also tested for off-state power consumption. Each of the task lights and one of the undercabinet lights tested to date consume energy in the off-state (also called standby power consumption or 'vampire' loading, discussed in more detailed below).

In addition to performing product testing following LM-79, photometric data published by manufacturers for SSL products (in the form of standard IES photometric data files) were collected and analyzed for purposes of comparison.

Observations and Analysis of Test Results

Energy Use and Light Output

Although the test results demonstrate considerable ranges of light output and efficacy and the overall sample size is still small, there are SSL products in each category that approach parity to luminaires using other light sources, in terms of both light output and efficacy. Discounting one outlier, the increasing luminaire efficacies seen in CPTP results confirm that LED chip efficacy improvements are trickling into commercially available products. Although the SSL products may not yet equal the most powerful incandescent sources or the most efficient fluorescent sources, the light outputs are reaching acceptable levels for specific applications. The efficacies are already beginning to rival the efficacies of some CFL-based fixtures, in part due to the directional nature of LEDs.

Today's markets offer a huge variety of fluorescent products with a range of outputs and efficacies. Based on manufacturer published photometric data for fluorescent and incandescent undercabinet lights, all three of the undercabinet SSL luminaires tested have per linear foot light output comparable to some incandescent and fluorescent products. Regarding energy use, all of the SSL undercabinet luminaires have better efficacy than similar incandescent products, with one product reaching an efficacy comparable to fluorescent undercabinet luminaires. This is possible because of the directional nature of LEDs: while a fluorescent lamp may have a source efficacy of 40-70 lm/W, after accounting for typical fixture losses, the computed fluorescent luminaire efficacy ranges from 20-50 lm/W.

For task/desk lights, all but one of the four luminaires tested provide a light output comparable to luminaires using 20W and 35W halogen bulbs. In each case, the SSL luminaires have efficacies which exceed (and in some cases double) the efficacy of similar incandescent luminaires. The tested SSL luminaires have efficacies which are about ½ to ¾ the efficacy of similar CFL luminaires.

The surface mount luminaire, 06-06, provided an output of 960 lumens from a 2 foot long product using 36 LEDs. Comparing this surface mount to fluorescent fixtures, however, requires caution. There are many types of surface mount luminaires available today, presenting a huge range of fixture efficiencies, and capable of using a choice of fluorescent lamps with a range of efficacies. Very different conclusions could be drawn depending on what luminaires are used for comparison.

As an illustration, consider two comparisons:

1. A 4 foot wrap-around surface mount luminaire using two T12 fluorescent tubes
2. A range of surface mount fluorescent undercabinet fixtures (which in some cases are commercialized for similar applications such as stairway lighting)

The 4 foot long version of 06-06 (incorporating 90 LEDs) would have produced approximately 2400 lumens—a little more than half the 4600 lumens one would obtain from one manufacturer's 4 foot surface mount using two 4' fluorescent T12 tubes. In efficacy, the SSL luminaire would be 1/3 the efficacy of this particular fluorescent luminaire.[3] Alternatively, when compared to undercabinet surface mounts, the SSL surface mount 06-06 produces more light output (lumens) than the average output of 23 commercially available fluorescent undercabinet luminaires, and results in a luminaire efficacy which is greater than the least efficacious and about 2/3 the average efficacy of these fluorescent undercabinet luminaires.[4]

The outdoor area light, 06-05, produced the most light of any single luminaire tested during Round 1: 2638 lumens, with a luminaire efficacy of 24 lm/W. Because of the wide range of sources (halogen, metal halide, high pressure sodium) that may be used in outdoor area lighting, and specific directional and white-light needs of given outdoor applications, it is difficult (and possibly inappropriate) to draw a simple comparison based on the output and efficacy of this product as compared to luminaires using more traditional sources.

The wall/step light tested in Round 1 was an outlier among tested products, with an efficacy of only 4 lm/W. This result is still comparable to incandescents, but nevertheless much lower than possible for SSL products today. The same or similar LED engines can be expected to render efficacies 3-5 times greater in a fixture designed to take advantage of the directional nature of LEDs.

For the majority of products tested to date, literature published by the luminaire manufacturer provides some indication of efficacy and/or light levels. For a number of products, manufacturers publish the LED luminous efficacy (lamp efficacy) and expected lumen output levels based on the LED lamp performance. This could be misleading because the actual measured luminaire efficacy is far less than the LED lamp efficacy (on average, about 1/3 of the LED luminous efficacy). In some cases, manufacturers indicate expected output levels by providing a comparison (such as, "35 Watt halogen equivalent"). This practice can provide useful information if the comparison is based on actual luminaire outputs. But in some cases, it is highly misleading when the comparison is based on source (lamp) performance. For only one product tested in Round 1, the manufacturer published information provides accurate values for both the output and efficacy of their product based on luminaire testing.

[3] Based on a major manufacturer's published relative photometry and fixture efficiency for a commercially available, 4 foot long, wrap-around surface mount luminaire (fitted with 2 T12 fluorescent lamps) suitable for industrial, commercial and residential applications.

[4] Based on manufacturer published photometry for 23 fluorescent undercabinet luminaires.

Measurements of Color Quality

Round 1 spectro-radiometric testing provides chromaticity coordinates, correlated color temperature (CCT), and color rendering index (CRI), along with spectral power distributions for each luminaire. The CCTs of Round 1 luminaires range from a minimum of 2724 Kelvin (in the warmest CCT range, comparable to incandescent sources), to a maximum of 7000 K (in the coldest CCT range), with an overall average of 4200 K. All but one of the luminaires tested use phosphor-conversion LEDs—with an overall average CRI of 75 for the luminaires using phosphor-conversion LEDs.

CRI values are reported with the reminder that, in certain cases, a light source may be acceptable (and even preferred) by users for given applications, even though its CRI value is relatively low. Readers are urged to be aware of the complexities of assessing color quality and aware of the limitations of CRI with regard to SSL technologies.[5,6] Alternative metrics are under development, but until they are adopted in industry standards, DOE will use CRI for measuring color rendering.

Figures 1 through 4 present relative spectral power distribution curves. Each figure groups curves from a given luminaire category (downlight, outdoor area, task/desk, and undercabinet). Hashed lines provide curves for traditional light sources as a reference. The luminaires plotted in these figures represent a range of color temperatures, so the curves can provide a qualitative picture of the spectral power curve shapes, but should not be used for quantitative comparison. CRI values are indicated as points of reference, but readers are reminded that CRIs should not be compared across luminaires with different CCTs.

Given the range of color temperatures, CRI values, and spectral power distribution curves of the products tested, and the range of applications for these luminaires, drawing generalizations from this relatively small and diverse set of results should be done with caution. The presence of products with relatively warm color temperatures (the warmest tested: 2724 K) and acceptable CRI values (the highest tested: 84.9) demonstrates that SSL luminaires have the potential to provide suitable color quality for general lighting applications. However, some products tested have very cold color temperatures (one tested at 7003 K), which may not be suitable for most general lighting applications. At this stage, qualitative visual assessment by human observers may provide important additional insight regarding the suitability of color quality of a luminaire for a given application.

[5] Protzman, J. Brent and Kevin W. Houser. October 2006. LEDs for General Illumination: The State of the Science. Leukos. Vol. 3, No. 2, pp. 121-142.
[6] Narendran N, Deng L. 2002. Color rendering properties of LED light sources. Proc. of SPIE: Solid State Lighting II.

Figure 1. Relative Spectral Power Distribution Overlay for Downlights

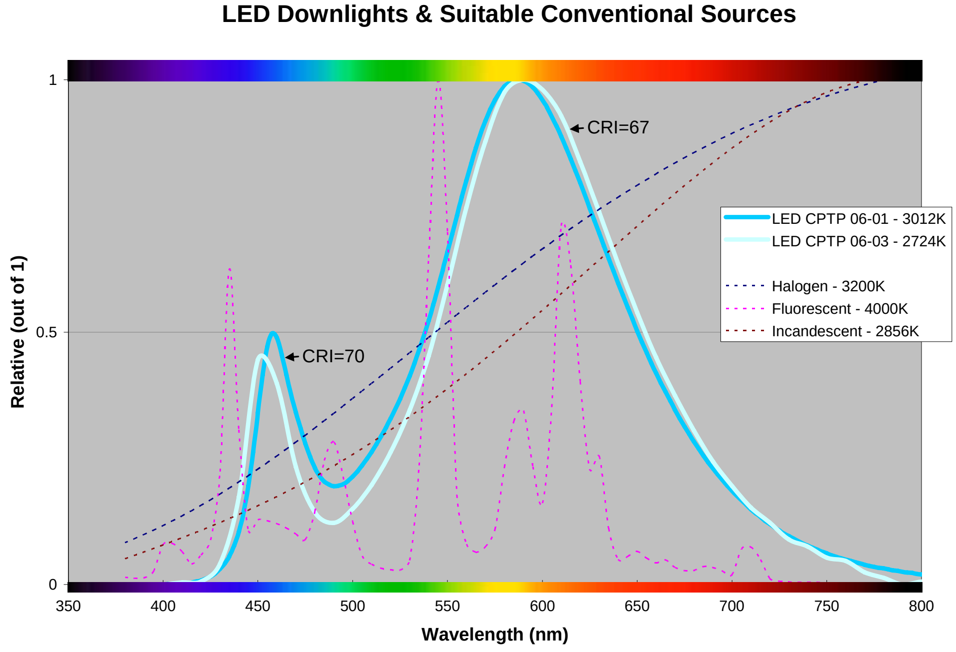


Figure 2. Relative Spectral Power Distribution Overlay for Outdoor Area Light

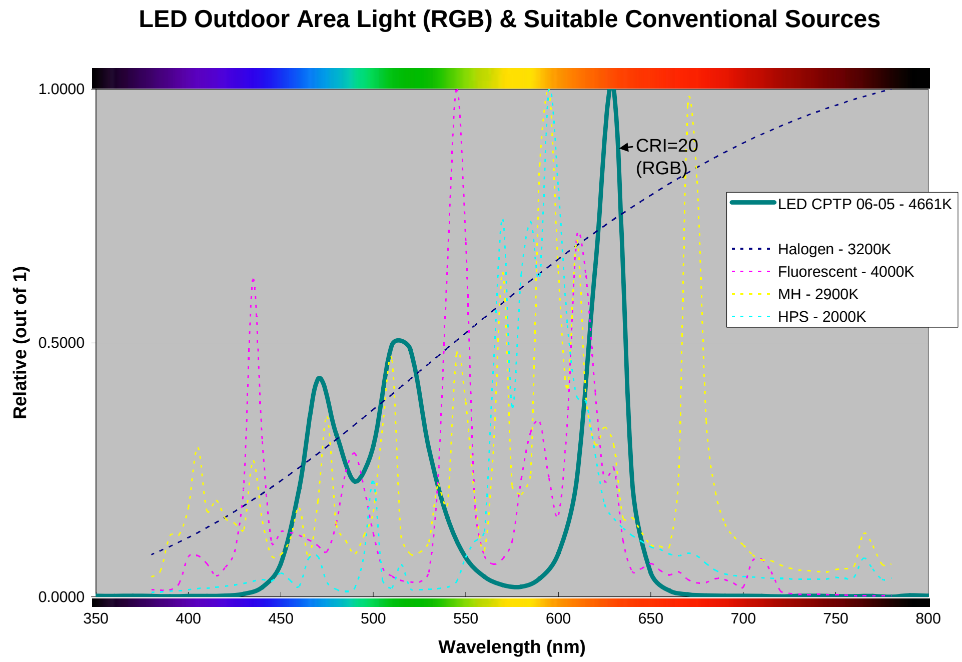


Figure 3. Relative Spectral Power Distribution Overlay for Task/Desk Lights

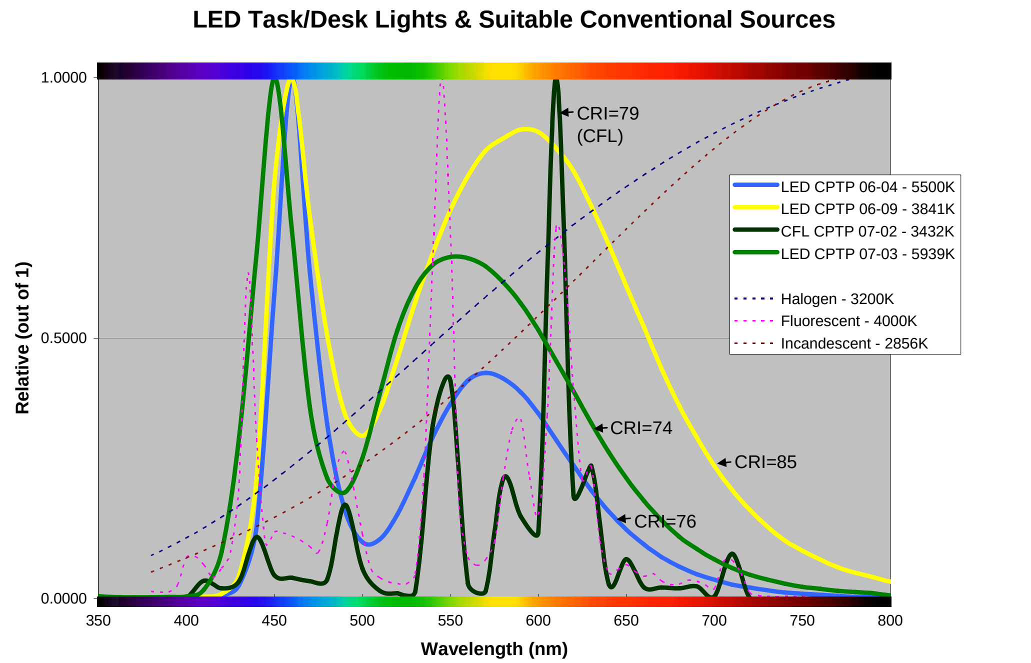
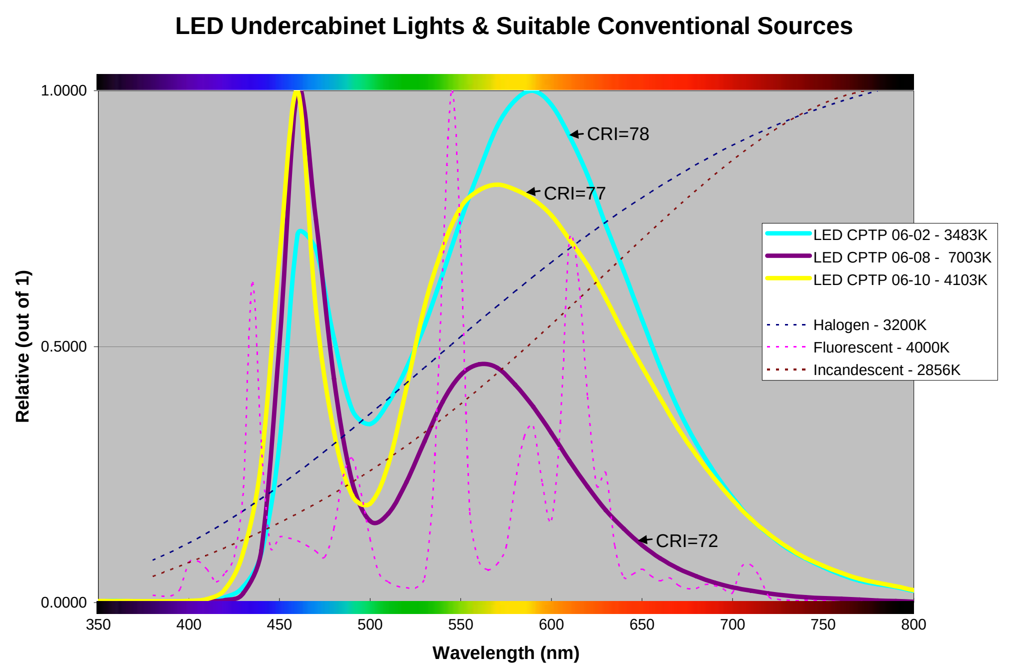


Figure 4. Relative Spectral Power Distribution Overlay for Undercabinet Lights



Electrical and Thermal Design

Off-state Power Consumption

All products in Round 1 that incorporate an on/off switch were tested for off-state power consumption. Each of the task lights (including the CFL-based product) and one of the undercabinet lights tested to date consume energy in the off-state (also called standby power consumption or 'vampire' loads). Measured off-state power consumption in these products ranged from 0.36 to 2.0 watts.

These readings show that the product continues to draw power even when it has been turned "off." This continuous use of electricity reduces the true efficacy of the product. One way to prevent this off-state power consumption would be to use the luminaire in conjunction with an occupancy sensor that would turn off power at the wall plug when the space is unoccupied. Ultimately, to eliminate vampire loads, the electrical design for the on/off switch would need to turn off power on the line side (wall-plug side) of the power supply. The true luminaire efficacy, or "Effective Average Efficacy," which accounts for continued power use when a product is off will depend on the number of hours of use per day. Based on performance measurements and off-state power consumption, the efficacy averaged over a day estimated for various hours of use per day is summarized the Table 2. [7]

Table 2. Effective Average Efficacy

		Measured Efficacy w/ Power On (lm/W)	Measured Power in Off State (W)	Effective Average Efficacy (lm/W)		
				1 hour on per day	3 hours on per day	5 hours on per day
CPTP 06-04 Task Light		11.6	0.88	3.8	7.1	8.7
CPTP 06-09 Task/Desk		15.3	0.98	7.4	11.6	13.0
CPTP 06-10 Undercabinet		32.8	0.36	12.4	21.9	25.8
CPTP 06-11 Task/Desk		17.0	1.96	3.7	8.2	10.7
CPTP 07-02 Task/Desk	***CFL***	24.2	1.14	6.6	13.3	16.8
CPTP 07-03 Task/Desk	LED	18.4	2.00	3.9	8.6	11.4

Note that units operated for fewer hours per year will consume less energy, despite lower efficacies.

If these luminaires are only used for a few hours per day or less, then both CFL and SSL products can result in lower average efficacy than some incandescent luminaires, indicating that serious consideration should be given to eliminating off-state energy use. The problem of off-state power is particularly prevalent in products that use a remote ballast or power supply.

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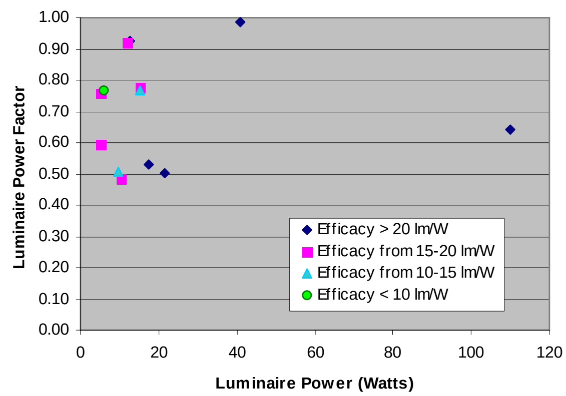
[7] Effective average efficacy can be estimated by computing total lumen-hours per day divided by total watt-hours per day:

1. Calculate daily energy consumption (Wh) by the luminaire at full power ("on"), assuming a given average hours of use per day. For example: 21.4W * 3 hrs/day = 64.2 Wh/day.
2. Calculate daily energy consumption (Wh) by the luminaire when "off," assuming (24 – average "on" hours per day). For example: 0.98W * (24-3) hrs/day = 20.58 Wh/day.
3. Divide total lumen-hours per day by total Wh per day (on state + off state Wh) for effective lumens per watt. For example, based on 3 hours use per day:
   327 lumens * 3 hrs/day → 981 lm-hrs/day / (64.2+20.58) Wh/day = 11.6 lm/W

Power Factor

The average power factor (PF) of the SSL products tested to date is 0.7, with half of the products showing a power factor over 0.75, and one-quarter with power factors over 0.9.[8] These products are not necessarily designed for use in commercial buildings (none of the products tested is categorized specifically as commercial or residential). So the relatively good power factors (PF > 0.7) are not necessarily attributable to products being designed to meet the higher power factor requirements for some commercial sector products (PF > 0.9). The relatively high power factors may reflect attention given to good power quality, or it may be inherently more feasible to design SSL drivers and power supplies for better power quality than CFL ballasts. Figure 5 plots power factor versus luminaire wattage. For the SSL luminaires tested to date, there appears to be no correlation between the wattage of the product and its power factor, and similarly, no correlation between the efficacy and power factor.

Figure 5. Power Factor vs Wattage for CPTP tested SSL Luminaires



This high power factor in early market entrants may bode well for SSL. It shows promise that this technology which has potential to displace a large proportion of the lighting load may be able to do so while maintaining a relatively good power quality profile. Securing a reputation for good power quality may increase the chances that SSL technology will be warmly embraced and supported by the utility sector as it progresses.

Thermal Design

Temperature measurements were taken at the two hottest spots on the outside cases of each luminaire (located via a thermal imaging camera—note that these are not junction temperatures). The average measured outside case temperature for all luminaires tested was 47°C. The highest temperature measured on a luminaire was 73°C.

For most products, visual inspection of the luminaire design revealed the use of a heat sink for thermal management. In many cases, the luminaire body is designed to act as a heat sink. In some cases, thermal management may be inadequate due to inappropriate use of heat sinks. For example, a heat sink encased in a plastic cover inhibits air flow over the heat sink and may reduce its effectiveness.

Insufficient thermal management of LED products can reduce the efficacy of the LEDs and can result in faster lumen depreciation. Round 2 of CPTP testing will include lumen depreciation testing to better document the long-term impact of thermal management and other factors in commercially available SSL luminaires.

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[8] Power factors measured during CPTP testing are calculated as follows: PF = Measured Power / (Measured Voltage * Measured Current).

Repeatability and Variability

Both spectroradiometry and goniophotometry can be used to measure luminaire output (lumens) and efficacy (lumens/Watt). For all of the Round 1 tests, the average difference between output measurements determined by spectroradiometry (using an integrating sphere) and goniophotometry was approximately 1%. One outlier, a gimbaled downlight, had a difference of 7%. The average difference in efficacy observed between spectroradiometry and goniophotometry results for a given luminaire was approximately 3%.

One product underwent identical testing at two testing laboratories. Comparing the measured results from these two laboratories showed little difference.[9]

To obtain insight on variability between units of a given product model, tests 06-06 and 06-07 were each conducted on two units (ordered at the same time from the same distributor). Although the sample size from these two products is too small for analysis at this stage, initial examination shows negligible variability for one product and some variability in efficacy and output results for the other product. This is possibly due to large fixture losses in this luminaire and/or the small number of LEDs (3 LEDs per luminaire), which may result in greater variation from one unit to another.

Round 2 of the CPTP will enable more extensive testing of repeatability and variability, including testing by different laboratories using a range of equipment and further tests of multiple units of certain products.

Direct Comparison: CFL to SSL

Products 07-02 and 07-03 are the same luminaire design, the first using a CFL and the second using SSL for its light source, enabling a direct, side-by-side comparison of CFL and SSL. The measured wattage of the CFL version of this portable desk light, 07-02, was 9.8 W and the measured wattage of the SSL version, 07-03, was 12.3 W. The lumen output of these two products is nearly identical, and both show acceptable CRI values. The luminaire efficacy of the SSL product is ¾ that of the CFL. The SSL luminaire has very good power factor (0.92), while the CFL power factor is much lower (0.54). The CFL product has a much warmer color temperature than the SSL product (3432 K vs 5939 K).

The bottom line from this comparison is that the SSL luminaire comes very close to rivaling the CFL luminaire in terms of energy efficiency. Suitability of the SSL luminaire would depend in part on the color requirements of the intended application. Given the progress announced in LED chip design in the past 6 months, if the latest LED chips were used, the next generation of this SSL luminaire can be expected to surpass the CFL luminaire in most performance metrics.

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[9] Comparing values across results from two testing laboratories shows difference in efficacy = 1.6%; difference in output lumens = 2.9%; difference in CCT = 1.4%; and difference in CRI = 0.6%.

Conclusions from Round 1 of Product Testing

Key Points

A wide range of performance is seen across the twelve SSL general illumination products that were tested. Some of these commercially available products achieve acceptable levels of light output, with luminaire efficacies that significantly exceed incandescents, and even equal the efficacies of some fluorescent-based luminaires when directionality and fixture losses are factored in. Some products on the market today provide less light output than traditional light sources, and most are less efficacious than might be implied by product literature. There are also products that perform relatively well, and a few are now providing credible and accurate information in product literature. As industry professionals become aware of the importance of assessing SSL luminaires on overall luminaire performance (i.e., testing of the entire luminaire, including LEDs, drivers, heat sinks, optical lenses and housing), more reliable performance information will be available to support the nascent SSL markets.

Next Steps for Testing

The next round of testing in the DOE SSL Commercial Product Testing Program will continue to explore a range of product categories, including downlights and replacement bulbs. Round 2 will include more in-depth performance testing, exploring the repeatability and variability of results (including round-robin style testing), and will include lumen maintenance testing (based on the draft IESNA LM-80 testing standard). Upcoming testing will also enable further benchmarking—providing more quantitative comparisons between SSL and traditional sources, and also residential versus commercial products. The general aim is to increase our understanding of how to compare across different sources and different luminaires.

Next Steps for the Industry

While SSL technologies continue to progress rapidly, industry groups can use these testing results to help formulate practices that will protect the potential of SSL. There are ongoing efforts across industry groups, standards organizations and the DOE to develop product standards and testing procedures for SSL technologies. Luminaire manufacturers are continually integrating improvements in component efficiencies and new LEDs and LED engines, which will lead to improvements in overall luminaire efficacy and color quality. Underlying characteristics of SSL luminaires can be strengthened by developing best practices for good thermal management, good power quality profiles and the elimination of off-state power consumption.

The products tested in Round 1 were designed in 2005 or early 2006, and are already coming close to rivaling CFL luminaires in output and efficacy. In late 2006 and early 2007, numerous announcements were made about significant improvement in LED chips and engines. There is great promise that the next generation of commercially available SSL luminaires (using the latest LED chips and engines) will provide solid energy performance competition across the board in many categories of general illumination products.

DOE SSL Commercial Product Testing Program

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