DOE Solid-State Lighting
Commercial Product Testing Program

Summary of Results:
Round 2 of Product Testing

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Round 2 of testing for the DOE Solid-State Lighting (SSL) Commercial Product Testing Program (CPTP) was conducted from March to May 2007. In Round 2 of the testing program, 13 products were selected for testing, representing a range of applications, designs, and manufacturers, continuing along the same lines of testing conducted in Round 1. [1] All luminaires and replacement lamps were tested with both spectroradiometry and goniophotometry. Testing also included measurements of surface temperatures (taken at the hottest accessible spots on the luminaire) and off-state power consumption. This testing does not include lumen depreciation testing or other forms of testing product reliability—these subjects will be addressed in future testing program studies.

The lighting testing laboratories were instructed to follow test procedures specified in LM-79 (IESNA Guide for Electrical and Photometric Measurement of Solid-State Lighting Products) which covers '…SSL fixtures as well as SSL sources used in conventional light source fixtures (e.g., replacement of screw base incandescent lamps).' [2] This method tests the luminaire or replacement lamp as a whole—as opposed to traditional testing methods that separate lamp ratings and system efficiency or as opposed to testing LED devices or arrays without control electronics and heat sinks. 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. Similarly for replacement lamps, the integration of LED devices, heat sinks, drive electronics, and optics within an integral replacement lamp impacts the performance of the LED components within the lamp. For these reasons, luminaire efficacy (efficacy of the whole luminaire or integral replacement lamp) is the measure of interest for assessing energy efficiency of SSL products, as specified in LM-79.

Products which are sold as luminaires are tested using the entire luminaire. Products which are sold as replacement lamps are mounted for testing in standard lampholders corresponding to the format of the replacement lamp and the measurement instrument used for a given test. Performance results for replacement lamps are thus for the bare lamp, to which appropriate fixture losses should be applied to determine the luminaire output for the replacement lamp installed in a given fixture.

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[1] The DOE Solid-State Lighting Commercial Product Testing Program Summary of Results: Pilot Round of Product Testing, December, 2006 and DOE Solid-State Lighting Commercial Product Testing Program Summary of Results: Round 1 of Product Testing, March 2007. Available online at http://www.netl.doe.gov/ssl/comm_testing.htm.

[2] The draft testing standard entitled "IESNA Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products," designated LM-79, is currently under review. This testing procedure is being developed by the Subcommittee on Solid-State Lighting of the IESNA Testing Procedures Committee (http://www.iesna.org/about/committees/) in collaboration with the ANSI Solid State Lighting Committee. This method describes the procedures to be followed and precautions to be observed in performing reproducible measurements of total luminous flux, electrical power, luminous efficacy (lumens per watt), and chromaticity, of solid-state lighting (SSL) products under standard conditions. It covers LED-based SSL products with control electronics and heat sinks incorporated, that is, those devices that require only AC mains power or a DC voltage power supply to operate. It does not cover SSL products that require special external operating circuits or external heat sinks.

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 Round 2 of testing.[3]

The selection of products for Round 2 was designed to provide initial insight into variability across units, to provide benchmarking data with respect to other light source technologies, and to allow for initial round-robin testing. To enable observation of variability across units, two samples were purchased and tested for each replacement lamp and for one luminaire. To enable a direct comparison between different light sources, one product was purchased and tested in both an LED version and a halogen version of the same desk lamp. To investigate variability due to testing equipment and methods, round-robin testing was conducted by all four pre-qualified independent testing laboratories on one replacement lamp and on one complete luminaire.

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.

[3] Detailed test reports for products tested under the DOE's SSL testing program can be requested online: http://www.netl.doe.gov/ssl/comm_testing_request.htm.

Table 1. DOE SSL CPTP ROUND 2 SUMMARY

Photometrics based on IESNA LM-79 draft for --Luminaires and replacement lamps --25º C ambient temperature	DOE TEST ID	Total Power (watts)	Output (lumens)	Efficacy (lm/W)	CCT	CRI
Replacement Lamps						
R30 Replacement Lamps						
R30 Replacement Lamp Warm	CPTP 07-08*	8.8	239.1	27.1	2945	71.8
R30 Replacement Lamp Cool	CPTP 07-09*	9.1	310.3	34.1	5973	81.9
R30 Replacement Lamp, Warm, RGB	CPTP 07-13*	15.6	405.6	25.9	2689	14.5[1]
R30 Replacement Lamp, Cool, RGB	CPTP 07-14*	13.8	351.6	25.4	4006	13.3[1]
A-lamp Replacement Lamps						
A19 Replacement Lamp	CPTP 07-06*	0.7	10.3	15.7	3161	70.4
A-lamp (~A17) Replacement Lamp	CPTP 07-12*	1.5	19.7	13.4	25263[2]	79.1
Downlights (complete luminaires)						
Downlight	CPTP 07-04	31.0	356.7	11.6	5964	76.4
Downlight	CPTP 07-05	26.2	662.2	25.3	4402	76.0
Desk-Task Lamps[3]						
Desk-Task	CPTP 07-16	4.4	74.5	16.9 [6.3]	5800	77.8
Desk-Task	CPTP 07-22	13.1	156.6	12.0 [5.1]	3204	74.3
Desk-Task, Halogen[4]	CPTP 07-10	38.3	351.2	9.2 [8.9]	2856	99.5
Other Application Categories						
Outdoor Wall	CPTP 07-01	5.6	92.2	16.3	2693	68.3
Refrigerated Display	CPTP 07-07*	40.7	1237.0	30.5	5261	69.7

*For products shown with an asterisk, two units were tested, results show average between two units. The extent of variation between units is discussed under ‘Variability and Repeatability’ below.

[1]Note that CRI value does not reflect color quality of white light for RGB sources.

[2]This high CCT value is not a typo, see section, ‘Measurements of Color Quality,’ below.

[3]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.

[4]Test 07-10 was conducted on a product with a halogen source for benchmarking purposes. This luminaire has the same fixture head as 07-22, with a different light source.

Observations and Analysis of Test Results

Energy Use and Light Output

The range in application and performance of luminaires included in Round 2 is vast, from very weak, A-lamp style replacement ‘bulbs’ that put out less lumens than a typical 7W incandescent night light or sewing machine bulb, to some impressive downlights providing output levels and beam characteristics that directly rival incandescent replacement flood lamps for downlights. There is a similar range of results on the efficacy side, from desk-task lamps which are less efficacious than halogens due to their significant off-state energy draws, to downlights and the refrigerated display light that can rival fluorescent technologies in efficacy and luminaire light output delivered to the application area. This vast divergence in applications and in product performance is a key point to remember: any comparison between SSL products and luminaires using more traditional light sources should rely on specific performance data for the luminaires in question. Generalizations can provide an indication of the overall progress of SSL technology and markets, but should not be relied upon to make decisions regarding SSL luminaires.

A discussion of the performance of the products tested in Round 2 is provided for each different application below, as well as more general discussions on the continuing lack of credibility found in manufacturer literature, and issues of color quality, electrical design, and variability and repeatability.

Lack of Credibility of Manufacturer Literature

In Round 1 of testing, major discrepancies were seen between the output and efficacy values published in marketing material and the actual tested values. In general, Round 2 results show little to no improvement in the accuracy or credibility of published values for output or efficacy, save a few examples: exactly two products tested in Round 2 had accompanying manufacturer literature which presented values for luminaire output and efficacy which were close to measured values. All other tested products that offered claims of efficacy and lumen output overstated efficacy by 25 to 35% and light output by 30 to 95%.

Marketing literature for some products does not include values for efficacy or light output, but includes statements that may be entirely misleading. For example, one flyer referring to a desk lamp states “…the advanced optics allow the LED system to use 70 percent less energy than a comparable incandescent unit, even though the two light sources have similar energy efficiency.” Another marketing article states that the same lamp “…produces more light than a 40-watt halogen bulb.” This desk lamp was tested in comparison to the same luminaire in a halogen version. While the LED version uses 65% less energy than the halogen unit when it is on, it provides less than half the light output of the halogen version and consumes over 2.5 W of power in the off-state—making it far less energy efficient and far dimmer than the incandescent version.

Similarly, marketing literature for a replacement A-lamp that was tested states “Electricity consumption reduced 80-90%.” Yet this lamp was found to have an efficacy of 13.4 lm/W—similar to an incandescent—so any reduction in electricity consumption from this lamp stems from the reduction in light output rather than efficiency gains. Furthermore, the lumen output of this lamp, less than 20 lumens, is less than 5% of a typical A17 or A19 lamp, making it unsuitable as a 'replacement' for most applications. The marketing literature about the product makes no mention of this.

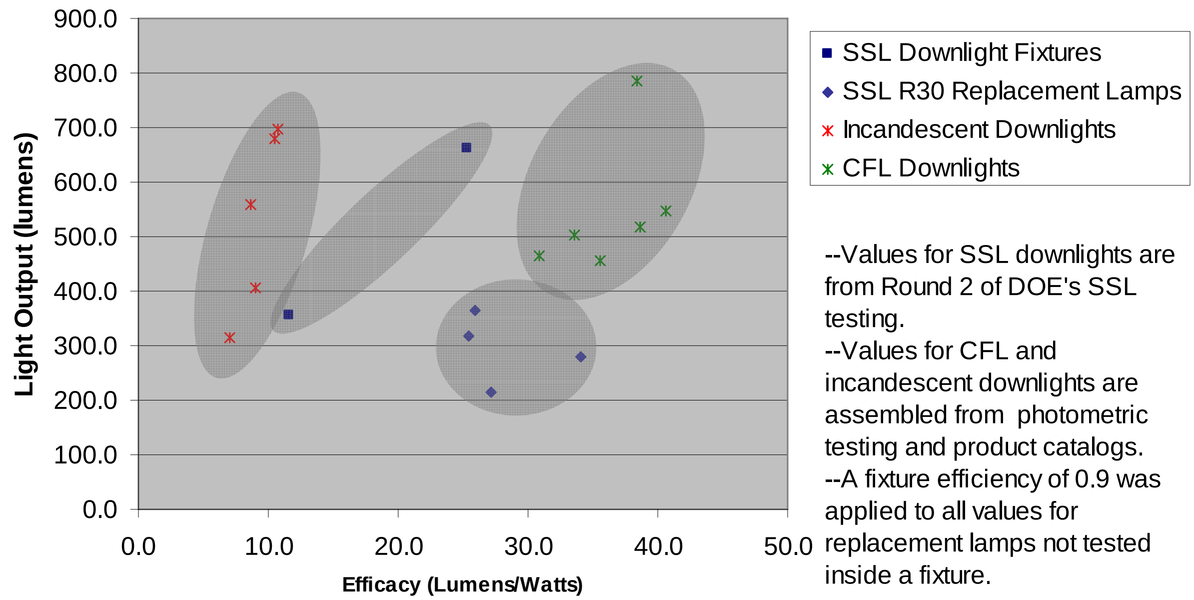
There may be a number of reasons for discrepancies between values published in marketing material and actual tested values:

- Lumen output and efficacy values in product literature may refer to the performance ratings of the LED device as published by the LED device manufacturer. Yet, there is currently no published standard testing method for measuring stand-alone LED device performance, and there is currently no consistent way to use the LED device performance values to accurately predict the performance the LED device when installed in a luminaire with power electronics and heat sinking.
- In some cases, marketing material clearly indicates that output and efficacy values are for the LED device and not for the luminaire. In some cases, marketing material does not indicate whether output and efficacy applies to the LED device or to the luminaire, leaving the data open to misinterpretation.
- Luminaire manufacturers may be publishing performance values from testing of luminaires conducted using methods or conditions that are very different from those specified in LM-79. In some cases, luminaire manufacturers specify the procedure they wish to have followed. In some cases, a testing laboratory may choose the procedure to follow but not yet be employing LM-79 (which is still a draft standard, not yet published and not yet familiar to some testing laboratories).
- Luminaire manufacturers may be publishing values which correspond to a product configuration that is not exactly the same as the production line version that was ordered and tested by the DOE testing program.
- Luminaire manufacturers may be inflating values to exaggerate performance.

Downlights and Replacement Lamps for Downlights

Figure 1 and the bullets below provide a general comparison between downlights based on Round 2 results. Note that these are very broad generalizations (not conclusions) to give a feel for where the industry is today. Such generalizations should never be used as a rule of thumb to compare one product to another. Comparisons must be done on a case-by-case basis due to the wide range in product performance, quality, and directionality, taking into consideration the specific requirements of a given lighting application.

Figure 1: Downlight Comparison: Light Output vs Efficacy



A general comparison (on average, without outliers) to similar **CFL reflector lamps** reveals the following:

- The SSL downlights and SSL R30 lamps have ½ to ¾ the efficacy of similar CFL lamps
- The SSL downlights and SSL R30 lamps are achieving ⅔ the output of similar CFL products on average
- The SSL downlights and SSL R30 lamps have tighter beam and field angles than the CFLs on average
- The SSL downlights and SSL R30 lamps have higher Center Beam Candle Power (CBCP) on average than the CFL lamps

Compared to similar **incandescent reflector lamps** (flood-style, not spot):

- SSL downlights and SSL R30 lamps achieve 2 to 3 times the efficacy of similar incandescent products
- SSL downlights and SSL R30 lamps are producing ⅔ to ¾ the output of similar incandescent products on average, though some SSL downlights surpass some incandescent downlights in output
- The SSL downlights and SSL R30 lamps tend to have a slightly wider beam angle than the incandescents (excluding one diffuse style of R30 replacement, the SSL average beam angle is 72 deg vs 60 deg in incandescents)
- The CBCP of SSL downlights and SSL R30 lamps is on average ¾ the CBCP of the similar incandescent products

For center beam candlepower, SSL lamps tested do not compete with 'PAR' lamps or 'reflector spot lamps', although the SSL lamp efficacies are higher and the overall lumen output of one downlight is as high as the output on some 40W and 50W PAR30s.

Close examination of results from LED downlights and R30 replacement lamps compared to similar incandescent and CFL products, reveals that the LED replacement lamps are generally still less 'focused' than the incandescents (i.e., competing incandescent reflector flood lamps tend to have tighter beam angles than LED replacement lamps), but the results are nuanced. We have tested two different R30 lines, with very different results for beam characteristics.[4] Basically, although some lamps use LEDs that emit light in a single hemisphere direction, they are still not at all focused in a tight beam—manufacturers have chosen wide angle LEDs in a product generally associated with directional lighting. This may reflect a choice on the part of manufacturers: that downlights, thought of as producing directional light, are very often used for large area lighting, and thus may be valued by users for having wide beam angles.

Figure 1 above highlights a wide divergence in performance across the products that were tested. Upcoming testing on more recent SSL downlights is expected to show more products that are close to or surpassing CFL products in output and efficacy.

Replacement A-Lamps

The two types of SSL replacement A-lamps tested very poorly. Both products had light output levels far below what would be expected in a replacement lamp for an A-lamp and one had a CCT value which placed it markedly outside the standard range for white light.

Task-Desk Lamps

As in Round 1 of testing, the results vary from product to product, but generally do not meet performance expectations, particularly if we consider off-state power use. One halogen desk lamp (07-10) was tested to provide a point of comparison, being a similar model to one of the SSL desk lamps (07-22), from the same manufacturer. Both of the two SSL desk lamps tested in Round 2 provide considerably less light output than a halogen or CFL desk lamp (¼ to ½ the output), and both have a cooler color temperature and lower CRI than the halogen desk lamp. In particular, both SSL desk lamps consume significant off-state power, making them less efficacious than the halogen desk lamp under average conditions of use (e.g., being used 5 hours or less per day).

Outdoor Lamps

One outdoor wall lamp tested in Round 2 demonstrated a lamp design which takes advantage of the low profile of LED technology—not restricted to the concept and dimensions of an Edison based socket and lamp. While we currently have no benchmarking available for outdoor wall lamps, based on the wattage of replacement lamps typically used in outdoor wall lamps, this lamp would be expected to exceed incandescent and halogen efficacy by 2 to 3 times, with probably ½ to ¾ the efficacy expected in a similar luminaire using a CFL source. Note that characteristics such as the cold temperature performance and longer life (particularly in cold

[4] Detailed test reports present CBCP values and intensity distribution curves. They can be requested online: http://www.netl.doe.gov/ssl/comm_testing_request.htm.

temperatures), and controllability (e.g., compatibility with dusk/dawn sensors) may be as important as efficacy factors for this application.

Refrigerated Display Case Lamps

We currently do not have data on fixture losses or delivered light for comparable fluorescent luminaires used in refrigerated display cases. Nevertheless, the luminaire efficacy (30.5 lm/W at 25° C) and intensity distributions of this luminaire place it within the range of competing with fluorescent for this application. Further testing was conducted to examine the luminaire at low temperatures, showing stable color quality and an improvement of 0.8% in efficacy at -5° C. Initial thermal imaging shows excellent heat management with almost no heat loss toward the front surface of the luminaire. SSL technology may be well suited to this application because of its comparative robustness: long life, improved performance in cold temperatures, dimmability, and insensitivity to frequent on/off cycling.

Measurements of Color Quality

ANSI chromaticity specifications define nominal CCT ranges for white light. Similar to the ANSI 7-step MacAdam ellipses which are used to define nominal white ranges for fluorescent light, draft ANSI C78.377A specifies eight nominal CCT quadrangles for solid-state lighting.[5,6] As shown in Figure 2, the quadrangles define ranges of CCT values and distances from the Planckian locus on the chromaticity diagram that are appropriate for solid-state lighting. These nominal CCT values range from 2700 K to 6500 K, (spanning 2600 K to 7000 K from the lower-most to the upper-most quadrangle limits). One of the products tested, sold as a white replacement lamp (similar in size to an A17 or A19 lamp), had CCT values far beyond the nominal CCT ranges—one unit was measured at 14588 K and the other at 35938 K. This does not meet the standard criteria for white light even though it is being marketed as a white light. All of the other luminaires tested in Round 2 had CCT values ranging from 2619 K to 6039 K, with an average of 4059 K.

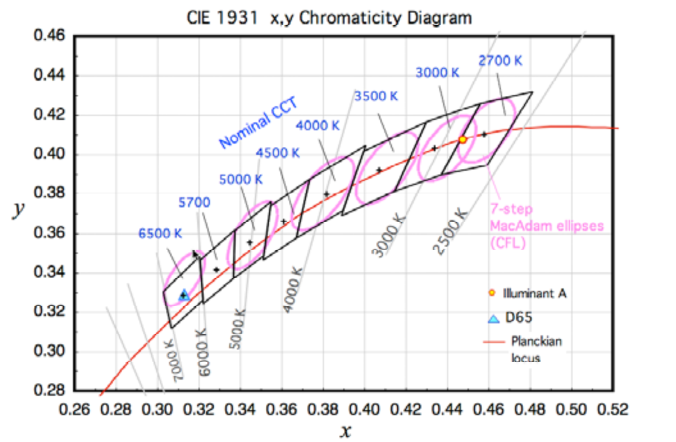


Figure 2. Draft Diagram Showing Eight Nominal CCT Quadrangles

The Color Rendering Index (CRI) of the luminaires using phosphor-conversion LEDs ranged from 68 to 84, with an average of 74. 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 of the limitations of CRI with regard to SSL technologies.[7,8]

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[5] American National Standards Institute: www.ansi.org.

[6] Dowling, Kevin. 2007. "Standards Required for Further Penetration of Solid-State Lighting." In *LEDs Magazine*, April 2007, pp. 28-31.

[7] 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.

Qualitative visual assessment by human observers may provide important insight regarding the suitability of color quality of a luminaire for a given application, particularly for RGB luminaires for which CRI should not be used.

Electrical Design

Off-state Power Consumption

Off-state power consumption, also called standby power consumption or 'vampire' loading, refers to power drawn by an electronic device while it is, in essence, switched off. Some electronic devices do need to power circuitry in permanence for control purposes or for other functional purposes, but many electronic devices consume power when turned off simply due to inefficient electrical design. In most cases, there is no functional reason for lamps and luminaires to draw power when they are turned off.

All products which incorporate an on/off switch are 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. In Round 2, one desk lamp was tested in both the halogen and LED models (07-10 and 07-22, respectively). While the LED version had slightly better efficacy than its equivalent halogen model, its off-state power use was very high (2.54 W), making it much less efficacious than the halogen model for any typical usage (such as 3 hours on per day). Even the other desk lamp which was tested would not out-perform the halogen desk lamp with a usage of 5 hours per day due to its off-state power consumption of 1 W. None of these desk lamps included features that would justify a need for off-state power.

Table 2. Effective Average Efficacy Due to Off-State Power Use

		Measured Efficacy w/ Power On (lm/W)	Power Consumed 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 07-10 Task/Desk	*Halogen*	9.2	0.16	8.4	8.9	9.0
CPTP 07-22 Task/Desk	LED	12.0	2.54	2.2	5.1	6.9
CPTP 07-16 Task/Desk	LED	16.9	1.06	2.6	6.3	8.9

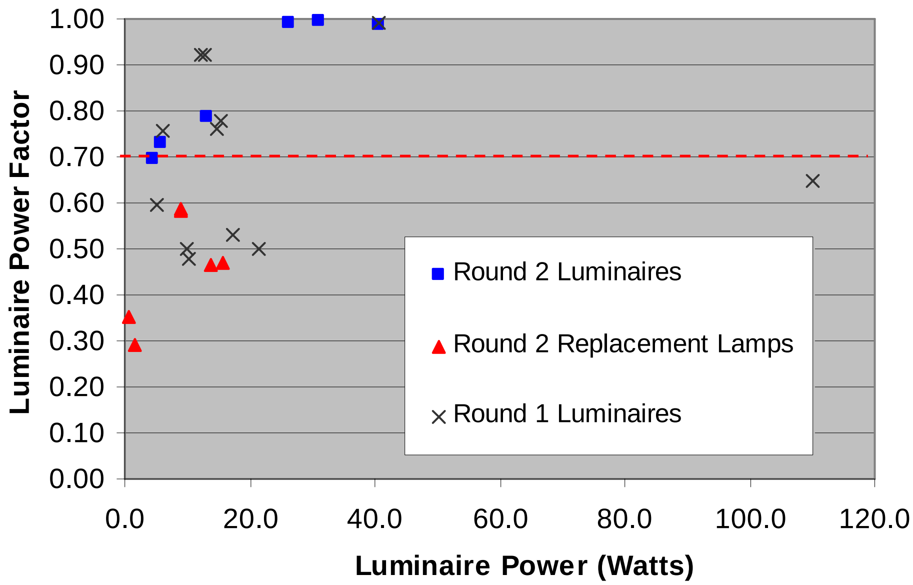
Note that units operated for fewer hours per year may consume less energy, despite lower efficacies.
Lamps 07-10 and 07-22 are the same format from the same manufacturer, one with a halogen source and the other using an LED source.

[8] Narendran N, Deng L. 2002. Color rendering properties of LED light sources. Proc. of SPIE: Solid State Lighting II.

Power Factor

The average power factor of all SSL products tested to date is 0.7—equal to the minimum power factor currently required in the draft "ENERGY STAR® Program Requirements for Solid-State Lighting Luminaires."[9] The power factors are plotted in Figure 3 below, with a dashed red line representing this ENERGY STAR criteria limit at 0.7. All of the Round 2 products that are integral fixtures (as opposed to screw in replacement lamps) have power factors of 0.7 or higher; all of the Round 2 products that are replacement lamps have power factors below 0.7. In particular, the A-lamp style replacement lamps have very poor factors, below 0.4.

Figure 3. Power Factor vs Wattage for CPTP tested SSL Luminaires



Variability and Repeatability

Two samples of each replacement lamp were tested to check for variability across units. In addition, three luminaires have been tested for variability to date (performing the same tests on two samples of a given luminaire). Excluding luminaires with very low levels of light output (i.e., excluding products that provide less than 30 lumens of light), the variability in output and efficacy between units of the same product has averaged less than 4%. For luminaires with very low levels of light output, (three products with outputs less than 30 lumens have been tested to date), the variability between units is much larger, averaging 10 to 15% variability of output and efficacy across units. With respect to color qualities, for non-RGB products with CCT values in the white range (up to 7000K), the variability of both CCT and CRI values across units was on average 1% or less.

[9] ENERGY STAR® Program Requirements for Solid State Lighting Luminaires Eligibility Criteria (draft 04/09/07) is available online: http://www.netl.doe.gov/ssl/energy_star.html.

Four independent lighting testing laboratories were pre-qualified to perform CPTP testing. Round-robin testing by each of these laboratories is being conducted on one integral downlight and one R30 replacement lamp to gain knowledge about variability stemming from testing equipment, geometries, and methods. Initial round-robin testing commenced in Round 2 has provided insight and feedback for standards groups such as the IESNA Solid-State Lighting Subcommittee of the Testing Procedures Committee. This feedback contributes to refining testing methods and to identifying areas where clarification or additional standards may be needed.

Conclusions from Round 2 of Product Testing

Key Points

Round 2 of the DOE's testing of commercially available solid-state lighting products has revealed examples of both excellent and dismal performances. Some downlights and directional replacement lamps produce light output comparable to similar incandescent and CFL downlights, while significantly surpassing the incandescents and approaching the CFLs in efficacy. On the other hand, a number of non-directional replacement lamps (A-lamps) perform very poorly and do not produce enough light output to be suitable replacements for any similar products in use today. Refrigerated display case and outdoor wall lamps that were tested performed quite well, while SSL desk lamps still tend to compare poorly due to their use of power in the off-state. This vast divergence in applications and in product performance provides a key point to remember: any comparison between SSL products and luminaires using more traditional light sources should rely on specific performance data for the luminaires in question. Generalizations can provide an indication of the overall progress of SSL technology and markets, but should not be relied upon to make decisions regarding SSL luminaires.

SSL product performance cannot be easily generalized. The large divergence in performance characteristics means that buyers will need to consider the performance of each product separately and require clear (and accurate) luminaire performance information from manufacturers.

Unfortunately there is still a wide disparity between performance claims in marketing literature and actual tested luminaire performance. While a few manufacturers are publishing credible values for luminaire output and efficacy, many are still making wild and misleading claims.

The poor results for omni-directional, A-style replacement lamps reinforce DOE's decision to emphasize whole luminaire measurements. Poorly performing products are seen when SSL technology is introduced without sufficient attention toward treating it as an integrated system. A well designed, integrated system for SSL technology can be designed into a complete luminaire or a replacement product—that is, designers need to consider thermal management, drivers, optics, the LED sources and their directionality as an integrated system and performance measurements need to assess the integrated system.

Next Steps for Testing
Upcoming SSL product testing will continue to encompass products in a range of categories. Further benchmarking tests will be conducted to improve our understanding of how SSL test results compare to similar results for products using other light sources. 'In situ' style testing and lumen depreciation testing will be conducted to better assess the effectiveness of thermal management and the long-term performance behavior of selected products. Round-robin testing across laboratories will continue to provide input to testing Standards Committees and convey lessons learned about SSL testing to other stakeholders.

Next Steps for the Industry
A problem with many designs is the off-state power use when there is no functional need for it. The small profile of SSL technology makes it particularly well adapted to applications like desk lamps that may not be connected to a wall power switch. This would imply that SSL will see significant market opportunities in applications that require an on/off switch, but the net end result on energy efficiency as compared to existing technologies will not improve—and may possibly worsen—if cost-effective designs are not found to eliminate off-state power consumption.

DOE and industry leadership will be applying "lessons learned from CFLs" to address the concerns raised by the subset of products that are underperforming or providing misleading performance information.[10] This focused effort may contribute to understanding why some products are under-performing, with luminaire efficacies that are 20 to 50% of the LED rated efficacy, which may lead to effective improvements in designs and their associated product literature.

[10] See the June 2006 report, "Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market," http://www.netl.doe.gov/ssl/publications/publications-lightingtechreports.htm.