CALiPER

SUMMARY REPORT

October 2007

DOE Solid-State Lighting CALiPER Program

Summary of Results: Round 3 of Product Testing

Prepared for the U.S. Department of Energy by
Pacific Northwest National Laboratory

DOE Solid-State Lighting CALiPER Program

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Round 3 of testing for the DOE Commercially Available LED Product Evaluation and Reporting (CALiPER) Program (formerly the SSL Commercial Product Testing Program) was conducted from June to August 2007. In Round 3 of the testing program, 24 products were selected for testing, representing a range of applications, designs, and manufacturers, continuing along the same lines of testing conducted in Rounds 1 and 2.[1] Luminaires and replacement lamps were tested with both spectroradiometry and goniophotometry when possible. Testing also included measurements of surface temperatures (taken at the hottest accessible spots on the luminaire) and off-state power consumption. Lumen depreciation and other product reliability testing are not included—these characteristics are being tested using other testing methods and will be addressed in future reports.

Testing Methods

The lighting testing laboratories were instructed to follow test procedures specified in the draft LM-79 standard (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 fixture 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 particularly 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 sold as luminaires are tested using the entire luminaire. Products sold as replacement lamps are mounted for testing in standard lampholders corresponding to the format of the

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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, and "DOE Solid-State Lighting Commercial Product Testing Program Summary of Results: Round 2 of Product Testing," August 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.

replacement lamp and the geometry of 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.[3]

Selection of Products for CALiPER Round 3

The general policy of the CALiPER program is to test units of products which are commercially available and have been purchased by the CALiPER program through distributors or other market mechanisms. In some cases sample products are accepted for testing, either because there is no market for purchasing small quantities of a product or because other DOE SSL programs request CALiPER testing of fixture samples. Detailed CALiPER test reports always indicate whether a product tested was purchased or was a sample product. Detailed CALiPER test reports are issued only for those products that are considered to be commercialized (available or soon to be available for purchase on the open market).

For Round 3 of CALiPER testing, a number of units tested were samples submitted to DOE in the context of other DOE SSL Commercialization Support activities, such as the Lighting for Tomorrow 2007 SSL Competition and the Technology Demonstrations Program. Round 3 products that were conducted for these purposes are identified as such in Table 1. All other products in Round 3 were purchased (anonymously from distributors or manufacturers) as per CALiPER's product acquisition policy.

To enable benchmarking comparison to other light source technologies, Round 3 also included two CFL downlights and two undercabinet fixtures equipped with fluorescent tubes. To enable observation of variability across units, two samples were purchased and tested for two replacement lamp products, for one downlight retrofit lamp and for three luminaires.

Round 3 CALiPER Testing Results

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 CALiPER in Round 3 of testing.[4]

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.

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3 De-rating factors for specific fixtures or fixture and lamp combinations are not specified, recommended nor studied by the DOE at this time.

4 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.htm.

Table 1. DOE SSL CALiPER ROUND 3 SUMMARY						
Photometrics based on IESNA LM-79 draft for --Luminaires and replacement lamps --25º C ambient temperature	DOE CALiPER TEST ID	Total Power (watts)	Output (lumens)	Efficacy (lm/W)	CCT	CRI
Directional Replacement Lamps & A-lamp Replacement Lamps						
Replacement Lamp MR16	07-17*	3.9	77	20	6381	80
Replacement Lamp E27	07-18*	8.6	180	21	7878	77
Replacement Lamp Par30	07-19*	17.1	650	38	2854	52
Replacement Lamp A-lamp	07-23 retest**	0.7	33	48	3099	70
Downlights						
Downlight Retrofit Lamp (6” ø)	07-31*	11.8	719	61	2754	95
Downlight Retrofit Lamp (6” ø)	07-47	10.8	663	61	3402	91
Downlight (7.5” square)	07-35‡	15.5	553	36	3442	81
Downlight (4” ø)	07-42	6.3	101	16	2719	66
Downlight (CFL) (5” ø)	07-15	12.8	346	27	3928	79
Downlight (CFL) (6” ø)	07-21	12.2	514	42	2729	82
Task Lamps						
Task-Desk	07-33‡	10.2	430	42 [38]	3631	71
Undercabinet	07-27‡	6.4	281	44	6842	78
Undercabinet	07-28‡	6.4	264	42	4044	79
Undercabinet	07-29‡*	6.4	218	34	2797	79
Undercabinet	07-30‡*	21.1	760	36	3328	83
Undercabinet	07-32‡	8.0	344	43 [24]	3552	71
Undercabinet	07-36‡	8.7	265	31	2767	70
Undercabinet (T5 fluorescent)	07-20	18.9	689	36	3015	84
Undercabinet (T5 fluorescent)	07-41	11.6	235	20	5734	71
Outdoor Fixtures						
Outdoor Wall	07-25‡	70.5	3758	53	6145	77
Outdoor Wall	07-34‡	4.7	124	27	3270	70
Outdoor Area	07-26‡	188.6	9808	52	--	--
Outdoor Parking	07-24‡	116.4	6272	54	5948	76
Outdoor Path	07-37‡	4.3	24	6	3792	77

All output, efficacy, CRI, and CCT values are rounded to the nearest integer for readability in this table.

Tests 07-15, 07-20, 07-21, 07-41 were conducted on CFL and fluorescent fixtures for the purposes of benchmarking.

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.

Outdoor Area fixture 07-26 TD was not tested for color qualities in an integrating sphere due to fixture size and weight.

See “Downlights and Replacement Lamps for Downlights”, below, for details on the geometries and configurations of the various downlight units.

* 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.

** 07-23 is a newer version of lamp 07-06 which was tested in Round 2, retested at the manufacturer’s request.

‡ For products shown with a cross, testing was conducted on sample units submitted in the context of DOE SSL Commercialization programs including Lighting for Tomorrow and Technology Demonstrations.

Observations and Analysis of Test Results: Overall Progression in Performance of Products

Energy Use and Light Output

Round 3 testing included luminaires representing a wide range of applications, with a wide range of wattages as indicated in Table 2. Naturally, the variation in measured performance across this spread of products is significant, in part due to the differences in application and power level of these products and in part due to significant differences in performance even across products designed for the same application and with the same general power levels. These wide variations reinforce the need for rigorous and consistent performance metrics. Until these metrics become widely adopted by the industry, application specific decisions regarding SSL alternatives must be made carefully following analysis of candidate product performance and other relevant data.

Table 2. Wide Range of Luminaire Characteristics Tested in CALiPER Round 3

	from		*to*
Power	0.7 W	↔	189 W
Output	24 lm	↔	6272 lm
Efficacy	6 lm/W	↔	62 lm/W
CCT	2700	↔	>7000
CRI	52	↔	95

Many of the products tested in Round 3 show clear progress in performance compared to products tested in earlier rounds of testing, demonstrating appropriate levels of light output particularly for applications benefiting from the directionality of LEDs (e.g., task lights, downlights, and outdoor area lights). In these applications, the SSL products tested clearly surpass incandescents in luminaire efficacy and are now able to equal and, for some products, surpass CFLs and fluorescent luminaires in luminaire efficacy. The benchmarking tests allow for side-by-side comparison of the performance of SSL and CFL or fluorescent tube products. The specific points of comparison are detailed for each application below.

Performance Reports in Manufacturer Literature

In Rounds 1 and 2 of testing, major discrepancies were observed between the light outputs and efficacies published by manufacturers and their CALiPER-tested performance. In Round 3 of CALiPER testing, this discrepancy is less apparent. For the 17 products whose efficacy or output data are published by the manufacturer, only four present values that considerably overstate performance (ranging from 35-90% overstated). Seven products have marketing literature presenting performance data within + or – 10% of the CALiPER measured results. Four products have performance values published in marketing literature that are significantly lower than measured through CALiPER (i.e., they may be understating the actual performance of their products), a case which was not seen in prior testing.

The majority of products with accurate marketing literature (± 10% of CALiPER values) were sample products that had been submitted to DOE in the context of SSL commercialization support programs, so the superior accuracy may reflect the higher level of engagement of these manufacturers, or the fact that submissions to these programs explicitly required accurate performance reporting.

The appearance of products which are understating performance may be due to the rapid changes in LED chip technologies—manufacturers that are frequently updating their products with new and improved chips may not be reflecting those improvements immediately in marketing literature. The understatements of performance may also stem from a lack of understanding of SSL technologies and SSL testing. Or perhaps the CALiPER-tested product performs significantly better than the average product of that model as a consequence of LED performance variability within a product batch.

As suggested in our Round 2 report, for the products with overstated published values for performance, the divergence from actual tested values may stem from a number of issues:

- Misinterpretation or lack of experience relative to SSL testing concepts (LED device performance vs. luminaire performance, lamp efficacy vs. luminaire efficacy…)
- Lack of industry standardization in LED device performance testing and reporting and infeasibility of determining luminaire performance based on reported LED device performance
- Inconsistent specification parameters of LED performance by specifiers including luminaire manufacturers.
- Confusion or lack of clear distinction in marketing literature between LED device performance and luminaire performance
- Use of inconsistent testing methods including alternatives to LM-79 (such as Japanese or Chinese standards) that may yield different results
- Manufacturers product literature may not clearly indicate what specific product configuration was tested to produce the performance values published (e.g., differences in LED devices, drivers, and optics may greatly influence results)
- Possible inflation of performance claims (or selection of test conditions not representative of actual use; e.g., chilled or pulsed device testing)

The observed general increase in accuracy of SSL luminaire performance claims in Round 3 may be primarily an artifact of the specific pool of products selected and tested for this round, but it may also be an indication that product literature is starting to improve. Time will tell whether this trend toward more accurate reporting continues to be observed in subsequent rounds of CALiPER testing.

With respect to manufacturer literature for the benchmark fluorescent products, one industry norm for these traditional light sources is to publish lamp efficacy and then fixture/system losses can be applied to determine overall luminaire efficacy. CALiPER testing measures luminaire efficacy directly based on total luminaire light output and power measured at the wall plug (or rated voltage AC input). Using the luminaire efficacy measured in CALiPER testing and the manufacturer published lamp efficacies for these benchmark products, their fixture/system losses can be estimated. On average, the fixture/system loss based on the difference between CALiPER measured luminaire efficacy and manufacturer published lamp efficacy for these products was 59% (ranging from 40-67%). Such high observed fixture/system losses argue for the consistent reporting of luminaire efficacy for all light sources, particularly for products which are directional in nature.

Downlights and Replacement Lamps for Downlights

Round 3 testing included six SSL products for downlight applications (2 complete downlight fixtures, 2 downlight retrofit lamps, and 2 Edison socket directional replacement lamps) and 2 CFL downlight fixtures (both are ENERGY STAR® Qualified Fixtures and selected to represent 'typical' CFL downlights).[5] All units were tested under similar conditions, using absolute photometry on the complete luminaire. The differences in geometry and configurations of these downlight products should be kept in mind when comparing their performance results. The two downlight retrofit lamps are integral units which include light source, trim, reflector, diffuser, heat sink and means of support/attachment within a typical existing 6" diameter aperture downlight housing. Accordingly, fixture losses should not be applied to these units (although a small thermal loss may be applicable—to be determined by future CALiPER testing). One of the SSL downlight fixtures tested (CALiPER #07-42) is a 4" diameter aperture product. The other SSL downlight fixture tested (#07-35) is in a square 7.5"x 7.5" housing. Of the two CFL downlights included in Round 3, the lower output fixture has a 5" diameter aperture, and the other is 6". Replacement lamps and retrofit lamps were mounted in simple lampholders for testing.

As in earlier rounds of testing, a wide range of performance was observed, from the lowest performing SSL downlight producing 101 lumens of light with an efficacy of 16 lm/W to the highest performing SSL downlight retrofit lamp producing 719 lumens with an efficacy of 61 lm/W. Figure 1 plots the luminaire output and Figure 2 plots the luminaire efficacy for thirteen SSL downlight products of various geometries tested by CALiPER to date. The plots illustrate the wide range of performance observed across these products—another reminder to be cautious about generalizations regarding product performance.

While there is still a wide range of product performance, a number of these products rival CFLs and the 2 downlight retrofit lamps (one warm white and one neutral white version of the same product) substantially surpass CFL downlights in performance. The two CFL downlights tested to provide benchmarks have luminaire outputs of 346 and 514 lm respectively and luminaire efficacies of

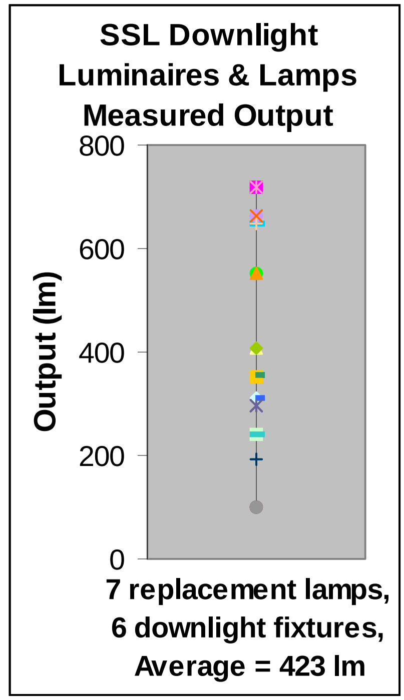


Figure 1. Range of Output of 13 SSL Downlight Products (from CALiPER Rounds 1-3)

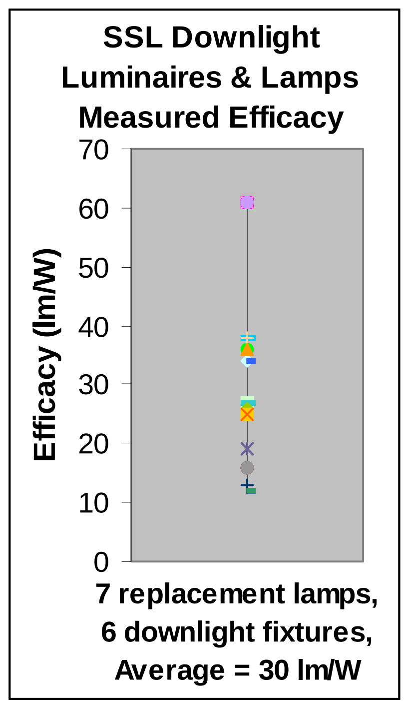


Figure 2. Range of Efficacy of 13 SSL Downlight Products (from CALiPER Rounds 1-3)

[5] See the Energy Star Residential Light Fixture listing, http://www.energystar.gov/index.cfm?c=fixtures.pr_light_fixtures.

27 and 42 lm/W. The average output, 423 lm, of the 13 SSL products (shown in Figure 1) is within the range defined by these two CFL benchmarks, as is the average luminaire efficacy, 30 lm/W (shown in Figure 2). Thus, comparing the CFL benchmark examples to the SSL downlight products, on average the SSL product performance falls between the two CFL examples. The best SSL downlight product, tested in Round 3, clearly has higher efficacy and output than both CFL examples.

With respect to color qualities, the CFL benchmarks represent both the warm white and cool white CCT ranges, as do the SSL products. The CRIs for the CFL and SSL products vary. The highest performing SSL product has a much higher CRI—95—than the CFL examples, while one SSL product tested in Round 3— using phosphor-converted LEDs (as opposed to red-green-blue)—has a CRI of only 52 (see below for discussion on "Measurements of Color Quality") .

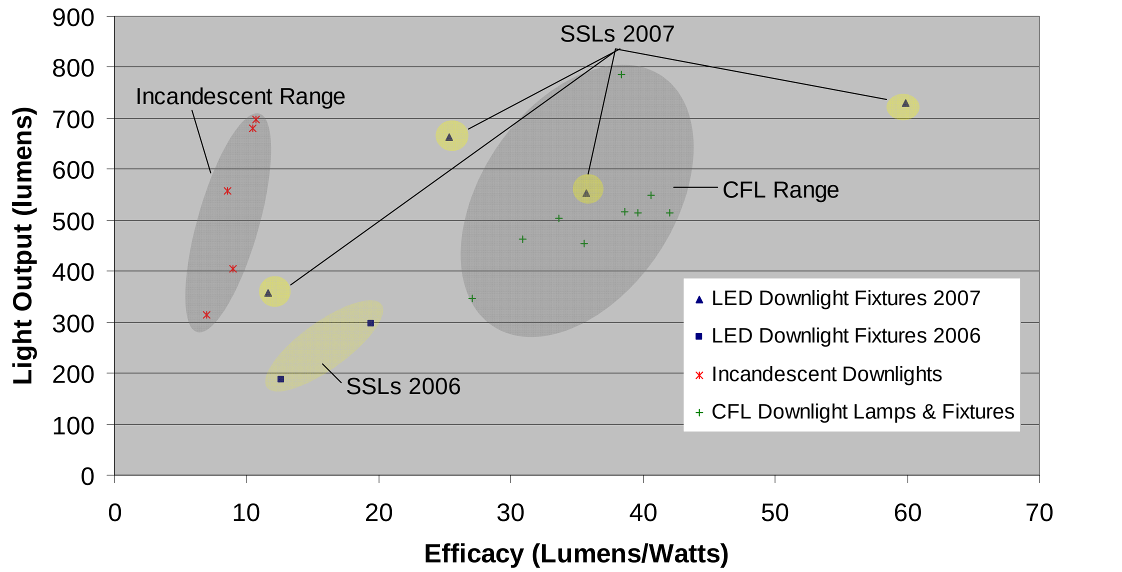
For beam characteristics, all except one of the Round 3 SSL downlight products provide a Center Beam Candle Power (CBCP) higher than the two CFL benchmarks. Based on estimates of luminaire CBCP for luminaires equipped with flood-style incandescent and halogen reflector lamps, on average the Round 3 SSL downlight products have values for CBCP similar to incandescent reflector lamps, but less than halogen reflector lamps. The beam angles of the SSL products range from fairly narrow (28°) to fairly wide (106°). The CFL benchmarks both had fairly wide beam angles (84° and 124°). On average, the beam angles of the Round 3 SSL products were slightly higher than the beam angles of flood-style incandescent reflector lamps.

Figure 3 provides a visual illustration of SSL downlight performance as compared to similar CFL and incandescent products. The data points for SSL products are all obtained from CALiPER testing. The data points for CFL and incandescent downlights are obtained from a combination of CALiPER testing, earlier DOE photometric testing and product catalogs. The grey 'clouds' serve to provide a general picture of the range of operation of CFL and incandescent downlights and to remind us that for each of these general types of product, actual performance can vary widely.

A general comparison of SSL downlights to similar CFL and incandescent downlights based on the data provided above and Figure 3 reveals the following:

- A wide range in product performance is observed in SSL products so comparisons must be done on a case-by-case basis, taking into consideration the specific requirements of a given lighting application.
- The SSL downlights clearly surpass the incandescent products in efficacy.
- The SSL downlights and SSL directional replacement lamps have efficacies similar to CFL downlights (with one SSL product clearly exceeding CFL luminaire efficacy).
- The SSL downlights and SSL directional replacement lamps achieve similar light output to CFL and incandescent downlights, on average.
- Some of the SSL downlights and SSL R30 lamps have tighter beam and field angles than the CFLs.
- The SSL downlights and SSL R30 lamps have higher Center Beam Candle Power (CBCP) than the CFL lamps.

Figure 3. Benchmarking for Downlight Comparisons



* *Values for SSL downlights are from CALiPER testing.*

** *Values for CFL and incandescents are assembled from CALiPER testing, earlier photometric testing and product catalogs (of 45W-65W incandescent products and CFL equivalents).*

*** *A fixture efficiency of 0.9 is applied to all replacement lamps unless tested inside a fixture.*

Upcoming testing on SSL downlights is expected to show more products that are close to or surpassing CFL products in output and efficacy. Further testing is also underway to examine aspects of reliability and in situ performance and to provide more side-by-side comparisons of downlights using different light sources.

Non-Directional Replacement Lamps

One A-lamp style replacement lamp was tested in Round 3. This lamp is the newer version of lamp 07-06 which was tested in Round 2.[6] The output (33 lm) and efficacy (48 lm/W) of this product are over 3 times what they were for the earlier version. Nevertheless, the light output level is still far below what would be expected in a replacement lamp for an A-lamp.

Task Lamps

Six SSL undercabinet fixtures, one SSL desk lamp, and two fluorescent undercabinet fixtures were tested in Round 3. All of the SSL task lamps tested in this round were sample products (either submitted to the Lighting for Tomorrow 2007 SSL Competition or submitted to the DOE's SSL Technology Demonstration Program). The two fluorescent undercabinet fixtures use

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[6] The CALiPER program allows manufacturers to request a retest on their products under the condition that the manufacturer pays for the testing and that the product to be retested is purchased anonymously by the DOE following normal CALiPER purchasing policies.

T5 fluorescent tube lamps and are sold as ENERGY STAR® Qualified Fixtures.[7] As with SSL luminaires, the fluorescent fixtures were tested as complete luminaires (including fixture, ballast, and lamp) to enable direct comparison of overall luminaire output and efficacy between SSL and fluorescent luminaires.

Table 3 presents the luminaire efficacy and output per lineal foot of all of the undercabinet fixtures tested in Round 3, from most efficacious to least. As samples submitted to programs with specific performance requirements, the performance of the SSL undercabinet fixtures tested here might exceed the average performance of SSL undercabinet commercialized today. Nevertheless, these results demonstrate that SSL undercabinet luminaires can clearly meet and exceed similar fluorescent products in both light output and luminaire efficacy, with similar color temperatures and CRI values.

Similarly, the SSL desk lamp tested in Round 3 (a product sample submitted to the Lighting for Tomorrow competition) has higher output and efficacy than halogen and CFL desk lamps tested in earlier rounds, even when losses due to off-state power use are considered (see further discussion about off-state power below). The efficacy of this SSL desk lamp is more than 4 times the efficacy of a halogen desk lamp tested in Round 2.

Table 3. Performance of Undercabinet Luminaires Tested in Round 3 (Listed from most efficacious to least)

CALiPER Test Sample	*Manufacturer Published Efficacy (lm/W)*	Luminaire Efficacy (lm/W)	Output per lineal foot (lm)	CCT
07-27 (SSL)	--	44	293	6842
07-32 (SSL)	*36-38*	43 [24]*	197	3552
07-28 (SSL)	--	42	275	4044
07-30 (SSL)	--	36	525	3328
07-20 (T5 fluorescent)	*100 (lamp)*	36	230	3015
07-29 (SSL)	--	34	227	2797
07-36 (SSL)	*28.6*	31	133	2767
07-41 (T5 fluorescent)	*53 (lamp)*	20	134	5734

* Adjusted efficacy values in brackets [ ] include the effect of measured off-state power consumption assuming 3 hours on-time per day.

[7] See the Energy Star Residential Light Fixture listing, http://www.energystar.gov/index.cfm?c=fixtures.pr_light_fixtures. The fixture used for CALiPER test 07-20 was tested using the high efficiency lamp received with the fixture. The fixture used for CALiPER test 07-41 was not shipped with a lamp, so a typical T5 lamp was purchased for use in this test.

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 continuously 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 (outside of specific applications), there is no functional reason for lamps and luminaires to draw power when they are turned off.

All products incorporating an on/off switch are tested for off-state power consumption. Each of the SSL desk lights and one of the SSL undercabinet lights with an on/off switch tested to date consume energy in the off-state. Four CFL and halogen products tested for benchmarking purposes include an on/off switch; of these four products, two consume off-state power. Two SSL products tested in Round 3 are designed to work in conjunction with an occupancy sensor, so the off-state power use would be reduced if these products are indeed used appropriately with such a sensor that would turn off power at the wall socket when the space is unoccupied.

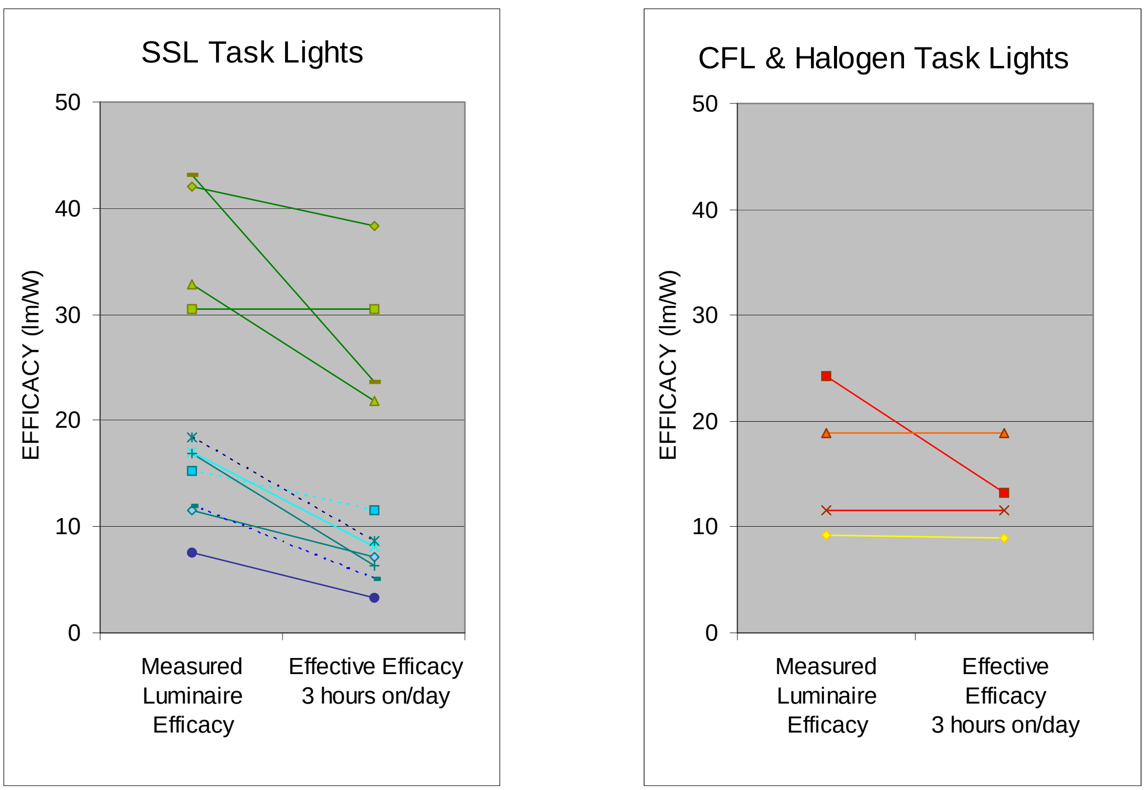

Figure 4. Efficacy and Effective Efficacy with Off-State Power Use of Desk Lamps and Undercabinet Lights Comporting On/Off Switches

Figure 4 illustrates the effective reduction in efficacy due to off-state power use for the products tested to date based on the example case of 3 hours of luminaire 'on' time per day. The right hand and left hand portions also provide a visual comparison of the off-state power use for SSL task lights as compared to fluorescent and halogen task lights.[8] The halogen desk light that was tested has a very small off-state power use, while the CFL desk light has significant off-state power use. The two fluorescent undercabinet lights do not consume off-state power. One SSL undercabinet light with an on/off switch does not consume off-state power. All other tested SSL desk lights and undercabinet lights with on/off switches consume off-state power.

Unfortunately, the highest performing SSL task light also has the highest off-state power use, so its effective efficacy (based on total power use both during on and off hours) drops to a level not much better than the luminaire efficacy of fluorescent task lights (though still better in effective efficacy than any of the tested fluorescent task lights).

If these SSL luminaires did not consume off-state power, all but one would exceed the halogen and the lower performing fluorescent task light benchmarks in efficacy. Due to off-state power use, only the four highest efficacy SSL luminaires clearly outperform the halogen and fluorescent task lights in effective efficacy.

Outdoor Lamps

Five products targeting outdoor applications were tested in Round 3, from a low wattage path light to a high wattage outdoor area light. Table 4 summarizes the performance of these luminaires and includes the results from two previous tests of outdoor luminaires.

While we currently have no benchmarking examples available for outdoor wall lamps, based on the wattage of replacement lamps typically used in outdoor wall lamps, the SSL wall lamps would be expected to exceed incandescent and halogen efficacy by 2 to 3 times, and at least equal the efficacy expected in similar luminaires using a CFL source.

The luminaire efficacy of the SSL outdoor path light tested in this round is very low, possibly not meeting the performance of similar luminaires using other light sources.

The larger SSL area and parking lights provide suitable output for these applications with an efficacy exceeding 50 lm/W. Future benchmarking and in situ evaluation is expected to provide insight as to the comparative performance of these products with other technologies used for large outdoor area and parking lights. Additional characteristics such as the cold temperature performance and longer life (particularly in cold temperatures), controllability (e.g., compatibility with dusk/dawn sensors), color, and low level lighting performance may be as important as efficacy factors for this application.

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8 The luminaire efficacy measured during photometric testing does not take into account continued power usage by a product when the product has been turned “off”. The true luminaire efficacy or ‘effective efficacy’ of a product depends on the hours of use.

Table 4. SSL Outdoor Lights, Round 3 (results from earlier testing rounds included in grey)					
	Manufacturer Published Efficacy	**Efficacy (lm/W)**	**Output (lumens)**	**CCT (K)**	**CRI**
		Outdoor Area			
07-26, Area	*55 lm/W*	52	9808	--	--
06-05, Area	*24 lm/W*	24	2638	4661	*20 (RGB)*
		Outdoor Parking			
07-24, Parking	*55 lm/W*	54	6272	5948	76
		Outdoor Wall			
07-25, Wall	*55 lm/W*	53	3758	6145	77
07-34, Wall	*40 lm/W*	27	124	3270	70
07-01, Wall	--	16	92	2693	68
		Outdoor Path			
07-37, Path	--	6	24	3792	77

Measurements of Color Quality

The products tested in Round 3 are fairly evenly distributed across the different ranges of white light, from warmer (~2700-~3000K ranges), to mid-range (sometimes referred to as soft or neutral white, ~3500-~4000K ranges), to cold (~5700-~6500K ranges). [9,10] One product had a CCT value of 7878K, higher than the ANSI defined nominal CCT ranges for white light.

The average CRI of SSL products tested in Round 3 is 76, with a minimum at 52 and maximum at 95. No luminaires based on Red-Green-Blue (RGB) LEDs for white light generation were tested in Round 3. 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.[11,12] 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.

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[9] ANSI chromaticity specifications define nominal CCT ranges for white light. Similar to the ANSI 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. The nominal CCT values specified for solid-state lighting range from 2700 K to 6500 K, (spanning 2600 K to 7000 K from the lower-most to the upper-most quadrangle limits). American National Standards Institute: www.ansi.org.

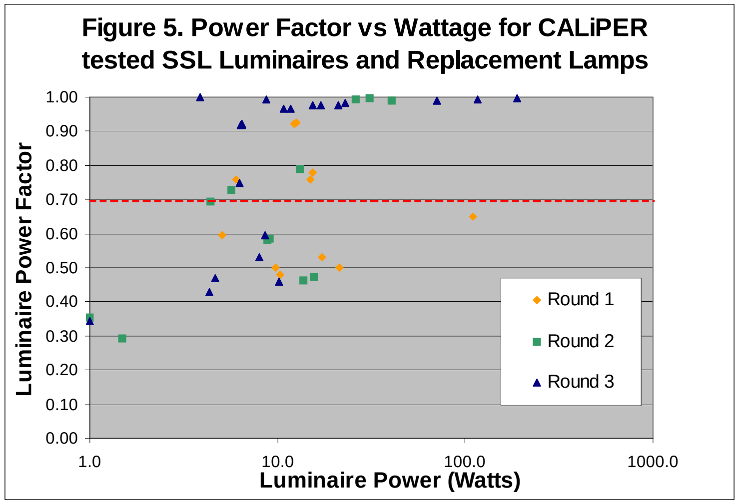
[10] Dowling, Kevin. 2007. "Standards Required for Further Penetration of Solid-State Lighting." In *LEDs Magazine*, April 2007, pp. 28-31.

[11] 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.

[12] 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 0.75—exceeding the minimum power factor, 0.7, currently required for residential products in the "ENERGY STAR® Program Requirements for Solid-State Lighting Luminaires."[13] The power factors of all SSL products tested to date are plotted in Figure 5, with a dashed red line representing this ENERGY STAR criteria limit at 0.7. (The ENERGY STAR power factor requirement for commercial sector SSL products is 0.9.) The x-axis in this figure is logarithmic in order to include the higher wattage luminaires. The measured power factors range from 0.3 to 1.0. A small correlation is now observable between power factor and luminaire power (similarly, between power factor and efficacy): in general, the higher wattage and higher efficacy SSL products have power factors exceeding 0.9.



Variability and Repeatability

Whenever possible, luminaire and replacement lamp outputs were measured both in an integrating sphere and a goniophotometer. As in earlier rounds of testing, the average variation between goniophotometer and integrating sphere measurements for output on a given luminaire or replacement was approximately 2%. In 90% of the Round 3 tests, the goniophotometer provided a slightly higher lumen output measurement than the integrating sphere. Variation observed between goniophotometry and sphere measurements was slightly higher for fluorescent benchmark samples than for SSL samples, and, on average, slightly higher for lower output devices than for higher output devices.

For three types of replacement lamps, two types of luminaires, and the downlight retrofit lamps two samples of each product were tested to evaluate variability across units. Two products—the replacement lamps with the lowest output and efficacy—exhibited significant variation in light output, efficacy and color qualities between 2 units. For all other products, the difference in output and efficacy between two units was 4% or less and the difference in color quality measurements was less than 2%.

[13] ENERGY STAR® Program Requirements for Solid State Lighting Luminaires Eligibility Criteria Version 1.0 (09/12/07) are available online: http://www.netl.doe.gov/ssl/energy_star.html.

Conclusions from Round 3 of Product Testing

Key Points

Round 3 of CALiPER testing included a very wide range of products for a wide variety of applications, from a low wattage 0.6 W replacement lamp to a 189 W outdoor area light. While the majority of products tested in Round 3 performed quite well, some products performed poorly. Because of the wide variation in performance, it is essential for buyers to request explicit indications of luminaire output and luminaire efficacy from vendors. Application-specific decisions regarding SSL alternatives must be made carefully following analysis of product performance.

On average, the SSL downlights are providing light output levels on par with 45-65W incandescent reflector lamps, and greatly surpassing them in efficacy. They are also now clearly rivaling similar downlight CFLs, with one SSL product significantly surpassing the CFL benchmarks in performance.

The Round 3 results also show that SSL undercabinet and desk lights are now able to perform better than benchmarked halogen and fluorescent task lights, and would do so even more consistently if their off-state power consumption were eliminated.

We can note several products tested in Round 3 that would meet the criteria for luminaire output, luminaire efficacy, and color quality requirements of the ENERGY STAR® Program requirements for Solid State Lighting.[14] Version 1.0 of the ENERGY STAR requirements for SSL defines requirements for a number of application categories: undercabinet (kitchen and shelf-mounted), desk lamps, downlights, and outdoor (step, path, and porch). In the downlight category, CALiPER fixtures 07-31, 07-35, and 07-47 would meet the criteria. In the undercabinet category, fixtures 07-27, 07-28, 07-29, and 07-30 would meet the criteria. In the outdoor categories, fixtures 07-25 and 07-34 would meet the criteria. Although the ENERGY STAR qualification process has not yet commenced for SSL products, observing which fixtures would meet the criteria's photometric requirements can serve as a useful reference point at this time.

Product literature regarding SSL luminaires and replacement lamps is still inconsistent and does not always provide reliable or straightforward product performance information. However, the significantly more accurate performance claims seen in product literature for products that were submitted as samples to the DOE SSL commercialization support programs (for SSL demonstrations and Lighting for Tomorrow) is encouraging.

While the generally strong performance of Round 3 SSL products implies great promise for the upcoming generations of commercially available SSL luminaires, SSL product performance still should not be 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 for each product under consideration.

[14] ENERGY STAR® Program Requirements for Solid State Lighting Luminaires Eligibility Criteria Version 1.0 (09/12/07) are available online: http://www.netl.doe.gov/ssl/energy_star.html.

Next Steps for Testing

Upcoming CALiPER testing will continue to explore a range of lighting applications. More extensive benchmark testing will be conducted to enable side-by-side comparison of SSL products with other technologies in each application area. Lumen depreciation and 'in situ' style testing is underway for a number of products to assess thermal management and long-term reliability of SSL luminaires and replacement lamps.

CALiPER tests that assess testing variability, repeatability, and divergence will continue to be analyzed and used to provide feedback to testing laboratories, standards committees, and other stakeholders. CALiPER testing is also underway to assess SSL luminaire reliability through lumen depreciation and in situ testing.

Next Steps for the Industry

Participating in industry trade groups and in DOE SSL commercialization projects or informational venues can clearly provide manufacturers with a better understanding of SSL technology. This increased awareness and understanding can lead to more accurate assessment and reporting of product performance.[15]

DOE and industry leadership are starting to address the concerns raised by the subset of products that are underperforming or providing inaccurate or misleading performance information, exploring ways to provide guidance for consistent reporting of product performance, from the LED device level to the luminaire level. For example, guidance may be established to advise luminaire manufacturers to measure and report luminaire output and luminaire efficacy (and label the values as such), and to be clear about what testing methods have been employed and what version of a product was tested.

[15] On-line resources for relevant industry and DOE efforts include:

- The Next Generation Lighting Industry Alliance (NGLIA): http://www.nglia.org/
- Fact sheet on LED standards (with links to standards efforts) and other relevant fact sheets: http://www.netl.doe.gov/ssl/publications/publications-factsheets.htm
- Lighting for Tomorrow Competition: http://www.lightingfortomorrow.com/
- ENERGY STAR® for Solid State Lighting Luminaires: http://www.netl.doe.gov/ssl/energy_star.html

DOE SSL Commercially Available LED Product Evaluation and Reporting Program

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