DOE Solid-State Lighting
CALiPER Program

Summary of Results:
Round 4 of Product Testing

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Round 4 of testing for the DOE Commercially Available LED Product Evaluation and Reporting (CALiPER) Program (formerly the SSL Commercial Product Testing Program) was conducted from September to December 2007.[1] In Round 4 of the testing program, 20 products were selected for testing, comprising 15 SSL replacement lamps and luminaires representing a range of applications, and five luminaires using fluorescent or halogen sources to provide benchmark comparisons. All products were tested with both spectroradiometry and goniophotometry using absolute photometry.[2] Testing also included measurements of surface temperatures (taken at the hottest accessible spots on the luminaire) and off-state power consumption.

Round 4 testing includes five SSL replacement lamps (a candelabra lamp, a T8 drop-in replacement, and three MR16 lamps), two downlight products, several desk lamps and undercabinet fixtures, and a number of diverse outdoor luminaires. The results from this round of testing are nuanced: while the performance is quite disappointing for a few products and none show overall exceptional performance, many positive and encouraging points have been highlighted.

Round 4 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 4 of testing. 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. Further details on each set of testing results and related manufacturer information are assembled in a detailed report for each product tested.[3]

These results are analyzed and discussed below, in the broader context of test results from earlier rounds of testing and with respect to particular areas of interest — product performance in different application categories, measurements of color quality, power factors, and repeatability and variability of SSL testing.

An initial, interim report on reliability testing is provided as well, presenting a first look at *in situ* and lumen depreciation testing that is being conducted through the CALiPER program.

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[1] Summary reports for Rounds 1-3 of DOE SSL testing are available online at http://www.netl.doe.gov/ssl/comm_testing.htm.

[2] Please see the Appendix for more detailed description of CALiPER testing methods and product selection processes.

[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 CALiPER ROUND 4 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 (initial lumens)	Efficacy (lm/W)	CCT	CRI
Replacement Lamps						
Replacement - T8	07-56*	25	1058	42	3494	75
Replacement - MR16	07-53*	3	82	27	3007	74
Replacement - MR16	07-59*	9	133	16	3338	89
Replacement - MR16	07-64*	3	75	26	3458	74
Replacement - Candelabra	07-57*	2.2	28	13	2855	71
Downlights						
Downlight (2" ø)	07-61	2.5	29	11	6401	67
Tracklight (RGB, Tunable CCT)	07-50**	40	672	17	tunable	n.a.
Task Lamps						
Desk	07-52	20	321	17 [13.1]	5804	74
Desk	07-54	7	89	12 [9.2]	4472	87
Desk	07-55	10	148	16	4390	88
Desk (CFL, 18W GU24)	07-49	16	700	43	2819	81
Undercabinet	07-51***	3.5	89	26	5147	66
Undercabinet	07-62†	2.8	150	46	8204	82
Undercabinet (T5-Flourescent)	07-60	16	360	23	3865	60
Outdoor & Other Fixtures						
Outdoor Area	07-43	71	2310	33	6394	79
Outdoor Streetlight	07-63	170	6294	37	5223	75
Outdoor Wall (CFL 13W GU24)	07-48	14	639	46	2648	83
Step/Wall LED	07-38‡	16	154	10	5166	73
Step/Wall (CFL 13W GU24)	07-39‡	12	199	16	3956	77
Step/Wall (Halogen 20W)	07-40‡	23	174	8	3085	98

All values are rounded to the nearest integer for readability in this table.

Tests 07-39, 07-40, 07-48, 07-49, and 07-60 were conducted on CFL, fluorescent, or halogen 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.

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.

** 07-50 is a product providing 6 selectable color temperatures (2652, 2945, 3444, 3921, 4862, and 6247 K). Results for power, output, and efficacy in this table are averaged over all six positions. Product uses Red-Green-Blue LEDs to create white light, so CRI is not applicable.

*** 07-51 consists of four light bars that can be operated together or separately. Testing of one light bar alone resulted in an output of 23 lm and efficacy of 20 lm/W. With four bars connected, output is 89 lm and efficacy is 25.7 lm/W.

† 07-62 has a measured luminaire efficacy of 54 lm/W with an input voltage of 12VDC, a transformer loss of 85% is applied.

‡ Tests 07-38, 07-39, and 7-40 are all conducted on the same fixture model available in three different versions each using a different light source.

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

Energy Use and Light Output

As in previous rounds of SSL product testing, Round 4 testing included luminaires representing a wide range of applications, operating characteristics and performance levels, as illustrated in Table 2. While some products tested in Round 4 show progress in performance compared to products tested a year ago, half of the products tested in this round are still achieving efficacy levels that are only slightly more than would be expected in similar products using halogen sources. Similarly, when considering appropriate light output levels and color characteristics for each application, about half of the products tested in Round 4 would be suitable substitutes for products using other sources, while half would have levels of output that might be considered too low or color qualities that might be inappropriate as compared to products using traditional sources for the same application. Results from this and earlier rounds of CALiPER testing show that it is possible to design SSL products that can solidly compete (on output, efficacy, and color levels) with products using traditional sources. Unfortunately, many SSL products on the market today are not using SSL technology to its full advantage. With these wide variations in product performance, purchasing decisions regarding SSL alternatives must be made carefully following analysis of candidate product performance and other relevant data.

Table 2. Range of SSL Luminaire Characteristics Tested in CALiPER Rounds 1-4

	from		*to*
Power	0.7 W	↔	189 W
Output	23 lm	↔	9808 lm
Efficacy	4 lm/W	↔	62 lm/W
CCT	2600	↔	>7000
CRI	n.a. (RGB)	↔	95

In applications that can benefit from the directionality of LEDs—such as task lights, downlights, and outdoor lights—Round 4 testing has revealed both SSL products that provide suitable levels of light output and those that provide insufficient light output for their intended application. For these applications, the SSL luminaire performance can be compared to luminaire performance from benchmarking tests on luminaires using other light sources; benchmarking calculations for luminaire performance based on manufacturer IES files; and knowledge about fixture efficiencies and ballast factors for fixtures using other light sources. The specific points of comparison are detailed for each application below.

Performance Reports in Manufacturer Literature

In earlier rounds of testing, discrepancies were observed between the light outputs and efficacies published by manufacturers and their CALiPER-tested performance. In Round 4 of CALiPER testing, these discrepancies continue to abound. Fifteen SSL products were included in this round; the remaining five products, tested for benchmarking purposes, use fluorescent or halogen sources. Out of the 15 SSL products, the accuracy of manufacturer performance reporting can be summarized as follows:

- Accurate performance reporting (1): One manufacturer provided accurate performance information for its luminaire (CALiPER 07-43—publishing luminaire output and efficacy values within 10% of the CALiPER measured results).
- No performance reporting (4): For four products, no manufacturer-published information was found regarding output or efficacy.
- Understated performance reporting (1): For one product, the manufacturer literature understated the output and efficacy of its SSL product by 50%.
- Overstated performance reporting (9): For the other nine SSL products, information published by manufacturers regarding product output and/or efficacy overstated performance (by factors ranging from 30-600%).

For the manufacturer who understated product performance, detailed below under "Step/Wall," the understatements of performance appear to stem from a lack of understanding of SSL technologies and SSL testing. In using relative photometry, as opposed to the recommended absolute photometry for SSL, the photometric report from the manufacturer inappropriately presented values for lamp lumens and for fixture efficiency for this product, resulting in calculations for luminaire performance which understated the actual luminaire output and efficacy by 50% in this case.

For the nine manufacturers who published overstated performance information, some compared the outputs of their products to incandescent products; some have published explicit, but inaccurate, values for the output or efficacy of their luminaire; and some have published values for output or efficacy, but have omitted to indicate what the values correspond to (i.e., they may be publishing a 'lamp' output for the LED devices, without explicitly stating that). A number of manufacturers claim their products provide equivalent output to a 20W halogen MR16 or 15-25W incandescent, yet, based on CALiPER testing, they only produce one-sixth to one-half the output expected from such incandescent or halogen lamps. In another case, a 170W outdoor luminaire which has a measured output of 6294 lumens claimed to be 'equal to HPS (high pressure sodium) lumen efficiency' of 13800 lumens. Through this claim, the manufacturer may be trying to account for the HPS luminaire losses (due to directionality and optics), spectral differences between HPS and LED sources, and effects of initial vs. mean lumen output, but the consumer may be misled or confused by such a comparison made without further explanation.

As suggested in earlier reports, 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 (e.g., LED device performance vs. luminaire performance, lamp efficacy vs. luminaire efficacy, relative photometry vs. absolute photometry)
- Lack of industry standardization in LED device performance testing and reporting and infeasibility of determining luminaire performance based on reported LED device performance
- 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)

Addressing and resolving these issues should be of vital concern to SSL manufacturers. Performing appropriate SSL testing and providing accurate, understandable information regarding product performance will increase confidence in SSL technology. Continuing to provide inaccurate or misleading SSL product performance information may undermine market acceptance of this new technology in the long term.[4]

Replacement Lamps

Three different types of replacement lamps were tested in Round 4: a drop-in replacement lamp for T8 fluorescent tubes, three different SSL MR16 products, and a candelabra lamp. The basic photometric measurements from CALiPER testing for these 5 products are summarized in Table 3, along with the performance values for these products suggested in product literature (specification sheets or Web pages). For all of these products, manufacturer literature does not provide an accurate description of the product performance.

Table 3. Summary of Round 4 Replacement Lamp Performance

Replacement Lamps	Manufacturer Reported Performance	CALiPER Measurements					
		Power (W)	Output (lm)	Efficacy (lm/W)	CBCP (cd)	CCT	CRI
SSL T8	~ 2800 lm (~112 lm /W)	25	1058	42	--	3494	75
SSL MR16	120-150 lm (25-31 lm/W)	3	82	27	283	3007	74
SSL MR16	150-200 lm (20-25 lm/W)	9	133	16	220	3338	89
SSL MR16	"Equivalent to Halogen 20W MR16"	3	75	26	59	3458	74
SSL Candelabra	"Equivalent to 15-25W incandescent"	2.2	28	13	--	2855	71

The T8 drop-in replacement can be inserted directly in a ballasted fixture designed for fluorescent T8 tubes. While lamp efficacy of 48-inch fluorescent T8 tubes can typically range from around 50-95 lm/W, fluorescent tubes emit light over 360°, so the luminaire efficacy of a fixture equipped with fluorescent T8 tubes would be less than these lamp ratings. The SSL T8 product's measured efficacy is 42 lm/W (much less than would be implied by manufacturer

[4] An example of this danger is described in the DOE report on lessons learned from CFLs, "Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market," is available online: http://www.netl.doe.gov/ssl/publications/publications-lightingtechreports.htm.

literature, which claims an output of 2800 lm for 25 W power draw — which would imply 112 lm/W). Round 5 of CALiPER testing will test SSL T8 drop-in replacements and benchmark fluorescent T8 tubes in troffers to enable direct comparison between the two sources used in fixtures. The Round 4 testing of this drop-in lamp was not performed in a fixture, so a reference ballast was used. Further testing of this and similar products in Round 5 will use typical magnetic and electronic ballasts (in troffers), as well as the reference ballast measurements.

The SSL MR16 products all claim to be replacements for halogen 20W MR16 lamps, but do not produce output levels or center beam candle power at levels that would typically be seen in 20W MR16 halogen lamps. Considering only 20W, flood-style, 40° halogen lamps, IES files from lamp manufacturers indicate outputs ranging from 200-450 lm, center beam candle power (CBCP) of around 500, and efficacies of 9-19 lm/W.[5] Across the three SSL MR16 products that were tested, the output and CBCP are, in general, less than half of what would be typical of traditional products used in this application: the highest output was 133 lm (averaged over two units of the same product) and the highest CBCP was 283 cd. Two of the SSL MR16 products have efficacies which are indeed higher than halogen MR16s, and the third has an efficacy similar to the high end of halogen efficacies. Surface temperature measurements taken on the heat sinks of these products indicate relatively high operating temperatures ranging from 54-83° C —indicating that *in situ* and lumen depreciation testing should be conducted to study the reliability of these products.

The SSL candelabra replacement lamp that was tested purports to be equivalent to 15-25W incandescent lamps, but only produces 28 lm — where the 15-25W incandescents would typically produce 120-210 lm. The efficacy of the SSL candelabra replacement lamp is about 50% higher than would be expected in similar incandescent products, but only about one-third the efficacy of a CFL candelabra lamp. With a low wattage level, 2.2 W, this product may be particularly suited for decorative lighting applications,where higher wattage incandescent or fluorescent products would be over-dimensioned, but with its low output level, it should not be considered to be a direct replacement for traditional candelabra lamps.

Downlights

The two products included in the 'downlight' category in Round 4 are quite different from each other: first, a product sold as a 2-inch diameter recessed downlight; second, a track light offering six, tunable color temperatures of white light.

While the 2-inch diameter downlight product literature claims that it provides 90% of the light of a 20W halogen MR16 lamp (which would typically provide 200-450 lm), the output measured in CALiPER testing is less than 30 lm. Its efficacy is similar to the low end of the expected efficacy range for a similar halogen product, and its measured correlated color temperature is 6401 K (even colder than the manufacturer's specified value of 5500 K for this product). The low power level, 2.5W, of this product may make it a suitable option for decorative applications requiring

[5] IES files for a range of halogen MR16 products were studied. Only 20W, flood-style lamps are used in this comparison because they have the lowest output and CBCP values, so they are the only types of halogen MR16 products which SSL MR16 products come close to competing with at this time.

very low power and output levels, but it should not be considered as a direct replacement for any halogen or fluorescent downlight products.

The tunable track light that was tested creates white light using RGB (red-green-blue phosphors) LED technology and provides a simple switch which can be used to immediately select any one of six color temperatures: 2652, 2945, 3444, 3921, 4862, and 6247 K. The product also includes a dimmer switch. The light output (622-711 lm, depending on the CCT selected), narrow beam (19°) and CBCP (~6000 cd, depending on the CCT selected) of this 40W SSL track light allow it to compete squarely with 75 W (and possibly higher wattage) incandescent reflector lamps and reflector halogen lamps (with similar beam characteristics such as ‘narrow flood’ or ‘spot’). While the measured output and efficacy of this product are about 30% less than the values announced in product literature, it still has better efficacy than similar incandescent and halogen products and provides color tunability and dimming controls.

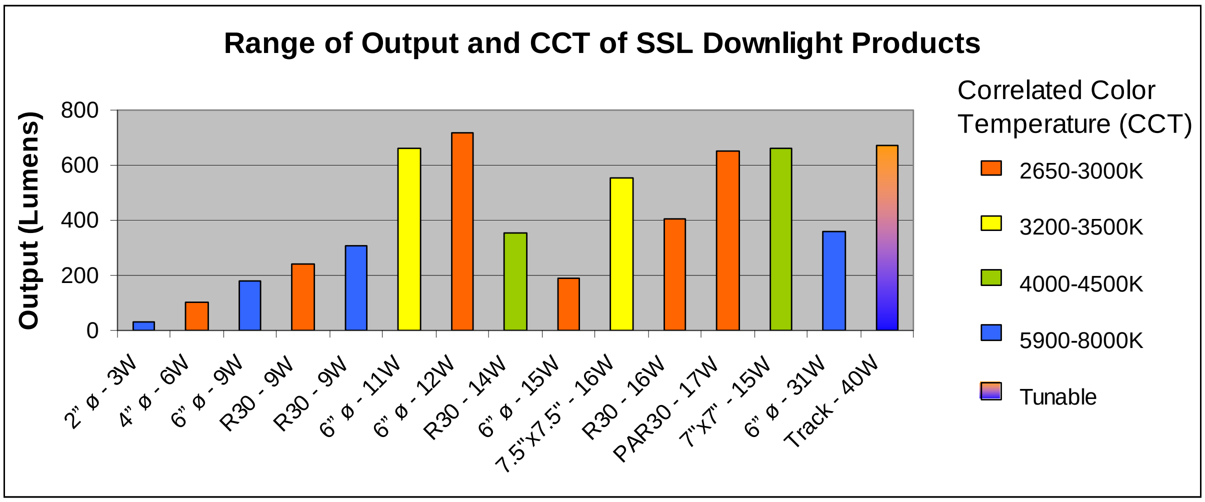


Figure 1a. Outputs and Color Temperatures of SSL Downlights, Rounds 1-4

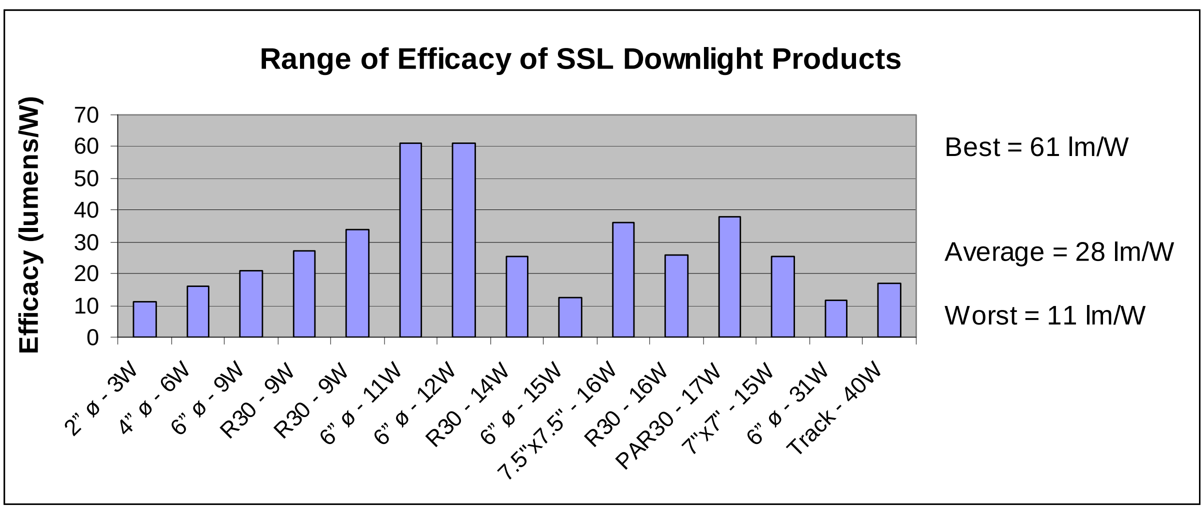


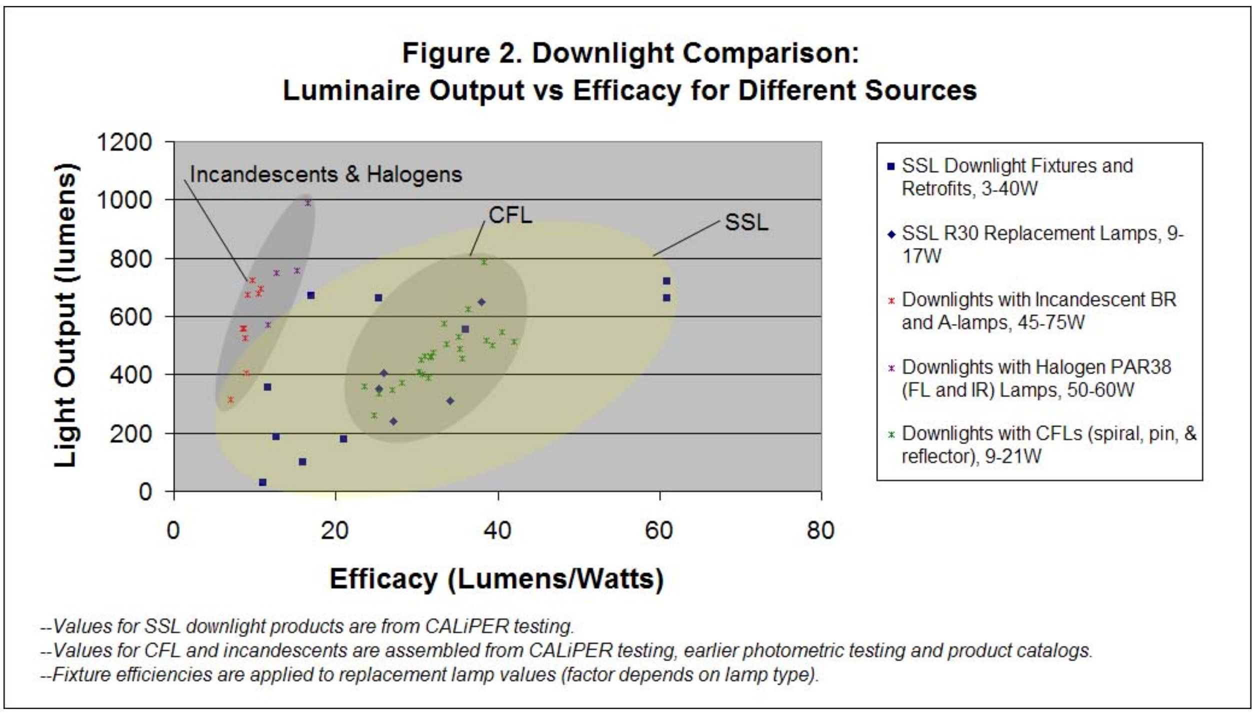
Figure 1b. Efficacies of SSL Downlights, Rounds 1-4

(The two downlight products tested in Round 4 are the right-most and left-most products)

Figures 1a and 1b allow us to put these two products (right-most and left-most in Figures 1a and 1b) in perspective with respect to all other SSL downlight products which have been CALiPER tested, showing the range of outputs, color temperatures, and efficacies of each of the different products tested to date. These figures indicate the size and wattage of each product as a reminder that these products vary in configuration.

The spread of CCT values in Figure 1a demonstrates that output and efficacy of these luminaires and replacement lamps do not necessarily depend on the color temperature of a product. That is, the ability to produce higher efficacies with colder temperature LED devices is not translated to the end product level, where efficacies appear more to be a factor of the overall system design, including heat sinking, drivers, choice of LEDs, and optics. Similarly, the smaller products are not the most efficacious, even though, in theory, they should generate less heat and thus be easier to design efficaciously.

Figure 2 goes one step further in summarizing the outputs and efficacies of SSL downlight products, along with similarly dimensioned products using incandescent, halogen, and CFL light sources. While the variation across SSL downlight products is very large, almost all equal or surpass incandescents in efficacy, with the majority falling within or above the range of comparable CFL downlight products.



Task Lamps

Round 4 of testing included three SSL and one CFL desk lamps, and two SSL and one fluorescent undercabinet fixtures; both CFL and fluorescent task lamps are ENERGY STAR®

qualified products.[6] None of the SSL task lights tested in Round 4 meet ENERGY STAR criteria for their niche application categories — each misses the mark on efficacy, output, off-state power and/or CCT requirements.[7]

The three SSL desk lights tested in this round provide outputs ranging from 89 to 321 lm, and efficacies from 12-17 lm/W (if off-state power is not considered).[8] Unfortunately, two of these products draw power in the off-state, reducing their effective efficacies to levels not much better than incandescent or halogen products. One SSL desk light, 07-55, is the first SSL desk light tested to date in the CALiPER program that does not draw off-state power. The CFL desk lamp that was tested provides significantly more output with about three times greater efficacy than these three desk lamps.

The two SSL undercabinet lights tested in this round provide outputs of 89 and 150 lm, and efficacies of 26 and 46 lm/W.[9] Both have fairly cold color temperatures, but the higher efficacy fixture provides a very cold 'white' CCT of 8204 K.

Figure 3 summarizes the efficacy performance of all of the task lights tested to date in the CALiPER program, indicating both the measured efficacy and the calculated effective efficacy based on the example case of 3 hours of luminaire 'on' time per day. The left-hand side of this figure includes six SSL undercabinet fixtures and 11 SSL desk lamps. The right-hand side includes three fluorescent tube undercabinet fixtures, two CFL desk lamps, and one halogen desk lamp. Most of the fluorescent task lights are designed to use no off-state power, as are most of the SSL undercabinet lights, but the SSL desk lamps almost all have significantly reduced effective efficacy because of the power they draw when they are in the off-state.

While there is quite a range in task light efficacy, Figure 3 shows that SSL undercabinet products perform as well or better than fluorescent undercabinet products with regard to efficacy. Over this small set of products, the SSL undercabinet products are on average smaller wattage and shorter in length than the fluorescent undercabinet products. Out of the products tested to date, the SSL undercabinets have slightly lower output per linear foot, slightly lower CRI, and slightly higher (colder) correlated color temperatures.

For the desk lamps, due to off-state power use, only the four highest efficacy SSL luminaires clearly outperform the halogen task lights in effective efficacy. Only one SSL desk lamp tested to date rivals the CFL energy star desk lamp that was tested in Round 4.

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[6] See the ENERGY STAR® Residential Lighting Fixture program website: http://www.energystar.gov/index.cfm?c=fixtures.pr_light_fixtures.

[7] 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.

[8] 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.

[9] Note that undercabinet product 07-62 is sold as a 12 VDC product. The measured efficacy using 12 VDC input is 54 lm/W. A transformer efficiency factor of 85% is applied to obtain 46 lm/W.

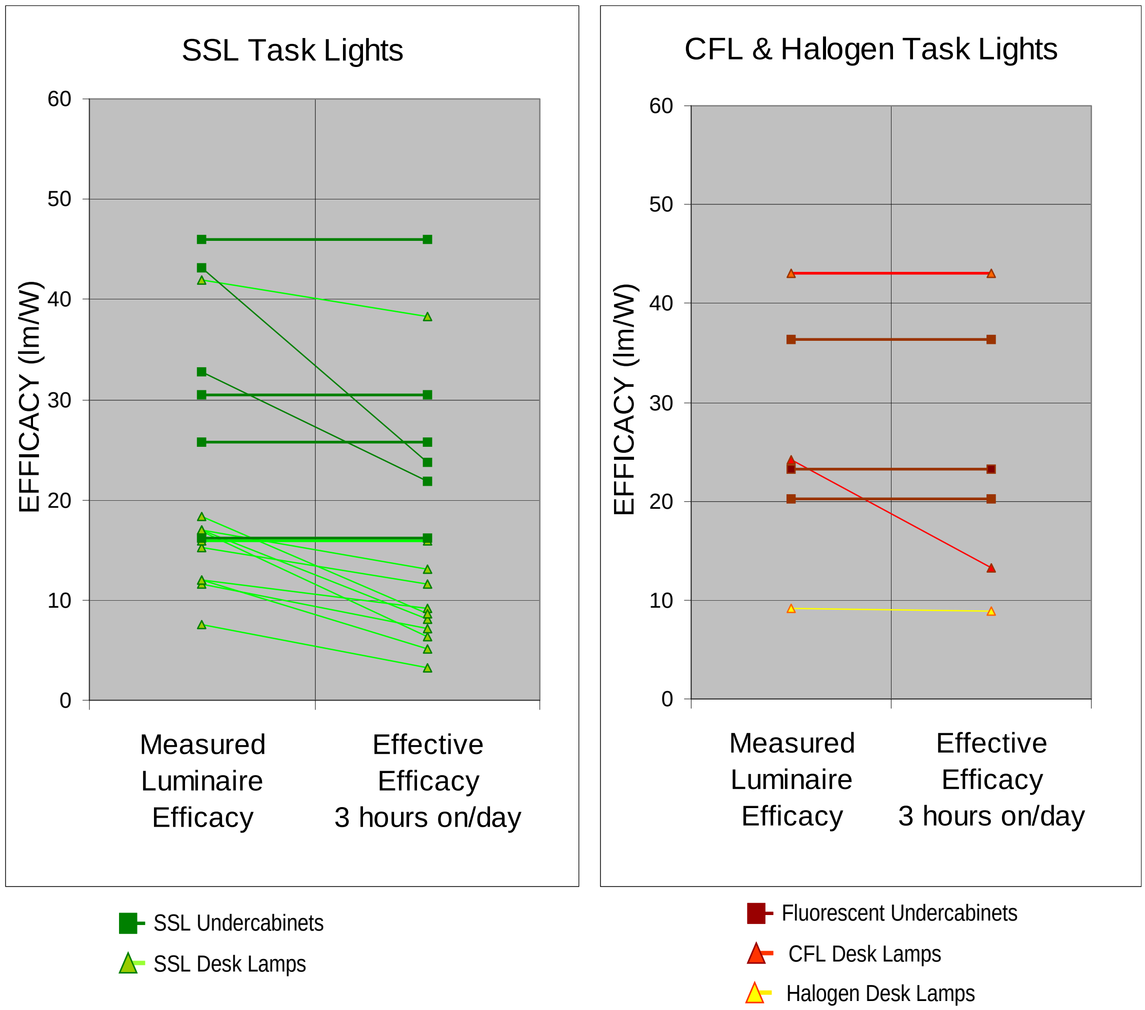

Figure 3. Efficacy and Effective Efficacy with Off-State Power Use of Desk Lamps and Undercabinet Lights Comporting On/Off Switches

Outdoor & Other Fixtures

Three different types of outdoor fixtures were included in Round 4: two higher wattage outdoor lights (one 'area' light and one 'street' light), one CFL ENERGY STAR qualified outdoor wall light (tested for benchmarking purposes), and three recessed wall lights (all the same basic model, using three different sources—LED, halogen, and CFL).

Figure 4 provides a visual summary of the output and efficacy levels of the higher wattage outdoor fixtures tested in Rounds 1-4. The shaded, colored lines over-laying each graph provide points of reference, indicating levels of output and efficacy for similar wattage outdoor products that use other light sources. While a range of light sources, fixture types, and wattage levels are possible, these reference points provide a general indication of practical benchmark performance levels. Three of the six SSL outdoor products in these figures have output and efficacy levels that meet or surpass performance levels for similarly dimensioned products using more traditional sources. The two high wattage outdoor fixtures tested in Round 4 (the 71 W area light and the 170 W streetlight), approach the lower ranges of the luminaire output and efficacy of comparable products, but may be suitable alternatives for applications based on additional criteria such as intensity distribution and uniformity of illuminance, robustness, product lifetime, color characteristics or controllability.

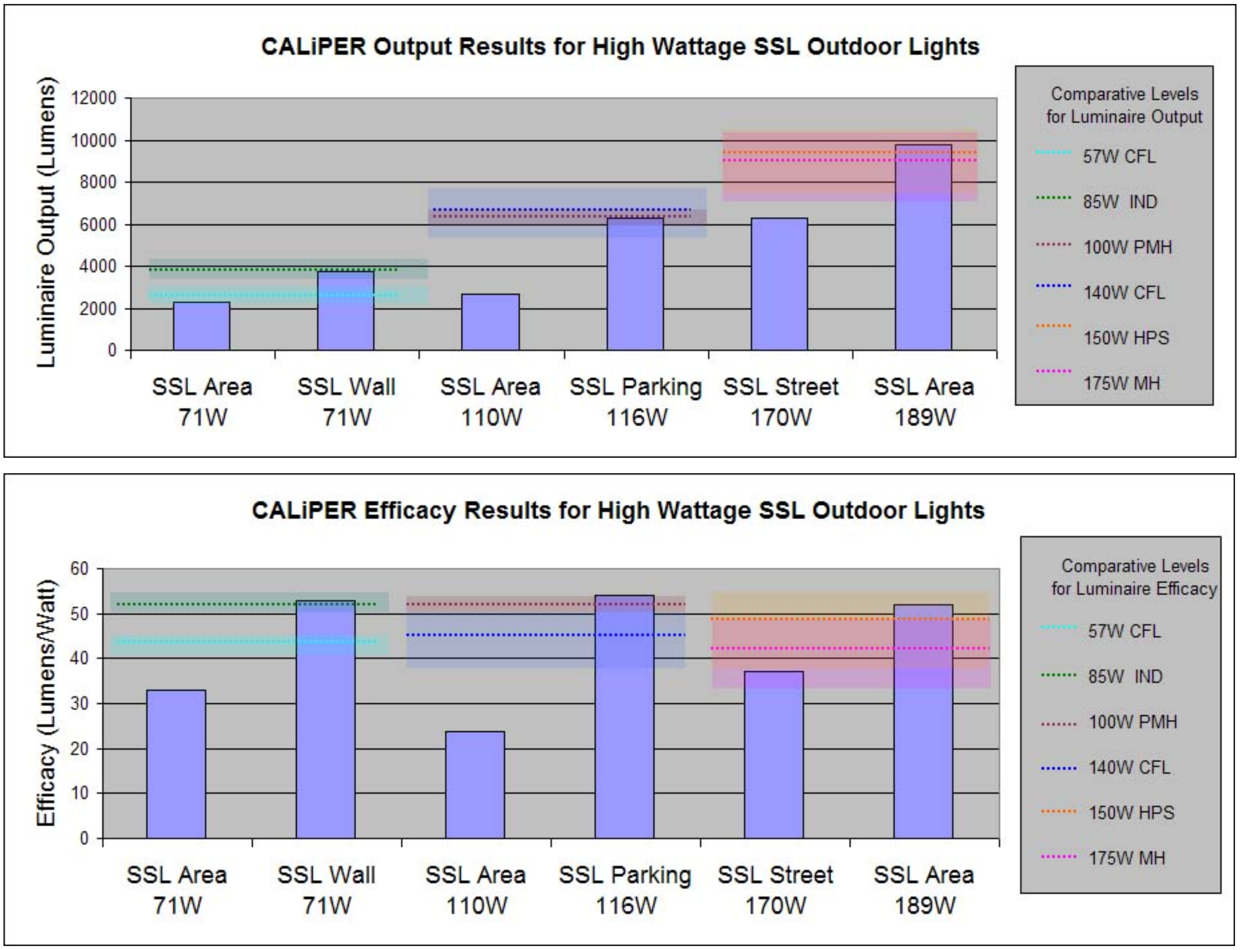

Figure 4. CALiPER Output and Efficacy Values Showing Comparable Levels for Other Light Sources

Comparative levels represent initial luminaire efficacy established using IES files and ballast factors for outdoor area lights, cobraheads, post-top, and pedestrian lights for CFL, induction, metal halide, pulse start metal halide, and high pressure sodium fixtures.

The outdoor wall light tested in Round 4 provides a practical example of the luminaire performance of a 13W CFL ENERGY STAR outdoor wall fixture, producing 639 lm, with an efficacy of 46 lm/W and warm white color temperature. Two similar small outdoor fixtures using SSL sources have been tested in earlier rounds of testing, surpassing incandescent efficacy, but performing at only about one-half the efficacy of this benchmark CFL fixture. While not yet achieving the efficacy of ENERGY STAR CFLs, the SSL fixtures in this category may be competitive with the higher performing CFL fixtures on the basis of cold temperature performance, robustness, and controllability (e.g., the ability to operate with day/night sensors).

The recessed step-wall lights that were tested in Round 4 could be indoor or outdoor fixtures. In this case, three products were selected from the same line from one manufacturer, simply using three different light sources: one halogen, one CFL, and one LED. Table 4 summarizes the key performance values for these three variations of this product. The LED version has slightly lower output than the halogen and CFL and has a colder white CCT, with a lower power level than both the halogen and CFL versions; its efficacy is slightly higher than the halogen, but lower than the CFL model. Qualitatively, the light surface of the LED product is more homogeneous in light level, creating a more visually appealing result. While the efficacy of this SSL fixture is somewhat lower than should be possible using LED device technology available today, it shows considerable promise — particularly if characteristics such as improved cold temperature performance and long life are considered. If future versions of this product use more efficient and better integrated LED devices, they can be expected to clearly outperform the halogen and CFL options.

Table 4. Comparison: Same Recessed Wall Fixture, Three Different Sources

Source/Power	Halogen (20W)	CFL (13W)	LED (12W)
Luminaire Output (lm)	174	199	154
Luminaire Efficacy (lm/W)	8	16	10
CCT	3085	3956	5166
CRI	98	77	73
Power Factor	0.99	0.97	0.97

This example of direct comparison among three versions of one product can serve to illustrate difficulties which manufacturers may face in grappling with photometric testing of SSL products. Table 5 summarizes information about these three products found in the manufacturer product brochure and manufacturer-provided IES files. The output 'lumens' indicated in the manufacturer brochure appear to correspond to the lamp rating for each light source (although there is currently no standardized method of determining a 'lamp rating' for LED devices). The IES files then indicate a 'fixture efficiency' to apply to this lamp rating, used to determine luminaire output levels and intensity distributions for the various lamp configurations (although there is no recognized method to determine fixture efficiency for fixtures using LED sources).

Table 5. Manufacturer Photometric Reporting for Three Different Sources in the Same Product Family

	Manufacturer Brochure Output "Lumens"	Fixture Efficiency from Manufacturer IES files (percentage)	Luminaire Efficacy Calculated from Manufacturer IES files (lumens/W)	**CALiPER Absolute Luminaire Efficacy (lumens/W)**
LED (12W)	195	43 %	5	**10**
CFL (13W)	900	25 %	19	**16**
Halogen (20W)	350	45 %	8	**8**

If a buyer uses the manufacturer IES file to determine the efficacy of each version of the product (shown in Table 5 under 'Efficacy Calculated from Manufacturer IES files'), the resulting efficacy is accurate for the halogen product, slightly overstated for the CFL product, and only half of the true luminaire efficacy for the LED version — in this case putting the LED version at an unjustified disadvantage in the eyes of prospective buyers.

Measurements of Color Quality

As in earlier rounds of testing, the products tested in Round 4 are fairly evenly distributed across the different ranges of white light, from warmer (~2700-~3000K range), to mid-range (sometimes referred to as soft or neutral white, ~3500-~4000K range), to cold (~5700-~6500K range).[10,11] For these and previously tested products, there is no correlation between efficacy and CCT — even though LED devices with higher CCTs (colder white) can function at higher efficacies than warmer-white products, this relationship between CCT and efficacy at the device level does not carry over to the luminaire and replacement lamp level. Of note in this round are a few products with colder-white color temperatures than would be expected for their applications (e.g., a downlight with a CCT of 6400 K and an undercabinet fixture with a CCT of 8200 K, higher than the ANSI defined nominal CCT ranges for white light).

The tunable white track light tested in this round provides six different white light levels in one product, ranging from 2652 to 6247 K, selectable using a simple switch on the track light. The efficacy and output of this product vary by about 12% across its different correlated color temperature positions.

The average CRI of SSL products tested in Round 4 is 76, consistent with earlier rounds of testing (excluding the product using red-green-blue (RGB) LEDs). The track light with tunable color temperature uses RGB LEDs for white light generation — CRI values are not an indicator of color quality for light sources that use RGB technology to generate white light. 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.[12,13] 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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[10] 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.

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

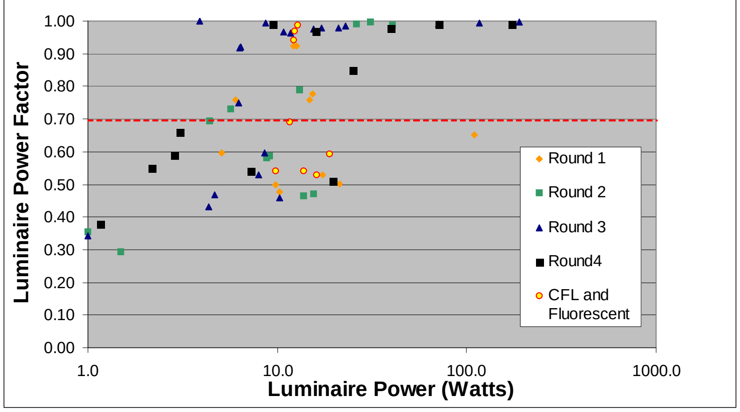
[12] Protzman, J. Brent and Kevin W. Houser. October 2006. LEDs for General Illumination: The State of the Science. Leukos. Vol. 3, No. 2, pp. 121-142.

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

Power Factor

The power factor of products tested to date is plotted in Figure 5, along with the luminaire power. The mean 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."[14] In general, the higher wattage and higher efficacy SSL products have power factors exceeding 0.9 (as required by the ENERGY STAR SSL criteria for commercial products).

Figure 5. Power Factor vs Wattage for CALiPER tested Luminaires and Replacement Lamps



Variability and Repeatability

All products in Round 4 were measured both in an integrating sphere and a goniophotometer. The average difference between goniophotometer and integrating sphere measurements for output on a given luminaire or replacement lamp was 2.4%. In 80% of these tests, the goniophotometer provided a slightly higher lumen output measurement than the integrating sphere. Also, as in earlier rounds, 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 all replacement lamps in Round 4 (a candelabra lamp, a T8 drop-in replacement, and three different types of MR16 replacement lamps), two samples of each product were tested to evaluate variability across units. In each case, the test results for the two units were compared, and the percentage difference between the two units in power, output, efficacy, CCT, and CRI was examined. For two of the MR16 products and for the T8 drop-in replacement lamps, variation across units was limited to a few percentage points for all measured characteristics. Measured output for the candelabra lamp was 5.6% greater for one of the two lamps (not surprising, given the low output level of these lamps). Of note is one SSL MR16 lamp (07-59), that shows considerable variation between two samples for every parameter, summarized in Table 6 below.

Table 6. Wide Variation between Two Samples for Product 07-59

	Power	Output	Efficacy	CCT	CRI
07-59 A	9.1	121.7	13.4	3561.0	91.5
07-59 B	8.0	143.4	17.8	3114.0	86.1
Difference	**12.1%**	**16.4%**	**28.2%**	**13.4%**	**6.1%**

[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.

Reliability: *In Situ* and Lumen Depreciation Testing

In addition to testing the photometric performance of products, the CALiPER program is also investigating their reliability — studying how *in situ* conditions may affect product performance and how product performance varies over time by measuring lumen depreciation. Standardized testing procedures are not yet available for performing *in situ* or lumen depreciation on SSL luminaires and replacement lamps. The CALiPER program has defined testing procedures for these situations in conjunction with qualified independent testing laboratories and drawing on standards for similar procedures where available or under development for other product types. CALiPER *in situ* and lumen depreciation testing is ongoing, so results presented below should be considered as preliminary, introductory information only. More detailed reporting on *in situ* and lumen depreciation testing will be available after this tests are completed.

In Situ Example

LED device performance is dependent on the device temperature, and thus the performance of SSL luminaires depends on the effectiveness of the product's thermal management (heat sinking, thermal bonds, and product configuration). *In situ* testing is being conducted on SSL products that are intended for operation under conditions that may result in increased ambient temperature or decreased airflow around the product and its heat sink. In particular, recessed fixtures and replacement lamps that are intended to be installed in fixtures (such as recessed cans) may increase in temperature and decrease in performance when operated in their intended environment. Recessed downlight products that have already been photometrically tested through CALiPER are now being tested in a UL1598-style testing box under three conditions: in a ventilated (open-lid) testing box, in a semi-ventilated testing box, and in an insulated testing box.[15] For these tests, relative photometry is used to obtain spot illuminance and spot spectral measurements under each condition, along with product surface temperatures.

Table 7 summarizes the results from *in situ* testing on three similar products tested in an integrating sphere and goniophotometer in Round 3. For these three samples, efficacy drops by only a few percentage points between the open air and insulated conditions. Similar testing is currently underway for a number of other downlight products.

Table 7. Example of Interim Results for In Situ Testing

	Open-Air Efficacy (Measured in Sphere, lm/W)	In Situ Efficacy (Calculated from spot measurements, lm/W)		
	Bare 'Luminaire'	UL 1598 Open	Semi-Ventilated	Insulated
07-31B warm	59.9	59.4	58.9	57.7
07-31C warm	62.4	61.8	62.0	61.1
07-47A cool	61.3	60.3	60.1	59.4

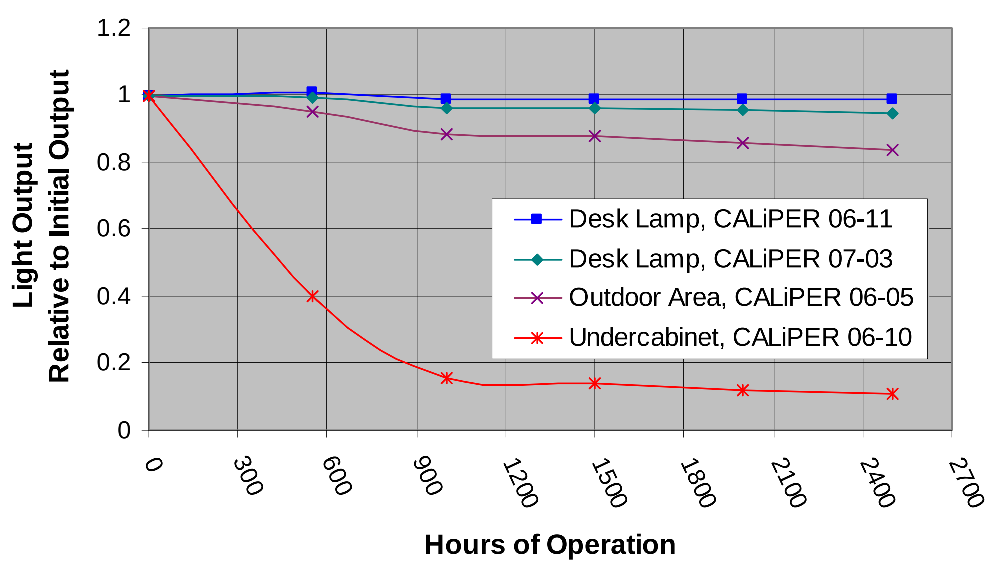
[15] See Underwriters Limited standard, UL 1598 – Luminaires, http://www.ul.com/lighting/standards.html.

Lumen Depreciation Interim Example

While LED devices and hence SSL products are expected to have very long lives, the true rate of lumen depreciation of SSL luminaires and replacement lamps is largely unknown. Lumen depreciation characteristics for LED devices may be available from device manufacturers, but when those devices are integrated in luminaires, the LED device's long-term performance will be affected by many factors stemming from the luminaire as a whole. These factors include, most obviously, operating point characteristics (such as forward current) and thermal management (such as heat sinking and thermal bonding), but also other factors such as the use of materials during manufacturing which may effect LED device lifetime such as cyanoacrylates (super glue) and O-rings. Lumen depreciation of the LED source is not the only failure mode contributing to the reliability of SSL luminaires, but it is a primary facet of luminaire reliability that is being studied by the CALiPER program.

A subset of products that has already undergone standard CALiPER testing is currently undergoing lumen depreciation testing. For this long-term testing (each cycle requiring 6000 hours of operation), each sample is securely mounted in an environment for continuous, stable operation and all external light is cloaked during measurements. Products are visually inspected and spot illuminance and spot spectral measurements are taken at 500-hour intervals. All samples were tested in an integrating sphere before the lumen depreciation testing cycle and will be retested in an integrating sphere after each 6000 hours of operation (if the product is still functioning). Figure 6 provides an example of interim results for lumen depreciation testing on four luminaires.

Figure 6. Example of Lumen Depreciation Interim Results



Of note in these results:

- For one product, 06-10, the output dropped to less than one-fifth of the initial output in less than 1000 hours. This product used LED chips from an undisclosed source and only a copper core printed circuit board as a heat sink.
- Not quite as drastic, but still not in line with manufacturer claims of a 50,000-hour life, product 06-05 is an RGB outdoor area light. The measured heat sink temperature of this product was 73° C.
- Desk lamps 06-11 and 07-03 are both made by the same manufacturer, using the same design for the LED device package and driver but different thermal management. The shape, size, and sheathing of the heat sinks used are different. To determine whether lumen depreciation differences between these two fixtures stem from simple variation across samples or from differences between the two thermal management designs, testing of more units would be required.

Note that these results are only interim results. These tests, and lumen depreciation testing on other products, will continue for several months.

Color Shift

In addition to measuring shifts in output and efficacy due to *in situ* conditions and lumen depreciation over time, this CALiPER testing is also studying shifts in color. Spot spectral measurements are taken along with spot illuminance measurements in each case. The ENERGY STAR® Criteria for Solid-State Lighting requirement for color maintenance states, “The change of chromaticity over the lifetime of the product shall be within 0.007 on the CIE 1976 (u’,v’) diagram.”

Analysis of the initial color shift results must take into consideration that the uncertainty factors for these spot color shift measurements have not yet been determined and may be relatively large. Nevertheless, for the two luminaires that have shown significant lumen depreciation in the first 2500 hours of operation, the color shift is also significant: the color shift for the undercabinet fixture, 06-10, is .056 (eight times more than the ENERGY STAR lifetime color shift limit), and the shift for the RGB outdoor area light, 06-05, is 0.024 (three times more than the ENERGY STAR lifetime color shift limit).

For the other two products in lumen depreciation testing and for the downlight *in situ* testing examples presented above, color shift appears to be well within the ENERGY STAR limit of 0.007. Further analysis of measurement uncertainties is needed before presenting quantified results for relatively small color shifts.

Conclusions from Round 4 of Product Testing

Key Points

Results from Round 4 of CALiPER testing are quite nuanced. As in earlier testing, a wide range of products, exhibiting a wide range of performance has been tested, so care should be taken in generalizing about results. None of the products tested in this round of testing would pass ENERGY STAR® Program requirements for solid-state lighting, although some of the products present very positive qualities. The greatest concern revealed by this testing, as in earlier rounds, is the inaccuracy of performance data presented in manufacturer product literature. The continued practice of providing incorrect qualitative comparisons to other light sources and inappropriate quantitative performance values in manufacturer literature may mislead consumers and damage SSL market potential in the long-run.

The replacement lamps tested in Round 4 provide examples of products which do not necessarily have poor performance results (their efficacy is better than similar halogen and incandescent products), but which have been misrepresented in product literature. The MR16 and candelabra lamps that were tested may fill needs in market niches (for example, for low wattage devices in decorative applications), but cannot serve as direct replacements for 20W halogen or incandescent products as claimed in marketing publications because their output levels are too low. The T8 drop-in replacement product that was tested produces far less light output than claimed in its product literature, but with its fairly good efficacy, it may be a suitable replacement for fluorescent tubes for specific applications.

While none of the task lamps tested in this round would meet the full array of ENERGY STAR requirements for task lamps, they show promise. The three desk lamps all have efficacies that are higher than the halogen benchmark desk lamp that was tested in Round 2, although none of them come close to competing with the CFL ENERGY STAR desk lamp that was tested. Encouragingly, for the first time, one desk lamp (out of 11 SSL desk lamps tested to date) was found to have a zero off-state power draw. SSL undercabinet fixtures are consistently performing well, with efficacies that solidly rival CFL undercabinet fixtures, but still somewhat low output levels and cold color temperatures.

The outdoor area and outdoor streetlight tested in this round have fair performances — somewhat low in output and efficacy compared to similar products using other light sources, but may be viable alternatives if other product characteristics are taken into consideration. The LED recessed step-wall light is somewhat disappointing, but shows a promising side-by-side comparison to a CFL and halogen alternatives in the same product line, particularly considering that higher efficacy levels should be possible using recent LED device technology.

The most surprising results in Round 4 are in the downlight category covering two extremes. One product is a 2-inch diameter downlight which is only slightly more efficacious than incandescent, has a very low output level, and a very cold correlated color temperature. The other is a track light which provides six selectable white-light levels and is a clear rival for similar reflector incandescent and halogen spot lights. Although the efficacy of this track light is somewhat disappointing (not meeting the levels announced by the manufacturer), it still surpasses incandescents and halogens (and there are no suitable CFL alternatives with similar spot light characteristics).

The intermediate results from *in situ* and lumen depreciation testing serve as a reminder that the reliability of SSL products is still largely theoretical. Claims of consistent color maintenance in luminaires and 50,000-hour lifetimes (or more) are at this point only speculative. Decisions which take into account the expected life of an SSL product should consider product guarantees, knowledge about which LED devices are used in a product, the reputation of the manufacturer of the LED devices used in the luminaire, and the reputation of a luminaire's manufacturer.

While the relatively strong performance of some SSL products tested in Rounds 1-4 implies great promise for the upcoming generations of commercially available SSL luminaires, SSL product performance still should not be generalized. Because of the wide variation in performance and the immaturity of this industry, it is essential for buyers to request explicit indications of luminaire output and luminaire efficacy and to be informed enough to question the information provided by manufacturers carefully.

Next Steps for the Industry and CALiPER efforts

With ENERGY STAR qualification for SSL products coming into effect in the fall of 2008, demands for SSL testing will increase. Numerous resources exist today to help stakeholders understand the particulars of SSL testing and how to compare SSL fixtures to those using other light sources. Development of standards for SSL testing is progressing rapidly (including the publication of IESNA LM-79, expected shortly), and efforts are also under way to provide guidance to manufacturers regarding what performance values should be reported in SSL product literature. Workshops and Webcasts are also available to help stakeholders better understand the nuances of SSL testing.[16]

A CALiPER Roundtable meeting was recently held, assembling SSL testing experts from across the country.[17] This meeting resulted in a number of recommendations for SSL standards development and for CALiPER testing plans. These ideas, along with suggestions gathered at industry forums, are woven into plans for upcoming rounds of CALiPER testing.

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[16] 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

[17] Proceedings from the "DOE Solid-State Lighting CALiPER Program 2007 Roundtable" are available online: http://www.netl.doe.gov/ssl/PDFs/2007DOECALiPERRoundTableProceedings_final.pdf.

DOE SSL Commercially Available LED Product Evaluation and Reporting Program

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Appendix

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).'[18] 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 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.[19]

Selection of Products for CALiPER Testing

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).

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[18] 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.

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