CALiPER

SUMMARY REPORT

September 2008

DOE Solid-State Lighting CALiPER Program

# Summary of Results: Round 6 of Product Testing

Prepared for the U.S. Department of Energy by
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# DOE Solid-State Lighting CALiPER Program

## Summary of Results: Round 6 of Product Testing

Round 6 of testing for the DOE Commercially Available LED Product Evaluation and Reporting (CALiPER) Program was conducted from May to August 2008.[1] In this round, 24 SSL products, representing a range of products and technologies, were tested with both spectroradiometry and goniophotometry using absolute photometry, following the recently published IESNA LM-79-08 testing method.[2] Testing also included measurements of surface temperatures (taken at the hottest accessible spots on the luminaire) and off-state power consumption for products with an on/off switch.

The focus in Round 6 of testing was on small replacement lamps (MR16 lamps, A-lamps, candelabra lamps, etc.). A variety of luminaires were also tested, including four desk lamps, a downlight, a recessed wall fixture, and two different types of outdoor products. In addition to testing SSL products, a number of products using traditional sources were tested for benchmarking purposes—20W halogen MR16 lamps, an incandescent outdoor wall fixture, and CFL desk lamps and outdoor wall-mounted fixtures that are ENERGY STAR® qualified under the Residential Lighting Fixture (RLF) criteria version 4.1.[3]

### Round 6 CALiPER Testing Results

Tables 1a, 1b, and 1c summarize 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 6. Table 1a assembles the key performance results for 16 SSL replacement lamp products that were tested. Table 1b assembles the key results for 8 SSL luminaires that were tested. Table 1c assembles the results for the benchmark testing that was conducted. Additional data for each set of testing results and related manufacturer information are assembled in a detailed report for each product tested.[4]

As shown by the sub-categories of replacement lamps in Table 1a, both directional lamps (such as MR16s and PAR lamps) and omni-directional lamps (such as replacements for A-lamps or candelabra lamps) were tested. An in-depth discussion of the results is provided below under "MR 16 Replacement Lamps," "Small Omni-Directional Replacement Lamps," and "Other Replacement Lamps."

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[1] Summary reports for Rounds 1-5 of DOE SSL testing are available online at http://www.netl.doe.gov/ssl/comm_testing.htm.

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

[3] See http://www.energystar.gov/index.cfm?c=fixtures.pr_light_fixtures for current lists of qualified CFL fixtures. The ENERGY STAR Residential Light Fixtures Specification, version 4.1 can be downloaded from http://www.energystar.gov/index.cfm?c=archives.rlfs_spec.

[4] Detailed test reports for products tested under the DOE's SSL testing program can be found online: http://www.netl.doe.gov/ssl/caliper_search.html.

| Table 1a. DOE SSL CALiPER ROUND 6 SUMMARY – Replacement Lamps | | | | | | | |
|---|---|---|---|---|---|---|---|
| --SSL testing following IESNA LM-79-08 --25ºC ambient temperature | **DOE CALiPER TEST ID** | **Total Power (Watts)** | **Output (initial lumens)** | **Efficacy (lm/W)** | **CCT (K)** | **CRI** | **Power Factor** |
| **Replacement MR16s** | | | | | | | |
| Replacement - MR16 | 08-83* | 3 | 121 | 35 | 2620 | 84 | 0.71 |
| Replacement - MR16 | 08-84* | 4 | 106 | 27 | 3255 | 61 | 0.63 |
| Replacement - MR16 | 08-97* | 5 | 159 | 33 | 2808 | 96 | 0.64 |
| Replacement - MR16[1] | 08-98* | 1 | 29 | 29 | 5793 | 79 | 0.61 |
| **Replacement A-lamps** | | | | | | | |
| Replacement A-lamp[2] | 08-55* | 5 | 116 | 25 | 5061 | 66 | 0.44 |
| Replacement A-lamp | 08-80* | 5 | 292 | 62 | 7272 | 79 | 0.48 |
| Replacement A-lamp | 08-81 | 14 | 445 | 33 | 3388 | 52 | 0.62 |
| Replacement A-lamp | 08-92 | 13 | 403 | 31 | 3143 | 49 | 0.57 |
| Replacement A-lamp | 08-82* | 5 | 167 | 35 | 3023 | 66 | 0.55 |
| **Replacement Candelabras** | | | | | | | |
| Replacement Candelabra | 08-56* | 0.7 | 29 | 40 | 3193 | 66 | 0.51 |
| Replacement Candelabra | 08-78* | 0.5 | 22 | 45 | 2888 | 64 | 0.41 |
| Replacement Candelabra[3] | 08-99 | 1.5 | 88 | 61 | 6378 | 79 | 0.40 |
| **Replacement "Night Light" Lamp** | | | | | | | |
| Replacement C7[4] | 08-91* | 0.4 | 2 | 4 | 21106 | 73 | 1.0 |
| **Other Directional Replacement Lamps** | | | | | | | |
| Replacement - Par 30 | 08-58* | 8 | 206 | 25 | 2648 | 67 | 0.48 |
| Replacement - Par 30 | 08-101* | 5 | 144 | 28 | 5609 | 78 | 0.43 |
| Replacement Spot-lamp | 08-100 | 3 | 140 | 41 | 3755 | 77 | 0.52 |

Values over 2 are rounded to the nearest integer for readability in this table.

See "MR 16 Replacement Lamps," "Small Omni-Directional Replacement Lamps," and "Other Replacement Lamps" below for further discussion of results.

* For products shown with an asterisk, two or more units were tested; results show average among units tested.

[1] Four units of 08-98 were sent for testing, but two out of the four units failed, so testing could only be completed on two units. Results show average between the two units.

[2] Note that 08-55 could be viewed as an A-lamp replacement based on its size and form factor, but might also be considered as a wide angle (116° beam angle) directional lamp by virtue of its beam pattern.

[3] Two units of 08-99 were sent for testing. One unit failed after goniophotometry testing was completed, but before sphere testing could be conducted.

[4] One out of three samples of 08-91 failed during testing. Results show average between the two units.

Table 1b assembles the results for SSL luminaires that were tested in Round 6, including four desk lamps, one 6 ⅜-inch square recessed downlight, one recessed wall-step fixture, one outdoor area acorn insert, and one outdoor wall-mounted fixture. For the desk lamps, two power values are provided, one with the product in the "on" position and one with the product in the "off" position (in brackets). Similarly, the efficacy is shown first based on only the power consumed when the product is "on" and then based on the total power consumed assuming the product is used 3 hours per day (in brackets). Further discussion of these results is provided under the corresponding sections below.

**Table 1b. DOE SSL CALiPER ROUND 6 SUMMARY – Luminaires**

| --SSL testing following IESNA LM-79-08 --25ºC ambient temperature | DOE CALiPER TEST ID | Total Power (Watts) | Output (initial lumens) | Luminaire Efficacy (lm/W) | CCT (K) | CRI | Power Factor |
|---|---|---|---|---|---|---|---|
| **Task Lamps** | | | | | | | |
| Desk | 08-36 | 5 [0.8] | 87 | 17 [8] | 4516 | 91 | 0.43 |
| Desk | 08-57 | 6 [0.5] | 206 | 34 [21] | 6784 | 79 | 0.40 |
| Desk | 08-85 | 11 [0.2] | 254 | 22 [20] | 3588 | 78 | 0.50 |
| Desk | 08-86 | 16 [0.2] | 251 | 16 [15] | 6255 | 76 | 0.50 |
| **Downlight** | | | | | | | |
| 6 ⅜" x 6 ⅜" Recessed Downlight | 08-77* | 23 | 984 | 43 | 4203 | 85 | 0.99 |
| **Recessed Wall** | | | | | | | |
| Recessed Wall-Step | 08-79** | 3 | 19 | 7 | 7017 | 73 | 0.86 |
| **Outdoor** | | | | | | | |
| Outdoor Area Insert for Acorn Fixture | 08-44† | 67 | 2515 | 38 | 6631 | 77 | 0.99 |
| Outdoor Wall Lantern | 08-40 | 5 | 104 | 22 | 3485 | 73 | 0.48 |

Values over 2 are rounded to the nearest integer for readability in this table. All lamps use LED sources unless otherwise noted.

Power consumption in brackets [ ] shows power in watts drawn when product is in the "off" position. 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.

* For product 08-77, three units were tested; results show average between the three units.

** For product 08-79, two units were purchased but one failed to function. Only one was tested.

† For product 08-44, two units were tested; results show average between the two units.

Table 1c summarizes performance results for benchmark products that were tested in CALiPER Round 6. These benchmark results are used along with earlier CALiPER benchmark tests to provide clear points of comparison between SSL products and more traditional lighting products. Manufacturer ratings and published photometric data for products using traditional light sources are also used and compared to these results to gain a clearer picture of the performance of traditional products.

**Table 1c. DOE SSL CALiPER ROUND 6 SUMMARY – Benchmark tests**

| --25ºC ambient temperature | DOE CALiPER TEST ID | Total Power (Watts) | Output (initial lumens) | Efficacy (lm/W) | CCT (K) | CRI | Power Factor |
|---|---|---|---|---|---|---|---|
| **Replacement – 20W Halogen MR16 Lamps** | | | | | | | |
| Halogen – MR16/FL36 – Benchmark | 08-50* | 20 | 172 | 8 | ** | ** | 1.00 |
| Halogen – MR16/SP10 – Benchmark | 08-51* | 20 | 239 | 12 | ** | ** | 1.00 |
| Halogen – MR16/FL35 – Benchmark | 08-93* | 21 | 253 | 12 | 2775 | 99 | 1.00 |
| Halogen – MR16/FL35 – Benchmark | 08-94* | 20 | 288 | 14 | 2907 | 99 | 1.00 |
| Halogen – MR16/FL40 – Benchmark | 08-95* | 18 | 237 | 13 | 2917 | 99 | 1.00 |
| Halogen – MR16/FL35 – Benchmark | 08-96* | 20 | 340 | 17 | 2850 | 99 | 1.00 |
| **Outdoor – Incandescent Luminaires** | | | | | | | |
| Outdoor Coach Fixture – 60W Incandescent Source | 08-59 | 60.2 | 385.5 | 6.4 | 2700 | 99 | 1.00 |
| **Compact Fluorescent Luminaires†** | | | | | | | |
| **CFL Task Lamps** | | | | | | | |
| Desk Lamp – ENERGY STAR | 08-102 | 26 | 1349 | 51 | 3050 | 84 | 0.45 |
| Desk Lamp – ENERGY STAR | 08-103 | 20 | 765 | 39 | 2740 | 82 | 0.52 |
| Desk Lamp – ENERGY STAR | 08-104 | 19 | 869 | 45 | 3092 | 80 | 0.51 |
| **CFL Outdoor Wall Lights** | | | | | | | |
| Outdoor Wall – ENERGY STAR | 08-105 | 16 | 590 | 36 | 2710 | 82 | 0.53 |
| Outdoor Wall – ENERGY STAR | 08-106 | 12 | 615 | 52 | 2775 | 85 | 0.40 |

Values over 2 are rounded to the nearest integer for readability in this table.

* For products shown with an asterisk, two or more units were tested; results show average among units tested.

** Integrating sphere tests were not conducted for 08-50 and 08-51 so color measurements are not available.

† All CFL luminaires tested in Round 6 are listed as ENERGY STAR qualified under RLF v 4.1. Products 08-102 and 08-106 have power factors below 0.5 (shown in red), which would not meet the ENERGY STAR RLF v 4.1 criteria.

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

## Energy Use and Light Output

The efficacies of SSL products tested in Round 6 exhibit a huge range of performance: from 4 lm/W up to 62 lm/W. Nevertheless, as illustrated in Figure 1, compiling CALiPER results to date reveals a steady increase in efficacy of market available SSL products.

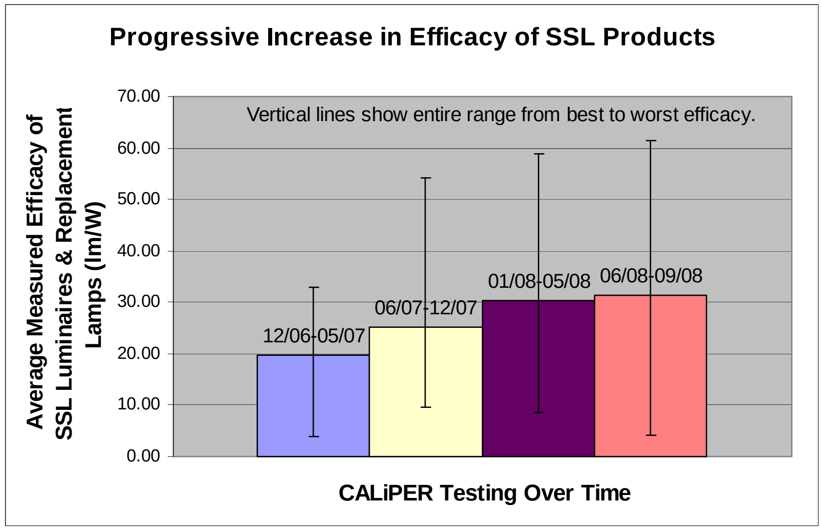


**Figure 1. Measured Luminaire Efficacy of Market-Available SSL Products is Increasing.**

For some product categories, such as small replacement lamps and downlights, luminaire output is also steadily increasing over time, but there are still huge differences between the best and the worst products. Unfortunately, increases in performance are not resulting in more accurate product literature. In most cases, manufacturer performance claims for energy use, light output, or comparable wattage are highly overstated and misleading.

The sections below address each product category that was tested in this round, considering efficacy, light output, power characteristics, color quality, and product labeling and reporting.

## MR16 Replacement Lamps

Four SSL MR16 replacement lamp products were tested in Round 6, adding to six others that were tested in previous rounds. Table 2 summarizes the results from SSL MR16 testing to date, including Center Beam Candle Power (CBCP) and beam angle. Six 20W halogen MR16s were tested for benchmarking purposes (as summarized in Table 1c above). Benchmarking values for halogen MR16 products were also assembled from product ratings in the catalogs of three major lamp manufacturers where available.

Figures 2a-d below illustrate key points from these results. First, Figure 2a shows that the lumen output of these SSL MR16 replacement lamps does not yet meet the minimum output levels of 20W halogen MR16 lamps. While on average the lumen output has increased from the earlier products that were tested, even the highest performing SSL MR16 tested to date does not meet the lumen output of the lowest performing halogen MR16.

| Table 2. Summary of MR16 Replacement Results to Date | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | DOE CALiPER TEST ID | Total Power (Watts) | Output (initial lumens) | Efficacy (lm/W) | CBCP (cd) & Beam Angle | CCT (K) | CRI | Max Duv |
| **Replacement MR16 Lamps** | | | | | | | | |
| MR16 | 07-53 | 3 | 82 | 27 | 283/23° | 3007 | 74 | 0.005 |
| MR16 | 07-59 | 9 | 133 | 16 | 220/38° | 3338 | 89 | *0.011* |
| MR16 | 07-64 | 3 | 75 | 26 | 59/49° | 3458 | 74 | 0.001 |
| MR16 | 07-17 | 4 | 78 | 20 | 381/15° | 6381 | 80 | 0.006 |
| MR16 | 07-58 | 5 | 90 | 19 | 72/60° | 2691 | 67 | *0.008* |
| MR16 | 08-07 | 2 | 34 | 17 | 739/11° | 6254 | 75 | 0.004 |
| MR16 | 08-83 | 3 | 121 | 35 | 899/19° | 2620 | 84 | 0.002 |
| MR16 | 08-84 | 4 | 106 | 27 | 339/24° | 3255 | 61 | 0.004 |
| MR16 | 08-97 | 5 | 159 | 33 | 290/23° | 2808 | 96 | 0.001 |
| MR16 | 08-98 | 1 | 29 | 29 | 86/23° | 5793 | 79 | *0.008* |

$D_{UV}$ is the closest distance between the chromaticity coordinates and the Planckian locus. Max $D_{UV}$ presents the absolute value of the higher $D_{UV}$ out of the two samples tested for each product. Values in red italics are outside of ANSI defined tolerances for $D_{UV}$ at a given CCT as defined in ANSI Standard C78.377. [5]

Efficacy of SSL MR16s is also increasing as testing rounds progress. All four SSL MR16s tested in this round (08-83, 08-84, 08-97, and 08-98) have higher efficacy than the highest efficacy 20W halogen MR16 as illustrated in Figure 2b. While these SSL lamps achieve 2 to 3 times the average efficacy of 20W halogen lamps, they do not necessarily perform at the levels claimed in product literature. Of the four SSL MR16s tested in this round, one had accurate product literature. Another had product literature which overstated performance by a factor of 2, but it was recently corrected and now corresponds more closely to the CALiPER measured values. The literature, however, may still be misleading by mixing statements concerning cold-white and warm-white products on one page (implying that those claims apply to the warm-white product, too). Two products have overstated performance claims, with one product sold through a major retail store claiming to be comparable to a 20W halogen lamp when it actually produces only $^{1}/_{9}$ of the output of an average 20W halogen lamp.

Color temperature and color quality of the SSL MR16 lamps are diverse. Figure 2c shows that 7 out of 10 SSL MR16s have warm-white CCTs (below 3500 K), similar to halogen lamps. Table 2 shows CRI values ranging from 61 to 96, and of even greater concern, $D_{uv}$ values for three MR16 lamps, shown in red italics, that are outside of ANSI norms—an issue discussed below under "Measurements of Color Quality."

MR16 lamps are directional products, so CBCP and beam angle can be important criteria. Figure 2d plots CBCP against beam angle for the SSL MR16 replacement lamps and for 20W halogen MR16 lamps (from both CALiPER testing and manufacturer ratings). It is clear that, at any particular beam angle, the SSL MR16 products are not yet producing the CBCP of an average halogen MR16.

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[5] ANSI/NEMA/ANSLG C78.377-2008, Specifications for the Chromaticity of Solid State Lighting Products. Downloadable from http://www.nema.org/stds/ANSI-ANSLG-C78-377.cfm, February 15, 2008.

**Figure 2a.**

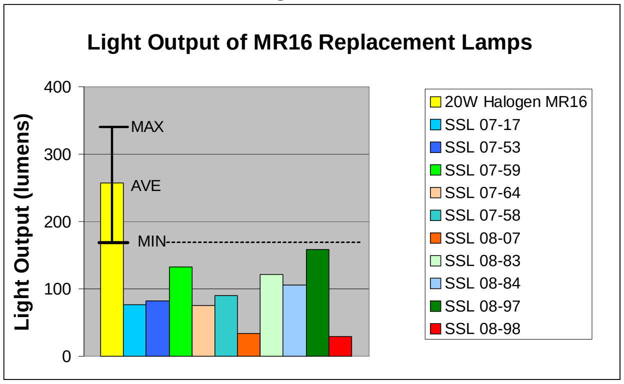



**Figure 2b.**

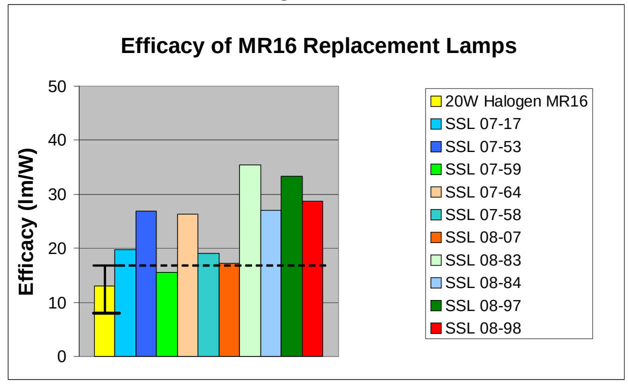



**Figure 2c.**

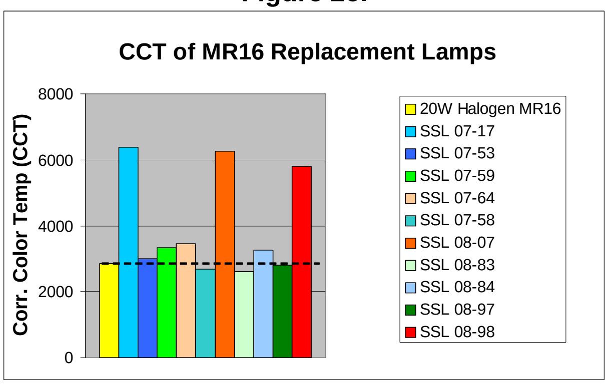
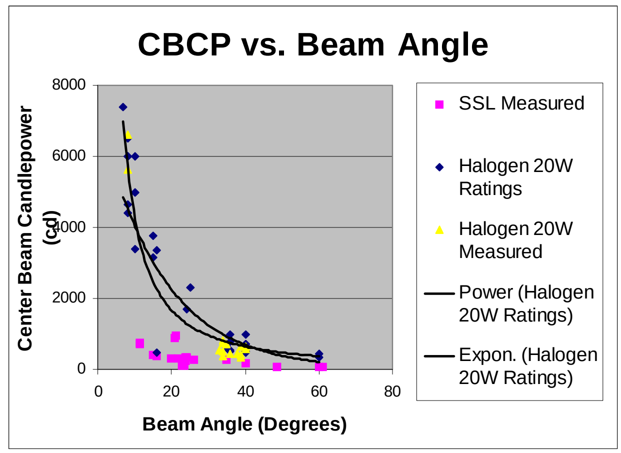



**Figure 2d.**




A number of other concerns for SSL MR16 lamps should be noted. These replacement lamps have not yet been subjected to lumen depreciation testing, so their reliability over time is unknown. Because of the very low power levels on some of these products, their general behavior with typical power supplies for MR16 luminaires is unknown and may vary greatly depending on the replacement lamps and on the power supplies. Finally, for some of these products, form factor and weight may cause concern in certain applications. While many SSL MR16 products have fairly standard formats, Figure 3 below shows the bottom of two SSL MR16 lamps, one which is fairly typical and one which might be unusable in most fixtures.

**Figure 3. Examples of Formats for MR16 Bases in SSL Replacement Lamps.**

## Small Omni-Directional Replacement Lamps

Several omni-directional replacement lamps, described as replacements for A-lamps, candelabra lamps, and nightlight lamps, were tested in Round 6. Table 3 presents basic measured performance data for all small, omni-directional replacement lamps tested by CALiPER to date. Values for CCT, CRI, Duv, and power factor that are clearly outside of industry norms are in red italics.

**Table 3. Summary of Small Replacement Lamp Results to Date**

| | DOE CALiPER TEST ID | Total Power (Watts) | Output (initial lumens) | Efficacy (lm/W) | CCT (K) | CRI | Max Duv | Power Factor |
|---|---|---|---|---|---|---|---|---|
| **Replacement A-lamps** | | | | | | | | |
| A-lamp | 07-06 | 0.7 | 10 | 16 | 3161 | 70 | 0.003 | *0.35* |
| A-lamp | 07-12 | 1.5 | 20 | 13 | *25263* | 79 | *0.014* | *0.29* |
| A-lamp | 07-23 | 0.7 | 33 | 48 | 3099 | 70 | 0.002 | *0.34* |
| A-lamp | 08-03 | 3 | 81 | 31 | 3127 | 92 | 0.001 | *0.55* |
| A-lamp | 08-25 | 5 | 194 | 39 | 3418 | 86 | *0.007* | *0.33* |
| A-lamp | 08-55 | 5 | 116 | 25 | 5061 | *66* | *0.017* | *0.44* |
| A-lamp | 08-80 | 5 | 292 | 62 | *7272* | 79 | 0.001 | *0.48* |
| A-lamp | 08-81 | 14 | 445 | 33 | 3388 | *52* | 0.003 | *0.62* |
| A-lamp | 08-82 | 5 | 167 | 35 | 3023 | *66* | 0.004 | *0.55* |
| A-lamp | 08-92 | 13 | 403 | 31 | 3143 | *49* | 0.003 | *0.57* |
| **Replacement Candelabras** | | | | | | | | |
| Candelabra | 07-57 | 2.2 | 28 | 13 | 2855 | 71 | 0.004 | *0.55* |
| Candelabra | 08-56 | 0.7 | 29 | 40 | 3193 | *66* | *0.013* | *0.51* |
| Candelabra | 08-78 | 0.5 | 22 | 45 | 2888 | *64* | *0.011* | *0.41* |
| Candelabra | 08-99 | 1.5 | 88 | 61 | 6378 | 79 | 0.002 | *0.40* |
| **Replacement – Other** | | | | | | | | |
| C7 (night light) | 08-91 | 0.4 | 2 | 4 | *21106* | 73 | *0.008* | 1.0 |

As CALiPER testing progresses from quarter to quarter, light output levels are increasing steadily for these products, but they still on average produce far less light output than claimed in product literature. For A-lamp replacement products, the highest-output SSL lamps produce equivalent lumens to a 40W incandescent lamp, with about 3 times the efficacy of the incandescent lamps, but are claimed to be comparable to a 100W lamp. Compact fluorescent lamps which produce the equivalent of 40W incandescent lamps are, on average, 4½ times more efficacious than incandescent lamps (based on manufacturer ratings). More typically, SSL A-lamp replacements on the market today produce output levels equivalent to a 15 or 25W incandescent while claiming to be replacements for 40–60W lamps.

For candelabra lamp replacements, one SSL product tested—claimed to replace a 40W lamp— produces lumen output similar to typical 15W incandescent candelabra lamps, but with a very cold color appearance (CCT > 6000 K). The other, warmer-appearing SSL candelabra replacement lamps would be the equivalent of about a 5 or 6W incandescent. All have significantly higher efficacy than the incandescent candelabra lamps.[6] One SSL lamp which claims to replace "all standard night lights" (ANSI C7 format) only produces a negligible light output of 2 lm, whereas 4W night light replacement lamps typically produce 16 lm and 7W night light replacement lamps typically produce 33–43 lm.

Traditional lamps, which all of these small SSL replacement lamps are intended to replace, emit light in a fairly even, omni-directional pattern. Close to half their output is emitted upward, with half emitted downward; a maximum candela value occurs at the horizontal angle, perpendicular to the length of the lamp. Figure 4a provides an example of an intensity distribution plot for a 40W incandescent lamp. The small, omni-directional SSL replacement lamps tested in Round 6 exhibit a variety of distributions. One product has cosine distribution as shown in Figure 4b (typical of a directional lamp with a very wide beam angle). A number of products have spiky, downward distributions (with a base-up lamp orientation), as illustrated by the example in Figure 4c. Three products have fairly diffuse beams, as illustrated by the example in Figure 4d, more closely approximating their incandescent counterparts, with 60–66% of light emitted downward and 34–40% emitted upward.

Taken as a whole, the small SSL replacement lamps also raise serious quality concerns—from poor color quality to poor power quality to failures of products during testing. Half of the products have poor color quality, with CCT outside of the accepted range for white light, or very low CRI values, or unacceptably high $D_{uv}$ values (distance from the blackbody locus) which result in greenish, bluish, or yellowish light.

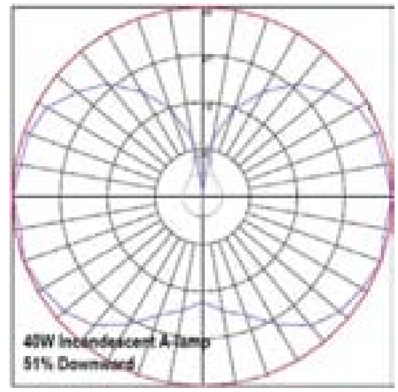



**Figure 4a. Incandescent Distribution**

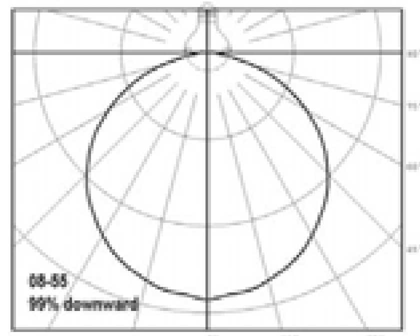



**Figure 4b. SSL "Cosine" Distribution**

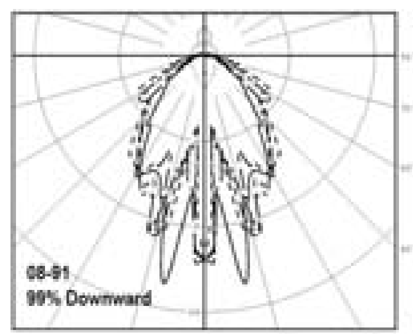



**Figure 4c. SSL "Spiky" Distribution**

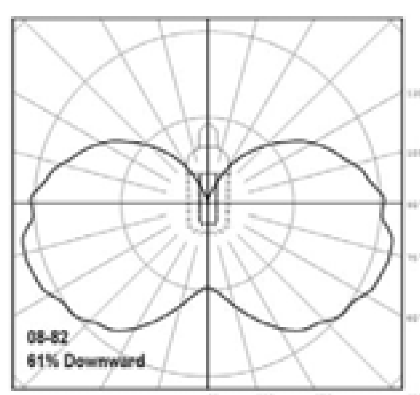



**Figure 4d. SSL Fairly Omni-Directional Distribution**

[6] Benchmark data is not yet available for CFL candelabra replacements.

Out of 15 small, omni-directional SSL replacement lamps tested to date, only one has an acceptable power factor, and over half have power factors below 0.5. A number of replacement lamp samples that were sent for testing failed before testing could be completed. Also, one product is sold with selectable dimming, where stepping through three output settings is achieved by quickly switching the product on and off; however, the highest output setting only operates for 3½ minutes and then shifts to the middle setting. The lower setting on the product only produces $^{1}/_{5}$ the lumens claimed in the product literature.

Form factor can also be an issue for the A-lamp replacement products: many are purported to replace A-lamps but are too long or too large in bulb diameter or too wide in the bulb neck at the base (near the socket). Some products are ambiguous in form and function, e.g., sold as replacements similar to A-lamps in shape, but emitting light in a directional beam. Size and form factor were also problems for CFL replacement lamps through the mid-1990s.[7]

## Other Replacement Lamps

Three other SSL directional lamps were tested: a "PAR30," an "accent lamp" (about the size and shape of an A-19 lamp, but with a directional beam), and a "flood lamp" (similar in size to a PAR38). All of these products have performance claims that are overstated or highly misleading. The best of the three claims to be comparable to a 35 or 40W incandescent lamp, where the CALiPER results show it is comparable in lumen output to a 25W incandescent. Furthermore, even a manufacturer supplied IES file for this product overstates its performance by about 30% for both lumen output and efficacy.

The "accent lamp" (with measured beam angle of 13°) and "flood lamp" (with measured beam angle of 25°) are both products distributed through a major retailer and both claim on the product packaging: "Replaces 45W." However, these lamps only produce $^{1}/_{3}$ the lumen output of a 45W incandescent or halogen lamp, with CBCP values 4 to 17 times less than halogen lamps with similar beam angles. The chromaticity coordinates for these lamps are so far from the blackbody locus (with $D_{uv}$ values of 0.016 and 0.013) that their light appears greenish rather than white.

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[7] See the DOE report on lessons learned from CFLs, "Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market," http://www.netl.doe.gov/ssl/publications/publications-lightingtechreports.htm.

## Desk Lamps

Round 6 included four SSL desk lamps and three CFL desk lamps that are listed as ENERGY STAR® products in the Residential Lighting Fixture (RLF) v4.1 category. All four SSL desk lamps would fail the criteria from the ENERGY STAR Program Requirements for Solid-State Lighting Luminaires, based on their off-state power use and their low power factors.[8, 9] Most would also fail efficacy (all have effective efficacy below the 29 lm/W threshold), output (one produces only 87 lm), color requirements (two have CCT > 6000 K), or distribution (two have very narrow beams).

Three of these SSL products have slightly better luminaire efficacy than halogen desk lamps, but compared to ENERGY STAR CFL desk lamps (performing at 39–51 lm/W in benchmark testing), these SSL desk lamps perform at only about ½ the luminaire efficacy.

Unfortunately, these products are sold with very little literature about their performance, and what information is published is inaccurate. One SSL desk lamp has no performance information at all. Literature for another product claims "Conforms to California Energy Commission 2008 standards of maximum consumption in the off state of 0.5 watts," when in fact it consumes slightly more than 0.5W when turned off and might not meet CEC requirements for efficacy and color. Three of the products understate their power ratings by 20–30% in their product literature (which could lead a consumer to infer they have higher efficacy than they do in reality). One manufacturer claims to offer "the brightest LED desk lamp," and another claims that its product achieves 450 lm output when the CALiPER measured output is 254 lm.

Desk lamps would appear to be an ideal "niche" application for SSL technology, harnessing LED directionality and compact form to create energy-efficient, high-performance task lighting. However, CALiPER test results to date indicate that most manufacturers have not yet attained this goal.

## Downlights

One 6 ⅜" x 6 ⅜" integrated, recessed downlight fixture was tested in Round 6, producing 985 lm (at 23 watts) with a measured luminaire efficacy of 43 lm/W. Consequently, this SSL downlight is comparable in output and efficacy to recessed downlight cans equipped with similar wattage CFL and reflector CFL (RCFL) lamps (on average, assuming a 40% fixture loss for CFL or 20% fixture loss for RCFL sources), with good power factor and color performance (CCT of 4203 K and CRI of 85). This fixture would appear to qualify under the ENERGY STAR for SSL v1.0 criteria as a commercial downlight.

The manufacturer publishes web pages, data sheets, and photometric IES files for this product. None of the published data appears to correspond precisely with the "LED type" included in the model that was received for testing. Based on the order code for the product and CCT of the

[8] Note that while the RLF v 4.1 ENERGY STAR criteria for CFL luminaires only require a minimum power factor of 0.50, one of the three benchmark desk lamp products would not qualify as ENERGY STAR with a PF of 0.45, and the other two are very close to the lower limit (at 0.51 and 0.52).

[9] 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.

fixture, the product data sheet implies that it should perform at 49 lm/W and 1022 lm or 54 lm/W and 1105 lm. Such ambiguities in published performance values may be due in part to the nature of LED chip production and classification (i.e., different bins, different batches, different chip characteristics, rapid progress, etc.). In many cases such as this, product literature emphasizes the best performing models in a series of products (usually with the highest color temperatures and most recently available chips), which can lead to end-user misconceptions and high expectations regarding product performance.

## Recessed Wall-Step Fixture

A recessed wall-step fixture (which is listed as "suitable for dry locations") uses 2.6W, so it could also provide slight energy savings over an incandescent wall light, but it is a disappointing implementation of SSL technology with regard to energy use, resulting in an efficacy of only 7 lm/W. With a total luminaire output of 19 lm, it could compare to a similar incandescent fixture using a 7W night light (with a source output of ~40 lm and fixture loss of 50%), although the color appearance is very cold, with a CCT over 7000.

This product is sold with a power rating of 1W, when it actually draws 2.6W. For this type of niche application, SSL technology today should be able meet the application needs in lumen output and distribution using only 0.5–1 W of power, even with warm white LEDs.

## Outdoor Fixtures

Two very different SSL outdoor fixtures were tested in Round 6: a wall-mounted lantern and an acorn insert for outdoor area lighting. Also, a version of the wall-mounted lantern using a 60W incandescent source was tested for comparison (from the same manufacturer and of the same size and shape as the SSL sample), along with two CFL outdoor wall fixtures which are listed as ENERGY STAR fixtures under the RLF v4.1 criteria.[10] Both of the SSL outdoor fixtures showed disappointing performance results because 1) they perform quite poorly with respect to similar traditional products, or 2) their performance is much less than claimed.

The luminaire output for the SSL wall fixture was measured at 104 lm, or less than $^1/_3$ the output of the incandescent version of the same fixture using a 60W lamp (despite the 50% fixture loss in the incandescent luminaire), and less than $^1/_6$ the output of typical ENERGY STAR CFL outdoor wall fixtures. While the SSL product has three times the luminaire efficacy of the incandescent version, its efficacy is only about ½ the luminaire efficacy of the CFL fixtures. The efficacy, output, and power factor of the SSL product would not meet ENERGY STAR for SSL.

This outdoor wall-mounted SSL fixture is sold by a major retailer. Retail product packaging claims that it compares to a 60W light and manufacturer published data claims it has a light output of 200 lm—both claims that are highly exaggerated. While the SSL fixture could save

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[10] Note that one of the ENERGY STAR CFL wall-mounted fixtures has a measured power factor of 0.40, which should disqualify it from ENERGY STAR under the RLF v4.1 criteria.

energy compared to the incandescent version of the same product, it could also disenchant buyers due to the very low light output level compared to similar incandescent and CFL products.

The second outdoor product tested in Round 6 was an acorn insert for outdoor area luminaires. This product has not been tested by CALiPER in a fixture, so readers should keep in mind that the performance results would be somewhat reduced *in situ* due to fixture losses, although the losses might be less than with an omni-directional light source. The SSL acorn insert uses 67W of input power, so it can be compared with sources for outdoor area lights which use metal halide (MH), high pressure sodium (HPS), or CFL sources with power ratings of 55–60W. With an output of 2515 lm and an efficacy of 38 lm/W, this product has slightly lower initial efficacy and output than the comparable MH, HPS, and CFL sources, but would probably be subject to less luminaire loss than the more omni-directional sources. In many installations, it is likely that the SSL fixture would provide a more uniform distribution of light over the application area than a source such as HPS; however, further *in situ* and benchmark testing would be needed to assess comparable performance of similar outdoor area fixtures.

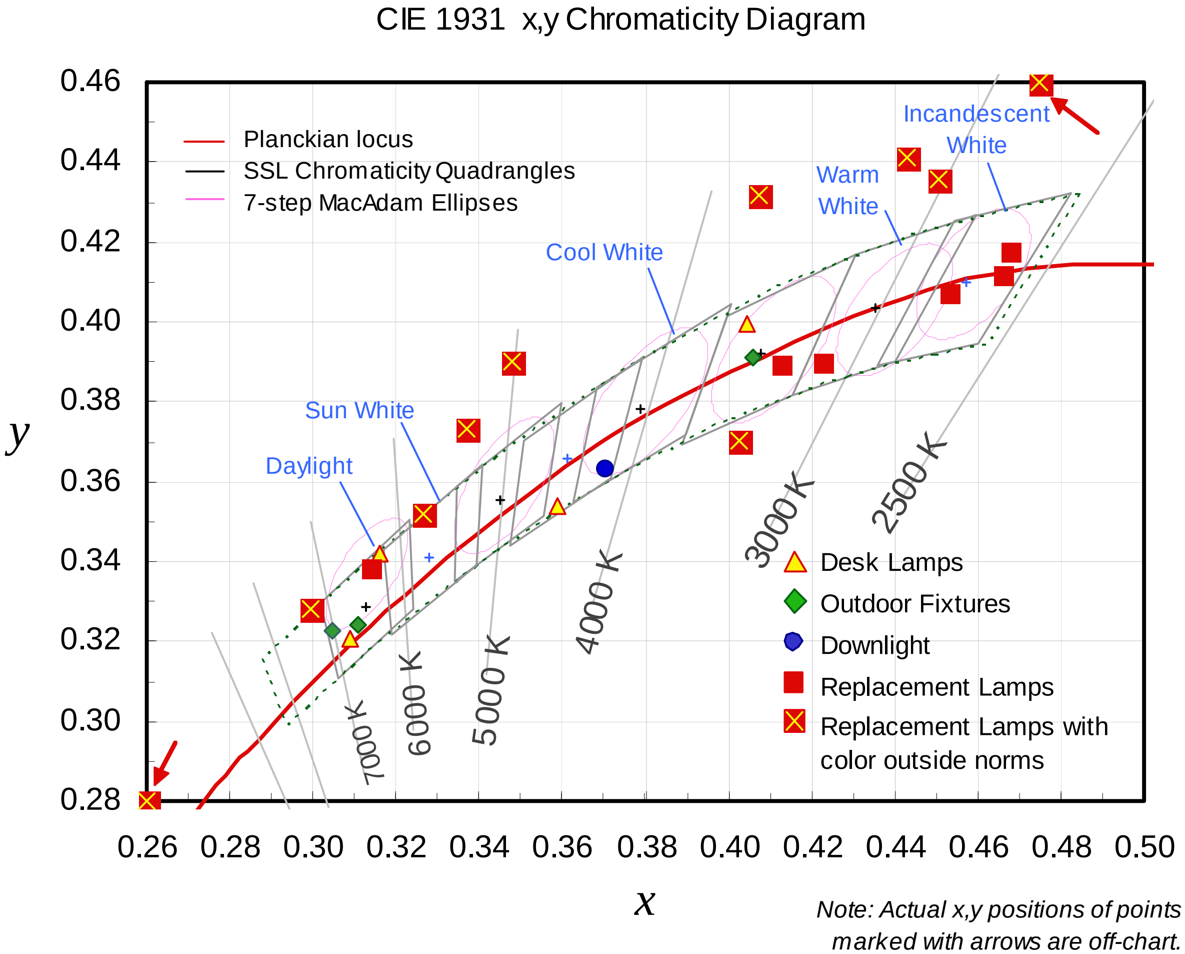
In product literature, the rated power of this product is 50W, whereas the measured input power was 67W. One claim for this product is that the 50W LED insert is equal to a 100W MH lamp. A CALiPER benchmarking survey reveals that a MH lamp rated at 100W (actually drawing 114W) would produce about 8000 initial lumens with an efficacy of 70 lm/W. Even accounting for better directionality of the SSL product, this equivalency claim appears to be overstated or misleading. The photometric data from an IES file furnished by the manufacturer indicates that the total lumen output of the acorn insert is 2644, which is only about 5% more than measured in CALiPER testing.

## Measurements of Color Quality

As in earlier CALiPER tests, the white light SSL products tested in Round 6 represent a wide range of color appearances, from warm to very cool, with CCTs from 2640 K to as high as 22410 K (well outside standard CCT ranges defined for white light). With the focus on small replacement lamps in this round of testing, issues surrounding color tolerances are very apparent. Figure 5 below plots the x,y chromaticity coordinates of Round 6 products on a CIE Chromaticity Diagram, with overlays showing the SSL quadrangles for tolerances which define acceptable ranges of white light as defined by ANSI standard C78-377.[11] The larger, marked red squares indicate the color coordinates for replacement lamps that do not fall within the tolerances in CALiPER performance tests. Note that these values are measured at initial product life; they can be expected to drift over the lifetime of the products. At least half of the small replacement lamps tested in this round have colors that do not meet the norms for acceptable white light. Furthermore, a number of products—from each category of products tested in Round 6—have color values that are close to the limits for acceptable white, which would put them at higher risk of falling outside of the tolerances as their color shifts over the life of the product.

[11] ANSI/NEMA/ANSLG C78.377-2008, Specifications for the Chromaticity of Solid State Lighting Products. Downloadable from http://www.nema.org/stds/ANSI-ANSLG-C78-377.cfm, Feb. 15, 2008.

## Figure 5. CALiPER Round 6 Products Dxy Illustration




Figures 6a and 6b below provide another illustration of these color concerns, overlaying the x,y values of two products over a colored depiction of the CIE 1931 chromaticity diagram and the blackbody (Planckian) locus. Characterizing the true color appearance of a light source is complex, so this is only an approximation of the color appearance: sources with x,y values near the locus will appear "white," sources with values in the lower left side of the color space will appear blue or purple, etc.  In both cases, the version of the image on the right also includes an overlay indicating the area corresponding to acceptable white light. Figure 6a shows the x,y position of one replacement lamp with x-y coordinates so far off the blackbody locus that the light was described by an observer as "yellowish-orange." Figure 6b shows the x,y position of a replacement lamp with a CCT of 22410K; while the x-y value lies on the blackbody locus, it is in the portion of the locus where CCT values tend to infinity and its light appears "bluish-purple" to the human eye.

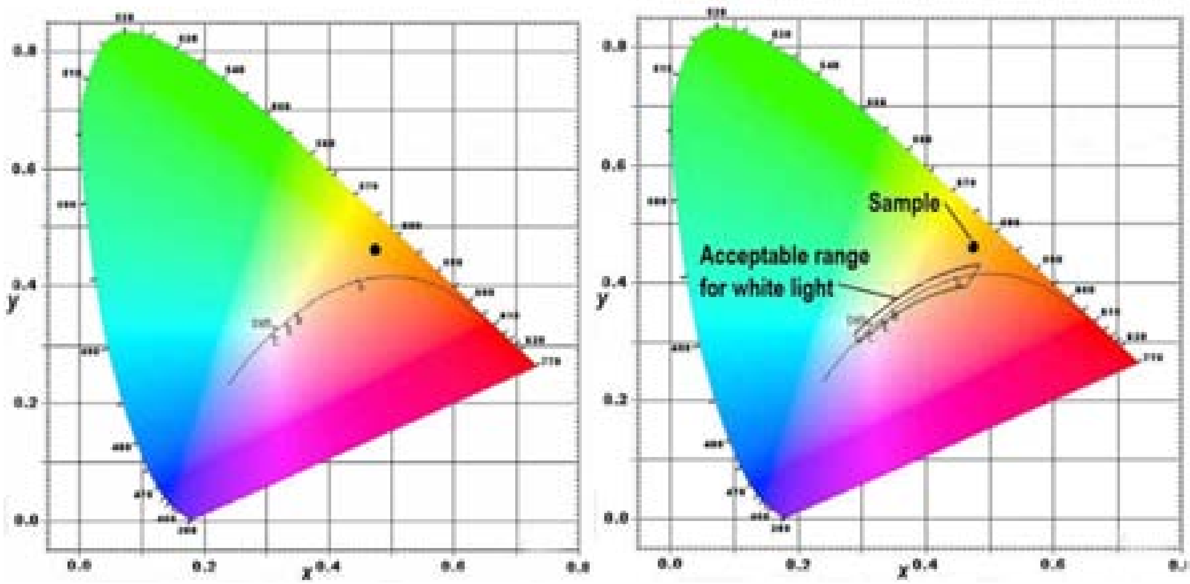



**Figure 6a. Chromaticity Coordinates of a Yellowish-Orange Sample**
**Duv excursion highlighted with respect to chromaticity tolerances on the right.**

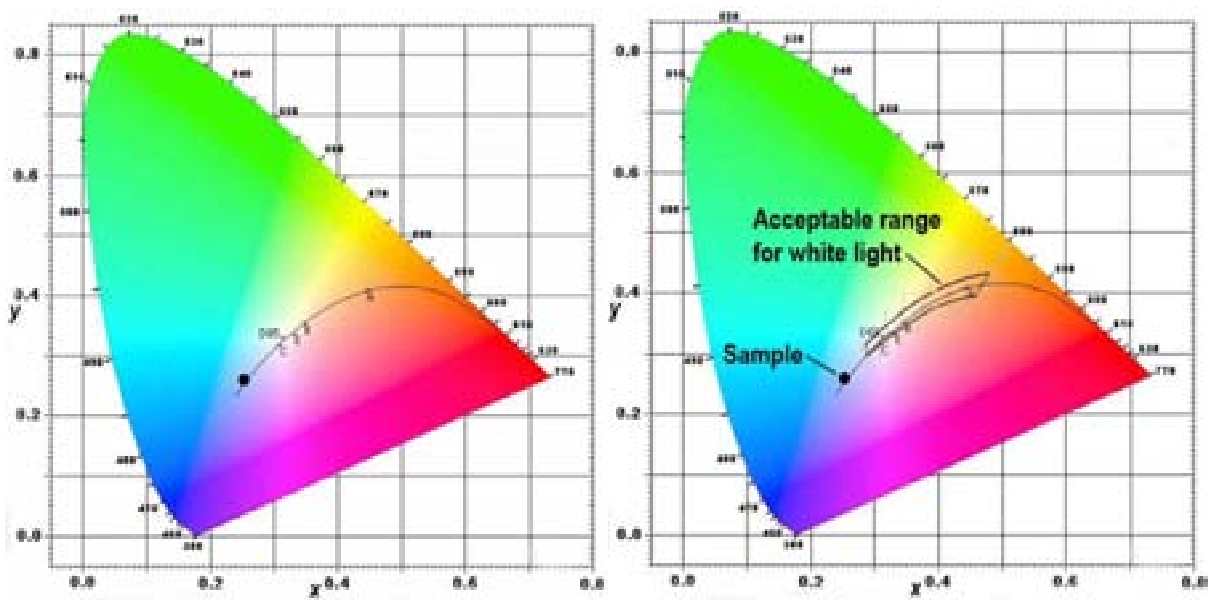


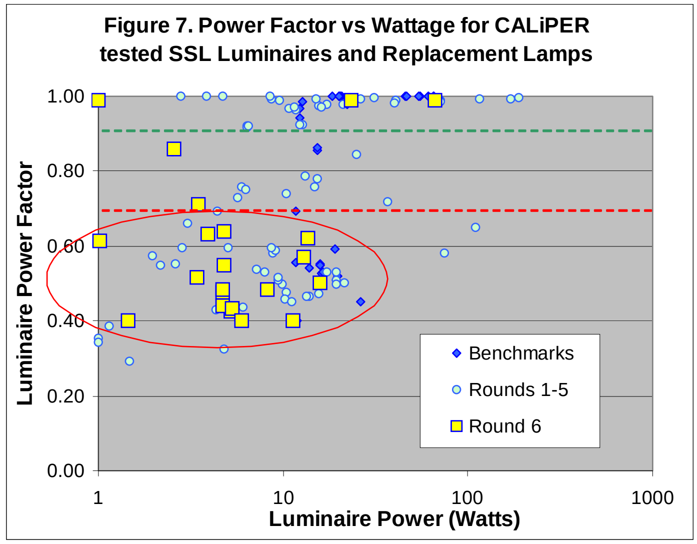

**Figure 6b. Chromaticity Coordinates of a Bluish-Purple Sample**
**CCT excursion highlighted with respect to chromaticity tolerances on the right.**

In the right-hand figures, showing the region surrounding the locus which corresponds to acceptable white light, it is clear that the chromaticity coordinates of these samples are not within tolerances. Chromaticity plots provided in photometric reports have not typically included an overlay of this sort, which provides a visual indication of where standardized white light would fall, but it might be a useful addition to consider.

These results can serve as a clear reminder that the color standards for white light include both CCT and $D_{uv}$ requirements. Acceptable CCT does not guarantee acceptable color quality, if a source's chromaticity coordinates stray too far from the blackbody locus. LED chip manufacturers and SSL luminaire and replacement lamp manufacturers need to understand these requirements and understand the nuances of selecting and combining LED color characteristics to make white light products of suitable color quality.

## Power Factor

The power factor of Round 6 products was on average worse than in previous rounds of CALiPER testing. Nineteen out of 24 SSL products tested had a power factor under 0.70, the current minimum allowed for residential products by ENERGY STAR for SSL. In fact, over half of the Round 6 products had a power factor under 0.50, as highlighted in Figure 7. Testing laboratories should consider including power factor values with all testing results to help stakeholders better monitor and address this problem.




## Performance Reports in Manufacturer Literature

As evidenced in this round of testing, a preponderance of inaccurate and misleading performance claims on SSL product literature persists in the marketplace. This phenomenon is increasingly worrisome with more LED products becoming available through major retail outlets.

Only two of the 24 SSL products tested in this round provided accurate or somewhat accurate performance data in product literature. For some products, little to no performance information is provided. Most products tested have packaging and/or advertisement material and/or data sheets that make highly overstated claims of wattage equivalencies to traditional sources. Such equivalency statements are published for the majority of products tested, e.g., “Replaces 40W”, “Compare to 60-watt light!”, or “50W LED head is = to 100W Metal Halide.” In every case, these comparisons are inaccurate—often overstated by a factor of 2 or 3.

These erroneous and misleading comparisons, like other inaccurate performance claims, may stem from a number of factors:

- Lack of understanding of SSL testing concepts (e.g., that LED device performance does not translate to product performance once the LED device is integrated in a replacement lamp or luminaire);
- Manufacturers’ product literature that does not clearly indicate what specific product configuration was tested to produce the published performance values (e.g., rapidly evolving LED devices and a tendency to publish data for the highest performing version of a product—often that with the highest color temperature);

- Differing interpretations of benchmark values for products using traditional light sources (note that the CALiPER program will soon be issuing benchmark reports for a number of applications to provide a clearer basis for comparison); and
- Inflation of performance claims (e.g., from selection of test conditions not representative of actual use, such as chilled or pulsed device testing or testing without optics, or from testing of prototype units that are not representative of production units).

In addition to false performance claims, SSL replacement lamps purchased from major retail stores may have questionable reliability. For one product, 2 out of 4 units failed before testing could be completed. Another product from the same manufacturer and purchased from the same retail chain had 1 out of 2 samples fail, and yet another type of lamp from the same line had 22 out of 80 LEDs in the lamp fail during testing. For another replacement lamp, purchased from a different retail chain, 1 out of 3 units failed. On visual inspection, the design and construction (as well as quality control) of these products do not appear to be robust—thermal management is not apparent and structural defects are visible. While the CALiPER program recognizes that these are not statistically large samples, these failures can be seen as reasons for caution. Manufacturers and retailers need to be wary.

## Reliability: Lumen Depreciation Testing & Variability Testing

Fundamental CALiPER testing as reported above is conducted with new products, at time t=0 in the life of a product. To increase our understanding of the long-term performance of SSL luminaires and replacement lamps, CALiPER is also conducting long-term studies examining lumen depreciation and color shift over the first several thousand hours of operation of a product. The first "batches" of lumen depreciation testing have been completed recently (i.e., from 0 to over 6000 hours of operation), and a report on these results will be issued in Fall 2008.

Similarly, CALiPER performs specific tests and analyses to assess different types of variation surrounding SSL testing. Differences in results are examined between different testing methods (e.g., integrating sphere vs. goniophotometry), among multiple samples of a given product (in many cases two or three samples are tested; for specific studies, up to 10 samples have been tested), among different testing laboratories (in round-robin style testing), and among repeated test runs over different days or months. A report compiling and examining these various perspectives on testing and sampling will be issued in a separate report in Fall 2008.

## Conclusions from Round 6 of Product Testing

### Key Points

CALiPER testing continues to reveal that many SSL products do not meet manufacturer performance claims, although a few high-performing products are emerging on the market and definite progress can be seen in some product categories. Of greatest concern at this time is the appearance of underperforming products on shelves in major retail stores, which carries the potential of disappointing early adopters and endangering the future market potential of SSL technologies for years to come (as witnessed through the CFL legacy).

On a positive note, CALiPER results are indicating, on average, steady improvements in output and efficacy for small replacement lamps, despite some very poor performers among the products tested. One MR16 SSL replacement lamp is close to reaching the lower levels of output and CBCP for a 20W halogen. Some SSL replacement lamps are achieving output levels comparable to 40W incandescent lamps. The efficacy of these SSL replacement lamps is, in most cases, a few times higher than incandescent lamps with similar light output. Few CFL products are available for the lower output, smaller replacement lamp types, and the efficacy of these smaller CFL products is lower than for larger wattage (larger format) CFL lamps. As a result, SSL replacement lamps could be competitive with CFL replacement lamps in these lower wattage categories.

Also on a positive note, a high-performing SSL integral downlight luminaire was tested. Based on the CALiPER results, it appears that this product would meet the ENERGY STAR for SSL criteria for all of the CALiPER measured characteristics.

Unfortunately, Round 6 has also revealed some somber points. As in earlier CALiPER testing, SSL desk lamps are observed to have disappointing performance (i.e., off-state power use, poor power factor, and unsatisfactory luminaire efficacy). A recessed wall/step fixture and an outdoor wall fixture show disappointing performance levels as well—they might save energy if used to replace incandescent products, but their low output levels might also disappoint buyers. In almost every case where product literature compares an SSL product to traditional products, the comparisons are highly overstated and misleading.

The quality and color appearance of white light produced by SSL products, particularly replacement lamps, needs to be followed closely too. Industry standards for white light define both nominal CCT and chromaticity "$D_{uv}$" tolerances (i.e., how far chromaticity coordinates can deviate from the blackbody locus). Nearly half of the SSL replacement lamps tested in Round 6 do not meet industry standards for one or both of these measures.

**Next Steps for the Industry and CALiPER efforts**

DOE is working continually with luminaire manufacturers, standards groups, independent testing labs, energy efficiency programs, and the trade press to address the points revealed in CALiPER testing. Each stakeholder group can play an active role in moving the SSL market in the best direction:

- Energy efficiency programs and SSL buyers can exercise purchasing savvy. Always request luminaire testing results from an independent testing lab and check that LED chips used in tested products correspond to LED chips in the product under consideration for purchase. An ever-increasing array of DOE SSL fact sheets is available to help stakeholders understand what to look for and how to compare SSL products with more traditional fixtures.
- Mechanisms are needed to help manufacturers climb the learning curve. DOE is participating in forums and in writing articles in the trade press. CALiPER testing results are shared and discussed with luminaire manufacturers.
- Testing laboratories and measurement standards groups can play a role toward increasing awareness of performance issues. Testing labs should systematically incorporate reporting on power factor, $D_{uv}$, and off-state power along with photometric reports. Standards groups can consider reinforcing guidelines to ensure that all relevant characteristics are tested, reported, and understood.
- Trade groups can participate in efforts to increase awareness across the board regarding SSL product quality. DOE has worked with the Next Generation Lighting Industry Alliance (NGLIA) to develop the SSL Quality Advocates initiative to address quality and accurate labeling in SSL products.[12] Manufacturers and retailers are encouraged to learn about this initiative and join in the effort.

[12] SSL Quality Advocates, Critical Parameters, and Pledge Program: http://www.netl.doe.gov/ssl/qualityadvocates.html.

**DOE SSL Commercially Available LED Product Evaluation and Reporting Program**

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# Appendix A

## Testing Methods

The lighting testing laboratories were instructed to follow test procedures specified in the LM-79-08 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)."[13] 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.[14]

### Selection of Products for CALiPER Testing

The general policy of the CALiPER program is to test units of products that 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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[13] The testing standard entitled "IESNA Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products," designated LM-79-08, is now published. This testing procedure was 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.

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