CALiPER

SUMMARY REPORT

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DOE Solid-State Lighting CALiPER Program

Summary of Results: Round 8 of Product Testing

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

DOE Solid-State Lighting CALiPER Program

Summary of Results: Round 8 of Product Testing

Round 8 of testing for the Department of Energy (DOE) Commercially Available LED Product Evaluation and Reporting (CALiPER) Program was conducted from February 2009 to June 2009.[1] In this round, 35 products, representing a range of product types and technologies, were tested with both spectroradiometry and goniophotometry using absolute photometry. All solid-state lighting (SSL) products were tested following the IESNA LM-79-08 testing method.[2] Testing also included measurements of surface temperatures (taken at the hottest accessible spots on the luminaire).

Round 8 of testing focused primarily on **replacement lamps**, including MR16 lamps, PAR lamps, and small, omni-directional replacement lamps. Benchmark replacement lamps using incandescent, halogen, and CFL light sources were also tested in each application category to obtain complete absolute photometry results for comparison with SSL. Three undercabinet SSL products were also tested, providing a snapshot of SSL progress in this lighting application. Two of the products tested in Round 8—a downlight and an undercabinet fixture—are ENERGY STAR® products, recently qualified under the ENERGY STAR for SSL Criteria.[3] One outdoor streetlight was also tested, providing a second test from a different production batch on a product that was first CALiPER-tested in Round 7. This report summarizes the performance results for each product and discusses the results with respect to similar products that use traditional light sources, results from earlier rounds of CALiPER testing, and manufacturer ratings.

Round 8 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 products tested under CALiPER in Round 8. Table 1a assembles the key results for six MR16 replacement lamps, six SSL PAR and R lamps, and six directional replacement lamps using more traditional light sources. Table 1b assembles the key performance results for eleven small omni-directional replacement lamps that were tested. Table 1c assembles the results for six SSL luminaires that were

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[1] Summary reports for Rounds 1-7 of DOE SSL testing are available online at http://www.ssl.energy.gov/caliper.html. Please see earlier CALiPER Summary Reports and the CALiPER FAQ for further details regarding the CALiPER product selection process and regarding CALiPER testing methods.

[2] The published IESNA LM-79-08 testing standard entitled "IESNA Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products," 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. http://www.iesna.org/

[3] The current list of products qualified under ENERGY STAR for SSL can be downloaded from: http://www.energystar.gov/index.cfm?c=ssl.pr_residential and http://www.energystar.gov/index.cfm?c=ssl.pr_commercial

tested. Additional data for each set of testing results and related manufacturer information are assembled in CALiPER detailed reports for each product tested.[4]

Table 1a. CALiPER ROUND 8 SUMMARY – Directional 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**
Directional Replacement Lamps—MR16*							
SSL							
MR16 GU 5.3 12V	09-26	2	51	29	3552	*72*	0.69
MR16 GU 5.3 12V	09-28	4	148	34	3155	81	0.95
MR16 GU 5.3 12V	09-29	3	150	46	2938	84	*0.61*
MR16 GU 5.3 12V	09-43	5	177	35	2894	87	0.96
MR16 GU 5.3 12V	09-49	6	291	48	2842	93	*0.60*
CFL Benchmark (BK) Data							
MR16 CFL (12VAC)**	BK 09-11	3	62	20	3310	84	0.64
Directional Replacement Lamps—PAR and R Lamps							
SSL							
PAR20 SSL	09-23	6	194	35	2888	83	*0.50*
PAR20 SSL	09-25	3	104	33	3186	*74*	*0.61*
PAR20 SSL	09-35	7	272	36	2993	*77*	0.87
R30 SSL	09-37	11	470	43	2893	83	*0.55*
PAR38 SSL	09-30	15	632	43	2924	83	*0.55*
R38 SSL	09-36	14	653	47	3072	*78*	0.90
Incandescent, Halogen, CFL Benchmark (BK) Data							
R16 Incandescent	BK 09-08	40	233	6	2529	100	1.0
R20 Incandescent	BK 09-05	40	227	6	2516	99	1.0
K19 Incandescent	BK 09-06	41	388	10	2667	99	1.0
R20 Incandescent	BK 09-07	29	181	6	2560	99	1.0
R20 Halogen	BK 09-09	41	596	15	2687	98	1.0
R20 CFL	BK 09-10	13	468	36	2778	81	0.52

Values greater than 1 are rounded to the nearest integer for readability in this table. Two or more samples were tested for all replacement lamps.

Power factor and CRI levels that do not meet the minimum draft ENERGY STAR criteria for integral SSL replacement lamps are shown in *red italics* (minimum power factor is 0.7 and minimum CRI is 80 for integral replacement lamps).[5]

* All MR16 samples in Round 8 were tested using 12V input. Readers should factor in additional transformer or system losses for 12V products before comparing efficacy with products using 120VAC.

** Note that CFL is not a typical benchmark for MR16 lamps; in this case it is included in testing to provide concrete performance parameters for this point of comparison. More typical benchmark lamps for MR16 use halogen sources and are available in earlier CALiPER benchmark testing.

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[4] Detailed test reports for products tested under the DOE's SSL testing program can be obtained online: http://www1.eere.energy.gov/buildings/ssl/search.html

[5] ENERGY STAR® Program Requirements for Integral LED Lamps DRAFT 2 – May 19, 2009. http://www.energystar.gov/index.cfm?c=revisions.ssl_luminaires

As shown in Table 1a, a variety of directional replacement lamps were tested. Five SSL MR16 replacement lamps and one CFL MR16 replacement were tested, with power ratings ranging from 2W to 6W. Benchmark data on 20W halogen MR16 lamps are available from earlier rounds of CALiPER testing. Three SSL PAR20 lamps were tested along with a number of reflector incandescent, halogen, and CFL lamps, which could be considered as benchmark comparisons for the SSL PAR20 lamps. Three larger SSL replacement lamps were also tested, an R30 lamp, an R38 lamp, and a PAR38 lamp. An in-depth discussion of the results for these directional replacement lamps is provided below.

Table 1b. CALiPER ROUND 8 SUMMARY – Omni-Directional 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
Omni-Directional, Decorative Replacement Lamps							
SSL							
A19 Replacement Lamp SSL	09-18	8	352	45	*6426*	80	0.85
G19 Small Globe Lamp SSL	09-19	2	25	15	*6135*	77	*0.46*
G50 Semi-Transparent SSL	09-20	3	49	14	2758	83	*0.54*
E12 Globe Candelabra SSL	09-21	3	149	44	3425	*66*	*0.43*
B10 Candelabra SSL	09-22	2	38	23	3265	*68*	*0.31*
Incandescent and CFL Benchmark (BK) Data							
C7 (night light) Incandescent	BK 09-01	4	16	4	2170	100	1.00
C7 (night light) Incandescent	BK 09-02	7	27	4	2147	99	0.99
B10 Candelabra Incandescent	BK 09-03	14	61	4	2440	100	1.00
B10 Candelabra Incandescent	BK 09-34	26	205	8	2590	100	1.00
F15 Candelabra Halogen	BK 09-27	26	266	10	2641	100	1.00
Dimmable Candelabra CFL	BK 09-04	4	152	35	2623	85	0.98

Values greater than 1 are rounded to the nearest integer for readability in this table. Two or more samples were tested for all replacement lamps.

Power factor, CRI, and CCT levels that do not meet the minimum draft ENERGY STAR criteria for integral SSL replacement lamps are shown in *red italics* (minimum power factor is 0.7, minimum CRI is 80 for integral replacement lamps, and CCT range is from 2555-4260K).

Table 1b assembles the results for omni-directional replacement lamps tested in Round 8, including three SSL products using standard Edison (E26) bases and two using candelabra (E12) bases. Small replacement lamps were also tested for benchmarking purposes: two night light lamps and four candelabras. Discussion of these results is provided under "Omni-Directional Replacement Lamps" below.

Table 1c summarizes results for SSL luminaires that were tested in CALiPER Round 8. These results include downlights, undercabinet fixtures, and an outdoor streetlight. Further details, discussion, and comparison with previous CALiPER results and with traditional lamps are provided below under "Downlights and Track Lights," "Undercabinet Fixtures," and "Outdoor Fixtures."

Table 1c. CALiPER ROUND 7 SUMMARY – SSL Luminaires

-- 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
Downlights							
6" Diameter IC-rated	09-24*	14	589	42	2987	73	0.97
Downlight – track light	09-33*	9	204	22	2557	83	0.80
Undercabinets							
Undercabinet Lighting System, large load (18" + 18" + 12" linear strips)[1]	09-31	34	1164 [291 lm/ft]	34	3015-3045	74-93	0.83
Undercabinet Lighting System, small load, (6" + 6" strips + puck)[1]	09-31	14	411 [274 lm/ft]	29	2872-3015	*72*-95	0.75
14.5" SSL Linear Strip	09-32*	11	235 [194 lm/ft]	21	2973	96	0.96
12" SSL Linear Strip	09-38*	5	200 [200 lm/ft]	41	5407	74	*0.48*
Outdoor							
Outdoor Streetlight[2]	08-110B	41	2172	53	5182	71	0.99

Values are rounded to the nearest integer for readability in this table. All samples use SSL sources.

Power factor and CRI levels that do not meet the minimum ENERGY STAR for SSL requirements for residential applications are shown in *red italics* (minimum power factor is 0.7 for residential applications, 0.9 required for commercial applications, and minimum CRI is 75 for indoor applications with -2 tolerance).

For linear undercabinet luminaires, light output per lineal foot is shown in brackets […].

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

[1] Product 09-31 is an undercabinet lighting system for which consumers may choose combinations of subcomponents, including puck lights, 6" linear strips, 12" linear strips, or 18" linear strips. CALiPER tested subcomponents separately and in combination. Results for electrical and light output performance presented in this summary table show two illustrative system combinations, one with a very light overall load (two 6" strips plus one small puck light) and one with a much more significant load (two 18" trips plus one 12"strip). A range of CCT and CRI performance was observed across the subcomponents.

[2] Product 08-110B is a second sample of the same product tested in Round 7, with exactly same model number. The 08-110 sample tested in Round 7 (relabeled 08-110A) is labeled with a manufacture date of July 2008, and 08-110B has a manufacture date of October 2008. Sample 08-110A was provided by the manufacturer for testing as part of a DOE GATEWAY demonstration, whereas sample 08-110B was acquired anonymously.

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

Energy Use and Light Output

The SSL products tested in Round 8 exhibit a wide range of efficacy: from 14 lm/W to 53 lm/W. While no exceptionally high or exceptionally low efficacy products were tested in this round, the overall average efficacy per round is still climbing, now reaching 36 lm/W. As illustrated in Figure 1, market-available SSL products have shown a continuous positive trend in performance since CALiPER testing began in December 2006.

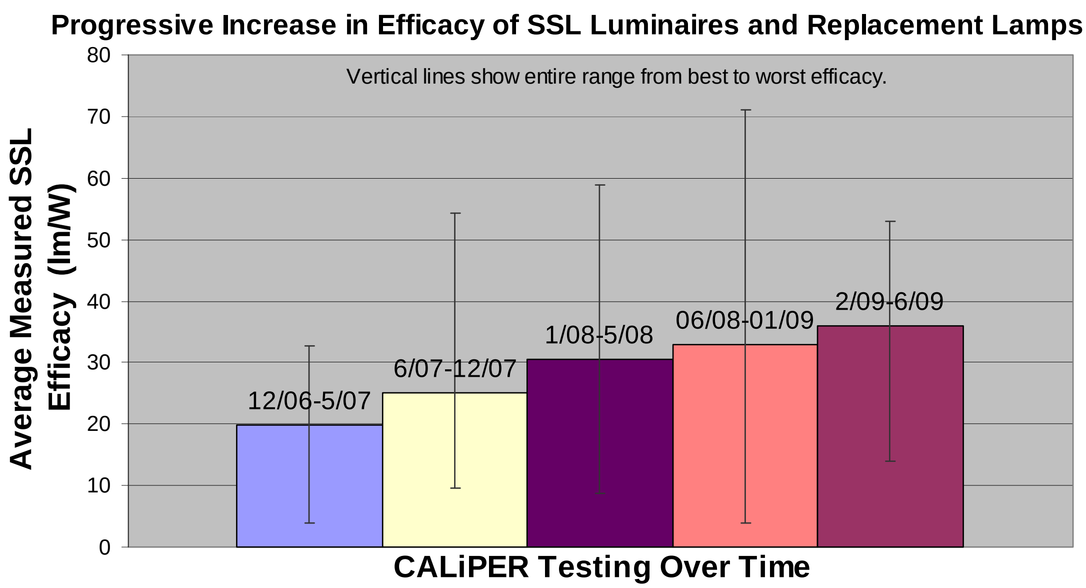


Figure 1. Average Measured Luminaire Efficacy of Market-Available SSL Products Continues to Increase

For each application category in this round of testing, clearly more SSL products are now approaching, matching, and sometimes exceeding the light output levels, distribution, and color quality of similar lamps and luminaires that use traditional sources such as incandescent, halogen, and CFL. Unfortunately, more than half of the products tested in this round have inaccurate or misleading product literature. Most severely, equivalency claims in product literature for replacement lamps are almost always false and misleading (e.g., "…directly replaces 35W halogen…," "…compare to standard 60W bulb…").

The sections below address each product category tested in this round, considering efficacy, light output, power characteristics, color quality, product labeling and reporting, and comparative performance to incumbent lighting technologies.

Replacement Lamps

Five SSL MR16 replacement lamps, six SSL PAR and R replacement lamps, and five SSL omni-directional replacement lamps (A-lamps, globe lamps, and candelabra lamps) were tested. Tables 1a and 1b (above) summarize key performance characteristics of these replacement lamps and additional tables and figures below assemble data regarding light distribution (center beam candlepower [CBCP] and beam angle), white-light fidelity (D_{uv}), and manufacturer claims about product performance.

Taken as a whole, a wide range of performance is observed among these SSL replacement lamps, with some clearly representing viable replacements for incandescent, halogen, or CFL, and some performing clearly far below manufacturer claims. In general they perform quite well with respect to efficacy, color quality, and intensity, but not necessarily so well with respect to total light output, power factors, and accuracy of product ratings. The average efficacy of these 16 SSL replacement lamps is 36 lm/W, which is slightly more than the average of 30 lm/W seen in the small CFL benchmark replacement lamps that were tested, almost 3 times more than the average efficacy of the halogen benchmarks that were tested, and 6 times more than the average efficacy of the eight incandescent benchmark lamps that were tested. Almost all of the 16 SSL replacement lamps are warm white, with a few neutral white and two that are cool white. The average CRI of these 16 SSL lamps is just slightly less than the average CRI of the small CFL replacement lamps that were tested.

With respect to light output and intensity levels, a few of these SSL replacement lamps are clearly meeting the levels of some benchmark products, but there are still others that produce only one quarter of the light output expected in their intended application, or less than half the light intensity (in candela), or sufficient light intensity but only over a very small beam angle. The points of comparison and general performance trends for these SSL replacement lamps are organized below by application type: MR16 lamps, PAR and R lamps, and omni-directional replacement lamps.

Directional Replacement Lamps: MR16

Five SSL MR16 lamps and one CFL MR16 lamp were tested, as summarized in Table 2. The CFL MR16 lamp product is available for purchase off-the-shelf in home improvement stores, in packaging stating “Replaces up to 50W, uses only 5W.” All except one SSL product tested show good or fairly acceptable performance. Compared to all the SSL MR16s tested in Round 8, the CFL MR16 lamp has the lowest efficacy, a very wide beam angle with very low CBCP, and far lower overall light output.

Table 2. Summary of MR16 Replacement Lamp Results

	DOE CALiPER TEST ID	Total Power (Watts)	Output (Initial Lumens)	Efficacy (lm/W)	CBCP (cd) & Beam Angle	CCT (K)	Max D_{uv}	Provides Accurate Product Reporting
Replacement SSL MR16* Lamps								
MR16	09-26	2	51	29	398/13°	3552	0.001	*No*
MR16	09-28	4	148	34	216/48°	3155	-0.006	*No*
MR16	09-29	3	150	46	75/84°	2938	-0.001	*No*
MR16	09-43	5	177	35	336/31°	2894	0.003	Yes
MR16	09-49	6	291	48	1653/17°	2842	0.001	Yes
Replacement CFL MR16 Lamps**								
MR16-CFL*	BK 09-11	3	62	20	18/112°	3310	0.001	*No*

D_{uv} is the closest distance between the chromaticity coordinates and the Planckian locus. Max D_{uv} presents the largest value of D_{uv} out of the two samples tested for each product. For D_{uv}, values in red italics are outside defined tolerances at a given CCT as defined in ANSI Standard C78.377.[6]

* Note that MR16 samples were tested using 12V input. Readers should factor in additional transformer or system losses for 12V products before comparing efficacy with products using 120VAC.

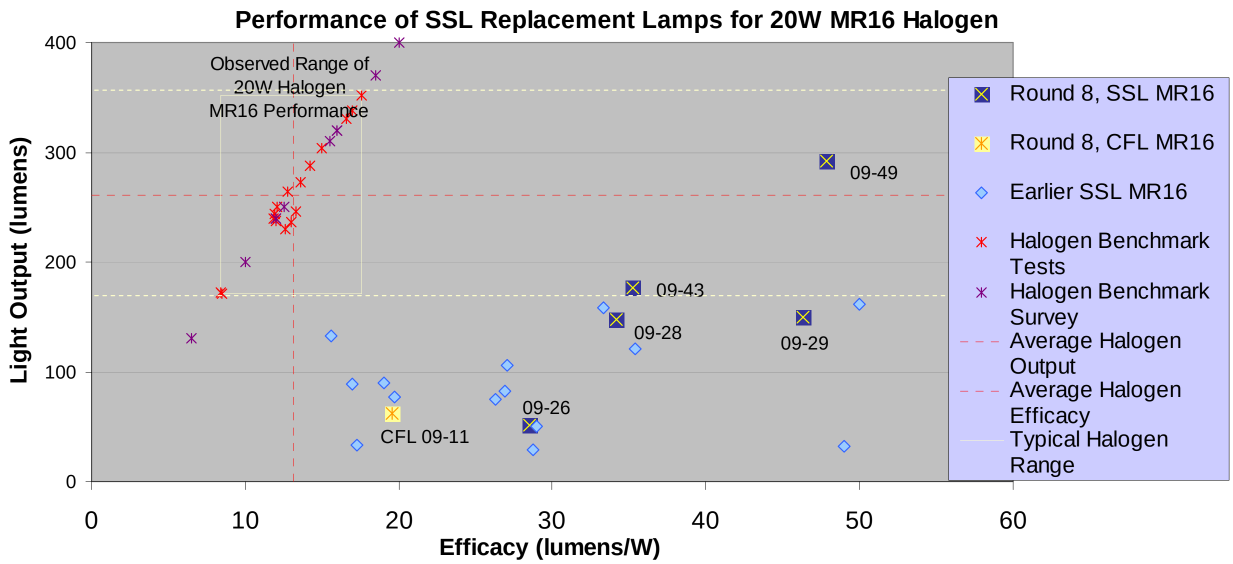
** Note that CFL is not a typical benchmark for MR16 lamps; in this case it is included in testing to provide concrete performance parameters for this point of comparison. More typical benchmark lamps for MR16 use halogen sources and are available in earlier CALiPER benchmark testing.

Overall, the results for SSL MR16 lamps tested in Round 8 are quite encouraging. With respect to color, all have CRI over 70, with the best at 93; all have warm white or neutral white CCT levels (thus fairly similar to the most common halogen replacement lamps); and none have D_{uv} outside of ANSI-defined tolerances for white light.

With respect to total light output, as illustrated in Figure 2, one of the lamps, 09-49, clearly meets and exceeds average output levels for 20W halogen lamps and three of the products achieve levels within range, though at the lower limit of the output levels for 20W halogen. Only one MR16 sample and the CFL sample tested clearly far below light output levels of 20W halogen.

With respect to meeting product ratings, only two out of six of these MR16 products achieve their manufacturer performance claims. Product 09-26 only produces one-quarter of the light output and the appropriate CBCP to the corresponding beam angle implied in product literature. Product 09-28 claims to be the world's most efficient LED MR16, and to directly replace 20-25W halogen with 265 cd in the wide beam version, but CALiPER measurements show only 216 cd, and clearly show that other products are more efficacious than this one. Product 09-29—while performing admirably at 46 lm/W—clearly does not meet its own claims of 70 lm/W. The two best, highest-output MR16 products tested in this round both have accurate performance data published in their product literature.

[6] 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.



Benchmark values are based on CALiPER benchmark tests, surveyed ratings, and averaged manufacturer ratings for 20W MR16 halogen lamps. Values are based on initial output, not average life-time output.

Figure 2. Performance of Halogen, CFL, and SSL MR16 Lamps

The CFL MR16 product has more exaggerated claims than any of the SSL products, alleging to replace the 50W halogen, when in fact it does not achieve even one-quarter of the average light output of a 20W halogen.

Considering light distribution, Figure 3 plots CBCP versus beam angle for the samples that were tested, as well as for previously tested SSL and halogen MR16 lamps, and manufacturer ratings for halogen MR16 lamps. As in previous rounds of CALiPER testing, at any given beam angle, the CBCP provided by most SSL MR16 lamps and for the CFL MR16 lamp falls below typical values for halogen lamps.[7] One SSL product however—the best-performing SSL MR16 product (circled in green)—had CBCP with respect to its beam angle meeting expected

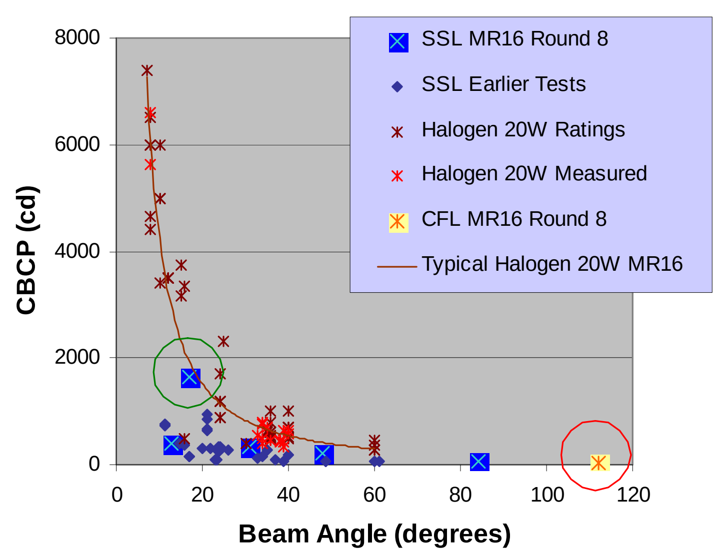


Figure 3. CBCP Versus Beam Angle for SSL, CFL and Halogen MR16 Lamps

[7] An online tool (http://www.drintl.com/temp/ESIntLampCenterBeamTool_5_19.xls) associated with the draft ENERGY STAR Program Requirements for Integral LED Lamps can be used to determine predicted and minimum CBCP as a function of nominal wattage for directional replacement lamps.

CBCP levels of MR16 20W halogen with similar beam angles. The CFL MR16 (circled in red) had a far wider beam angle than typical of MR16 products, with very low CBCP.

Form factor has been a potential issue for SSL MR16 products. One SSL MR16 tested in Round 8 has a form factor that is clearly much wider at the base than typical for an MR16, so it would not fit in some luminaires intended for halogen MR16s. Three of the MR16 lamps have a longer maximum overall length (MOL), or a diffuser lens extending beyond the body of the lamp, such that they might not fit in fixtures that include an additional lens cover or other mounting bracket limiting the extent to which the face of the lamp can extend. The labeling on the CFL MR16 package aims at addressing form factor issues through instructions: "If bulb does not fit into fixture with glass cover, insert bulb and safety clip and eliminate glass."

As mentioned in earlier CALiPER reports, these replacement lamps have not yet been subjected to lumen depreciation testing, so their reliability over time is unknown. Also, 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.

Directional Replacement Lamps: PAR and R Lamps

A number of lamps tested are sold as replacements for reflector and parabolic reflector lamps. All these products are grouped together for purposes of analysis, since there does not appear to be any clear performance or form factor difference that would make these lamps better described as either 'PAR' lamps or 'R' lamps—aside from a manufacturer's choice to market them as replacements for one or the other type of lamp. Three SSL PAR20 products, one SSL R30, one SSL PAR 38, and one SSL R38 were tested. Also, to increase our understanding of small reflector lamps, six different benchmark reflector lamps were tested, including one incandescent R16, one incandescent K19 (similar in format to an R20), two incandescent R20 lamps, one halogen R20, and one ENERGY STAR CFL R20 (RCFL). Data were also gathered from manufacturer catalog ratings for various sizes of PAR lamps.

Tables 1a and 3 summarize the performance of all the R and PAR lamps tested in Round 8. Overall, the SSL products have better performance than similar products tested in earlier rounds, with a few negative points noted. Four out of six SSL lamps have power factors below 0.70 (as well as the RCFL, although historically CFL power factor requirements are 0.50). Two of the SSL lamps have D_{uv} outside of the ANSI-defined tolerance for white light. Manufacturer ratings for one SSL lamp and for one incandescent lamp were clearly inaccurate. Another SSL lamp had partially correct and partially misleading manufacturer claims. Published ratings for one SSL lamp and one incandescent R20 could not be found. All other SSL and traditional lamps tested in Round 8 were found to have accurate product ratings.

Table 3. Summary of PAR and R Replacement Lamp Results

	DOE CALiPER TEST ID	Total Power (Watts)	Output (Initial Lumens)	Efficacy (lm/W)	CBCP (cd) & Beam Angle	CCT (K)	Max D_{uv}	Provides Accurate Product Reporting
PAR20 SSL	09-23	6	194	35	1297/18°	2888	-0.003	Yes
PAR20 SSL	09-25	3	104	33	378/20°	3186	-0.006	--
PAR20 SSL	09-35	7	272	36	594/28°	2993	*0.008*	Yes/*No**
R30 SSL	09-37	11	470	43	766/46°	2893	-0.004	Yes
PAR38 SSL	09-30	15	632	43	1094/41°	2924	0.001	*No*
R38 SSL	09-36	14	653	47	1876/31°	3072	*0.008*	Yes
R16 Incandescent	BK 09-08	40	233	6	135/43°	2529	0.000	Yes
R20 Incandescent	BK 09-05	40	227	6	67/129°	2516	0.000	--
K19 Incandescent	BK 09-06	41	388	10	62/141°	2667	0.001	*No*
R20 Incandescent	BK 09-07	29	181	6	111/70°	2560	0.001	Yes
R20 Halogen	BK 09-09	41	596	15	413/43°	2687	0.002	Yes
R20 CFL	BK 09-10	13	468	36	133/110°	2778	0.003	Yes

D_{uv} is the closest distance between the chromaticity coordinates and the Planckian locus. Max D_{uv} presents the largest value of D_{uv} out of the two samples tested for each product. For D_{uv}, values in red italics are outside defined tolerances at a given CCT as defined in ANSI Standard C78.377.[8]

* Note that sample 09-35 meets manufacturer claims for light output and efficacy values, but not for CRI nor for its equivalency statement (claims to replace 50W halogen).

Characterizing the performance of the PAR and R lamps and comparing them to lamps that use more traditional light sources is problematic because traditional directional lamps exhibit a very wide range of performance characteristics, depending on the degree of directionality of the lamps (beam angle), the power rating of the lamps, the type of source used, and other factors. The importance of different performance parameters may vary from one application to another—in some cases a minimum overall light output may be important, in other cases, providing a certain intensity level over a certain beam angle may be more important.

In general, PAR lamps available from major lamp manufacturers usually use halogen light sources and are available in narrower beams than R lamps. R lamps often use incandescent light sources (coupled with a reflector surface) or compact fluorescent light sources (again, coupled with a reflector surface), and while these are more directional in nature than standard incandescent or CFL lamps, they nevertheless tend to have quite wide beams, with relatively lower light intensity than PAR lamps. These are broad generalizations and do not hold true for every PAR or R lamp, as illustrated by some of the benchmark lamps described in the bottom half of Table 3.

[8] 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.

First, observing the results from the six benchmark lamps in Table 3 illustrates the range and diversity of performance of small R-lamps. All these benchmark lamps appear fairly similar, with the same basic reflector lamp shape and appearance (the K19 lamp looks fundamentally the same as the R20 lamps; the R16 lamp is similar, though with a slightly smaller bulb diameter). All the incandescent or halogen reflector lamps in this set are rated 30 or 40W. The RCFL is rated at 14W, but labeled as a 50W R20 replacement. Four of these benchmark R20 lamps have very wide beam angles, from 70 to 141°, with relatively low intensity, from 62-133 candela in CBCP. Two of these benchmark R lamps could be called flood lamps with beam angles of 43°. The 40W Halogen R20 has the highest light output (596 lm) and CBCP (413 cd for a beam angle of 43°), with an efficacy of 15 lm/W. The 14W RCFL provides about three-quarters the total light output of the 40W halogen, with three times the efficacy, but only about one-third the CBCP over a much broader beam than the halogen.

Second, analyzing the ratings provided in manufacturer catalogs illustrates the range and diversity of performance of small halogen PAR flood lamps, as summarized in Table 4, which looks only at 35-50W lamps and excluding lamps with beams narrower than 25°.[9] These surveyed data give ballpark averages of 330 lm for 35W PAR lamps or 500 lm for 50W PAR lamps, with an overall average efficacy of 10 lm/W for small, halogen PAR lamps. For the narrower-beamed 25° PAR20 lamps, the ballpark benchmark CBCP is about 1000 cd. For the wider-beamed 40° PAR lamps, the ballpark benchmark CBCP is about 500 cd. Typical center beam intensity of directional incandescent/halogen lamps depends on many factors such as lamp diameter, nominal wattage, and beam angle.

Table 4. Examples of Halogen PAR and R Replacement Lamp Ratings

Lamp Format	Rated Power (W)	Light Output (lm)	CBCP (cd)	Beam Angle (deg)	Calculated Efficacy (lm/W)
PAR20 Halogen	35	260	520	25	7
PAR16 Halogen	35	280	500	30	8
PAR14 Halogen	35	450	200	50	13
PAR16 Halogen	40	340	1040	27	9
PAR20 Halogen	44	420	880	25	10
PAR20 Halogen	50	570	1500	25	11
PAR20 Halogen	50	520	900	26	10
PAR20 Halogen	50	500	1000	30	10
PAR16 Halogen	50	450	800	30	9
PAR20 Halogen	50	525	525	40	11
R20 Halogen	50	540	470	40	11

[9] Two basic beam types for small PAR lamps—flood or spot—were observed in manufacturer catalogs,. The flood lamps typically had beam angle ratings of 25-27° or more and the spot lamps typically had beam angle ratings of 10-12°. Spot lamps were not included in this table because none of the SSL PAR lamps tested had such narrow beams. An interactive online tool (http://www.drintl.com/temp/ESIntLampCenterBeamTool_5_19.xls) for determining minimum center beam intensities is available in conjunction with the draft ENERGY STAR Program Requirements for Integral LED Lamps. This tool can be used to determine predicted and minimum CBCP as a function of nominal wattage for directional replacement lamps, based on models from statistical analysis of 432 PAR and 122 MR16 lamps produced by NEMA manufacturers. For a given target lamp wattage and target beam angle, mathematical functions for each lamp type yield the minimum required center beam intensity in candelas (cd).

While the SSL PAR20 lamps have narrower beam angles than any of the benchmark R lamps tested in this round, their performance can be compared to the surveyed benchmark PAR lamps. The smallest wattage SSL lamp, 09-25, drawing 3W of power, only provides one-third the overall light output of 35W halogen and for its beam angle of 20°, it provides only about one-third of the center beam intensity that would be expected in the 35W PAR20 lamps. Even compared to 20W MR16 lamps, 09-25 provides only half the light output and insufficient intensity for such a narrow beam. The other two SSL PAR20 lamps, at 6 and 7W, come much closer to meeting the 35W PAR lamp benchmarks, meeting or surpassing some of the 35W halogen lamps in either light output or expected CBCP. All three SSL PAR20 lamps achieve over 3 times the efficacy of the small halogen PAR lamps and are close to or matching the RCFL in efficacy.

A similar assessment can be made comparing the R30, R38, and PAR38 SSL lamps to reflector incandescent, reflector CFL, and halogen PAR lamps of similar sizes. Again, looking at the lower-wattage existing products in these formats with similar beam angles, and looking at results from earlier CALiPER benchmark tests, the SSL R30, R38, and PAR38 lamps tested in Round 8 achieve light output levels and beam intensities of 45-60W incandescent/halogen lamps. Rated light output levels for 40-50W incandescent R30 lamps were found to range from 340-630 lm, with similar or slightly higher output levels noted for wide-flood halogens. The lowest wattage reflector CFL products seen in catalogs of major manufacturers were at 9-15W, and their rated efficacies were only 33-50 lm/W, so these three SSL lamps have efficacy and light output levels similar to the RCFL products. The three SSL lamps have significantly narrower, higher intensity beams than RCFL lamps.

Omni-Directional Replacement Lamps

Five omni-directional SSL replacement lamps were tested in Round 8, including three that could be marketed to replace A-19 lamps (4-4 11/16" long, with standard Edison, E26, socket bases and with 2-2 3/8" globe-shaped bulb) and two with candelabra bases (a B10 and an E12 replacement). While each of these lamps may be a suitable replacement for some incandescent lamps in some applications, none of them meet their manufacturer's published performance claims.

Figure 4 compares the measured light output and efficacy of these products with benchmark data from both incandescent lamps and CFL lamps. Three of the lamps tested provide fairly low light output levels, from 25-49 lm, which would fall within the range of 4-15W incandescent lamps, as defined in manufacturer catalogs and confirmed by benchmark tests conducted on smaller wattage incandescent lamps. One of the SSL lamps, 09-21, provides light output typical of a 25W incandescent and another, 09-18, provides light output typical of a 40W incandescent. In all cases, the efficacy of the SSL products is 3 to 4 times higher than the efficacy of incandescents with similar output ranges. The lower light output products cannot be compared to CFL lamps, since no CFL benchmark products are identified that operate in these low light output ranges. The two higher output products have efficacies that are comparable to CFL efficacies.

Unfortunately, all these products underperform when compared to product claims. Product 09-18 claims, “It puts out more light than a standard 60-watt bulb…,” and yet it provides a little less than an average 40W incandescent (numerically, it claims 446 lm as compared to 352 lm measured). Product 09-19 claims, “They are available in 1 and 3 watt varieties and can replace 7 to 20 watt incandescent lamps.” The products ordered were the 3W lamps, which would therefore be expected to produce at least 120 lm, but the products received only draw 1.7 W and only produce 25 lm. Similarly, product 09-20 claims to compare to a 20W incandescent, but only produces 49 lm.

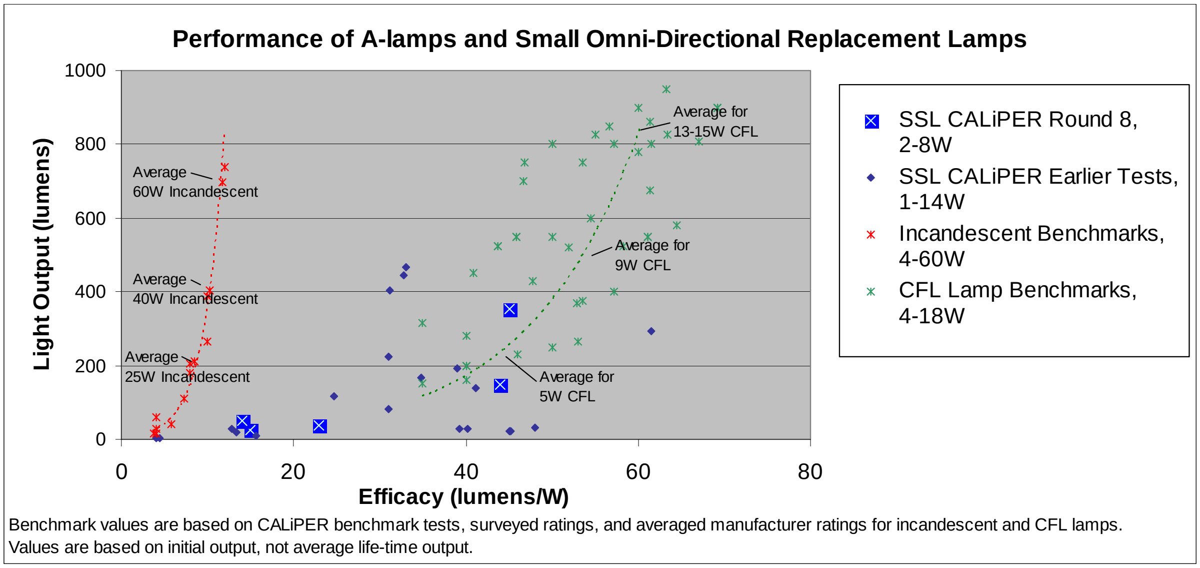
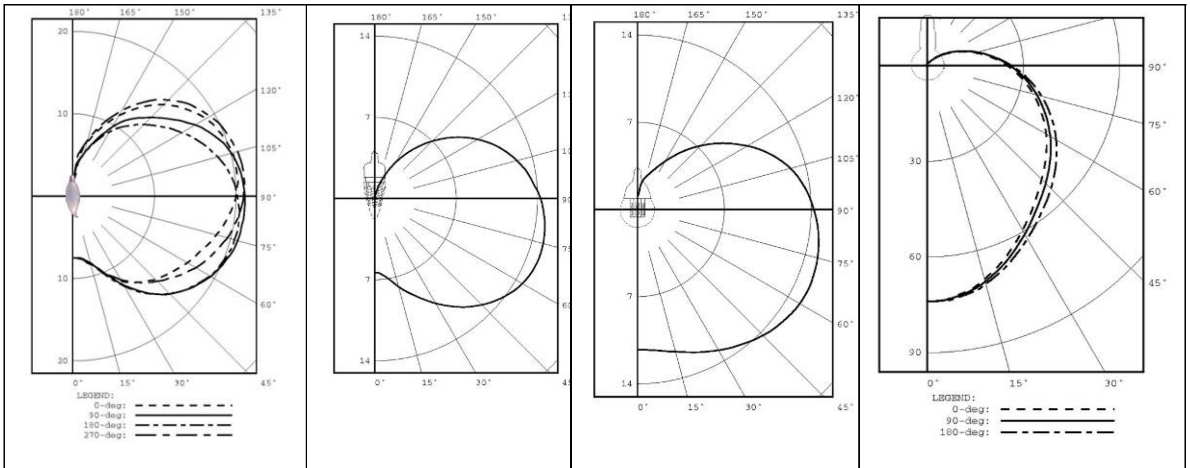


Figure 4. Comparison of A-lamp SSL Products Versus Benchmarked Traditional Lamps

The two candelabra-base SSL lamps achieve about 60-80% of their claimed light output. The larger, globe-shaped lamp, 09-21, claims to produce 180 lm, but was measured at 149 lm. The more traditional B10 style SSL candelabra replacement claims to produce 60 lm, but was measured at 38 lm.

The power factors and color qualities of these omni-directional SSL products are also inconsistent. Four out of the five SSL omni-directional lamps have poor power factors, ranging from 0.31 to 0.54. All five products have D_{uv} values within ANSI-defined tolerances for white light, but two have CRI values under 70. Also, three of the products have measured CCT values higher than claimed in product specifications: product 09-18 claims to provide white light at 5223K, but measured at 6426K; product 09-21 claims to provide “warm white similar to halogen”, but measured at 3425K—far higher than 2700K typical of halogen; and 09-22 is sold as 2700K, but measured at 3265K.

The left hand polar plot in Figure 5 shows the distribution pattern from an incandescent candelabra lamp, which emits about half of its light output (51%) in the downward direction and half of the light (49%) upward (tested with lamp oriented base up). The CFL candelabra lamp tested was slightly less omni-directional, with 59% of light output downward and 41% upward. The SSL samples intended to replace omni-directional lamps exhibit a range of performance: the most omni-directional was 09-21 with 60% of light output going downward and 40% upward, and the least omni-directional was 09-18 with 82% of light output going downward and 18% emitted upward. Depending on the application or luminaire for which these lamps are used, the heavily downward distribution may or may not provide desirable results.



Incandescent (09-34)	CFL (09-04)	SSL (09-21)	SSL (09-18)
0-90° : 51%	**0-90° : 59%**	**0-90° : 60%**	**0-90° : 82%**
90°-180° : 49%	**90°-180° : 41%**	**90°-180° : 40%**	**90°-180° : 18%**

Figure 5. Comparison of Light Distribution of SSL Omni-directional Replacement Lamps with Incandescent and CFL

In earlier rounds of CALiPER testing, some products were observed to have significantly atypical form factors—in some cases very large diameter bulbs, in some cases very long in overall lamp length, and in some cases very wide at the base of the neck approaching the Edison socket. The omni-directional replacement lamps tested in Round 8 show clear improvement with respect to form factor. None of the five SSL omni-directional samples tested have significantly atypical form factors.

Overall the performance of the five SSL omni-directional lamps tested in Round 8 is disappointing because none meets the claims published in manufacturer specifications and sales literature. All five products provide less light output than claimed; four of the five have poor power factor (0.5 or less); and three of the five provide much cooler white light than claimed. Some of these products could be suitable replacements for some lighting applications, particularly those requiring lower levels of light. Unfortunately, buyers cannot rely on manufacturer specifications or equivalency claims when making decisions regarding these products.

Downlights and Track Lights

One recessed downlight and one accent light fixture were tested in Round 8. The recessed downlight was a 6” IC downlight with open white trim. This product is listed as ENERGY STAR-qualified as of March 16, 2009.[10] The track light is a modular, track mountable accent light claiming to replace products using 35W halogen MR16 lamps. The key performance characteristics of these two products are summarized in Tables 1c and 5.

Table 5. CALiPER ROUND 8 SUMMARY – Downlight and Accent Light

Product Type	DOE CALiPER TEST ID	Total Power (Watts)	Output	Luminaire Efficacy (lm/W)	ENERGY STAR for SSL Performance on Key Parameters*	Provides Accurate Product Reporting
6" ø recessed can, ENERGY STAR-qualified as of 3/16/2009	09-24	14	589 lm CBCP: 297 cd Beam angle: 85°	42	Unit purchased before 3/16/2009 does not meet ES CRI requirement	Yes
Track light	09-33	9	204 lm CBCP: 425 cd Beam angle: 38°	22	Would not meet ES efficacy requirement	*No*

* ENERGY STAR qualification also includes other requirements not examined in this study (such as lumen maintenance, zonal lumen distribution, electrical safety characteristics, and size requirements).

The 6” recessed downlight product received ENERGY STAR qualification on March 16, 2009. The order for the first sample tested by CALiPER was placed one business day before this qualification was issued, and the sample was received several days after the ENERGY STAR qualification was issued. Three other samples with exactly the same model number were purchased two months after the product received the ENERGY STAR rating. While the product now meets its published performance specifications, the first sample meets ENERGY STAR criteria for recessed downlights, except for CRI. Technically speaking, this sample was purchased (ordered) before it had received ENERGY STAR qualification and the packaging material did not carry the ENERGY STAR label, so it was not required to meet ENERGY STAR criteria. The product design had to change from before ENERGY STAR qualification to after in order to meet the CRI criteria, but the product version number was not changed. Consequently, there is no way for purchasers to know that units of this product purchased before March 16, 2009 are different from units sold after this date and do not meet ENERGY STAR criteria. This example may influence both the DOE ENERGY STAR program and manufacturers to address the need to adequately reflect evolutions in product performance in version numbering systems and in product literature.

The track light that was tested in Round 8 claims to be equivalent to a 35W halogen MR16 lamp, but in fact provides about the same light output and CBCP as an average track light using 20W halogen MR16 with a similar 40° beam angle. To compare a track

[10] The current list of products qualified under ENERGY STAR for SSL can be downloaded from: http://www.energystar.gov/index.cfm?c=ssl.pr_residential

light using a halogen MR16 lamp to SSL track lights, the fixture losses must be taken into consideration (including driver losses for track lights using 12V lamps and factors related to fixture efficiency), but even with those losses considered, this product is only equivalent to a 20W halogen-based product; it does not provide the output and CBCP of a 35W halogen.

Figure 6 provides a quick comparison of three CALiPER-tested SSL track lights against 20W and 35W halogen MR16 products. A factor of 75% is applied to benchmark halogen lamp data to account for the combined fixture optical losses and transformer losses of the halogen lamps installed in track fixtures powered with 120VAC. All three SSL track lights shown in Figure 6 are integral fixtures using 120VAC. All five products have CCT between 2550K and 3150K and beam angles from 35-40°.

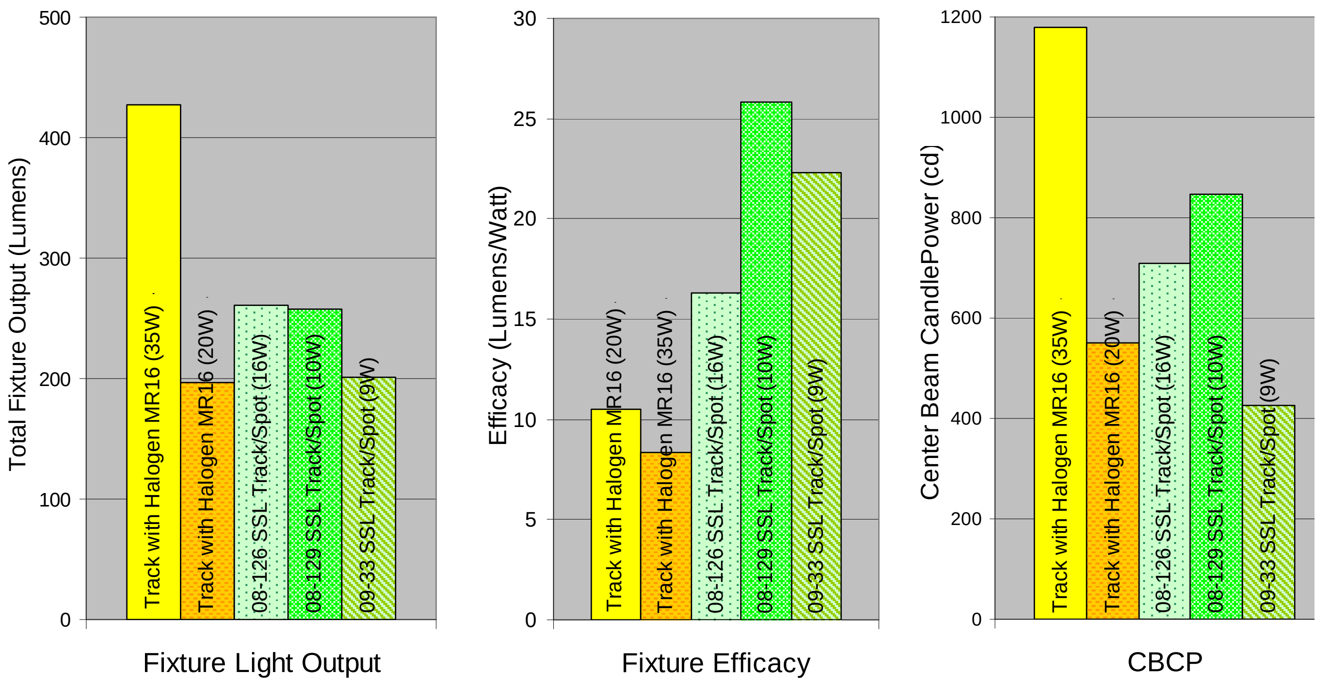


Figure 6. Comparison of SSL Track Lights to Track Light Fixtures Using 35W and 20W Halogen MR16 Lamps
Based on 120VAC input, assuming overall fixture efficiency (including optical and driver/transformer losses) of 0.75 for halogen-based track lights, using average surveyed manufacturer ratings for MR16 halogen and HIR lamps.

Figure 6 illustrates that the SSL track lights have about 1.5-3 times the efficacy of both halogen track lights. None of the SSL track lights meets the levels of total light output or CBCP provided by 35W halogens, but they are close to or exceeding the light output and CBCP for 20W halogens. These charts provide a simple estimate—fixture and transformer losses in halogen-based track lighting may vary widely depending on types and numbers of lamps used, fixture geometries, lenses, transformer losses, etc. Nevertheless, the generalized picture for these SSL track fixtures is positive, as long as they are compared to 20W halogen products rather than 35W halogen. Unfortunately, two out of three of these SSL track lights have product claims that exceed their measured levels of performance.

Undercabinet Fixtures

Three SSL undercabinet products were tested. Two were simple linear strips and the third was a product that includes a number of optional subcomponents, including 6”, 12”, and 18” strips and small puck lights. This undercabinet SSL lighting system has received ENERGY STAR qualification. CALiPER testing examined each of the subcomponents separately, as well as two alternative configurations of the lighting system: one representing a larger overall system load (with two 18” strips and a 12” strip) and one representing a smaller system load (with two 6” strips and one puck light).

To provide points of comparison, Table 6 summarizes the performance of these three SSL products along with the performance of three fluorescent ENERGY STAR-qualified products previously tested by CALiPER as benchmark products. Because these six products are all different lengths, light output per linear foot is used for comparison. On average, the SSL products produce more light output per linear foot than the ENERGY STAR fluorescent fixtures. Similarly, on average, the SSL undercabinets have better efficacy than the fluorescent undercabinets—with the lowest efficacy SSL undercabinet exceeding the lowest efficacy fluorescent undercabinet. Two out of three of the SSL products exceed the fluorescent products in power factor as well. One of the SSL undercabinet products, 09-38, includes an on-off switch and is correctly designed so that it does not draw power when it is in the ‘off’ position, as confirmed by CALiPER testing (the other two products use remote drivers).

With respect to color characteristics, two out of three of the SSL products tested provide warm white (around 3000K); likewise, two of the three fluorescent undercabinets provide fairly warm white (3000-3900K). All three of the SSL products have higher CRI than two of the fluorescent products. The lowest efficacy SSL product provides the best CRI of 96.

The SSL undercabinet system does not provide consistent performance across the various subcomponents. The 18” strip and puck components both exhibit excellent performance (efficacies over 30 lm/W and CRI of 93-95). The 6” and 12” strips appear to use different quality LEDs and only achieve efficacies of about 23 lm/W and CRI of 72-74. The D_{uv} values for some of these components are also at the limit of the acceptable range for ANSI-defined white light. This product qualified for ENERGY STAR as an overall system, as confirmed by the CALiPER verifications of two different combinations of subcomponents. Nevertheless, it may be important for some users to be informed of the differences in color characteristics and efficacy of the various subcomponents.

Table 6. Comparison of SSL Undercabinet Fixtures to ENERGY STAR-Qualified Fluorescent Undercabinet Fixtures

Undercabinet Fixtures	CALiPER Ref.	Output (Lumens / Linear Foot	Luminaire Efficacy (lm/W)	CCT (K)	CRI	Power Factor	ENERGY STAR qualified?
SSL System-large	09-31	291	34	~3030	74-93	0.83	Y
SSL System-small	09-31	274	29	~2950	72-95	0.75	
SSL Strip	09-32	194	21	2973	96	0.96	
SSL Strip	09-38	200	41	5407	74	0.48	
Fluorescent 21W T5	07-20	230	36	3015	84	0.59	Y
Fluorescent 13W T5	07-41	135	20	5734	71	0.70	Y
Fluorescent 15W T8	07-60	235	23	3865	60	0.55	Y

Figure 7 below plots the light output per linear foot and efficacy of these three SSL undercabinet products as compared to products tested in earlier CALiPER rounds. Two out of three of these products meet ENERGY STAR criteria for these parameters and surpass levels achieved by previously-tested SSL undercabinet fixtures. One of these two already has obtained the ENERGY STAR rating; the other product would need to have slightly lower CCT in order to qualify as an ENERGY STAR non-residential, undercabinet task light. The third product, 09-32, is close to achieving the efficacy required for ENERGY STAR qualification.

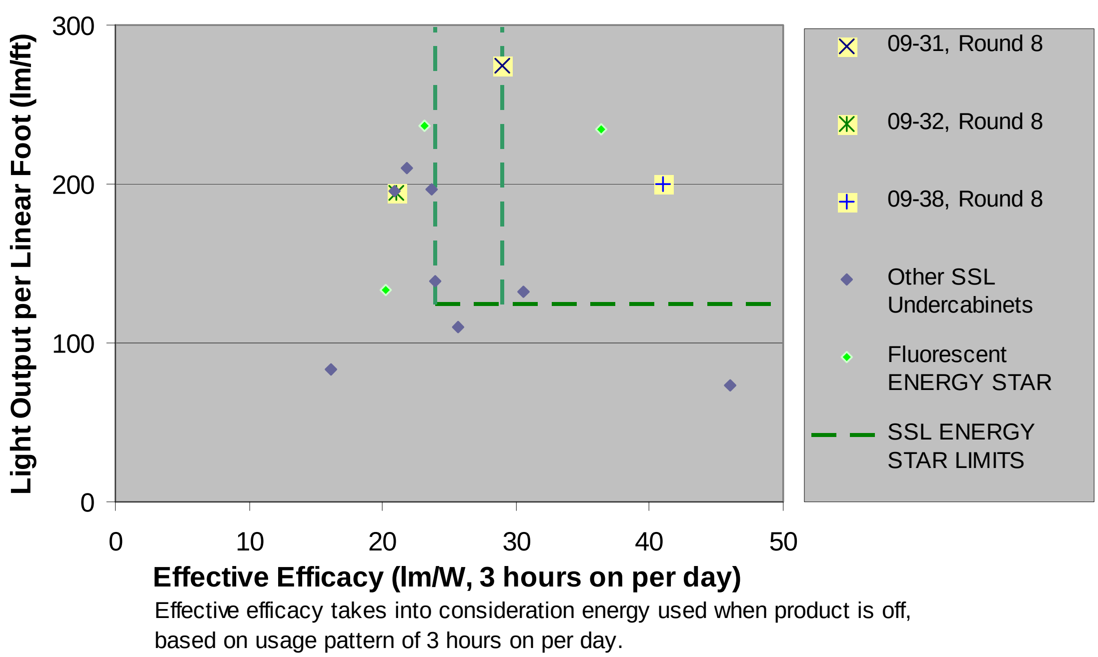


Figure 7. Undercabinet Fixture Performance

Relatively little manufacturer-published data regarding the performance of these SSL undercabinets were available. For the SSL undercabinet system, no explicit performance values were found, but the ENERGY STAR label implies that the product meets the minimum criteria required for this category of product, which was confirmed by the

CALiPER testing on the overall product system. For the lower efficacy, higher color quality product, 09-32, no manufacturer claims were found regarding light output or efficacy. For the third product, 09-38, the product specifications claim 66 lm/W, but CALiPER tests reveal that it only achieves 41 lm/W—less than two-thirds of the performance claim.

Outdoor Fixtures

One outdoor SSL streetlight fixture was tested in CALiPER Round 8. This fixture is in fact a second sample of the same product, 08-110, that was tested in Round 7. The first sample, tested on October 26, 2008, had been submitted by its manufacturers to the DOE GATEWAY demonstration program and was then tested jointly for the purposes of the GATEWAY program and for CALiPER. The test results from that sample were considerably higher than published in manufacturer literature, so a second sample was obtained outside the context of any DOE program to perform a retest. This second sample was tested on May 20, 2009. These two samples have exactly the same model number and exactly the same manufacturer number and the same CCT, but were produced in different lots, one dated July 2008 (the first product tested) and the second dated October 2008. At the time of testing, manufacturer literature did not indicate any difference in product performance from one manufacturing lot to another.

Table 7 summarizes the CALiPER results for these two samples. The sample tested in Round 8 provided a luminaire efficacy of 53 lm/W— a level very similar to the value indicated in photometric data for this product provided by the manufacturer on its website. The sample tested in Round 7, which had been submitted to the GATEWAY program for performance testing and possible use in a demonstration project, achieved a luminaire efficacy of 71 lm/W. Both samples exhibit similar color qualities and similar distribution patterns—though significantly lower candela values for 08-110B, corresponding to lower light output levels.

Table 7. Summary of Results for CALiPER Round 7 and Round 8 Product 08-110 Testing

Outdoor Streetlight -- Same manufacturer -- Same model number	**DOE CALiPER Ref.**	**CALiPER Test Date**	**MFG Date**	**Total Power (Watts)**	**Output (Initial Lumens)**	**Efficacy (lm/W)**	**CCT (K)**	**CRI**
Round 7	08-110A	10/26/2008	**Jul 2008**	**37**	**2588**	**71**	5210	68
Round 8	08-110B	5/20/2009	**Oct 2008**	**41**	**2172**	**53**	5182	71

The difference in performance observed between these two samples can serve as a reminder for both SSL manufacturers and specifiers. The wide range of performance options available in LED chips and the constant evolution of SSL technology and markets can impact production runs of commercially-available SSL products. There can also be an inherent degree of variation between different LED chips and different SSL end-products. In some cases, it may be desirable or possible to produce different versions of a same product, with quite different performance characteristics. In this case, the earlier-produced unit has significantly higher efficacy than a unit manufactured and distributed 5 months later.

Manufacturers can develop strategies to manage product evolution tightly and reduce the potential for confusing or misleading customers about product performance. Versioning practices can be implemented to manage product generations and to reflect variation or marked changes in product performance. Manufacturers can ensure that these degrees of variation are clearly communicated in product specifications and ordering nomenclature. Specifiers can be wary and ask whether or not there are multiple, different generations of a product and explicitly request that manufacturers provide performance information that corresponds to the versions of a product they are considering for purchase. Both manufacturers and specifiers can take precautions to address potential variation in product performance in contractual arrangements and to ensure that performance is verified on multiple units, particularly when working with large lots of delivered products or lots drawn from multiple production cycles.

CALiPER purchases products for testing anonymously whenever possible. Unfortunately in some cases, acquisition of small quantities of a product is not possible, or a manufacturer or distributor may become savvy to CALiPER purchasing channels. In other cases, CALiPER testing might be performed on a sample that does not represent the typical performance in a product line. In all these cases, CALiPER proactively implements practices aimed at detecting and verifying inconsistencies in product performance or in published test results, including sharing test results with manufacturers before they are published, allowing manufacturer-requested retests of products, and obtaining new samples for test from different production batches in some cases. Manufacturers and specifiers can also contribute to improving clarity and consistency of SSL product marketing literature.

Measurements of Color Quality

All SSL products tested in Round 8 have CCT values within ANSI-defined ranges for white light, and all but two products have D_{uv} that meet ANSI-defined tolerances for acceptable deviation of chromaticity coordinates from the black-body locus.[11] The average CRI of SSL products tested in Round 8 is 79—showing a significant increase over earlier rounds of testing.

Power Factor

The majority of products tested in Round 8 were replacement lamps, with only six SSL luminaires included. The average power factor among replacement lamps was 0.65, while the average power factor for luminaires was 0.82. The current minimum allowed for residential products by ENERGY STAR for SSL is 0.70 and the minimum for non-residential products is 0.90. While the majority of replacement lamps did not meet the

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[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.

0.70 minimum for power factor, all but one SSL luminaire achieved power factors above the 0.70 required by ENERGY STAR for residential products. A number of omni-directional SSL replacement lamps are still below 0.50 in power factor, as illustrated in Figure 8.

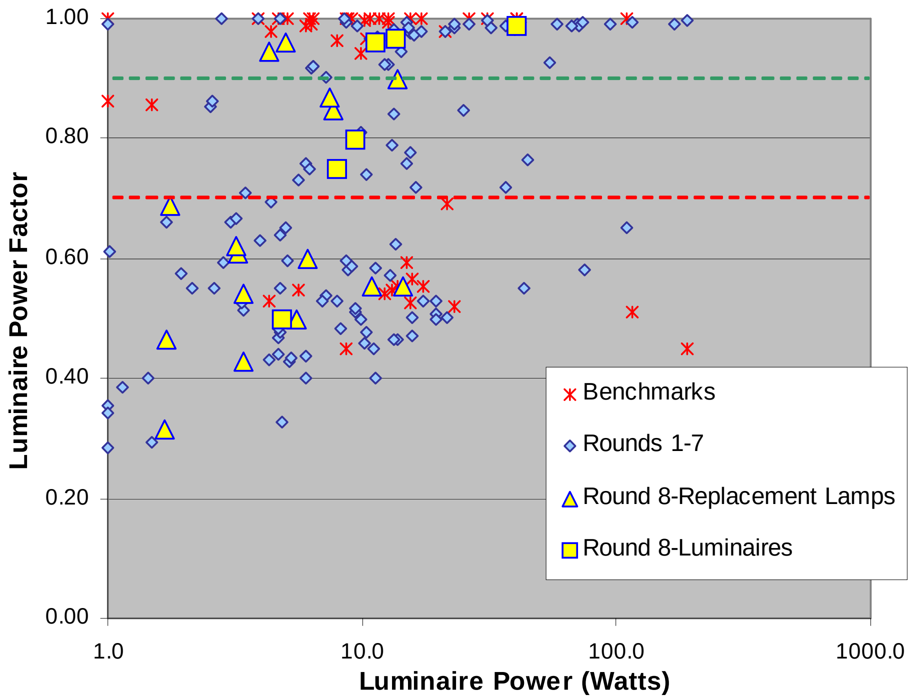

Figure 8. Power Factor Versus Wattage for CALiPER-tested SSL Luminaires and Replacement Lamps

Performance Reports in Manufacturer Literature

Overall, across the products tested in Round 8, the accuracy of manufacturer ratings for SSL products has not shown improvement from earlier rounds of testing. Over half of the products tested were described by the manufacturers or distributors with false or misleading performance claims. This lack of improvement on average may reflect the high proportion of replacement lamps included in this round of testing. Inaccurate or misleading ratings appear to be more common in replacement lamps than in luminaires. The greatest discrepancies were observed in small omni-directional replacement lamps, none of which met manufacturer claims.

As in earlier rounds of testing, equivalency statements play a significant role in misleading claims. Without clearly standardized, recognized characterizations of traditional lamp types, it is easy for a manufacturer to use an example of the very worst performing type of lamp and base comparative claims on that poor performer. As demonstrated by the lessons from early CFL market challenges, this type of practice may greatly damage SSL market potential. Industry publications and CALiPER benchmark reports should be used as points of reference by manufacturers who wish to include equivalency statements for their products. These resources provide surveys of ratings and benchmark tests for a variety of types of lamps, indicating typical averages and ranges for key performance parameters.

In most cases, purchasers and specifiers would be best served by disregarding any manufacturer-published equivalency claims. The credibility of manufacturer ratings is greatly increased if explicit performance values are published (such as light output, efficacy, CBCP, CCT), and further reinforced if LM-79 test results are published for a product. Nevertheless, even with published LM-79 test results, it is important to ensure that those results reflect the exact version of a product under consideration and to cross-check that information with other sources whenever possible.

Reliability: Lumen Depreciation Testing and Variability Testing

The CALiPER program has not yet subjected any of the products tested in this round to reliability testing. Long-term testing of SSL luminaires involves many months of operation and monitoring of lumen depreciation and color shift. Some of the products in Rounds 7 and 8 of CALiPER testing will be entering long-term testing during the summer of 2009, including some recessed downlights operated in UL1598 environments (representing the typical conditions experienced in insulated ceiling installations). Results from this long-term testing are expected in 2010.[12]

In addition to long-term continuous operation of SSL products, CALiPER is also exploring other facets of SSL reliability, including testing performance across larger sets of samples and testing long-term, cycled performance of some products. As failure modes or other issues are identified by CALiPER, they are shared with relevant trade groups and standards groups. Figure 9 illustrates one example of a failure mode that was detected during testing on a directional replacement lamp. In this case, a metal plate between the LED chips and the lens of the lamp shifted, blocking a portion of the light emitted by the LED chips. The effect in this case was an immediate reduction in light output and efficacy.

[12] A CALiPER report on the first batches of long-term testing of SSL luminaires and replacement lamps summarizes the performance results for 13 SSL products, along with testing techniques and observations from this testing. This report is available from the DOE upon request, "Long-Term Testing of Solid-State Lighting, Solid-State Lighting CALiPER Program." January 2009.

Normal sample | Sample with shifted internal plate

Figure 9. Example of Unexpected SSL Failure Mode

Conclusions from Round 8 of Product Testing

Key Conclusions

No extremely poor performing or unusually high efficacy SSL products were tested in Round 8. Efficacy of SSL products tested ranged from 14 lm/W to 53 lm/W, with an overall average of 36 lm/W—showing steady improvement over earlier rounds of CALiPER testing. In particular, the number of products that clearly represent viable replacements for incumbent products is increasing, although not always at levels claimed by manufacturers.

The MR16 replacement lamps tested demonstrated two extremes, with a retail CFL MR16 replacement lamp that clearly underperforms both 20W halogen MR16s and most recent SSL MR16 lamps. On the other extreme, a warm-white SSL MR16 lamp clearly meets and exceeds the average performance of 20W halogen MR16 lamps in light output and beam characteristics. This high performance SSL MR16 lamp achieves 20W halogen performance with over 3 times the average efficacy of halogens.

SSL lamps also show clear improvement in larger directional lamps. PAR20, PAR30, and PAR38 SSL lamps are now capable of meeting light output levels and beam characteristics of 35-50W incandescent and halogen lamps with efficacy levels similar to smaller wattage RCFL products. Some of these products need improvements in product performance reporting, power factor, or color quality, but overall they are now becoming competitive with lower wattage incandescent, halogen, and RCFL, particularly for applications requiring directional light output. Similarly, track light fixtures using SSL products are now capable of matching the performance of 20W halogen track fixtures, although unfortunately they are often labeled with inflated claims of 35W halogen equivalency.

For undercabinet luminaires, the three SSL products tested in this round clearly meet or exceed performance levels of fluorescent undercabinet products, as demonstrated by direct comparison to three RLF ENERGY STAR undercabinet fixtures. As with fluorescent products, the SSL undercabinets exhibit a wide range of performance characteristics, with different color characteristics, different efficacy levels, different levels of light output, and different geometries, so buyers and specifiers would be wise to demand LM-79 test results or choose products that have obtained the ENERGY STAR rating.

Two examples of products tested in Round 8 highlight the importance of careful versioning of SSL products. With the lack of standardization in LED source technologies and the rapid rate of change at various levels of SSL product components, ongoing evolutions in production processes and subcomponents may significantly impact the end performance of an SSL product. These evolutions may result in significant performance variations from one generation of a product to another or from one production run to another. Such variations may impact the suitability of a product for some applications and may cause confusion for buyers and specifiers, ultimately resulting in reduced credibility for a particular product or for SSL technology in general. Manufacturers are urged to be aware of these issues, to ensure that changes in product performance are reflected in specifications and in versioning, to avoid misleading or disappointing consumers.

Next Steps for the Industry and CALiPER Efforts

Two of the products tested in Round 8 were ENERGY STAR-qualified SSL products, and one product was tested in cooperation with the DOE GATEWAY program. Upcoming CALiPER testing will continue to provide support to other DOE lighting efforts including GATEWAY, ENERGY STAR, Lighting for Tomorrow, Next Generation Luminaires, SSL Quality Advocates, and L-Prize.[13]

The CALiPER program also works closely with the technical investigations and standards development surrounding photometric testing, working with independent and manufacturer testing laboratories, research laboratories, and standards development. [14]

CALiPER welcomes input from industry and has established a guidance committee to provide a more direct link to receive feedback and testing ideas through the eyes and ears of key stakeholders, such as energy efficiency programs, utilities, and lighting designers.

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[13] Visit the DOE SSL website for further information regarding DOE commercialization support programs such as GATEWAY, Lighting for Tomorrow (LFT), Next Generation Luminaires (NGL), ENERGY STAR for SSL, and SSL Quality Advocates. http://www.ssl.energy.gov

[14] Proceedings from the 2007 CALiPER Roundable Meeting are available online: http://www1.eere.energy.gov/buildings/ssl/about_caliper.html

In response to needs identified by the CALiPER Guidance Committee, additional CALiPER testing is underway on troffers, and new CALiPER benchmark reports are under development. Also, to better serve all CALiPER report readers, a new, more powerful search function for finding and comparing CALiPER results online is under development and expected to be available in July 2009.

DOE SSL Commercially Available LED Product Evaluation and Reporting Program

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