CALiPER

SUMMARY REPORT

June 2011

DOE Solid-State Lighting CALiPER Program

Summary of Results: Round 12 of Product Testing

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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

DOE Solid-State Lighting CALiPER Program

The Department of Energy (DOE) Commercially Available Light-Emitting Diode (LED) Product Evaluation and Reporting (CALiPER) Program has been purchasing and testing general illumination solid-state lighting (SSL) products since 2006. CALiPER relies on standardized photometric testing (following the Illuminating Engineering Society, IES LM-79-08) conducted by qualified, independent testing laboratories.[1] Results from CALiPER testing are available to the public through detailed test reports for each product tested and through periodic summary reports that assemble data from numerous product tests and provide comparative analyses.[2]

It is not possible for CALiPER to test every SSL product on the market, and SSL technology is continually evolving, so it is important for buyers and specifiers to reduce risk by learning how to compare products and by examining every potential SSL purchase carefully. CALiPER summary reports and detailed reports are an extensive resource, providing unbiased photometric data and explanations covering SSL product performance in a wide range of lighting applications. Previous summary reports include:

- Round 11 Summary Report (October 2010)—roadway arm-mount and post-top luminaires; high-bay luminaires; linear replacement lamps; and small replacement lamps.
- Round 10 Summary Report (May 2010)—parking structure luminaires; outdoor wallpack luminaires; cove lighting luminaires; and replacement lamps.
- Round 9 Summary Report (October 2009)—recessed downlights; a desk lamp; linear replacement lamps; and smaller replacement lamps.
- Round 8 Summary Report (July 2009)—downlights and track lights; undercabinet luminaires; outdoor fixtures; and replacement lamps.
- Round 7 Summary Report (January 2009)—outdoor area and streetlights; downlights; and replacement lamps.
- Round 6 Summary Report (September 2008)—desk lamps; a downlight; a recessed wall fixture; two different types of outdoor lighting products; and small replacement lamps (MR16, A-lamps, and candelabra lamps).
- Round 5 Summary Report (May 2008)—downlights; desk/task lamps; undercabinet lighting; outdoor lighting; and linear, A-lamp, and MR16 replacement lamps.
- Round 4 Summary Report (January 2008)—downlights; desk/task lamps; undercabinet and outdoor lighting; and linear, MR16, and candelabra replacement lamps.
- Round 3 Summary Report (October 2007)—directional and A-lamp replacement lamps; downlights; task lamps; and outdoor fixtures.
- Round 2 Summary Report (August 2007)—downlights; desk/task lamps; outdoor wall lighting; refrigerated display lighting; and R30 and A-lamp replacement lamps.
- Round 1 Summary Report (March 2007)—downlights; desk/task lamps; and undercabinet, outdoor area, and surface-mount lighting.
- Pilot Round Summary Report (December 2006)—downlights; a task light; and undercabinet lighting.

[1] IES LM-79-08 testing standard, *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: http://www.iesna.org/.
[2] Summary reports for Rounds 1-11 of DOE SSL testing are available online at http://www1.eere.energy.gov/buildings/ssl/reports.html. Detailed test reports for products tested under the DOE's SSL testing program also can be obtained online: http://www1.eere.energy.gov/buildings/ssl/search.html.

Summary of Results: Round 12 of Product Testing

Round 12 of CALiPER testing was conducted from January to March 2011. In this round 40 products (31 SSL and 9 conventional), representing a range of product types and technologies, were tested with both spectroradiometry and goniophotometry using absolute photometry. All 31 SSL products were tested following the IESNA LM-79-08 testing method; 9 benchmark products were also tested using absolute photometry to enable direct comparison of results between SSL and benchmark products.

Round 12 of testing includes six primary focus areas:

1. SSL recessed downlights
2. SSL track lights
3. SSL A-lamps
4. Benchmark 100W incandescent A-lamps and 70–100W halogen equivalents
5. SSL replacements for linear fluorescent lamps
6. SSL and benchmark cove lights

This report summarizes the basic photometric performance results for each product and discusses the results with respect to similar products that use conventional light sources, results from earlier rounds of CALiPER testing, and manufacturer ratings.

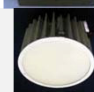
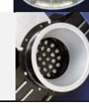
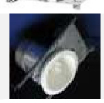
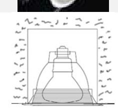
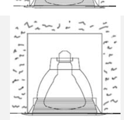
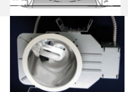
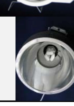
Round 12 CALiPER Testing Results

Tables 1a–d summarize results for energy performance and color metrics—including light output, luminaire efficacy, color rendering index (CRI) and correlated color temperature (CCT)—for products tested under CALiPER in Round 12. For some product types, benchmark CALiPER testing from earlier CALiPER rounds is also included for comparison. A thumbnail photo of each product is included. These tables assemble key results as follows:

- Table 1a: Ten SSL recessed downlights, from 3" to 6" in diameter, with beam angles ranging from 26–94°; six benchmark recessed downlights tested during previous rounds are also included for reference (five recessed downlights using 13–32W CFLs and one recessed downlight using a 65W R30 incandescent lamp).
- Table 1b: Nine SSL track-spot lights, with beam angles ranging from 20–40°, along with one small, narrow-beam puck light; halogen benchmark data is also included for one track light equipped with 20W MR16 as well as for three halogen MR16 lamps—20W halogen infra-red (HIR), 35W halogen, and 45W HIR, adjusted for typical fixture losses.
- Table 1c: Eight SSL A-lamps; nine incandescent A-lamp benchmarks and halogen equivalents; one 60W frosted incandescent A-lamp tested in Round 11 is also included for reference.
- Table 1d: Two SSL linear replacement lamps that were initially tested in Round 11 were retested in Round 12 to obtain luminaire performance when operated in high-performance, architectural troffers. Performance values for the same troffers equipped with benchmark fluorescent lamps (from Round 11) are provided for reference; results for an asymmetric SSL cove light and a CFL cove light also are presented.

Additional data for each set of testing results and related manufacturer information are assembled in CALiPER detailed reports for each product tested. Discussions of each category of results and further data are provided in the sections below.

Table 1a. CALiPER ROUND 12 SUMMARY – Recessed Downlights

-- SSL testing following IESNA LM-79-08 -- 25ºC ambient temperature	DOE CALiPER TEST ID	Total Input Power (Watts)	Initial Output (Lumens), CBCP, Beam Angle	Efficacy (lm/W)	CCT (K) [D_{uv}]	CRI	Photo
SSL Recessed Downlight Luminaires							
Downlight (3" recessed)	10-47	18	597 2525 cd, 26°	33	3095 [0.000]	84	
Downlight (4" recessed)	10-48	17	562 561 cd, 57°	34	3361 [0.000]	82	
Downlight (4" recessed)	10-49	18	874 963 cd, 62°	48	2967 [0.002]	78	
Downlight (5" recessed)	10-50	17	699 430 cd, 77°	41	3028 [-0.002]	82	
Downlight (6" recessed)	10-38	10	596 322 cd, 83°	58	2776 [0.000]	93	
Downlight (6" recessed)	10-41	12	935 536 cd, 76°	75	2729 [-0.001]	91	
Downlight (6" recessed)	10-42	25	1516 740 cd, 94°	61	3509 [-0.001]	82	
Downlight (6" recessed)	10-52	27	983 1388 cd, 49°	36	*3436** *[0.008]*	76	
Downlight (6" recessed)	10-53	24	1072 796 cd, 72°	44	2995 [0.002]	84	
Downlight (6" recessed)	10-37	55	2580 4493 cd, 45°	47	3424 [-0.002]	80	
Benchmark (BK) Recessed Downlights (Earlier CALiPER Testing), CFL and Incandescent R30							
Downlight (5" recessed) 13W, Triple Tube CFL	*Round 3* *BK 07-15*	13	346 210 cd, 84°	27	3928	79	
Downlight (6" recessed) 13W, Spiral CFL	*Round 3* *BK 07-21*	12	514 154 cd, 124°	42	2729	82	
Downlight (6" recessed, insulated IC-rated) 15W Reflector CFL	*Round 5* *BK 08-06*	16	841 236 cd, 110°	53	2740	82	
Downlight (6" recessed, insulated IC-rated) 65W Incandescent R30	*Round 5* *BK 08-13*	65	732 431 cd, 74°	11	2681	99	
Downlight (6" recessed) 26W, Triple Tube CFL	*Round 9* *BK 09-45*	28	872 473 cd, 80°	31	3166	83	
Downlight (6" recessed) 32W, Triple Tube CFL	*Round 9* *BK 09-66*	33	952 971 cd, 62°	29	3392	82	

Values are rounded to the nearest integer for readability. Results shown in this table are from testing at 120VAC.
CCT and D_{uv} values that are not within ANSI-defined (C78.377-2008) tolerances for white light in SSL products are shown in *red italics*.
*Product 10-52 has rated (nominal) CCT of 3000K.

Table 1b. CALiPER ROUND 12 SUMMARY – Track-Lights (Spot Lights)

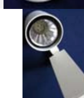
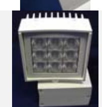
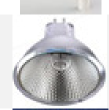
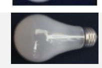
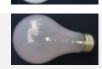
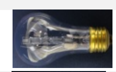
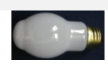
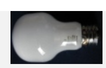
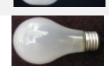
-- SSL testing following IESNA LM-79-08 -- 25ºC ambient temperature	DOE CALiPER TEST ID	Total Input Power (Watts)	Initial Output (Lumens), CBCP, Beam Angle	Efficacy (lm/W)	CCT (K) [D_{uv}]	CRI	Photo
SSL Track-Spot Luminaires							
Track/spot light	10-40	9	249 1332 cd, 21°	26	2723 [-0.006]	79	
Track/spot light	10-43	9	309 1116 cd, 28°	36	3028 [-0.002]	81	
Track/spot light	10-44	15	419 962 cd, 40°	28	3061 [-0.004]	84	
Track/spot light	10-51	25	1205 3496 cd, 31°	48	2978 [-0.001]	79	
Track/spot light	10-56	21	946 4900 cd, 25°	45	3045 [0.000]	84	
Track/spot light	10-57	5	136 912 cd, 20°	25	2996 [0.000]	93	
Track/spot light	10-58	25	726 4156 cd, 22°	29	2928 [0.002]	82	
Track/spot light	11-02	15	643 1970 cd, 28°	44	3193 [0.001]	81	
Track/spot light	11-07	13	571 2277 cd, 24°	45	3392 [0.001]	91	
SSL Puck Light Downlight/Spot Light Luminaires (Display Case)							
Downlight (3" puck--display)	10-46	3	57 246 cd, 23°	16	2742 [0.002]	80	
Benchmark (BK) Track-Spot (Based on Earlier CALiPER Testing & Calculated) Halogen							
Halogen Spot (20W Halogen MR16)	*Round 5 BK 08-12*	22	185 1047 cd, 14°	8	2873	97	
20W Halogen IR MR16 (Less 10% transformer loss, 15% fixture loss)	*Based on BK 08-96*	22	300 684 cd, 34°	14	2850	99	
35W Halogen MR16 (Less 10% transformer loss, 15% fixture loss)	*Based on BK 10-21*	39	500 2685 cd, 23°	13	3040	98	
45W Halogen IR MR16 (Less 10% transformer loss, 15% fixture loss)	*Based on Ratings*	55	750 2422 cd, 35°	14	3000	--	--
Values are rounded to the nearest integer for readability. Results shown in this table are from testing at 120VAC.							

Table 1c. CALiPER ROUND 12 SUMMARY – Omni-Directional SSL Replacement Lamps

-- SSL testing following IESNA LM-79-08 -- 25ºC ambient temperature	DOE CALiPER TEST ID	Total Input Power (Watts)	Initial Output (Lumens)	Efficacy (lm/W)	CCT (K) [D_{uv}]	CRI	Photo
SSL Omni-Directional Lamps: A-lamps							
Replacement A-lamp	10-39	7	345	50	2668 [0.001]	80	
Replacement A-lamp	10-54	7	*437*	60	2799 [0.001]	80	
Replacement A-lamp	10-55	13	859	69	2718 [-0.001]	81	
Replacement A-lamp	11-03	12	814	68	2676 [-0.003]	87	
Replacement A-lamp	11-04	7	*361*	54	4125 [0.005]	*74*	
Replacement A-lamp	11-05	8	*400*	52	2948 [-0.001]	81	
Replacement A-lamp	11-06	8	*409*	50	2779 [0.000]	85	
Replacement A-lamp	11-43	6	614	97	2881 [0.002]	93	
Benchmarks (BK): Omni-Directional Lamps: A-lamps Incandescent and Halogen Equivalents							
Replacement A-lamp 100W Incandescent	BK 11-09	100	1618	16	2819	100	
Replacement A-lamp 72W Halogen	BK 11-10	71	1550	21	3020	100	
Replacement A-lamp 100W Incandescent	BK 11-11	101	1694	17	2854	100	
Replacement A-lamp* 100W Incandescent	BK 11-12	99	1322	13	2871	81	
Replacement A-lamp* 75W Halogen	BK 11-13	75	837	11	2805	84	
Replacement Lamp (BT15) 75W Halogen	BK 11-14	79	1433	18	2974	99	
Replacement Lamp (BT15) 100W Halogen	BK 11-15	98	1503	15	2858	100	
Replacement A-lamp 70W Halogen	BK 11-24	71	1671	24	2863	99	
Replacement A-lamp 100W Incandescent	BK 11-25	90	1245	14	2765	100	
Replacement A-lamp 60W Incandescent	*Round 11* BK 10-31	61	823	14	2771	100	

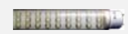
Values are rounded to the nearest integer for readability. Two or more samples were tested for replacement lamps—values are average of two samples.

For replacement lamps, lumen output requirement is based on target replacement wattage as claimed by the manufacturer. Performance levels that do not meet the minimum ENERGY STAR® criteria for integral SSL replacement lamps are shown in *red italics*.[3]

*Samples BK11-12 and BK11-13 are modified spectrum lamps.

[3] *ENERGY STAR® Program Requirements for Integral LED Lamps Partner Commitments*. http://www.energystar.gov/ia/partners/manuf_res/downloads/IntegralLampsFINAL.pdf, March 22, 2010.

Table 1d. CALiPER ROUND 12 SUMMARY – Linear Fluorescent and Cove Lights

-- SSL testing following IESNA LM-79-08 -- 25ºC ambient temperature	DOE CALiPER TEST ID	Total Input Power (Watts)	Initial Output (Lumens)	Efficacy (lm/W)	CCT (K) [D_{uv}]	CRI	Photo
SSL 4' linear lamps: Bare Lamp and Testing in High-Performance Lensed Troffers							
Bare Lamp	*Round 11*	15	1368	93			
In troffer (2 lamps in parabolic louvered troffer)	*Round 11*	29	2173	74	5389 [-0.004]	77	
In troffer (2 lamps in high-performance troffer BK 09-67)	*Round 12* 10-16	29	2217	77			
Bare Lamp	*Round 11*	17	1533	91	5602 *[0.009]*	75	
In troffer (1 lamp in high-performance troffer BK 10-34)	*Round 12* 10-18A	17	1303	79			
Fluorescent Benchmarks (BK): Bare Lamp and Testing in High-Performance Lensed Troffers							
Bare Lamp (fluorescent)*	*Round 9*	32	3246	101			
In troffer (2 lamp troffer, Ballast Factor BF=1.18)	*Round 9*	69	4767	69	3248 [0.002]	83	
In troffer (2 lamp troffer, Ballast Factor BF=0.88)	*Round 11* BK 09-67	55	4045	74			
Bare Lamp (fluorescent)*	*Round 11* BK 10-34	32	3353	105	3387 [0.004]	82	
In troffer (1 lamp troffer, Ballast Factor BF=1.18)		38	2708	71			
SSL Cove Luminaire							
Asymmetric Cove (36" long)	10-45	51	980 [324 lm/ft]	19	3017 [-0.002]	88	
Benchmark CFL Cove Luminaire							
Cove Fluorescent (18" long)	BK 10-24	36	2025 [1322 lm/ft]	56	3334 [0.003]	82	

Values are rounded to the nearest integer for readability.

10-16 and 10-18 in fluorescent troffers require bypassing fluorescent ballast. For 10-18, one of two lamps underperformed by a wide margin, the higher-performing lamp was used for in troffer testing in the single lamp high-performance troffer (BK10-34). Lamps 10-16 were already tested in a parabolic troffer in Round 11 and have been retested in a high-performance troffer in this round.

D_{uv} values that are not within ANSI-defined tolerances for white light in SSL products are shown in *red italics*.

*Bare lamp testing for linear fluorescent lamps conducted with reference ballast, Ballast Factor (BF)=1.0.

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

Energy Use and Light Output

The SSL products tested in Round 12 exhibit a wide range of light output and efficacy performance as summarized in Figure 1.[4] The overall average efficacy for SSL products tested in Round 12 is 46 lm/W, ranging from a minimum of 16 to a maximum of 97 lm/W. The 46 lm/W average is lower than the overall average in 2010, most likely because almost all Round 12 products have CCT below 3500K, while the average CCT of SSL products tested in 2010 was above 4000K. The average efficacy was also brought down by two outliers with efficacy below 20 lm/W and by most of the track light products.

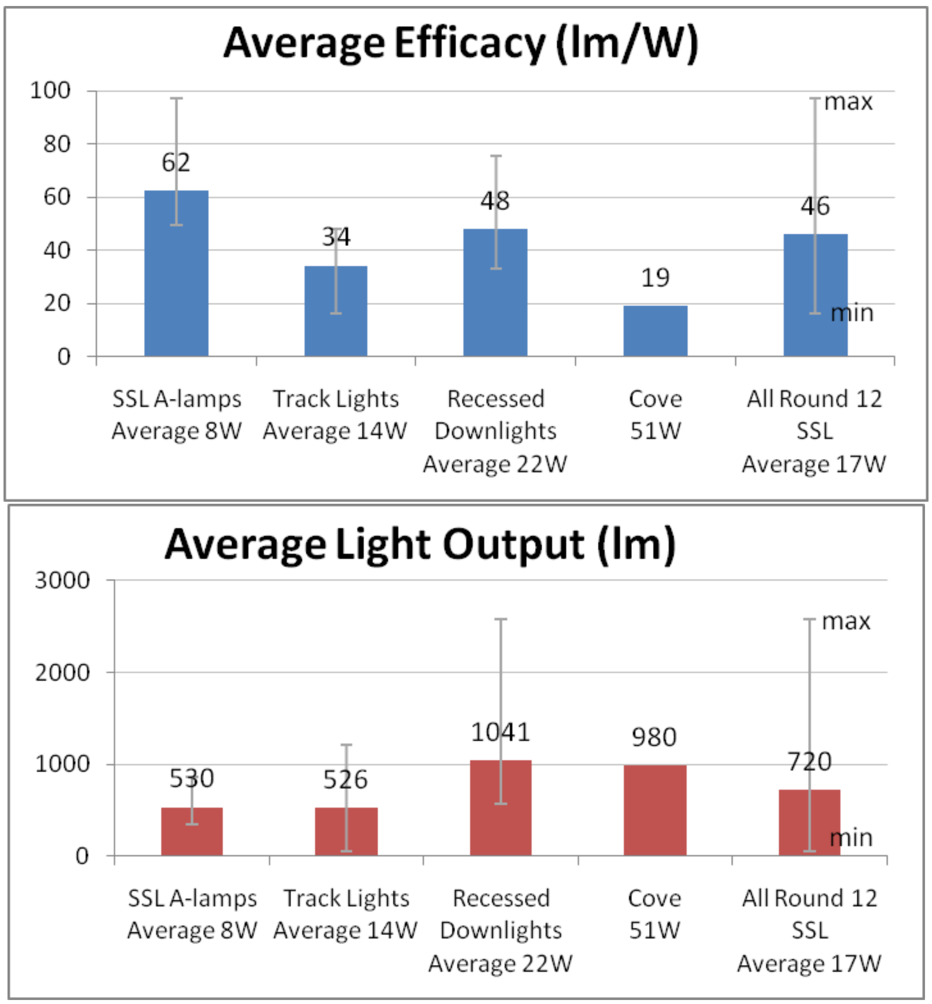


Figure 1. Average Round 12 Results for SSL Luminaires and Replacement Lamps

The average efficacy of SSL track lights tested is 36 lm/W, and even the highest efficacy track light achieves only 48 lm/W (which is below the overall 2010 average efficacy of CALiPER tested SSL products of 50 lm/W). SSL A-lamp products are subject to considerably greater thermal management challenges than larger-format integrated products, such as recessed downlights. Nevertheless, the average

[4] Retests of linear fluorescent lamps in high-performance troffers are not included in Round 12 averages because these products were initially presented in Round 11 testing.

efficacy of SSL A-lamps tested in Round 12 is 62 lm/W (bare lamp), compared to 45 lm/W on average for recessed downlights. One warm-white (2881K CCT) A-lamp tested in Round 12 achieves the highest initial efficacy of any commercially available SSL product tested by CALiPER to date: 97 lm/W.

The average light output is similar for SSL track lights and SSL A-lamps in Round 12, with the track lights exhibiting greater variation and drawing far more power, on average, than the A-lamps. The cove light produces a similar level of luminaire light output compared to the average for recessed down lights, while using 2.5 times the power.

The majority of the SSL products tested have rated CCT of 2700 or 3000K, four products have rated CCT of 3500K, and one has rated CCT of 4000K. Showing clear progress over earlier rounds of testing, only two SSL products have CCT or D_{uv} outside standardized tolerances for white light in SSL products.[5] Color rendering characteristics are also improving with an average CRI of 83 and only one product with CRI below 75.

Power characteristics and labeling of products also show progress. The average power factor, including replacement lamps, is 0.9. Three quarters of the products are labeled as dimmable or offer optional dimming. The majority of the products that are dimmable provide a specific indication, such as "Dimmable to 10%." Only three products do not carry any indication regarding dimmability. Half the SSL products are either labeled as ENERGY STAR qualified or carry the Lighting Facts label.

Figure 2 shows the yearly progress in efficacy based on CALiPER results, from the inception of CALiPER testing in 2006 through Round 12. Vertical bars indicate the spread in performance. The steady increase in average and maximum efficacy is clear. The minimum efficacy seen in Round 11 is actually higher than the overall average efficacy observed in 2007 (26 lm/W *minimum* Round 11 versus 21 lm/W *average* in 2007).

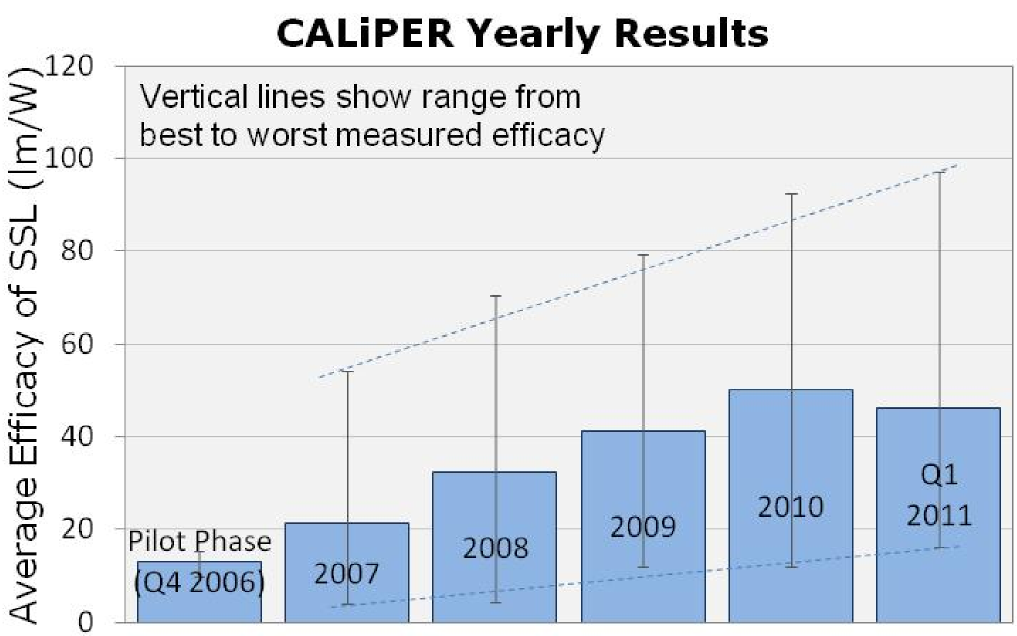


Figure 2. Average Measured Efficacy of Market-Available SSL Luminaires and Replacement Lamps

[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.

Recessed Downlights and Track Lights

The primary focus for luminaires in Round 12 was downlight products, examining both recessed downlights and track head fixtures (which incorporate driver and power supply such that they operate on 120VAC). General characteristics and light output and efficacy of each group of downlights are discussed below, followed by a discussion of beam characteristics and light distribution from these products.

Recessed Downlights

Ten recessed downlights with apertures ranging from 3" to 6" were tested in Round 12, as summarized in Table 1a; six of these were 6" diameter recessed downlights. These ten SSL downlights represent a range of designs addressing a variety of application needs. All are designed for general illumination, except the 3" product, which is for accent lighting.

Some of these downlights are sold as complete luminaires, including housing (making them dedicated fixtures for which relamping would require replacing the entire fixture); some are sold as retrofit or replacement inserts (with Edison or other socket options or a variety of retrofit-mounting designs) to be installed in 6" diameter recessed fixtures. Product 10-38, for example, is a retrofit insert for recessed downlights with an Edison-base socket. The recessed downlights have nominal CCT values ranging from 2700–3500K and CRI ranging from 76 to 93. Only one recessed downlight, 10-52, has measured CCT that does not meet its rated value and D_{uv} outside ANSI-specified tolerances.

The 6" recessed downlights underscore the diversity and range of performance of SSL products available in the same basic product dimensions, with power levels ranging from 10–55W. The most efficacious 6" recessed downlight, 10-41, achieves 75 lm/W, which is more than double the efficacy of the least efficacious 6" downlight, 10-52, which achieves only 36 lm/W. Luminaire light output levels range from 562 to 2580 lm, beam angles range from 26 to 94°, and CBCP range from 322 to 4493 candelas (cd). One SSL 6" recessed downlight, 10-37, is designed at a significantly higher power level and light output level than the other products—this product might be comparable in luminaire light output to a 12" x 12" or 24" x 24" troffer luminaire, rather than to a typical wattage CFL 6" recessed downlight.

Table 1a also lists benchmark performance of recessed downlights equipped with CFL (spiral and tube lamps), Reflector CFL (RCFL), and R30 incandescent from earlier CALiPER testing to provide points of comparison. It should be noted that two of these benchmark tests were performed in insulated housings. In earlier CALiPER testing, SSL and CFL products in insulated housings were shown to lose 10–15 percent of output and efficacy relative to non-insulated housings.

The light output, efficacy, light distribution, and accuracy of manufacturer ratings for the SSL recessed downlights are discussed below.

Output and Efficacy of Downlights

Figure 3 charts the luminaire light output and efficacy of SSL recessed downlights tested in Round 12 compared to earlier CALiPER testing of both SSL and benchmark recessed downlight products. All the 4–6" SSL recessed downlights in Round 12 meet or exceed average light output levels for similar, higher-wattage recessed downlights equipped with CFL, incandescent, or halogen lamps.

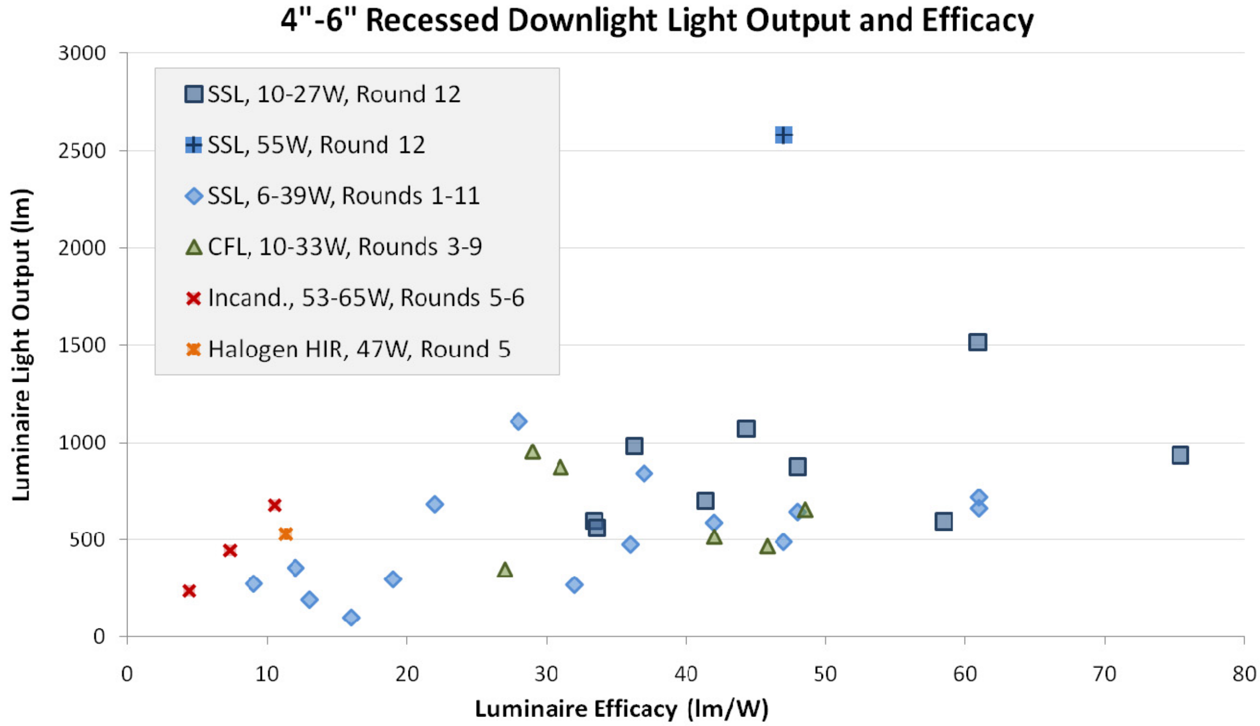


Figure 3. Luminaire Light Output and Efficacy of Recessed Downlights

With respect to efficacy, two of the ten Round 12 SSL products exceed the highest performing 6" downlight products previously tested by CALiPER. The Round 12 SSL recessed downlights surpass incandescent (recessed downlights equipped with incandescent A-lamp or R30) and halogen (recessed downlights equipped with Halogen HIR PAR38), achieving three to six times the luminaire efficacy of incandescent and halogen. All ten SSL recessed downlights also achieve better efficacy than the two CALiPER tested examples of 6" recessed downlights equipped with 26W and 32W triple-tube, pin-based CFL lamps. Half the SSL recessed downlights have comparable or greater efficacy than the CALiPER tested RCFL installed in an insulated 6" IC recessed downlight.

Track Lights

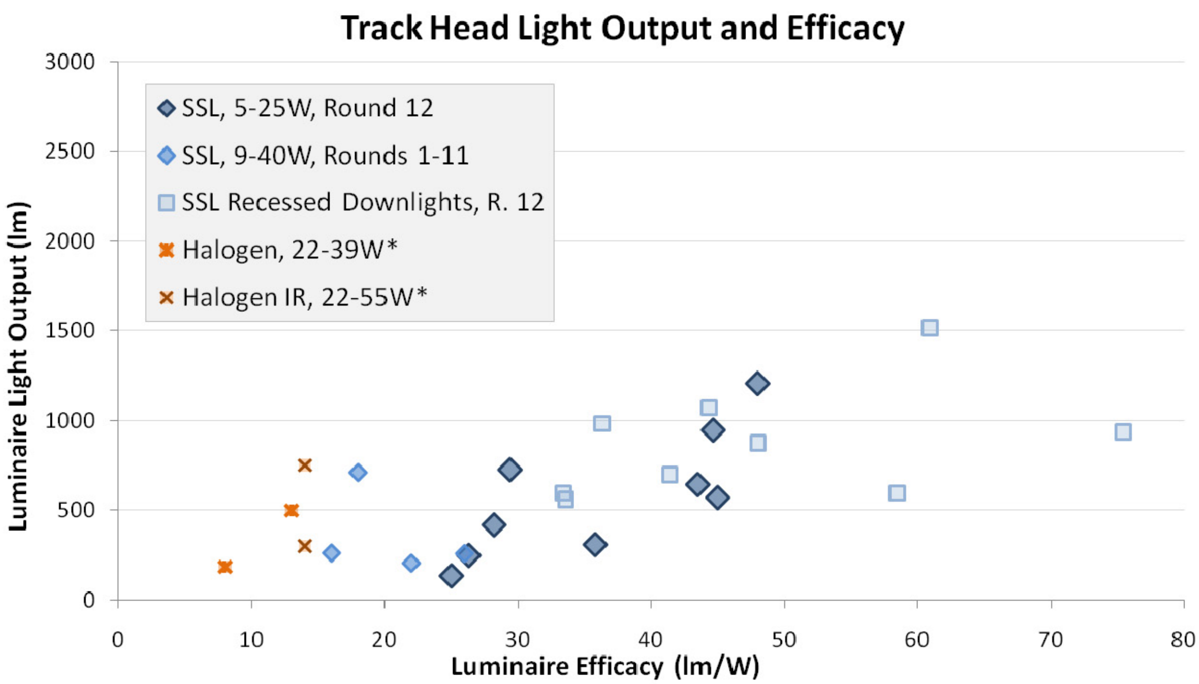
Nine orientable SSL track lights were purchased and tested. Each product consists of one track head with driver and/or power supply, such that the track light is powered by 120VAC. The nine track heads represent a wide range of performance: from power levels of 5–25W, light output of 136–1205 lm, 20–40° beam angles, and CBCP of 912 to 4900 cd. Product 10-57 is sold as a unit, but contains an SSL MR16 lamp inside a track housing—this sample exhibits significantly lower performance than the other track heads, which are integral designs. All the SSL track lights have nominal CCT ranging from 2700–3400K, with CRI ranging from 79 to 93.

One additional product, 10-46, is included with the track head listing. This product is an SSL puck light, marketed for display cabinet accent lighting and described as an “AC LED.” While providing a fairly narrow, directional beam like the track heads, this product produces significantly lower light output, efficacy, and CBCP than even the poorest-performing track head.

A spot light using a 20W halogen MR16 lamp, tested by CALiPER previously, provides surrogate benchmark data for track heads. This product was marketed as a landscape spot light, but is of similar design and performance to typical halogen track heads. Also, a range of halogen MR16 lamps representing 20W, 35W, and 50W halogen and halogen infrared (IR) lamps that were CALiPER tested are included, with a correction factor applied to represent typical transformer loss and fixture loss that could be expected with the lamps installed in a track head as indicated in Table 1b.

Output and Efficacy of Track Heads

Figure 4 compares the overall light output and efficacy of each SSL track head tested in Round 12 with SSL track heads tested previously, SSL recessed downlights tested in Round 12, and the halogen benchmarks. All the Round 12 SSL track head products exceed the efficacy of benchmark halogen track heads, typically by a factor of 2 or 3. Almost all the Round 12 track heads also have greater efficacy and similar light output to SSL track heads tested in previous rounds. Four SSL track heads do not meet the minimum efficacy observed in the Round 12 recessed downlights. None of the SSL track heads achieve the efficacy levels of the three best-performing SSL recessed downlights.



*Halogen and Halogen IR benchmark values are based on one CALiPER tested halogen landscape spot light (track head-style) and on CALiPER MR16 lamp testing, adjusted for fixture and transformer loss.

Figure 4. Luminaire Efficacy of SSL and Benchmark Track Lights

Intensity Distribution of Recessed Downlights and Track Lights

Levels of light output and center beam intensity are criteria of importance when comparing downlight products, but beam edge characteristics and uniformity across the beam also can be of importance in many applications. With the exception of 10-47, the intensity distributions (beams) of the track luminaires were more focused than those of the recessed downlights, as illustrated in Figure 5. Two key metrics are used to compare the intensity distribution of recessed downlights and track luminaires aimed downward: spacing criterion and beam angle. The spacing criterion is the approximate maximum ratio of spacing to height above horizontal work plane yielding acceptable work plane uniformity, and beam angle is simply twice the angle from center beam to the point at which intensity drops to half of maximum.[6] As with troffers, spacing criterion is typically applied to fixed (non-adjustable) recessed downlights, which traditionally utilize either omni-directional or directional lamps, producing a “beam” centered at nadir. In contrast, beam angle is generally applied to track luminaires because they traditionally utilize directional lamps tilted at some angle from nadir for accenting purposes. The SSL track lights, like benchmark track lights, have relatively narrow beam angles (in the examples in Round 12 ranging from about 20–40°). The SSL recessed downlights, as expected, have wider beams than the track heads (ranging from about 40–95°, with the exception of 10-47). On average, however, the SSL recessed downlights’ beams are not as wide as the beams of the benchmark recessed downlights.

Beam angle and spacing criteria provide generalized metrics describing light distribution, but other indicators are needed to look more closely at beam characteristics that might affect qualities, such as perceived smoothness of the beam, symmetry, tapering of the edge (hard versus soft edge), and striations or other beam irregularities. Beam quality metrics have been explored in lighting research, but few standardized, commonly used metrics exist other than beam angle and field angle to characterize beam quality.[7] An examination of beam qualities—without a more technical study of luminance ratios, gradients, and associated human perceptions—can at least consider surface illuminance, polar distributions, and beam renderings generated by lighting design tools.

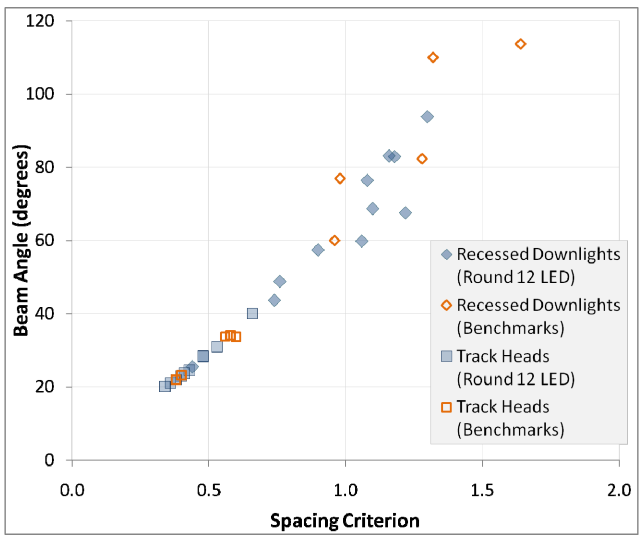


Figure 5. Intensity Distribution of Recessed Downlights and Track Heads

The series of figures on pages 14-16 provides a synopsis of basic visualizations describing beam qualities for products having similar beam and field angles. First, in Figures 6a-d, one benchmark and three SSL recessed downlights having relatively narrow beams (57–69° beam angles) are compared. Second, in Figures 7a-d, one benchmark and three SSL recessed downlights having wider beams (76–110° beam angles) are compared. Third, in Figures 8a–c, one benchmark and two SSL track heads with beam angles of 20–22° are compared.

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[6] IES RP-16 uses half of maximum intensity, whereas ANSI C78.379 uses half of center-beam intensity. Also note that some lighting software requires that Type C photometry must be converted to Type B for calculation of beam angle, thereby introducing some error.

[7] See, for example, Simonson, K., Narendran, N., Boyce, P. and Bierman, A. “Development of a metric to quantify beam quality of reflectorized lamps.” *Journal of the Illuminating Engineering Society,* 32, no. 1, 63-71, 2003.

For each product shown in these figures, the beam angle, field angle, and CBCP are indicated alongside a polar distribution plot, an isocandela plot, and a "photo-realistic" rendering.[8] The isocandela plots are drawn with successive isolines plotting percentages of maximum intensity, dropping by a fifth between each line. The five isolines included on each plot represent percentages of maximum intensity as follows:

- 50 percent (blue)
- 10 percent (red)
- 2 percent (green)
- 0.4 percent (purple)
- 0.08 percent (black)

The photo-realistic renderings illustrate the familiar "scallop" pattern of light produced on a 10-foot-high wall by a nearby recessed downlight or track luminaire set back 3 feet from the wall. A tilt of 30 degrees from nadir, commonly used for accenting vertical displays to minimize direct and reflected glare, was applied to the track heads.[9] The renderings assist in visualizing the pattern of light visible on horizontal or vertical surfaces, particularly near the beam edge. Most general lighting luminaires feature fairly broad distributions, putting the beam edge at higher angles, whereas lower-incidence angles often cause the beam edge to be more noticeable on vertical surfaces than on horizontal surfaces. A soft beam edge is often desirable, characterized by a low illuminance gradient across the wall surface.

The renderings suggest that beam edges are comparable for the LED and benchmark recessed downlights; while beam edges for several of the LED track heads appear to be somewhat more abrupt than their non-LED benchmarks, they still are comparable to the recessed downlights. Further studies of these beam characteristics could be useful to investigate quantitative relationships between beam angles, field angles, and abruptness of beam edges.

CALiPER analyses of intensity distribution also considered criteria that might be related to glare. To minimize glare and to increase horizontal illuminance, ENERGY STAR requires that LED downlights produce a minimum of 75 percent of total lumens in the zone 0° to 60° from nadir, and that integral LED replacements for directional (reflectorized) lamps produce 80 percent of output in this same region.[10] Analyses of zonal lumens demonstrate that the LED recessed downlights, the LED track heads, and the benchmark products all easily satisfy this requirement. Likewise, in spaces where visual display terminals (VDT) are used, IES provides recommended limits for luminous intensity at angles likely to reduce screen contrast. Analyses of the detailed CALiPER test results demonstrate that the recessed downlights easily comply, but these products are smaller and may have lower output than the troffers typically used in such applications.

Without providing conclusive results, further CALiPER analyses explored beam gradients and potential metrics that could be used as indicators for softness (fuzziness) or abruptness of beam edges. Metrics included, for example, consistency of spacing of concentric isolines (as illustrated in the isocandela plots of Figures 6–8) and gradients defined by percent difference in illuminance per distance along an illuminated surface. Other examples of areas to consider for quantifying such beam qualities, such as those using signal analysis, are found in lighting research. More extensive future research involving visual evaluation could lead to metrics or other tools that could facilitate comparison of beam qualities, although such metrics are likely to be relatively complex.

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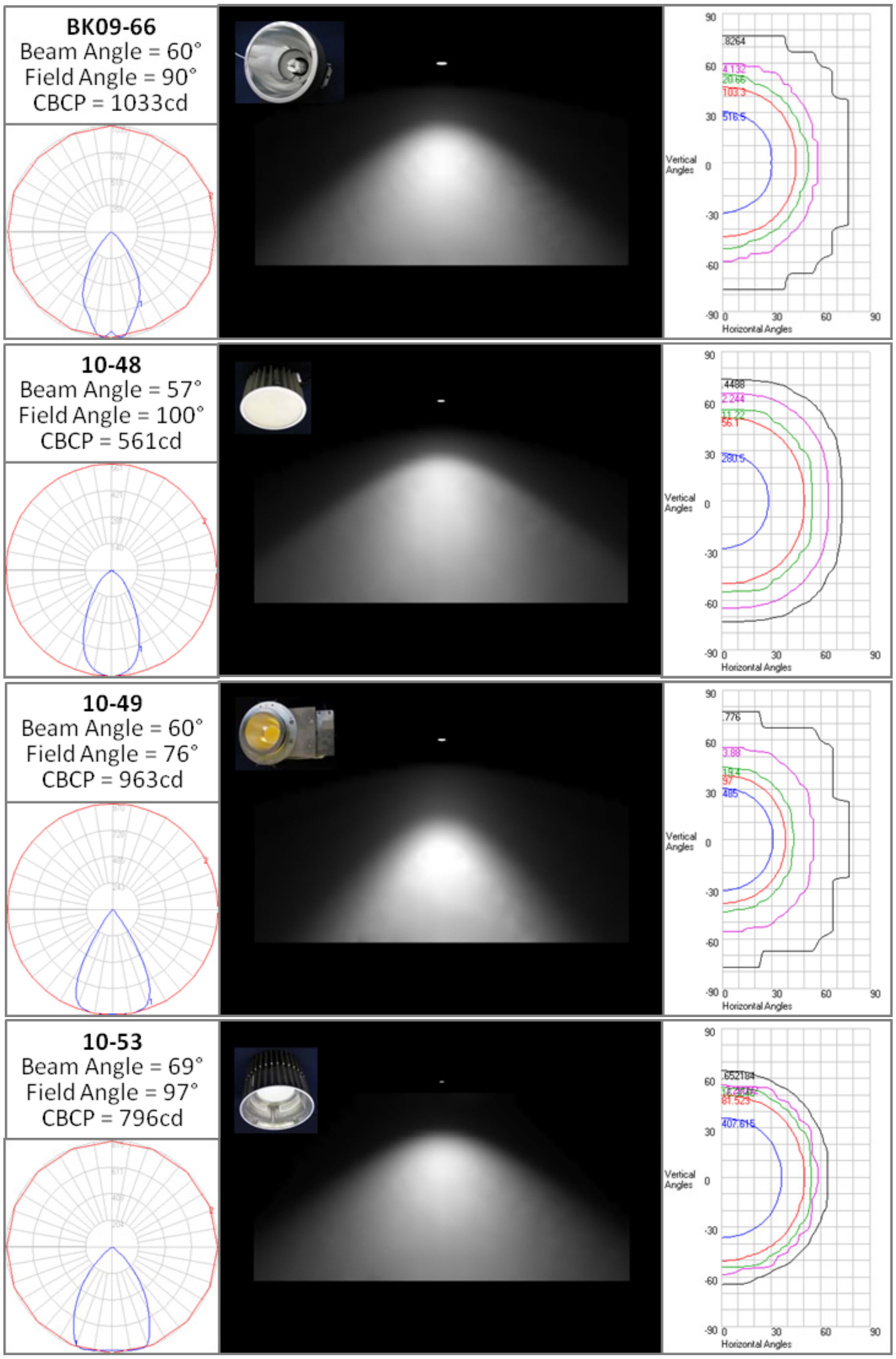
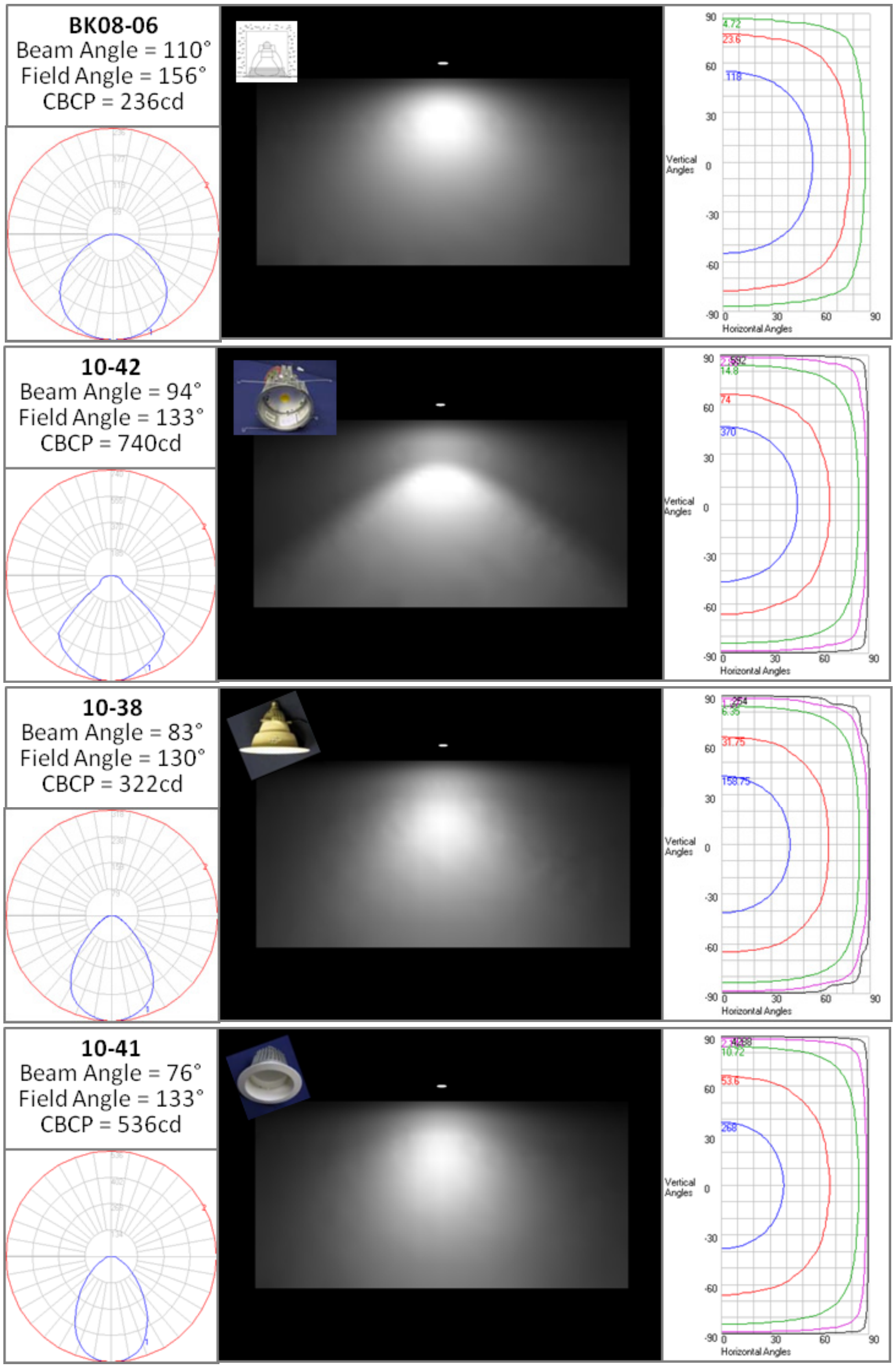
[8] Renderings generated using AGi32 software.

[9] See Figure 14-6 of the 9th edition IESNA Lighting Handbook.

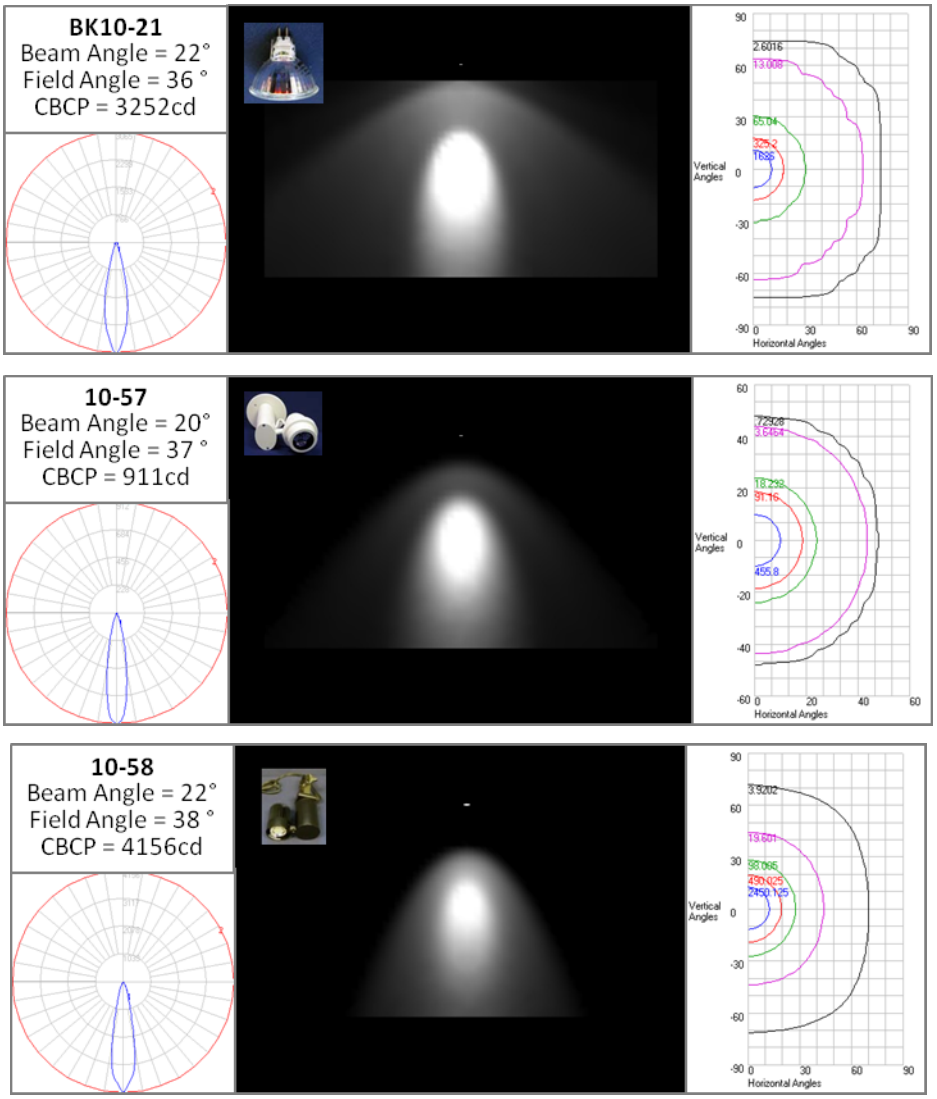
[10] ENERGY STAR Program Requirements for Solid-State Lighting (SSL) Products, Eligibility Criteria, Version 1.3.



Figures 6a–d. Light Distribution of Narrower Beam Recessed Downlights



Figures 7a–d. Light Distribution of Wider Beam Recessed Downlights



Figures 8a–c. Examples of Light Distribution of Track Heads

Manufacturer Claims for Recessed Downlights and Track Heads

Among the 20 downlight products (recessed and track head) that were tested, some are Lighting Facts labeled, some are ENERGY STAR rated, some are both or neither, and some carry no manufacturer published photometric information. Four products carry the Lighting Facts label—recessed downlights 10-38 and 10-41 and track lights 10-58 and 11-02. CALiPER testing indicates these products meet or exceed the Lighting Facts label values for light output, efficacy, and CCT (with an allowance of 10 percent discrepancy for light output, efficacy, and CRI and within nominal CCT ranges). However, one product, 10-58, claims a CRI of 96, but testing reveals a CRI of 82.

It is difficult to ascertain exactly which products carry the ENERGY STAR rating. In some cases products carry the label on packaging or marketing material, but the correspondence between the model number ordered and the ENERGY STAR listing cannot be determined. In other cases, products do not carry the label on marketing material, but the model number is included in the ENERGY STAR listing. Five products fairly clearly carry the ENERGY STAR label, while another four or five also might be ENERGY STAR rated. Of the products that are clearly ENERGY STAR labeled, four of five meet manufacturer ratings and/or ENERGY STAR criteria. One product with the ENERGY STAR label on the spec sheet has light output and efficacy performance that fall short of rated values by 11 percent. Of the five other products that appear to be ENERGY STAR rated (but have mismatching model numbers or no ENERGY STAR label on the spec sheet or product), four products achieve expected performance levels, and one product fails to achieve its rated efficacy.[11]

Overall, 75-80 percent of tested downlights and track heads that carry the Lighting Facts label and/or ENERGY STAR rating meet expectations, and those not meeting expectations fail by only a small margin. For products that do not carry the Lighting Facts label and/or ENERGY STAR rating, only one-third meet photometric performance expectations, and more than one-half fail to meet manufacturer claims for light output, efficacy, CCT, and/or CRI.

Beam characteristics are not included on the Lighting Facts label. For products that publish beam characteristics, beam angle tends to be understated, while CBCP tends to be overstated. The three products that had significantly overstated CBCP carry neither the Lighting Facts Label nor ENERGY STAR rating.

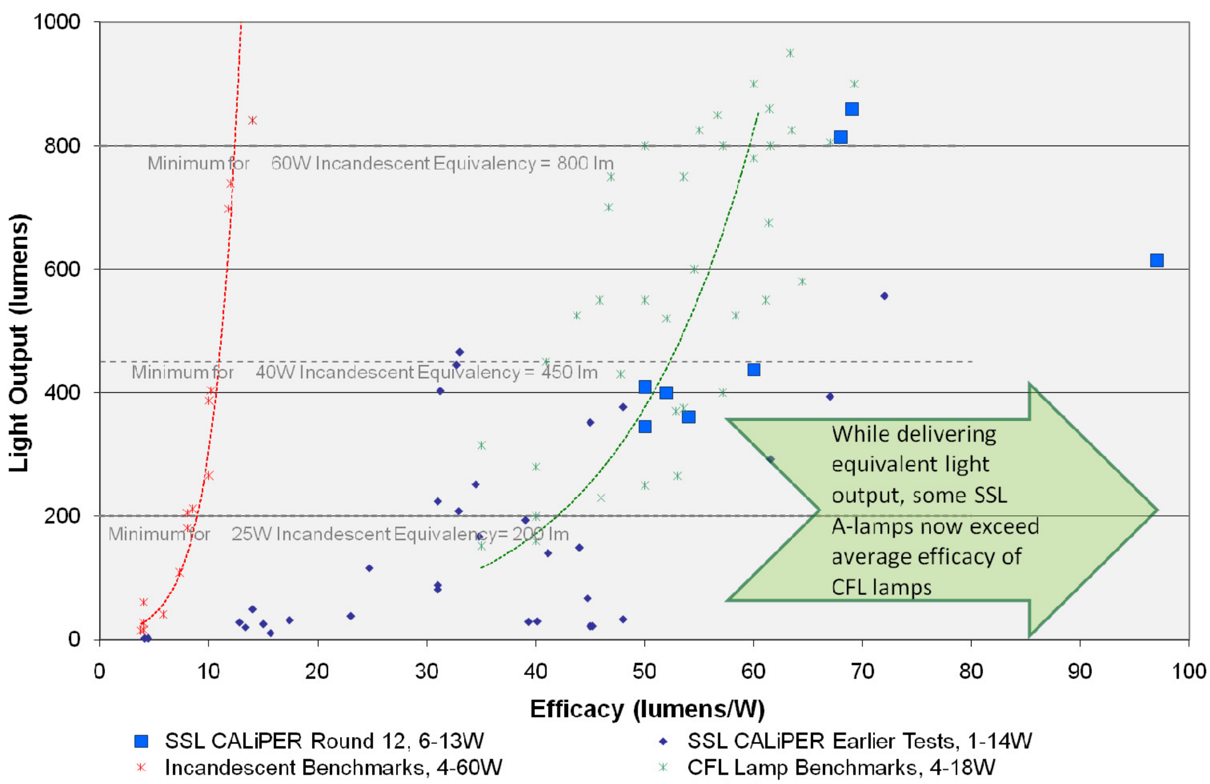
Dimming and reliability testing have not yet been conducted on these products. The majority are marked as dimmable, two products are marked not dimmable, and three have no indication of dimmability. The majority of products claim a life of 50,000 hours; one product claims 100,000 hours. Warranties range from one year to five years.

[11] Note that CALiPER testing for downlight products typically includes only one sample, so results are indicative, but not statistically verified. For conclusive verification in programs such as ENERGY STAR or Lighting Facts, follow-up testing on multiple samples would be needed to confirm results.

A-Lamps—SSL Replacement Lamps

Eight SSL A-lamps were tested, ranging in power from 6 to 13W. All but one of these replacement lamps are warm-white with CRI > 80 and D_{uv} within ANSI tolerances for SSL white light (product 11-04 has CCT of 4125K and CRI of 74). All eight products have efficacy of 50 lm/W or higher, with one product achieving 97 lm/W. Two products, 10-55 and 11-03, have light output equivalent to 60W incandescent A-lamps, producing more than 800 lumens while drawing only one-fifth the power. Product 11-43 achieves an efficacy of 97 lm/W, with a light output level between the typical levels for 40 and 60W incandescent—used in directional applications, this lamp would meet or exceed the light output of a 60W incandescent A-lamp. The five remaining lamps come close to meeting minimal output levels for 40W incandescent, although three of five claim to be 60W equivalents. Three of eight of these products meet ENERGY STAR criteria for integral replacement lamps for light output, efficacy, and color qualities.

Figure 9 summarizes the light output and efficacy of SSL replacement lamps, showing all lamps tested in Round 12 at or above 50 lm/W, with three pushing the performance envelope for either light output or efficacy. Producing similar warm-white light, these SSL lamps achieve light output levels of 40 or 60W incandescent while using no more than one-fifth the power. For equivalent light output, some SSL replacement lamps are now surpassing CFL efficacy.



Benchmark values are based on CALiPER benchmark tests, surveyed ratings, and averaged manufacturer ratings for incandescent and CFL lamps. Values are based on initial output, not average maintained output. Minimum equivalency values are as defined in ENERGY STAR criteria for SSL.

Figure 9. Overall Light Output and Efficacy of SSL A-Lamps

SSL A-Lamp Light Distribution

Using the same plot scale for all lamps, Figure 10 presents polar intensity plots of each of these SSL A-lamps compared to the incandescent A-lamps they claim to replace. In each case, the black line plots the distribution for a 60W A-lamp, while the red-line plots the SSL lamp distribution. For 10-39, which claims equivalency to 25W incandescent, the blue line plots the distribution of a 25W incandescent, showing that 10-39 has somewhat similar distribution in the upper hemisphere and considerably more intensity in the lower hemisphere. For 11-06, which claims equivalency to a 40W incandescent, the orange line represents the distribution of the 40W incandescent, illustrating that product 11-06 provides a directional distribution (all in the downward direction) as opposed to the omni-directional distribution typical of incandescent A-lamps.

One product, 10-55, provides omni-directional light with both the same magnitude of intensity and the same distribution as a 60W A-lamp. However, the distribution patterns and the light output levels show that most of these SSL A-lamps would be better replacements for directional 14W R20 CFL, 15W R30 CFL, 40W R20 incandescent, or 65W R30 incandescent than for omni-directional A-lamps.

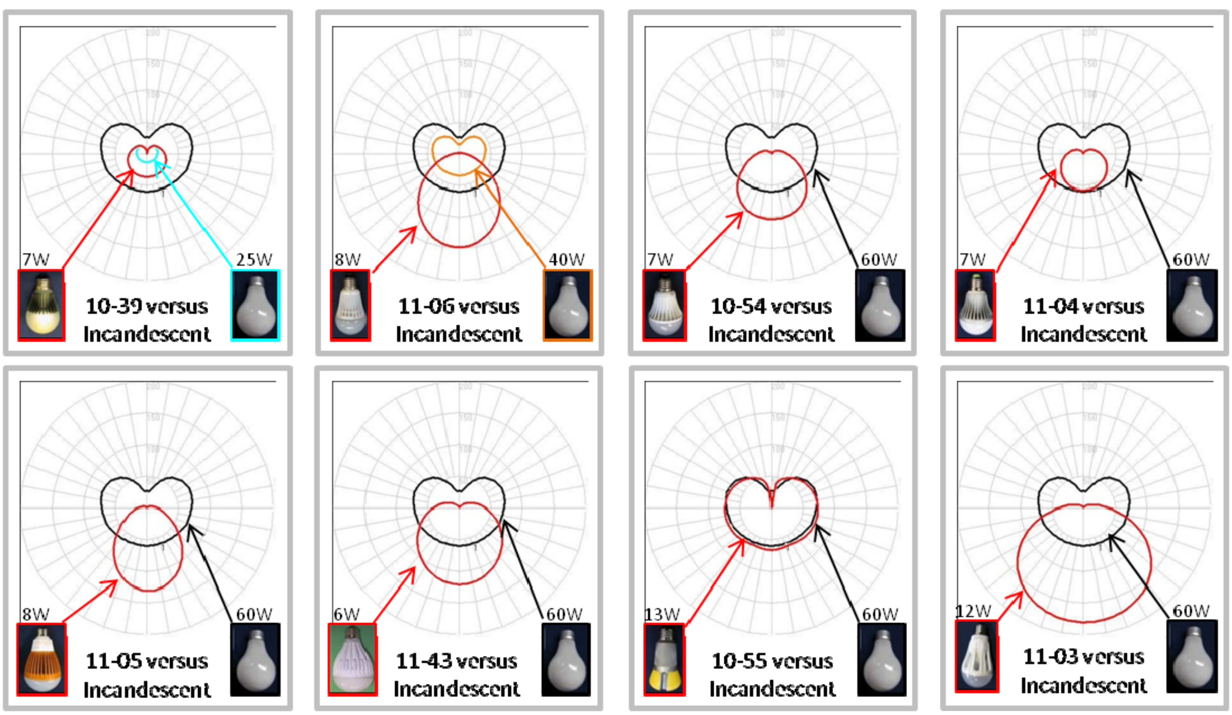


Figure 10. SSL Intensity Distribution Compared to Incandescent Equivalent

SSL A-Lamp Format

In order to fit existing fixtures, lamps that are marketed as A-lamps should conform to ANSI standards for a given size A-lamp.[12] Most of these products, as illustrated in Figure 11, come close to mimicking the size and shape of an A19 lamp. One lamp shown on the left in Figure 12, 11-43, is visibly larger than a typical A19 lamp, but still falls within ANSI-defined form factor dimensions for A19 lamps (note that for each lamp type, a range of dimensions is specified in the standard). Another lamp however, 11-05, shown on the right in Figure 12, is considerably larger than tolerances for A19 lamps, although the lamp specifications state, "A19 LED lamp" and "Shape and size of bulb are based on standardized lighting industry measurement." This lamp was measured by CALiPER to be 141.2 mm Maximum Overall Length (versus ANSI limit of 112.7 mm), 78.5 mm diameter (versus ANSI limit of 69.5 mm), and 9.4 ounces in weight. Although ANSI has no weight specifications, it is interesting to note that a conventional incandescent lamp weighs less than 2 ounces.

Figure 11. Majority of Lamps Are of Comparable Size to A19 Lamp

Figure 12. Some Lamps Are Larger than Typical A19 Lamps

Dimmability, flicker, and lifetime for these products have not been CALiPER tested. All but one of the SSL A-lamps claim to be dimmable.

SSL A-Lamp Performance Claims

Table 2 summarizes the accuracy of performance claims for these SSL A-lamps on packaging and manufacturer literature. Packaging claims for 10-39 indicate equivalency to a 25W incandescent A-lamp; packaging claims for 11-06 claim equivalency to 40W incandescent; all others claim equivalency to 60W A-lamps or to a range of products that includes 60W incandescent. 11-04 claims to be a replacement for 25–60W incandescent, and 11-05 claims to replace 60–75W incandescent.

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[12] NEMA ANSI C78.20:2003, "America National Standard for electric lamps - A, G, PS, and Similar Shapes with E26 Medium Screw Bases."

Table 2. CALiPER ROUND 12 – Omni-directional Replacement Lamp Manufacturer Claims

A-lamps	Lighting Facts Label?	Meeting Manufacturer Ratings	Performance Level Meets Equivalency Claims	Light Distribution Type	Comments
10-39 	✓	✓	✓	Somewhat omni-directional	25W A-lamp equivalent
10-54 	none	✓	✗	R20/R30	Claims 60W incandescent equivalency, meets 40W
10-55 	✓	✓	✓	Omni-directional	60W A-lamp equivalent
11-03 	✓	✓	✓	R20/R30	60W A-lamp output 65W R30 distribution
11-04 	✓	(Borderline)	✗	R20/R30	Claims 25-60W incandescent equivalency, meets 35W
11-05 	none	✗	✗	R20/R30	Claims inflated by ~25%. Large format lamp, not standard
11-06 	✓	✓	✓	R20/R30	40W A-lamp output 40W R20 distribution
11-43 	✓	✓	✓	R20/R30	Marketed for downlight applications Large, but standard format lamp

Six of the eight SSL A-lamps carry the Lighting Facts label. All six meet manufacturer ratings, although one is borderline (tested at about 10 percent below values claimed on the Lighting Facts label). Similarly, five of the six lamps with Lighting Facts labels provide accurate equivalency statements, but one lamp (which is borderline on meeting ratings) claims equivalency to 25–60W incandescent, but meets the light output of only a 35W incandescent. Both lamps that do not have Lighting Facts labels have inflated equivalency claims, and one, 11-05, does not meet manufacturer-rated performance levels.

Benchmarking 70 to 100W Incandescent and Halogen A-Lamps

As described earlier, some market-available SSL A-lamps are now achieving light output levels equivalent to 60W incandescent A-lamps (while drawing only 12W). In 2007 and 2008 CALiPER benchmarks for incandescent A-lamps were 25–40W incandescent lamps, progressing to 60W incandescent lamps in 2010. With 60W A-lamp equivalents now available, a next hurdle for SSL technology will be to replace 75–100W incandescent lamps.

Benchmarking 75–100W incandescent lamps is also timely because the new federal performance standards for general service incandescent lamps will affect sales of 100W incandescent lamps and the halogen lamps expected to replace them. The U.S. Federal Government created a new performance standard with minimum efficiency and lifetime requirements for general service incandescent lamps as part of the Energy Independence and Security Act of 2007.[13] These new regulations take effect for lamps manufactured in or imported to the United States starting January 1, 2012, and similar regulations have already taken effect in California. The energy saving halogen lamps are intended to replace the 100W general service incandescent lamps, fulfilling the performance requirements detailed in Table 3.

Table 3. Standards for Federally Regulated General Service Incandescent Lamps and Modified Spectrum General Service Incandescent Lamps

Maximum Rated Wattage	General Service Incandescent Rated Lumen Range	Modified Spectrum Rated Lumen Range	Minimum Rated Lifetime	Effective Date
72	1490 – 2600	1118 – 1950	1,000 hours	January 1, 2012
53	1050 – 1489	788 – 1117	1,000 hours	January 1, 2013
43	750 – 1049	563 – 787	1,000 hours	January 1, 2014
29	310 – 749	232 – 562	1,000 hours	January 1, 2014

To meet the first constraint of these regulations, 100W incandescent lamps will be replaced by lamps with a maximum wattage of 72W, producing a minimum of 1490 lm (1118 lm for modified spectrum lamps). To meet these new requirements, manufacturers are offering a variety of new products, in particular halogen A-lamps, which are incandescent lamps with halogen gas added to improve the efficiency and lifetime. “Modified spectrum” lamps, carrying a label such as shown in Figure 13, are incandescent lamps that use a different material for the envelope and may also have halogen gas added.

Modified spectrum general service lamps have lower lumens than typical general service lamps, but similar requirements for rated wattage and lifetime. Those with a modified spectrum must have CRI at or above 75, while general service incandescent must have CRI at or above 80. These two types of general service lamps—modified spectrum and standard—are intermingled on retail stores shelves, so buyers will need to learn to identify and understand labeling and performance

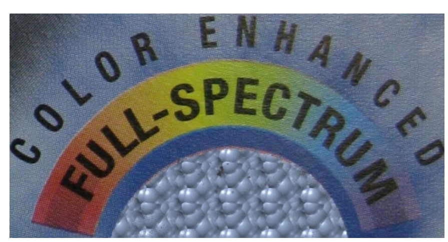


Figure 13. "Modified Spectrum" Label

[13] See, “FACT SHEET: General Service Incandescent Lamp Provisions Contained in EISA 2007,” http://www1.eere.energy.gov/buildings/appliance_standards/residential/pdfs/lighting_legislation_fact_sheet_03_13_08.pdf. These performance standards are for lamps manufactured in or imported to the United States starting January 1, 2012. California took on these same regulations, shifting the dates one year ahead in the CEC 2010 Appliance Efficiency Regulations requiring these performance standards for lamps manufactured in or imported into California after December 31, 2010.

differences. Within the context of SSL lamps now available on retail shelves, this represents yet another challenge and reason for buyers to learn to understand and read labels on lighting products.

To establish the next target benchmark for incandescent A-lamps (above and beyond the 60W benchmark), CALiPER purchased and tested a number of 100W traditional incandescent A-lamps and halogen incandescent lamps that could be considered as alternatives for the 100W A-lamps. Some products marketed as replacements for 100W A-lamps have a slightly different shape, labeled as "BT15." Ordering and purchasing these benchmark products revealed a number of potential points of confusion for consumers regarding product naming and marketing terms. Also, at the time of testing, 70–72W halogen energy efficient lamps were not widely available—70W or 72W halogen energy efficient lamps from only two manufacturers were available in our local stores or online or through our distributors. CALiPER 70 to 100W incandescent and halogen A-Lamp benchmarks (two samples of each lamp were tested) included:

- Two 100W soft white incandescent A-lamps from two different name brand manufacturers (BK 11-09 and BK 11-11)
- One 100W modified spectrum incandescent A-lamp (BK 11-12)
- One 100W frosted long-life incandescent A-lamp (BK 11-25). Note that this 100W long-life lamp actually operates at 88W when used on a 120VAC circuit.
- One 100W halogen BT15 lamp (BK 11-15)
- One 75W modified spectrum halogen A-lamp (BK 11-13)
- One 75W halogen BT15 lamp (BK 11-14)
- One 72W halogen soft white A-lamp (BK 11-10)
- One 70W halogen A-lamp (BK 11-24)

Figure 14 illustrates a number of the labels on the halogen lamps. Of the five products marked "halogen" that were tested, only two would be considered energy-efficient products ready to replace a 100W incandescent. Their labels say either "70W = 100W" or "100W replacement using only 72W." Two others were 75W and easily might have been mistaken for these more efficient types even though one had an output that was only half the output of the two more efficient products (approximately the same as a 60W incandescent) and the other was about 10 percent lower in output. Without further consumer education, buyers might not realize that some halogen lamps are designed particularly for energy efficiency. As they did with SSL lighting, buyers must now learn to understand ratings on halogen and incandescent lamps.

Figure 14. Halogen Lamp Labeling

Figure 15 plots the light output and efficacy of these benchmark replacement lamps. The results show quite a range of performance:

- The 100W standard incandescent lamps' output ranged from 1245 lm to 1694 lm. The 100W halogen and the 100W modified spectrum lamps were also within that range with 1503 lm and 1322 lm respectively.
- In terms of efficacy the 100W standard incandescent lamps ranged from 14 lm/W (the long-life BK 11-25) to 17 lm/W (one of the soft whites, BK 11-09). The 100W halogen was in the middle at 15 lm/W and the 100W modified spectrum was below the range at 13 lm/W.

- The 75W rated modified spectrum halogen lamp (BK 11-13) had similar lumen output to the benchmark 60W replacement (BK 10-31) tested in Round 11 with 837 lumens compared to 823 lumens. The efficacy was thus much lower at 11 lm/W versus 14 lm/W for the standard 60W incandescent A-lamp.
- The other halogen lamps (70–75W) performed well compared to standard 100W incandescent A-lamps, with output between 1433 lm and 1671 lm. Their efficacy ranged from 18 lm/W to 24 lm/W.

All the incandescent lamps were similar in color temperature at about 2800K and had 100 CRI. The halogen lamps were a bit cooler, ranging from 2858K to 3020K with 99 to 100 CRI. The modified spectrum lamps were 2805K and 2871K. The CRI of the modified spectrum lamps were 84 and 81, however, it is important to note that CRI by definition compares a lamp spectrum to incandescent and these lamps by design have a different spectrum from standard incandescent.

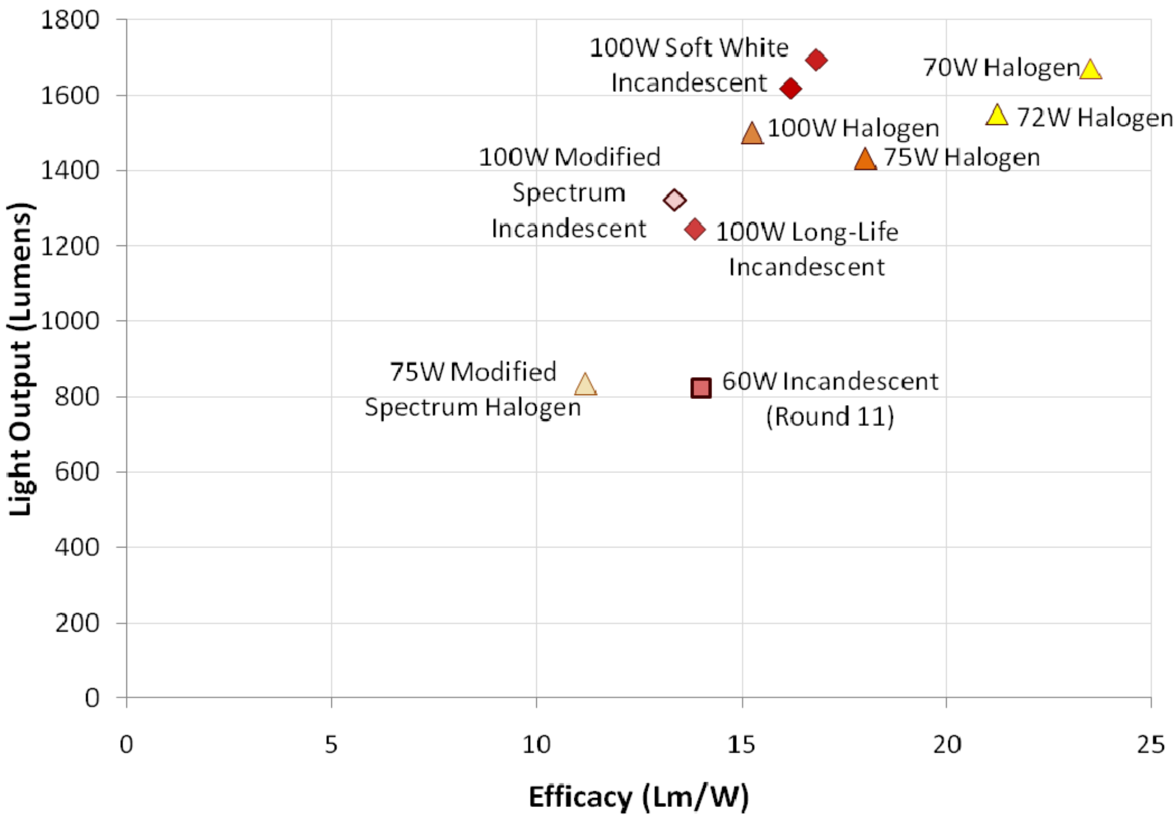


Figure 15. Light Output and Efficacy of Incandescent and Halogen Lamps

All the non-halogen incandescent lamps are rated at 750 hours, except BK 11-25, which is rated at 750 hours with higher lumens when running at 130V but at 2120 hours and lower lumens at 120V. All products marked halogen are rated for 3,000 hours except for BK 11-10 (one of the newer energy-efficient lamps), which is rated at 1,000 hours.

The incandescent lamps were all $1.00 or less, the halogen lamps ranged from $4 to $8, the modified spectrum were $1.25 and $9.00. 100W equivalent CFL lamps are easily attainable for approximately $2 and have a rated lifetime of at least 8,000 hours[14]—less expensive than the halogen lamps and lasting at least twice as long.

The two energy efficient 70–72W halogen lamps were equivalent in output, CCT, and CRI to incandescent, while still being more energy efficient. The modified spectrum lamps had similar color temperatures but lower CRI and lower efficacy than the standard lamps, so low that the 75W modified spectrum lamps had similar lumen output to the 60W incandescent. Neither modified spectrum lamp tested will meet the required maximum rated wattage for EISA or California standards. There are also other, normal spectrum halogen lamps on the market that have performance similar to standard incandescent lamps and do not save energy: the 100W BT15 halogen could be a direct replacement for either soft white 100W incandescent A-lamp; the 75W BT15 halogen was slightly more efficient than the 100W soft white lamps, but would not pass the required maximum rated wattage for EISA or California standards. CALiPER has not yet identified SSL products that are equivalent to 100W incandescent A-lamps. Nevertheless, consumers will need to understand lumen output and wattage labels to ensure they are getting the product they want and expect, whether traditional incandescent, halogen, CFL, or SSL.

[14] The current average rated lifetime for ENERGY STAR-qualified CFLs is 8,000 hours. http://www.energystar.gov/index.cfm?c=cfls.pr_crit_cfls

4-Foot Linear Replacement Lamps and Troffers

Benchmark linear fluorescent and SSL replacement lamps have been tested as bare lamps and in troffers in previous CALiPER testing (Rounds 5, 9, and 11), showing progressive improvement in efficacy of SSL linear replacement lamps, but insufficiencies in the light output and light distribution of SSL as compared to linear fluorescent in troffers. Initial comparisons were made using a prismatic lensed troffer equipped with T12 fluorescent lamps and a parabolic louvered troffer equipped with T8 fluorescent lamps. In Round 9, a two-lamp, high-performance troffer benchmark was added. In Round 11, a single-lamp high-performance troffer was added as a benchmark, along with an additional test of the two-lamp high-performance troffer using a different ballast. Figure 16 provides a sketch of the configuration of the parabolic louvered and high-performance troffers. The most recent SSL lamps in the parabolic louvered troffer still could not provide comparable light output or distribution to the high-performance troffers equipped with linear fluorescent lamps.

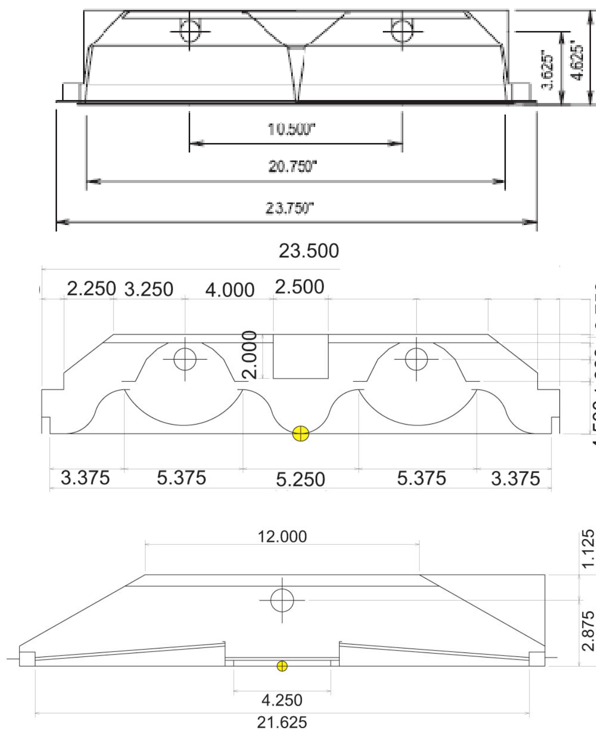


Figure 16. Cross-Section Sketches of Parabolic Louvered Troffer (BK 08-28), Two-Lamp High-Performance Troffer (BK 09-67), and One-Lamp High-Performance Troffer (BK 10-34)

A key challenge for SSL products that are designed as linear replacements stems from the inherent omni-directionality of fluorescent and the inherently directional nature of LED devices. Fluorescent troffers are purposefully designed and optimized for use with omni-directional lamps, so SSL replacement lamps that have LED devices mounted along one side of a long tube cannot take advantage of the troffer optics. During Round 11, a question was raised as to how well the SSL linear replacement lamps would function in the high-performance (HP), lensed non-planar architectural troffers.

Up to and including Round 11, testing of SSL linear lamps within fixtures had been conducted in a lensed troffer and in a parabolic louvered troffer, but not in a high-performance troffer. To provide a sense of SSL performance in HP troffers, the SSL replacement lamps from Round 11 with the highest bare lamp efficacy (10-16 and 10-18) were selected and tested in the high-performance troffers (BK 09-67 and BK 10-34) to enable examination of fixture losses and light distribution. Note that both SSL lamps selected for this testing have much higher CCT than the fluorescent lamps used for the benchmark testing, giving LED the best chance of competing.

Figure 17 summarizes the power, light output, and efficacy of each of these troffers equipped with fluorescent T8 lamps and equipped with SSL replacement lamps. SSL product 10-16 was used in the parabolic louvered troffer and the two-lamp HP troffer. SSL product 10-18 was used in the 1-lamp HP troffer. In each case the SSL-equipped troffers draw about one-half the power of the troffer systems using fluorescent lamps, and likewise the SSL options provide only about one-half the total luminaire light output of the same troffer equipped with fluorescent lamps. These SSL linear replacement lamps (among the most efficacious tested to date by CALiPER) do provide a luminaire efficacy in the troffers that slightly exceeds the luminaire efficacy of the fluorescent-lamped troffers.[15]

Parabolic troffers are known for a tailored light distribution. Figures 18a–c show the different distributions of the SSL lamps and fluorescent lamps and the three different troffers (black is the fluorescent baseline, and red is the troffer equipped with SSL). In Figure 18a, it is clear that the SSL distribution lacks the pronounced triangular "batwing" shape corresponding to the broader, more even distribution of the fluorescent-equipped parabolic louvered troffer. Figures 18b and 18c illustrate that the SSL lamps provide similar distribution patterns to T8 fluorescent in the HP troffers, but significantly less light output.

Typical spacing of troffers is 8' x 8' or 8' x 10' on center, primarily driven by the acoustical ceiling tile grid (either in 2' x 4' or 2' x 2' increments) and the troffer's spacing criterion (SC). Figure 19 summarizes the SC for the three types of troffers, comparing the SC of the troffers equipped with fluorescent T8 to the same troffers equipped with SSL linear replacement lamps. Note that in CALiPER Round 11, distribution patterns and SC were examined for more than a dozen different SSL lamps installed in the parabolic louvered troffer, showing very little variation between the luminaire distributions across different SSL replacement lamps at that time.

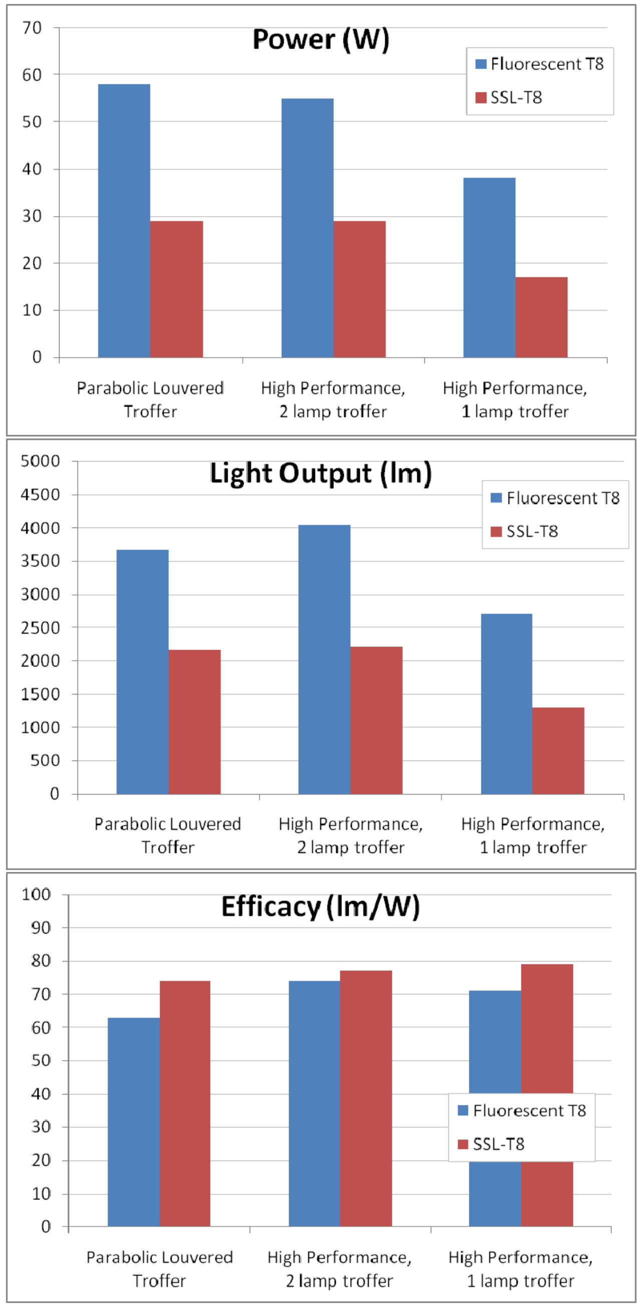
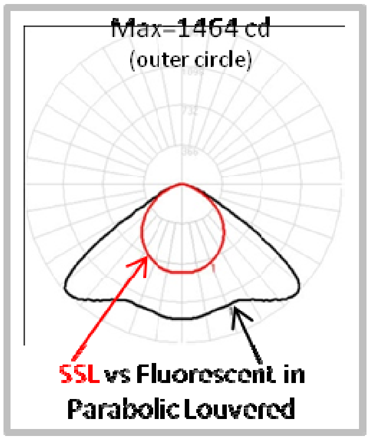
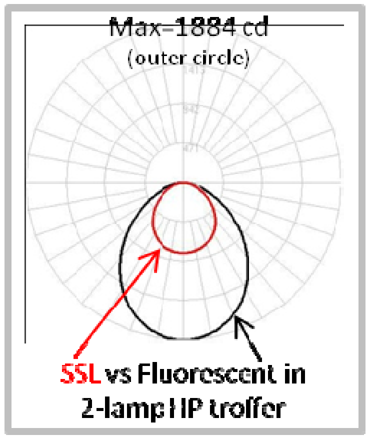


Figure 17. A Variety of 2'x4' Troffers Equipped with Fluorescent or SSL T8 Lamps

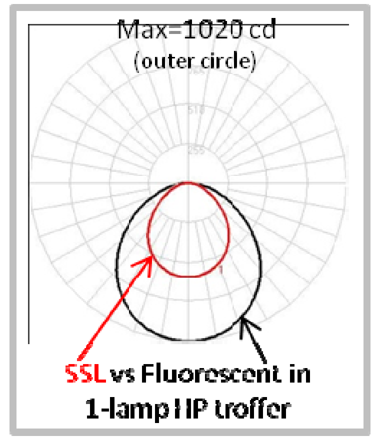
[15] Note that for BK 10-34, the testing conducted in Round 11 used the troffer system with a ballast factor of 1.18. An additional test of this luminaire is currently under way with a ballast factor of 0.88. The BK 10-34 troffer is expected to achieve a slightly higher luminaire efficacy with the lower BF ballast but still be at similar levels to the SSL-equipped results.



a. 10-16 in Parabolic Louvered Troffer (BK 08-28)



b. 10-16 in Two-Lamp High-Performance Troffer (BK 09-67)



c. 10-18 in One-Lamp High-Performance Troffer (BK 10-34)

Figures 18a–c. Comparison of Distribution of SSLs Versus Fluorescent T8 in Troffers

The parabolic troffer with fluorescent lamps (BK 08-28) has greater SC values than LED lamps installed in the parabolic troffer (as does the prismatic lens troffer—BK 08-30, equipped with T12 lamps—included in Round 11, but not presented here). However, the SC values are quite similar between fluorescent and LED lamps for the high-performance troffers (BK 09-67 and BK 10-34).

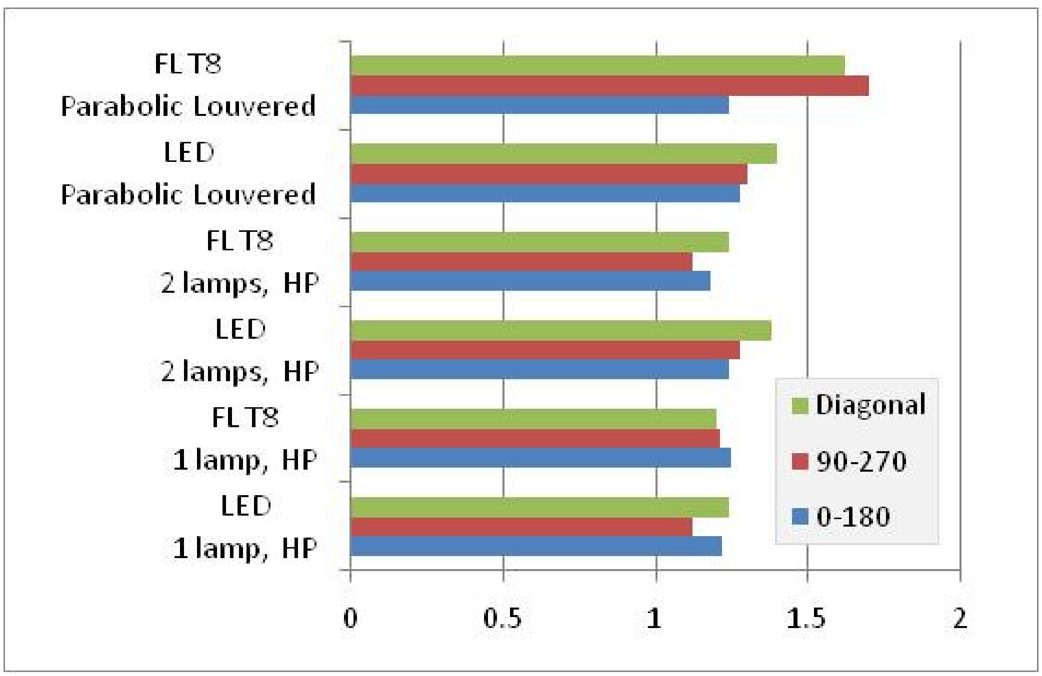


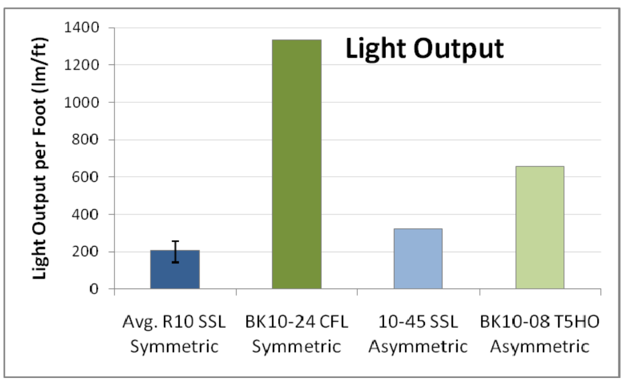
Figure 19. Spacing Criteria

Cove Lights

In Round 10 of CALiPER testing, published in May 2010, nine cove light products were tested, including seven SSL luminaires and two benchmark products. Of the SSL cove lights, five were linear strips (typical of general illumination cove lights) and the other two were smaller linear strips (more typical of decorative cove lighting). Some cove lights are designed to provide an asymmetric distribution, some have adjustable track heads, and some provide a symmetric, cosine distribution but with the option of tilting the luminaire to obtain a somewhat asymmetric effect. All the linear strip SSL cove lights tested in Round 10 provided symmetric, cosine distributions, with similarly shaped distributions and similar or more intensity than the xenon benchmark, but their intensity was dwarfed when compared to the linear fluorescent benchmark cove product. None of the SSL cove products produced even one-half the light output per linear foot of the T5HO fluorescent cove fixture. All had higher luminaire efficacy than the xenon linear strip light, but lower luminaire efficacy than the T5HO fluorescent cove fixture.

Two additional cove light products were tested in Round 12 to add to the information provided in Round 10. First, a symmetric cove using CFL lamps was tested to provide additional benchmark data (BK 10-24). Second, an asymmetric SSL cove light product was tested (10-45). It might be expected that, because of the inherent directionality of LED devices, SSL cove lights should be able to take advantage of this directionality for applications like asymmetric cove lighting.

Figure 20 provides a general overview of the performance of the different types of products, examining light output per linear foot and luminaire efficacy. The asymmetric SSL cove, 10-45, provides more light output per linear foot than any of the SSL cove lights tested in Round 10, but it only provides one half the light output of the CALiPER-tested asymmetric fluorescent cove (BK 10-08), and only about one-quarter of the light output per foot of the symmetric CFL cove (BK 10-24). Regarding luminaire efficacy, the asymmetric SSL cove, 10-45, achieves only 19 lm/W—far less than both benchmark products and even significantly less than the average efficacy of SSL cove lights tested in Round 10.



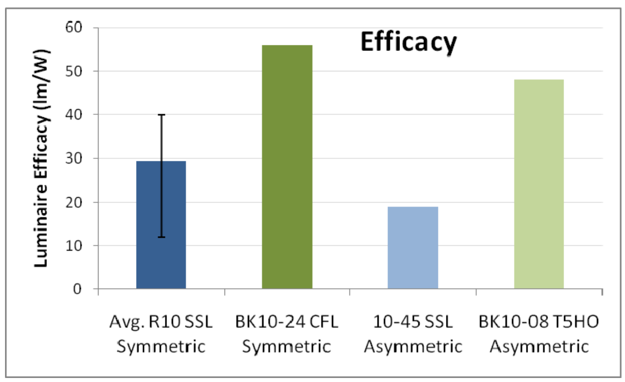


Figure 20. Efficacy of SSL and CFL Asymmetric Cove Lights Compared to Average Performance of Symmetric SSL Cove Lights Tested in Round 10[16]

[16] Average Round 10 cove performance is based on the average of five linear strip SSL cove products tested in CALiPER Round 10. Error bars show maximum and minimum range of the five products used for the average. Asymmetric fluorescent T5HO cove BK 10-08 was also tested in Round 10.

The symmetric CFL cove light has higher fixture efficiency and achieves higher luminaire efficacy than the asymmetric T5HO fluorescent cove (56 lm/W compared to 48 lm/W), and double the light output per linear foot (1322 lm/ft compared to 660 lm/ft). Compared to the SSL asymmetric cove, the CFL cove achieves three times the efficacy (56 lm/W versus 19 lm/W) and four times the light output per foot (1322 lm/ft compared to 324 lm/ft), as illustrated in Figure 20. While the SSL asymmetric cove produces more light output per linear foot than all the linear strip SSL cove lights tested in Round 10, it also draws significantly more power (51W), so it has lower efficacy than four of five of the Round 10 products.

Figure 21 provides a comparison of polar distribution plots for asymmetric SSL cove light 10-45 compared to two asymmetric fluorescent cove lights (both using T5HO lamps, one tested by CALiPER in Round 10 and one based on manufacturer photometry). The photometric distribution data used for these plots has been scaled so that all represent performance of products of equal length, and the curves are rotated (tilted) so that the angle of maximum illuminance aligns for all three products.

The intensity distribution of the SSL asymmetric cove mimics the distribution of the fluorescent asymmetric coves at a scaled-down intensity level. The maximum intensity of the SSL product is about two-thirds the maximum intensity of the fluorescents, while the total light output per linear foot of the SSL product is less than one-half the light output per foot of the fluorescent products. This accentuated difference for total lumen output arises from the narrowness of the beam of the SSL cove. The SSL beam is not as wide as the two fluorescent cove beams, possibly indicating fewer zonal lumens in angular zones where zonal multipliers are the highest. As noted, the maximum intensity of the three coves (as tested) does not occur at the same angle—the orientation of the products can be adjusted for appropriate angling of maximum intensity. For Figure 21, curves were rotated to align angles of maximum intensity.

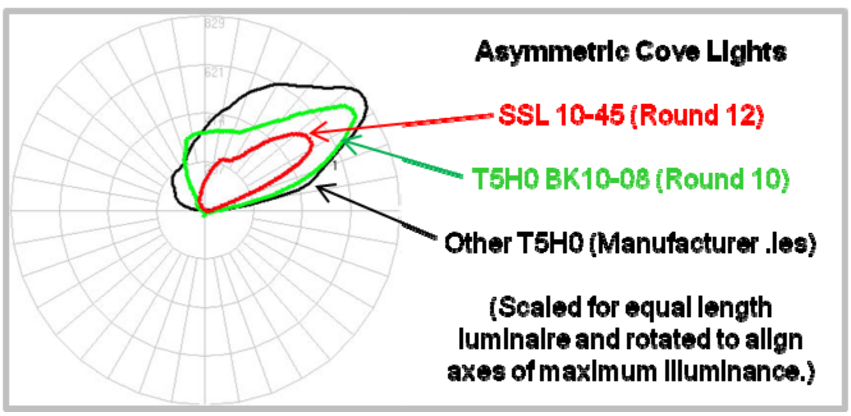


Figure 21. Candela Distribution of Asymmetric SSL Cove Light Compared to Asymmetric T5HO Fluorescent Coves

Table 4 compares the symmetric LED coves to the baseline CFL symmetric cove. Overall, the CFL cove emits more light and is the most efficacious cove product tested. All products in Table 4 are roughly the same length, nominal 1' long. It should be noted that these products are not necessarily designed for the same applications, but the CFL benchmark cove is provided here to offer some points of comparison. Future benchmark testing on a standard T5 strip light could provide an additional, applicable point of comparison.

Table 4. Comparison of Round 10 SSL Symmetric Cove Lights with Round 12 CFL Cove Light

CALiPER #	Length	Lumens	Power (W)	Efficacy (lm/W)	Max (CD) Angle	Max CD
BK 10-24 (CFL)	1.29'	2021	36	56	145	371
09-83	0.83'	182	6.7	27	165	72
09-84	0.90'	245	6.5	38	178	88
09-85	1.00'	145	4.7	31	178	55
09-86	1.01'	194	16	12	178	72
09-99	--	50	2.4	21	163	15

Another item of note is distribution of the symmetric cove lights, as illustrated in examples provided in Figure 22. The best-performing SSL cove tested in Round 10 provided less than one-third the maximum intensity of the CFL cove light. Distribution characteristics of coves luminaires are hard to broadly generalize. The intensity distribution of the cove luminaire needs to be matched to the geometries of the cove and larger ceiling cavity as a whole. The maximum intensity of the symmetric LED cove luminaires almost always occurs near 180° (zenith). Many LED products tested exhibit a cosine distribution, indicating little or no optical control. The CFL cove maximum intensity is at 145° from nadir (35° from zenith), but it is not vastly different from the intensity at zenith.

The goal of a cove luminaire is to light the ceiling plane uniformly and to limit socket shadow and differences in luminance values within the cove channel (cove cavity). Based on these CALiPER tests on cove products, SSL cove lights provide less light output than fluorescent cove lights and in some cases quite different light distribution, so buyers and specifiers should be wary of the differences and be careful to verify luminaire photometry to ensure that a product meets application needs, looking at overall energy use of a cove lighting system.

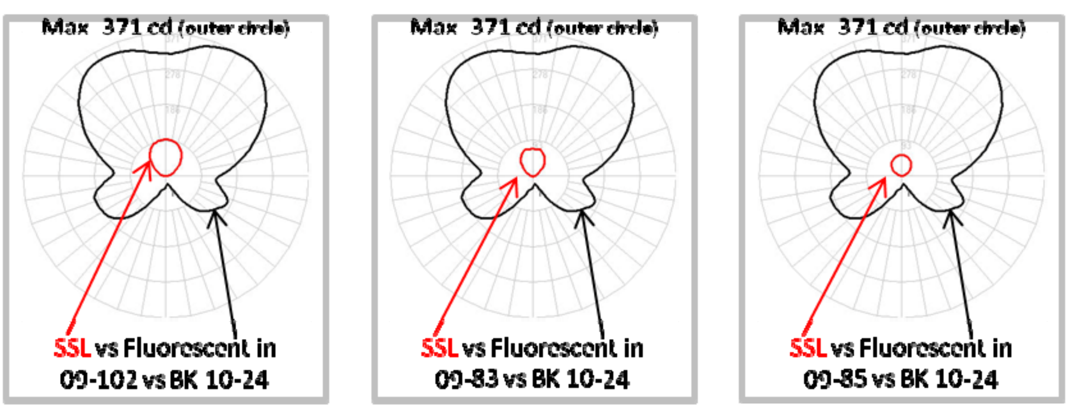


Figure 22. Examples of Candela Distribution Symmetric CFL Fluorescent Cove Compared to Linear Cove Lights Tested in Round 10

Conclusions from Round 12 of Product Testing

Key Conclusions

CALiPER Round 12 focuses on recessed downlights, track lights, and replacement A-lamps. A few additional tests examine linear replacement lamps in high-performance troffers and provide an additional look at cove lights. Almost all products tested in Round 12 have a warm-white CCT and CRI above 80. The average efficacy for all Round 12 SSL products is 46 lm/W, which is slightly lower than the overall average seen in Round 11 but higher than the average for warm-white SSL products tested in previous rounds. Color quality metrics (CRI and D_{uv}) are also significantly better than for Round 11 products.

Based on Round 12 results, for both recessed downlight and track light applications, SSL can now provide high-efficacy alternatives to products using traditional light sources:

- The 10 SSL recessed downlights present a variety of products with a range of light output levels, beam characteristics, and efficacy levels. All 4–6" SSL recessed downlights in Round 12 match or exceed average light output levels for similar products equipped with CFL, incandescent, or halogen lamps, achieving three to six times the luminaire efficacy of incandescent or halogen recessed downlights.
- The track lights similarly represent a range of performance characteristics. Although the average efficacy of the SSL track lights is less than the average of the SSL recessed downlights, the SSL products still significantly outperform benchmark products. Because of the narrower beams and smaller formats of track heads as compared to recessed downlights, the benchmarks for track lights use halogen lamps, not CFLs.
- SSL recessed downlights and track lights that carry the Lighting Facts label and/or the ENERGY STAR rating were found to be more likely to meet manufacturer performance claims than products with no Lighting Facts label or ENERGY STAR rating.

SSL A-lamps tested in Round 12 demonstrate significant performance improvements over earlier products:

- All eight SSL products have efficacies of 50 lm/W or higher, with one product achieving 97 lm/W. These are significant results for products where the relatively small format limits thermal management and forces drive electronics to be compact and positioned in close proximity to the LED devices.
- Two SSL A-lamps achieve light output levels of a typical 60W incandescent A-lamp, one of which also mimics the omni-directional light distribution of a traditional A-lamp.
- All but one SSL A-lamps are warm-white and have CRI > 80.
- Most SSL A-lamps have directional rather than omni-directional beam patterns, making them more comparable to R-lamps (reflector lamps) than to the A-lamps they claim to replace.
- Seventy-five percent of the SSL A-lamps in Round 12 carry the Lighting Facts label. All except one of the lamps with the Lighting Facts label meet manufacturer ratings and equivalency claims.
- Both lamps that do not have a Lighting Facts label have inaccurate equivalency statements, and one also has inaccurate manufacturer ratings and is significantly larger than the standard format for A19 lamps, which it claims to replace.

Now that there are market-available SSL A-lamps capable of replacing 60W incandescent A-lamps, a series of benchmark tests was conducted on 70–100W incandescent and halogen incandescent A-lamps to provide reference points for the next echelon of SSL replacement lamp performance achievements. However, this series of benchmarks also illustrates the wide range of performance in both light output and efficacy of 100W A-lamps and lamps that consumers might purchase as potential equivalents to 100W incandescent (that is, 70–100W halogen incandescent). To make well-informed purchasing decisions for both SSL and energy-efficient halogen lamps, consumers will need to understand key lighting performance metrics such as power, lumens, CCT, and CRI.

A few tests were performed to further investigate the performance of SSL replacements for linear fluorescent lamps when installed in troffers. The Round 12 results reconfirm results found in previous testing, demonstrating that SSL lamps are not yet viable one-for-one replacements for linear fluorescent lamps in troffers or in cove applications. SSL linear replacement lamps installed in high-performance troffers produce similar beam patterns to T8 fluorescent lamps in the same troffers, but the SSL lamps result in significantly lower CBCP and lower overall luminaire light output than the fluorescent lamps in the same troffers. In addition, the first SSL asymmetric cove light tested by CALiPER achieved a somewhat asymmetric light distribution, similar to but narrower than T5HO asymmetric cove fixtures, but with significantly lower intensity and less overall light output compared to asymmetric coves that use T5HO lamps.

With each round of CALiPER testing, an increasing proportion of SSL products are carrying the Lighting Facts and/or ENERGY STAR labels. For all lighting applications included in Round 12, products that carry the Lighting Facts or ENERGY STAR labels are significantly more likely to meet manufacturer claims than products that do not carry one of these labels. A promising sign among Round 12 SSL A-lamps is that SSL lamps that carry the Lighting Facts label also tend to have suitable equivalency claims.

Next Steps for the Industry and CALiPER Efforts

Upcoming CALiPER testing will include 2' x 2' SSL panels designed as integral luminaires to replace 2' x 2' fluorescent troffers. Round 9 of CALiPER testing, published in October 2009, already demonstrated the potential competitiveness of SSL in this application category. Round 13 will investigate a number of new market-available products in this category, incorporating technological progress of the past two years.

Recent and ongoing CALiPER exploratory research addresses flicker, uncertainty budgets, glare metrics, and long-term testing.[17] CALiPER provides support to testing standards communities through exploratory reports and through the annual CALiPER Standards and Testing Roundtable meetings.[18]

A special series of CALiPER testing was recently concluded covering SSL replacement lamps purchased from "big-box" retail stores during the summer of 2010. [19] A variety of types of small replacement lamps from a variety of manufacturers were purchased and tested in an integrating sphere at time zero and after 1,000 hours of operation. Whereas most Round 12 SSL A-lamps are marketed to commercial lighting sectors and showed good performance, the small replacement lamps purchased from big-box retail stores showed far less consistency of performance and significantly poorer performance on average.

CALiPER testing works closely with and provides information to a number of DOE SSL commercialization support efforts, tying into programs such as the Federal Energy Management Program, the Commercial Building Energy Alliance, retail sector education efforts, standards development organizations, and the development of energy codes and regulations.

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[17] Two new DOE CALiPER exploratory reports are available upon request: "Exploring Flicker in SSL Integral Replacement Lamps," April 2011, and "CALiPER Exploratory Study: Accounting for Uncertainty in Lumen Measurements ," March 2011.
[18] The 2011 CALiPER Roundtable was recently conducted in San Antonio, Texas, April 4-5, 2011. Proceedings from CALiPER Roundtable meetings are available online, http://www1.eere.energy.gov/buildings/ssl/about_caliper.html.
[19] The "CALiPER Special Summary Report: Retail Replacement Lamp Testing," May 2011, is available for download, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_retail-replacement_summary.pdf.