CALiPER

Summary Report

October 2010

DOE Solid-State Lighting CALiPER Program

Summary of Results: Round 11 of Product Testing

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 which assemble data from numerous product tests and provide comparative analyses. [2]

SSL technology and market-available products have improved dramatically in the past three years, yet there is still a wide disparity in quality among different products and manufacturers and in many cases, wide disparity between manufacturer's claims and the actual performance of their SSL products. SSL products are evolving quickly and the lighting market is constantly seeing the arrival of new products for every lighting application. With this rapid evolution and relatively immature market come risks for buyers and specifiers—not all products perform as claimed, not all products are appropriately designed for a given lighting application, and not all products are as reliable as suggested by marketing literature.

In this context, it is impossible for CALiPER to test every SSL product on the market. Nevertheless, buyers and specifiers can reduce risk greatly by learning how to compare products and by examining every potential SSL purchase carefully. Before considering an SSL product for any lighting application, it is key to 1) ensure that you understand your lighting needs by determining the desired photometric characteristics for your application (how much light, where is the light needed, what color qualities are needed); 2) ensure that you have quantitative points of comparison (how many watts are drawn, how much overall light output is produced, what is the correlated color temperature of the current or more traditional light sources for that application); and 3) obtain LM-79 test reports for the SSL products under consideration and compare them to your requirements and points of reference. If a manufacturer does not publish performance results for an SSL product from LM-79 testing conducted by a qualified laboratory, the product should not be considered for purchase until those standardized performance metrics are provided.

Without using LM-79 results to determine the adequacy of an SSL product for a given application, chances are very high that the product will not meet manufacturer performance claims and the customer will be dissatisfied. LM-79 testing alone is not enough to fully characterize a product—quality, reliability, controllability, physical attributes, warrantees, and many other facets should also be considered carefully. Nevertheless, understanding and requiring LM-79 data is an essential point of passage for adopting SSL technology.

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[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 1-10 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 can also be obtained online: http://www1.eere.energy.gov/buildings/ssl/search.html.

Summary of Results: Round 11 of Product Testing

Round 11 of CALiPER testing was conducted from March 2010 to September 2010. In this round, 35 products, representing a range of product types and technologies, were tested with both spectroradiometry and goniophotometry using absolute photometry. All SSL products were tested following the IESNA LM-79-08 testing method; benchmark products were also tested using absolute photometry to enable direct comparison of results between SSL and benchmark products.

Round 11 of testing includes five primary focus areas:

1. Roadway, arm-mount luminaires
2. Roadway, post-top luminaires
3. Linear replacement lamps
4. High-bay luminaires
5. Small replacement lamps (MR16, PAR lamps, A-lamps, and a candelabra lamp)

As a benchmark, traditional lighting products using incandescent, halogen, fluorescent, high pressure sodium (HPS), pulse-start metal halide (PSMH), or ceramic metal halide (CMH) light sources were also tested (using absolute photometry performed on anonymously purchased samples) and included in this summary report. 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.[3]

Round 11 CALiPER Testing Results

Tables 1a, 1b, 1c, and 1d 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 11. A thumbnail photo of each product is included. These tables assemble key results as follows:

- Table 1a: Six SSL arm-mounted roadway luminaires, two SSL post-top luminaires, one CMH and one PSMH post-top luminaire. Three benchmark roadway luminaires tested during Round 7 are also included for reference (one HPS and two induction).
- Table 1b: Six SSL 4' linear replacement lamp products (bare lamp tested and tested in a parabolic louvered troffer whenever possible), one high performance 2-lamp architectural fluorescent troffer (retest of product tested in Round 9, using alternative ballast), one high-performance lensed 1-lamp fluorescent troffer, and two high-bay SSL luminaires.
- Table 1c: Two SSL MR16 lamps, two 35W halogen MR16 lamps, one SSL PAR30, three SSL PAR38 lamps, one CMH PAR38, and two SSL AR111 retrofit lamps.
- Table 1d: Two SSL A-lamps, one SSL candelabra, and one 60W frosted incandescent A-lamp.

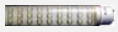
[3] In addition to basic photometric testing per IES LM-79-08, CALiPER periodically performs additional testing—examining, for example, dimmability, reliability, flicker, or in situ performance. Directly applicable published standards are not available for these additional tests, so CALiPER works with standards organizations, industry trade groups, and independent testing laboratories to explore and determine appropriate testing methods.

Table 1a. CALiPER ROUND 11 SUMMARY – Outdoor Roadway 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) [D_{uv}]	CRI	Photo
SSL Arm-mount Roadway Luminaires/Replacement Lamps							
Outdoor Roadway (Bare lamp only, not installed in a luminaire)	09-62	38	970	26	3080 [0.006]	69	
Outdoor Roadway	09-113	79	2549	32	5058 [0.003]	70	
Outdoor Roadway	10-09	73	4994	68	5302 [0.004]	80	
Outdoor Roadway	10-10	72	4469	62	6262 *[0.011]*	70	
Outdoor Roadway	10-14	44	3994	90	4947 [0.007]	66	
Outdoor Roadway	10-26	150	7004	47	5127 *[0.019]*	66	
Benchmark (BK) Arm-mount Roadway Luminaires: High Pressure Sodium (HPS) and Induction from Earlier CALiPER Testing							
Outdoor Roadway High Pressure Sodium	*Round 7 BK 08-122*	117	6540	56	2042 [0.001]	21	
Outdoor Roadway Induction	*Round 7 BK 08-152*	67	3960	59	3906 [0.001]	75	
Outdoor Roadway Induction	*Round 7 BK 08-153*	71	3561	50	4253 [0.006]	77	
SSL Post-top Luminaires							
Outdoor Post-top	10-13	48	2701	56	4302 [0.003]	68	
Outdoor Post-top	10-27	25	854	35	6789 [0.006]	77	
Benchmark (BK) Post-top Luminaires: Ceramic Metal Halide (CMH) and Pulse Start Metal Halide (PSMH)							
Outdoor Post-top Ceramic Metal Halide	BK10-15	178	9104	51	3017 [-0.003]	85	
Outdoor Post-top, solid top PSMH	BK10-35	192	7812	41	3400 [0.005]	62	

Values are rounded to the nearest integer for readability. Results shown in this table are from testing at 120VAC.
Duv values which are not with ANSI-defined tolerances for white light in SSL products are shown in *red italics*.

Table 1b. CALiPER ROUND 11 SUMMARY –Troffers and High-Bay 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) [D_{uv}]	CRI	Photo
SSL Replacement Lamp (4' linear): Bare Lamp and Testing in Parabolic Louvered Troffer							
Bare Lamp	09-107C	22	1539	70	3548 [-0.002]	73	
*One lamp failed, no in situ**		--	--	--			
Bare Lamp	10-16	15	1368	93	5389 [-0.004]	77	
In situ (2 lamps in troffer)		29	2173	74			
Bare Lamp	10-17	19	1362	70	3249 *[0.007]*	65	
In situ (2 lamps in troffer)		39	2194	57			
Bare Lamp	10-18A	17	1533	91	5602 *[0.009]*	75	
*One lamp failed, no in situ**		--	--	--			
Bare Lamp	10-19	22	1887	86	5091 [0.008]	69	
In situ (2 lamps in troffer)		43	3247	75			
Bare Lamp	10-36	18	1628	90	4300 *[0.012]*	70	
In situ (2 lamps in troffer)		36	2785	78			
Fluorescent Benchmark (BK): Bare Lamp and Testing in High-Performance Lensed Troffers							
Bare Lamp (fluorescent)	BK10-34	32	3353	105	3387 [0.004]	82	
In situ (1 lamp troffer, Ballast Factor BF=1.18)		38	2708	71			
Bare Lamp (fluorescent)	Round 9 BK09-67	32	3247	101	3248 [0.002]	83	
In situ (2 lamp troffer, BF=1.18)		69	4767	69			
In situ (2 lamp troffer, retest, BF=0.88)		55	4045	74			
SSL High-Bay Luminaires							
High-Bay	09-79	110	5612 20230 cd, 21°	51	2802 *[0.007]*	57	
High-Bay	10-25	111	7822 8376 cd, 38°	71	5593 [0.008]	71	

Values are rounded to the nearest integer for readability.

09-107—One out of two lamps underperformed (apparently due to damage during shipping), no in situ testing possible. Samples 09-107C & D were follow-up testing after Round 10 testing on samples A & B revealed underperforming samples that the manufacturer suspected of having been damaged during shipping.

10-18—One out of two lamps underperformed by a wide margin, no in situ testing was possible.

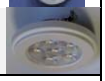
10-19—Of three lamps tested, one underperformed, in situ testing was performed on two best samples.

BK 09-67—Originally tested in Round 9, retest was requested by manufacturer using a different ballast.

For high-bay luminaires, center beam candlepower in candela (cd), and beam angle in degrees (°) are included under light output.

Duv values which are not with ANSI-defined tolerances for white light in SSL products are shown in *red italics*.

Table 1c. CALiPER ROUND 11 SUMMARY –Directional SSL Replacement Lamps

-- SSL testing following IESNA LM-79-08 -- 25ºC ambient temperature	DOE CALiPER TEST ID	Total Power (Watts)	Output (Initial Lumens), CBCP, Beam Angle	Efficacy (lm/W)	CCT (K) [D_{uv}]	CRI	Photo
SSL							
Directional Replacement Lamps: MR16							
Replacement Lamp (MR16)*	10-02	5	*152 lm* *199 cd,* 55°	*31*	2895 [-0.001]	*73*	
Replacement Lamp (MR16)*	10-30	7	296 lm 1536 cd, 20°	42	3067 [0.001]	84	
Directional Replacement Lamps: PAR and R							
Replacement Lamp (PAR30)	09-112	12	594 lm 1954 cd, 25°	49	2642 *[0.007]*	*64*	
Replacement Lamp (PAR38)	10-04	11	*565* lm *4465* cd, 18°	50	2667 [-0.002]	93	
Replacement Lamp (PAR38)	10-11	17	*705* lm *7528* cd, 13°	*42*	2759 [-0.001]	82	
Replacement Lamp (PAR38)	10-29	18	959 lm 3684 cd, 25°	52	*4056*** [0.003]	87	
Directional Replacement Lamps: AR111							
Replacement Lamp (AR111)*	09-114	15	451 lm 1381 cd, 26°	*30*	3727 *[-0.006]*	*75*	
Replacement Lamp (AR111)*	10-01	10	388 lm 2988 cd, 16°	*40*	3937 [-0.005]	84	
Benchmarks (BK): Ceramic Metal Halide, Halogen							
Directional Replacement Lamps: MR16							
Replacement Lamp (MR16) Halogen	BK10-21	36	603 lm 3159 cd, 23°	17	3040 [0.001]	98	
Replacement Lamp (MR16) Halogen	BK10-22	34	500 lm 3286 cd, 22°	15	2909 [0.002]	99	
Directional Replacement Lamps: PAR and R							
Replacement Lamp (PAR38) CMH Integral Ballast	BK09-111	25	1504 lm 5162 cd, 26°	60	3012 [-0.004]	86	

Values are rounded to the nearest integer for readability. Two or more samples were tested for all small replacement lamps—values are average of two samples. For MR16, PAR, and R lamps, light output in lumens is provided, along with center beam candlepower in candela (cd), and beam angle in degrees (°).

For MR16, PAR, and A-lamps, performance levels that do not meet the minimum ENERGY STAR criteria for integral SSL replacement lamps are shown in *red italics*, based on manufacturer equivalency claims and ENERGY STAR minimum requirements.[4]

*MR16 lamps and sample 10-01 tested using 12VAC. Sample 09-114 tested using 12VDC.

**PAR38 lamp 10-29 is ordered, packaged and stamped as 2700K, warm-white.

[4] *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 11 SUMMARY – Omni-Directional SSL 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) [D_{uv}]	CRI	Photo
SSL							
Omni-directional Lamps: A-lamps and Candelabras							
Replacement Lamp (A-lamp)*	10-03	8	*557*	72	3951 [-0.001]	84	
Replacement Lamp (A-lamp)	10-28	8	*377*	*48*	2757 [-0.001]	86	
Replacement Lamp (Candelabra)	10-23	3	86	*31*	3022 [0.001]	83	
Benchmarks (BK): Incandescent							
Omni-directional Lamps: A-lamps and Candelabras							
Replacement Lamp (A-lamp) incandescent	BK10-31	61	823	14	2771 [0.001]	100	

Values are rounded to the nearest integer for readability. Two or more samples were tested for all small replacement lamps—values are average of two samples. For MR16, PAR, and R lamps, light output in lumens is provided, along with center beam candlepower (in candela), and beam angle in degrees.

For replacement lamps, lumen output requirement is based on target replacement wattage as claimed by the manufacturer. For MR16, PAR, and A-lamps, performance levels that do not meet the minimum ENERGY STAR criteria for integral SSL replacement lamps are shown in *red italics*.[5]

*For replacement lamp 10-03, during initial testing, one lamp was found to have significantly lower light output and efficacy than expected and different color characteristics. The manufacturer identified the faulty sample as a very early production unit as evidenced by the date code. The faulty sample had a failure traced to early units that had not been fully transitioned to the production process at the supplier, in which the LED had a thermal related failure related to the packaging being performed on a prototype line. More recent lamps of the same version were procured anonymously and tested, showing no sign of this failure. Values reported are for the more recent lamps, not the faulty, early-production lamp.

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 set of results and further data are provided in the sections below.

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

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

Energy Use and Light Output

The SSL products tested in Round 11 exhibit a wide range of performance, as summarized in Figure 1, showing averages in efficacy, CCT, CRI, and power factor for all SSL products in Round 11, but also separately for replacement lamps as compared to outdoor and high-bay products. The overall average efficacy for SSL products tested in Round 11 is 57 lm/W, ranging from a minimum of 26 to a maximum of 93 lm/W. The color temperatures, in part due to selection choices and in part dependent on product options, are on average much closer to warm and neutral white for replacement lamps, and over 5000K for outdoor and high-bay products. The average CRI is now 75, with slightly better CRI on average in replacement lamps. Most commendably, the average power factor is 0.99—essentially 1.0 for outdoor and high-bay products.

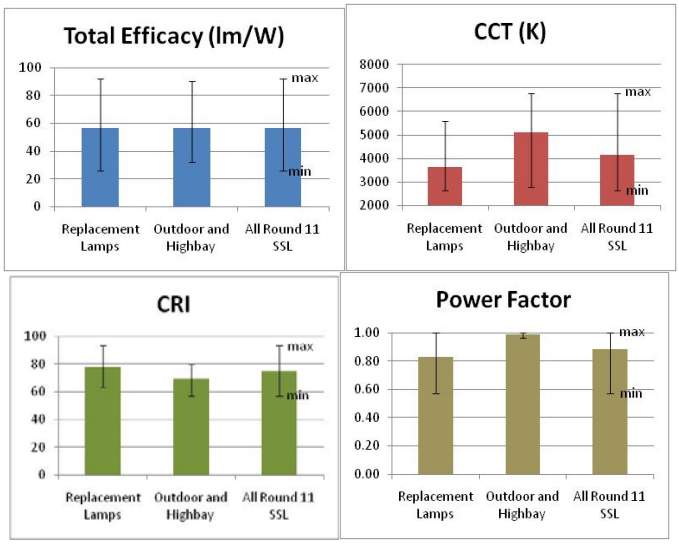


Figure 1. Average Round 11 Results for SSL Luminaires and Replacement Lamps

Figure 2 shows the yearly progress in efficacy based on CALiPER results, from the inception of CALiPER testing in 2006 through Round 11. Vertical bars are included to 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 vs 21 lm/W *average* in 2007).

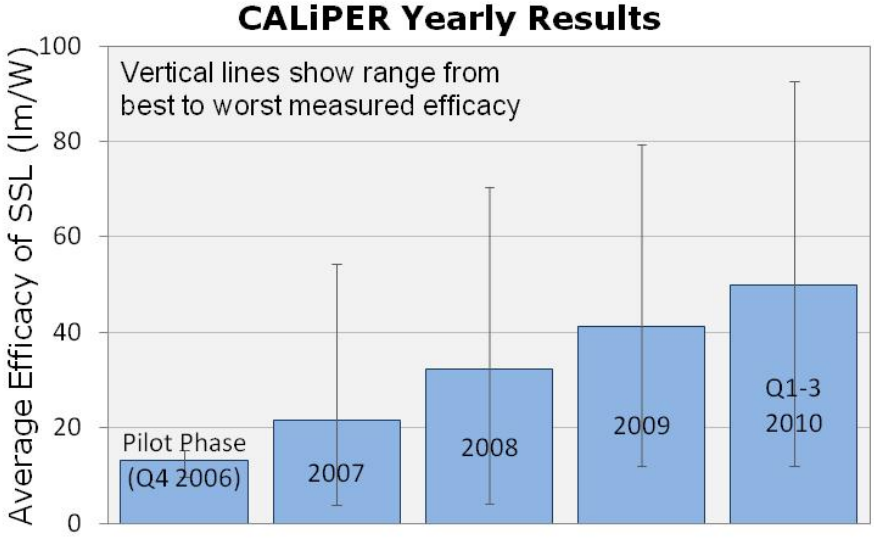


Figure 2. Average Measured Efficacy of Market-Available SSL Luminaires and Replacement Lamps

Outdoor Roadway Arm-Mount Luminaires

Six SSL roadway arm-mount products were tested in Round 11. One product, 09-62, is a replacement lamp intended for use in cobrahead fixtures, the other products are roadway luminaires. Table 1a summarizes the CALiPER-measured photometric performance of these products and also includes data for three benchmark roadway luminaires (one HPS and two induction) tested previously by CALiPER. Taken as a whole, these nine roadway products represent a wide range of designs, with a range of wattage levels, overall lumen levels, and distribution characteristics. Comparisons between these diverse products should be conducted with caution and taking into consideration the differences in distribution, lumen output, and application needs.

Output and Efficacy

With power levels ranging from 38 to 150W, the nine outdoor roadway products vary in total light output from 970 to 7004 lumens. However, five of the luminaires have fairly similar light output levels from around 4000-5000 lumens. Most of these five luminaires use approximately 70W, but one product, 10-14, stands out by producing 3994 lm while using only 44W. Figure 3 illustrates the comparative performance in efficacy, plotting the efficacy of the three benchmark products, earlier CALiPER roadway samples, and the Round 11 CALiPER roadway products. The average efficacy of the three benchmarks is 55 lm/W. The average efficacy observed in earlier CALiPER roadway samples was 41 lm/W. The Round 11 products show a wide range in efficacy, from a low of 26 lm/W to a high of 90 lm/W, but averaging 54 lm/W—similar to the benchmark products.

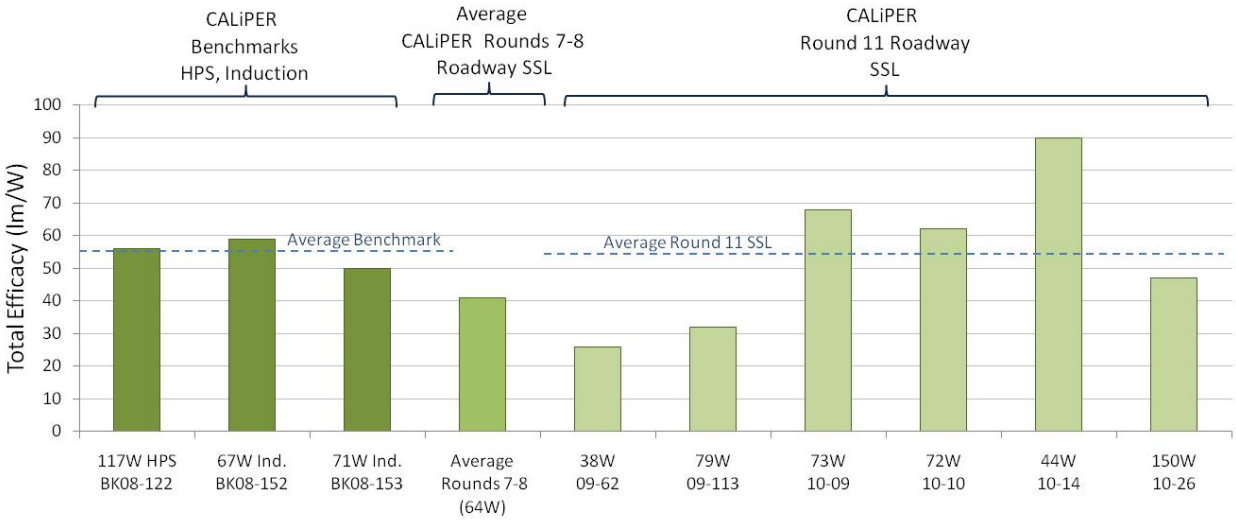


Figure 3. Luminaire Efficacy of SSL and Benchmark Roadway Luminaires

Color Qualities of Roadway Luminaires

Roadway lighting uses sources ranging from very low (warm or "yellowish") CCTs near 2000K from HPS luminaires, up to very high (cool or "bluish") CCTs over 6000K observed in some SSL luminaires. The majority of the SSL roadway products tested in Round 11 are in the 5000-6000K range. The replacement lamp product 09-62 is warm-white (3080K).

Beyond the color temperature of white light, a range of performance is also observed in other characteristics. The benchmark HPS product provides a CRI of 21 (making it difficult to differentiate colors under HPS lighting), while the induction benchmarks have CRIs around 75. One of the SSL products has a CRI of 80, while the others only produce CRI of 66-70. Also, two of the SSL products, 09-62 and 10-14, have D_{uv} at the ANSI-defined limit for white light and two products, 10-10 and 10-26,

have D_{uv} that is clearly outside of tolerances for white light. The D_{uv} for product 10-26 is 0.019, placing it well outside the range for white light (giving it a greenish appearance).

As a general note, some manufacturers of LED packages or modules/arrays have introduced special products with color characteristics intended for use in outdoor luminaires. Whereas the efficacy of most white-phosphor LEDs tends to improve with increasing CCT, some products are designed to sacrifice color rendition and quality to reduce the performance gap for lower CCTs. Ongoing research into the visual and non-visual effects of spectrum is attempting to clarify the relative significance of each and the potential advantages and disadvantages of different choices in CCT, CRI, and other color characteristics in outdoor applications. This work may inform future recommendations of the Illuminating Engineering Society of North America, which could in turn provide guidance in the selection of light sources having optimum spectral content for specific outdoor applications.

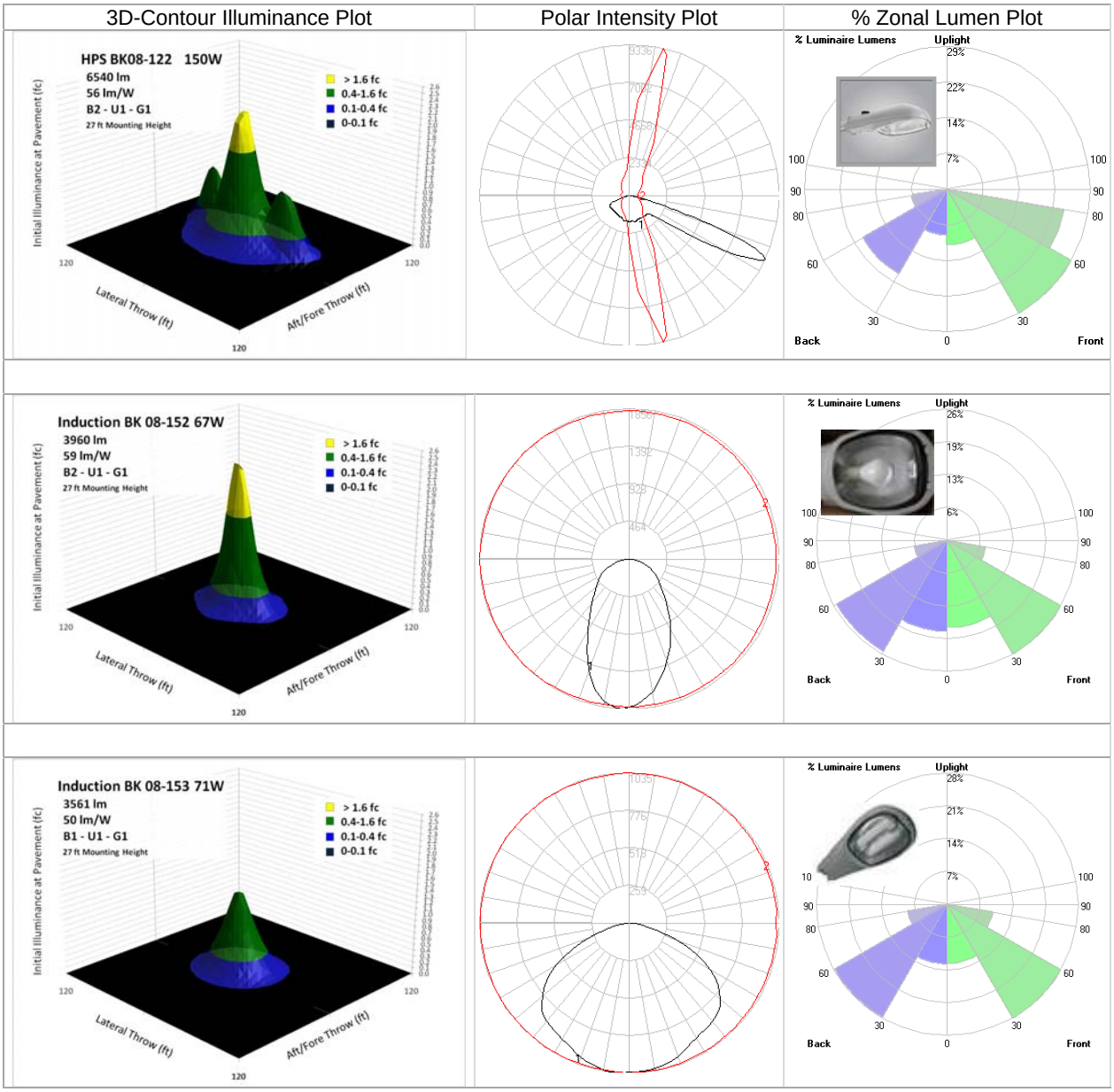
Spatial Distribution of Roadway Luminaires

Figures 4a-i below illustrate the wide range of distribution characteristics of the six SSL roadway products and the three benchmarks. For each luminaire, three graphics are provided: a 3D view of initial horizontal illuminance, a polar intensity (candela) plot, and a plot showing zonal lumens as a percentage of total lumens. The 3D-contour illuminance plots are all based on a mounting height of 27 feet, to enable direct comparison between the samples. Note that the optimal mounting height for each product may depend on many factors including product wattage, overall light output, light distribution, and application requirements. All of the 3D plots use the same color coding scheme, showing areas below 0.1 footcandle (fc) in black, blue for 0.1-0.4 fc, green for 0.4-1.6 fc, and yellow for areas receiving over 1.6 fc. The ranges used here are for illustrative purposes; criteria defining appropriate maintained footcandle levels may vary for different applications and actual illuminance produced will depend on mounting height and other site geometries.

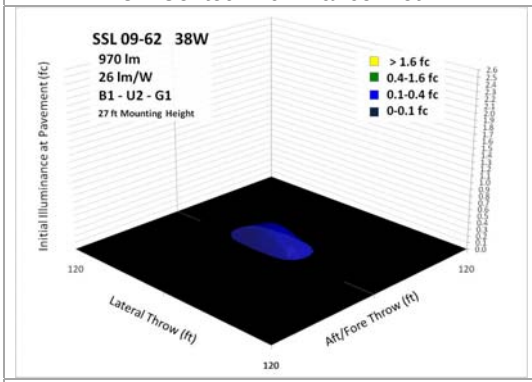
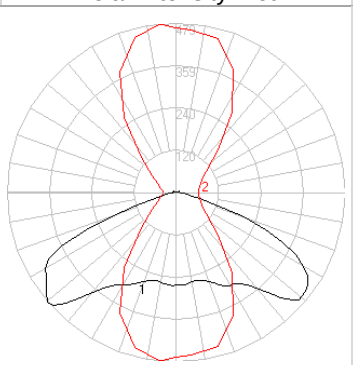
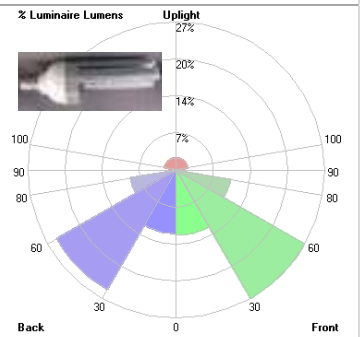
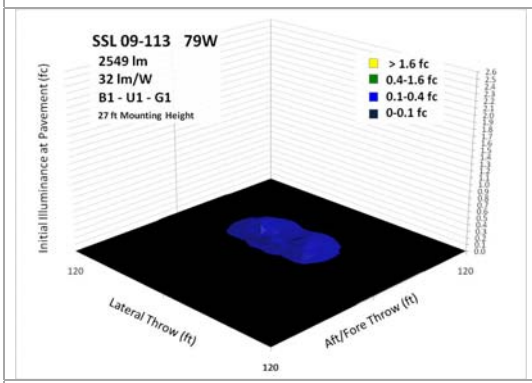
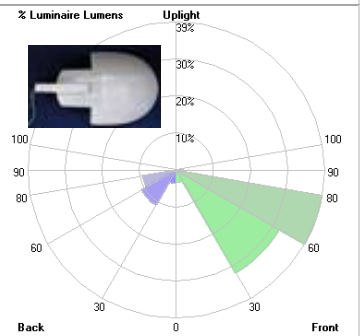
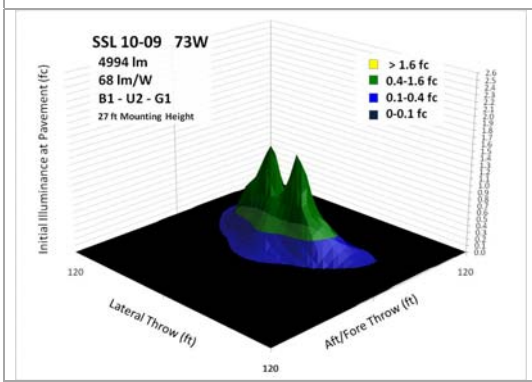
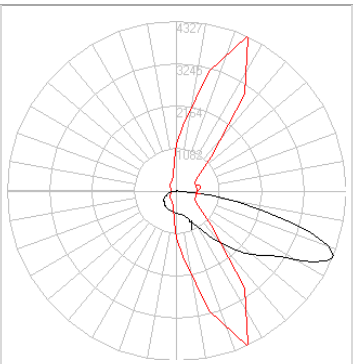
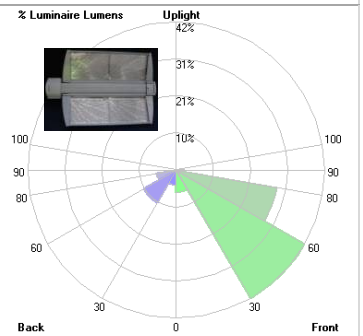
The multicolored 3D-contour plots provide a conceptual indication of suitable light levels (which may be particularly useful for readers who are not lighting specialists) and zonal distribution of light. Initial illuminance, in footcandles, is shown over an area extending four mounting heights from the luminaire in each direction. Providing these three different views of the distribution data may allow readers to better picture how, for example, a batwing or cosine distribution actually translates into a broad/shallow or narrow/deep “pool” of light.

Figures 4a-c show the distributions of the three benchmark products and Figures 4d-i show the six SSL products. Focusing on the 3D plots, it becomes clear that some products, such as BK 08-152 and 10-10, have narrow light distribution and others, such as 10-09 and 10-14 provide a much broader, more uniform light distribution.

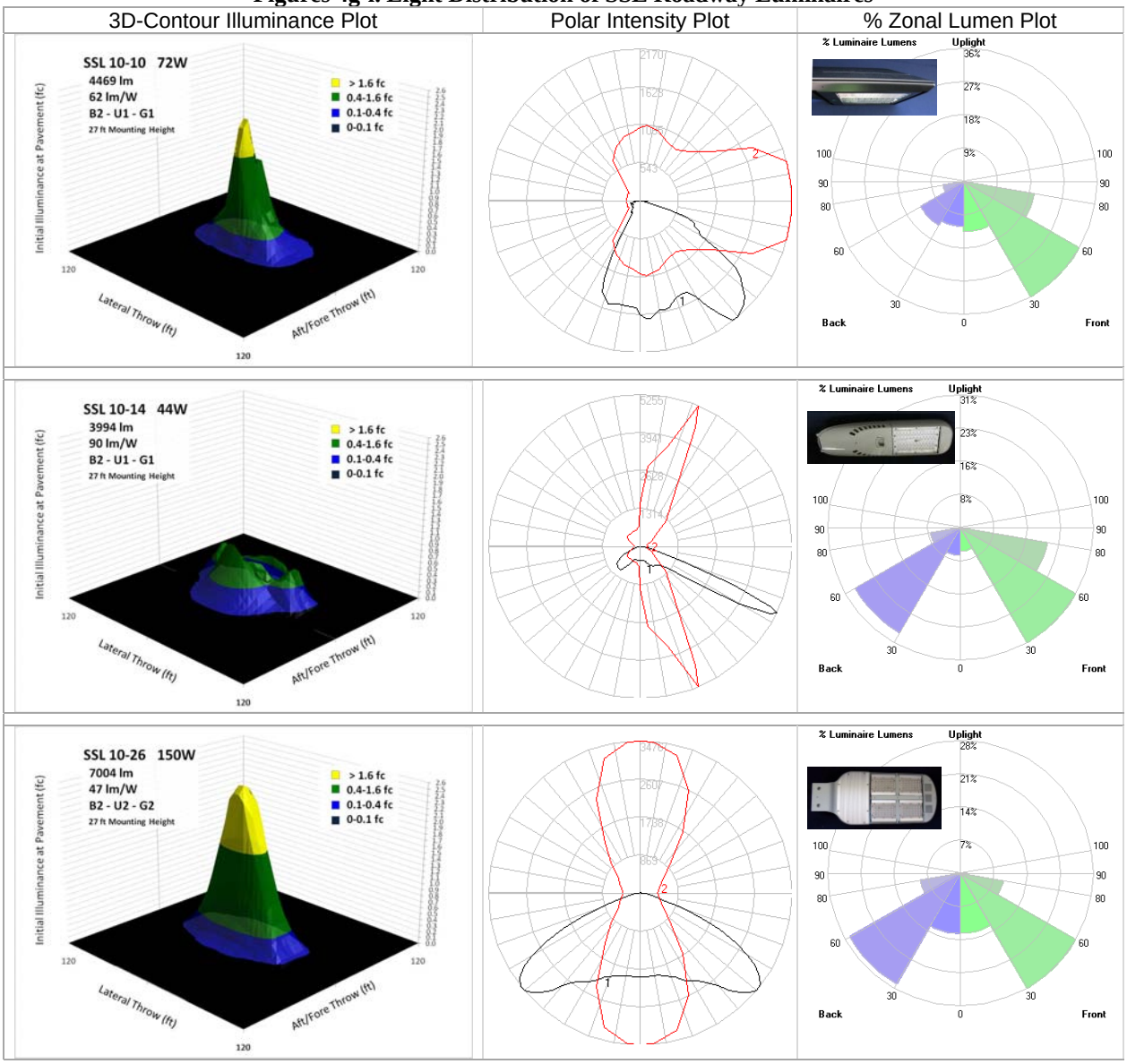
Figures 4a-c. Light Distribution of Benchmark Roadway Luminaires



Figures 4d-f. Light Distribution of SSL Roadway Luminaires

3D-Contour Illuminance Plot	Polar Intensity Plot	% Zonal Lumen Plot
		
		
		

Figures 4g-i. Light Distribution of SSL Roadway Luminaires



Direct comparisons between these products are complicated by the range of distributions and light output levels. Manufacturer literature for a number of these SSL roadway products claims that they are equivalent to 100 or 150W HPS. With this in mind, Table 2 provides an example comparing the adequacy of each product to the HPS benchmark, based on one arbitrarily defined scenario. Note that when using application-specific criteria such as illuminance and uniformity ratios, the relative performance of each product will vary from scenario to scenario. In this scenario, all of the products provide lower initial average illuminance than the HPS, and all but one use less energy than the HPS. Because of differences in distribution, only two SSL products and the HPS benchmark provide uniformity better than 6:1 average-to-minimum. One of these two LED products, 10-09, provides energy savings which outweighs the initial light reduction versus the HPS benchmark. Other scenarios, particularly those for new installations which may allow for different pole spacing, may result in suitable uniformity and energy savings using some of the other LED products such as 10-10 or 10-14. Extreme caution should be taken when making broad statements about equivalency of outdoor products and selecting products for any given application: the equivalency claim may be valid for some specific installation scenarios but will not be valid in every case.

Table 2. Sample Performance Analysis of Complete Lighting System (Not Just Luminaire)[6]

Calculations for retrofit of a somewhat overlit 24-foot wide 2-lane street with 27-foot high HPS luminaires set back 6-foot and spaced 170-foot on center (based on initial performance, not end of life). Other installation configurations (e.g., street widths, mounting heights, and pole spacing) may render significantly different results.									
CALiPER test source type	08-122 HPS	08-152 Ind.	08-153 Ind.	09-62 LED	09-113 LED	10-09 LED	10-10 LED	10-14 LED	10-26 LED
Input watts	117	67	71	38	42	73	72	44	150
Energy reduction	-	43%	39%	68%	64%	38%	38%	62%	-28%
Initial average illuminance	0.66	0.25	0.23	0.07	0.14	0.57	0.42	0.32	0.50
Initial light reduction	-	62%	65%	89%	79%	14%	36%	52%	24%
Avg:min uniformity	5.5	12.5	11.5	7.0	2.8	5.7	7.0	16.0	16.67
Avg:min uniformity < 6:1	yes	no	no	no	yes	yes	no	no	no
Avg initial illuminance > 0.4	yes	no	no	no	no	yes	yes	no	yes
Initial %energy reduction greater than %light reduction	-	no	no	no	no	yes	yes	yes	no

The various distributions of these eight products can also be evaluated by examining the zonal lumen densities, as shown in the right hand Figure 4 diagrams for each product. The corresponding Backlight-Uplight-Glare (BUG) ratings for each product are also indicated (overlaying the 3D plots), and summarized in Table 3 below along with the Type classifications of each product.[7] For the SSL products and the benchmark products, the Backlight, Uplight, and Glare ratings vary from a minimum of 1, to a maximum of 2, with the majority (5 out of 9) products having 2 for Backlight, the majority (6 out of 9) have 1 for Uplight, and the vast majority (8 out of 9) have 1 for Glare. The apparent homogeneity of the BUG ratings can be nuanced and misleading.

Table 3. Type Classifications and BUG Ratings for Roadway Samples

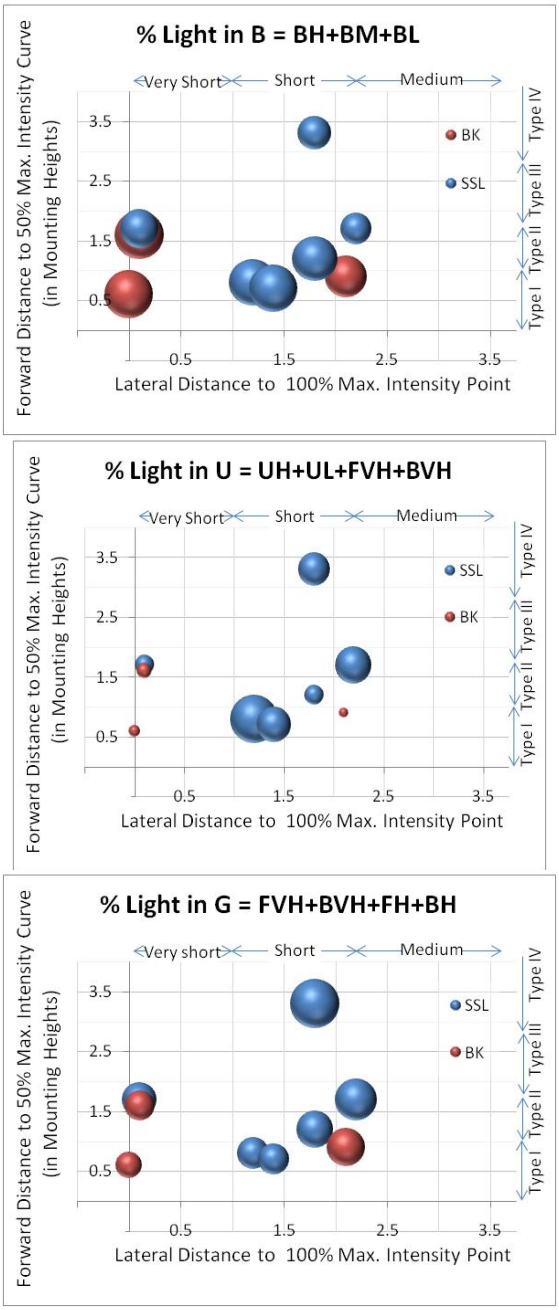
Source	Test	Output (lm)[8]	Type		BUG Rating		
			Forward	Lateral	Backlight	Uplight	Glare
SSL	09-62	992	I	Short	1	2	1
	09-113	1744	IV	Short	1	1	1
	10-09	5040	II	Short	1	2	1
	10-10	4443	II	Very Short	2	1	1
	10-14	4016	II	Short	2	1	1
	10-26	6930	I	Short	2	2	2
BK	08-122	6456	I	Short	2	1	1
	08-152	3695	I	Very Short	2	1	1
	08-153	3235	II	Very Short	1	1	1

[6] Note that Table 2 provides a simplified example of performance analysis for roadway lighting systems. Other illustrative examples of similar analyses can be found in DOE Gateway Demonstration reports (see http://www1.eere.energy.gov/buildings/ssl/gatewaydemos_results.html).

[7] The old "cutoff" classification system, which was deprecated by IES, characterized the high-angle brightness and uplight produced by outdoor luminaires. This system was based on rated lamp lumens and relative photometry, and so cannot be applied to LED products (which utilize absolute photometry). IESNA TM-15-07 details the new Luminaire Classification System. The BUG rating system is defined in Addendum A.

[8] Note that light output values in Table 3 are as measured by goniophotometry. These may differ slightly from light output values listed in Table 1a, which were established using integrating sphere measurements.

BUG ratings are a function of distribution and total light output, so the BUG rating data in Table 3 may appear homogeneous, while in fact, the distribution characteristics of the samples taken as a percentage of total light output (normalized for light output levels), shows greater differentiation. Figures 5a-c illustrate how the percentages of light output in the LCS zones used to determine BUG ratings relate to the diverse beam characteristics of these products. The y-axes indicate forward distance to the 50% maximum intensity curve used for Type I-II-III-IV "forward" classification. The x-axes indicate lateral distance to the point of maximum intensity, which is used for Short-Medium-Long "lateral" classification.[9] The bubble diameters correspond to the total percentage of light in each LCS zone (B includes BH, BM, BL; U includes UH, UL, FVH, BVH; and G includes FVH, BVH, FH, and BH). It stands to reason that the broadest distributions (approaching Type IV Long, in the upper right of each plot) may tend to produce a greater percentage of light in the high-angle glare regions. Results from earlier CALiPER testing of roadway SSL fixtures are also included to provide a larger data set illustrating how BUG ratings may vary with different beam characteristics. In contrast to the homogeneity of BUG-ratings shown in Table 3, the central plot of Figure 5 reveals that while the percentages of light in the Backlight and Glare zones are fairly similar between benchmark and SSL products, the SSL samples tend to have a greater percentage of Uplight than the benchmark samples. Note, however, that some light below horizontal is treated as Uplight.



Figures 5a-c. Percentage Light in LCS Zones as a Function of Forward and Lateral Throw for SSL and Benchmark Roadway Luminaires

Manufacturer Claims

Five out of six of the SSL arm-mount roadway luminaires meet or come close to meeting manufacturer ratings for expected light output and efficacy (within approximately 10% of manufacturer published efficacy). The only product which highly overstates performance is the replacement lamp, 09-62, which claims 2-½ times the light output and efficacy that it actually achieves. This product also claims to replace metal halide and HPS, but would probably not be an adequate replacement for even a 35W HPS lamp (rated 2250 lumens) in a 70% efficient HID luminaire.

[9] See IESNA TM-3-95, A Discussion of (RP-8-83) Appendix E, "Classification of Luminaire Light Distributions."

With respect to color characteristics, half of the products have a measured CCT which is not within ANSI-defined tolerances for the range of CCT permitted corresponding to the nominal (manufacturer rated) CCT and four out of six have D_{uv} which is either out of ANSI-defined tolerance or at the limit for the D_{uv} permitted for a given CCT. In all, only one product, 09-113, has both CCT and D_{uv} that are clearly within ANSI-defined tolerances for its rated CCT. Outdoor lighting applications may be less sensitive to variations in color quality than indoor applications, but it is important to note the wide extent of variation between the products' rated values (claimed by manufacturer) and the CALiPER-measured chromaticity characteristics.

Round 11 testing of roadway luminaires did not address characteristics such as controllability (facility to dim, cycle on-off without affecting product life, long-term reliability, dirt depreciation), which are qualities which may also enter into purchasing decisions for roadway and area lighting.[10]

[10] A number of DOE GATEWAY demonstrations of roadway lighting have been conducted, in some cases touching on these additional considerations. Reports on GATEWAY demonstrations are available online: http://www1.eere.energy.gov/buildings/ssl/gatewaydemos_results.html.

Outdoor Post-top Luminaires

Although a retrofit acorn luminaire insert was tested in Round 7 (not installed in a luminaire), the three products tested in Round 11 are the first post-top luminaires tested by CALiPER. The two benchmark samples provide examples of typical outdoor post-top luminaires using 150W ceramic metal halide (CMH) and 150W pulse-start metal halide sources, one with a clear prismatic glass refractor on the top (allowing significant uplight), and the other with an acrylic lens and an opaque cap (reducing uplight, but also luminaire efficiency). In light distribution, the two SSL post-top products are more similar to the second benchmark (reducing uplight and directing a greater percentage of light output in lower angles), but in overall light output and in wattage, neither of the SSL post-tops comes close to achieving the light levels provided by the two benchmarks. Product 10-13 uses less than one-third the power of the benchmark post-tops, but also provides less than one-third the light output (achieving similar efficacy).[11] Product 10-27 has lower efficacy than both benchmarks and does not provide one-tenth of the light output of the benchmarks.

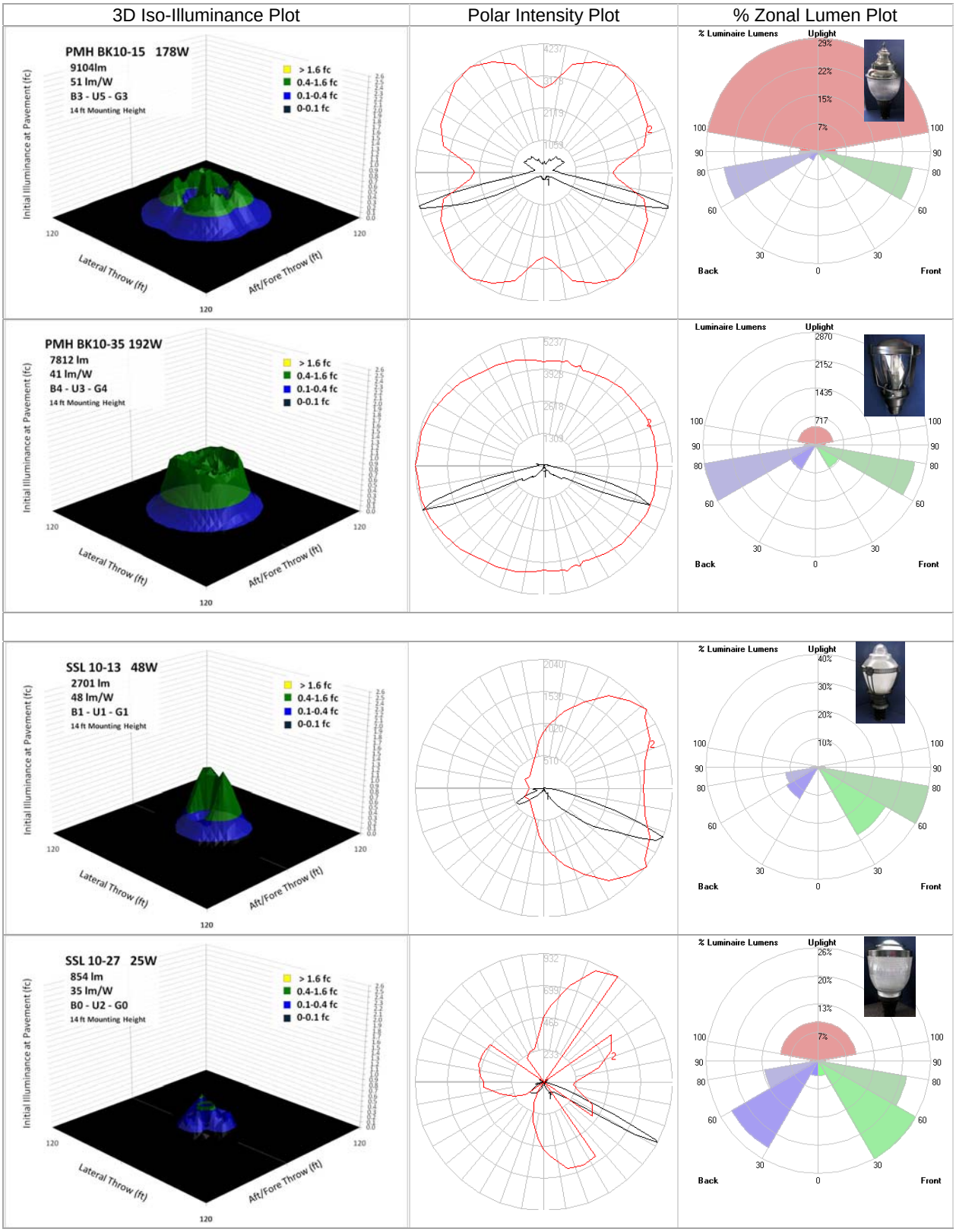
Figures 6a-d provide graphic summaries of the light distribution characteristics of these four post-top luminaires, first the two benchmarks, then the two SSL luminaires. As with the arm-mount roadway luminaires, three graphics are provided for each luminaire: a 3D view of the initial horizontal illuminance, a polar intensity (candela) plot, and a plot showing zonal lumens as a percentage of total lumens. The 3D-contour illuminance plots are all based on a mounting height of 14 feet, to enable direct comparison between the samples. Note that the optimal mounting height for each product may depend on many factors including light distribution, overall light output, and application requirements. All of the 3D-contour plots use the same color coding scheme, showing areas below 0.1 footcandle (fc) in black, blue for 0.1-0.4 fc, green for 0.4-1.6 fc, and yellow for areas receiving over 1.6 fc. The ranges used here are for illustrative purposes; criteria defining appropriate illuminance values may vary for different applications and the amount of footcandles in situ will depend on mounting height and other site geometries.

The two benchmark products provide the majority of their light in the 60-80° range. One SSL product provides the majority from 30-60°, and the other also provides a higher percent of light in the 30-60° range than the benchmark products, although a majority in the 60-80° range like the benchmarks. The higher performing SSL post-top also has close to zero Uplight, like the solid top benchmark, putting a greater percentage of light on the roadway surface—ultimately achieving higher illuminance levels over a greater area than the benchmark products, relative to the amount of power used. With optimal installation (mounting height and spacing), the SSL post-top, 10-13, could be more energy efficient than the benchmarks.

The manufacturer reported data for BK10-15 is accurate and complete. For BK10-35, the manufacturer does not supply photometric data for the solid-top versions of the product which have significantly lower efficacy than the versions emitting significant uplight (for which they do publish photometric data). For the lower performing SSL product, 10-27, no performance data was published (which could mislead buyers who might think this product is comparable to more traditional post-top luminaires, while it only provides one-tenth the light output). The higher performing SSL product, 10-13, provides claims for light output and efficacy which are approximately 25% overstated.

[11] A 95W version of this product is also available, rated for slightly lower efficacy and approximately 80% more light output, but still significantly less than the 150W benchmarks.

Figures 6a-d. Light Distribution of CMH and SSL Post-top Luminaires



Smaller Replacement Lamps

A wide variety and number of SSL and benchmark small replacement lamps were tested in Round 11. Directional lamps included two SSL MR16 lamps and two 35W halogen MR16 lamps (earlier MR16 benchmarking was conducted on 20W halogens), one PAR30, three PAR38, and two AR111 SSL lamps, and one ceramic metal halide PAR38 (with integral ballast). Omni-directional lamps included two SSL A-lamps and one SSL decorative candelabra-based lamp, along with one typical, frosted 60W incandescent A19 lamp. Many of the SSL replacement lamps were selected because they appear to have improved performance levels compared to earlier products.

The choices in benchmark replacement lamps reflect this increasing SSL performance. Some SSL MR16s are now clearly competitive with 20W halogen, so 35W halogen MR16 lamps are now included as benchmarks. Similarly, some SSL PAR lamps are now clearly competitive with 50W halogen, so a 25W metal halide PAR38 lamp is included as a benchmark, comparable to a 60W halogen infrared PAR38 or 90W standard halogen PAR38. A number of SSL A-lamps are now clearly competitive with 40W incandescent A-lamps, so a typical 60W incandescent lamp is now included as a benchmark. Unfortunately, a significant portion of the SSL replacement lamps do not meet ANSI-defined formats (such as diameter, maximum length, or neck geometries) of the lamps they purport to replace.[12]

MR16 Lamps

The basic performance of the four MR16 lamps tested in Round 11, one 20° SSL, one very wide beam 55° SSL, and two 35W halogens (with beam angles of 22° and 23°), is summarized in Table 1c. Figures 7 and 8 put these results in perspective, showing that one of the SSL lamps, 10-30 clearly meets the performance levels of 20W halogen, while the other SSL lamp, 10-02 comes close to achieving the lower limits of 20W halogen performance.

Figure 7 plots the beam angle and center beam candlepower (CBCP) against the curves defined by ENERGY STAR criteria for minimum halogen performance equivalence. The lamp with a narrower beam, 10-30, clearly meets and exceeds the level for 20W halogen MR16 (defined by the red curve), but the much wider beam lamp, 10-02, remains slightly below the 20W halogen mark. None of the SSL lamps tested by CALiPER thus far achieve the level defined by the 35W halogen curve (orange), which is clearly surpassed by the two 35W halogen benchmark samples.

Figure 8 plots the light output (lm) and efficacy (lm/W) of the MR16 lamps, compared to benchmark performance values and compared to earlier CALiPER MR16 results. Both SSL MR16 lamps achieve greater efficacy than halogens, providing two to three times the light output per wattage of power used as compared to halogens. In overall light provided, sample 10-30 exceeds the average overall lumen level for 20W halogen MR16, while sample 10-02 achieves the output levels of the lowest performing halogens. Overall, there is a clear trend from year-to-year showing continual improvement in light output and efficacy.

[12] See NEMA ANSI C78.20:2003 For electric lamps - a, g, ps, and similar shapes with e26 medium screw bases, NEMA ANSI C78.21:2003 For electric lamps - par and r shapes, and NEMA ANSI C78.24:2001, Electric lamps - two-inch (51-mm) integral-reflector lamps with front covers and gu5.3 or gx5.3 bases: http://webstore.ansi.org/.

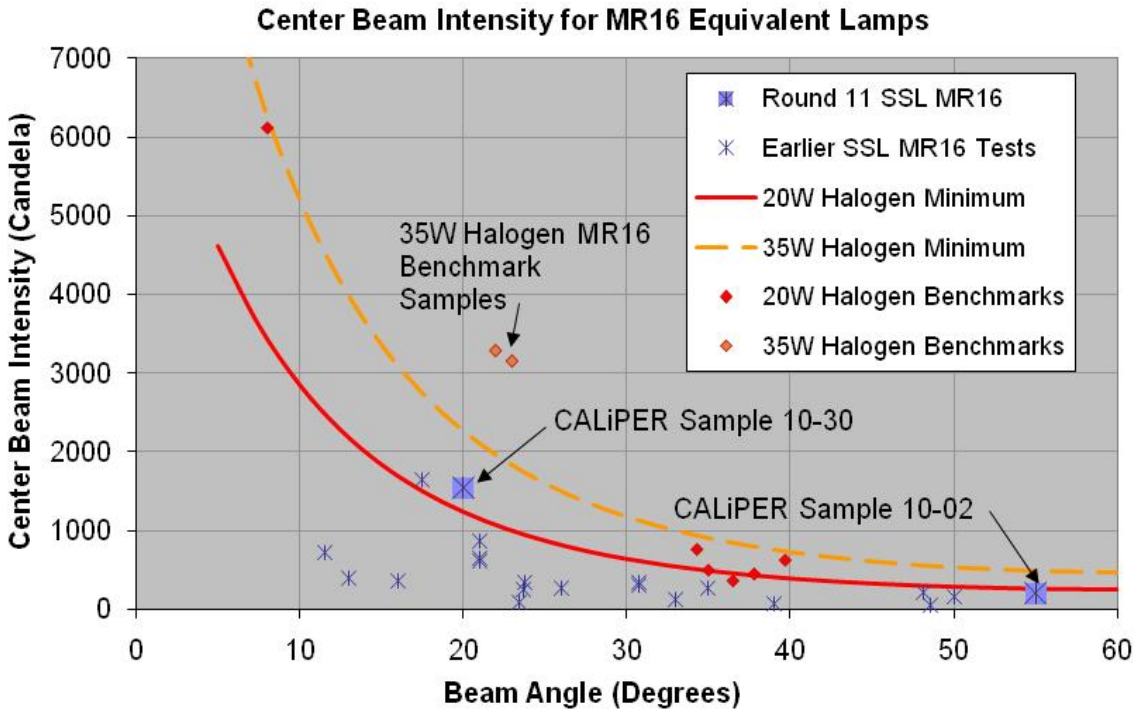
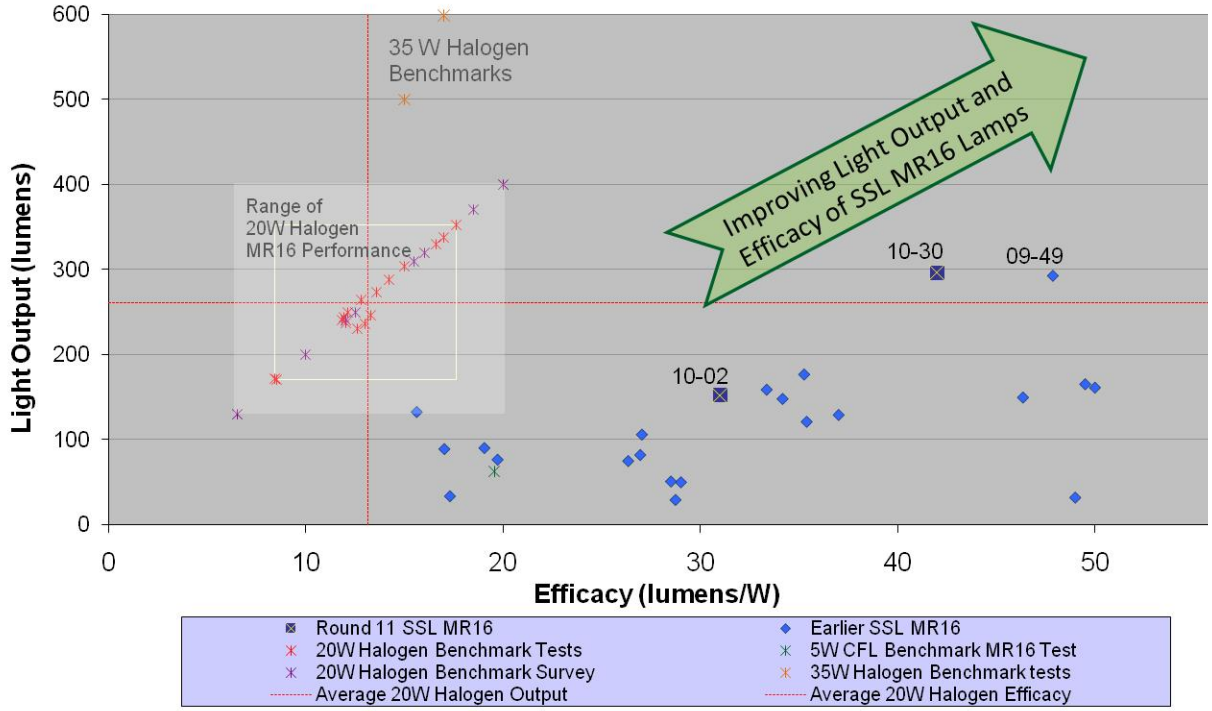


Figure 7. Intensity and Beam Angle of MR16 Lamps



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, 12V AC or DC input.

Figure 8. Light Output and Efficacy of MR16 Lamps

The difference in performance of the two SSL samples is also reflected in the accuracy of their performance claims. Table 4 summarizes how well these lamps meet manufacturer claims. The higher performing lamp carries a Lighting Facts® label and meets or exceeds all performance levels published on the Lighting Facts label and in product specifications.[13] The lower performing lamp does not carry a Lighting Facts label and publishes performance levels which claim three times higher performance than those found by CALiPER.

Table 4. CALiPER ROUND 11 – MR16 Replacement Lamp Manufacturer Claims

Sample	Performance Level and Equivalence	Meeting Manufacturer Claims	Meeting Lamp Format	Lighting Facts Label?	Comments
10-02 MR16 	✗ Claims 35W and 50W equivalence, does not meet 20W minimum.	✗ Claims 450 lm, 90 lm/W; CALiPER shows 152 lm, 31 lm/w	✗ Slightly exceeds max overall length and neck length.	None.	Significantly overstates performance claims.
10-30 MR16 	✓ Compares to and exceeds average performance of 20W halogen.	✓ Meets or exceeds claimed performance levels.	✗ Exceeds max length (2.1" vs 1.9") and lens height.	✓	Cannot be covered (includes internal fan).

In summary, the MR16 testing shows:

- Warm-white color for both MR16 lamps—both near 3000K, with good CRI for 10-30 (84), passable CRI for 10-02 (73), and good D_{uv} for both lamps.
- One MR16 clearly meets 20W halogen performance in light output and in CBCP (for comparable beam angle). The other MR16 comes close to achieving the lower limit of performance in light output and CBCP for 20W halogens.
- Two SSL products tested by CALiPER thus far (sample 10-30 from Round 11 and sample 09-49 from Round 8) exceed the average light output and exceed minimum CBCP requirements (as defined in ENERGY STAR criteria) for 20W halogen.
- Both MR16 lamps exceed 20W halogen in efficacy, the better of the two achieving three times the efficacy of halogen MR16 lamps and the other achieving double the efficacy of halogen.
- The better performing MR16, which carries the Lighting Facts label, meets and exceeds the manufacturer performance claims. The MR16 lamp which does not carry the Lighting Facts label has significantly overstated performance claims.
- Both lamps exceed the standard maximum length for MR16 lamps, with the optic extending slightly beyond the maximum permitted. One carries the mention "Not for use in totally enclosed fixtures."
- The MR16 SSL lamps tested are not yet achieving light output or CBCP levels of 35W halogens, as shown by the two 35W halogen benchmark products included in this round.
- MR16 lamp 10-30 is the only replacement lamp tested in Round 11 that meets all principal initial photometric measures defined in the ENERGY STAR SSL criteria for integral LED lamps (light output, CCT, CRI, CBCP).

[13] See http://www.lightingfacts.com/.

PAR and AR Lamps

The basic performance of the five PAR lamps and two AR111 lamps tested in Round 11 is summarized in Table 1c. The discussion below centers on the PAR lamp performance, because this is the first time that AR111 lamps have been CALiPER tested and benchmark results for this category of product are not available at this time.

Figure 9 examines the light output and efficacy of the PAR lamps as compared to averages for similar products in earlier CALiPER tests and as compared to a CALiPER halogen infrared (HIR) PAR30 benchmark. All four of the SSL PAR lamps tested in Round 11 clearly surpass the HIR PAR30 benchmark in light output, as well as the lamps tested in earlier CALiPER rounds, but they only have one-third to one-half the light output of the 25W metal halide lamp. The increased light output compared to the HIR benchmark and compared to earlier CALiPER rounds is in part due to higher power levels of lamps available on the market (and thus those being selected for testing), and in part due to increased efficacy of these lamps. The PAR lamps tested in Round 11 range from 11W to 18W, whereas the average power levels of PAR lamps tested in Rounds 1-8 and Rounds 9-10 were only 10 W and 8W respectively. The lower light output compared to the metal halide benchmark is in part due to the higher power level (25W) in that lamp, but also the higher efficacy of the ceramic metal halide (60 lm/W as compared to 42-52 lm/W for the SSL lamps). All of the PAR lamps tested in Round 11 achieve at least 3-4 times the efficacy of the benchmark HIR PAR30 lamp, but fall short of achieving the 60 lm/W of the metal halide lamp.

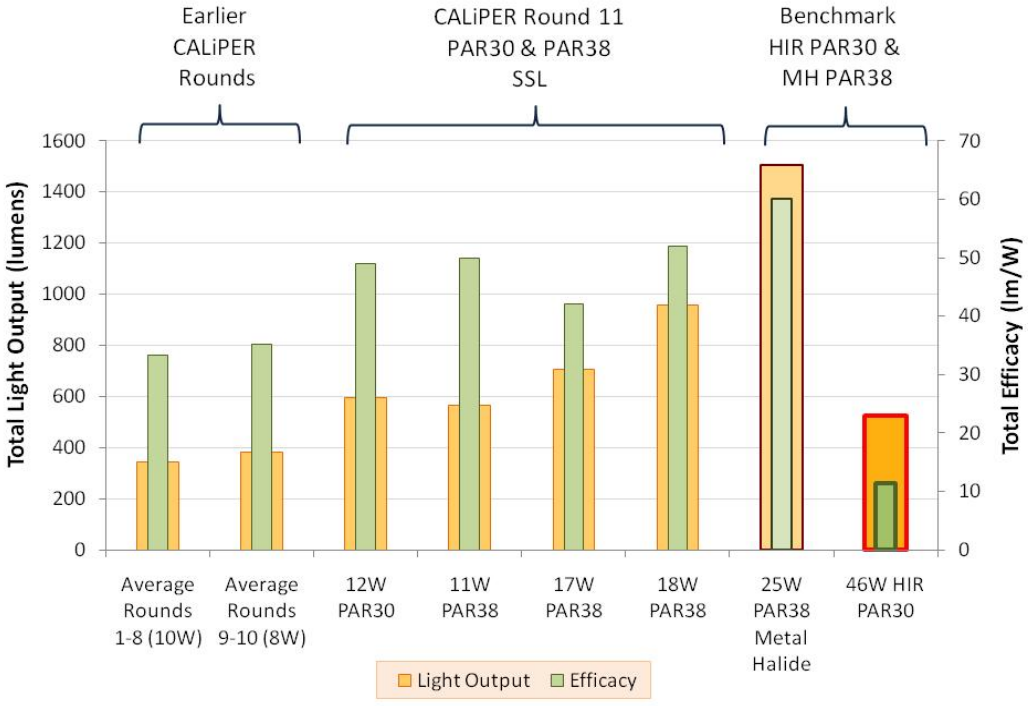


Figure 9. Light Output and Efficacy of PAR Lamps

Examining the intensity and beam characteristics of the PAR lamps shows similar improvement, as illustrated in Figure 10. All four of the SSL products surpass the curve representing minimum requirements for 50W equivalent—one also borders on the limit for 75W halogen and another even

surpasses the mark for 75W halogen. None of the four achieve the level of the 25W metal halide, which is compared in package labeling to 90W halogen PAR38.

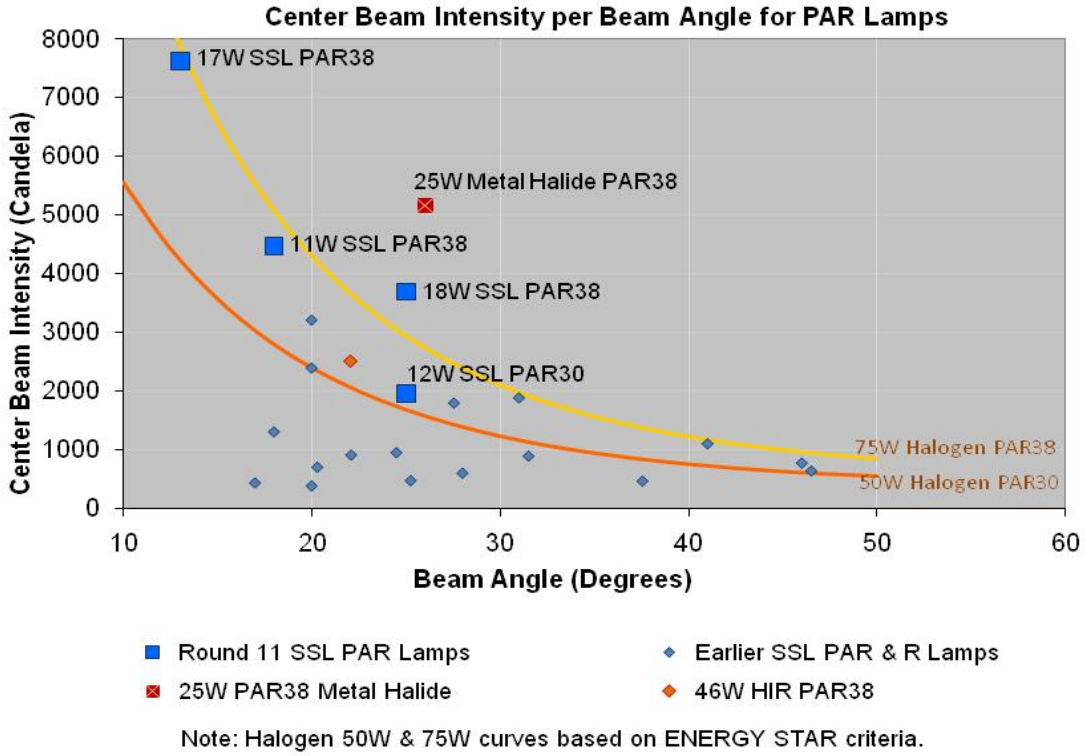


Figure 10. Intensity and Beam Characteristics of PAR Lamps

Table 5 summarizes the accuracy of manufacturer claims for the PAR and AR lamps tested in Round 11. None of the PAR lamps have highly overstated performance claims as compared to product specifications or Lighting Facts labels, although one does underperform by about 10-20%. However, consumers could be misled by equivalency claims: for the two PAR lamps that carry equivalency claims, those claims are either only partially true or are somewhat exaggerated.

For the AR111 lamps, one lamp achieves the light output and efficacy stated in product specifications which would represent performance of a 45W halogen, but it claims to provide equivalent light output to a 75W halogen. The other AR111 lamp has significantly overstated performance claims and does not match the light output and beam characteristics of a 45W halogen.

All of the SSL PAR lamps that were selected claimed to be warm-white (2700K) products, however, one product, 10-29, while labeled on the lamps and packaging as 2700K, actually tested at 4056K. None of the initial received samples of this product were 2700K, which may be indicative of a production or handling mishap, but could nevertheless result in dissatisfied consumers. Two additional samples were subsequently ordered (after Round 11 testing was completed)—both appear to be 2700K based on visual inspection. These more recent samples carry the exact same product number as the lamps measured at 4056K, but a different date and batch code. PAR lamp 09-112 also exhibited relatively poor color characteristics, with a CRI of 64 and D_{uv} of 0.007, outside of ANSI defined tolerances for nominally 2700K white light.

Table 5. CALiPER ROUND 11 – PAR38 and AR111 Replacement Lamp Manufacturer Claims

Sample	Performance Level and Equivalence	Meeting Manufacturer Claims	Meeting Lamp Format	Lighting Facts Label?	Comments
09-112 PAR30 	✓ (No equivalency claims.) Meets ~50W halogen equivalence.	✓ Meets or exceeds manufacturer claims.	✗ Not standard or diameter length for short or long PAR30.	None.	D_{uv} (color quality) exceeds ANSI tolerance and has low CRI (64).
10-04 PAR38 	✗ Claims 50-90W halogen equivalence, meets 50-55W, not 90W halogen equivalence.	✓ Meets or exceeds manufacturer claims.	✓	✓	
10-11 PAR38 	✗ Claims 75W halogen equivalence, meets 65-70W halogen equivalence.	✗ Overstates performance by 15-20%	✗ Slightly exceeds max overall length.	✓ / ✗ Meets CCT and CRI, but not light output and efficacy.	Adjustable power product (3 wattage levels), tested at highest power setting. Somewhat overstates performance.
10-29 PAR38 	✓ No equivalency claims. Meets ~85W halogen equivalence.	✓ / ✗ Meets light output and efficacy, but incorrect CCT (labeled 2700K, measured 4056K)*	✗ Slightly too short neck + skirt length.	✓ / ✗ Meets light output and efficacy, but has incorrect CCT*	"Added weight of the device may cause instability of a free-standing portable lamp." (Heavy.)
BK09-111 PAR38 	✓ Compares to 60W HIR and 90W standard halogen.	✓	✓	Not applicable.	Ceramic Metal Halide with integrated ballast
09-114 AR111 	✗ (No equivalency claims.) Does not meet equivalence of 45W halogen.	✗ Claims 600 lm, 40 lm/W; CALiPER shows 451 lm, 30 lm/w	✗ Irregularities in product wiring. Two samples had different, non-standard connectors.	None.	Significantly overstates product performance.
10-01 AR111 	✗ Claims equivalent output up to 75W halogen. Meets ~45W halogen equivalence.	✓ Meets or exceeds manufacturer performance claims.	✓	None.	

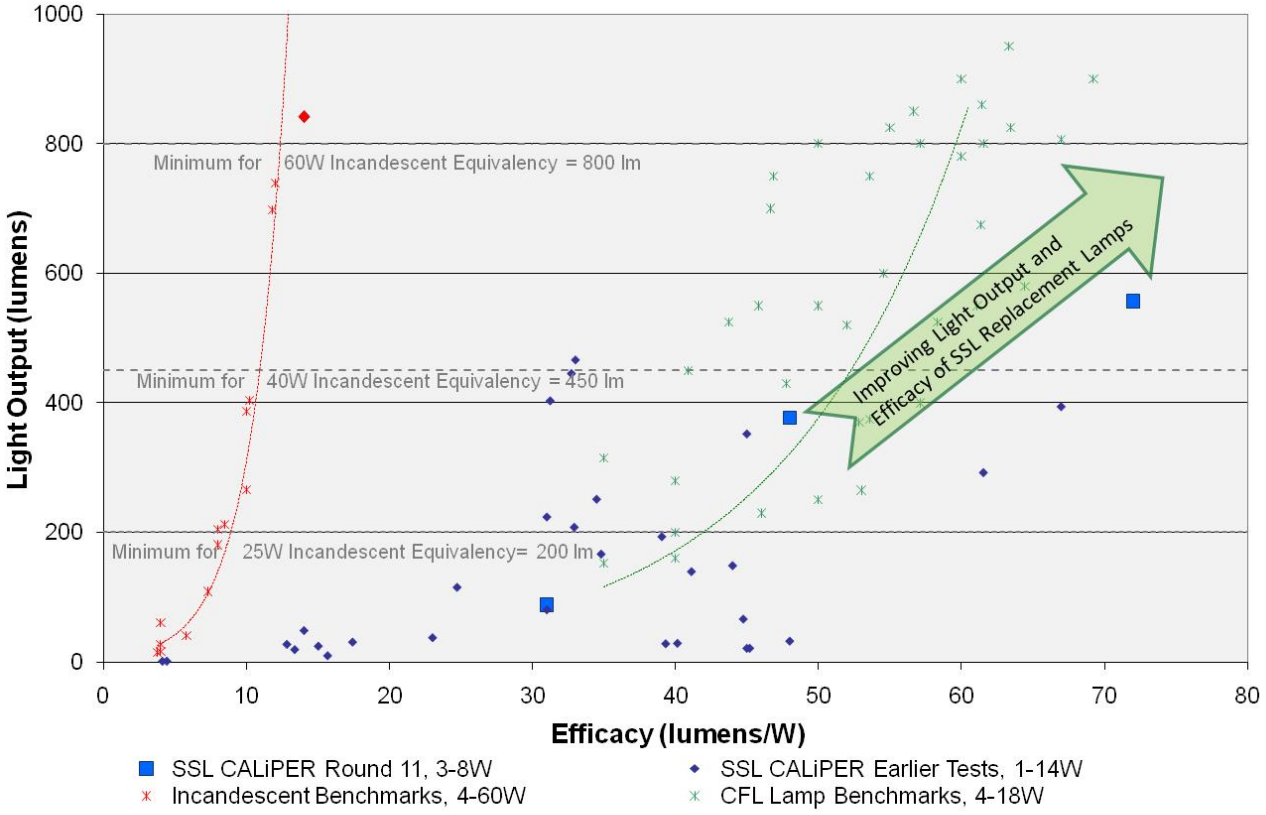
* Note that after receiving test results on product 10-29, two additional samples were ordered to determine whether the incorrect CCT was an on-going problem. While these samples were received too late to be LM-79 tested, visual inspection shows that the samples from a more recent batch have the correct CCT (~2700K).

Three out of four of the SSL PAR lamps would not meet ANSI standards for lamp dimensions. One in particular, 09-112, clearly did not correspond to the standard diameter or length for a PAR30 lamp.

Omni-Directional Replacement Lamps

Two SSL products marketed as A19 replacement lamps and one decorative SSL candelabra lamp were included in Round 11, along with a standard 60W frosted A19 incandescent lamp for benchmarking. Figure 11 plots the light output and efficacy of each of these lamps as compared to earlier CALiPER testing and benchmark incandescent and CFL.

For similar light output levels, the SSL omni-directional replacement lamps achieve efficacy levels similar to, or surpassing, CFL lamps (as averaged in the green curve in Figure 11). The 3W candelabra lamp surpasses the light output of a 15W incandescent benchmark flame-tip candelabra, while using 20% of the power. One of the A-lamps, 10-28, comes close to achieving the minimum light output for a 40W incandescent equivalency rating, while using 20% of the power. The other A-lamp, which is a "neutral-white" color (3951K), surpasses the minimum light output for 40W incandescent, but does not meet the overall minimum light output for 60W incandescent. However, with a light output of 557 lm and efficacy of 72 lm/W, this product could be a suitable replacement for A-lamps in relatively directional applications, while using only 13% of the power. None of the SSL A-lamps tested thus far achieve the light output or distribution characteristics of the benchmark 60W incandescent A19 lamp, but they are now surpassing 40W incandescent.



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 life-time output. Minimum equivalency values are as defined in ENERGY STAR criteria for SSL.

Figure 11. Light Output and Efficacy of Omni-Directional Replacement Lamps

Table 6 summarizes the manufacturer claims for the three omni-directional replacement lamps. All three products carry relatively accurate performance claims, although the two A-lamps carry potentially misleading equivalency statements.

Table 6. CALiPER ROUND 11 – Omni-directional Replacement Lamp Manufacturer Claims

Sample	Performance Level and Equivalence	Meeting Manufacturer Claims	Meeting Lamp Format	Lighting Facts Label?	Comments
10-03 A19-lamp 	✗ Claims 60W incandescent equivalence, does not meet average.	✓ Within 10% of manufacturer claims	✗ Exceeds diameter for A19 bulb (2 ¾" vs. 2 ⅜")	Only listed for more recent versions of this product.	"60W Incandescent & CFL replacement lamp optimized for down light applications"
10-28 A-lamp 	✗ Claims 40W incandescent equivalence, does not meet average.	✓ Within 5% of manufacturer claims	✓	Only listed for 3000K version of this product.	
10-23 Candelabra 	✓ Meets (within 5%) performance of 15W incandescent.	✓	✓	✓	"Equivalent to 15W, suitable for 25W accent applications."

For A-lamps, ENERGY STAR publishes equivalency tables for CFL and SSL lamps, as illustrated in Figure 12, so it should be fairly straightforward to determine incandescent equivalencies and publish literature with suitable indications.[14] However, in every category of incandescent A-lamps, a wide range of performance can be observed in products on the market, so some manufacturers may be justifying inflated equivalency claims by comparing to lower performing products rather than averages or published criteria. In other cases, manufacturers may be publishing misleading equivalency claims in an effort to grapple with differences in directionality of incandescent and SSL products, which can result in higher fixture inefficiencies in some applications for incandescent lamps as compared to SSL lamps. For example, product 10-03 includes the mention "60W Incandescent & CFL replacement lamp optimized for down light applications" and product 10-23 includes the mention "equivalent to 15W, suitable for 25W accent applications" (where "accent" may imply applications requiring directional light). In both cases, the comparisons may be true: fixture losses of 30-50% are common for directional applications using A-lamps, whereas the fixture loss for the SSL lamp in these cases may be only 10-15%. Nevertheless, consumers may not read the fine-print, or may not retain the packaging, so making such nuanced equivalency statements may lead to customer dissatisfaction. Efforts may be needed to educate consumers regarding the directional differences in lamps and to identify more effective (and fair) ways for manufacturers to present equivalencies.

Nominal wattage of lamp to be replaced (watts)	Minimum initial light output of LED lamp (lumens)
25	200
35	325
40	450
60	800
75	1,100
100	1,600
125	2,000
150	2,600

Figure 12. A-lamp Equivalencies

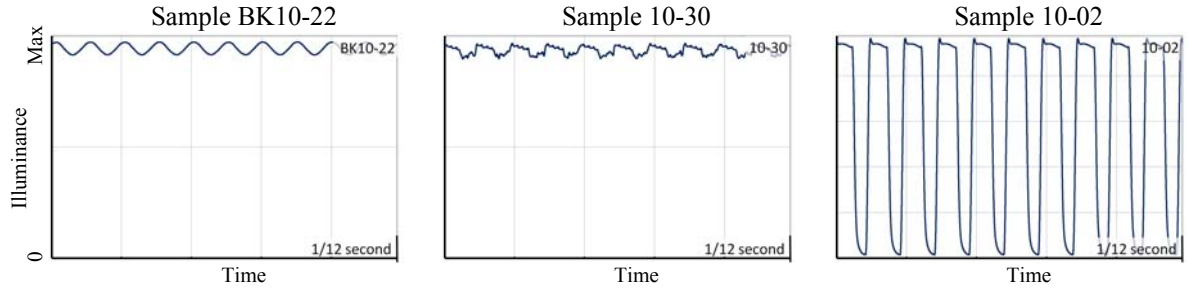
[14] See "ENERGY STAR® Program Requirements for Integral LED Lamps ENERGY STAR Eligibility Criteria," (March, 2010), http://www.energystar.gov/ia/partners/manuf_res/downloads/IntegralLampsFINAL.pdf.

Electrical Characteristics of Small SSL Replacement Lamps

Figure 13. Power Factor Achievements of SSL Replacement Lamps

In earlier rounds of CALiPER testing, the lowest power factors were most often observed in small replacement lamps. When manufacturers design small lamps, space and cost constraints, along with other design requirements, can force trade-offs which can be particularly apparent in small replacement lamps. Nevertheless, the performance of small SSL replacement lamps tested in Round 11 clearly demonstrates that the current power factor requirements defined for SSL products in the ENERGY STAR criteria (0.70 for residential products and 0.90 for commercial products) are achievable. Figure 13 provides a summary of the power factor for small SSL replacement lamps in Round 11. The majority of products achieve power factors over 0.9, three of the products achieve levels around or slightly above 0.7, and only one product (PAR30, 09-112) fails to achieve a power factor within levels required by ENERGY STAR criteria for SSL.

Designing flicker-free and dimmable lamps also raise challenges surrounding electrical characteristics of small SSL replacement lamps. CALiPER dimming testing has not yet been conducted on Round 11 lamps, however a few of the lamps have been subject to flicker testing, in the context of a broader ongoing CALiPER flicker study. For illustrative purposes, Figure 14 presents waveforms of the photometric output of the two SSL MR16 lamps and one of the halogen MR16 lamps included in Round 11. The waveform for SSL sample 10-30 has similar modulation to the halogen benchmark, whereas the waveform for SSL sample 10-02 shows significant amplitude modulation, with the light levels dropping to zero or close to zero with every cycle. The testing methodology used and an extensive dataset of flicker waveforms and corresponding metrics will be published in an upcoming CALiPER exploratory report.



Lighting Facts Labels of SSL Replacement Lamps

Out of 11 SSL replacement lamps, 6 replacement lamps tested in Round 11 carry the Lighting Facts label. Similar to a nutrition label, the Lighting Facts label provides a quick summary of product performance data. Luminaire manufacturers can voluntarily take the SSL Quality Advocates pledge and agree to use the label to disclose performance results in five areas — lumens, efficacy, watts, CCT, and CRI — as measured by the new industry standard for testing photometric performance, IES LM-79-2008.

As indicated in Tables 4, 5, and 6, among replacement lamps which carry the Lighting Facts label, all except two meet manufacturer performance claims.

One product not meeting its Lighting Facts claims fails on the basis of CCT: all initial samples received consistently have CCT around 4000K, rather than the 2700K indicated on the packaging and on the product code stamped on the lamps. These products do, however, meet their light output and efficacy claims, and subsequent samples received with the same product number but different date and batch code appear to perform at 2700K. In this case, the CCT discrepancy on some units probably signals a packaging/production line error, rather than a problem with product design or LED device quality, but is still a problem which could ultimately result in consumer dissatisfaction (leading buyers to think LED lighting is bluish white rather than warm white). The other product which fails to meet the Lighting Facts label only fails by a small percentage. Products carrying the Lighting Facts label which fail to meet performance claims are asked to take immediate corrective actions and demonstrate correct performance or they are removed from the Lighting Facts program.

New Federal Trade Commisssion (FTC) lamp labeling requirements for medium screw-based lamps will go into effect in less than one year.[15] Widespread use of these labels, which are similar in appearance to the Lighting Facts label, may lead to improved accuracy of manufacturer performance claims and better consumer comprehension of expected performance. However, as illustrated by the example of a lamp tested here that does not have the CCT indicated on its Lighting Facts label, verification and follow-through will be needed to ensure that lamps consistently meet the performance claims of their FTC or Lighting Facts labels.

4-Foot Linear Replacement Lamps and Troffers

Six SSL 4-foot linear replacement lamp products were tested in Round 11. CALiPER testing of linear replacement lamps includes bare lamp testing on 2 or more separate lamps and then mounting 2 lamps and testing their performance in a typical, parabolic louvered troffer—all tests conducted following LM-79. Unfortunately, out of the six pairs of SSL linear products, a number of samples failed during or after the initial bare lamp testing, or performed so differently from the other similar sample that representative testing in the troffer could not be conducted. For products 10-18 and 09-107, one out of two lamps failed or underperformed significantly so troffer testing was not conducted. For product 10-19, one sample underperformed, but a third sample performed adequately, so troffer testing was conducted on the two better performing samples.

Two new benchmark tests are also included in Round 11, both on high-efficiency lensed 2-foot x 4-foot troffers using high-performance T8 lamps. Benchmark 10-34 is a high-performance, single lamp lensed troffer.[16] Benchmark 09-67 is a two lamp high-performance architectural troffer which was tested in Round 9 and retested in Round 11 at the manufacturer's request using a different ballast.[17]

Table 1b summarizes some key performance metrics for the linear replacement lamps and troffer tests and Figure 15 below plots the light output and efficacy of each Round 11 troffer test, with dashed lines at the levels of the two benchmark fixtures. It should be noted that efficacy and light output are important metrics in selection of a troffer, but so are distribution and other characteristics related to user acceptability. The two fluorescent T8 benchmark high-performance lensed troffers provide overall

[15] See FTC, "Coming in 2011: New Labels for Light Bulb Packaging:" http://www.ftc.gov/opa/2010/06/lightbulbs.shtm.

[16] Based on terms observed in manufacturer literature and without a more generic industry denomination, troffers BK 09-67 and BK 10-34 are referred to as "architectural" and/or "high performance" to differentiate them from prismatic lensed or parabolic-louvered troffers herein.

[17] CALiPER test results are shared with manufacturers, who may request retesting. CALiPER retests at manufacturers' request are subject to the same requirements as initial CALiPER testing (anonymous purchase and use of qualified, independent testing laboratories).

luminaire efficacy ranging from 71-74 lm/W. Three out of four of the troffer tests using SSL replacement lamps in Round 11 achieve 74-78 lm/W. Furthermore, two SSL products provide more overall light output with two lamps installed in a parabolic troffer than the benchmark, single lamp high-performance lensed fluorescent troffer, and provide ~80% of the total initial light output of the two-lamp architectural fluorescent troffer.

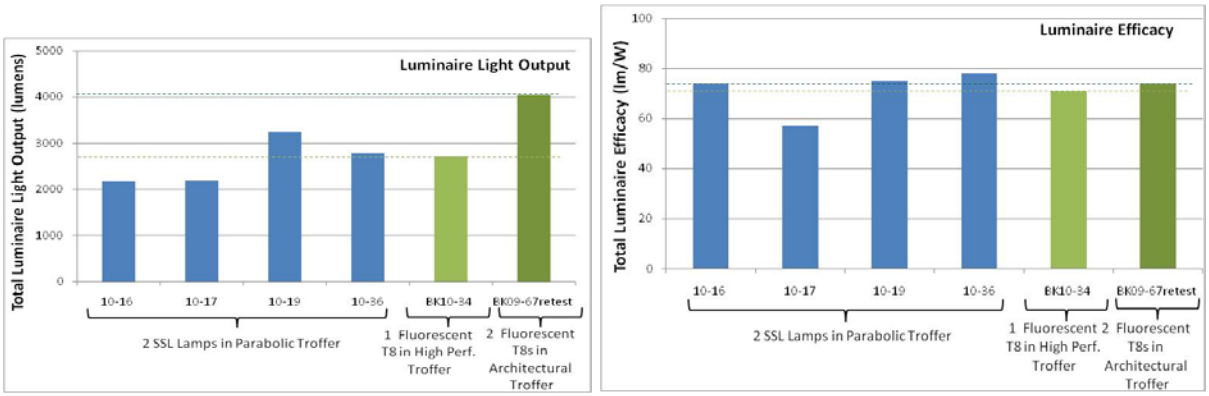


Figure 15. Overall Light Output and Efficacy of Troffers Equipped with SSL or Fluorescent Lamps

Figure 16 below provides a visual summary of the light output and power use of each troffer test, including data from earlier CALiPER testing on 2-foot x 4-foot SSL and benchmark troffers.

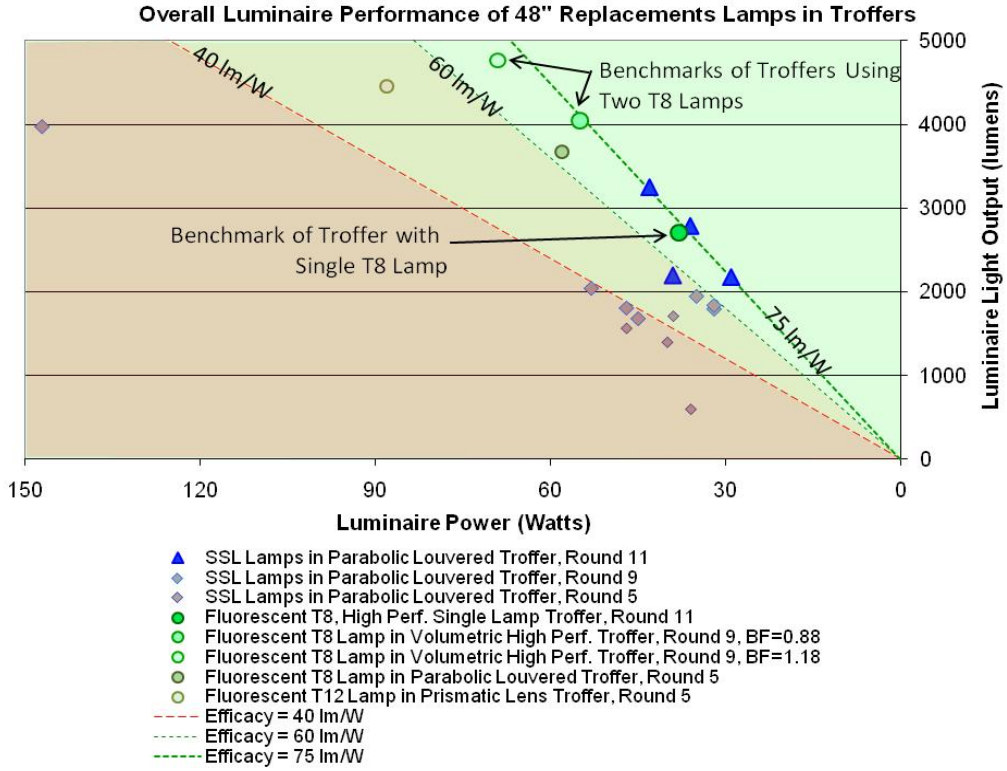


Figure 16. Comparison of Troffer Power and Light Output

The fluorescent, CALiPER-tested T8 benchmark troffers provide overall luminaire efficacy ranging from 63-74 lm/W. The continual progress of the SSL linear replacement lamps is clear, with all three Round 11 tests of troffers equipped with SSL lamps exceeding previous SSL results in both light output and efficacy. (Note that one earlier test of an SSL equipped troffer shows higher light output, but required

using three SSL lamps and drew significantly more power.) SSL product 10-19, which falls between the two benchmark troffers in light output, could be a comparable alternative to the benchmarks, although it should be noted that it has a significantly higher color temperature (5091K) and lower CRI (69) than the fluorescent benchmarks.

As indicated above, many factors such as cost, reliability, and light distribution should also be considered in comparing the SSL linear lamps to fluorescent alternatives. To provide comparable light output to the single-lamp fluorescent troffer, two SSL lamps would be required, impacting cost. One out of three units of product 10-19 underperformed significantly, as did one of two units for products 10-18 and 09-107, raising questions of risk and reliability. Units C & D of 09-107 were acquired and tested following Round 10 testing on samples A & B of the same product which appeared to underperform. Because the manufacturer had indicated that the underperformance of samples A & B was probably due to damages suffered during shipping, units C & D were acquired after receiving indication from the manufacturer that the shipping problems had been addressed. Unfortunately, once again, a unit suffered damage to pins during transit, and subsequently underperformed during testing. The purchaser e-mailed the manufacturer to notify them of the problems with the product, but received no response to the e-mail. Replacement samples were again ordered in hopes of being able to have two undamaged samples to test in a troffer, but samples were once again not received after 2-½ months due to the product being temporarily out-of-stock.[18]

On average, for all CALiPER testing of SSL linear lamps which bypass the fluorescent ballast, the fixture efficiency for the lamps installed in recessed troffers is 84% (with typically not more than 1-2% variation). For parabolic louvered troffers equipped with fluorescent T8 lamps, the fixture efficiency is on average 67% (subject to much wider variation than for SSL). Some SSL lamps are designed to use the fluorescent ballast, resulting in unpredictable performance, so fixture losses cannot be predicted for SSL lamps which rely on the fluorescent ballast.

With respect to fixture losses, all SSL linear replacement lamps tested to date emit light hemispherically, rather than over the entire 360° of the fluorescent tube surface, so light distribution using SSL linear replacement lamps cannot use the troffer reflector design and optics in the same way as fluorescent lamps. This results in less light loss in the fixture when using SSL linear lamps, but also requires more attention on the part of the SSL linear lamp design to ensure appropriate and sufficient light distribution.

Figure 17 summarizes the zonal distribution of light in the 6 troffer systems tested in Round 11 plus sample BK08-28 (the parabolic-louvered troffer equipped with T8 fluorescent lamps), comparing percentage lumen output in the 0-30°, 0-40°, and 0-60° zones. The four SSL troffer systems (with the parabolic louvered troffer equipped with two SSL lamps) all have quite similar zonal distribution of light, in fact, they all emit 41% of light output between 40° and 60°. In general, the zonal distributions do not appear to differ significantly from the fluorescent benchmarks. A closer look at the distributions in the polar intensity plots shown in Figure 18, however, reveals considerable differentiation.

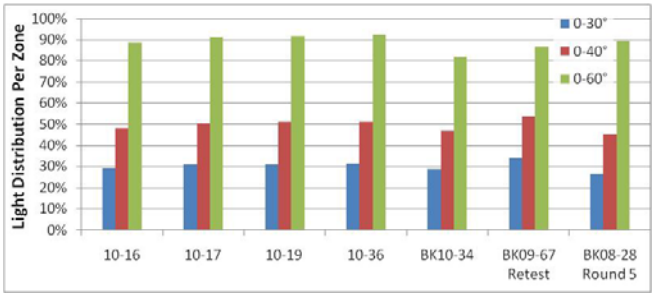
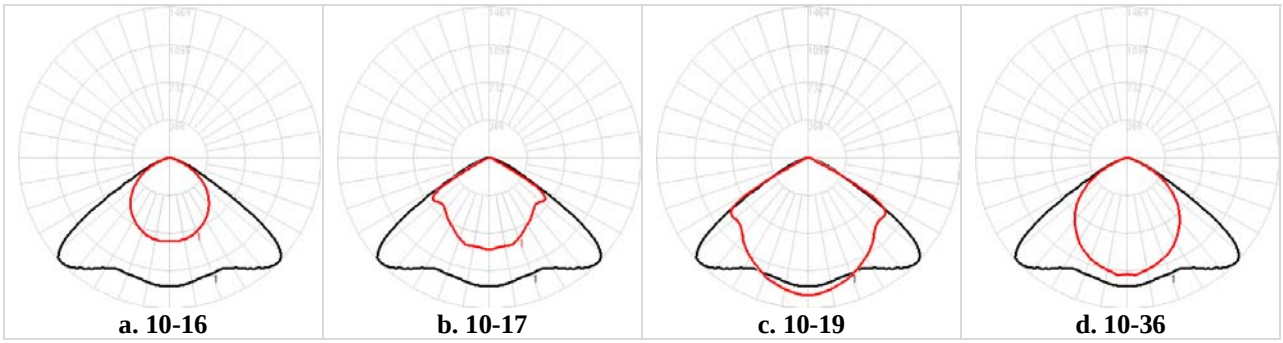


Figure 17. Percentage Light Output by Zone

[18] The manufacturer indicates that the units damaged in shipment would be replaced without this delay if the product warranty was invoked to request replacement. No response was received to the purchaser's e-mail regarding problems with the product, and because of the necessity of remaining an anonymous purchaser, invoking the warranty more insistently could increase the risk of revealing that the samples are being used for CALiPER testing.



a. 10-16 **b. 10-17** **c. 10-19** **d. 10-36**

Figure 18a-d. Comparison of Distribution of SSLs versus Fluorescent T8 in Parabolic-Louvered Troffer

Parabolic troffers are known for a tailored light distribution. Figure 18 shows the different distributions of the SSL lamps and T8 fluorescent lamps in the same parabolic troffer (black is the fluorescent baseline, BK08-28, and red is the SSL lamp). Figures 18b and 18c illustrate SSL lamps that had broader distributions than those in Figures 18a and 18d. The "jutting out" and then the "ledge" in the figures is light leaving the SSL lamp between the louvers. All four SSL distributions lack the pronounced triangular shape, corresponding to a wider, more even distribution, of the fluorescent-equipped troffer.

Typical spacing of troffers is on 8' x 8' or 8' x 10' centers. The acoustical ceiling tile system is either in 2' x 4' or 2' x 2' increments and that drives part of the layout. Another element that drives the layout is the spacing criterion (SC) of the troffer systems.[19] Figure 19 summarizes the spacing criteria for CALiPER-tested troffers for the 0–180°, 90–270°, and diagonal axes, including tests conducted from 2007-2009.

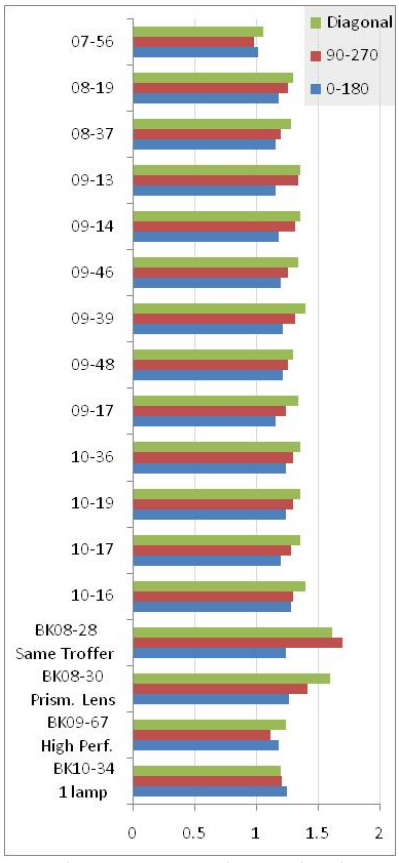


Figure 19. Spacing Criteria

Notice for all of the LED tubes tested in a parabolic troffer (except the very first one tested in 2007) that the SC is similar for the 0–180°, 90–270°, and diagonal axes. The parabolic troffer with fluorescent lamps (BK08-28) has greater SC values than any of the LEDs installed in the parabolic troffer, as does the prismatic lens troffer (BK08-30, equipped with T12 lamps). Tests BK09-67 and BK10-34 are fluorescent "high performance" troffers and have lower SC values than the fluorescent parabolic troffer. Based on the reduced SC of the parabolic troffer when equipped with LED tubes as compared to fluorescent tubes, the SC of the high-performance lensed troffer systems would be similarly reduced when equipped with the LED tubes.

Glare is also a characteristic that should be considered when considering the use of SSL linear replacement lamps in troffers. One possible quantitative measure relevant to evaluating glare in office

[19] The IES defines luminaire Spacing Criterion (SC) as a classification parameter for indoor luminaires relating to the distribution of the direct illuminance component produced on the work plane. The SC of a luminaire is an estimated maximum ratio of spacing to mounting height above the work plane for a regular array of luminaires such that the work plane illuminance will be acceptably uniform.

lighting is the maximum luminaire luminous intensity (candelas) for both video display terminal (VDT) and VDT-intensive office environments as defined by IES RP-1.[20] Based on the recommendations in RP-1, maximum candela values at vertical angles from 55-85° are specified for computer monitor (VDT) and intensive computer monitor work. For computer monitor intensive environments, all of the SSL troffer systems tested in Round 11 exceeded the maximum intensity criteria at the 55° and 65° vertical angles, as did the similar benchmark fluorescent system (BK08-28 in the parabolic troffer), while meeting the criteria at the 75° and 85° vertical angles. For the less stringent (not intensive) computer monitor environments, the benchmark parabolic troffer and the SSL product with the highest light output, 10-19, exceeded the maximum intensity criteria at the 65° vertical angle in at least one intensity measurement. Out of these five tests of a parabolic troffer, the two with the highest light output do not pass the VDT criteria, even though a close look shows significant difference in intensity distribution—indicating that additional metrics might be necessary to evaluate glare.

Color Quality of Linear Replacement Lamps

Table 7 summarizes the chromaticity performance of the six SSL linear replacement lamps, two SSL high-bay luminaires, and two linear fluorescent lamps used in the two benchmark fluorescent troffers. For SSL products, the chromaticity standards are summarized by target CCT levels, along with corresponding permitted ranges of variation in CCT and D_{uv}. For fluorescent lamps, the chromaticity standards define objective chromaticities for each nominal CCT level, and allow chromaticity tolerance defined by a 4-step MacAdam ellipse.[21]

Table 7. Summary of Chromaticity Performance of Linear Replacement Lamps and High-Bays

CALiPER Sample	Manufacturer Claimed CCT	Target CCT Range (K)	Target D_{uv}	CALiPER Measured CCT (K)	CALiPER Measured D_{uv}	Both CCT and D_{uv} Within Tolerance?
09-107	3500K (nominal CCT)	3255-3745	-0.006 to 0.006	3548	-0.002	**YES**
10-16	5000K (nominal CCT)	4717-5283	-0.004 to 0.008	5394	-0.004	**NO**
10-17	3400K (flexible CCT)	3178-3622	-0.006 to 0.006	3249	0.007	**NO**
10-18	6000K (flexible CCT)	5446-6554	-0.003 to 0.0087	5602	0.009	**NO**
10-19	4000-4500K (two nominal CCTs)	3725-4745	-0.005 to 0.007	5091	0.008	**NO**
10-36	4100K (flexible CCT)	3803-4397	-0.005 to 0.007	4300	0.012	**NO**
09-79	3000-3500K (two nominal CCTs)	2825-3745	-0.006 to 0.006	2802	0.007	**NO**
10-25	5000K (nominal CCT)	4717-5283	-0.004 to 0.0079	5593	0.008	**NO**
BK09-67	3500K (fluorescent nominal CCT)	Fluorescent 3500K, x=0.411, y=0.393 4-step MacAdam Ellipse		CCT= 3248, x=0.4227, y=0.4033		**NO**
BK10-34	3500K (fluorescent nominal CCT)			CCT= 3387, x=0.4163, y=0.4056		**YES/NO***

Target CCT and Duv ranges as defined for LED products in ANSI_NEMA_ANSLG C78.377-2008 and for fluorescents as defined in ANSI C78.376-2001.

*Sample BK10-34 would meet target CCT and D_{uv} ranges for SSL products (based on a 7-step MacAdam Ellipse), but does not fall within the tighter, 4-step MacAdam Ellipse, range required for fluorescent products.

[20] The IES "Recommended Practice for Office Lighting" (RP-1) published in 2004 set the maximum luminaire luminous intensity (candelas) for both video display terminal (VDT) and VDT-intensive office environments: http://www.iesna.org/.

[21] NEMA ANSI ANSLG C78.377-2008, "Specifications for the Chromaticity of Solid State Lighting Products for Electric Lamps" and NEMA ANSI C78.376:2001, "Electric Lamps - Specification for the Chromaticity of Fluorescent Lamps: http://webstore.ansi.org/.

The ANSI chromaticity standards which define tolerances for white light for SSL lighting provide leeway as compared to the fluorescent tolerances: SSL products may opt for using flexible CCT levels and are permitted tolerances which correspond approximately to those of 7-step MacAdam ellipses, as compared to the tighter 4-step MacAdam ellipses defined for fluorescents. Furthermore, for two of the SSL products the manufacturer specifies a wide range of possible CCT values, spanning two nominal CCT levels—therefore potentially including very perceptible color differences between multiple units of the same product. Despite this additional leeway, only one of the SSL linear replacement lamps, 09-107, meets ANSI-defined tolerances for white light. All of the other samples fail on the basis of CCT or D_{uv} (or both CCT and D_{uv}) outside of tolerance for white light.

Both of the fluorescent benchmarks also fail to fall within fluorescent tolerances for white light, although product BK10-34 would meet the looser SSL chromaticity requirements. Large variations in chromaticity can result in perceptible and undesirable variation in color in installations with multiple luminaires and can increase color matching challenges over the life-cycle of a lighting installation, when lamps are replaced or other updates are made.

Manufacturer Claims for Light Output, Efficacy, and Equivalency

As summarized above, almost all of the linear replacement lamps tested in Round 11 fail to meet product ratings or manufacturer claims regarding color qualities. Manufacturers have more accurate claims regarding light output and efficacy, although they are still publishing potentially misleading statements regarding product equivalency. The manufacturer claims for light output, efficacy, and equivalency of the linear replacement lamps is summarized as follows:

- ✓ Four of the SSL linear replacement lamps carry Lighting Facts labels—three meet or exceed their Lighting Facts claims for light output and efficacy, one falls slightly short of meeting its Lighting Facts claimed efficacy (by ~9%).
- ✓ All six SSL linear replacement lamps meet or exceed the manufacturer claims for light output in lumens (disregarding samples which were deemed to be malfunctioning).
- ✓ Four out of six of the SSL linear replacement lamps meet or exceed efficacy levels as determined by manufacturer claims. Product 10-17 does not meet its expected efficacy level. Product 10-36 meets efficacy published on the product specification sheet, but not on its Lighting Facts label.
- − Manufacturer published photometric data for BK10-34 differs significantly from the CALiPER results, most likely due primarily to the difference in ballasts between the two tests (and inefficiencies for fluorescent tubes operating under higher ballast factors). The luminaire efficacy under manufacturer testing is stated as 86 lm/W, while it is only 74 lm/W in CALiPER testing. For CALiPER testing of this troffer, a ballast factor (BF) of 1.18 was used in order to represent a single-lamp fluorescent alternative to a troffer system using two SSL lamps (typically ~40W).
- × Product BK09-67 also achieves only 74 lm/W in CALiPER testing (based on absolute photometry) versus 85 lm/W (based on relative photometry) claimed by the manufacturer. In this case, a lower BF ballast was used at the manufacturer's request to replicate operating conditions during manufacturer testing, so the difference in performance should not be attributed to the ballast.
- × Four of the SSL products include misleading equivalency statements: "20W: Compare to 32W," "20W: Compare to 40W," "Saves 50% to 70% energy compared to standard fluorescent," and "F32T8 replacement (48in x 1in tube)...candle power at work surface is equivalent to a 32watt T8 fluorescent tube." In all of these cases the equivalency statement implies that the SSL lamp could directly replace a T8 fluorescent lamp, whereas CALiPER testing has shown that, as yet, none of

the SSL linear replacement lamps achieves as much light output (or average work surface candlepower) as a T8 lamp, whether tested as a bare lamp or in a troffer.

Format and Installation of SSL T8 Lamps

In order to be used as replacement or retrofit lamps in recessed troffers, SSL linear replacement lamps face the challenge of being designed to be mounted and powered safely and easily in troffers. This raises questions and challenges because most troffers are equipped with fluorescent ballasts powering the tombstones (linear lamp mounting brackets). A number of different approaches are used by SSL manufacturers today, ranging from powering the lamps with the fluorescent ballast, to powering the lamps with an onboard driver, to replacing the ballast with an external driver and rewiring the tombstones, to mounting and powering the lamps with separate, dedicated mounting brackets.

The majority of SSL linear lamps tested to date require removal of the troffer ballast, with input voltage passing from pins on one end of the lamp to the other end of the lamp. Some lamps carry sketches regarding wiring and installation (ballast removal and rewiring) on the lamp, some include installation instructions, some have little or no indication regarding troffer rewiring requirements. When the ballast is removed and replaced with a driver or with direct connection to 120VAC line voltage, the tombstones and associated wires are no longer operating as when wired for fluorescent lamps.

The challenges surrounding retrofitting fluorescent troffers for SSL raise questions surrounding cost, procedure, safety, commissioning, labeling, and future maintenance and lamp replacing. Related trade groups, and standards and safety organizations have provided some initial guidance and CALiPER has participated in joint discussions with NEMA, CSA, and UL working toward clear, coherent guidance for manufacturers and buyers regarding SSL linear lamps.

High-Bay Luminaires

In 2007, SSL manufacturers struggled to create desk lamps with adequate levels of light output. Now, manufacturers are designing products to compete in high output lighting applications like high-bay fixtures. High-bay lighting, like fluorescent troffers, represents a challenging application where the incumbent technology is already mature and high performance. Nevertheless, SSL products are now being designed and marketed for this application—with the potential advantages of greater controllability, longer lamp life, and vibration-resistant, inherently non-breakable light sources.

The first high-bay products tested by CALiPER are of similar design, one warm-white with a narrower beam, and one cool-white with a wide beam, with efficacies of 51 and 71 lm/W, respectively (both using ~110W). Based on benchmark photometric data for high-bay fixtures (published by manufacturers, not CALiPER tested), these efficacy levels would be competitive with high-bay fixtures using probe-start MH, HPS, and CFL light sources, but would not meet efficacy levels of some linear fluorescent or PSMH high-bay fixtures.

With regard to light output, comparisons are more difficult because the relatively narrow beams (21° and 38°) of the two SSL high-bay products are not common in traditional high bay fixtures. Comparing on the basis of intensity requires examining both the CBCP and the beam angle, so although these two products provide fairly high CBCP (20230 and 8376 cd, respectively), compared to some traditional products, they are only providing that intensity over a relatively narrow beam. The product literature for these SSL high-bays says that they replace 100-400W MH/HPS fixtures, and have effective lumen output of 400W. However, compared to manufacturer photometric data for a variety of high bay fixtures (using T5HO, T8, CFL, MH, PSMH, and HPS light sources ranging from 110-250W), these two SSL luminaires do not achieve the overall initial light output levels of any of the benchmark data sets that were examined.

Product 10-25 carries a Lighting Facts label and achieves the performance levels on the label. Product 09-79 is an older version of this product, sold through a different distributor and not carrying the Lighting Facts label. The specifications for this product indicate that the product is available in three CCT versions, but only indicates one lumen output level (7000 lm), which clearly was not achieved by the warm-white version that was tested.

Reliability: Lumen Depreciation Testing

Long-term operation and testing of subsets of CALiPER products was conducted and reported on in 2008 and 2009. Another series of 6000 hours of operation and periodic testing on 24 CALiPER samples was recently completed and analysis of the results is underway. Initial lumen depreciation curves from this recent testing are presented in Figure 19, with depreciation of luminaires shown on the left and depreciation of replacement lamps shown on the right.[22]

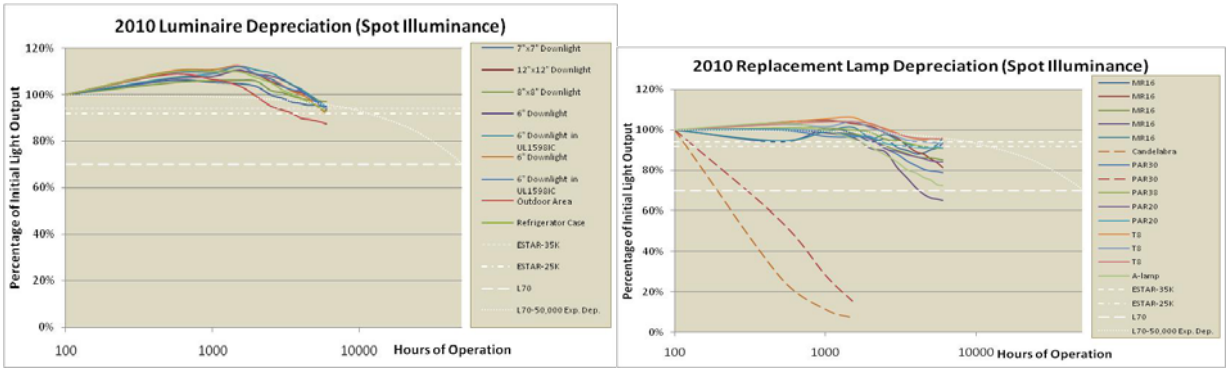


Figure 19. Lumen Depreciation Behaviors Observed During Long-Term Continuous Operation

Out of 24 products subjected to 6000 hours of operation, only a few maintain lumen levels that would indicate that the product is expected to maintain at least 70% of initial light output at 50,000 hours (70% initial light output shown by the wide, white dashed line). Based on the rule of thumb cut-off levels applied in ENERGY STAR criteria, after 6000 hours of operation, SSL products claiming 25,000 hour life should maintain at least 94.1% of initial output and products claiming 35,000 hour life should maintain 91.8% of initial output.

Based on these cut-off levels and spot illuminance measurements (integrating sphere measurements may differ from spot testing results), the 24 samples subjected to 6000 hours of testing in 2010 performed as follows:

- Above 94.1%: 4 luminaires 3 replacement lamps →Should last 35,000 hours
- Between 91.8-94.1%: 4 luminaires 2 replacement lamps →Should last 25,000 hours
- Below 91.8%: 1 luminaire 10 replacement lamps →Not expected to last 25,000 hours

Due to the range of behaviors observed in long-term operation and rapid rate of change of SSL technology, buyers and specifiers should be wary of all product life claims. Lumen depreciation is only one of many possible failure mechanisms in SSL luminaires and replacement lamps. Although some products are achieving very high levels of lumen maintenance after several thousand hours of operation, many products fail much more rapidly, through lumen depreciation, color shift, driver failure, or other modes of failure. Educational material is available for SSL buyers and manufacturers regarding LED lifetime and reliability.[23]

[22] See DOE, Long-Term Testing of Solid-State Lighting, 2010, PNNL, January 2010: available upon request.
[23] See DOE/NGLIA Solid-State Lighting Product Quality Initiative, "LED Luminaire Lifetime: Recommendations for Testing and Reporting," May 2010: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide.pdf, and DOE Fact Sheets: http://www1.eere.energy.gov/buildings/ssl/factsheets.html.

Conclusions from Round 11 of Product Testing

Key Conclusions

Round 11 of CALiPER testing focuses primarily on outdoor roadway and post-top applications and replacement lamps. Average overall efficacy of products tested in this round shows steadily increasing performance. While many products continue to carry misleading equivalency claims and inaccurate manufacturer published performance metrics, a number of products now carry accurate performance claims—in particular those that carry the Lighting Facts label.

For both outdoor roadway and post-top luminaires, a wide range of performance was measured in SSL products—showing, on average, significant improvement over earlier CALiPER testing:

- Half of the SSL outdoor luminaires achieve overall light output and efficacy levels that match or exceed levels of benchmark outdoor luminaires.
- Most of the SSL outdoor luminaires exhibit wide variations in color characteristics (CCT and/or D_{uv}) as compared to their rated CCT.
- Outdoor roadway and post-top luminaires exhibit a wide range of distribution characteristics, requiring photometry and close analysis to determine adequacy for a given application. In a sample calculation for a 24ft wide street, as compared to a benchmark HPS installation, one SSL product was found to provide adequate uniformity and potential energy savings for equivalent initial illuminance levels. Other installation scenarios could provide quite different results.
- Caution should be exercised when considering claimed equivalencies in outdoor products—the comparative suitability of products will depend on the product performance, but also on the installation parameters (mounting height, pole spacing, illuminance requirements…). Selection of SSL roadway luminaires or other types of roadway luminaires should be conducted on a case-by-case basis using thorough photometric analysis.
- Five out of six of the SSL arm-mount roadway luminaires meet or come close to meeting manufacturer ratings for expected light output and efficacy (within approximately 10% of manufacturer published efficacy). The only product which highly overstates performance is the replacement lamp, 09-62, which claims 2 ½ times the light output and efficacy that it actually achieves.

Round 11 testing of linear replacement lamps shows clear progress, with recent SSL lamps achieving respectable efficacy, though not the light levels and distribution of fluorescent lamps. Using two SSL lamps to replace a single-lamp troffer, where lower light levels are needed or where other characteristics of SSL provide an advantage, may now be viable in some cases. The SSL lamps, however, will not likely be the most cost effective or reliable option at this time. In summary:

- All SSL linear replacement lamps tested in Round 11 show better performance than in previous testing, but when operated in situ they still do not provide equivalent levels of light output to 2-lamp fluorescent troffers whether considering bare lamps or overall troffer systems.
- The four cooler (CCT of 4300-6000K) SSL linear lamps achieve bare-lamp efficacy levels of 85-95 lm/W. With an average loss of 17% when installed in a louvered troffer, these lamps can result in overall luminaire efficacy comparable to troffers equipped with linear fluorescent lamps.
- The majority of claims of light output and efficacy for SSL linear lamps were accurate, particularly for products carrying the Lighting Facts label. Equivalency statements, however, were misleading, implying or claiming comparable light output to T8 fluorescent lamps.
- None of the four SSL products that were tested in a parabolic louvered troffer achieved the spacing criteria and even light distribution achieved by fluorescent T8 lamps in the same troffer.

- The majority of linear lamps tested in Round 11 have color qualities which are not within standard tolerances for white light at their respective nominal (manufacturer-rated) CCTs.
- Reliability and life cycle should factor in purchasing decisions surrounding SSL linear lamps. Fluorescent products have a known history and relatively long lifetime. SSL products promise somewhat longer lamp lifetime, but there is little to no track record for SSL lamps and the lifetime of the integral product is yet to be proven. The repeated shipping and handling mishaps and perpetual "out of stock" status of some products may shed doubt on the general reliability and long-term availability of product lines, as well as on the longer-term integrity of product warrantees. Buyers of SSL linear lamps should also be aware of installation challenges and evolving design approaches.
- Trade groups and standards organizations are working to provide coherent guidance—regarding safe retrofit designs and practices, installation, instruction, and labeling—for SSL linear lamps which require removal of the fluorescent ballast and rewiring of troffers.

Round 11 testing of small replacement lamps, including MR16 lamps, PAR lamps, AR111, and omni-directional lamps, shows progress for each lamp type. Challenges remain with respect to lamp equivalencies, with a number of products not meeting standard lamp geometries for the type of lamp they claim to replace and with a number of products not meeting average light output levels or beam characteristics of the lamps with which they claim to be equivalent. In summary:

- Slight irregularities in lamp geometry (overall length, diameter, neck length, etc.) were observed for about one-half the replacement lamps. Significant differences in lamp geometry were observed for two lamps.
- Two-thirds of the lamps meet manufacturer numerical performance claims, but out of those that carry equivalency claims, only one-third meet manufacturer claims.
- Products which carry the Lighting Facts label have a much greater chance of meeting numerical performance claims, but still frequently carry misleading equivalency claims.
- Significant improvement in light output and efficacy is observed on average.
- The majority of the small replacement lamps have CCT, CRI, and D_{uv} characteristics which would meet ENERGY STAR criteria for integral SSL replacement lamps. Three of the lamps have either CRI or D_{uv} that would not qualify. One of the lamps has CCT which does not match the lamp packaging claims or model number stamped on the lamps.
- For MR16 lamps, CALiPER testing to date shows two products achieve performance levels equivalent to 20W halogen MR16s, while using about 70% less power. As yet, no SSL MR16 lamps that have been CALiPER tested meet light output and beam characteristics of 35W halogen MR16s.
- For PAR lamps, a number of SSL products now meet light output and beam characteristics of 50-75W halogen PAR lamps, while using 70-80% less power. None of the SSL PAR lamps achieve the light output or efficacy of a 25W ceramic metal halide PAR 38. (Note that SSL lamps have some qualities not shared by CMH, such as instant start.)
- For A-lamps, a number of SSL lamps now achieve light output levels equivalent to 40W incandescent lamps (although with a more directional light distribution), while using ~80% less power. As yet, no SSL A-lamps that have been CALiPER tested meet light output levels equivalent to an average 60W incandescent lamp.
- In a few cases, the replacement lamps exhibit some form of failure. Given the lack of experience regarding long-term performance of SSL integral lamps, the immaturity and rapid evolution of the production process carries some risk with regard to product reliability.

With rapid evolution of SSL products resulting in new, improved, and increasingly diverse versions of products becoming available on a regular basis, it can be difficult to determine the performance of any

particular product. Even with manufacturer data in hand, there is often uncertainty as to whether that data corresponds to a particular version of a product. Nevertheless, manufacturer numerical claims regarding product performance metrics are becoming more accurate, in particular when the manufacturer provides an LM-79 test report or publishes the data on a Lighting Facts label (based on LM-79 testing). Carrying a Lighting Facts label is not a guarantee that a product will perform as labeled, but it does appear to improve the chances that a product will meet or exceed claims or come close to meeting those claims. Products with no published performance data were among the lowest performing products tested in Round 11. Unfortunately, less accuracy is seen in equivalency claims—when present, these claims were only accurate for a few products.

Next Steps for the Industry and CALiPER Efforts

Upcoming rounds of CALiPER testing will continue to revisit key lighting applications, such as downlights, and explore SSL products which are targeting new application areas, such as asymmetric cove lighting. Selection of products for CALiPER testing continues to include attempts to find products which are innovative or pushing the performance envelope for solid-state lighting, as well as products which appear to be poorly applying SSL technology or misinforming buyers about the product's performance. Also, with an ever increasing number of SSL products joining the Lighting Facts program, verification of products listed on the Lighting Facts website will continue.

Other ongoing CALiPER testing includes long-term testing, flicker testing, and research on glare metrics. New reports on these topics are in progress. In all of these testing arenas, CALiPER works with a variety of industry stakeholders, staying in close contact with testing laboratories, standards organizations, and lighting designers. The CALiPER Guidance Committee provides a constructive channel for receiving feedback and testing ideas from key stakeholders, such as energy-efficiency programs, utilities, engineers, and lighting designers. Evolving needs for SSL testing were clearly identified during previous CALiPER Standards and Testing Roundtable meetings.[24]

CALiPER detailed reports for products discussed in each CALiPER summary report are made available online shortly after the summary reports are available. The detailed reports can be downloaded and searched with an online tool that enables finding specific reports, listing results, and comparing products based on a number of performance parameters. If a type of lighting product of interest was not included in this report, it is likely to have been covered in previous summary reports which are also available online. These summary reports provide test results for specific products and insight into how to compare that performance to more traditional lighting products.

[24] Proceedings from CALiPER Roundtable meetings are available online, http://www1.eere.energy.gov/buildings/ssl/about_caliper.html.

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