CALiPER

Summary Report

October 2009

DOE Solid-State Lighting CALiPER Program

Summary of Results: Round 9 of Product Testing

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

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Summary of Results: Round 9 of Product Testing

Round 9 of testing for the Department of Energy (DOE) Commercially Available LED Product Evaluation and Reporting (CALiPER) Program was conducted from June 2009 to September 2009.[1] In this round, 30 products, representing a range of product types and technologies, were tested with both spectroradiometry and goniophotometry using absolute photometry. All solid-state lighting (SSL) products were tested following the IESNA LM-79-08 testing method.[2] Testing also included measurements of surface temperatures (taken at the hottest accessible spots on the luminaire).

Round 9 of testing includes four primary focus areas:

- Recessed downlights
- 2'x 2' troffers (and 2'x2' flat panel luminaires)
- 4' linear replacements lamps (tested as bare lamps and in 2'x 4' troffers)
- Small replacement lamps (including 1000-hour continuous operation test)

An SSL desk lamp was also tested. Five fluorescent luminaires were tested using absolute photometry for benchmarking (labeled as BK) purposes. This report summarizes the performance results for each product and discusses the results with respect to similar products that use traditional light sources, results from earlier rounds of CALiPER testing, and manufacturer ratings.

In addition to basic photometric testing per IESNA LM-79-08, CALiPER periodically performs additional testing—examining, for example, dimmability, reliability, thermal management, 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. For example, linear replacement lamps are tested using absolute photometry, both as bare lamps and *in situ*: installed in typical troffers to determine fixture losses and measured distribution. Also, a limited number of products are selected from each round of CALiPER testing to be subjected to long-term testing. Preliminary results from recent long-term tests are also included in this report.

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[1] Summary reports for Rounds 1-8 of DOE SSL testing are available online at http://www.ssl.energy.gov/caliper.html. Please see earlier CALiPER Summary Reports and the CALiPER FAQ for further details regarding the CALiPER product selection process and regarding CALiPER testing methods. 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.

[2] The published IESNA 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/

Round 9 CALiPER Testing Results

Tables 1a, 1b, 1c, 1d, and 1e 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 9. A thumbnail photo of each product is included. These tables assemble key results as follows:

- Table 1a: five SSL recessed downlights and two CFL downlights
- Table 1b: one SSL desk lamp
- Table 1c: three SSL 2’x2’ panel fixtures and two fluorescent 2’x2’ troffers
- Table 1d: seven SSL and one fluorescent 4’ linear replacement lamps, tested as bare lamps and in 2’x4’ troffers
- Table 1e: nine SSL replacement lamps including MR16, PAR and R lamps, A-lamps, and candelabras

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

Table 1a. CALiPER ROUND 9 SUMMARY – Recessed Downlights

-- SSL testing following IESNA LM-79-08 -- 25ºC ambient temperature	DOE CALiPER TEST ID	Total Power (Watts)	Output (Initial Lumens)	Efficacy (lm/W)	CCT (K)	CRI	Photo
SSL Luminaires							
Downlight (4" recessed)	09-44*	10	490	47	2727	93	
Downlight (6" recessed)	09-61	8	*269*	*32*	2779	83	
Downlight (6" recessed)	09-69*	39	1110	*28*	3385	91	
Downlight (6" recessed)	09-70	30	683	*22*	3334	86	
Downlight (6" recessed)	09-75	23	843	37	3456	83	
CFL Benchmark (BK) Luminaires							
Downlight (6" recessed) CFL	BK 09-45	28	872	31	3166	83	
Downlight (6" recessed) CFL	BK 09-66	33	952	29	3392	82	

Values are rounded to the nearest integer for readability in this table.
Performance levels that do not meet the minimum ENERGY STAR criteria for downlights are shown in *red italics*.[3]
*For products 09-44 and 09-69, three samples of each were tested. Values present averages of three samples.

[3] *ENERGY STAR® Program Requirements for Solid-State Lighting Luminaires Eligibility Criteria Version 1.1*. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/energystar_sslcriteria.pdf

Table 1b. CALiPER ROUND 9 SUMMARY – Desk Lamps

-- SSL testing following IESNA LM-79-08 -- 25ºC ambient temperature	DOE CALiPER TEST ID	Total Power (Watts)	Output (Initial Lumens)	Efficacy (lm/W)	CCT (K)	CRI	Photo
SSL Luminaires							
Task-Desk	09-42	8	213	28 [19]	2940	93	 *Off-state Power Use= 0.52 W*
Values are rounded to the nearest integer for readability in this table. Efficacy values shown in brackets [ ] indicate the overall efficacy that the product would have if operated 3 hours per day and turned off 21 hours per day (due to power consumption in the off-state).							

Table 1c. CALiPER ROUND 9 SUMMARY – 2' x 2' Troffers

-- SSL testing following IESNA LM-79-08 -- 25ºC ambient temperature	DOE CALiPER TEST ID	Total Power (Watts)	Output (Initial Lumens)	Efficacy (lm/W)	CCT (K)	CRI	Photo
SSL Luminaires							
Troffer (2'x2'x6"panel)	09-41	41	3250	79	3339	89	
Troffer (2'x2' thin panel)	09-71	65	3190	49	*3544**	75	
Troffer (2'x2' thin panel)	09-81	64	2610	41	3521	93	
Fluorescent Benchmark (BK) Luminaires							
Troffer (2'x2') fluorescent	BK 09-72	57	2541	44	3349	81	
Troffer (2'x2') fluorescent	BK 09-73	35	1706	49	3318	86	
Values are rounded to the nearest integer for readability in this table. *For product 09-71, Duv = 0.009, which is outside of ANSI defined tolerances for white light.[4]							

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

Table 1d. CALiPER ROUND 9 SUMMARY – 4’ Linear Replacement Lamps

-- SSL testing following IESNA LM-79-08 -- 25ºC ambient temperature	DOE CALiPER TEST ID	Total Power (Watts)	Output (Initial Lumens)	Efficacy (lm/W)	CCT (K)	CRI	Photo
SSL Replacement Lamp (4’ linear)—Bare Lamp and Testing in Parabolic Louvered Troffer							
Bare Lamp	08-121	49	1579	32	3667	75	
In situ (3 lamps in troffer)		147	3975	27			
Bare Lamp	09-13AB	32	1407	44	3758	76	
In situ (2 lamps in troffer)		47	1802	39			
Bare Lamp	09-13CD	32	1357	42	3756	76	
In situ (2 lamps in troffer)		45	1674	37			
Bare Lamp	09-17	16	1062	66	4657	*72*	
In situ (2 lamps in troffer)		32	1789	56			
Bare Lamp	09-39	16	1108	69	3182	*66*	
In situ (2 lamps in troffer)		32	1834	57			
Bare Lamp	09-40	16	1218	76	3221	*66*	
(not tested *in situ)*		--	--	--			
Bare Lamp	09-46	27	1198	45	3394	*64*	
In situ (2 lamps in troffer)		53	2038	39			
Bare Lamp	09-48	18	1136	64	*2993**	*63*	
In situ (2 lamps in troffer)		35	1942	55			
Fluorescent Benchmark (BK)—Bare Lamp and Testing in High Performance Troffer							
Bare Lamp (fluorescent)	BK 09-67	32	3246	101	3248	83	
In situ (2 lamps in troffer, Ballast Factor=1.18)		69	4767	69			

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

For *In Situ* tests, all SSL Products except 09-13 required rewiring of troffer to bypass ballast. Product 09-13 uses troffer ballast (ONE SYLVANIA QTP2X32T8/UNV ISN-SC). Reference ballast is used for bare lamp testing.

For product 09-13, initial efforts to purchase samples anonymously were unsuccessful, so product was purchased with manufacturer knowledge that samples were destined for CALiPER testing (samples 09-13AB). Subsequently, anonymously purchased samples (09-13CD) were received, so both pairs were tested.

Products 09-39 and 09-40 represent a frosted and non-frosted version of the same product. Only the frosted version was subjected to *in situ* testing because one 09-40 lamp failed before *in situ* testing could be conducted.

CRI values below 75 are in *red italics*.

*For product 09-48, Duv = 0.014, which is outside of ANSI defined tolerances for white light.

Table 1e. CALiPER ROUND 9 SUMMARY – Replacement Lamps

-- SSL testing following IESNA LM-79-08 -- 25ºC ambient temperature	DOE CALiPER TEST ID	Total Power (Watts)	Output (Initial Lumens)	Efficacy (lm/W)	CCT (K)	CRI	Photo
SSL							
Directional Replacement Lamps—MR16*							
Replacement Lamp (MR16)	09-80	3	*165*	50	3014	76	
Directional Replacement Lamps—PAR and R Lamps							
Replacement Lamp (R20)	09-78	6	263	42	4159	*68*	
Replacement Lamp (R30)	09-64	3	*186*	54	*5554*	*71*	
Replacement Lamp (PAR30)	09-76	8	*468*	59	2904	76	
Replacement Lamp (PAR38)	09-63	5	*289*	58	*6177*	*72*	
Omni-directional Lamps—A-lamps and Candelabras							
Replacement Lamp (A-lamp)	09-60	7	*251*	*34*	2643	*67*	
Replacement Lamp (A-lamp)	09-77	6	208	*33*	2960	85	
Replacement Lamp (Candelabra)	09-65	1	*67*	45	2893	*59*	
Replacement Lamp (Candelabra)	09-74	2	*31*	*17*	2870	83	

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

Performance levels that do not meet the minimum draft ENERGY STAR criteria for integral SSL replacement lamps are shown in *red italics*. For MR16, PAR and R lamps, lumen output is shown in *red italics* if CBCP does not meet criteria based on measured lamp beam angle and based on target replacement lamp wattage as claimed by the manufacturer. For replacement lamps, lumen output requirement is based on target replacement wattage as claimed by the manufacturer. [5]

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

[5] *ENERGY STAR® Program Requirements for Integral LED Lamps, Draft 3*. http://www.energystar.gov/index.cfm?c=new_specs.integral_leds, September 18, 2009.

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

Energy Use and Light Output

The SSL products tested in Round 9 exhibit a wide range of efficacy: from 17 to 79 lm/W. The overall average efficacy for products tested in Round 9 is 46 lm/W, where it was 36 lm/W in Round 8. Compiling the CALiPER results on a year-by-year basis, Figure 1 illustrates the clear, steady increase in performance of market-available SSL products since CALiPER testing began in December 2006. Essentially, the average efficacy of all SSL products tested has doubled between 2007 and 2009 (with 2009 results only covering the first three quarters of the year).

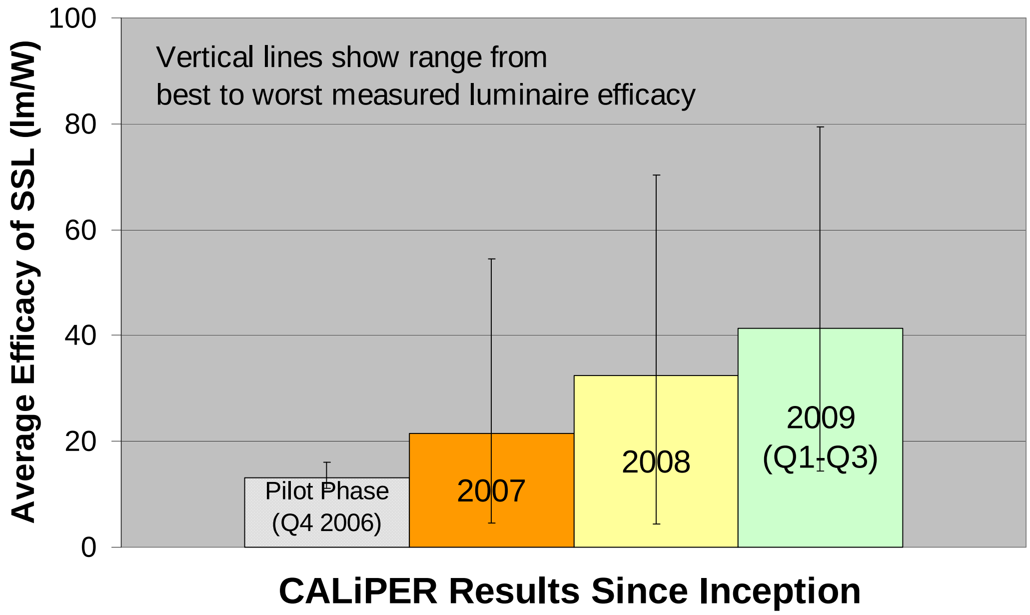

Figure 1. Average Measured Luminaire Efficacy of Market-Available SSL Products Increases Steadily

In addition to the doubling of efficacy in SSL luminaires and replacement lamps, other performance characteristics have also demonstrated notable improvements. More SSL products are observed to have adequate or good color quality, with CCT values and Duv values within ANSI defined norms for white light. For applications such as recessed downlights and 2’x2’ troffers, many SSL products are now clearly competitive with incumbent technologies with respect to light output levels, light distribution, and efficacy. For small replacement lamps, some products are now capable of meeting or exceeding performance characteristics of incumbent technologies, particularly for lower wattage replacements. For 4’ linear replacement lamps, SSL technology is still not competitive with T8 fluorescent lamps. The sections below address each product category tested in this round, considering efficacy, light output, power characteristics, color quality, product labeling and reporting, and comparative performance to incumbent lighting technologies.

Recessed Downlights

Five recessed downlight products using SSL sources and two using CFL sources were tested. One of the SSL products was a 4" diameter downlight, while the four others and the CFL downlights were 6" diameter products. The SSL products represent a range of power ratings, drawing from 8 to 39W, while the CFL downlights used 26W and 32W triple-tube, pin-based CFL lamps.[6]

Both SSL and CFL downlights that were tested provide fairly warm-white light (from 2700-3400K in CCT) and all have CRI greater than 80. On average, the CRI of the five SSL downlights is higher than the two CFL downlights. Both CFL downlights and four out of five SSL downlights have power factors greater than 0.95.

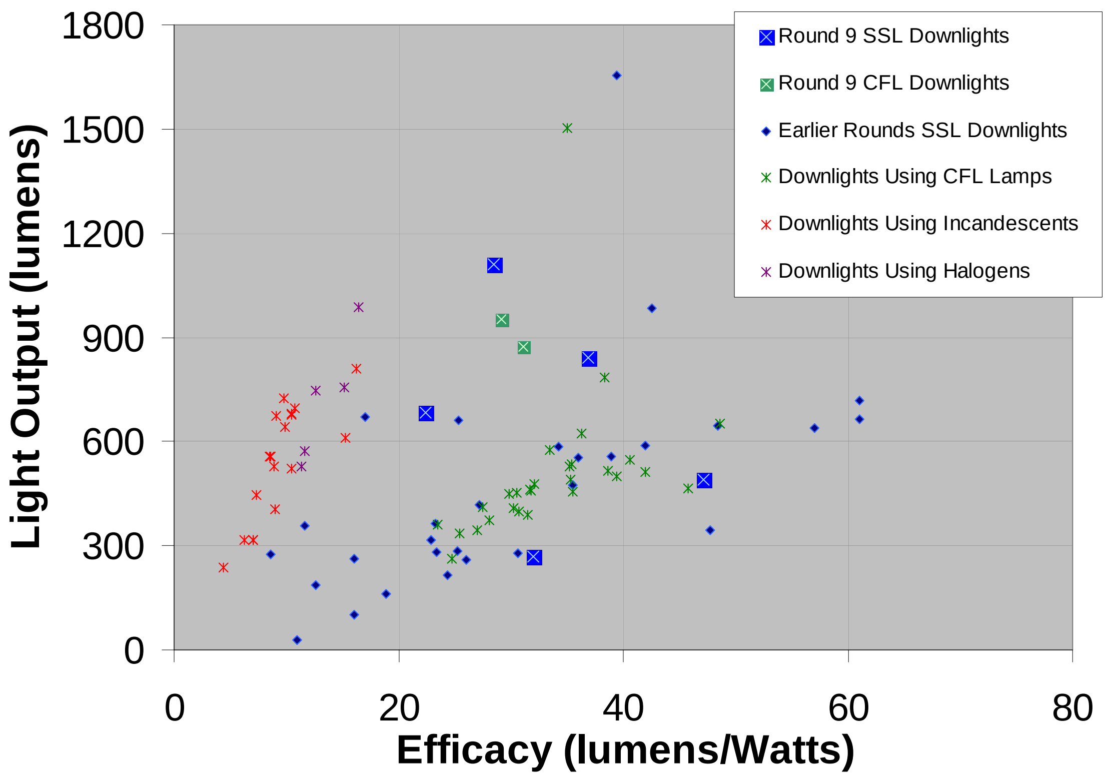

Figure 2. Performance of SSL Downlights Compared to Downlights Equipped with CFL, Incandescent, or Halogen Lamps

Figure 2 assembles light output and efficacy data from the Round 9 downlight tests, along with data from downlight testing in earlier CALiPER rounds and from surveyed manufacturer data for downlight products. For every light source, a range of performance can be observed. Despite the wide ranges, the SSL downlights tested in Round 9 surpass the efficacy and can achieve light outputs that meet or exceed levels of downlights equipped with 45-75W incandescent and halogen lamps. Aside from product 09-70, the SSL downlights in Round 9 meet or exceed the efficacy levels of downlights equipped

[6] CFL BK lamp types are CFTR26W/GX24q/835 and CFTR32W/GX24q/835 respectively (i.e., with rated CCT=3500 and CRI=82).

with CFL. Aside from product 09-61, the SSL downlights tested also meet or exceed the light output levels of CFL downlights. As a whole, the CFL downlights shown in Figure 2 draw from 9-43W of power, while the SSL downlights from earlier rounds of testing cover a range of 3-43W—in every case, the CFL and SSL downlight products draw less power than any of the downlights equipped with incandescent or halogen lamps.

Table 2 provides additional details regarding downlights tested in Round 9, including beam characteristics (center beam candlepower [CBCP], and beam angle) and an assessment of how the product stands up to ENERGY STAR criteria for recessed downlights and whether or not the product performs within 10% of levels published in manufacturer literature. The CBCP of the SSL downlights ranges from 378 to 835 candela (cd)— which is on par with CFL downlights. The beam angles of the SSL downlights range from 29° to 98°—on par with CFL downlights for the wider beam products and more representative of halogen downlights for the narrower beam products (though in some cases without the 'punch'—or higher CBCP levels—of some halogen lamps).

Table 2. CALiPER ROUND 9 SUMMARY – Recessed Downlights

Product Type	DOE CALiPER TEST ID	Total Power (Watts)	Output	Luminaire Efficacy (lm/W)	ENERGY STAR for SSL Performance on Key Parameters*	Provides Accurate Product Reporting
4" ø recessed can, SSL ENERGY STAR-qualified as of 3/25/2009	09-44	10	490 lm CBCP: 460 cd Beam angle: 55°	47	Yes	Yes
6" ø recessed SSL downlight	09-61	8	269 lm CBCP: 778 cd Beam angle: 29°	32	Would not meet ES lumen output and power factor requirements	*Performance specs not published*
6" ø recessed SSL downlight	09-69	39	1110 lm CBCP: 658 cd Beam angle: 86°	28	Would not meet ES efficacy requirement	*No*
6" ø recessed SSL downlight	09-70	30	683 lm CBCP: 833 cd Beam angle: 42°	22	Would not meet ES efficacy requirement	*No*
6" ø recessed SSL downlight	09-75	23	843 lm CBCP: 377 cd Beam angle: 98°	37	Yes	Yes
6" ø recessed can, 26W triple tube CFL lamp	BK09-45	28	872 lm CBCP: 473 cd Beam angle: 80°	31	Would not meet ES (SSL) efficacy requirement	*No* *Eff=48%*
6" ø recessed can, 32W triple tube CFL Lamp	BK09-66	33	952 lm CBCP: 971 cd Beam angle: 62°	29	Would not meet ES (SSL) efficacy requirement	*No* *Eff=40%*

*Note: ENERGY STAR qualification also includes other requirements not examined in this study (such as lumen maintenance, zonal lumen distribution, electrical safety characteristics, and size requirements). For the purposes of comparison, both SSL and CFL benchmark performance have been considered in relationship to criteria for recessed downlights from the 'ENERGY STAR® Program Requirements for Solid-State Lighting Luminaires Eligibility Criteria Version 1.1. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/energystar_sslcriteria.pdf.

One of the SSL downlights, 09-44, already has achieved ENERGY STAR qualification, and another shows performance levels that would typically qualify for ENERGY STAR. For these two products, manufacturers provide accurate performance claims. The other three SSL downlights and the two CFL downlights would fail SSL ENERGY STAR criteria (there is a separate ENERGY STAR criteria for CFL fixtures), either on the basis of insufficient light output or insufficient efficacy. Manufacturers do not publish accurate performance values for these products. In one case, no published photometric data could be found. For one of the SSL downlights, light output values were overstated by about 20%. For another SSL downlight, a wide distribution (beam angle 64°) product was ordered, but the testing revealed a beam angle of only 42°. The power draw of the product was measured to be 25% greater than suggested in the product specs and lumen output slightly lower, so the product efficacy was significantly lower than suggested by the manufacturer literature. For the CFL downlights, both products had measured luminaire efficiency based on absolute photometry significantly lower than published in product specifications based on relative photometry (48% efficiency instead of 62% in one case and 40% efficiency instead of 50% in the other).

The two benchmark CFL products selected for this round use higher wattage CFL lamps and are considered to be higher performance than the benchmarks tested a couple of years ago—the current benchmarks are rated as 26W and 32W CFL downlights, where CALiPER used 13W CFL downlight products as points of comparison in 2007. Figure 2 clearly shows that some SSL products are now capable of competing with the 26W and 32W CFL downlights. Making such a clear leap in both quality and output level of benchmarks underscores the progress that SSL downlights have made.

Now that a number of SSL downlight products are clearly competitive with CFL and incandescent products with respect to light output, color, and light distribution, comparisons can also consider other more nuanced characteristics, such as glare, shadowing, and luminaire reliability. One important potential issue with SSL downlights is glare. Because of the small source size and high luminance of an LED required for significant light output, glare has been a problem in the past. Some manufacturers are moving to indirect methods to avoid this problem, others are using remote phosphors and/or diffusers on the luminaire lens to distribute the light output more evenly, and some are recessing the light source deeper in the can. Existing measurement standards can, in some cases, be applied to clarify these issues, but no explicit standardized testing methods exist at this time to assess these more nuanced characteristics. In many cases, it is essential to purchase product samples and assess them qualitatively in a realistic (*in situ*) environment to determine their suitability for various lighting applications.

2’x2’ Troffers and 4’ Linear Replacement Lamps for 2’x4’ Troffers

Round 9 testing provides examples from two different approaches to using SSL technology to replace fluorescent troffers. In products that are designed to replace 2’x2’ troffers, SSL products tested are integral luminaires: that is, complete fixtures rather than replacement lamps for existing troffers. In products that are designed to be used in 2’x4’ troffers, SSL products tested are linear replacement lamps, marketed to replace the 4’ fluorescent T8 or T12 lamps in existing troffers.

Some of the SSL linear replacement lamps are designed to function using the same ballast as fluorescent lamps, so their installation does not require removing the ballast from the troffer. However, lamps designed to use the fluorescent ballast have lower overall efficacy than those designed to use their own drivers (in CALiPER testing, losses are 10-20% higher for SSL lamps using the fluorescent ballast). Most of the SSL linear replacements lamps require that the ballast in existing troffers be bypassed, using their own driver; an approach which enables somewhat more efficacious designs. Buyers, however, should be wary that rewiring a troffer to bypass the ballast may jeopardize the UL certification (or other testing certification) of the troffer, requiring recertification which may be difficult to obtain.

Fluorescent troffers can be among the most efficacious lighting applications today, using high-performance lamps, high-performance troffer designs, and judicious choices in ballasts. Thus, this is one of the most challenging lighting application areas for SSL when it comes to providing similar levels of energy efficiency. Given the targeted high efficacies and light outputs required by troffer applications, optimal SSL product design will be needed to be competitive. Over all CALiPER testing, the highest efficacies, highest levels of light output, and optimal light distributions can be observed in SSL products which are integral luminaires, rather than replacement lamps. Better performance levels are obtainable in luminaire designs as opposed to replacement lamps for several reasons, but primarily because there are fewer volumetric and geometric constraints for thermal management and driver designs and the natural directionality of LED chips can be used advantageously along with innovations in optics.

The resulting performance differences between these two approaches are illustrated clearly in the Round 9 results for troffer products. CALiPER testing for both SSL and fluorescent products is based on absolute testing. For replacement lamp products, the samples are tested at the lamp level and then mounted in a typical troffer to determine the actual overall light output *in situ*. Figures 3 and 4 compare the overall fixture performance in light output, power used, and efficacy for the SSL troffer fixtures or troffers equipped with 4’ SSL replacement lamps, as compared to comparable fluorescent fixtures. For these figures, power is plotted from highest to lowest, so that the highest performing products fall in the upper right-hand (green) portion of the figures.

First, Figure 3 presents 4’ SSL replacement lamps tested in Round 9, in comparison with the high-performance fluorescent troffer also tested in Round 9, and in comparison with similar CALiPER testing on troffers equipped with SSL and fluorescent replacement lamps in 2008. One SSL product, 08-121, is marketed as retrofit lamps for use in troffers to be installed on the basis of three lamps per troffer (instructions and mounting brackets are provided with the product to enable relamping of troffers that were designed for two fluorescent lamps). This product was tested as suggested by the manufacturer using three lamps in the troffer—it produces light levels on par with the fluorescent benchmarks, but uses over two times the power, resulting in an overall luminaire efficacy of only 27 lm/W. All of the other 4’ SSL replacement lamps result in only half the light output of troffers equipped with fluorescent lamps, and all are below the T8-equipped fluorescent troffer efficacy levels of 63 and 69 lm/W.

Fixture efficiencies for 4’ SSL replacement lamps in the parabolic louvered troffer were 85% on average (except lamps that use the fluorescent ballast). At the time this testing was conducted, a manufacturer-submitted sample of a very recent product was also tested. It still did not meet fluorescent levels, but came somewhat closer to performance levels of fluorescent benchmarks, resulting in a fixture output of approximately 3000 lm and fixture efficacy of 61 lm/W. This product was not yet market available so anonymous samples could not be obtained for strict CALiPER testing.

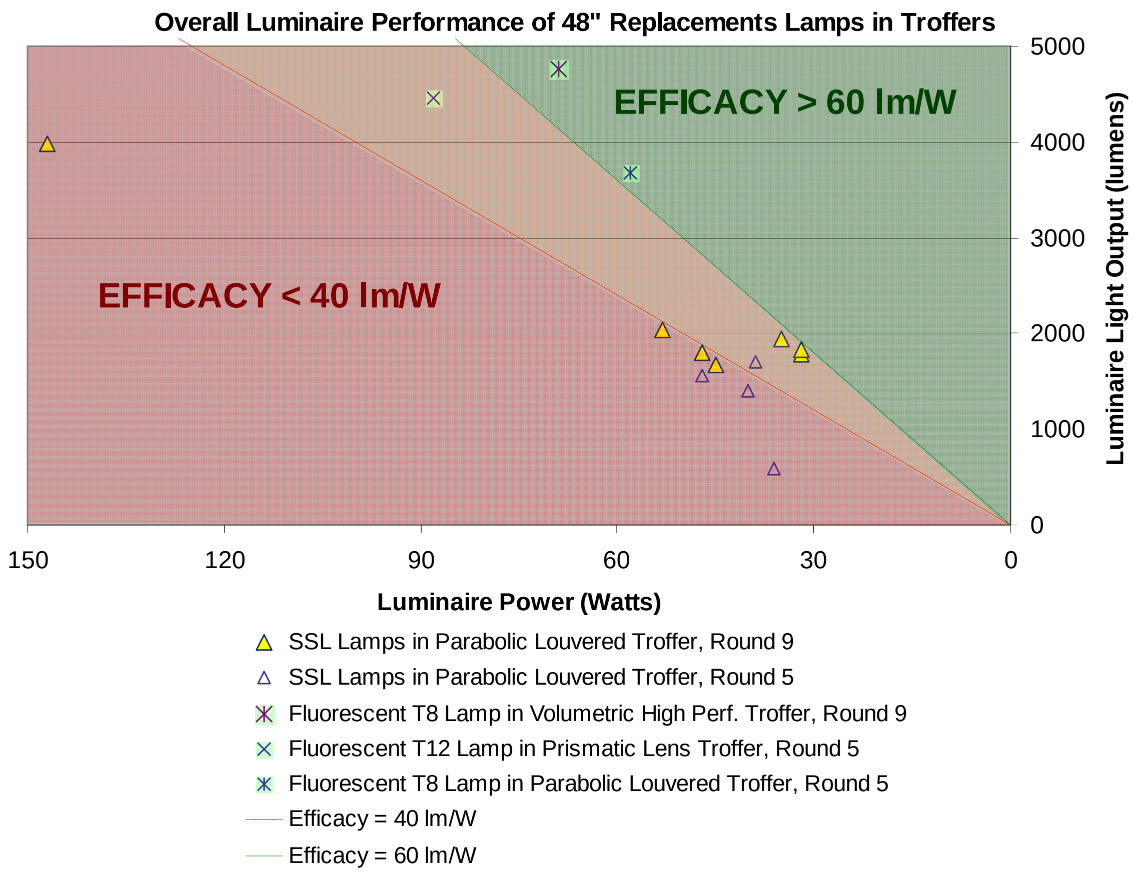

Figure 3. Luminaire Light Output and Power for Troffers Equipped with 4’ SSL Replacement Lamps and 4’ Fluorescent Replacement Lamps

Figure 4 presents results for 2’x2’ SSL products, including 2 thin panel luminaires and a 6” deep luminaire, in comparison to two fluorescent benchmark 2’x2’ troffers, and in comparison to similar SSL products that were tested in earlier CALiPER rounds. The results for 2’x4’ fluorescent troffer benchmarks are also included in Figure 4 because the

2’x2’ SSL products are being marketed, in some cases, as replacements for 2’x4’fluorescent troffers. This figure (as compared to Figure 3) underscores the significant performance differences between SSL fixtures and SSL linear replacement lamps. The 2’x2’ SSL fixtures meet or exceed light output levels of the 2’x2’ fluorescent troffers and on average meet or exceed the efficacy levels of the fluorescents. Two of the SSL products draw more power than the fluorescent benchmarks, but about the same as the 2x4’ fluorescent troffers. One of the SSL products, 09-41, achieves higher overall fixture efficacy than any of the fluorescent benchmarks, including the high performance T8 troffer, although it does not quite achieve the light output levels of the fluorescent 2’x4’ troffers.

The SSL 2’x2’ luminaires (note, expressly not replacement lamp designs) are clearly competitive in performance with fluorescent-lamped troffer options. Numerous other performance criteria should be considered when comparing SSL to fluorescent, as discussed in more detail below.

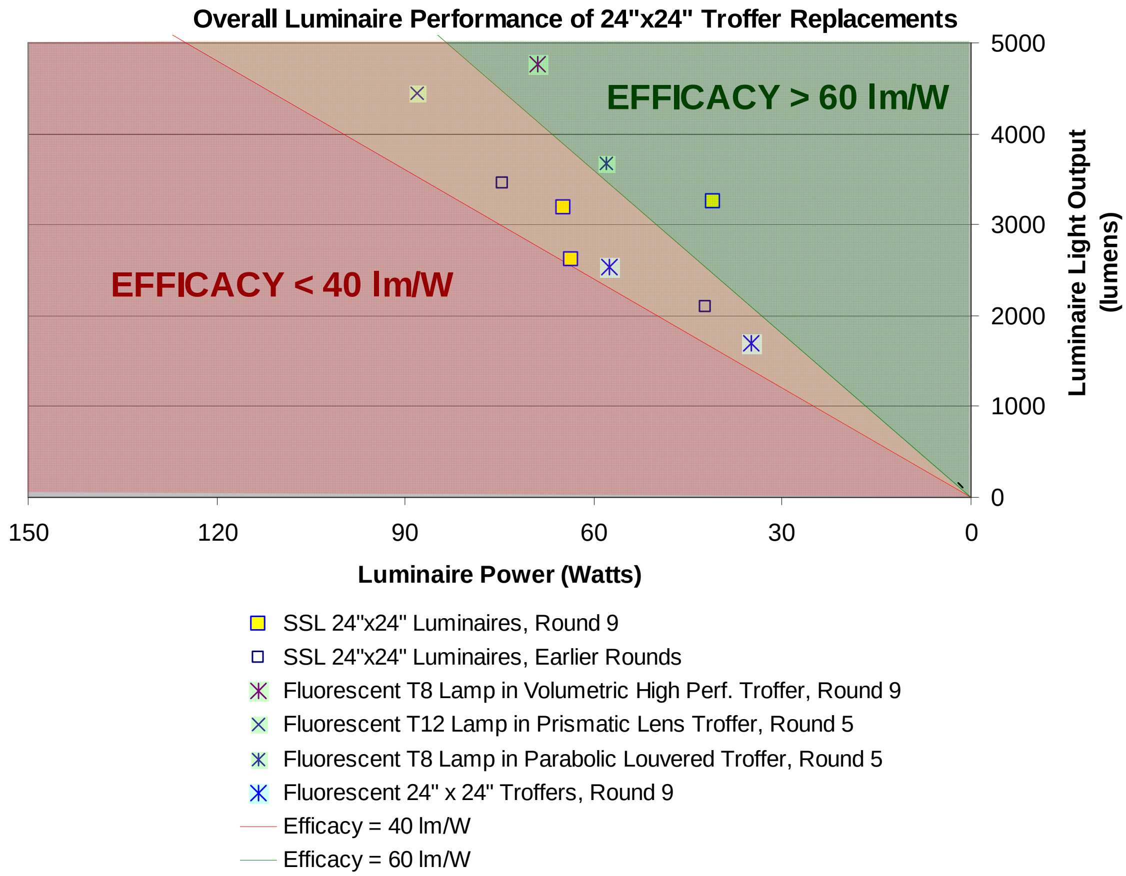

Figure 4. Luminaire Light Output and Power for 2’x2’ SSL Fixtures and Fluorescent Troffers

4' Linear Replacement Lamp Testing Details

Seven SSL linear replacement lamp products were tested for Round 9, along with a high-performance fluorescent benchmark. For the SSL linear replacements, two lamps of each were tested as bare lamps. The pair of lamps was then installed and tested in a 12-cell parabolic louvered troffer to determine performance of a complete troffer equipped with these replacement lamps. The benchmark test used high-performance fluorescent lamps, tested separately as bare lamps, and then installed in a nonplanar lensed high-performance troffer to determine overall performance of the 'stretch' benchmark troffer. In Round 5, similar testing was conducted on earlier SSL products and on two benchmark fluorescent troffers—one prismatic lensed troffer equipped with T12 lamps and one parabolic louvered troffer equipped with T8 lamps.

Two of the products tested in Round 9, 09-39 and 09-40, are the same product in frosted and non-frosted versions. Only the frosted version was tested in the troffer. Another product, 09-13, was tested twice, first with samples acquired anonymously (09-13AB) and then with samples purchased by CALiPER, but not anonymously (09-13CD). Three out of these four lamps performed similarly, the fourth lamp (one of the two acquired anonymously) provided 6.5% less light output and efficacy than the other three lamps. This difference may be due to typical variation between units, however it is greater than that observed within any other pair of SSL linear replacement lamps tested to date.

Power factors of SSL linear replacement lamps tested in Round 9 range from 0.59 to 0.99. Color temperatures range from about 2990-4650K. Over half of the SSL linear replacement lamps have fairly low CRI ranging from 63-72: The best CRI of an SSL linear replacement lamp was 76, while the fluorescent benchmark achieved a CRI of 83. One of the SSL products, 09-48, had a very high Duv of 0.014, which is well outside of ANSI defined tolerances for white light in SSL products.[7]

1500 lumens and 15 Watts (and thus 100 lumens per Watt) appears to be the favored description used by manufacturers for their SSL linear replacement lamps, but the products are not delivering at that level. The majority of manufacturers of SSL linear replacement lamps tested provide incorrect data—some promising as much as 50% more lumens than their products deliver. Similarly the lumens per Watt documented by the manufacturers ran between 30 and 50% higher than the products measured. CRIs in general were also lower—most promised 80 or higher, when in fact, a few had CRIs in the mid-70s and half were in the mid-60s.

As illustrated by Figure 3 above, none of the SSL linear replacement lamps tested by CALiPER to date are suitable one-for-one replacements for linear fluorescent tubes in 2'x4' troffers. While they exhibit about 10-15% less fixture loss than the fluorescent tubes when installed in a troffer, this difference does not compensate for the insufficient light output of the SSL linear replacement lamps. Furthermore, none of SSL linear

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

replacement lamps tested to date achieve the luminaire efficacy (when installed in a louvered troffer) of the two T8 fluorescent benchmark troffers tested by CALiPER.

2'x2' Troffer Testing Details

Table 1b, above, summarizes key performance parameters for the 2'x2' troffer products tested in Round 9. Table 3 provides additional performance details for these products Round 9, including accuracy of manufacturer reporting, and light intensity and distribution indicators such as maximum candela, spacing criteria and video display terminals (VDTs) intensity limit compliance.

Table 3. CALiPER ROUND 9 SUMMARY – 2'x2' Troffers and Thin Panels

Product Type	DOE TEST ID	Total Power (Watts)	Output	Luminaire Efficacy (lm/W)	VDT & [VDT Intensive]	Provides Accurate Product Reporting
Troffer (2'x2' panel)	09-41	41	3250 lm 1539 cd (max) SC=1.06, 1.06	79	No [No]	Yes
Troffer (2'x2' thin panel)	09-71	65	3190 lm 1124 cd (max) SC=1.28,1.34	49	No [No]	Yes, but consumes more power than claimed
Troffer (2'x2' thin panel)	09-81	64	2610 lm 897 cd (max) SC=1.26, 1.26	41	No [No]	*No, 100% overstated*
Parabolic 9 cell Troffer (2'x2') Utube fluorescent	BK 09-72	57	2541 lm 1315 cd (max) SC=1.22, 1.12	44	Yes [No]	*No, 10% overstated*
High Efficiency Troffer (2'x2') F17T8 fluorescent	BK 09-73	35	1706 lm 544 cd (max) SC=1.38, 1.26	49	Yes [No]	*No, 20% overstated*

1. Spacing Criterion (SC) is listed by 0-90 degrees and 180-270 degrees respectively.
2. VDT Normal intensity limits per vertical angles are as follows: 65°/300 cd, 75°/185 cd, 85°/60 cd
3. [VDT Intensive] intensity limits per vertical angles are as follows: 55°/300 cd, 65°/220 cd, 75°/135 cd, 85°/45 cd)

All of these products have power factors close to 1.0 and similar color characteristics, ranging from 3300-3600K. CRI for these products (as indicated in Table 1b) ranges from 75-93. One sample, 09-71, has Duv outside of tolerance for ANSI defined white light.

The three SSL and two fluorescent products produce somewhat similar beam patterns (none has batwing distribution), except for 09-41 which has a slightly narrower beam, higher CBCP and smaller spacing criteria, and BK 09-73 which has a considerably lower maximum candela level, though similar spacing criteria. RP-1-04, the IESNA document for recommended practices for office lighting, provides intensity limits for different angles for fixtures to be used near video display terminals (VDTs, i.e., computer screens). These intensity limits replace the former luminance data limits. None of the luminaires tested met RP-1 requirements for VDT Intensive and only the conventional luminaires (BK09-72 and BK09-73) met the VDT normal requirements. However, both 09-41 and 09-81 exceeded the intensity limits in the 65° angle by only 10%.

Spacing Criteria (SC) is not a performance metric per se—when multiplied by the mounting height, it provides the horizontal distance between fixtures for "even" illumination. It can be used to help evaluate the correct luminaire for the correct application. The SC value also gives a rough idea about distribution. It helps describe the photometric distribution: a low SC (around 1.0), as in 09-41, is going to distribute light down in low vertical angles. In contrast a high SC (1.25 and greater), as in 09-73, will distribute light over more vertical angles. Figures 5a and 5b illustrate this graphically.

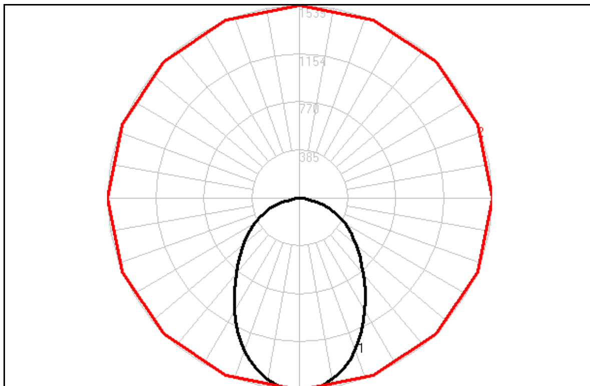


Figure 5a - CALiPER 09-41

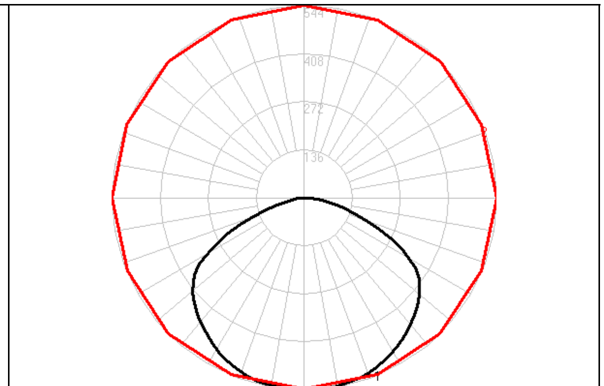


Figure 5b - CALiPER 09-73

Traditionally, photometric testing of fluorescent fixtures is based on relative photometry, whereas CALiPER testing uses absolute photometry.[8] The basic light output and efficacy performance of the two benchmark fluorescent products can be compared to the manufacturer specifications, keeping in mind that the manufacturer ratings are based on relative photometry. To perform such a comparison, care must be taken to adjust values from relative photometry to account for the lamp output and ballast factor used in the absolute photometry. In both cases, the absolute photometry conducted by CALiPER reveals performance which is 10-20% less than suggested in adjusted manufacturer specifications. This difference in performance may reflect the fact that fluorescent lamp output is impacted by thermal conditions and operating levels. Relative photometry is based on lamp ratings obtained at specific (often optimal) operating regimes, whereas the actual lamp temperature is likely to be higher when the lamp is installed in the fixture for absolute testing.[9] There may be circumstances where absolute photometry of fluorescent fixtures reveals higher performance than through relative photometry. To date, however, all CALiPER testing of fixtures that use linear fluorescent lamps has shown that absolute

[8] The DOE SSL fact sheet, *LED Measurement Series: Luminaire Efficacy*, provides an introduction to concepts surrounding luminaire testing.
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/luminaire_efficacy.pdf, September 2009.
[9] *Thermal Effects in 2'x4' Fluorescent Lighting Systems*, National Lighting Product Information Program (NLPIP), Lighting Answers Volume 2 Number 3, March 1995.
http://www.lrc.rpi.edu/nlpip/publicationDetails.asp?id=121&type=2

testing finds performance levels which are typically 10-20% below values published in manufacturer specifications (using relative photometry).

The three SSL 2'x2' troffers provide three different examples of manufacturer claims. The first product, 09-41, was found to have performance characteristics that meet or exceed manufacturer specifications in all respects. The second product, 09-71, was found to have light output and efficacy that meet or exceed manufacturer specifications, but the product draws more power than suggested on the product labeling and in manufacturer specifications. The product label states "45W," while the spec sheet indicates "Typical 54W / Max 61W"; CALiPER measured the power draw at 65W. The third product, 09-81, wildly overstates product performance, with manufacturer literature claiming a rating of 5400 lumens, while absolute photometry reveals that it provides less than half that light output.

Now that SSL products such as downlights and 2'x2' troffers are now able to compete with CFL and fluorescent fixtures in basic performance characteristics, comparisons of more subtle performance characteristics and of cost can be made. A cost comparison of these products might take into consideration initial cost of the product, expected or warranted life of the product, expected cost of electricity over the life of the product, spacing criteria and layout possibilities, mean or design lumens for the product, maintenance cost for relamping if applicable, etc. Each SSL product has a manufacturer rated life of 50,000 hours before reaching 70% of initial light output. Life for fluorescent products is rated differently, dependent on whether a lamp is instant start or rapid start, whether it is a linear or U-tube lamp, and reflecting a mean time between failures rather than an L_{70} life. With a given maintenance cost, fluorescent fixtures can be relamped and in some cases retrofitted with more efficacious ballasts. SSL fixtures at this time do not typically allow relamping or retrofitting. Because of these subtle differences, care should be taken in any cost comparison to consider the specific requirements of the application, the specific qualities of the products under consideration, and other factors.

Using results from absolute photometry conducted by independent or NVLAP-qualified laboratories and gaining knowledge from pilot installations can help clarify points of comparison. Using the examples of 2'x2' troffers that were tested by CALiPER, examining cost per kilolumen is not a straightforward task and can vary significantly depending on whether results from absolute testing or manufacturer specs are used. For products 09-41 and 09-71, which have accurate manufacturer ratings, cost estimates are equivalent or slightly lower when absolute test results are used. For products 09-81, BK 09-72, and BK 09-73, both initial and lifetime cost estimates per kilolumen increase significantly when results from absolute testing are used rather than manufacturer ratings. Based on CALiPER results and prices paid for CALiPER samples (which are not necessarily representative of standard market rates for negotiated purchases), cost per kilolumen for these five products is lowest for BK 09-72 and highest for BK 09-73, with the three SSL products falling in between (using both initial and life-cycle cost estimates), as illustrated in Figure 6. Also shown in this figure, the lifetime cost per kilolumen for SSL product 09-81, which has highly inflated performance claims, would appear to be significantly less if manufacturer specifications are used. Similarly, lifetime cost per kilo-lumen is also somewhat underestimated for the fluorescent products if manufacturer specifications are used. This assessment should only be considered as illustrative, since cost comparisons may be conducted in many ways.

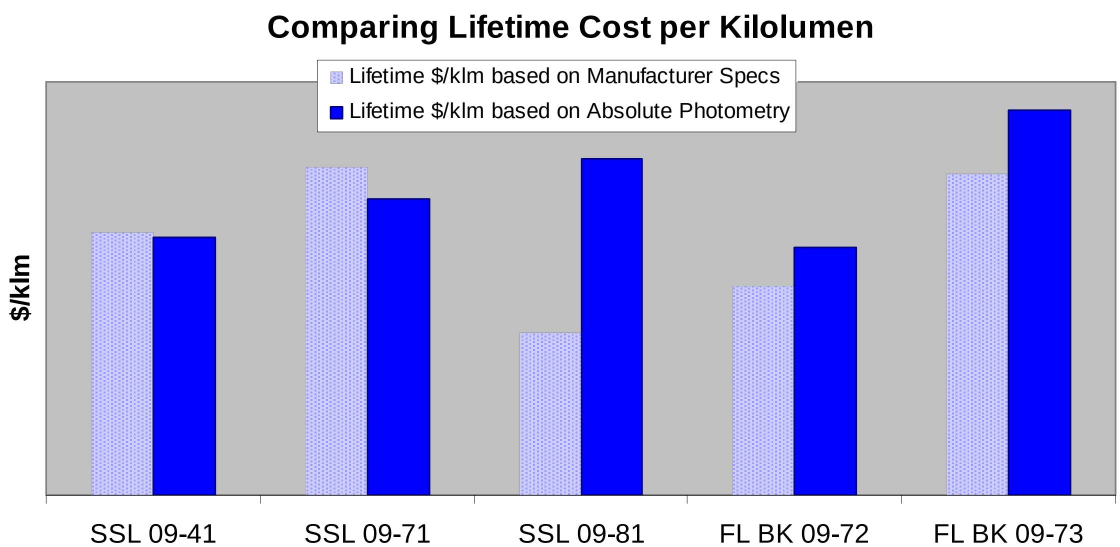


Figure 6. Comparative Cost per Kilolumen Based on Manufacturer Performance Data and Based on Results from CALiPER LM-79 Testing (Absolute Photometry)[10]

Smaller Replacement Lamps

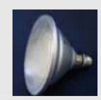
Nine types of small SSL replacement lamps were tested in Round 9, including an MR16 lamp, four directional PAR and R type lamps, and four omni-directional lamps (two A-lamp replacements and two candelabra replacements. None of the tested small replacement lamps have Duv outside of ANSI-defined tolerance for white light, although two of the directional lamps (an R30 and a PAR 38) provide cold-white light (CCTs of 5554K and 6177K, respectively). Six of the small replacement lamps have CRI less than 75. Five have power factors below 0.7, including three products with very poor power factors, below 0.5.

Over all nine small replacement lamps that were tested, only two products, 09-77 and 09-78, met manufacturer performance claims, as summarized in Table 4. Incorrect and misleading claims on the other seven products range from somewhat inaccurate claims (15-20% inflated) to claims that are double the measured performance levels. The most

[10] Note: Numerical quantities are intentionally removed from Figure 6 because unit prices paid by CALiPER may not be representative of volume pricing for other buyers. Figure 6 should be used to study relative values across the various products. Lifetime kilolumen values are based on 50,000 hour total luminaire life (representing a turnover of 13.7 years for 10 hours operation per day). No maintenance cost is included (only per unit cost of replacement lamps). An electricity rate of $0.10/kwh is used. Spacing considerations are not included in calculation. Initial cost and performance are based on CALiPER samples. Mean lifetime lumens of 85% initial lumens is used for SSL samples, 90% initial lumens used for fluorescent samples.

prevalent problem is with inflated and misleading equivalency claims. Guidance is provided below to help readers determine realistic wattage equivalencies between SSL and more traditional products.

Table 4. CALiPER ROUND 9 – Replacement Lamp Manufacturer Claims

Sample Type and CALiPER Reference	Manufacturer Claims	Actual Performance Level (e.g. Light Output, Efficacy, CBCP, Beam Angle)	Provides Accurate Product Reporting	
Replacement Lamp (MR16) 09-80	*180 lm*, (54-*69* lm/W) *Eq. to 35W halogen*	165 lm, 50 lm/W 304 cd, 31° **Less than average 20W halogen**	NO	
Replacement Lamp (R20) 09-78	230 lm, (32 lm/W) 7W=35W	263 lm, 42 lm/W 944 cd, 25° **Exceeds average 35W halogen**	YES	
Replacement Lamp (R30) 09-64	*Replaces 45W* *(450 lm, 128 lm/W)* *CRI=84, 30° beam*	186 lm, 54 lm/W CRI=71, 695 cd, 20° **Less than 20W eq.**	NO	
Replacement Lamp (PAR30) 09-76	*Eq. to 75W Incand.* *550 lm, 70 lm/W* *60-70° beam*	468 lm, 59 lm/W 190 cd, 100° **Eq. to 50W R30**	NO	
Replacement Lamp (PAR38) 09-63	*Replaces 45W* *(450 lm, 90 lm/W)*	289 lm, 58 lm/W 902 cd, 22° **Less than 25W eq.**	NO	
Replacement Lamp (A-lamp) 09-60	260 lm, (34.6 lm/W) *Replaces 40W incandescent*	251 lm, 34 lm/W **Eq. to 25W incandescent**	NO	
Replacement Lamp (A-lamp) 09-77	155 lm, (22 lm/W) Eq. to 25W	208 lm, 33 lm/W **Eq. to 25W incandescent**	YES	
Replacement Lamp (Candelabra) 09-65	*Replaces 40W* *(320 lm, 220 lm/W)*	67 lm, 45 lm/W **Less than average 15W incandescent**	NO	
Replacement Lamp (Candelabra) 09-74	30 lm, (12 lm/W) "Uses less energy than a 15W candelabra"	31 lm, 17 lm/W **Eq. to 7-15W night light**	YES (possibly misleading)	

Note: Claims in parentheses indicate calculated values for output or efficacy based on manufacturer light output and power ratings and equivalency statements.

Equivalency comparisons for directional lamps (MR16, PAR & R lamps) based on CBCP and beam angle.

Misleading, erroneous or false claims are indicated in *red italics*.

It is interesting to note that degrees of accuracy or inaccuracy or deception in product claims appear to be consistent across given manufacturers. In Round 9, three different manufacturers each had multiple products tested and each appeared to apply similar strategies in product labeling across all of their products. One manufacturer produced products 09-74, 09-77, and 09-78, which all had credible, fairly complete performance information on packaging. Another manufacturer produced products 09-76 and 09-80, which each provided slightly inflated performance ratings, along with somewhat inflated product equivalency statements. A third manufacturer produced products 09-63, 09-64, and 09-65, which all provided little to no performance data and highly exaggerated claims of product equivalency on packaging.

Because of multiple reports of customer dissatisfaction from stakeholders and industry sources, these three small replacement lamp products, 09-63, 09-64, and 09-65, were fast-tracked for lumen depreciation testing. These lumen depreciation results are summarized below.

MR16 Replacement Lamps

One SSL MR16 lamp, product 09-80, was tested in Round 9. The basic performance values presented in Table 1d show that this product provides warm-white light at 3014K with a CRI of 76 and a very good efficacy of 50 lm/W. It draws 2.6W and achieves an excellent power factor of 0.95. With respect to light output, this product provides 165 lm, which is just reaching the lower-end of light output levels observed in 20W halogen MR16 lamps. Figure 7 illustrates how the beam characteristics of this lamp compare to similar lamps tested by CALiPER in earlier rounds of testing. The figure also provides points of comparison for minimum center beam intensity of halogen MR16 lamps as a function of beam angle.[11] Product 09-80 only provides about one half the requisite center beam intensity of 20W halogens with similar beam angles. As illustrated by one blue star above the red curve, only one SSL MR16 product tested by CALiPER to date (tested in Round 8) has achieved sufficient center beam intensity to be considered a true replacement for 20W halogen.

[11] Minimum center beam intensities for directional replacement lamps set forth in ENERGY STAR draft criteria for integral replacement lamps. ENERGY STAR Program Requirements for Integral LED Lamps, *ENERGY STAR® Program Requirements for Integral LED Lamps, Draft 3*. http://www.energystar.gov/index.cfm?c=new_specs.integral_leds, September 18, 2009. Curves include allowance for standard deviations, so they represent minimum center beam intensity values, not average.

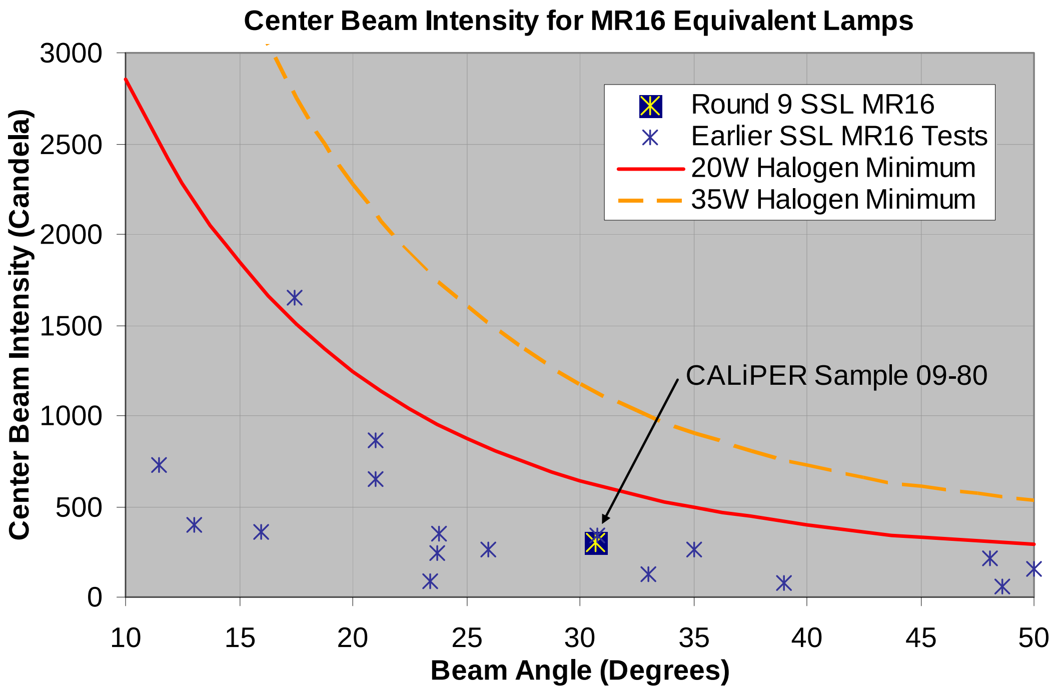


Figure 7. Center Beam Intensity for MR16 SSL Lamps Compared to ENERGY STAR Defined Minimum Center Beam Intensity for Halogen MR16 Lamps
(To achieve intensity level of halogen lamps, SSL lamps must fall above the target line for the equivalent wattage they intend to replace.)

While product 09-80 comes close to meeting manufacturer performance claims for light output and efficacy, it entirely fails to meet the manufacturer claim of being equivalent to a 35W halogen MR16. As clear from Figure 7, this lamp only provides one half of the center beam candlepower of a 20W halogen lamp, and is far below the intensity and output of 35W halogen MR16 lamps. Nevertheless, drawing only 2.6W of power, this product may be a suitable energy-saving choice for some applications which do not require the light output and beam intensity levels of 20W or 35W halogens. Buyers and specifiers should be wary of all equivalency claims on SSL products and always check light output and beam characteristics provided in spec sheets and in LM-79 test results. In the case of MR16 lamps, for example, plotting the rated beam angle and center beam candlepower on Figure 7 gives a quick check on how the product performs compared to 20W or 35W halogens.

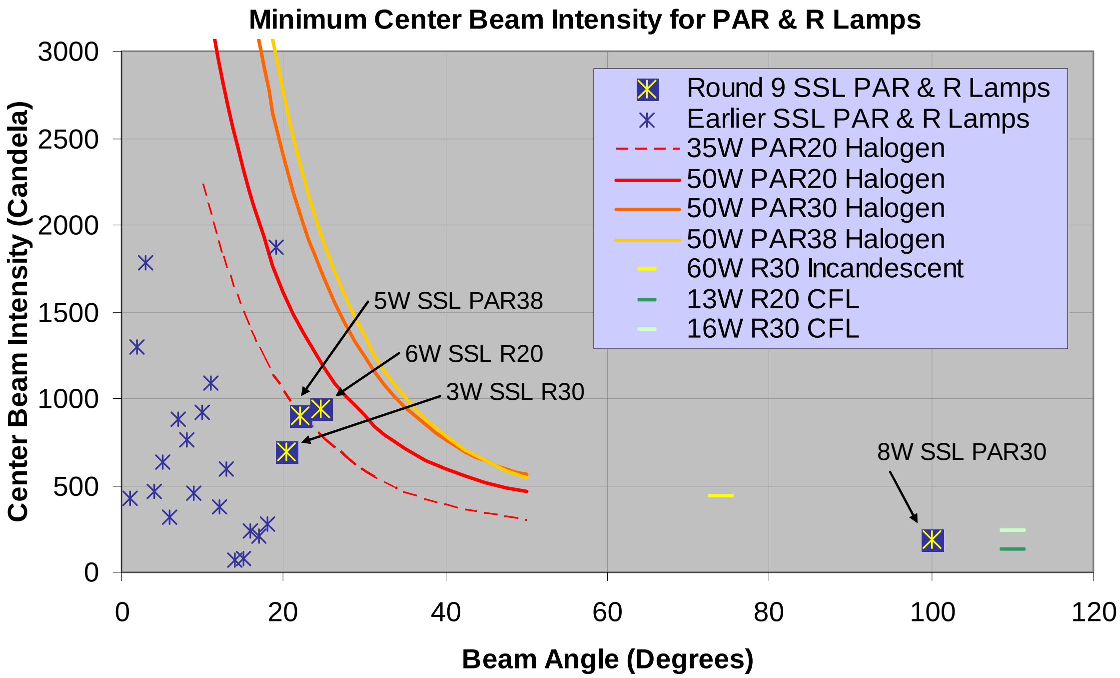
Directional 'PAR' and 'R' Replacement Lamps

As in earlier rounds of CALiPER testing, the designation of an SSL directional lamp as PAR versus R lamp does not provide any consistent indication of whether or not the lamp performs more like a highly directional PAR lamp (typically halogen) or less directional R lamp (typically incandescent or CFL). In Round 9, four directional PAR or R lamps were tested. Three are fairly focused with beam angles from 20-25° (packaging on these lamps indicates R20, R30, and PAR38 respectively), while one lamp, sold as a PAR30 lamp, has a very wide 100° beam angle. A very wide range of performance was observed across these four products, as summarized in Table 1d, above.

The R20 lamp, 09-78, performs at levels meeting or exceeding the performance claims indicated on the product packaging. The CRI for this product is 68 and power factor is 0.57 (neither CRI nor power factor is indicated on product packaging). The product is labeled 7W=35W. With respect to beam characteristics, this is clearly true as illustrated in Figure 8. This figure plots the center beam intensity as a function of beam angle, as compared to curves representing minimum center beam intensity for halogen PAR lamps. As shown, this 6W SSL R20 lamp clearly provides a center beam intensity exceeding the minimum center beam intensity curve for 25° beam angle 35W PAR20 halogen lamps. Overall lumen output of this lamp, while exceeding the manufacturer rating, would be somewhat less than the overall lumen output of a 35W halogen PAR20, but would be similar to a 30-40W incandescent R20 lamp.[12]

The other three directional lamps do not meet their manufacturer performance claims. The 8W PAR30 lamp, 09-76, comes close, with measured light output and efficacy values about 16% less than manufacturer claims, but it unfortunately claims to be equivalent to a 75W incandescent, where in fact it is more similar to a 40-50W incandescent R30. This product is sold as a 70° flood lamp, but was measured to have a beam angle of 100°. However, this product does achieve a CRI of 76 (close to claimed CRI of 80) and achieves a power factor of 0.92.

[12] Benchmark examples of incandescent, halogen, and CFL R20 lamps are provided in the CALiPER Round 8 summary report.
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_round_8_summary_final.pdf



Note: Halogen curves based on draft ENERGY STAR criteria. Incandescent and CFL data points from CALiPER benchmark testing.

Figure 8. Center Beam Intensity for SSL PAR and R Lamps Compared to ENERGY STAR Defined Minimum Center Beam Intensity for Halogen PAR Lamps and Tested Values for Incandescent and CFL R Lamps
(To achieve intensity level of halogen lamps, SSL lamps must fall above the target line for the equivalent wattage they intend to replace.)

The other two lamps, a 3W R30 (09-64) and a 5W PAR38 (09-63) by the same manufacturer, both performed very poorly. Manufacturer literature for the R30 lamp indicates a CRI of 84 and CCT of 65K, while the measured values are 71 and 5554K. The power factors of both lamps are below 0.5. Both lamps have packaging claims indicating that they replace 45W lamps, when in fact they are far from approaching overall light output or beam characteristics of 45W R or PAR lamps. For their respective beam angles, both lamps would need to provide double the center beam candlepower or twice the luminous flux to be compared to 45W lamps. Furthermore, as discussed below, both of these products exhibit extremely rapid lumen depreciation in the first 1000 hours of operation.

Omni-Directional Replacement Lamps

Four SSL products intended to replace omni-directional replacement lamps were tested in Round 9. Two lamps, 09-60 and 09-77, are marketed as A-lamp replacements with standard (E26) Edison bases, and two lamps, 09-65 and 09-74, are marketed as candelabra lamps with E12 bases. All four of these products provide warm-white light (with correlated color temperatures ranging from 2643 to 2960K); two have CRI over 80, but two lamps, 09-60 and 09-65, have lower CRI of 67 and 59, respectively. Candelabra lamp 09-65 also has a very low power factor of only 0.41.

Figure 9 compares the light output and efficacy of these lamps against similar incandescent and CFL lamps and against earlier tests of SSL omni-directional replacement lamps. The two A-lamp replacements provide about the same output level as a typical 25W incandescent A-lamp, but with four times the efficacy. One of the candelabra replacement lamps, 09-65, provides about the same light output level as a lower performing 15W incandescent candelabra, while the other SSL candelabra replacement, 09-74, provides about the same output as a 7W incandescent nightlight (C7 lamp)—both with far greater efficacy than these low wattage incandescent lamps. Unfortunately, product 09-65 exhibits extremely rapid lumen depreciation (discussed below), dropping to about one-tenth of its initial light output after only 1000 hours of continuous operation at room temperature.

Products 09-74 and 09-77 are both from the same manufacturer, are sold in big-box retail stores and home improvement stores, and even surpass the performance data provided on their packaging (consuming less power and producing more lumens than announced on the packaging). Product 09-77 includes an accurate equivalency mention, stating that the lamp is equal to a 25W incandescent. Product 09-74 includes a true, but possibly misleading equivalency statement, indicating that the product "uses less energy than a 15W candelabra." More accurate and complete disclosure would say "uses one-eighth of the energy of a 15W candelabra and produces one-third to one-half of the light output of a 15W incandescent."

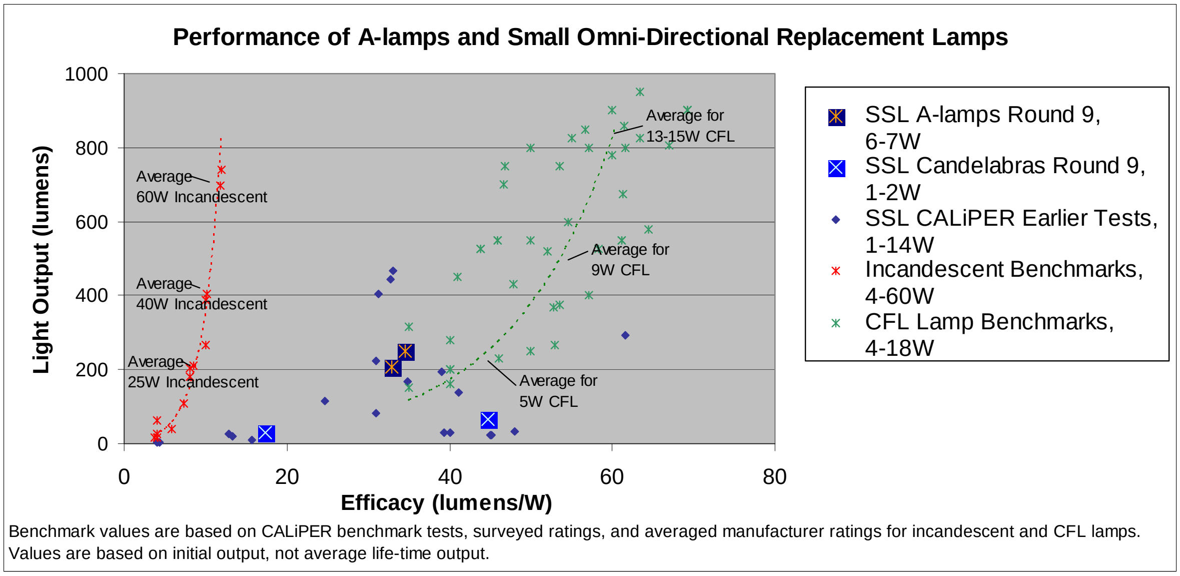


Figure 9. Comparison of A-lamp SSL Products Versus Benchmarked Traditional Lamps

Product 09-60 meets product claims for light output and efficacy, however it does not meet the manufacturer claim that the product is equivalent to a 40W incandescent. On average, 40W incandescent lamps produce about 400 lm, whereas this lamp only produces 251 lm, so it should only legitimately be compared to a 25W incandescent.

Product 09-65 is sold in big-box retail stores and home improvement stores, but includes blatantly misleading product labeling, claiming to replace 40W incandescent lamps. In fact, initial testing (per LM-79) reveals that it only produces the light output of lower performing 15W incandescent candelabras. Longer-term testing reveals that it depreciates to a level of negligible light output after 1000 hours of continuous operation, negating all cost-savings claims on the packaging because they are based on 30,000-hour bulb life.

As in earlier CALiPER tests on SSL lamps intended for replacement of omni-directional lamps, all of these products are more directional in nature than the incandescent or CFL lamps they might be replacing. In some applications—such as for lamps installed in recessed downlights ("cans")—this directionality may be desirable. In other applications, where lamps are installed in settings that are designed to be illuminated spherically—such as in transparent or semi-transparent globes or behind semi-transparent light shades—this directionality may result in undesirable lighting. When tested base-up (though unlike other light sources, the base orientation should not affect the light output for SSL), the two better lamps tested, 09-74 and 09-77, manage to emit 20-30% of light in the upward direction and 70-80% downward, while the other two emit only 5-15% of light upward and 85-95% of light downward.

Desk Lamp

This desk lamp would partially meet ENERGY STAR criteria for task lamps, achieving the minimal light output and efficacy, and has good color quality (providing warm-white light at 2940K and a CRI of 93). Unfortunately, as in earlier rounds of CALiPER testing of SSL desk lamps, this product has a low power factor of only 0.47 and consumes 0.52W of power when turned off. The poor power factor and the off-state power consumption would disqualify this lamp for ENERGY STAR. While the lamp would achieve an efficacy of 28 lm/W if it was used 24 hours per day, because of off-state power, the efficacy would only be 19 lm/W with three hours of use per day and would drop to 11 lm/W if used one hour per day. CALiPER has yet to discover an SSL desk lamp that would pass ENERGY STAR and not draw off-state power.

The manufacturer described this product's performance accurately in its literature, including indication of the standby power consumption.

Reliability: Lumen Depreciation Testing

Dozens of products have been subjected to CALiPER long-term testing, which examines the long-term performance of the entire fixture or replacement lamp, representing a wide range of LED sources, thermal management designs, driver technologies, and optics. CALiPER testing focuses on commercially available products such as lighting fixtures and integral replacement lamps, so the objectives of CALiPER long-term testing are not the same as LM-80 testing. IESNA LM-80 is a testing method for measuring long-term lumen depreciation of LED chips—there is currently no comparable published testing methodology for long-term lumen depreciation of LED fixtures and integral replacement lamps.[13] For testing needs where no appropriate, published testing standards are available, CALiPER applies draft standards and works with testing laboratories and industry to develop and apply relevant testing methodologies. The results from CALiPER long-term testing are shared with standards groups and industry stakeholders.

Typically, CALiPER long-term testing is conducted with monitoring of output through spot illuminance measurements at 500 hour intervals over a period of 6000 or more hours, corroborated with LM-79 testing at time zero and at 6000 hours.[14] Shorter monitoring intervals can be employed for products exhibiting very rapid rates of depreciation. One key objective of CALiPER lumen depreciation testing is to study long-

[13] The published IESNA LM-80-08 testing standard, *IESNA Approved Method: Measuring Lumen Maintenance of LED Light Sources*, addresses the measurement of lumen maintenance testing for LED light sources including LED packages, arrays and modules only. It does not provide guidance or recommendations regarding prediction estimations or extrapolations for lumen maintenance beyond the limits of the lumen maintenances determined from actual measurements. http://www.iesna.org/

[14] See CALiPER report on Long-Term Testing for a more detailed description of long-term testing procedures, drawing from early drafts of the LM-80 testing method and from methods used for long-term CFL lamp testing. This report is available from the DOE upon request, *Long-Term Testing of Solid-State Lighting, Solid-State Lighting CALiPER Program*, January 2009. Note that on average in CALiPER long-term testing comparing spot illuminance measurements to absolute photometry, differences of ±4% in relative lumen depreciation are observed (between spot illuminance and integrating sphere measurements).

term behavior—to investigate projections of product life—for SSL products which may be expected to have very long LED lamp life. Another objective of CALiPER long-term testing is to investigate other modes of failure.

Three of the replacement lamp products included in Round 9—09-63, 09-64, and 09-65—were subjected to lumen depreciation testing and found to have very rapid lumen depreciation rates, as illustrated in Figures 10a-c. Six samples of each product were operated at room temperature for 1000 hours and monitored regularly using spot illuminance measurements. Light output reduction in all samples was also clearly visible to the human eye when compared to control units which were not operated long-term. The long-term test samples all consistently depreciated as shown in Figures 10a-c.

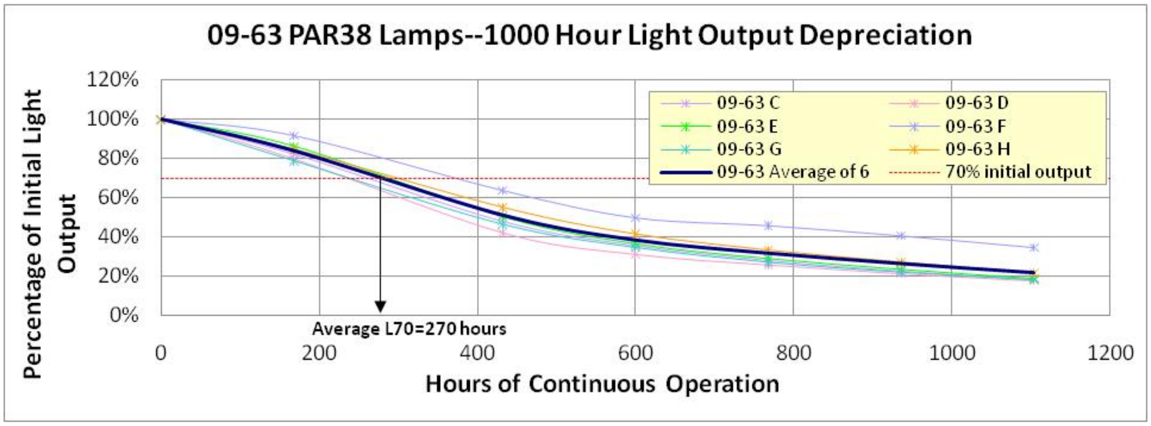


Figure 10a. Rapid Light Output Depreciation for SSL PAR38 Lamp

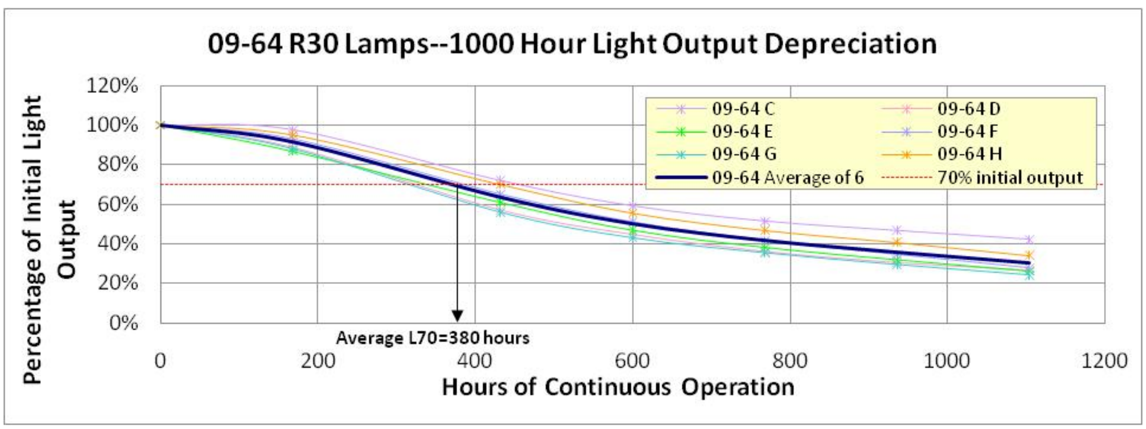


Figure 10b. Rapid Light Output Depreciation for SSL R30 Lamp

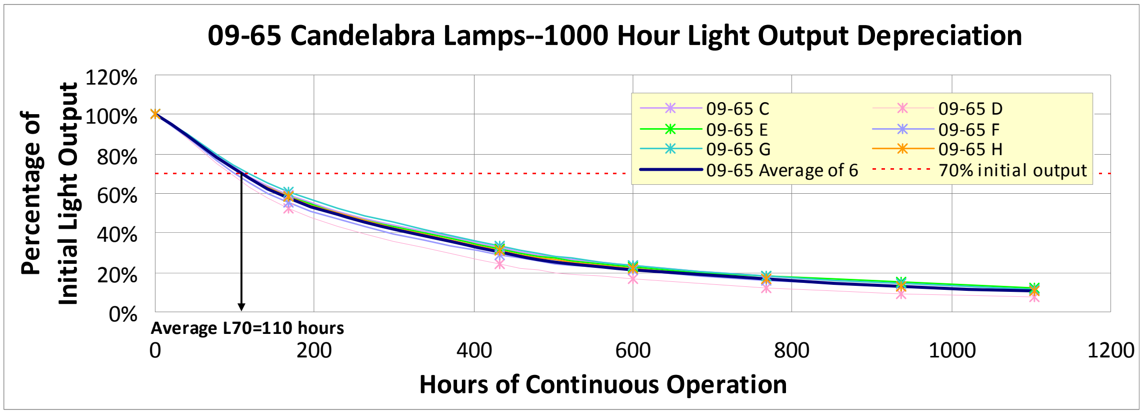


Figure 10c. Rapid Light Output Depreciation for SSL Candelabra Lamp

All three of these products have been widely sold by big-box retail stores and through online distributors for several months. All three products have both printed packaging claims stating "30,000 Hour Life (Life Rating of LED's)" and graphical depictions indicating that they last 10-15 times longer than incandescent bulbs. Yet, a simple, 1000 hour operational check reveals that the L_{70} life of these products is reached after less than 500 hours of operation at room temperature.

This exceedingly poor long-term performance does not appear to be typical across products on the market. Out of 15 different types of SSL replacement lamp products which have been long-term tested by CALiPER to date, these are the only products which have exhibited light output falling below 95% of initial light output within the first 1000 hours of operation. Nevertheless, because of their widespread distribution, these products may cause dissatisfaction in buyers for whom this might represent a first experience with LEDs used for general white lighting. This type of early failure in products with a wide market reach may threaten the long-term market potential for SSL technology.[15]

The great majority of SSL luminaires and integral replacement lamps do not appear to exhibit such early onset, rapid lumen depreciation—as illustrated in Figure 11, which summarizes preliminary results from CALiPER long-term testing on 26 products. Five of these products fall below 70% of initial light output well before 1000 hours of operation; four out of these five products are equipped with traditional 5mm LEDs (as opposed to surface mount LED package types).[16]

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[15] See the DOE report, *Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market*, for more information about market acceptance of CFLs and barriers to that acceptance. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/cfl_lessons_learned_web.pdf

[16] The results from long-term CALiPER testing will be detailed in a separate, exploratory report. Preliminary results are included here for the purpose of illustration. A paper summarizing testing comparing depreciation of traditional 5mm LEDs to High-Power LEDs can also be found in: Narendran, N., L. Deng, R.M. Pysar, Y. Gu and H. Yu, 2004. Performance characteristics of high-power light-emitting diodes. *Third International Conference on Solid State Lighting, Proceedings of SPIE* 5187:267-275. http://www.lrc.rpi.edu/programs/solidstate/pdf/LedPerformance.pdf

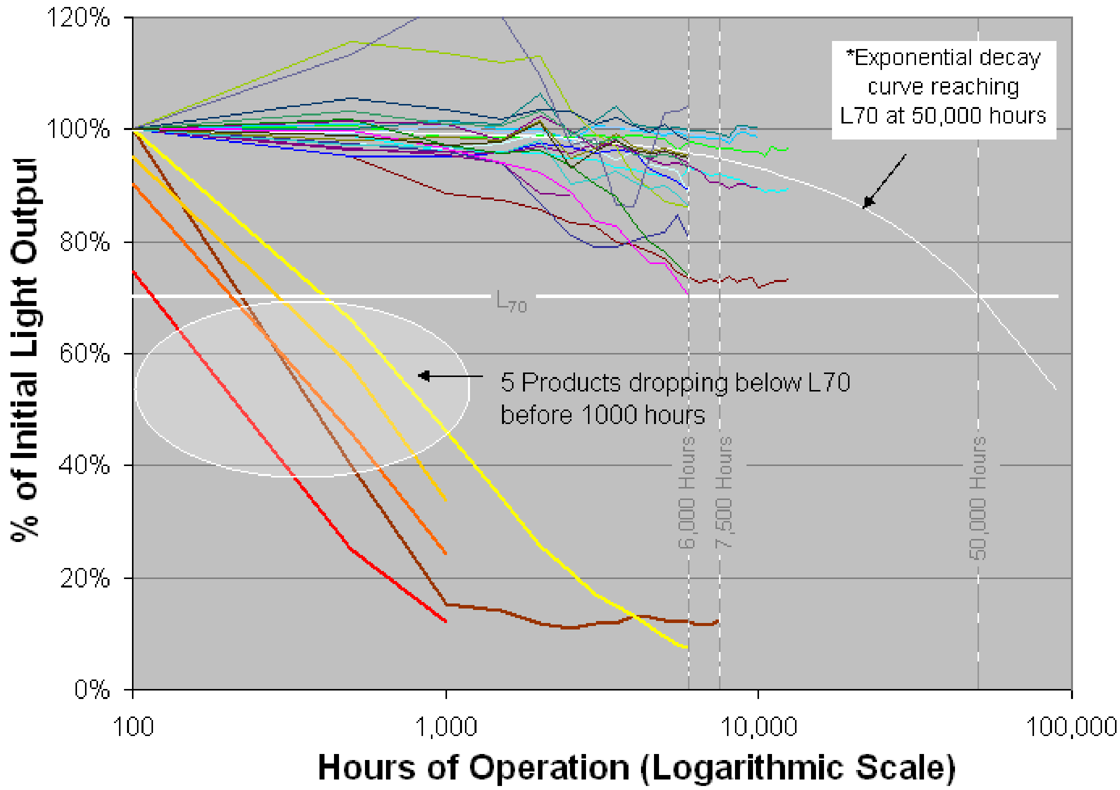

Figure 11. Long-term Lumen Depreciation for 26 CALiPER Fixtures and Replacement Lamps, Based on Spot Illuminance Measurements

The example provided by products which exhibit clear-cut, rapid lumen depreciation should serve standards committees, product buyers and specifiers, manufacturers, and numerous SSL stakeholder efforts. LM-79 and LM-80 testing provide solid, repeatable testing methods for the industry, but they are not pass/fail criteria, and, alone are not sufficient for determining and ensuring product reliability. To be effective, LM-79 and LM-80 test results must be interpreted by knowledgeable experts and used as pieces of a wider, rigorous design and product development process.

While LM-79 indicates that SSL testing can be conducted without seasoning samples, this does not preclude performing LM-79 testing at time equals zero and after 500 and 1000 hours of seasoning (usually a sphere test is sufficient), to perform a 1000 hour 'reality check.' This is not a conclusive test regarding long-term performance and results cannot be used to make projections, but can serve as a simple, powerful indicator. Any drop in light output of more than 5% in the first 1000 hours should send up red flags, indicating that more testing is needed to investigate reliability and long-term behavior of the overall product and to determine a justifiable basis for product ratings (other than the time=zero values). Likewise, if these tests show significantly different behavior between zero and 1000 hours when compared to expected variation based on LM-80 testing, then, again that is an indication that more testing is needed to investigate reliability and long-term behavior of the overall product. These tests should be conducted on a minimum of three to six samples (six samples is the default sample size for conventional lamps).[17]

Discussion of early onset depreciation testing or other overall product reliability testing is in the very early stages within standards organizations and may take months or years to develop into publishable standards or criteria. However, requesting test results from LM-79 at time-zero and after 1000 hours of seasoning (at 25° C ±5°) is straightforward and can be done by any of the LM-79 NVLAP or CALiPER-qualified independent testing labs. This is a simple reality check, to see if the initial lumen maintenance behavior of the overall product is indeed as predicted by LM-80 results for the LED chips and their operating regime in the product.

Conclusions from Round 9 of Product Testing

Key Conclusions

Round 9 of CALiPER testing clearly illustrates that SSL technology is more effectively implemented for some applications than others. While there are numerous commercially available SSL products which can compete admirably with incumbent technologies for recessed downlights and 2’x2’ troffer luminaires, other applications, such as replacement lamps show more nuanced results. In particular, 4’ linear replacement lamps that have been tested do not meet the light output and efficacies seen in 4’ T8 fluorescent lamps, even when those products are tested in troffers to obtain overall luminaire performance.

The general trend of increasing efficacy continues, with Round 9 products averaging 46 lm/W and ranging from 17 to 79 lm/W. Unfortunately, wide disparities are still observed in the accuracy of manufacturer specifications.

SSL recessed downlights are now capable of meeting or exceeding light output levels and light distribution characteristics of downlights equipped with 45-75W incandescent and halogen lamps, and the SSL products are meeting or exceeding color quality of CFL recessed downlights. One of the downlights is an ENERGY STAR-qualified product and fully meets the basic photometric performance levels defined in the criteria and published by the manufacturer. Another downlight exhibited performance characteristics which would appear to meet ENERGY STAR criteria, and it also has accurate, complete product performance claims. The other recessed downlight products (including the two CFL benchmarks) have absent, inaccurate, or misleading product literature. The fact that the choices for benchmark downlights are now 26W and 32W CFL products underscores the progress achieved. Two years ago, the highest performing SSL downlights were just achieving performance levels of 13W CFL downlights.

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[17] Note that for such a 1000 hour test to be valid, the initial measured performance at time-zero should be typical of the expected (rated) initial performance of the product. A measured performance at time-zero that is significantly different from the rated value may be a sign that the samples are not representative or that the samples have already been operated and depreciated before starting the testing cycle.

SSL troffer luminaires, designed as integral products to replace 2'x2' fluorescent troffers, are also performing admirably, with basic performance characteristics that meet or exceed the levels of two benchmark fluorescent 2'x2' troffers which were tested. One 2'x2' SSL troffer even exceeds the efficacy level of a benchmark high performance T8 fluorescent troffer. Conversely, 4' SSL linear replacement luminaires do not yet achieve performance levels of fluorescent linear replacement lamps—both when tested as bare lamps and when mounted in troffers and tested at the overall luminaire level.

A wide variety of small replacement lamps was tested, exhibiting a wide range of results. The average efficacy of SSL replacement lamps is increasing, but the majority of these lamps do not achieve the light output and intensity distributions of similar incandescent or halogen products and do not meet manufacturer equivalency claims. Two extremes are illustrated by two sets of products from two different manufacturers: both sets are sold in bubble-wrap packages in big-box retail stores. The replacement lamps from one manufacturer performed notably well and met packaging claims—one a replacement for 35W R20 lamps which only draws 7W, another a replacement lamp for 25W incandescent A-lamps which draws only 6W, and the third a 2W candelabra lamp (which unfortunately does not produce the lumen output of a 15W incandescent candelabra). The three replacement lamp products from another manufacturer illustrate the other extreme: a PAR38, an R30, and a candelabra lamp which all fail to meet the equivalency claims on their packages during initial testing and then exhibit very rapid lumen depreciation, falling below 70% of initial output after less than 500 hours of operation.[18]

Overall, about one-third of the products tested actually have accurate manufacturer ratings or specifications. About one-third of the products have manufacturer claims which only overstate the performance by about 10-20%. The remaining products either do not provide any manufacturer-published performance information or provide values which are vastly overstated by as much as 100%. The risk of consumer dissatisfaction due to products which do not perform as expected is great. Also, products such as the three SSL replacement lamps which use 5mm LEDs and depreciate down to negligible light output levels after only 1000 hours of operation, represent a serious threat for generating disappointment in early adopters of SSL technology, ultimately hindering SSL market potential.

[18] CALiPER shares all test results with manufacturers and distributors of products. Since receiving the CALiPER results, the retail chain where these three prematurely failing replacement lamps were purchased has indicated that they have recalled all of these products and implemented new, immediately applicable testing requirements for all SSL replacement lamps on order. These products were, however, still being sold through other retailers at the time of publication of this report.

Next Steps for the Industry and CALiPER Efforts

CALiPER, along with other DOE SSL commercialization support programs, is working with manufacturers, industry trade groups, and standards committees to address issues which may threaten long-term market potential for SSL. Insight from Round 9 of CALiPER testing is being used to improve and extend criteria for efforts such as ENERGY STAR criteria and the Lighting Facts label program.[19] Education efforts are ongoing though the technical information network (TINSSL). For example, CALiPER benchmark reports, DOE SSL fact sheets, and the Lighting Facts Product Performance Scale assemble guidance for manufacturers and buyers to better understand and evaluate equivalency statements on lighting products. LM-79 and LM-80 are standards which define testing methods, not pass/fail criteria. Educational material is available to help stakeholders understand and evaluate LM-79 test results. Similarly, the SSL Quality Advocates and other industry efforts are considering mechanisms for providing further guidance surrounding product reliability testing.

It is essential that manufacturers, retailers, and buyers understand that LM-79 and LM-80 are standards which explain how to perform testing on LED products, but they are not pass/fail tests and they are not all-encompassing. Testing using these standard methods is essential, but after the testing is completed, the results must be analyzed and used appropriately. LM-79 results reflect initial product performance at 25°C, so performance of the product in typical application settings and over time should also be considered. LM-80 reflects performance of the LED chips alone under various operating conditions, so actual behavior of the chips in the final product should be checked to ensure correlation with LM-80 long-term performance expectations.

Standards efforts are working to bridge gaps in testing standards. For example, while LM-80 provides a standardized method for testing long-term performance of LED chips, there is no current standard for testing long-term performance of integral products. Simple recommendations such as performing LM-79 testing at time-zero and again after 1000 hours of seasoning may serve in some cases to identify premature failure in products, or to reveal behavior in integral products which does not appear to coincide with expected long-term behavior based on LM-80 results.

CALiPER welcomes input from industry and has established a guidance committee to provide a more direct channel for receiving feedback and testing ideas from key stakeholders, such as energy-efficiency programs, utilities, engineers, and lighting designers. In response to needs identified by the CALiPER Guidance Committee, CALiPER testing is under way on outdoor products and cove lights, and new CALiPER benchmark reports are under development. Also, CALiPER detailed reports can now be easily searched with a powerful online tool which enables finding specific reports, listing results, and comparing products based on a number of performance parameters.

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

DOE SSL Commercially Available LED Product Evaluation and Reporting Program

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