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CALiPER

Application Summary Report 16:

LED BR30 and R30 Lamps

July 2012

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Prepared by:

Pacific Northwest National Laboratory

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1 Preface

The U.S. Department of Energy (DOE) 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 of North America [IES] approved method LM-79-08[1]) conducted by accredited, independent laboratories.[2] Results from CALiPER testing are available to the public via detailed reports for each product or through summary reports, which assemble data from several product tests and provide comparative analyses.[3]

It is not possible for CALiPER to test every SSL product on the market, especially given the rapidly growing variety of products and changing performance characteristics. Starting in 2012, each CALiPER summary report focuses on a single product type or application. Products are selected with the intent of capturing the current state of the market—a cross section ranging from expected low to high performing products with the bulk characterizing the average of the range. The selection does not represent a statistical sample of all available products. To provide further context, CALiPER test results may be compared to data from LED Lighting Facts,[4] ENERGY STAR® performance criteria,[5] technical requirements for the DesignLights™ Consortium (DLC) Qualified Products List (QPL),[6] or other established benchmarks. CALiPER also tries to purchase conventional (i.e., non-SSL) products for comparison, but because the primary focus is SSL, the program can only test a limited number.

It is important for buyers and specifiers to reduce risk by learning how to compare products and by considering every potential SSL purchase carefully. CALiPER test results are a valuable resource, providing photometric data for anonymously purchased products as well as objective analysis and comparative insights. However, LM-79-08 testing alone is not enough to fully characterize a product—quality, reliability, controllability, physical attributes, warranty, compatibility, and many other facets should also be considered carefully.

For more information on the DOE SSL program, please visit http://www.ssl.energy.gov.

[1] IES LM-79-08, *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. For more information, visit http://www.iesna.org/.

[2] CALiPER only uses independent testing laboratories with LM-79-08 accreditation that includes proficiency testing, such as that available through the National Voluntary Laboratory Accreditation Program (NVLAP).

[3] CALiPER summary reports are available at http://www.ssl.energy.gov/reports.html. Detailed test reports for individual products can be obtained from http://www.ssl.energy.gov/search.html.

[4] LED Lighting Facts is a program of the U.S. Department of Energy that showcases LED products for general illumination from manufacturers who commit to testing products and reporting performance results according to industry standards. The DOE LED Lighting Facts program is separate from the Lighting Facts label required by the Federal Trade Commission (FTC). For more information, see http://www.lightingfacts.com.

[5] ENERGY STAR is a federal program promoting energy efficiency. For more information, visit http://www.energystar.gov.

[6] The DesignLights Consortium Qualified Products List is used by member utilities and energy-efficiency programs to screen SSL products for rebate program eligibility. For more information, visit http://www.designlights.org/.

2 Report Summary

This report analyzes the independently tested performance of 13 LED products labeled as BR30 or R30 lamps. The test results indicate substantial improvement versus earlier CALiPER testing of similar products, and performance comparable to recent data from LED Lighting Facts and ENERGY STAR.

Many of the LED lamps tested could be effective replacements for conventional directional lamps in the right application. The lumen output of many of the products was equivalent to 65 W or 75 W incandescent BR30/R30 lamps, and all emitted between 450 and 860 lumens. Efficacy ranged from 51 to 91 lm/W, although all except one of the products was between 51 and 65 lm/W. The LED BR30/R30 lamps had luminous intensity distributions ranging from narrow to very wide; the suitability of these distributions depends on the application. Although there were a few exceptions, most of the lamps had color quality attributes that were similar to incandescent lamps. An improvement compared to earlier testing, 12 of the 13 products had a power factor higher than 0.70.

More than half of the LED products tested had luminous intensity distributions similar to compact fluorescent (CFL) R30 lamps, with wider beam angles than are typical of conventional incandescent directional lamps. Moving forward, increases in lumen output and improvement in luminous efficacy—although still worthwhile goals—may be less important than increasing the number of products with a luminous intensity distribution similar to incandescent benchmarks. Further, having multiple combinations of lumen output (e.g., 450 lumens, 700 lumens) and distribution type (e.g., spot, narrow flood, flood, wide flood) from a single manufacturer could help specifiers meet the needs of a given application.

With the introduction of integrated LED lamps, the existing designations for reflector lamps are becoming insufficient because they are primarily based on geometric and optical considerations rather than performance. LED lamp manufacturers are faced with a difficult task in identifying an appropriate designation, given the performance overlap between PAR, R, BR, and ER lamps. It is possible that a new or altered naming convention would be more appropriate for LED products, helping purchasers obtain products that best meet their needs.

3 Background

Directional Lamps

Directional lamps—sometimes referred to as reflector lamps—are an essential tool for both ambient and accent lighting, especially in residential and light commercial applications. Directional lamps come in many different shapes, including R (reflector), BR (bulged reflector), ER (elliptical reflector), and PAR (parabolic aluminized reflector), among other specialized forms. This family of lamps shares the attribute of having directional emission, with the different designations helping to indicate the material, shape, and optical system. Importantly, R, BR, and ER lamps are formed from blown glass, whereas PAR lamps combine a pressed glass lens with a separate reflector. There are no rigid performance criteria to delineate these lamp types, although generalized characterizations are possible. For example, conventional BR- and R-shaped lamps tend to have much softer distributions with wider beam angles and lower efficacies compared to PAR lamps.

All reflector lamps originally utilized incandescent filaments, which when uncontrolled are characterized as omnidirectional point sources. Taking advantage of this characteristic, reflector lamps were designed to control light using reflectors and/or lenses, resulting in a directional emission that is beneficial for many applications. Today, halogen technology is used to improve efficacy—most notably with PAR lamps—and efforts have been made to introduce energy-efficient CFL and metal halide lamps that can effectively replace standard incandescent reflector lamps.[7] However, the different operating characteristics of CFL and metal halide lamps (e.g., warm-up and restrike time, limited sizes, poor dimming performance, etc.) make them less suitable for meeting the performance requirements of the lamp type and/or application.

LEDs are inherently directional, which makes them well suited for use in lamps intended to replace conventional reflector lamps. Additionally, the optics can be arranged at the LED package level, eliminating the need for reflectors and lenses that shape the beam (e.g., integrated LED lamps do not use parabolic aluminized reflectors), although they may still be used. However, because they do not use the same optical system as conventional lamps, the designation process can be ambiguous. In other words, it is less clear when an LED lamp should be called a PAR lamp, BR lamp, R lamp or something altogether different. Nonetheless, some LED lamps that perform similarly to PAR lamps are identified as BR or R lamps by the manufacturer, and some LED lamps that perform similarly to BR or R lamps are called PAR lamps.

Definition and Physical Characteristics

The nomenclature for lamps is defined by the American National Standard Lighting Group (ANSLG) in document ANSI C79.1-2002. The first letter symbol used in a lamp designation identifies the shape classification of the bulb. The R symbol (generally meaning *reflector*) is defined to indicate, "A bulb that includes a parabolic or elliptical section below the major diameter designed to receive a reflective coating so as to direct the beam of light." Notably, the R designation is sometimes considered to be inclusive of subcategories such as PAR, BR, or ER; in this report, it is treated as a unique designation. The B symbol (generally meaning *bulged*) is defined to indicate, "A bulb in which the curve making up the major portion of the side of the bulb has a radius greater than one-half the bulb diameter and a center in the plane of maximum diameter." The first number symbol indicates the diameter of the bulb in eighths of an inch. For example, a BR30 lamp has a nominal diameter of 30 eighths of an inch, or 3.75 inches.

[7] CFL products are typically listed as R-, BR-, or PAR-shaped lamps, whereas metal halide products are typically PAR lamps.

Separately, ANSI C78.21-2003 defines standard lamp classes for PAR, R, BR, and ER lamps; both BR30- and R30-designated lamps must meet the dimensions provided in Figure C78.21-266. Accordingly, they must have an overall length between 4.875 inches and 5.375 inches, and a maximum diameter of approximately 4.25 inches, among other dimensional tolerances. There is no minimum diameter specified.

Classifying the Distribution of Directional Lamps

Directional lamps are commonly specified based on distribution (e.g., beam angle), although BR and R lamps are often specified more loosely than PAR lamps (e.g., simply *flood* or *spot*). Spot lamps typically have a nominal beam angle of 20° or less, whereas flood lamps typically have a nominal beam angle of 25° or more. Figure 1 illustrates the relationship between three descriptors of distribution: center beam candlepower (CBCP), beam angle, and field angle. Complete descriptions of these terms, among others, are included in Appendix A.

To be more specific, directional lamps can be classified with an adjective describing their nominal distribution: very narrow spot (VNSP), narrow spot (NSP), spot (SP), narrow flood (NFL), flood (FL), or wide flood (WFL). However, there is no industry standard defining these descriptors in terms of beam angle, and there is sometimes overlap in the categories across different manufacturers. ANSI C78.379-2006 recommends that distributions are denoted with both the descriptor and the beam angle, which allows the numerical designations to be compared (e.g., FL40 for a flood lamp with a 40° beam angle, or NSP9 for a narrow spot with a 9° beam angle).

Because of variability in the manufacturing process, beam angles for blown glass lamp types (R, BR, and ER) are assigned a tolerance of ±12°. For example, the 25° lamp classification can include lamps having a beam angle between 13° and 37°. The more precise pressed glass lamps (e.g., PAR) have smaller tolerances that vary based on the nominal beam angle. Importantly, even lamps having the same numerical classification can produce patterns of light that appear substantially different. In order to prevent ambiguity, CALiPER does not convert measured beam angles to nominal beam angles.

Regulations

Beginning with The Energy Policy Act of 1992 (EPAct 1992), the U.S. Government—specifically DOE—has required directional lamps to meet certain luminous efficacy requirements. EPAct 1992 set the minimum efficacy of some PAR and R lamps, whereas all ER and BR lamps—which at that time were considered niche products with small market share—were excluded. Specifically, the requirements applied to PAR and R lamps with diameters greater than 2.75 inches, having a medium base, and operating near line voltage. The legislation set minimum efficacy levels for wattage bins starting with 40–50 W (10.5 lm/W) and ending with 156–205 W (15.0 lm/W). These minimum efficacies were sufficiently high that it was almost impossible for R lamps to meet the requirements. However, instead of promoting more efficient PAR lamps, the market shifted to the exempted BR and ER lamps.

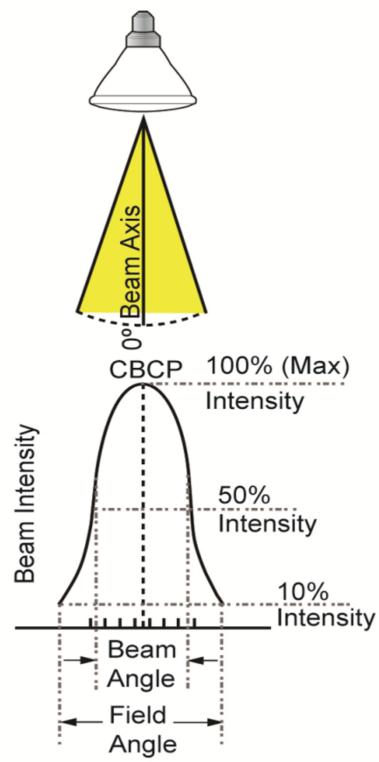

Figure 1. Describing and quantifying the distribution of directional lamps. Beam angle is the point at which the luminous intensity is 50% of its greatest value. Field angle is the point at which the luminous intensity is 10% of its greatest value.

To remedy the unforeseen outcomes of EPAct 1992, the wattage of ER and BR lamps has been regulated through the DOE Appliance Standards program.[8] In 1997, DOE limited BR30 lamps to 85 W or less and BR40 lamps to 120 W or less (62 FR 29222, 29237). Later, the Energy Independence and Security Act of 2007 (EISA), extended the 10.5 and 15.0 lm/W EPAct 1992 efficacy requirements to lamps with diameters greater than 2.25 inches (down from 2.75 inches), and removed the exemption for BR and ER lamps. In 2009, DOE published a final rule (74 FR 34080), which set efficacy values that account for differences in rated input power, emission spectrum, lamp diameter, and voltage. The regulation applies to all lamps manufactured on or after June 30, 2012. The formulaic approach results in a range of minimum lamp efficacies, from 14.2 to 22.9 lm/W. Consequently, new (or improved) light sources will have to replace current incandescent PAR, R, ER, and BR lamps. This represents a unique opportunity and challenge for directional LED lamps.

Installed Base

As of January 2012, DOE estimated that BR30 lamps made up approximately 38% of the installed base of PAR, BR, and R lamps, which corresponds to approximately 2.02 million units.[9] Approximately 89% of the products were estimated to be installed in residential buildings. The prevalence of BR30 lamps is likely a result of earlier energy efficiency regulations. Regardless of the cause, substantial energy savings are possible because of the typically low efficacy of incandescent BR30 lamps.

Selected Lamps

This analysis includes LED products that were labeled as BR30 or R30 lamps by the manufacturer. This methodology most closely corresponded to the situation that might be faced by a specifier replacing an incandescent BR30 lamp.

One product intended to be included in this group was listed as an "FL30/FL30L LED Lamp," but the lamp received was under a different brand and carried a PAR30 label. Further, the performance was most similar to a PAR lamp—the lamp had a spot distribution with a beam angle less than is typically seen for BR- or R-shaped lamps. This issue highlights the difficulty faced by manufacturers in labeling products, as well as the challenge faced by purchasers seeking the most appropriate LED directional lamp. It is possible that a new or altered naming convention would be more appropriate for LED products, given that they do not use the same optical systems as conventional directional lamps. However, it is also important that product names effectively communicate important performance criteria while maintaining consistency with established conventions.

[8] For more information, visit http://www1.eere.energy.gov/buildings/appliance_standards/.

[9] U.S. Department of Energy. 2012. *Energy Savings Potential of Solid-State Lighting in General Illumination Applications*. Solid-State Lighting Program. Available at: http://www1.eere.energy.gov/buildings/ssl/tech_reports.html

4 Results

CALiPER LED BR and R Lamp Test Data

Series 16 LED Lamps

This report analyzes the independently tested performance of 13 LED lamps labeled as BR30 or R30 replacements, which were anonymously purchased in March 2012. In this report, they are referred to as the Series 16 products. For more on the product selection parameters, both in general and as they pertain to this group of products, see Appendix B.

The Series 16 products are shown in Figure 2. The exact shape and construction of the lamps varied substantially, although most of the products met the ANSI-defined length and diameter requirements for BR30 and R30 lamps—a complete discussion is available in the analysis section. Most of the lamps used some type of diffusing lens covering the entire emitting area of the lamp.

All of the units were tested according to IES LM-79-08, using both an integrating sphere and goniophotometer; for each of the Series 16 products, the difference in measured lumen output between the two methods was less than 3%, which is typical. Except for luminous intensity distribution characteristics, all values included in this report were measured using the integrating sphere method. All reported values are the mean of the two samples that were tested; the exception is D_{uv}, which is reported as the value furthest from zero. Table 1 summarizes key results from CALiPER testing.

Past CALiPER Results for BR and R Lamps

The CALiPER program previously tested seven LED lamps labeled as replacements for R30 incandescent lamps. This dataset includes five products purchased in 2007, one product purchased in 2009, and one product

Figure 2. Photographs of products included in this series of CALiPER testing.

Table 1. Results of CALiPER tests for the Series 16 LED BR30/R30 lamps. Performance criteria include initial output, total input power, luminous efficacy, power factor, color rendering index (CRI), special color rendering index R_9, correlated color temperature (CCT), and D_{uv}. The *Labels* column indicates whether the product was ENERGY STAR qualified (ES) or listed by LED Lighting Facts (LF).

DOE CALiPER Test ID	Initial Output (lm)	Total Input Power (W)	Luminous Efficacy (lm/W)	Power Factor	CRI	R_9	CCT (K)	D_{uv}	Labels	
12-15	544	6.0	91	0.53	81	20	5389	0.0043		
12-16	564	11.1	51	0.97	83	20	3520	-0.0008		
12-17	745	12.1	62	0.74	84	25	2675	-0.0029	ES	
12-18	859	14.0	61	0.78	81	13	2704	-0.0025	ES	
12-19	740	11.3	65	0.98	77	-10	6586	0.0026		
12-20	550	9.5	58	0.93	83	40	2769	-0.0031		LF
12-51	595	11.7	51	0.88	92	87	2663	-0.0022	ES	LF
12-52	463	8.1	57	0.93	85	47	2966	-0.0028		
12-53	616	12.1	51	0.94	93	84	2729	-0.0021		
12-55	699	13.5	52	0.76	83	30	2734	-0.0014		
12-56	667	11.6	58	0.87	82	3	2709	0.0010	ES	
12-57	705	12.6	56	0.80	82	17	3112	0.0010	ES	LF
12-59	860	14.3	60	0.77	81	12	3000	0.0010		
Minimum	463	6.0	51	0.53	77	-10	2663	-		
Mean	662	11.4	59	0.84	84	30	3350	-		
Maximum	860	14.3	91	0.98	93	87	6586	-		

purchased in 2011. A summary of key results is available in Appendix C. In general, these products represent earlier iterations of integrated LED lamp technology; as expected, the performance is typically worse than for the Series 16 products.

Supplemental LED Downlight Data

ENERGY STAR

Both BR and R lamps are covered by the ENERGY STAR program; the pertinent performance criteria from the *ENERGY STAR Program Requirements for Integral LED Lamps* (version 1.4) are provided in Table 2. Other program requirements beyond the scope of LM-79-08 testing conducted by CALiPER are not included. As of May 30, 2012, 36 LED BR or R lamps were ENERGY STAR qualified, although there is no differentiation by lamp diameter. In contrast, over 500 LED PAR lamps were ENERGY STAR qualified, representing more than half of the nearly 900 qualified lamps. Although a majority of the requirements are the same, the minimum lumen output for PAR lamps is set by a tool that also considers luminous intensity distribution, whereas other directional lamp types must have a lumen output greater than 10 times the nominal wattage of the incandescent lamp they are intended to replace. Despite this difference, the breakdown of ENERGY STAR qualified directional lamps

Table 2. Minimum *ENERGY STAR Program Requirements for Integral LED Lamps* (v1.4) criteria relevant to CALiPER testing of LED BR30/R30 lamps.

Initial Output (lm)	Efficacy (lm/W)	Power Factor	Distribution	CRI	R_9	CCT (K)
Target wattage of standard incandescent lamp multiplied by 10	45 (> 2.5" diameter)	0.70 (> 5 W)	80% of total initial lumens within a solid angle of π steradians	80	0	2700 3000 3500 4000

provides anecdotal evidence that a majority of LED product manufacturers are classifying directional lamps as PAR lamps, despite conflict with the nomenclature.

Summary statistics for ENERGY STAR qualified BR and R lamps are provided in Table 3. Notably, because lamp diameter is not explicitly listed by ENERGY STAR, this data does not correspond exactly to the CALiPER Series 16 results. Specifically, the lumen output of LED lamps is often affected by the lamp size, because larger lamp sizes have more surface area available for dissipating heat from the LEDs.

LED Lighting Facts Data

As of May 30, 2012, LED Lighting Facts listed 398 PAR30 or R30 lamps, grouped in a single category. Given that PAR lamps are a specialized type of reflector lamp with unique performance attributes, this dataset does not necessarily correspond to the CALiPER Series 16 results. In particular, distribution characteristics may be different; however, this assumes LED product manufacturers are accurately labeling products to reflect performance similar to conventional products in the given category. Summary statistics for the PAR30/R30 lamps listed by LED Lighting Facts are provided in Table 4.

CALiPER Testing of Conventional Product Benchmarks

In conjunction with testing of the Series 16 LED products, three conventional benchmarks were tested, including one 65 W incandescent BR30, one 15 W CFL R30, and one 16 W CFL BR30. These three products supplement two conventional benchmarks from previous testing, including one 65 W incandescent R30 and one 15 W CFL R30. These five products all emitted between 650 and 841 lumens, with the incandescent lamps having a mean efficacy of 11 lm/W and the CFL products having a mean efficacy of 50 lm/W. All of the products had a nominal

Table 3. **Summary data for ENERGY STAR-qualified BR and R lamps.** Includes 36 products listed as of May 30, 2012. ENERGY STAR does not differentiate listed products based on lamp diameter.

	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	CRI	CCT (K)
Minimum	250	5.1	42	-	2700
Mean	501	9.6	52	-	2942
Maximum	850	14.0	88	-	3000

Table 4. **Summary data for R30/PAR30 lamps listed by LED Lighting Facts.** Includes 398 products listed as of May 30, 2012. LED Lighting Facts does not differentiate between R and PAR lamps.

	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	CRI	CCT (K)
Minimum	292	6.0	30	33	2662
Mean	619	11.8	53	82	3407
Maximum	1,100	20.4	95	95	7783

CCT of 2700 K, with the incandescent lamps having a CRI near 100 and the CFL lamps having a CRI in the low 80s. The CFL lamps had notably wider beam and field angles than their incandescent counterparts. Summary data for these five products is available in Appendix D. Figure 3 illustrates the difference in luminous intensity distribution for typical incandescent and CFL BR30 lamps.

Characterizing Conventional Products

CALiPER is focused on testing SSL products and is only able to test a limited number of conventional benchmarks. CALiPER cannot test enough conventional products to cover the entire scope of available incandescent BR and R lamps. To supplement the limited CALiPER data, a profile of the conventional product market was established by reviewing manufacturer literature.[10] This review included dozens of BR30, ER30, and R30 lamps from three major manufacturers (GE Lighting, Philips, and OSRAM SYLVANIA). Specialty lamps, such as colored lamps, were excluded. In many cases, only limited information in the form of nominal values was available, and IES-format files were only provided for a few products.

As evidenced by CALiPER testing of conventional products, actual performance can be substantially different from listed performance. For example, the most recent BR30 incandescent benchmark tested by CALiPER (12-54) had a beam angle of 83°, despite being listed as having a beam angle of 55°. This example highlights the limitations of collecting catalog data, which is usually comprised of nominal values. Another challenge in characterizing conventional BR/ER/R lamps is the prevalence of numerous iterations of similar products (e.g., clear lens versus frosted lens), which often have slightly different performance characteristics. Further, many incandescent BR/ER/R lamps are rated for operation at 130 V, and have substantially different performance if operated at 120 V. For example, one product surveyed was listed as producing 785 lumens if operated at 130 V, but 585 lumens when operated at 120 V.

Notably, manufacturing of some of the surveyed products will be prohibited in the near future as new energy efficiency regulations take effect. All three manufacturers offered both halogen and CFL alternatives to the standard incandescent products, although the diversity of options was generally more limited. The performance of the surveyed lamps of each source type can be summarized as follows:

Incandescent

- Output ranged from 320 lumens to more than 1,000 lumens, with luminous efficacy between 6 and 12 lm/W. A vast majority of products were listed as having an input power of 65 W.
- The nominal beam angle ranged from 20° to 60°. Notably, many products did not provide a numerical designation to indicate the distribution type. The most common listed beam angles were 20°, 30°, 55°, and 60°. A majority of products had a flood distribution (55 or 60 degree nominal beam angle).
- All products had a nominal CCT of 2700 K, and by definition a CRI approaching 100.
- The rated lifetime generally ranged from 1,600 to 2,500 hours, with some products rated at 4,000 hours.

Halogen

- Far fewer halogen BR/ER/R lamps were available, with two of the surveyed manufacturers offering only one each.
- Rated output ranged from 570 to 730 lumens, with luminous efficacy between 12 and 15 lm/W. The survey included lamps rated at 40, 50, and 60 W.

[10] The review was not intended to be comprehensive, but simply indicative of the typical range of performance.

- The listed beam angle ranged from 21° to 43°, although only two distinctly different products provided this information.
- The color quality attributes were similar to the incandescent lamps.
- The rated lifetime was either 2,500 or 3,000 hours.

CFL

- All three manufacturers offered several R30 or BR30 CFL lamps.
- Rated output ranged from 600 to 762 lumens, with luminous efficacy between 38 and 51 lm/W. As with halogen lamps, it appears the primary target is matching the output of 65 W incandescent lamps.
- The nominal beam angle ranged from 120° to 135°. As with the other source types, many products did not provide a numerical designation to indicate the distribution type. As confirmed in CALiPER testing, the CFL lamps do not provide the same distribution as incandescent or halogen lamps; rather they have much wider distributions, similar to a Lambertian emitter (cosine distribution), as demonstrated in Figure 3.
- A majority of products had a nominal rated CCT of 2700 K, but products with CCTs of 3000 K, 3500 K, 4100 K, 5000 K, and 6500 K were also available.
- The rated lifetime ranged from 6,000 to 8,000 hours.

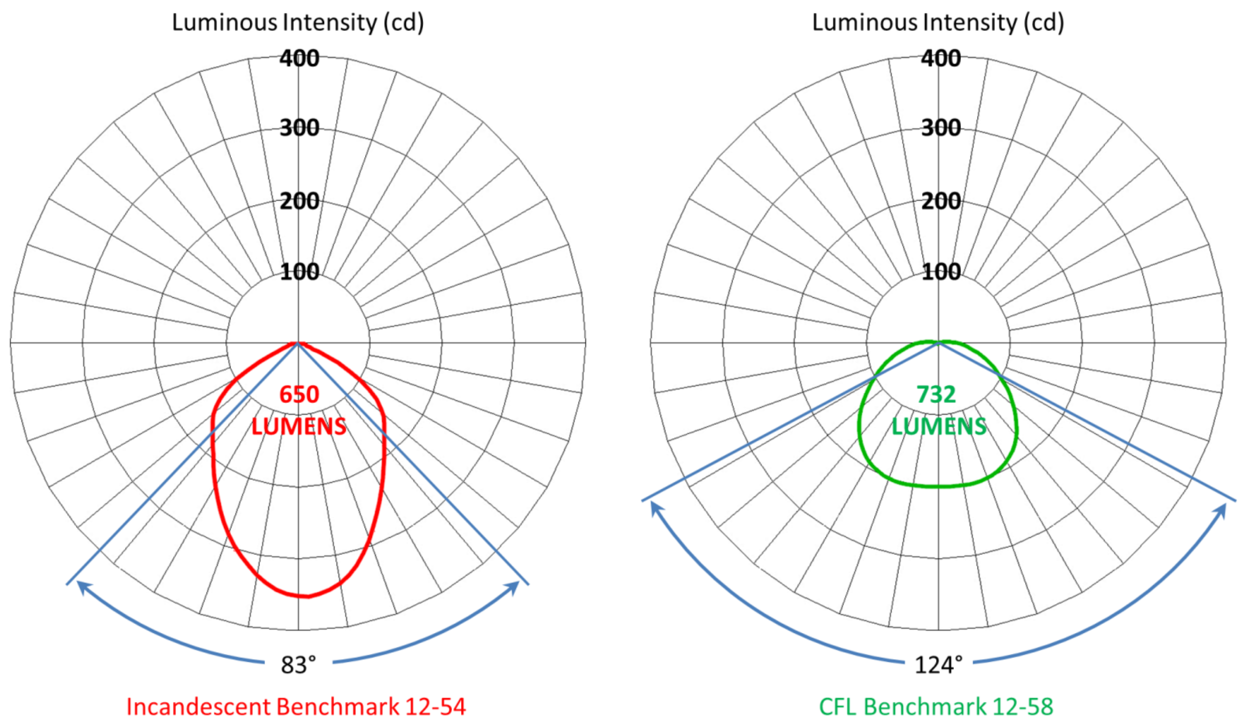

Figure 3. Polar plots of luminous intensity distribution for two of the Series 16 benchmarks, representing typical incandescent and CFL BR30 lamps. Despite emitting more lumens, the CFL had a much lower CBCP and its beam angle (124°) was much wider than the incandescent benchmark (83°). Like most CFL BR30 lamps, the luminous intensity distribution of 12-58 resembled a cosine distribution, which would appear as a circle on a polar plot.

5 Analysis

Lumen Output and Efficacy

The Series 16 LED BR30/R30 lamps had measured output ranging from 463 to 860 lumens, with a mean of 662 lumens. This is a substantial improvement over previously tested BR30/R30 lamps, as shown in Figure 4. The mean lumen output was approximately equivalent to the ENERGY STAR-defined level for a 65 W incandescent lamp, and 7 of 13 lamps reached that threshold. Two lamps exceeded the lumen output threshold for equivalence to a 75 W incandescent directional lamp. The range was somewhat smaller than that found for incandescent lamps in the review of manufacturer data. Similarly, the CALiPER datasets for both lumen output and efficacy are representative of the LED Lighting Facts and ENERGY STAR datasets, although they do not reach the high and low extremes. Efficacy versus lumen output is shown in Figure 4.

All of the Series 16 LED products exceeded 51 lm/W, which is greater than the ENERGY STAR criterion of 45 lm/W. The most efficacious product was measured at 91 lm/W, whereas the second most efficacious product was measured at 65 lm/W; notably, both had a CCT above 5000 K. The mean efficacy was 59 lm/W. This level of performance is generally better than the CALiPER-tested CFL BR30/R30 benchmarks, which ranged from 46 to 53 lm/W, and is much better than typical incandescent performance (6 to 12 lm/W).

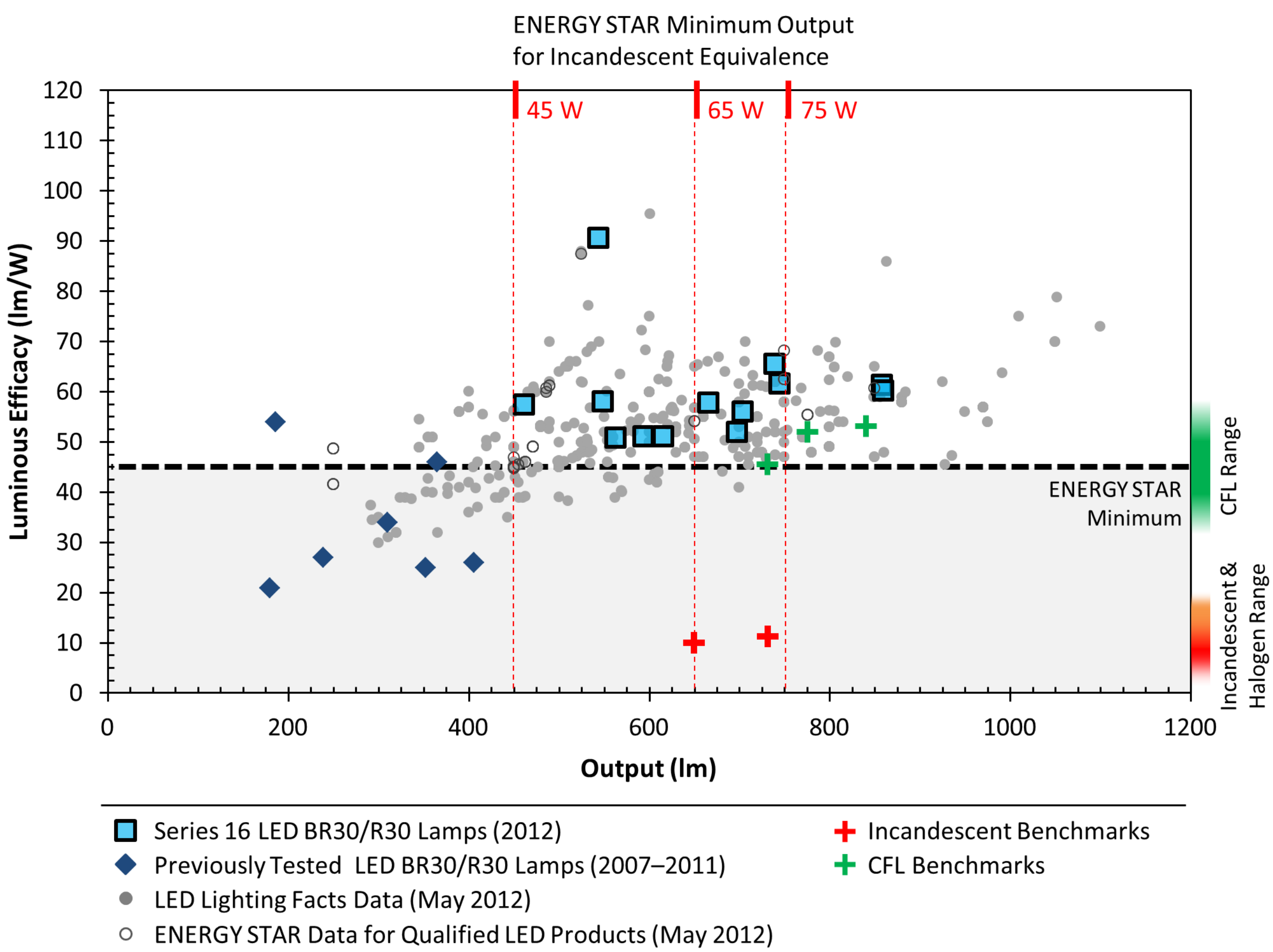

Figure 4. Luminous efficacy versus lumen output for the Series 16 LED BR30/R30 lamps compared to other datasets. The performance range was similar to LED Lighting Facts, and in general the LED lamps had higher efficacy than both incandescent and CFL BR30/R30 lamps. The lumen output has increased over time, with many lamps now matching the lumen output of 65 W or 75 W incandescent BR30/R30 lamps. Both of the CALiPER incandescent lamps were nominally 65 W.

Distribution of Light

Although there are no specific boundaries, luminous intensity distribution is a fundamental factor in differentiating between directional lamp types, at least for conventional incandescent and halogen products. Thus, it would seem that LED product manufacturers should strive to use product labels that best match performance with that of conventional products. However, this goal is already complicated by CFL reflector lamps, which do not match the luminous intensity distribution of their incandescent counterparts. Unfortunately, this may lead purchasers or specifiers to products that do not perform as expected.

There was substantial variability in the distribution of the Series 16 LED products, with beam angles ranging from 23° to 129°, as shown in Figure 5. Eight of the products performed most similarly to directional CFL lamps, rather

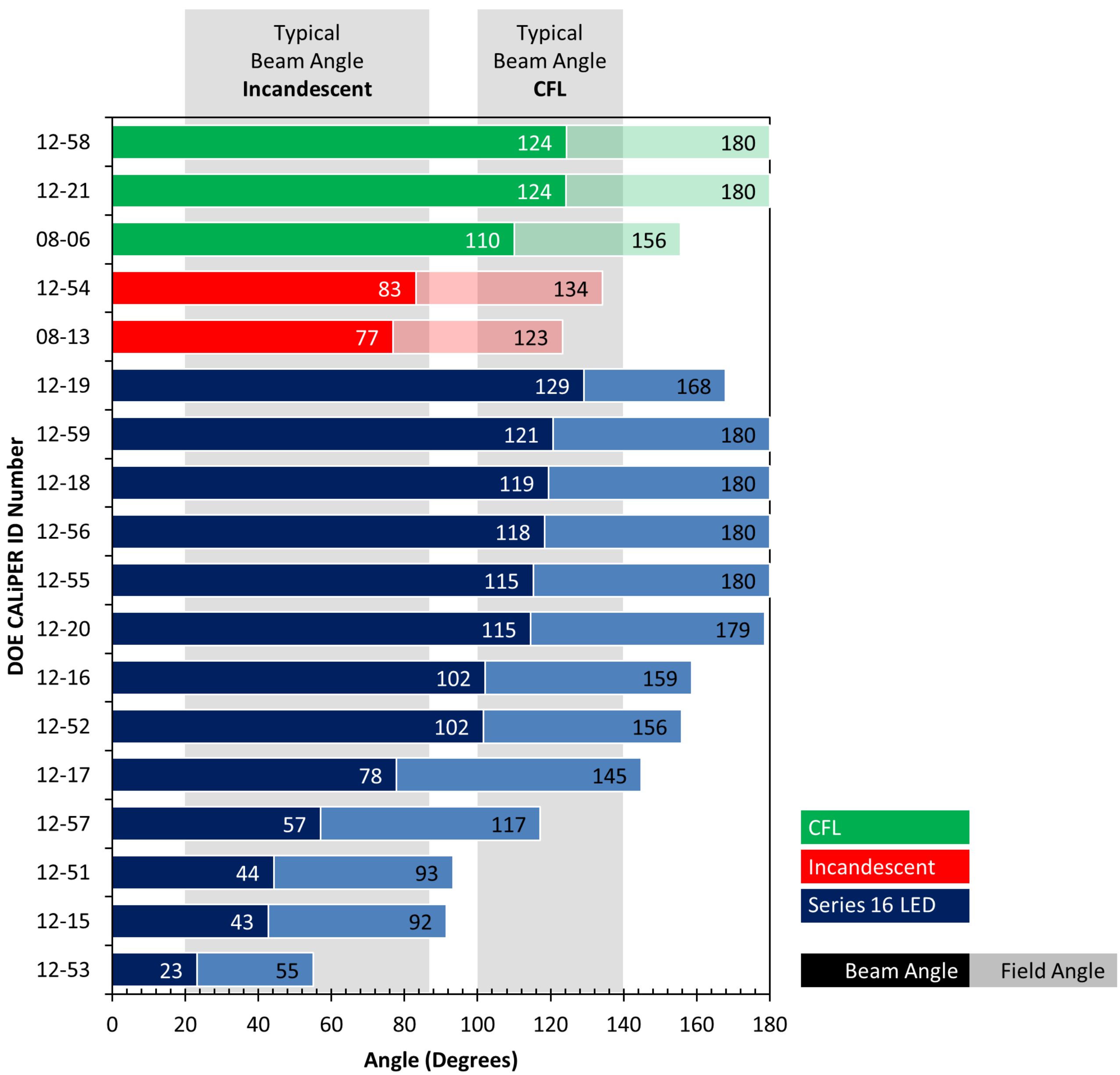

Figure 5. Beam angle and field angle of the Series 16 LED BR30/R30 lamps compared to CALiPER incandescent and CFL BR30/R30 benchmarks. The typical nominal beam angles are based on a review of manufacturer literature as well as CALiPER test data. Many of the Series 16 LED products had distributions similar to CFL reflector lamps rather than incandescent reflector lamps.

than the more common incandescent or halogen BR/R lamps. These eight products had beam angles ranging from 102° to 129°. Five products had luminous intensity distributions within the range of incandescent or halogen products found in the review of manufacturer literature and/or CALiPER test results. These products had beam angles between 23° and 78°, which covers both nominal spot and flood distributions.

Not all aspects of a luminous intensity distribution can be captured numerically. In some applications, the smoothness of the beam pattern from the center to the edge can be very important. This characteristic lacks a metric, but adjectives such as "smooth," "spotty," or "uneven" are sometimes used. This attribute was not analyzed as part of this series of CALiPER testing.

Color Characteristics

Because they are most often used for ambient or object lighting, color quality is an important aspect to consider when evaluating BR30/R30 lamps. Of particular importance is performance relative to incandescent lamps, which are the incumbent technology in this application category. The CCT of the Series 16 LED BR30/R30 lamps ranged from 2663 K to 6586 K, as shown in Figure 6. More importantly, 10 of the 13 products had a nominal CCT of 2700 K or 3000 K,[11] which matches typical incandescent and CFL BR30/R30 lamps. Only two products (12-15 and 12-19) did not fall within the range considered acceptable for ENERGY STAR qualification. Although higher

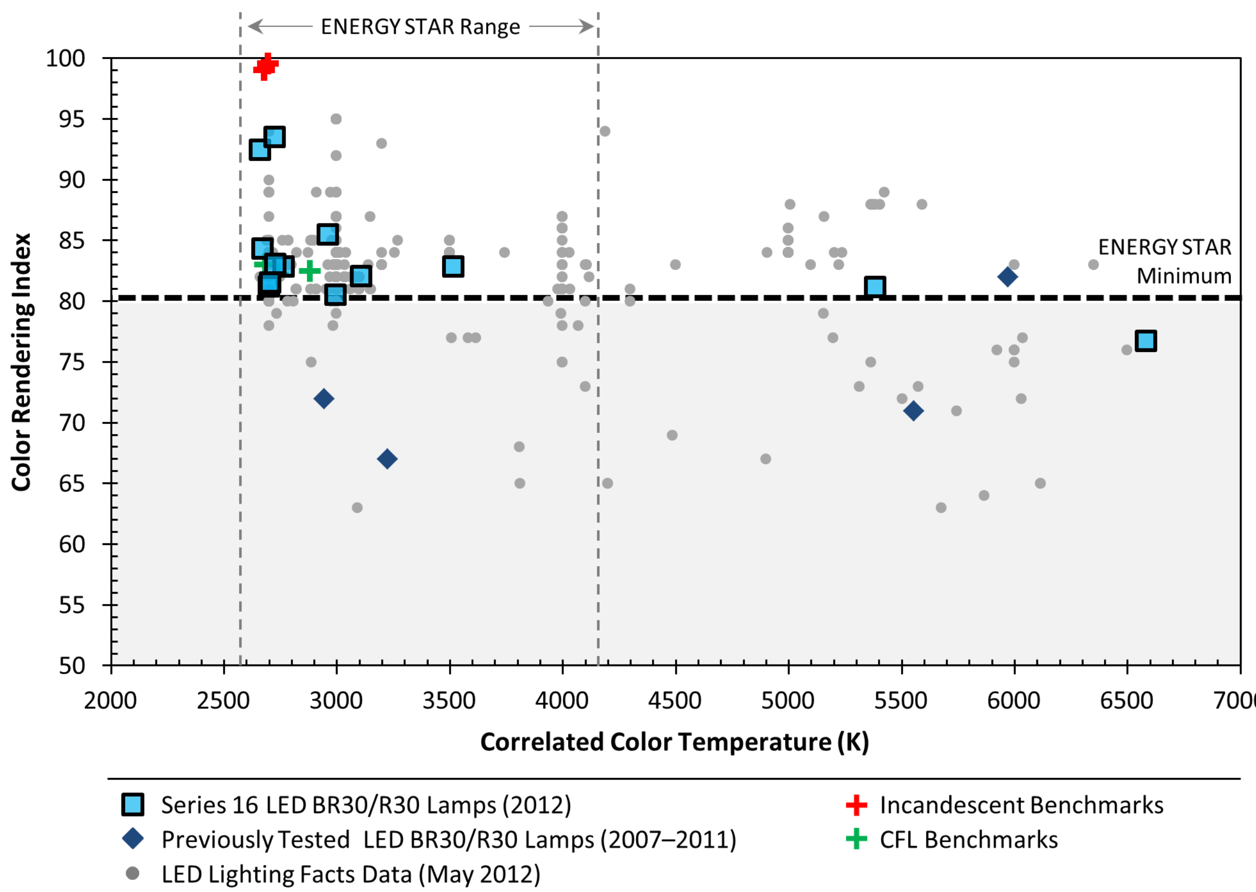

Figure 6. Color characteristics of the Series 16 LED BR30/R30 lamps compared to other data. Many of the Series 16 lamps had color characteristics similar to incandescent BR30/R30 lamps.

[11] Nominal CCT ranges are defined in ANSI C78.377-2008.

CCTs may be appropriate in some applications, these products may not provide suitable illumination for those seeking a direct replacement for an incandescent BR30/ R30 lamp.

All of the products had a D_{uv} within the ANSI-defined range for nominally white light, with the maximum deviation from zero being 0.0043. This is the first series of CALiPER testing without a product exceeding the limits for D_{uv}, marking continued progress in this area.

Each of the Series 16 LED products had a CRI between 77 and 93, with a mean for the group of 84. Only one product (12-19) had a CRI lower than 80, whereas two products (12-51 and 12-53)—both of which were sold by the same company—had a CRI greater than 90. The measured CRI for the remaining 10 products was between 81 and 85, a notably small range. It is plausible that the market is settling on this range as an acceptable level for replacement of conventional directional lamps. However, in some applications where directional lamps are a key component (e.g., museums), more exacting color performance may be necessary.

Similar to other recent CALiPER testing, the measured R_9 values for the Series 16 LED BR30/R30 lamps had a strong linear correlation with CRI (r = 0.97). The only product that had a CRI below 80 had an R_9 less than zero, and the two products with a CRI above 90 had an R_9 above 80. The remaining products with a CRI in the 80s had R_9 values between 3 and 47.

As with lumen output and efficacy characteristics, the color characteristics of the Series 16 LED products was similar to the products listed by LED Lighting Facts. The most recent testing also revealed some improvement versus lamps previously tested by CALiPER, where four of the seven lamps failed to meet both the CCT and CRI requirements of ENERGY STAR.

Electrical Characteristics

The input power for the Series 16 products ranged from 6.0 to 14.3 W, with 10 of the products between 11.1 and 14.3 W. Notably, the product with the lowest input power had the highest efficacy, allowing the lumen output to remain comparable.

The measured power factors ranged from 0.53 to 0.98, with a mean of 0.84. In contrast, the three CFL benchmarks had power factors between 0.55 and 0.60. All of the LED products except one had a power factor exceeding the ENERGY STAR minimum of 0.70. This is a substantial improvement over earlier CALiPER results in which all seven products had a power factor less than 0.70, as shown in Figure 7. This trend has been seen in multiple recently tested product types.

Size and Shape

ANSI defines size tolerances for lamps carrying the BR30 or R30 designation. Although the dimensional tolerances listed by ANSI are more detailed, length and diameter are two that are easily measured. All of the Series 16 products met the diameter requirement, but nearly half of the products were outside the acceptable range for length. Three of the products were too short—instead meeting the requirements for a PAR30 long-neck—and three of the products were too long. In general, the difference between the measurement and ANSI tolerance was less than 0.25 inches; however, one product (12-16) was 0.488 inches shorter than the minimum tolerance set by ANSI. Although small differences are often not problematic, manufacturers should strive to meet the ANSI requirements to help ensure physical compatibility with luminaires.

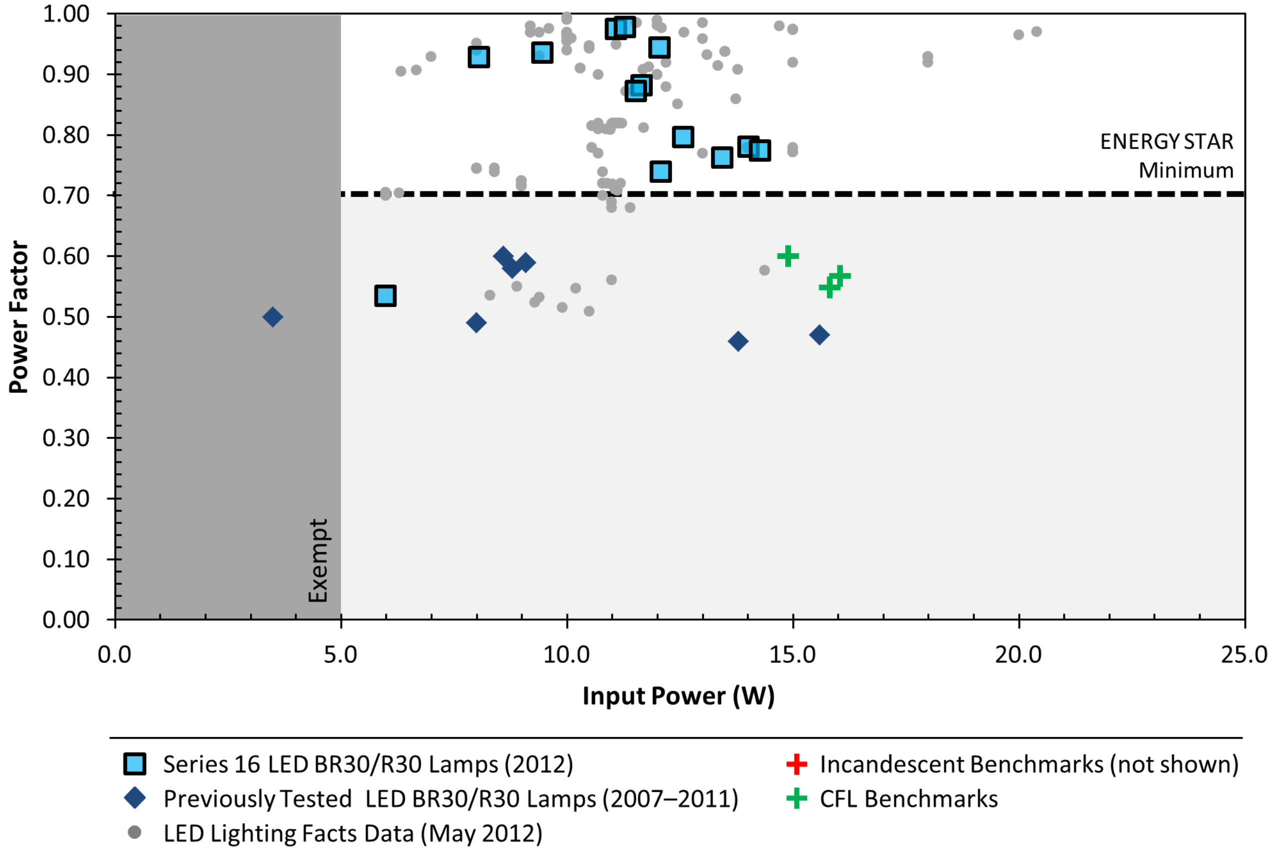

Figure 7. **Power factor versus input power for the Series 16 LED BR30/R30 lamps compared to other data.** The current products had substantially higher power factors than earlier BR30/R30 lamps. All but one product met the ENERGY STAR criterion of 0.70, and many had a power factor above 0.90.

Manufacturer Claims

Evaluating the accuracy of manufacturer's performance claims is an important component of the CALiPER program. Most of the Series 16 LED products listed data for all of the major performance criteria. Of the 13 products, 10 were measured to be within ±10% of the listed lumen output,[12] whereas the others produced more lumens than listed by 12% (12-15), 21% (12-18), and 25% (12-19). Although producing more lumens than claimed—potentially resulting in glare—is probably less likely to lead to consumer dissatisfaction, the accuracy of manufacturer data is still a fundamental concern.

Two of the thirteen products failed to meet the ±10% criterion for input power, with one product under by 14% (12-20) and one product over by 26% (12-19).[13] More apparent, however, was the trend for efficacy: 7 of 13 products did not meet the ±10% criterion, with six products exceeding the listed value. In general, lower input power and higher efficacy are favorable, but the accuracy of reported data is also important. Only one product (12-52) was measured to have a lower efficacy than claimed, although the associated values for lumen output and input power were within the tolerance. Several other products exhibited a similar relationship, with input power and lumen output considered accurate, but not efficacy. In contrast, all products were within the tolerance for CCT and CRI.

[12] The ±10% criterion is used by CALiPER and LED Lighting Facts for determining accuracy. This evaluation does not imply that conventional products meet this level of accuracy. Regardless, it is especially important for new technologies to perform as expected.
[13] Although not always the case, for product 12-19 the difference in lumen output and input power was commensurate.

Equivalency Claims

Especially for those with less experience and knowledge of lighting metrics, equivalency claims may be a key factor for purchasing. Nine of the thirteen products in this series made claims of equivalency to a specified wattage incandescent lamp. Although equivalency entails much more than lumen output, it is the easiest metric to use when evaluating the accuracy of these claims. Only one product (12-20) that made an equivalency claim emitted fewer lumens than the guideline for equivalency established by ENERGY STAR.

Cost

For several reasons, cost data is not typically included in CALiPER reports. However, many of the Series 16 products were purchased through web retailers, and in general the price of lamps is less sensitive to quantity than luminaires. The cost of the Series 16 products ranged from $34.99 to $104.00, with a mean of $55.39. The mean cost was substantially higher than the cost of incandescent, halogen, or CFL lamps of the same form factor and similar performance. It was also higher than the mean price for a collection of LED lamps purchased at retail stores in late 2011. Despite the wide range of prices, there was no noticeable correlation between cost and lumen output, luminous efficacy, or CRI.

6 Conclusions

As tested by CALiPER, the Series 16 LED BR30/R30 lamps showed substantial improvement from earlier tests of similar LED lamps. Many of the Series 16 products would be an effective energy-saving alternative to incandescent BR30 or R30 lamps. Further, the efficacy and color characteristics are similar to or better than directional CFL lamps, yet LED lamps offer a greater variety of luminous intensity distributions. Adding other factors such as dimmability and longer rated lifetime makes LED BR30/R30 lamps the best solution for replacing inefficient and soon-to-be regulated incandescent BR30 and R30 lamps.

The performance of the Series 16 products can be summarized as follows:

- The lumen output of many of the products was equivalent to 65 W or 75 W incandescent BR30/R30 lamps. All of the products emitted between 460 and 860 lumens, which is within the typical range of conventional BR30 and R30 lamps.
- Excluding one product with very high efficacy (91 lm/W), the Series 16 products had luminous efficacies between 51 and 65 lm/W. This is favorable compared to other light source types commonly used in directional lamps, and should continue to rise.
- The Series 16 LED BR30/R30 lamps had luminous intensity distributions ranging from very narrow to very wide. The suitability of these distributions depends on the application, but more than half of the products were more similar to CFL reflector lamps than incandescent BR30/R30 lamps.
- Although there were a few exceptions—two products had a CCT above 5000 K, including one with a CRI less than 80—most of the Series 16 lamps had color quality attributes similar to incandescent lamps.
- The power factor of the Series 16 LED BR30/R30 lamps was considerably better than previously tested LED BR30/R30 lamps, with all but one of the products exceeding the ENERGY STAR minimum requirement.
- Although not specifically examined or measured by CALiPER, the rated lifetime of LED lamps is typically longer than the rated lifetime for incandescent, halogen, or CFL lamps.
- Many of the manufacturer claims were accurate; however, there was a tendency for the lamps to exhibit higher efficacies than reported in the manufacturer's literature.

In terms of lumen output, luminous intensity distribution, and color quality, product 12-17 performed very similarly to incandescent benchmark product 12-54; it also had an efficacy of 62 lm/W compared to 11 lm/W for the benchmark. These two products were from the same manufacturer, and provide a good example of how LED products can be an equivalent replacement for incandescent reflector lamps when properly designed.

Although the results from this series of testing were encouraging, there is room for LED BR30/R30 lamps to improve and gain a larger market share. As with other directional lamps, it would be beneficial if more manufacturers offered a range of products (e.g., lumen packages, distributions) using a single form factor, allowing designers and specifiers to meet the demands of various applications. Another current concern is cost; on average, the Series 16 LED BR30/R30 lamps were several times more expensive than incandescent or CFL reflector lamps. In residential applications, where BR30/R30 lamps are most commonly used, economic justification is especially unlikely.

Appendix A: Definitions

Beam Angle Degrees (°)	The angle between the two directions for which the intensity is 50% of the maximum intensity (ANSI/IES RP-16-10) or center beam intensity (ANSI C78.379-2006), as measured in a plane through the beam axis. For example, if the maximum intensity is 1000 cd, the angle at which the intensity is 500 cd is half of the beam angle. If 500 cd occurs at 20° from center beam, then the beam angle is 40°.
Center Beam Candlepower (CBCP) Candela (cd)	The luminous intensity at the central axis of the beam, which typically corresponds to a vertical angle of 0° (called nadir for lamps oriented downward). Although candlepower is a deprecated term, it is still widely used in this context.
Correlated Color Temperature (CCT) Kelvin (K)	The absolute temperature of a blackbody radiator having a chromaticity that most nearly resembles that of the light source. CCT is used to describe the color appearance of the emitted light.
Color Rendering Index (CRI or R_a)	A measure of color fidelity that characterizes the general similarity in color appearance of objects under a given source relative to a reference source of the same CCT. The maximum possible value is 100, with higher scores indicating less difference in chromaticity for a sample of eight color samples illuminated with the test and reference source. See also: *Special Color Rendering Index R_9.*
D_{uv}	The distance from the Planckian locus on the CIE 1960 UCS chromaticity diagram (also known as u', 2/3 v'). A positive value indicates the measured chromaticity is above the locus (appearing slightly green) and a negative value indicates the measured chromaticity is below the locus (appearing slightly pink). The American National Standards Institute provides limits for D_{uv} for nominally white light.
Luminous Efficacy Lumens per watt (lm/W)	The quotient of the total luminous flux emitted and the total input power.
Field Angle Degrees (°)	The angle between the two directions for which the intensity is 10% of the maximum intensity (ANSI/IES RP-16-10) or center beam intensity (ANSI C78.379-2006), as measured in a plane through the beam axis. For example, if the CBCP is 1000 cd, the angle at which the intensity is 100 cd is half of the field angle. If 100 cd occurs at 32° from center beam, then the field angle is 64°.
Input Power Watts (W)	The power required to operate a device (e.g., a lamp or a luminaire), including any auxiliary electronic components (e.g., ballast or driver).
Luminous Intensity Distribution Candela (cd)	The directionality of radiant energy emitted by a source, which may be shown using one of several techniques. It is most often presented as a polar plot of the candelas emitted in a vertical plane through the center of the lamp or luminaire.
Output Lumens (lm)	The amount of light emitted by a lamp or luminaire. The radiant energy is weighted with the photopic luminous efficiency function, V(λ).
Power Factor	The quotient of real power (watts) flowing to the load (e.g., lamp or fixture) and the apparent power (volt-amperes) in the circuit. Power factor is expressed as a number between 0 and 1, with higher values being more desirable.

Special Color Rendering Index R_9	A measure of color fidelity that characterizes the similarity in color appearance of deep red objects under a given source relative to a reference source of the same CCT. The maximum possible value is 100, with higher scores indicating less difference in chromaticity for the color sample illuminated with the test and reference source. R_9 and R_a (CRI) are part of the same CIE Test-Color Method, but the R_9 color sample is not included in calculation of R_a.

Appendix B: Product Selection

Product selection is an important part of the CALiPER process. Products are selected with the intent of capturing the current state of the market—a cross section ranging from expected low to high performing products with the bulk characterizing the middle of the range. However, the selection does not represent a statistical sample of all available products.

Product selection starts with a review of the technology. Beyond relying on professional experience, the team surveys:

- Trade publications, including *Lighting Design + Application*, *LEDs Magazine*, *Mondo ARC*, and *Architectural Lighting*
- Internet websites, including Elumit, DesignLights Consortium, ENERGY STAR, LED Lighting Facts, ESource, and Lightsearch
- National retailers, including Grainger, Goodmart, The Home Depot, Lowe's, Amazon, and Sears
- Other sources, including trade shows (local and national) and manufacturer's representatives

After surveying available products, the CALiPER team characterizes the features of the products and determines what can be standardized to ease comparison. For this report focusing on LED BR/R30 lamps, the following features were evaluated and led to the final selection:

- Lumen package – Lamps matching the output of a 65 W incandescent BR30 lamp, approximately 650 to 750 lumens, were targeted.
- Color temperature – A CCT of 2700 to 3000 K, representative of incandescent and halogen sources, was sought, although as is common some lamps fell outside the range.
- Color rendition – LED BR/R lamps with the highest CRI possible were sought. Most of the lamps were listed as having a CRI above 80 by the manufacturer.
- Lamp diameter/shape – Most importantly, the manufacturer literature (including websites) had to indicate that the lamp was a BR30 or R30 replacement.

Other non-performance related criteria are also considered:

- Product availability – As a federally funded program, CALiPER focuses on products available in the United States.
- Energy efficiency programs – Some emphasis is given to including products listed by large energy efficiency programs (e.g., ENERGY STAR).

After establishing a list of appropriate products, attempts are made to anonymously purchase the products through standard industry resources (e.g., distributors, retailers). Sometimes, products are not available or cannot be shipped in a timely manner. Thus, the final group of products tested does not always match the intended results of the selection process.

Appendix C: Previous CALiPER Testing of BR30 and R30 LED Lamps

Table C1. Summary data for previous CALiPER tests of LED BR30 and R30 lamps. The first two digits of the CALiPER Test ID indicate the year in which the product was purchased. Product RT42 was purchased in 2011 as part of a retail replacement lamp study.

DOE CALiPER Test ID	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	Power Factor	CRI	R_9	CCT (K)	D_{uv}	CBCP (cd)	Beam Angle (deg)	Field Angle (deg)
07-08	239	8.8	27	0.58	72	-	2945	-	70	136	158
07-09	310	9.1	34	0.59	82	-	5973	-	84	140	160
07-13	406	15.6	26	0.47	14	-	2689	-	241	79	130
07-14	352	13.8	25	0.46	13	-	4006	-	210	77	130
07-18	180	8.6	21	0.60	77	-	7878	-	277	54	70
09-64	186	3.5	53	0.50	71	-	5554	0.0020	695	20	45
RT42	365	8.0	46	0.49	67	-52	3225	0.0061[1]	-	-	-
Minimum	180	3.5	21	0.46	13	-	2689	-	70	20	45
Mean	291	9.6	33	0.53	57	-	4610	-	263	84	116
Maximum	406	15.6	53	0.60	82	-	7878	-	695	140	160

Notes:
1. Exceeds ANSI-defined limits for nominally white light (ANSI C78.377).

Appendix D: CALiPER Testing of Conventional BR30 and R30 Lamps

Table D1. Summary data for CALiPER tests of benchmark conventional BR30 and R30 lamps. The first two digits of the CALiPER test ID indicate the year in which the product was purchased.

DOE CALiPER Test ID	**Source Type**	**Initial Output** (lm)	**Total Input Power** (W)	**Efficacy** (lm/W)	**Power Factor**	**CRI**	**CCT** (K)	**CBCP** (cd)	**Beam Angle** (deg)	**Field Angle** (deg)
12-54	Incandescent	650	65.7	10	1.00	100	2698	327	83	134
08-13	Incandescent	732	65.0	11	1.00	99	2681	431	77	123
12-21	CFL	776	14.9	52	0.60	83	2684	203	124	180
12-58	CFL	732	16.1	46	0.57	83	2883	190	124	180
08-06	CFL	841	15.8	53	0.55	82	2740	236	110	156
Minimum		650	14.9	10	0.55	82	2681	190	77	123
Mean		746	35.5	34	0.74	89	2737	277	104	155
Maximum		841	65.7	53	1.00	100	2883	431	124	180

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