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

CALiPER

Application Summary Report 22:

LED MR16 Lamps

June 2014

Revised September 2014

Prepared for:

Solid-State Lighting Program
Building Technologies Office
Office of Energy Efficiency and
Renewable Energy
U.S. Department of Energy

Prepared by:

Pacific Northwest National
Laboratory

PNNL-SA-23449

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
email: orders@ntis.gov <http://www.ntis.gov/about/form.aspx>
Online ordering: http://www.ntis.gov

This document was printed on recycled paper.
(8/2010)

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] Increasingly, CALiPER investigations also rely on new test procedures that are not industry standards; these experiments provide data that is essential for understanding the most current issues facing the SSL industry.

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. Instead, CALiPER focuses on specific groups of products that are relevant to important issues being investigated. The products are selected with the intent of capturing the current state of the market at a given point in time, representing a broad range of performance characteristics. However, the selection does not represent a statistical sample of all available products in the identified group. All selected products are shown as currently available on the manufacturer's web page at the time of purchase.

CALiPER purchases products through standard distribution channels, acting in a manner similar to that of a typical specifier. CALiPER does not accept or purchase samples directly from manufacturers to ensure that all tested products are representative of a typical manufacturing run and not hand-picked for superior performance. CALiPER cannot control for the age of products in the distribution system, nor account for any differences in products that carry the same model number.

Selecting, purchasing, documenting, and testing products can take considerable time. Some products described in CALiPER reports may no longer be sold or may have been updated since the time of purchase. However, each CALiPER dataset represents a snapshot of product performance at a given time, with comparisons only between products that were available at the same time. Further, CALiPER reports seek to investigate market trends and performance relative to benchmarks, rather than to serve as a measure of the suitability of any specific lamp model. Thus, the results should not be taken as a verdict on any product line or manufacturer. Especially given the rapid development cycle for LED products, specifiers and purchasers should always seek current information from manufacturers when evaluating them.

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

[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.

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, photometric 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. In the end, the best product is the one that best meets the needs of the specific application.

For more information on the DOE SSL program, please visit http://www.ssl.energy.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 photometric performance of 27 LED MR16 lamps. It describes initial performance based on light output, efficacy, distribution, color quality, electrical characteristics, and form factor, with comparisons to a selection of benchmark halogen MR16s and ENERGY STAR qualification thresholds.

Three types of products were targeted. First, CALiPER sought 3000 K lamps with the highest-rated lumen output (i.e., at least 500 lm) or a claim of equivalency to a 50 W halogen MR16 or higher. The test results indicate that while the initial performance of LED MR16s has improved across the board, market-available products still do not produce the lumen output and center beam intensity of typical 50 W halogen MR16 lamps. In fact, most of the 18 lamps in this category had lower lumen output and center beam intensity than a typical 35 W halogen MR16 lamp.

Second, CALiPER sought lamps with a CRI of 90 or greater. Only four manufacturers were identified with a product in this category. CALiPER testing confirmed the performance of these lamps, which are a good option for applications where high color fidelity is needed. A vast majority of the LED MR16 lamps have a CRI in the low 80s; this is generally acceptable for ambient lighting, but may not always be acceptable for focal lighting. For typical LED packages, there is a fundamental tradeoff between CRI and efficacy, but the lamps in the high-CRI group in this report are still comparable to the rest of the Series 22 products in other performance areas.

Finally, CALiPER sought lamps with a narrow distribution, denoted as a beam angle less than 15°. Five such lamps were purchased. Notably, no lamp was identified as having high lumen output (500 lm or greater), high CRI (90 or greater), a narrow distribution (15° or less), and an efficacy greater than 60 lm/W. This would be an important achievement for LED MR16s—especially if output could reach approximately 700–800 lm, approximately equivalent to that of a 50 W halogen MR16 lamp.

Many factors beyond photometric performance should be considered during specification. For example, performance over time, transformer and dimmer compatibility, and total system performance are all critical to a successful installation. Subsequent CALiPER reports will investigate more-complex issues.

3 Background

Multifaceted reflector (MR) lamps are used in many types of luminaires, including track heads, monopoints, and fixed or adjustable recessed downlights. As such, they are a key component of the focal lighting systems that are often used in retail, hospitality, residential, and museum applications. The most common MR-type lamp is the MR16, so named because it has a diameter of 16 eighths of an inch, or 2 inches. Halogen MR16 lamps are typically designed to operate at a low voltage (usually 12 V), because of the optical advantage gained through the use of a smaller filament. Low-voltage operation introduces an additional level of complexity that must be addressed when considering replacement of halogen sources with LEDs, however. This is especially relevant to track lighting systems, where multiple lamps on a single circuit may interact with other electronic components.

Typical halogen MR16 track lighting systems consist of low-voltage lamps (commonly 20, 35, or 50 W), luminaires (track heads), optical accessories (e.g., lenses, louvers), one or more electronic or magnetic transformers, and the track itself. A dimming system may also be incorporated. The track—which provides power as well as flexibility for mounting locations—can operate at either line voltage (120 V), requiring low-voltage track heads with integral transformers, or low voltage (12 V), requiring a single remote transformer for several track heads. The majority of currently installed track is line-voltage. To date, standards have not been developed for the track lighting market; as a result, track and track heads from different manufacturers typically are not directly interchangeable.

MR16 lamps are unique among directional lamps because they are most often operated at low voltage and their design is constrained by the small form factor. Beyond the usual performance characteristics that should be evaluated when comparing LED and conventional products, the interaction of electronic components must also be considered. These compatibility issues are of concern for both retrofit applications and new installations. Importantly, this report considers only the photometric performance of a single lamp, operated on a benchmark power supply providing 12 VAC (or 12 VDC if explicitly specified by the manufacturer).

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 letters used in a lamp designation identify the shape classification of the bulb. The MR designation—generally meaning *multifaceted reflector*—is defined to indicate "A curved focusing reflectorized bulb which may have a multifaceted inner surface that is generally dichroic coated. It…may be open faced or sealed together with a glass lens." Of particular note is the dichroic coating, which allows for some emission from the back side of the lamp, a trait that is desirable for some applications where the decorative appearance of the glowing lamp is a design feature.

Separately, ANSI C78.41-2001 provides dimensional tolerances for MR16 lamps with GU5.3 or GX5.3 bases, which are the base types used for 12 V lamps. Accordingly, they must have an overall length of not greater than 1.9 inches and a maximum diameter of 2.0 inches, among other dimensional tolerances. A similar specification does not exist for lamps with a GU10 base, which are sometimes used in residential applications and are typically 120 V. This CALiPER series focuses only on lamps with a GU5.3 base.

Classifying the Distribution of Directional Lamps

Directional lamps are commonly specified based on their luminous intensity distribution. 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. Of these, beam angle is the most widely cited value in manufacturer literature and on product packaging. ANSI recommends the following system for identifying the nominal beam angle of directional lamps:

- For beam angles of less than 13°, the angle rounded to the nearest whole number should be used: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12.
- For beam angles of 13° to 50°, the angle rounded to the nearest 5 should be used: 15, 20, 25, 30, 35, 40, 45, and 50.
- For beam angles of 51° or greater, the angle rounded to the nearest ten should be used: 50, 60, 70, 80, and 90.

Numerical designations are often augmented (or replaced) by written characterizations, although these can be nebulous. *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. Other common terms include very narrow spot (VNSP), narrow spot (NSP), spot (SP), wide spot (WSP), narrow flood (NFL), flood (FL), or wide flood (WFL), but 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 be 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 are assigned a tolerance that varies based on the nominal value:

- For a nominal beam angle of 1° to 12°, the tolerance is ±3°.
- For a nominal beam angle of 15°, the tolerance is ±4°.
- For a nominal beam angle of 20° to 40°, the tolerance is ±6°.
- For a nominal beam angle of 45° or higher, the tolerance is ±10°.

Although these tolerances are necessary, they can lead to some ambiguity. For example, the 25° lamp classification can include lamps having an actual beam angle between 19° and 31°. Thus, an accurately classified lamp with a measured beam angle of 19° may have been nominally classified as having either a 20° or 25° beam angle, making it either a spot or a flood lamp. Beyond this systematic quandary, 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.

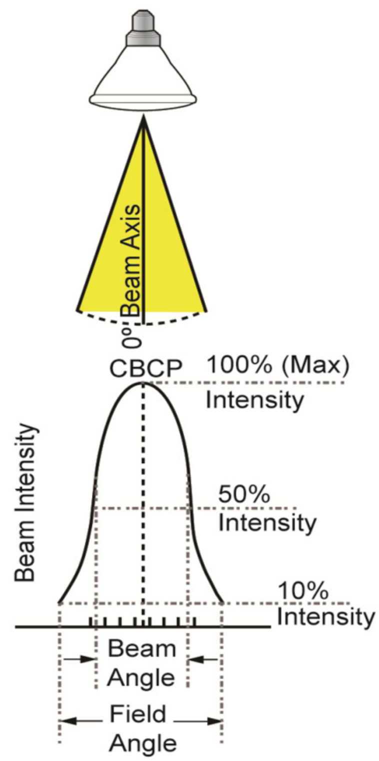

Figure 1. Describing and quantifying the distribution of directional lamps. According to the Illuminating Engineering Society (IES), beam angle is the point at which the luminous intensity is 50% of its greatest value. Field angle is the point at which the luminous intensity is 10% of its greatest value.

Installed Base

The DOE report *Adoption of Light-Emitting Diodes in Common Lighting Applications*, released in April 2013, estimated that 4.8 million LED MR16 lamps had been installed as of 2012, comprising 10% of the installed base of MR16 lamps.[7] This is the highest market

[7] U.S. Department of Energy. 2013. *Adoption of Light-Emitting Diodes in Common Lighting Applications*. Solid-State Lighting Program. Available at: http://www1.eere.energy.gov/buildings/ssl/tech_reports.html.

penetration rate of any product category considered in the report. Also of note is that of the estimated 46 million installed lamps, 43% were in households and 56% were in commercial installations. The total energy consumption of those 46 million lamps was approximately 70 tBtu in 2012, with the LED share saving approximately 3.7 tBtu. Instantaneous, universal conversion of all MR16 lamps to LED could result in 65 tBtu of energy savings compared to the baseline of halogen lamps, with an annual energy cost savings of about $0.6 billion.

LED MR16 Lamps

Halogen MR16 lamps deliver focused illumination from their 2"-diameter aperture, have desirable color quality, are easy to use with controls, and are available with a range of different options (e.g., beam angle and intensity) and accessories (e.g., spread lenses). Given this combination of features, the conventional halogen MR16 lamp is one of the most difficult lamps for LED technology to successfully replicate, which is why CALiPER chose to focus on MR16 lamps for this series. This is especially true for 12 V, 50 W halogen lamps. At the same time, halogen MR16 lamps have low efficacies—unlike some other technologies, such as fluorescent, with which LED products compete in other product categories—which provides an attractive energy-savings potential. They also have relatively short lives and generate substantial amounts of heat in the beam, which may be problematic in some applications.

As of January 2014, a CALiPER Snapshot Report based on data from LED Lighting Facts found that few MR16 lamps listed by LED Lighting Facts were comparable to a 50 W (12 V) halogen MR16 lamp. Of the small subset of MR16s that provided data for beam angle and center beam intensity, only one would meet the minimum ENERGY STAR CBCP criterion for equivalence to a 50 W halogen MR16 at the same beam angle (40°). Further, those data show that both lumen output and input power have been increasing steadily in recent years, with the net result being little change in luminous efficacy.

The LED lamps for this CALiPER series were selected because they met at least one of four conditions, based on manufacturer literature: they made an explicit claim of equivalency to a 50 W halogen MR16 lamp, claimed emission of 500 or more lumens, listed a color rendering index (CRI) of 90 or greater, or indicated a beam angle of 15° or less. Thus, the resulting sample of products represents the pinnacle of LED MR16 performance as of the purchase period (spring 2014). The selection criteria also required operation at 12 V and a GU5.3 base.

Compatibility Considerations

LED MR16 lamps require an integral driver, which means that electronic components must be fit into the small, ANSI-defined MR16 form factor. Additionally, low-voltage systems require a transformer and are often coupled with a dimmer. The combination of size limitations and multiple interconnected electronic components may result in compatibility issues, where performance is degraded in one or more areas (e.g., flicker). This is sometimes a result of tradeoffs that must be made, such as between flicker and power quality. More information can be found in the DOE SSL Fact Sheet on MR16 lamps.[8] Subsequent reports in CALiPER Series 22 will further investigate system-level performance, but this report considers only the photometric performance of single lamps operated on a benchtop power supply (i.e., standard LM-79 photometric testing).

[8] Available at: http://www1.eere.energy.gov/buildings/ssl/factsheets.html

4 Results

CALiPER LED MR16 Test Data

Series 22 LED Lamps

This report analyzes the independently tested performance of 27 LED products designated as MR16 lamps, which were anonymously purchased in January 2014.[9] In this report, they are referred to as the Series 22 products. For more on the product selection parameters, both in general and as they pertain to this group of products, see Appendix B. Using the selection criteria previously noted resulted in four products in the high-CRI group, five products in the narrow-distribution group; four products claiming equivalency to a 50 W halogen MR16, but emitting less than 500 lm; and 14 products claiming to emit more than 500 lm, with four making no equivalency claim and 10 claiming to be equivalent to a 50 W (or higher) halogen MR16 lamp. Some of the narrow-distribution and high-CRI products met more than one of the criteria. As a general rule, CALiPER selected each manufacturer's best-performing product in each category, if it met the given criteria; as a result, some manufacturers had multiple products selected.

All of the units were tested according to IES LM-79-08, using both an integrating sphere and a goniophotometer; for all but one of the Series 22 products, the difference in measured lumen output between the two methods was less than 6%, which is typical. Product 14-11 had a difference in average lumen output for the two methods of nearly 20%, but the exact cause of this discrepancy is unknown—within each method, the measurements for the two samples were similar. 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, with product identification provided in Appendix C. Importantly, all results presented in this report are for a single lamp operating on a laboratory power supply. Subsequent reports will examine performance under other conditions. Field performance may vary.

The Series 22 benchmark products are shown in Figure 2, with the LED products shown in Figure 3. The construction of the lamps varied substantially, with different strategies for thermal management and different quantities of LED packages being the most noticeable variations.

Past CALiPER Results for LED MR16 Lamps

The CALiPER program previously tested a few dozen MR16 lamps, but no 12 V products since 2012.[10] Many of the MR16 products tested by CALiPER were 120 V, GU10-base products that were included in the Retail Replacement Lamp Series of reports. In general, the performance of the previously tested MR16 lamps was inferior to those in Series 22, which is at least partially due to the selection methods. Thus, comparing the data can show that the performance range for MR16 lamps has expanded, but it should not be used to evaluate how a typical MR16 purchased in 2014 compares to a typical MR16 from 2012, for example.

Of the previously tested products, the maximum lumen output was only 327 lm, which is substantially lower than even a 35 W halogen MR16 lamp. Thus, the current results from Series 22 indicate substantial advancement in LED MR16 performance.

[9] Three of the Series 22 products were also included in CALiPER's Retail Replacement Lamp Study 3. They were originally purchased in 2013, but were still available for purchase in January 2014.

[10] The three 12 V LED MR16 products that were procured as part of CALiPER Retail Replacement Lamp Study 3 (denoted with the prefix 13RT), are considered part of this series. The products were still available in January 2014, when the other lamps in the series were tested. CALiPER utilized the existing data and supplemented it with additional tests, while reusing the existing identification number.

Table 1. Results of CALiPER tests for the Series 22 LED MR16 lamps. Performance data include initial output, total input power, luminous efficacy, power factor, color rendering index (CRI), correlated color temperature (CCT), D_{uv}, beam angle, and center beam intensity (CBCP). The Labels column indicates whether the product was ENERGY STAR qualified (ES) or listed by LED Lighting Facts (LF) at the time of processing.

DOE CALiPER Test ID	Initial Output (lm)	Input Power (W)	Efficacy (lm/W)	Power Factor	CRI	CCT (K)	D_{uv}	Beam Angle (deg)	CBCP (cd)	Equiv. Claim (W)	Labels	
14-01[1]	469	6.8	69	0.91	98	2957	0.0000	32	1,284	45	ES	LF
14-02[1]	319	5.9	54	0.64	93	3104	-0.0045	36	685	60	-	-
14-03[1]	446	11.8	38	0.92	96	3030	0.0015	32	1,308	65	-	-
14-04[1]	197	4.5	44	0.68	97	2918	-0.0005	20	1,097	20	-	LF
14-05[2]	279	4.0	70	0.64	80	2904	0.0035	18	1,665	-	-	-
14-06[2]	376	6.7	57	0.93	85	2970	-0.0015	15	3,326	35	ES	LF
14-08[2]	438	10.5	42	0.77	81	3063	0.0010	16	3,381	-	-	LF
14-09[2]	511	10.1	51	0.92	84	3010	0.0000	11	7,474	65	ES	LF
14-10[2]	301	4.9	62	0.70	82	2977	0.0000	7	5,896	30	-	LF
14-11	389	7.0	56	0.88	81	2844	0.0010	27	1,180	50	-	LF
14-13	585	9.0	65	0.91	83	3002	0.0000	22	2,592	50	-	LF
14-14	472	6.8	69	0.71	80	2904	0.0020	32	1,348	50	ES	-
14-15	392	6.2	64	0.91	83	2822	0.0020	36	916	-	-	-
14-17	520	7.5	69	0.96	82	3010	0.0010	33	1,256	50	-	-
14-18	543	6.8	80	0.91	84	2916	-0.0025	22	2,335	50	ES	LF
14-19	345	5.8	60	0.71	83	3016	-0.0010	26	1,244	50	ES	-
14-22	302	5.3	57	0.65	83	2961	-0.0015	27	968	50	-	-
14-23	540	6.9	79	0.91	83	3006	-0.0015	23	2,229	-	-	LF
14-24	553	10.0	55	0.77	86	3012	0.0005	24	2,368	-	-	LF
14-25	396	4.4	90	0.65	63	3015	0.0030	45	558	-	-	-
14-26	583	11.7	50	0.92	83	2949	0.0010	23	3,406	75	ES	LF
14-27	403	5.8	70	0.66	83	3028	-0.0015	24	1,582	50	ES	-
14-28	484	8.6	57	0.69	83	2969	-0.0020	25	1,845	50	ES	
14-29	503	7.9	64	0.90	84	2988	0.0015	22	1,968	50	ES	
13RT-39	487	6.6	74	0.67	85	3043	-0.0013	20	2,815	50		LF
13RT-41	434	6.6	66	-[3]	82	2963	-0.0004	21	2,136	50		LF
13RT-44	511	7.2	71	0.71	82	3085	-0.0016	31	1,225	50		
Minimum	197	4.0	38	0.64	63	2822	-	7	558	-	-	-
Mean	436	7.2	62	0.79	84	2980	-	25	2,151	-	-	-
Maximum	585	11.8	90	0.96	98	3104	-	45	7,474	-	-	-

1. Claimed CRI above 90.
2. Narrow distribution (beam angle less than 15°).
3. Measured at 12 V DC, using a laboratory power supply. All other products were measured at 12 V AC, using a laboratory power supply. Power factor is not applicable for DC-tested products.

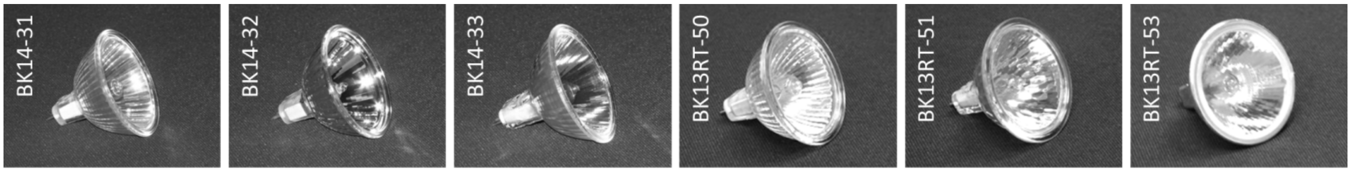

Figure 2. Photographs of six conventional MR16 lamps tested in conjunction with the Series 22 LED products or for Retail Replacement Lamps Study 3.

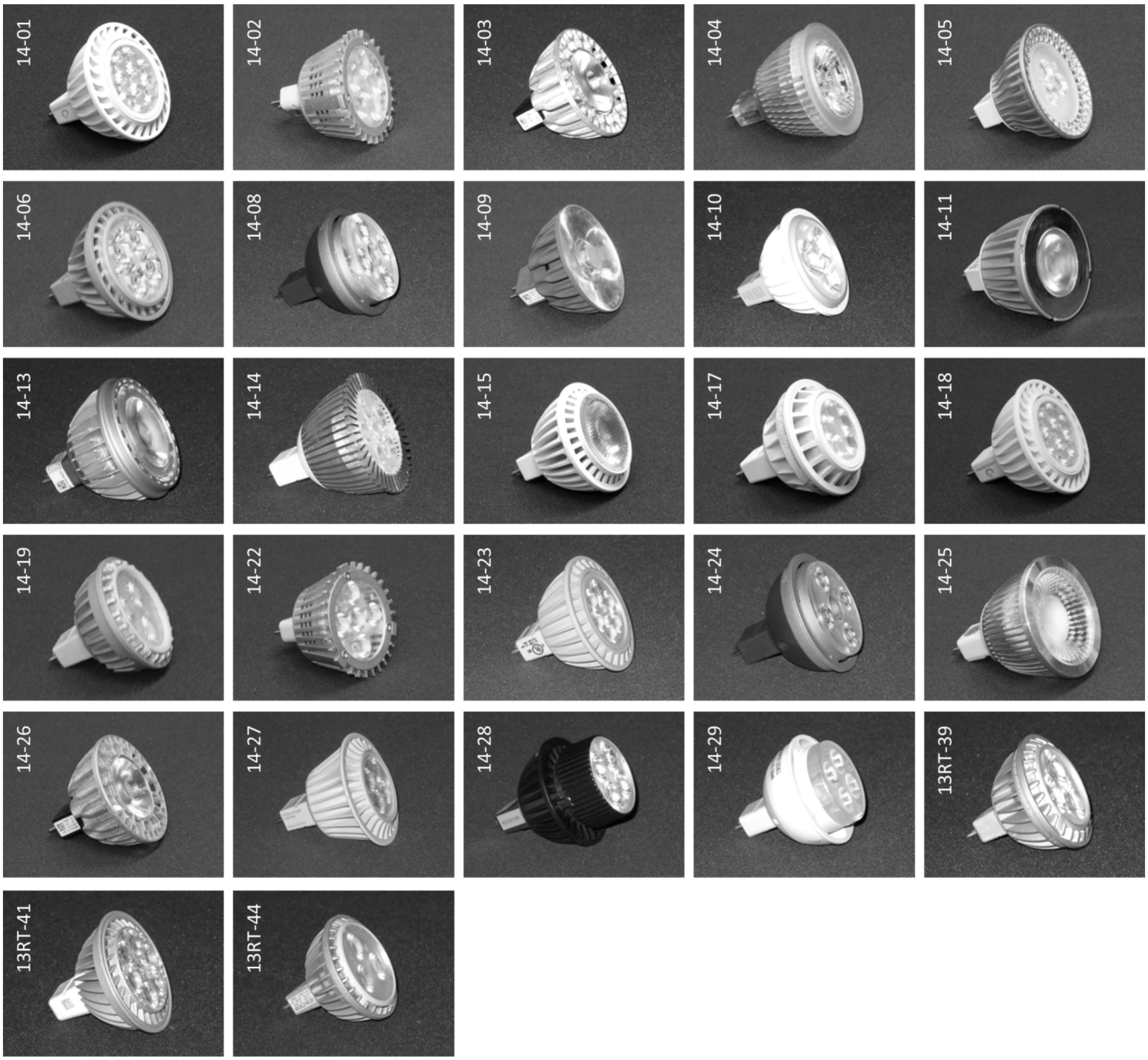

Figure 3. Photographs of the CALiPER Series 22 LED MR16 lamps. The photographs do not indicate the relative size of the products.

Supplemental LED MR16 Data

ENERGY STAR

The pertinent performance criteria from *ENERGY STAR Program Requirements for Lamps (Light Bulbs)* are provided in Table 2. Note that these requirements don't take effect until September 2014, but they are similar to past requirements. ENERGY STAR program requirements beyond the scope of LM-79-08 testing conducted by CALiPER are not included. As of June 16, 2014, 279 LED MR lamps were ENERGY STAR-qualified, with a vast majority having a GU5.3 base (a handful of products had a GU10 or medium screw base). Summary statistics for ENERGY STAR-qualified MR lamps are provided in Table 3.

LED Lighting Facts Data

As of June 19, 2014, LED Lighting Facts listed 522 MR16 lamps. LED Lighting Facts is not a qualification program, so the range in product performance may be more indicative of the broader LED MR16 market than ENERGY STAR data. However, it is notable that the mean performance is fairly similar in both databases, but that LED Lighting Facts includes some products that perform more poorly. Summary statistics for the MR16 lamps listed by LED Lighting Facts are provided in Table 4.

CALiPER Testing of Conventional Product Benchmarks

In conjunction with testing of the Series 22 LED products, three conventional benchmarks were tested, including two 50 W halogen MR16 lamps and one 37 W halogen-infrared (HIR) MR16. These three products supplement five halogen benchmarks from previous testing, including one (nominally) 50 W and four (nominally) 35 W products. Summary data for all eight products are available in Appendix D.

The eight benchmark products illustrate typical performance for both 50 W and 35 W halogen MR16 lamps, with which LED MR16 lamps are often compared. They were tested on a laboratory power supply at 12 V AC. Reported input power does not include losses from the transformer. The four 35 W halogen lamps emitted between 500 and 644 lm, with a mean efficacy of 16.5 lm/W. All four of these lamps had a medium distribution, with measured beam angles between 22° and 32°. The three 50 W halogen benchmarks and the 37 W HIR benchmark—which is intended to compete with regular 50 W halogen MR16s—emitted between 638 and 849 lm, with a mean efficacy of 15.9 lm/W. One of the products had a narrow distribution, with a measured beam angle of 12° and center beam intensity of 8909 cd.[11] All eight of the benchmark lamps had a CCT between 2859 K and 3152 K, which are within the nominal 3000 K quadrangle that ANSI specifies for solid-state lighting. By definition, the CRI for all of the lamps was near 100.

Table 2. Minimum *ENERGY STAR Program Requirements for Lamps* criteria relevant to CALiPER testing of LED MR16 lamps.

CBCP (cd)	**Efficacy** (lm/W)	**Power Factor**	**CRI**	**R_9**	**CCT** (K)
Determined using tool developed by ENERGY STAR that considers beam angle and input power	40 (< 20 W)	0.70 (> 5 W)	80	0	2700 K to 6500 K

[11] Reported beam angle calculated as the average of the horizontal and vertical beam angles included in the LM-79 report. Those values were 11°and 13°, respectively.

Table 3. Summary data for ENERGY STAR-qualified MR16 lamps. Includes 279 products listed as of June 2014.

	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	CRI	CCT (K)
Minimum	139	3.0	35	80	2700
Mean	351	6.1	57	84	3006
Maximum	620	10.0	89	91	5000

Table 4. Summary data for MR16 lamps listed by LED Lighting Facts. Includes 522 products listed as of June 2014.

	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	CRI	CCT (K)
Minimum	69	1.6	25	51	2400
Mean	347	6.3	56	83	3110
Maximum	640	13.0	84	97	6789

Most halogen MR16s are designed to operate at 12 V, and are tested using a laboratory power supply that delivers exactly 12 V to the lamp. Reported lumen output, CBCP, life, and CCT are all based on operation at a full 12 V. However, most luminaire manufacturers are interested in prolonging halogen lamp life, and install transformers that deliver approximately 11.5 V (with some variation), which effectively dims the halogen MR16 lamp, reducing its lumen output and CBCP as well as lowering its color temperature. In addition, halogen MR16 lamps are required to operate with a protective cover glass in front of the lamp aperture in most applications, which can be expected to reduce output by about 10%. Further, if halogen MR16 lamps are operated on a dimmer, the dimmer most often delivers less than 100% voltage, which effectively dims the lamps slightly. Depending on the specific transformer, dimmer, and cover glass, the reduction in the halogen lamp output could be as much as 30% below the tested values. LED lamps need no cover glass for protection, and the light output performance on a specific transformer and dimmer may or may not be reduced in the same manner as it is for the halogen lamp it replaces. Specifiers are encouraged to use mockups to evaluate actual field performance.

5 Analysis

Lumen Output and Efficacy

The Series 22 LED MR16 lamps had measured output ranging from 197 to 585 lm, with a mean of 436 lm. In previous CALiPER testing, no LED MR16 lamps were measured above 327 lm, a threshold that was exceed by all but five of the most recently tested lamps. This contrast exemplifies a more general trend of increasing lumen output in the LED market—although it does not indicate that lower-output products are no longer sold, because those were not the focus of the selection criteria. Both the lumen output and efficacy of the Series 22 CALiPER products are representative of the higher end of the LED Lighting Facts and ENERGY STAR datasets, although the CALiPER dataset is much smaller. Efficacy versus lumen output is shown in Figure 4.

Of the products that claimed to emit more than 500 lm, the mean was 501 lm, with three products emitting less than 500 lm. Perhaps more notable is that none of the tested lamps emitted comparable lumen output to the 50 W halogen MR16 lamps that CALiPER tested, despite 17 of the 27 products claiming equivalency to that wattage (or higher). The CALiPER, LED Lighting Facts, and ENERGY STAR databases all indicate that currently available LED MR16s cannot match the light output of 50 W halogen MR16s, and most are barely comparable to 35 W halogen MR16s. Importantly, center beam intensity is often a more important metric for determining the equivalency of

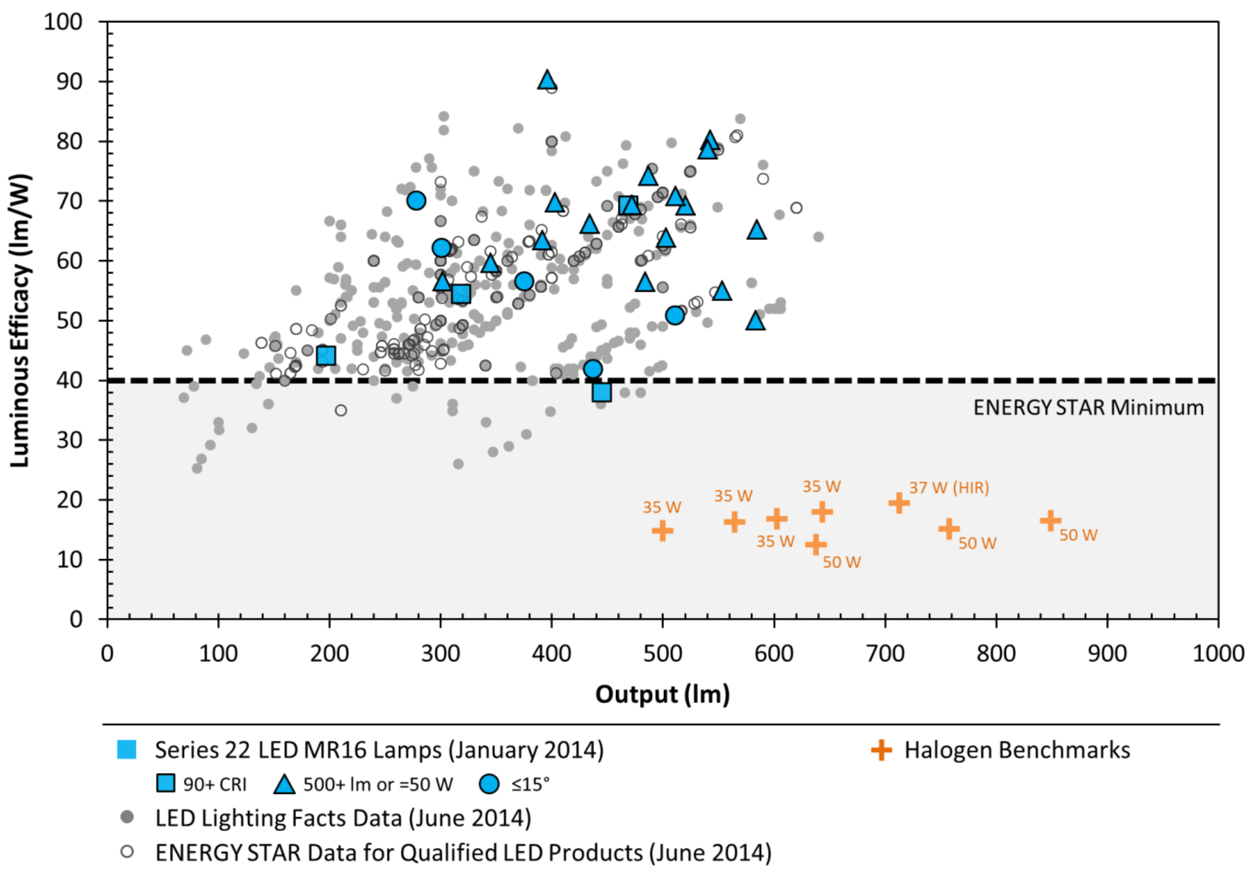

Figure 4. Luminous efficacy versus lumen output for the Series 22 LED MR16 lamps compared to other datasets. The performance range was similar to the LED Lighting Facts and ENERGY STAR datasets. Whereas every lamp had a higher efficacy than the halogen benchmarks, no lamps reached the lumen output level of a 50 W halogen MR16. The symbol for the LED products indicates the criterion by which they were selected for Series 22; refer to Table 1 for specific equivalency claims.

directional lamps,[12] but even if the same center beam intensity can be achieved, doing so with fewer total lumens—at the same beam angle—will require a sharper cutoff.

Although equivalency to 50 W halogen lamps is an important goal, it is important to remember that specifiers need a range of lamps with varying beam angles and lumen output (i.e., complete families of products). Such variety of offerings has contributed to the popularity of the halogen MR16 lamp. Although this CALiPER report focuses on the highest-output LED MR16 lamps available, lower-output lamps should not be discredited or ignored—at least as long as they make appropriate equivalency claims.

All but one of the Series 22 LED products exceeded 40 lm/W, which is the minimum level for ENERGY STAR qualification. The most efficacious product was measured at 90 lm/W, and the mean efficacy was 62 lm/W. This level of performance is typical of other directional LED lamp types tested by CALiPER. It is especially notable, however, given the size restriction of the MR16 form factor, which is more demanding of LED technology. While LED MR16s may still not be able to compete with the full range of halogen MR16 lamps, they are certainly vastly more energy-efficient. Nonetheless, specifiers should carefully consider the LED product they choose, with the highest-efficacy product nearly twice as efficacious as the lowest-efficacy product.

Distribution of Light

Directional lamps, and especially MR16 lamps, are most often specified based on their luminous intensity distribution, which is usually characterized by the beam angle and center beam intensity (CBCP). Figure 5 shows the beam angle and CBCP for each of the Series 22 LED MR16 lamps versus the *predicted* value at a given wattage from the ENERGY STAR Lamp Center Beam Intensity Benchmark tool. Note that the predicted value is not used for determining ENERGY STAR qualification; a lower threshold is used instead.

Consistent with the analysis of lumen output, none of the CALiPER-tested lamps can match the ENERGY STAR-predicted CBCP of 50 W halogen MR16s at any beam angle.[13] Furthermore, only one product (14-26) exceeded the CBCP predicted for a 35 W halogen lamp using the ENERGY STAR tool at its measured beam angle. Notably, this product also claimed equivalency to a 75 W halogen MR16, which produces vastly higher CBCP (and lumen output). This greatly overstated equivalency claim is not unique, however. Not a single product achieved the ENERGY STAR-predicted CBCP at its measured beam angle—and all but six products made such a claim.[14] For context, however, it should be noted that at least two of the 50 W benchmarks tested by CALiPER (BK14-32, BK14-33) also fell well below the ENERGY STAR-predicted CBCP—and they were also measured to have center beam intensities substantially lower than their rated values of 4,400 cd. Nonetheless, these products still outperformed most of the LED MR16s that were tested.

One of the goals for Series 22 was to identify currently available MR16 lamps with narrow distributions. Three products claiming a beam angle of 15° and two products claiming a beam angle of 10° were identified, and all five products generally produced their claimed distribution. The narrowest was measured at 7° and the widest at 18°. Importantly, these five products tended to have lower lumen output (mean of 381 lm), although one product was measured at 511 lm. The availability of additional and/or even narrower distributions would be

[12] ENERGY STAR uses a tool based on beam angle and center beam intensity to determine if equivalency claims are appropriate. This tool is based on a dataset of conventional lamp performance. An analysis based on this tool is provided in a subsequent section of this report.

[13] Note that one of the 50 W halogen MR16 benchmark products tested by CALiPER (BK14-32) also fell substantially below the predicted value indicated by ENERGY STAR.

[14] To repeat, the ENERGY STAR minimum requirement is based on a lower bound, which is two standard deviations below the predicted value, or approximately two-thirds of the equivalency curve level.

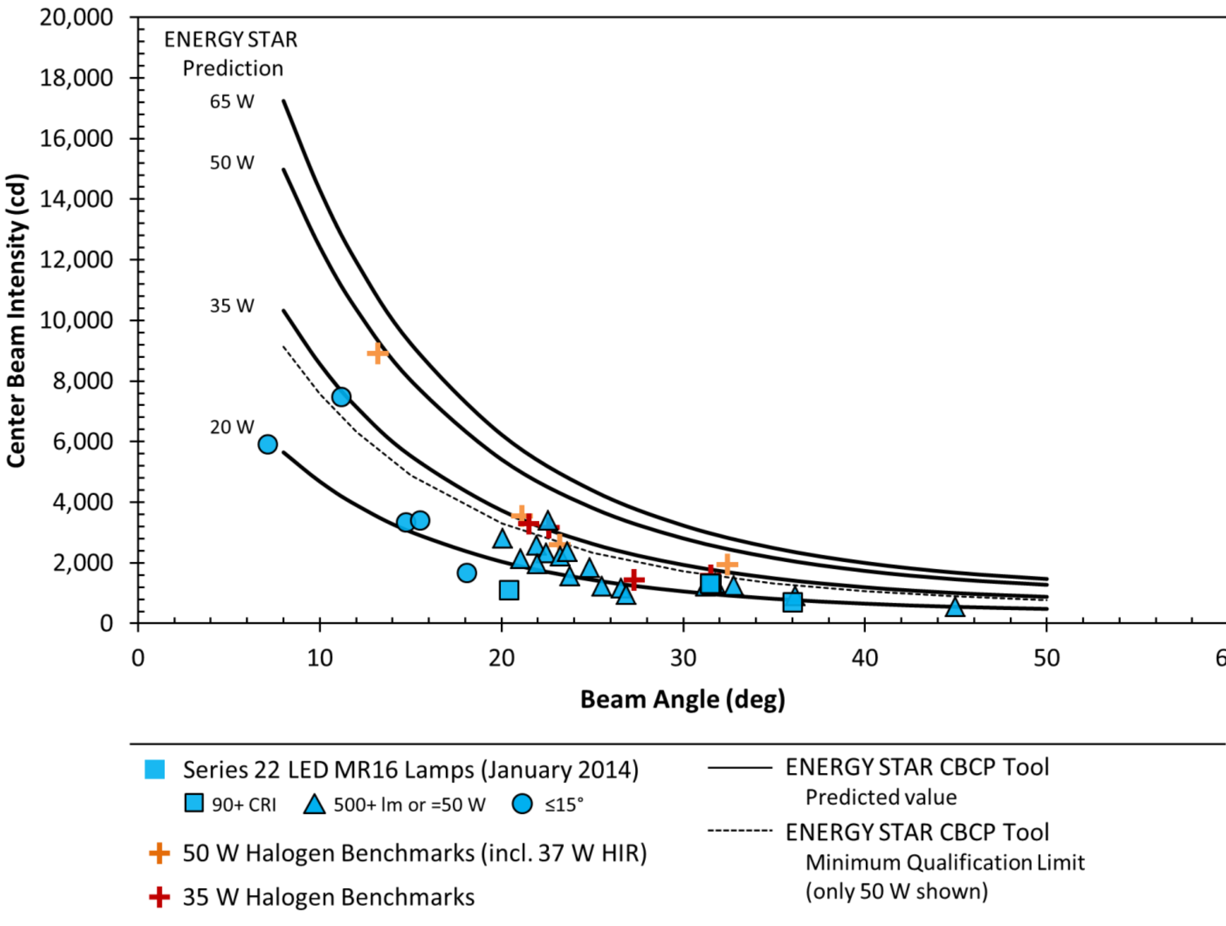

Figure 5. Center beam intensity versus beam angle for the Series 22 LED MR16 products versus the predicted center beam intensity of halogen MR16 lamps at the listed input power. The predicted halogen center beam intensity was calculated using the ENERGY STAR tool; for qualification, lamps must achieve the lower bound, not the predicted value. At the same beam angle, only one product achieved the center beam intensity of a 35 W halogen MR16, despite a majority claiming equivalency to a 50 W halogen MR16.

beneficial in the future, as would products with high lumen output (500 lm or more), high CRI (90 or higher), and a narrow beam—CALiPER did not identify any such products during its search.

Color Characteristics

MR16 lamps are frequently used for focal lighting, where color quality is critical. In some instances, an LED lamp with a CRI in the 80s may be insufficient, which is one reason CALiPER sought lamps with a CRI above 90—despite the limitations of CRI in effectively characterizing color quality for LEDs. For equal comparison, CALiPER selected lamps with a nominal CCT of 3000 K, although it should be noted that lamps with other CCTs (e.g., 2700 K, 5000 K) are also available. Users wishing to match the color appearance of halogen lamps should be sure to specify lamps at 2700 K or 3000 K, which are the typical CCTs of halogen MR16 lamps.

Of the 23 lamps that were not in the high-CRI selection group, all but one had a CRI between 80 and 86, as shown in Figure 6. This has become the de-facto standard for integral LED lamps of all types. Notably, one product had a CRI of just 63. Although it had an efficacy of 90 lm/W, such a lamp would be unacceptable for almost every application where MR16 lamps are used. As has been a trend in recent CALiPER reports, no lamps

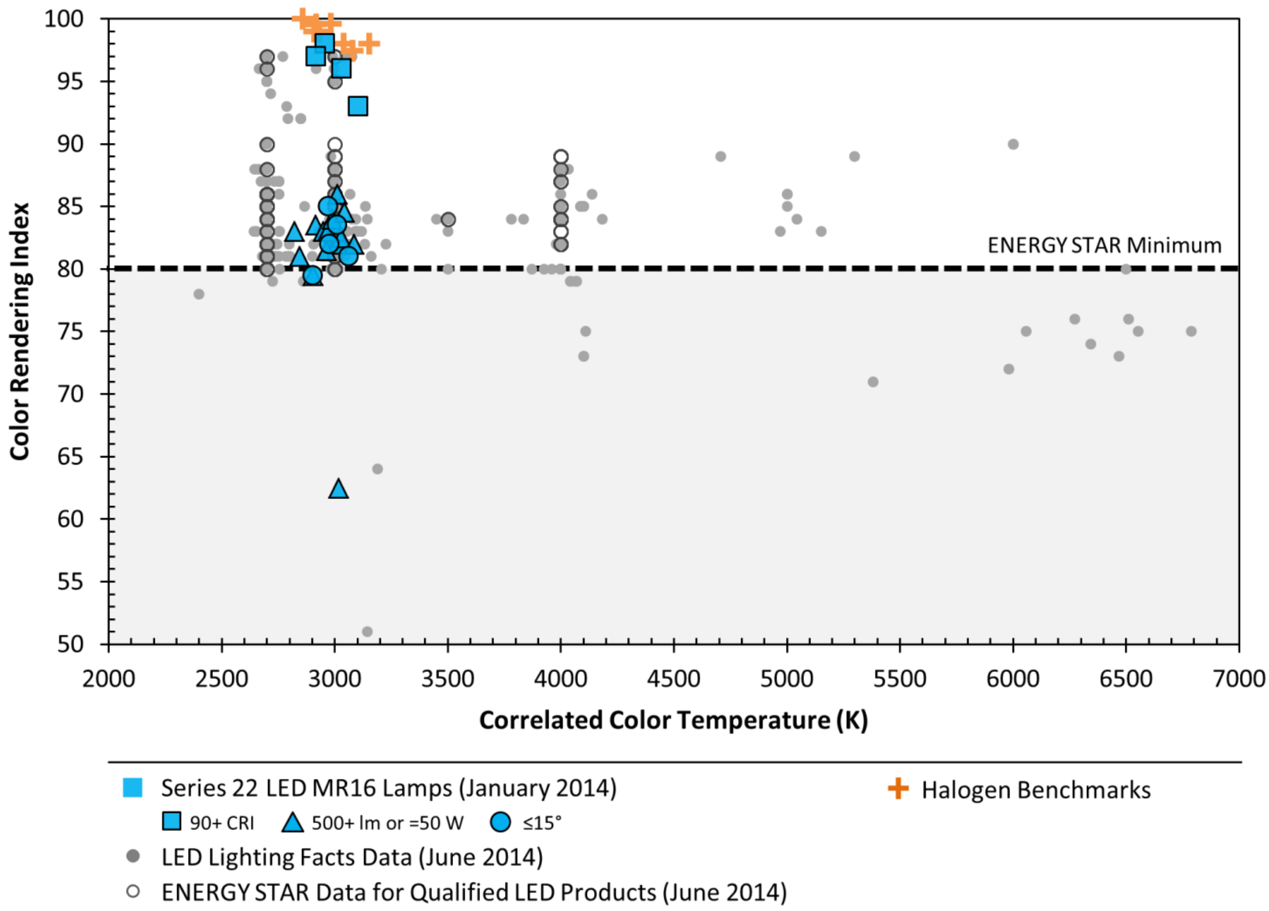

Figure 6. Color characteristics of the Series 22 LED MR16 lamps. A vast majority of the Series 22 lamps met the ENERGY STAR criteria, with all lamps having a nominal CCT of 3000 K and most having a CRI in the low 80s. Four lamps with a CRI in the 90s were also tested. Users should also be aware that MR16 lamps with low CRIs (e.g., 63) are on the market—product 14-25 did not list CRI in any available information.

exceeded ANSI-defined limits for D_{uv}, with each product between -0.0045 and 0.0035. Of the 27 products tested, 16 had a D_{uv} less than zero.

All four products selected because they claimed a CRI greater than 90 met that claim, with the highest-CRI product (14-01) measured at 98. All four products used a different phosphor mix than the "standard" LED products with a CRI in the low 80s. As shown in Figure 7, the result is increased long-wavelength emission, with peak output shifted from around 610 nm to around 630 nm. Conversely, the one low-CRI product emitted less long-wavelength (red) energy, with a peak emission at about 580 nm. Note that even LED products with a CRI as high as 98 still differ in spectral output from halogen or HIR lamps, which emit substantial amounts of energy above 680 nm, while LED products tail off.

Increasing CRI—particularly by increasing long-wavelength emission, does reduce energy efficiency. Although the sample size was small, the four products in the high-CRI category had a mean efficacy of 51, compared to a mean efficacy of 64 for the other products. However, it is also critical to distinguish that just because a product has a high CRI does not mean it cannot have high efficacy. For example, product 14-01 has a CRI of 98 with an efficacy of 69 lm/W.

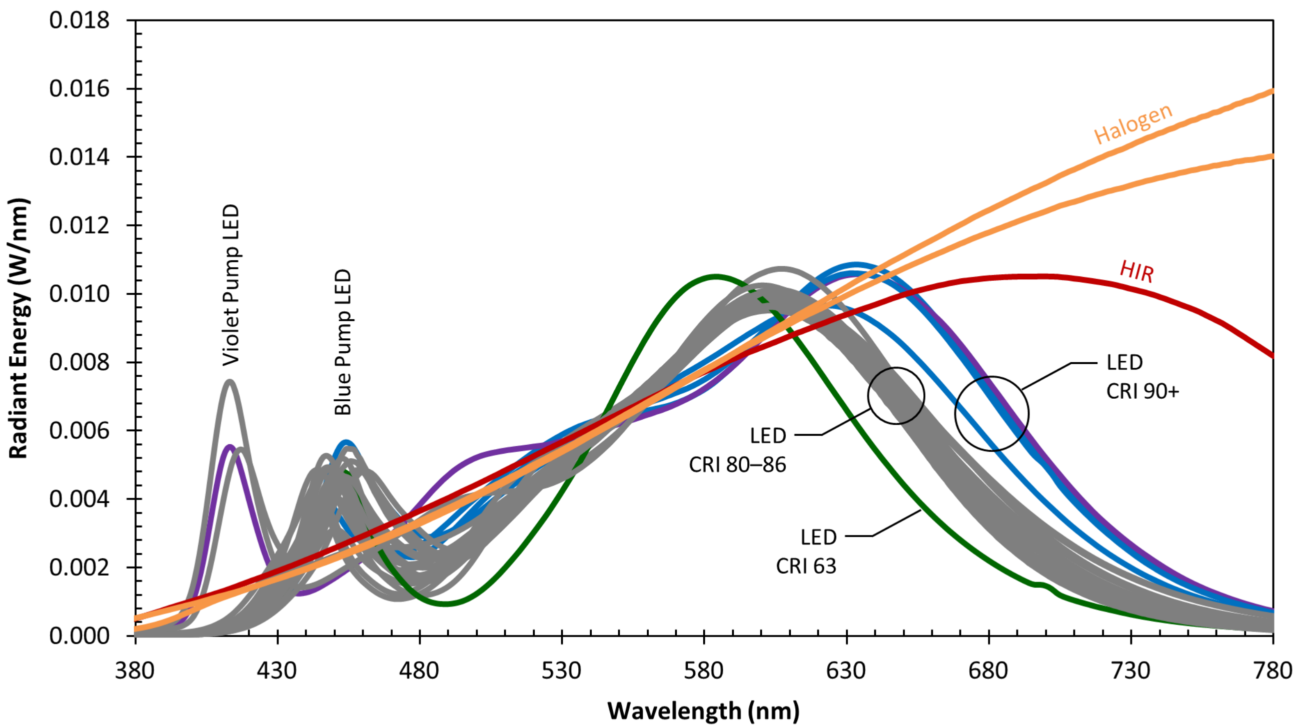

Figure 7. Spectral power distributions for the Series 22 LED products.

One other interesting observation for Figure 7 is the difference between violet-pump and blue-pump LEDs. Violet-pump products (14-03, 14-09, 14-26) use an LED with a peak emission around 410 nm, whereas the more typical blue-pump products use an LED with a peak emission around 450 nm. Importantly, either method can be used to produce "standard" products with a CRI in the 80s, or higher-performing products with a CRI in the 90s.

Electrical Characteristics

The input power for the Series 22 products ranged from 4.0 to 11.8 W. The measured power factors for the 26 products measured on AC power ranged from 0.64 to 0.96, with a mean of 0.79. Eight of the 27 products had a power factor below the ENERGY STAR minimum of 0.70, as shown in Figure 8, but three of those were less than 5 W and thus exempt from that criterion. Although this level of performance is lower than what CALiPER has observed for other integral LED lamp categories—which all have a larger form factor—it is critical to note that the reported data is for single lamps measured on a benchtop power supply. Field performance with multiple lamps on a typical transformer(s)—and potentially with a dimmer—would be different.

Size and Shape

As with other directional lamps, ANSI defines size tolerances for all lamps carrying the MR16 designation. Although the dimensional tolerances listed by ANSI are more detailed, length (maximum 1.9") and diameter (maximum 2.0") are two that are easily measured. Whereas all of the lamps had a measured diameter within the tolerance, 12 were measured to have a length longer than the ANSI-defined limit, as shown in Figure 9. Those products were between about one-eighth and seven-eighths of an inch longer than the three halogen benchmarks, which were measured at approximately 1.75". While some small differences may seem trivial, many MR16 luminaires and lamp holders are carefully engineered to fit around the lamp. Any substantial deviation could prevent an LED lamp from fitting altogether, or could limit the use of accessories, such as lenses.

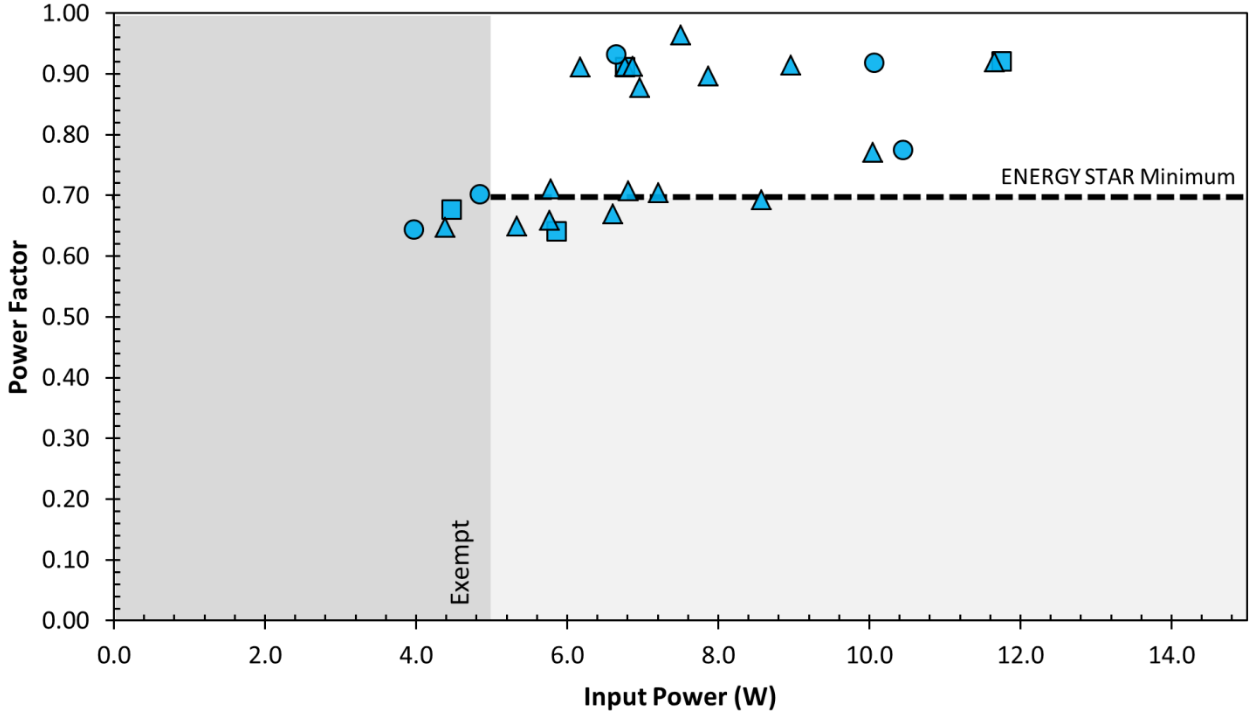

Figure 8. Power factor and input power for the Series 22 LED MR16 lamps. With the exception of two products, the lamps divided into two groups: those with a power factor at or just below 0.70, and those with a power factor around 0.90.

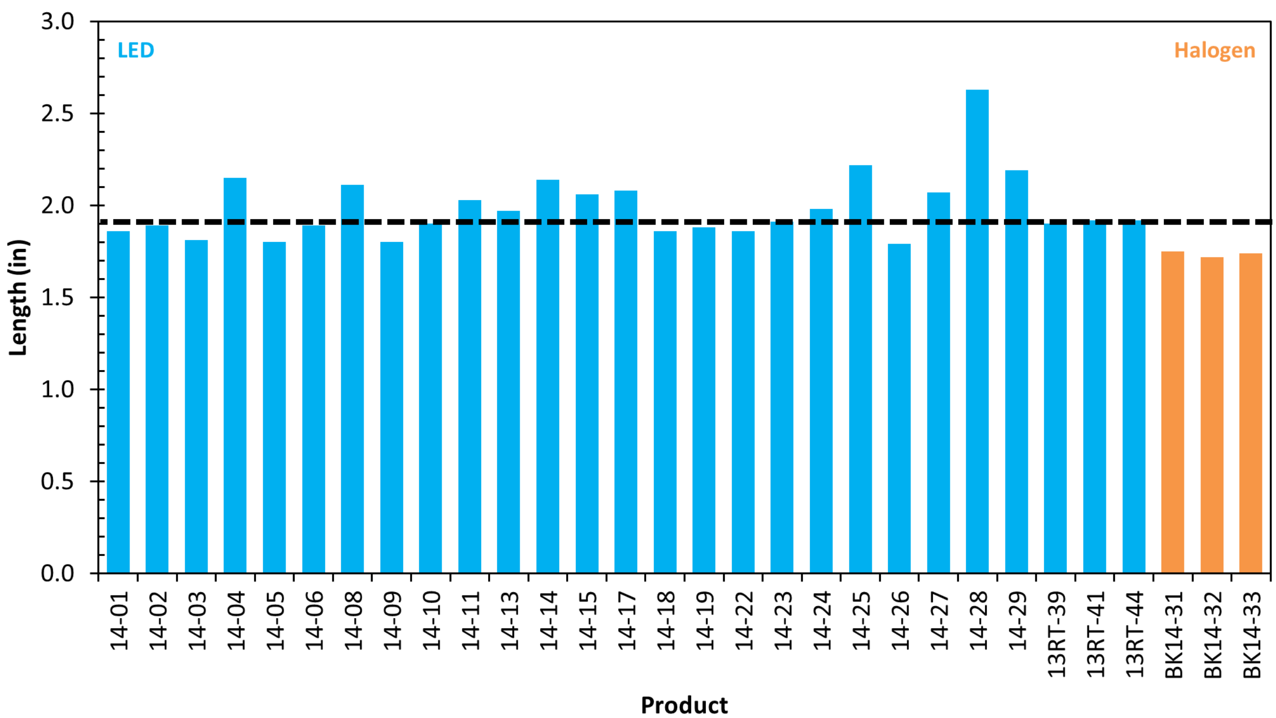

Figure 9. Measured length of the Series 22 products. Numerous products exceeded the allowable size according to ANSI.

Manufacturer Claims

Evaluating the accuracy of manufacturers' performance claims is an important component of the CALiPER program. This task is often difficult because different values are reported in different literature. For example, performance values listed on specification sheets are sometimes different from values listed by LED Lighting Facts or on product packaging. In some cases, these differences may be attributable to rounding to simplify visual appearance or improve legibility. In others, nominal values may be used instead of a single specific test result to better reflect the distribution of performance that can be expected from lighting products (i.e., not every product is identical). In other cases, updates to products may not be immediately reflected in literature. For this dataset, CALiPER generally used the highest (or best) listed value as the basis for comparison.

Most of the Series 20 LED products had data available for all of the major performance criteria. Of the 27 products, 19 were measured to be within ±10% of the listed lumen output,[15] whereas four products (14-19 and 14-24) emitted more than 110% of the listed lumens and six products (14-02, 14-04, 14-11, 14-25, 14-27, and 13RT-41) emitted less than 90% of the rated lumens. Two of those products (14-02 and 14-27) emitted 71% and 77% of their rated output, respectively. Although producing more lumens than claimed—potentially resulting in glare—is probably less likely to lead to consumer or specifier dissatisfaction, the accuracy of manufacturer data is still a fundamental concern.

Nine products failed to meet the ±10% criterion for input power, but all drew less than 90% of the rated input power. This is generally a positive outcome, although the inaccuracy is still notable. Likewise, three products had a measured efficacy greater than 110% of the listed value, but the efficacy of one product, 14-02, was 68% of the claimed value. In total, 14 of 27 products met all three claims for input power, efficacy, and lumen output, and six additional products could be considered to exceed the claim.

In general, the manufacturer claims for color quality metrics were accurate, with no products exceeding the ±10% criterion. Further, all products were within the same nominal CCT bin as claimed. The only notable product (14-25, with a CRI of 63) did not list a value for CRI in any literature.

Of 26 LED products that listed a value, 24 were found to have an appropriate measured beam angle based on the ANSI-defined tolerances. In contrast, 10 of 19 LED products that provided information on CBCP were found to have a measured value that was more than 10% different from the listed value. Three products (14-11, 14-27, and 14-28) had a measured CBCP that was substantially lower than claimed (74%, 48%, and 73%, respectively).

In total, the accuracy of the manufacturer claims for the Series 22 products was generally similar to what CALiPER has observed for other types of products. There are many possible contributing factors to the discrepancies, ranging from malicious intent of the manufacturer to performance variation not captured in the small sample of products measured by CALiPER. Further, it should be noted that conventional products are also prone to differences between measured and reported performance. For example, of the two Series 22 benchmark products that listed CBCP, both had a measured value that was more than 10% below the listed value.

[15] 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.

6 Conclusions

As tested by CALiPER, the Series 22 LED MR16 lamps demonstrated systemic inaccuracy in equivalency claims (comparisons to a specific-wattage halogen MR16 lamp). Every lamp that made a claim produced fewer lumens and had lower center beam intensity than would be predicted (for a lamp having the same beam angle) using the ENERGY STAR center beam intensity tool. Some products may still qualify for ENERGY STAR, because the qualification threshold is lower.

Other key takeaways on basic performance characteristics include:

- LED MR16 lamps producing up to 600 lm are widely available. This is a considerable improvement over past CALiPER testing from 2012 and earlier.
- All of the Series 22 LED products offer some efficacy advantage versus the halogen benchmarks, but the range in efficacy is substantial (38 to 90 lm/W). Unlike with some other categories, there does not appear to be substantial clustering just above an energy-efficiency program threshold—in this case, 40 lm/W for ENERGY STAR.
- A vast majority of the MR16 lamps identified in the CALiPER selection process had a medium distribution (i.e., beam angle between 20° and 30°). However, CALiPER was able to purchase five lamps with a listed beam angle of 15° or less. These products were measured between 7° and 18°. Even narrower distributions (e.g., 4° beam angle), as well as a wider variety of options, would make LED MR16s attractive for more applications.
- As with most types of integral LED lamps, a majority of the currently available MR16 lamps identified by CALiPER had a CRI in the low 80s. Lamps with a nominal CCT of 3000 K were prevalent. CALiPER also identified and purchased four LED MR16 lamps with a CRI in the 90s. These lamps may be more suitable for applications with high demand for color fidelity—that is, color rendering similar to that of halogen lamps.
- The power factor of the Series 22 lamps was essentially bifurcated, with one group having a power factor around 0.70 and another group having a power factor around 0.90. All measurements in this report are for a single lamp on a laboratory AC power supply, except for 13RT-41, which was tested on a DC power supply. Field performance may vary.

CALiPER plans to conduct additional testing on the Series 22 LED MR16 lamps to investigate performance attributes that are not captured by LM-79 testing. These results will be published in subsequent reports.

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 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 that the measured chromaticity is below the locus (appearing slightly pink). The American National Standards Institute provides limits for D_{uv} for nominally white light.
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 Efficacy Lumens per watt (lm/W)	The quotient of the total luminous flux emitted and the total input power.
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 calculating R_a. R_9 values should not be compared to R_a (CRI) values. As a shorthand approximation, an R_9 less than zero is poor, an R_9 greater than zero is good, an R_9 greater than 50 is very good, and an R_9 greater than 75 is excellent.

Appendix B: Product Selection

Product selection is an important part of the CALiPER process. While products are usually selected with the intent of capturing the current state of the market, for this series a different procedure was followed. The Series 22 products were selected based on meeting at least one of four criteria:

- Rated output of 500 lm or greater
- Equivalency claim of 50 W or greater
- Rated beam angle of 15° or less
- Rated CRI of 90 or greater

Additionally, preference was given to products with a CCT of 3000 K, if a product line included multiple CCTs.

After identifying the selection criteria, a database of products was created by evaluating:

- 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 manufacturers' representatives

After establishing a list of appropriate products, attempts were made to anonymously purchase the products through standard industry resources (e.g., distributors, retailers). Some identified products were not available or could not be shipped in a timely manner, and thus were not included in the final group. Some of the products received were different from those which were selected—with some manufacturers acknowledging a change and others not. If a substituted product did not meet the initial selection criteria, it was not included in the analysis.

The selection, purchasing, testing, analysis, and reporting process can take a considerable amount of time. It is acknowledged that the products included in the Series 22 set may have been replaced with a newer model and/or may no longer be sold. However, that does not diminish the broader relevance of the findings. In fact, the lamps generally represent a snapshot of performance at the time of purchase,[16] and serve as an effective tool for comparing LED to benchmark technologies while helping to illustrate some of the challenges of this specific application—challenges that are unlikely to abate in the near future. Further, the evaluation was not intended as a measure of the suitability of any specific lamp model, and the results should not be taken as a verdict on any product line or manufacturer.

[16] While the products were purchased at the noted time period, the date of manufacture may vary. CALiPER purchases products through standard distribution channels. The product model information is identified using manufacturer web pages and specification sheets. In some cases, "old" products are included because the model number was not changed after upgrades and/or the older stock remains in the distribution channel. This is a problem for all specifiers.

Appendix C: Series 22 Product Identification

Table C1. Make and model for the Series 22 products

DOE CALiPER Test ID	Brand	Model
14-01	Green Creative	7MR16G3DIM/930FL36
14-02	Nu Vue Lighting	NV/MR16/6.1/WW/FL/53/CT
14-03	Soraa	MR16-65-B01-12-930-36
14-04	TerraLUX	TLL-R16A-A2030NFD
14-05	Dauer LED	LED-MR16-4XBD-WW-15 (487054)
14-06	GE Lighting	LED7DMR16D/830/15 (69919)
14-08	Philips Lighting	10MR16/END/S15 3000 12V DM (414755)
14-09	Soraa	MR16-65-B01-12-830-10 (00265)
14-10	Toshiba	5MR16/30DSP-T
14-11	Acculamp	ALSMR16 450L 36 DIM
14-13	CREE Lighting	LM16-50-30K-25D
14-14	Cyber Tech Lighting	LB10MR16/D/WW
14-15	E2 Lighting	E2MR0727K-40D
14-17	Feit Electric	BPEXN/LED
14-18	Green Creative	7MR16G3DIM/830NF25
14-19	Han Star LED	PLM16D
14-22	Nu Vue Lighting	NV/MR16/5.1/WW/NFL/53/CX
14-23	OSRAM	LED7MR16/DIM/830/NFL25 (78420)
14-24	Philips Lighting	10MR16/END/F24 3000 DIM Model 9290002194
14-25	Shenzhen Kingliming Technology	MR 16 5W COB
14-26	Soraa	MR16-75-B01-12-830-25
14-27	TCP	LED7MR1630KNFL
14-28	Toshiba	9MR16/30GNF-UP
14-29	Turolight	HD-MR16/9W/30/FL25/GU5.3
13RT-39	GE Lighting	LED7XDMR16830/25
13RT-41	EcoSmart	ECS 16 WW V2 NFL
13RT-44	Verbatim	M16ES-L500-C30-B30
BK14-31	Litetronics International	L-3804
BK14-32	Osram Sylvania	50MR16/B/NFL25 (58320)
BK14-33	Osram Sylvania	37MR16/IR/NFL25/C 12V (58634)
BK13RT-50	CBConcept	MR16+C 12V 35W 30D
BK13RT-51	Philips Lighting	35MRC16/HES/FL 12V 12/1
BK13RT-53	GE Lighting	Q50MR16C/CG15

Appendix D: CALiPER Testing of Conventional MR16 Lamps

Table D1. Summary data for initial performance of CALiPER-tested benchmark conventional MR16 lamps. The first two digits of the CALiPER test ID indicate the year in which the product was purchased.

DOE CALiPER Test ID	Initial Output (lm)	Input Power (W)	Efficacy (lm/W)	Power Factor	CRI	CCT (K)	CBCP (cd)	Beam Angle (deg)	Field Angle (deg)
BK14-31	849	51.3	17	1.00	98	3152	1,940	32	51
BK14-32	638	50.9	13	1.00	100	2859	2,585	23	37
BK14-33	713	36.7	19	1.00	99	2932	3,533	21	30
BK13RT-50	564	34.7	16	1.00	100	2917	1,432	27	46
BK13RT-51	644	35.8	18	1.00	100	2982	1,592	32	47
BK13RT-53	757	50.1	15	1.00	97	3079	8,909	13	25
10-21	603	35.8	17	1.00	98	3040	3,159	23	35
10-22	500	33.8	15	1.00	99	2909	3,286	22	31
Minimum	500	33.8	13	1.00	97	2859	1,432	13	25
Mean	658	41.1	16	1.00	99	2983	3,304	24	38
Maximum	849	51.3	19	1.00	100	3152	8,909	32	51

DOE SSL Commercially Available LED Product Evaluation and Reporting Program
NO COMMERCIAL USE POLICY

The U.S. Department of Energy (DOE) is a federal agency working in the public interest. Published information from the DOE SSL CALiPER program, including test reports, technical information, and summaries, is intended solely for the benefit of the public, in order to help buyers, specifiers of new SSL products, testing laboratories, energy experts, energy program managers, regulators, and others make informed choices and decisions about SSL products and related technologies.

Such information may not be used in advertising, to promote a company's product or service, or to characterize a competitor's product or service. This policy precludes any commercial use of any DOE SSL CALiPER Program published information in any form without DOE's express written permission.