

CALIPER

BENCHMARK REPORT

NOVEMBER 2008

Performance of Halogen Incandescent MR16 Lamps and LED Replacements

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



DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes **any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.** Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161
ph: (800) 553-6847
fax: (703) 605-6900
email: orders@ntis.fedworld.gov
online ordering: <http://www.ntis.gov/ordering.htm>



This document was printed on recycled paper.

(9/2003)

Performance of Halogen Incandescent MR16 Lamps and LED Replacements

CALiPER Benchmark Report

ML Paget
RD Lingard
MA Myer

November 2008

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

Abstract

The U.S. Department of Energy (DOE) Commercially Available LED Product Evaluation and Reporting (CALiPER) Program was established in 2006 to investigate the performance of luminaires and replacement lamps which use light-emitting diodes (LEDs) as their light source. To help users better compare LED products with conventional lighting technologies, CALiPER has also performed benchmark research and testing of traditional (i.e., non-LED) lamps and fixtures. This benchmark report addresses the halogen MR16 lamp and its commercially available LED replacements. The construction and operation of halogen MR16 lamps, as well as lamp performance, are discussed based on manufacturer data and CALiPER benchmark testing. In addition, the report describes LED MR16 replacement lamps and compares their performance with halogen benchmarks on a range of standard lighting measures, including power usage, light output and distribution, source efficacy, correlated color temperature, and the color rendering index. Manufacturer claims for LED replacement lamps are examined, along with potential performance and application issues indicated by CALiPER testing results.

Contents

Abstract	iii
Introduction.....	1
MR16 Halogen Incandescent Reflector Lamps	1
Lamp Construction and Attributes.....	2
Lamp Operation.....	4
Performance of Halogen Incandescent MR16 Lamps	5
LED Replacements for MR16 Lamps.....	6
Performance of LED MR16 Replacement Lamps	7
Light Output	7
Efficacy.....	9
Directionality	10
Color Characteristics	11
Power.....	13
Dimming.....	13
Replacements That Fit.....	13
Conclusions.....	14
Bibliography	14

Figures

1 Typical MR16 Lamp.....	2
2 Common MR16 Lamp Bases.....	2
3 Relationship Between CBCP and Beam Angle in Directional Lamps	3
4 Light Output of MR16 Replacement Lamps Compared to Halogen MR16 Lamps	8
5 Measured Light Output of Halogen MR16 Lamps and LED Replacements Compared to Manufacturers' Reported Values	8
6 Comparison of Efficacy Values of Halogen MR16 Lamps with those of LED Replacements	9
7 Measured Efficacy of Halogen MR16 Lamps and LED Replacements Compared to Manufacturers' Reported Values	10
8 Measured Light Intensity and Beam Angles for 20-W Halogen MR16 Lamps and LED Replacements	11
9 Comparison of CCT Values of Halogen MR16 Lamps with Those of Tested LED Replacements	12
10 Chromaticity of LED MR16 Replacement Lamps plotted against ANSI Chromaticity Specifications.....	12

Tables

1	Summary of Basic Performance Characteristics of Low Voltage Halogen MR16 Lamps.....	6
2	Summary of CALiPER Test Results for LED MR16 Replacement Lamps	7

Introduction

Solid-state lighting (SSL) products using light-emitting diodes (LEDs) are proliferating in the lighting marketplace. Their low energy consumption, potential long life, and compact form make LEDs an attractive alternative to traditional light sources in some applications. It can be argued, however, that the marketing of SSL technology has outpaced the development and practice of using standard test procedures by which to characterize the performance of a product. Consequently, the consumer faces a rapidly increasing variety of LED luminaires and replacement lamps, along with a bewildering range of product claims—and a relative lack of information with which to accurately evaluate LED lighting products as well as compare them to traditional technologies.

To fill the LED lighting “data gap,” the U.S. Department of Energy (DOE) initiated the Commercially Available LED Product Evaluation and Reporting (CALiPER) Program in 2006. Industry standard test procedures now exist to measure the efficacy, photometric performance, and color characteristics of LED luminaires and replacement lamps. Related standard test procedures for determining LED product lifetime are nearing completion. Through independent testing laboratories, CALiPER has used these procedures to evaluate a variety of LED luminaires and replacement lamps available through common retail channels, and has made the test results available for public review.¹ For benchmarking purposes, CALiPER also includes testing of conventional (i.e., non-LED) lamp types and luminaires that use conventional light sources. Consumers and manufacturers now have a resource for evaluating and comparing LED and conventional lighting products; more product types are to be tested and benchmarked as CALiPER testing continues.

This benchmark report presents a comparison of the widely used halogen incandescent MR16 lamp with commercially available LED MR16 replacement lamps. CALiPER compared MR16s with LED replacements on a range of standard lighting measures, including power usage, light output and distribution, source efficacy, correlated color temperature (CCT), and the color rendering index (CRI). Photometric data published by manufacturers for SSL products also were collected and analyzed in order to compare manufacturer performance claims with measured performance results.²

MR16 Halogen Incandescent Reflector Lamps

The MR16 will be familiar to some readers as a reflector lamp originally used in slide projectors. Its small size, durable construction, and wide range of intensities and beam spreads have since made the MR16 a useful tool in lighting design as well. MR16 lamps now are commonly used for highlighting display objects (e.g., in museums, galleries, and retail spaces) and for accenting architectural and landscape features.



¹ Summary reports for DOE CALiPER testing are available online at http://www.netl.doe.gov/ssl/comm_testing.htm.

² Detailed test reports for products tested under the DOE SSL testing program can be requested online: http://www.netl.doe.gov/ssl/comm_testing_request.htm.

Lamp Construction and Attributes

The MR16 lamp is a compact, directional light source consisting of a single-ended quartz halogen filament capsule, mounted within a pressed glass reflector (Figure 1). As indicated by its designation, the MR16 is a multifaceted reflector (MR) lamp with a 16/8-inch (i.e., 2-inch) diameter. Typical bases for these lamps include the two-pin (GU5.3) base for low-voltage applications and a twist-and-lock (GU10) configuration for applications in which line voltage is used (Figure 2). Measured from the face of the lamp to the tip of the base, the maximum overall length (MOL) of most low-voltage MR16 lamps is approximately 1.75 inches (GU5.3 base); some line-voltage products are over 3 inches long, depending on base type.

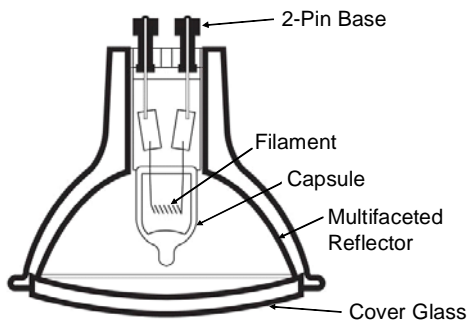


Figure 1. Typical MR16 Lamp

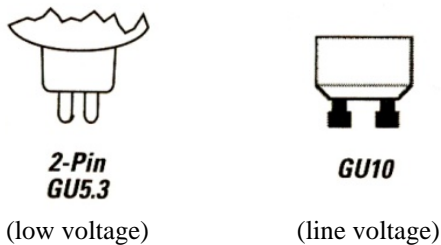


Figure 2. Common MR16 Lamp Bases

The quartz halogen filament capsule is designed to operate at significantly higher pressure than a standard incandescent lamp. Because the capsule can rupture under certain end-of-life conditions (referred to in the lighting industry as *non-passive failure*), MR16 lamps must either have an integrated cover glass or be used in an enclosed fixture.³ The quartz capsule transmits ultraviolet (UV) radiation from the filament; however, this undesirable effect is mitigated by the lamp cover glass and/or fixture shields and filters.

³ The quartz capsule also can be contaminated when handled directly, resulting in rupture and/or premature failure when operated.

Quick Facts

MR16 Lamp Designations

The designation **MR16** refers to the lamp construction and overall diameter at its largest circumference. **MR** stands for *multifaceted reflector*. Per standard lamp naming convention, the number **16** refers to the lamp diameter in eighths of an inch (i.e., 16/8 inches, or 2-inch diameter).

Lighting designers and specifiers often use a three-letter shorthand designation to describe MR16 lamp wattage and beam angle combinations (originally published in ANSI Standard C78.379-1994). For example, **BAB** designates a 20-W lamp with a 40° (flood) beam angle, and a 20-W MR16 with a 10° (spot) beam angle is called an **ESX**.

The majority of MR16 lamps are designed for low-voltage operation (typically 12 V or 24 V). The power consumed by a lamp (expressed in watts, W) is calculated by multiplying supply voltage (volts, V) by the supply current (amperes, A). Therefore, for a low-voltage lamp (e.g., 12 V) and line-voltage lamp (e.g., 120 V) of equal wattage, the filament in the 12-V lamp must handle *ten times* the current of the 120-V lamp.⁴ Consequently, the filaments in low-voltage MR16 lamps are shorter, thicker, and more robust than their line-voltage counterparts. The thick filament provides increased resistance to current flow, which allows the low-voltage MR16—with its inherently higher operating current—to generate greater luminous intensity than line-voltage lamps of equal wattage. In combination with lamp reflector design, the small filament also allows more precise control of light distribution and beam appearance.

MR16 reflectors generally use either a dichroic or aluminum coating. Dichroic coatings reflect light from the filament through the front of the lamp and transmit infrared radiation (IR) through the back of the reflector along with some colored light. In contrast, aluminum coatings are opaque, reflecting all light and IR forward. Many manufacturers provide different quality grades for MR16 reflector coatings and optics, allowing the user to match lamp performance and cost with application requirements.

The MR16 lamp is commonly characterized by its distribution (also referred to as beam angle or beam spread”), with beam angles for highlighting individual objects or features (e.g., very narrow spot), ranging up to broader distributions for general accent lighting (e.g., very wide flood). For directional lamps, intensity rather than total lumen output is the prevalent metric. Figure 3 illustrates the relationship between center beam candlepower (CBCP) and beam angle:

- CBCP is the intensity in candelas (cd) emitted at the center of a directional lamp beam (0°, or nadir). CBCP values for halogen MR16 lamps range from 230 to 16,000 cd and are affected by both the lamp wattage (as it relates to light output) and the beam angle of the lamp. A lamp with a large beam angle will have a lower CBCP than a lamp with narrow distribution.
- Beam angle is the angle at which the beam intensity is 50% of the CBCP. Beam angles for halogen MR16 lamps range from less than 10° (narrow spot) to greater than 50° (wide flood).
- Field angle is the angle at which the beam intensity is 10% of the CBCP. Field angle values often are not reported in manufacturer literature.

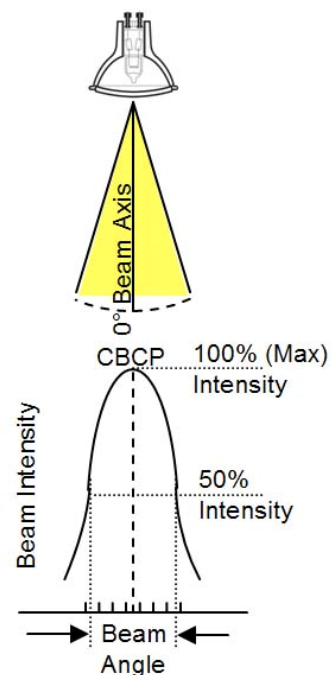


Figure 3. Relationship Between CBCP and Beam Angle in Directional Lamps

⁴ For example, a 50-W lamp operating at 12 V requires 4.17 A (i.e., $50 \text{ W}/12 \text{ V} = 4.17 \text{ A}$) versus 0.417 A at 120 V (i.e., $50 \text{ W}/120 \text{ V} = 0.417 \text{ A}$).

Lamp Operation

Low-voltage MR16 lamps require a transformer to step down supply voltage (e.g., 120 V or 277 V) to an appropriate operating voltage (e.g., 12 V or 24 V). There are two major types of low-voltage transformers: magnetic and electronic. Magnetic transformers offer simple construction, durability, and higher available output wattages (e.g., 1,200 W).

Although higher-output wattage enables operation of more lamps on a circuit, magnetic transformers experience a corresponding voltage drop with the number of connected lamps, reducing lamp light output. Voltage drop is affected further by lamp distance from the transformer as well as the size and type of circuit wiring. Older style (EI) magnetic transformers also can be heavy and noisy; however, newer toroidal magnetic transformers are considerably lighter, quieter, and more energy efficient.

For equivalent power output, electronic transformers are lighter, smaller, and quieter than magnetic transformers but limited in output wattage (typically no greater than 300 W). Electronic transformers with an alternating current (AC) output experience voltage drop like magnetic transformers, but their compact format permits installation near lamps—or integration with individual fixtures—helping to mitigate this effect. Direct current (DC) output electronic transformers practically eliminate voltage drop over long circuits.

Low-voltage lighting systems with magnetic transformers can be dimmed with conventional (i.e., inductive load) dimmers; however, electronic transformers should be paired with dimmers especially designed for low-voltage lighting. It is important to note that low-voltage transformers typically have minimum connected load requirements, below which lamps may operate erratically or not at all—a condition further complicated by dimming controls. As with all incandescent lamps, dimming a halogen MR16 lamp shifts its color to warmer appearance (i.e., lower CCT).

In normal operation, the high internal pressure of the quartz halogen capsule allows a higher filament operating temperature, resulting in a higher color temperature (i.e., 2900–3100 K) and “whiter” appearance than standard incandescent. Low-

Quick Facts

MR16 Transformer Voltage Drop

Both magnetic and electronic ballasts with AC output produce voltage drop in lighting circuits, depending largely on the

- number and combined wattage of connected lamps
- distance of lamps from the transformer
- size and type of circuit wiring.

Voltage drop reduces lamp power and light output, essentially dimming the connected lamps. Operating halogen MR16 lamps at less than rated wattage (as with all incandescent lamps) also shifts lamp color to a warmer appearance (i.e., lower CCT).

For magnetic and electronic ballasts with AC output, voltage drop over longer circuit runs can be reduced with thicker (i.e., lower gauge number) wire, which has lower resistance to current flow. Note, however, that voltage drop is not a significant issue for low-voltage lighting with DC output electronic transformers or for line-voltage MR16 lamps.

voltage halogen MR16 halogen lamps range in wattage from 20 W to 75 W, with rated lamp life ranging from 2,000 to 6,000 hours. Line-voltage MR16 halogen lamps are available in wattages from 20 W to 100 W.

In normal operation, approximately 90% of the power consumed by an incandescent or halogen lamp is emitted as heat radiating from the lamp, as evidenced by bulb wall temperatures in excess of 400°F (200°C) for a common A19 lamp. In fact, incandescent lamps are used as a radiant heat source in applications as diverse as poultry incubators and bathroom vent fixtures—even children’s toys like the iconic Easy-Bake oven. It follows that incandescent lamps are very inefficient light sources. Luminous efficacy is the light output of a source (in lumens, lm) divided by its power usage (in watts, W), expressed in lumens per watt (lm/W). Efficacies for halogen MR16 lamps generally do not exceed 20 lm/W for higher performance IR lamps and can be less than 8 lm/W for non-IR versions. It should be noted that the luminous efficacy of a tungsten filament increases with its operating temperature but decreases over the life of the lamp.

Performance of Halogen Incandescent MR16 Lamps

CALiPER benchmark testing focused on 20-W halogen MR16 products at this time because LED replacement lamps cannot yet compete with higher-wattage halogen MR16 products in light output or luminous intensity. Two sources of halogen MR16 benchmark data are rated values published in manufacturer catalogs and CALiPER benchmark testing of typical lamps. Manufacturer data used included rated wattage, CBCP, lamp life, and beam angle. Although typically not reported for directional sources, manufacturer data for initial light output also were evaluated where available. CALiPER benchmark test results provide more data than manufacturer catalogs but are currently available for only a small set of sample products (six halogen MR16 lamps total). All test results represent performance at 12 V (AC or DC), not including transformer losses.

Table 1 presents a summary of surveyed manufacturer data and CALiPER test results for low-voltage 20-W halogen MR16 lamps. Surveyed manufacturer data were obtained from lamp catalogs from four major lamp manufacturers. These data compile ratings on 64 different 20-W halogen MR16 lamps. In general, CALiPER test data corresponded well with typical values from manufacturer catalogs. Collectively, the data illustrates what specifiers often expect from lamps of this type—a warm-neutral color appearance with excellent color rendering and significant center beam “punch”—particularly with the spot versions of the MR16 lamp.

Table 1. Summary of Basic Performance Characteristics of Low-Voltage Halogen MR16 Lamps

	Performance of Low-Voltage 20-W Halogen MR16 Lamps			
	Average from Surveyed Manufacturer Ratings	Range Reported in Manufacturer Ratings	Average from CALiPER Benchmark Tests	Range Observed in CALiPER Benchmark Tests
Input power (W)	20	–	20	18–21
Power factor (AC tests)	1.00	1.00	1.00	1.00
Light output (lm)	278	130–400	263	172–352
CBCP (cd) by beam angle				
“Spot” (<20°)	–	3150–7400	–	5631–6595
“Narrow flood” (20–35°)	–	400–2300	–	384–805
“Wide flood” (>35°)	–	270–1000	–	326–629
Efficacy (lm/W)	14	7–20	13	8–18
CCT	2930 K	2900 K–3000 K	2862 K	2775 K–2917 K
CRI	–	–	99	99

LED Replacements for MR16 Lamps

Products that are sold as LED MR16 replacement lamps are generally (but not always) similar in shape and size to their halogen MR16 counterparts. Lamp bases include those available for low-voltage and line-voltage MR-16 lamps (e.g., two-pin GU5.3 base, medium base), allowing LED replacements to be used in most fixtures designed for halogen MR16 lamps (with exceptions—see Replacements That Fit section). Most LED replacement lamps come in either warm white (e.g., 3000 K) or cool white (e.g., 6000 K) appearance as well as in a range of distinct colors.⁵ Because they do not have multifaceted reflectors, the beam angles for LED MR16 replacements are dictated by the arrangement and optics of their integrated LEDs and secondary optics, which may include individual reflectors, apertures, and/or lenses.

Compared to halogen MR16 lamps, minimal infrared radiation (i.e., radiated heat) is projected with light from LED MR16 replacements. The heat from LEDs is conducted away by heat sinking, such as aluminum fins or lattices forming the body of the lamp.

Compatibility with low-voltage transformers can be an issue with LED MR16 replacement lamps. Transformers generally require a minimum connected load for proper operation of the connected lamps. Compared to the halogen MR16 lamps that they replace, LED versions draw significantly less power (e.g., 3 W vs. 20 W) and may not provide sufficient load to the transformer. Consequently, LED MR16 replacement lamps may not work or may flicker, strobe, or randomly shut down in an existing low-voltage lighting system. Similarly, existing dimmers, relays, and related-controls typically have minimum load requirements and may not operate properly with some LED replacement lamps.

⁵ This report examines only white light LED replacements for halogen MR16 lamps.

Performance of LED MR16 Replacement Lamps

Table 2 summarizes CALiPER test results for the 10 LED MR16 replacement lamps tested through September 2008. On average, the test data suggest that LED products can achieve acceptable color appearance and color rendering and better efficacy than 20-W halogen MR16 lamps. However, there was significant variability within the tested products, and, when compared to benchmarked halogen MR16 lamps, it is apparent that these LED versions lack the lumen output and intensity of the lamps they are intended to replace.

Table 2. Summary of CALiPER Test Results for LED MR16 Replacement Lamps

	Performance of LED MR16 Replacement Lamps	
	Average from CALiPER Tests	Range Observed in CALiPER Tests
Input power (W)	4	1–9
Power factor	0.63	0.57–0.77
Light output (lm)	90	29–159
CBCP (cd) by beam angle		
“Spot” (<20°)	560	381–739
“Narrow flood” (20–35°)	380	89–899
“Wide flood” (>35°)	117	59–220
Efficacy (lm/W)	25	16–35
CCT (K)	3961	2620 K–6381 K
CRI	78	61–96

Light Output

Light output (i.e., luminous flux) values provided for LED MR16 replacement lamps are initial values measured at 25°C, the standard ambient temperature for testing lighting products. In actual operation, light output for LED products is typically reduced by inefficiencies introduced in thermal management (e.g., heat sinking) and operating conditions (e.g., air flow around the lamp), typically by 10–15%.

As shown in Figure 4, CALiPER-measured light outputs for LED MR16 replacement lamps fall short of even the minimum measured light output for benchmarked 20-W halogen MR16 lamps.

Figure 5 presents a comparison of measured light output and corresponding manufacturer claims for tested MR16 lamps. A significant number of LED products claimed much higher light output than measured in CALiPER testing. Even the halogen example shown here does not quite meet its rated performance levels.

Considering the hashed grey bars, a consumer may be led to believe that a number of the MR16 LED replacement lamps provide light output close to or exceeding the level of the traditional halogen lamps. The average manufacturer rated output for 20-W halogen MR16 lamps is 278 lm, and the average measured output of CALiPER-tested halogen MR16 benchmark lamps is 263 lm—very close to the average of manufacturer ratings. Observation of the yellow bars in Figure 5, which show measured lumen output levels, reveals that only one or two of the LED products come close to matching the lumen output of the lamps they are intended to replace.

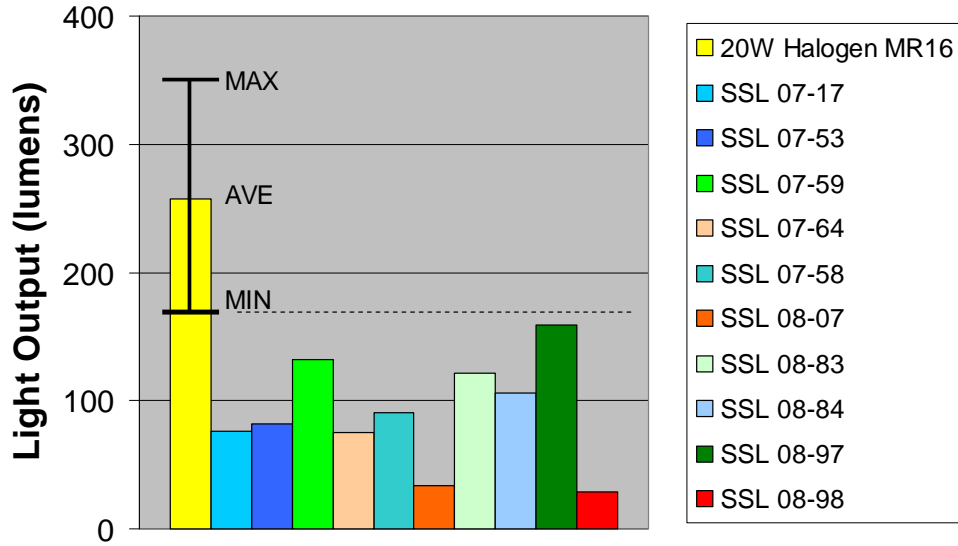


Figure 4. Light Output of MR16 Replacement Lamps Compared to Halogen MR16 Lamps

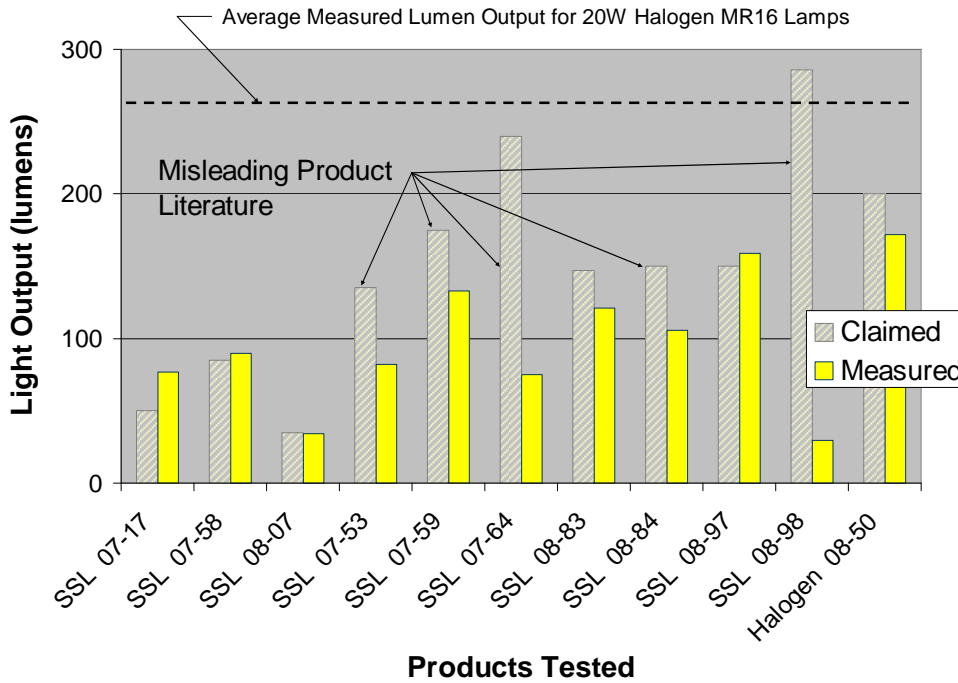


Figure 5. Measured Light Output of Halogen MR16 Lamps and LED Replacements Compared to Manufacturers' Reported Values

Efficacy

Source efficacy is the light output of a source (in lumens, lm) divided by its power usage (in watts, W), expressed in lumens per watt (lm/W).⁶ On average, LED replacement lamps outperformed halogen MR16 lamps in efficacy. As illustrated in Figure 6, most LED products tested exceeded the maximum halogen MR16 efficacy benchmark, represented by the dotted line. However, depending on application needs, users might have to combine multiple LED replacement lamps to approach the light output or CBCP of a single halogen MR16 lamp, thereby diminishing the potential energy savings of the LED product.

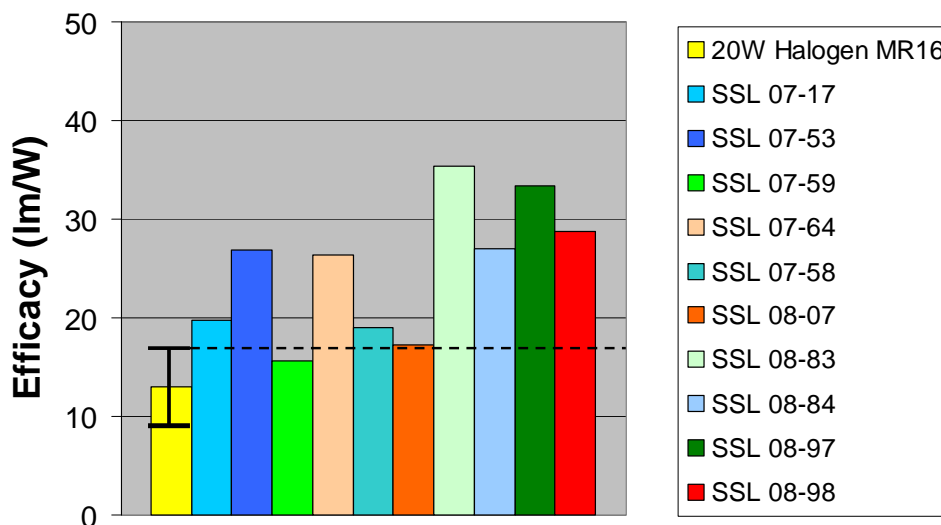


Figure 6. Comparison of Efficacy Values of Halogen MR16 Lamps with those of LED Replacements

Efficacy is an important metric in manufacturer claims and is subject to the same inaccuracies observed for total light output. Figure 7 presents the range of differences between claimed and measured efficacies for CALiPER-tested products, with manufacturer values ranging from accurate to highly exaggerated.

⁶ CALiPER testing was performed using both 12-V AC and 12-V DC inputs for a number of lamps, and revealed insignificant differences in performance and measured power between AC and DC operation.

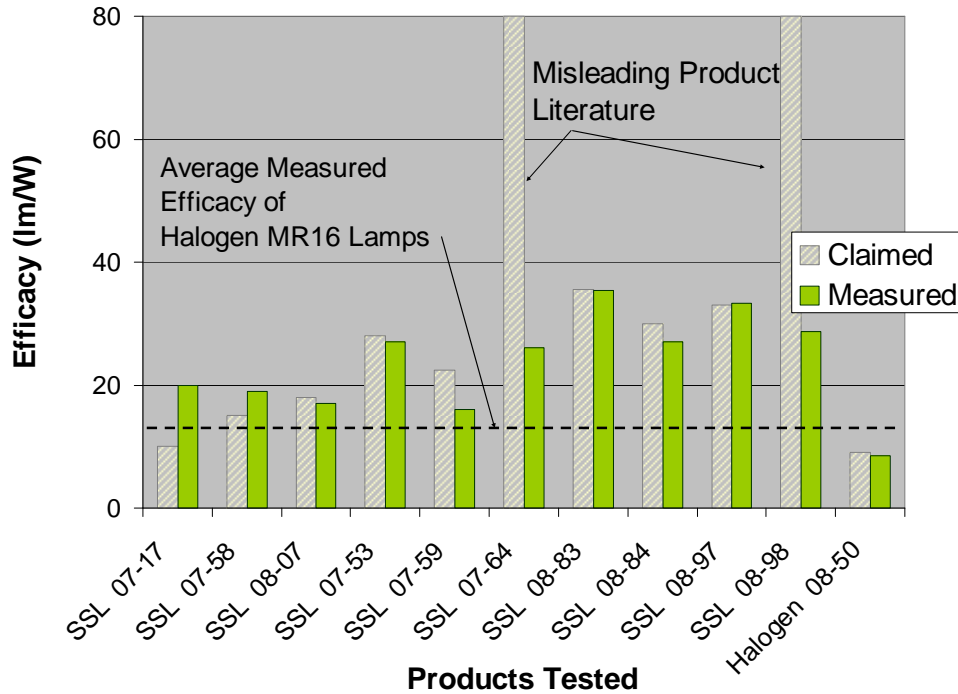


Figure 7. Measured Efficacy of Halogen MR16 Lamps and LED Replacements Compared to Manufacturers' Reported Values ⁷

Directionality

As shown in Figure 8, there is a predictable relationship between beam angle and CBCP for 20-W halogen MR16 lamps, i.e., CBCP increases as the beam angle becomes narrower. For an equivalent beam angle, the LED MR16 products generally do not provide CBCP levels as high as halogen products. This effect is most pronounced at smaller beam angles, where LED replacements lack the lumen output and intensity—literally, the “punch”—to match 20-W halogen MR16 performance. In a one-for-one replacement, particularly for “spot”-type distributions, users would likely be disappointed with the performance of current LED MR16 products. In fact, users might have to combine multiple LED replacement lamps to approach the CBCP or light output of a single halogen MR16 lamp, thereby diminishing the potential energy savings of the LED product.

⁷ For 08-50, the rated lamp lumens divided by a power level of 22 W (rated power + 10%) was used to calculate rated efficacy. For all other benchmarked halogen MR16 lamps, only CBCP is published, so an average halogen efficacy of 13 lm/W and output of 286 lm are used in place of manufacturer values.

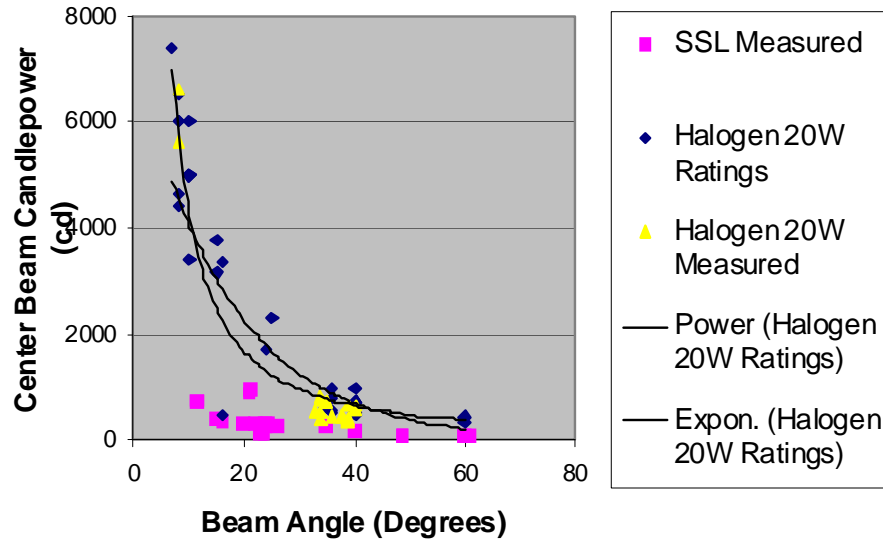


Figure 8. Measured Light Intensity (CBCP) and Beam Angles for 20-W Halogen MR16 Lamps and LED Replacements

Color Characteristics

The color properties of light sources are described by two commonly used measures: correlated color temperature (CCT) and color rendering index (CRI). Halogen products inherently produce warm-neutral white light, with CCT values in the 2900–3100 K range. Halogen sources also have high CRI values, close to 100. Given the known problems with applying CRI to white light LED products, users should evaluate LED replacement lamps visually to gauge their color quality for a given application.⁸

The color characteristics of LED MR16 replacement lamps varied in CALiPER testing. Most of the tested LED products had CCT values similar to those of the halogen MR16 lamps. However, three of the LED replacement lamps produced a very cool white light with CCT values near or above 6000 K (Figure 9).

ANSI Standard C78.377-2008 establishes chromaticity specifications for white light LED products and uses the CIE 1976 (u' , v') diagram to illustrate CCT boundaries that fall along a solid curve called the Planckian locus (Figure 10). To meet ANSI specifications, measured chromaticity coordinates for an LED product must plot not only within established CCT boundaries but also within prescribed distances of the Planckian locus (i.e., D_{uv} chromaticity targets and tolerances).⁹ As illustrated in Figure 10, the chromaticity coordinates of some white LED products tested fall far from the Planckian locus, not meeting CCT definitions and exceeding D_{uv} tolerances. These products tended to appear bluish, greenish, or yellowish.

⁸ See the fact sheet, “LED Measurement Series: Color Rendering Index and LEDs,” for more information about LED performance on CRI tests and recommendations for evaluating color characteristics of LEDs.

⁹ For the measured chromaticity coordinates of a source (as plotted on the CIE 1976 (u' , v') diagram), the target D_{uv} is the maximum allowable distance from the Planckian (blackbody) locus. This distance is specified for each nominal CCT defined in ANSI C78.377-2008 and relates to the relative whiteness of a light source appearance.

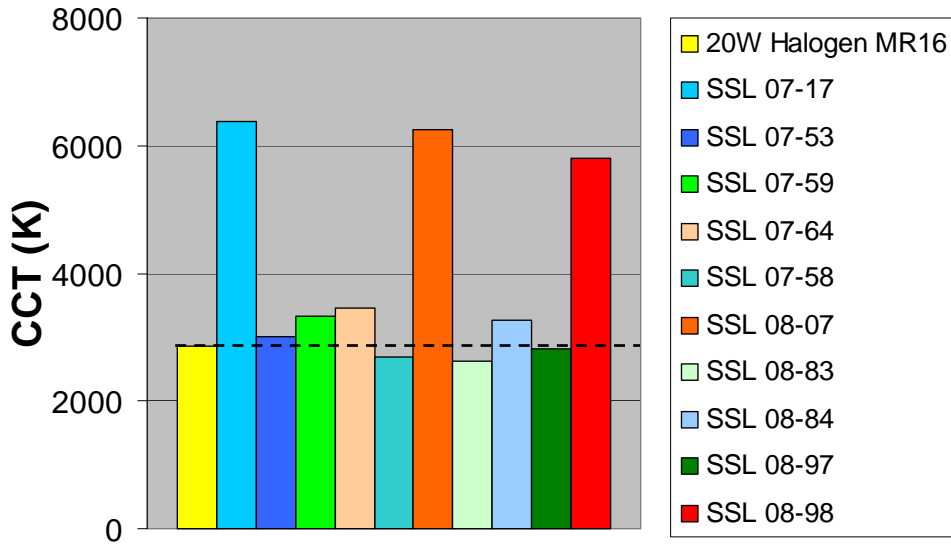


Figure 9. Comparison of CCT Values of Halogen MR16 Lamps with Those of Tested LED Replacements

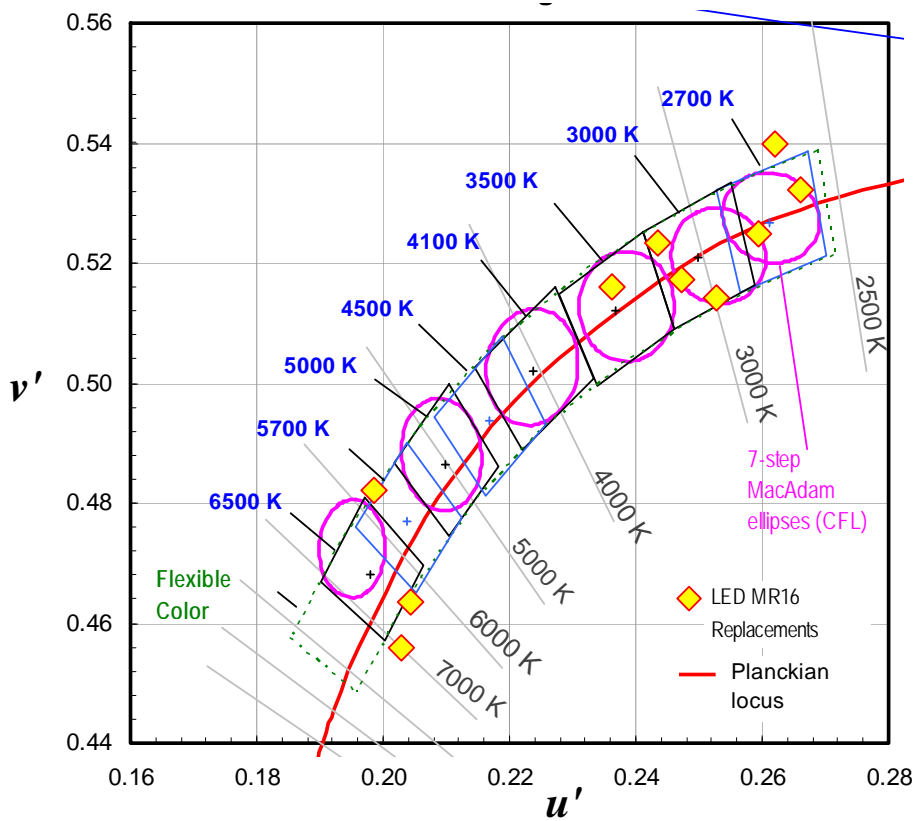


Figure 10. Chromaticity of LED MR16 Replacement Lamps (shown as diamonds) plotted against ANSI Chromaticity Specifications (chromaticity diagram from ANSI C78.377-2008)

Power

The power factor of a light source is an indicator of how efficiently a load uses the current that it draws from an AC power system. For example, a halogen MR16 lamp has a power factor of 1.0, which describes a state in which the lamp uses all input power in producing “output” (i.e., light and heat). LED systems consist of components independent of the light source (e.g., power supplies and other electronic components) that consume both reactive and harmonic power in addition to the power used to produce light, resulting in a power factor less than 1.0. To encourage efficient use of power in LED products, the ENERGY STAR[®] program requires power factors greater than 0.7 and 0.9 for residential and commercial applications, respectively for SSL products.¹⁰ In CALiPER testing to date, power factors for LED MR16 replacement lamps have ranged from 0.57 to 0.77, with an average of 0.63, thereby on average not meeting the ENERGY STAR lower criterion for residential products.

When addressing the energy-savings potential of a replacement lamp, manufacturers often compare the power use of one LED lamp versus the power use of one halogen MR16 lamp. As revealed in CALiPER testing, the light output and intensity of LED replacements fall short of their halogen counterparts—to an extent where two or more LED lamps might be needed to functionally replace one halogen MR16 lamp. Consequently, the overall power requirements of the replacement system as a whole, as well as the desired light level and effect, should be compared to the overall power use of the existing system. LED replacement lamps include driver electronics that also can result in a low power factor, lowering the effective energy efficiency of the technology.

Dimming

The dimmability of LED MR16 lamps is largely unknown at this time. The CALiPER program tested five LED MR16 replacements with 10 different dimmers. One of the LED MR16 lamps claimed to be dimmable, two provided no indication regarding dimmability, and two had product literature stating they were not dimmable. Upon testing, it was found that all five LED MR16 products were dimmable with at least half of the sample dimmers, including magnetic low-voltage, electronic low-voltage, and electro-magnetic (standard, resistive-type for incandescent lamps) dimmers. Unlike halogen MR16 lamps that shift to lower CCT values, the LED MR16 replacements that were tested have stable color when dimmed.

Replacements That Fit

CALiPER researchers encountered several problems with the shapes and sizes of LED MR16 lamps claimed as replacements for halogen MR16 lamps. Some LED lamps were significantly longer or larger in diameter than typical halogen MR16 lamps and would not fit in existing fixtures. Other LED products had the same nominal base (e.g., two-pin GU5.3) but neck dimensions that would not fit with a standard MR16 socket. Moreover, some lamps tested had pins that were too short and did not work in some sockets. Because this problem varies among manufacturers, users should test samples of LED MR16 replacement lamps in their intended fixtures before purchasing large quantities, if possible.

¹⁰ ENERGY STAR power factor requirements are found in “ENERGY STAR Program Requirements for Solid State Lighting Luminaires, Eligibility Criteria – Version 1.0” (2007), available at http://www.energystar.gov/ia/partners/prod_development/new_specs/downloads/SSL_FinalCriteria.pdf.

Conclusions

In CALiPER testing to date, the performance of LED MR16 replacement lamps varied greatly. Power usage for the LED replacements is considerably lower than for halogen MR16 lamps. However, light output and intensity for the tested LED products falls significantly short of the halogen benchmark levels, limiting the usefulness of LED MR16 lamps as a one-for-one replacement in typical highlighting and accent applications. The benchmarks used for this study are the lowest-wattage halogen MR16 lamps available, so it is clear that current LED MR16 lamps are not able to provide the “punch” that is typically expected from 35-W or 50-W halogen lamps. Also, if users must combine multiple LED replacement lamps to approach the light output or CBCP of a single halogen MR16 lamp, potential energy savings of the LED product is diminished.

For cases in which lower light levels are desirable, LED MR16 lamps may provide a more efficacious alternative to halogen lamps. Efficacy and color characteristics for LED replacements can be competitive with halogen MR16 lamps; however, wide variations were observed in tested performance.

LED performance will continue to advance, and MR16 lamps represent an excellent potential application for this inherently directional light source as the technology progresses. In the meantime, users should note that the performance and life of LED MR16 lamps are highly dependent on their design and thermal management. Note, too, that long-term reliability for this class of products is largely untested. Compatibility with intended fixtures and associated low-voltage transformers and lighting controls may vary from one LED replacement product to another. As evidenced by CALiPER testing results, manufacturer claims may or may not be relevant to actual product performance. Consequently, users should test LED replacement lamps, if possible, and resist the temptation to rely on manufacturers’ data alone.

Bibliography

ANSI C78.379-1994. *American National Standard for Electric Lamps—Classification of the Beam Patterns of Reflector Lamps*. American National Standards Institute, Washington, D.C.

ANSI_NEMA_ANSLG C81.61-2007. *American National Standard for Electrical Lamp Bases—Specifications for Bases (Caps) for Electric Lamps*. American National Standard Lighting Group, Washington, D.C.

ANSI_NEMA_ANSLG C78.377-2008. *American National Standard for Electric Lamps—Specifications for the Chromaticity of Solid State Lighting Products*. American National Standard Lighting Group, Washington, D.C.

GE Lighting. 2006. *Lamp Products Catalog 2006*. Publication 25265, GE Lighting, Cleveland, Ohio.

National Lighting Product Information Program. 2002. *NLPIP Lighting Answers: MR16 Lamps*. Volume 6, Issue 1. Lighting Research Center, Rensselaer Polytechnic Institute, Troy, New York.

Philips Lighting Company. 2006. *Lamp Specification and Application Guide 2006*. SAG-100, Philips Lighting Company, Somerset, New Jersey.

Rea M (ed). 2000. *IESNA Handbook*. 9th ed. Illuminating Engineering Society of North America, New York.

Sylvania. 2004. *Lamp and Ballast Product Catalog 2004*. Catalog04, Osram Sylvania, Danvers, Massachusetts.

U.S. Department of Energy. 2007. *ENERGY STAR® Program Requirements for Solid State Lighting Luminaires, Eligibility Criteria – Version 1.0*. Available at http://www.energystar.gov/ia/partners/prod_development/new_specs/downloads/SSL_FinalCriteria.pdf.

U.S. Department of Energy. 2007. *LED Measurement Series: Color Rendering Index and LEDs*, Available at <http://www.netl.doe.gov/ssl/PDFs/ColorRenderingIndex.pdf>.

U.S. Department of Energy CALiPER Program. 2008. *Summary of Results: Round 6 of Product Testing*. Available at http://www.netl.doe.gov/ssl/PDFs/CALIPER_ROUND_6_summary_final.pdf.

Ushio. 2006. *General Lighting Lamps Catalog*. Version 2006.06, USHIO America, Cypress, California.

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 expressed written permission.