U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Top Efficacy Performers

An investigation into high-achieving LED luminaires

June 2018

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An investigation into high-achieving LED luminaires

Final report prepared in support of the U.S. DOE Solid-State Lighting Technology CALiPER Program

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June 2018

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

Preface

The U.S. Department of Energy's Solid-State Lighting (SSL) program documents the performance of SSL products and systems based on standardized laboratory test results, additional specialized testing, mock-up studies, and real-world field evaluations. This information is provided publicly for several purposes: 1) to track SSL technology performance improvement over time; 2) to identify technology challenges that impact performance and application of SSL; 3) to spur continued advancements in SSL technology, product design, and application via critical feedback provided to manufacturers; and 4) to maximize energy efficiency and decrease U.S. energy use, while improving lighting quality. DOE does not endorse any commercial product or in any way provide assurance that other users will achieve similar results through use of these products. SSL technology continues to evolve quickly, so evaluation results should always be understood in the context of the timeframe in which products were acquired, tested, installed, and operated. Especially given the rapid development cycle for SSL products, specifiers and purchasers should always seek current information from manufacturers when evaluating such products. The two DOE SSL program activities primarily involved in product evaluations are CALiPER and GATEWAY.

CALiPER

When CALiPER was first launched, its role was largely to test products and compare actual performance to manufacturer claims and to benchmark technologies. Early CALiPER testing also contributed fundamentally to the development of standardized photometric test methods specifically for SSL and the associated accreditation of testing laboratories. As the SSL market has matured, CALiPER has continually transitioned its evaluations to the newest products and functions, such as OLED-based luminaires and color tunable products, as well as long-term product performance. CALiPER continues to support the development of new test procedures and application guidance, with DOE investigations providing data that are essential for understanding the most current issues facing the SSL industry. Data are gathered primarily through laboratory testing and mock-up installations.

GATEWAY

GATEWAY conducts field evaluations of high-performance SSL products to collect empirical data and document experience with field installations. GATEWAY provides independent, third-party data for use in decision-making by lighting manufacturers, users, and other professionals. Real-world installations often reveal product limitations and application issues that are not apparent from laboratory testing. GATEWAY typically documents pre- and post-installation light levels, color characteristics, energy intensity, and other performance attributes, and addresses application and maintenance of SSL products. In some cases, GATEWAY returns to projects after months or years of operation to take additional site measurements or remove luminaires and send to accredited laboratories for testing. While not possible for every project, such follow-up measurements have yielded useful data on dirt depreciation, color shift, luminous intensity distribution changes, and lumen depreciation over time. The DOE GATEWAY program is the only known public source of such data on long-term performance of LED products.

For more information on the DOE SSL program, please visit energy.gov/eere/ssl/solid-state-lighting.

This report was developed with funding from the DOE SSL Program, by the Pacific Northwest National Laboratory for the U.S. Department of Energy/Office of Energy Efficiency and Renewable Energy/Buildings Technologies Office.

Acknowledgments

In addition to laboratory testing results, this report relied on observations from experienced lighting professionals, energy-efficiency professionals, and professional energy managers. The 20+ individuals were recruited from the Portland, OR, Section of the Illuminating Engineering Society and the Association of Professional Energy Managers. Their time and sage input helped make this report relevant to the real world of construction and building occupants.

Executive Summary

The U.S. Department of Energy (DOE) LED Lighting Facts®[1] database has been a resource for identifying high-performing light-emitting diode (LED) luminaires since 2010. Receiving data on more than 70,000 products to date, it has been a way for the DOE to assess the progress of the solid state lighting industry and to help lighting specifiers find high-efficiency, high-quality luminaires. In 2017, several products were listed with claimed efficacies near or exceeding 200 lumens per watt (lm/W). The Top Efficacy Performers project was launched to procure samples of these luminaires for testing and visual evaluation.

Although there are luminaires exceeding 200 lm/W available on the market, there are many reasons why it is complicated to order products that perform at that level.

- The LED Lighting Facts database allows manufacturers to list families of luminaires under the performance characteristics of the top-performing product in the family. Consequently, many luminaires having different lumen output, different color and optical characteristics, and different sizes and drivers are listed under the same values as the top-performing product.
- The luminaire corresponding to a catalog number in the LED Lighting Facts database is often difficult to track down and order, so often it is not clear that the ordered product should have the same features and performance listed in the database.

Ultimately, samples of seven luminaires were anonymously ordered for this Top Efficacy Performers Study, five from the LED Lighting Facts database and two unlisted high-efficacy products found through a website search. All products were 5000K, and all but one had LED packages that were directly visible, either open to the air or behind clear plastic or glass covers. They underwent CALiPER photometric testing at Pacific Northwest National Laboratory’s (PNNL’s) Lighting Metrology Laboratory in Richland, WA, and the resulting values were compared to the manufacturer-claimed values as published on website specification sheets. (Note, this is not necessarily the same as performance values as listed on the LED Lighting Facts database.)

Two of each luminaire type were shipped to PNNL’s Portland, OR, lighting laboratory and mounted in a movable ceiling. The luminaire pairs were spaced 14’ on center, 11’-3” above the floor, each pair controlled by a single wall switch. (Figure ES.1) [The installation ceiling height was intended to be 15’, but mechanical limitations interfered with achieving the full mounting height, and that could have affected glare responses.] In situ measurements of horizontal illuminance, flicker, and maximum luminance were collected.

Twenty-three observers with experience in lighting and energy efficiency were recruited from local organizations and asked to evaluate the industrial luminaires, one pair at a time. Through a questionnaire, the observers provided comments and an overall perceived dollar value for the luminaire.

Results of laboratory testing showed the following maximum differences in performance compared to the manufacturer claimed values on website product specification sheets:

- 9.6% in lumen output
- 6.8% in power draw
- 12.0% in efficacy
- Color performance in correlated color temperature and color rendering index consistent with claimed values

[1] The DOE LED Lighting Facts program ended in June 2018.

Field measurements taken while the luminaires were mounted for visual evaluation showed that one of the seven luminaire types exhibited flicker exceeding the low-risk criteria of the IEEE Standard PAR1789-2015. All of the luminaires produced a fairly even light distribution across the workplane, with a maximum-to-minimum illuminance ratio below 1.7 at a 37” standing desk height. And, direct luminance measurements of the exposed LED packages revealed luminances ranging from 154,000 cd/m^2 up to 478,000 cd/m^2, although due to limitations in measurement, these values likely underestimate the actual luminances. One luminaire used diffusing tubes to cover the LED packages, with a luminance of 40,000 cd/m^2. (By comparison, a T5HO fluorescent lamp is about 25,000 cd/m^2 in luminance.) The high maximum luminances are likely to be the reason why glare was the biggest complaint from the observers.

The subjective evaluations showed that only two of the luminaires received reasonable ratings of visual comfort and overall quality, and those were the products with either diffusing lenses or reflector optics engineered to cut off the view of the bare LEDs above a fixed viewing angle. The top-rated three luminaires received positive comments in categories of light distribution, shadows, and color in addition to visual comfort. The least preferred luminaires correspond to the three luminaires receiving the most negative comments about glare. These rankings were corroborated by the overall dollar value observers assigned to each luminaire. The product receiving the highest rating was the luminaire with the lowest tested efficacy of 136 lm/W, showing that visual comfort needs to be considered in conjunction with efficacy because there are always tradeoffs in selecting the best luminaire for an application.

Luminaire efficacy is only one aspect of performance that should considered in a specification. Other attributes of performance such as visual comfort, light distribution, flicker, shadows, and color quality may end up being of equal or greater importance to the installation. However, this report demonstrates that there are truly LED products performing at very high levels of efficacy. The LED Lighting Facts and similar databases can be excellent sources of information for identifying high-performance LED products.

Figure ES.1. Mockup space with all seven pairs of Top Efficacy Performer luminaires installed and energized.

Table of Contents

1 Introduction

For the design professional, building owner and facilities specialist, selecting light-emitting diode (LED) luminaires is a challenging task. The luminaire needs to deliver light where it's needed, while providing a range of lighting qualities such as color quality, minimal flicker, and visual comfort. LED products posed a dramatic departure from earlier lighting technologies, and several publicly accessible databases were developed to help specifiers identify products with good characteristics and high efficacy. One such database is the LED Lighting Facts Listings,[2] supported by the U.S. Department of Energy (DOE). This searchable listing has recently exceeded 70,000 LED products, becoming a means to narrow down the highest-performing lighting systems. As the LED technology evolved, the database was populated with families of lighting products, all listed under the performance characteristics of the best individual product in the family. For the first time, in 2017, some products listed in LED Lighting Facts surpassed 200 lumens per watt (lm/W). Because the listing is used to assess the progress of the solid-state lighting (SSL) industry, and used by specifiers for choosing products, DOE wanted to know whether the listed luminaires actually perform to the efficacy level claimed, and what features or characteristics were consistent among those top performers. If accurate, this represents a significant milestone in the development of SSL luminaires.

The intent of this study was to anonymously order these top-efficacy luminaires from the database, using catalog numbers from the database, then conduct laboratory testing of the purchased products for a variety of performance measures. The second stage of the work was to install the tested luminaires in a mockup ceiling at the Pacific Northwest National Laboratory's (PNNL's) lab space in Portland, OR, so that observers with a background in energy efficient lighting or energy management in facilities could visually evaluate the products for quality issues that are more difficult to quantify using conventional metrics.

1.1 Methodology for evaluation, analysis, and report

The following is the approach taken in procuring products, testing them, installing them in a warehouse-type space for observation, and collecting data and observer responses for the report.

- Identify and procure top efficacy performers from the LED Lighting Facts database, supplementing with other known high-performing products from luminaire manufacturers not listed in the database. Products exceeding 140 lm/W were selected.
    - Three samples of 7 different products were anonymously purchased.
    - Ordered products were configured as closely as possible to the highest-performing products listed in the database, within a range of 15,000 to 22,000 lumens, suitable for mounting in an industrial setting with a ceiling height of approximately 15'.
- Obtain luminaire photometric performance data using LM-79 methods.
    - Tests were conducted at the PNNL Lighting Metrology Laboratory (LML) in Richland, WA.
    - Color, flicker, light output, and electrical data were obtained on two of the three samples (the third sample was available in case of inconsistency or component failure in the first two tested samples)
- Compare tested values to manufacturers' reported values, and those in LED Lighting Facts database.
- Install pairs of luminaires in a controlled environment.

[2] The DOE LED Lighting Facts program ended in June 2018.

    - An electrical contractor installed the luminaires in PNNL's Portland, OR, laboratory space, in an 18' x 18' movable ceiling. The ceiling was set to the maximum possible height, which was limited to 11'-3" above finished floor due to mounting complications.
    - Each pair of luminaires was controlled by a separate toggle wall switch. Typical industrial assembly tasks were located on a movable table below the ceiling.
- Host observation activity by lighting experts.
    - Twenty-three energy specialists, lighting specifiers, and facility managers were invited to experience and evaluate the installed industrial luminaires, one illuminated pair at a time
    - A questionnaire (Appendix 1) was provided to capture observations on characteristics of the luminaire for the application, including quality of the light in terms of color, shadows, light distribution, visual comfort, appearance, and functionality.
    - Observers were asked to assign an overall quality value for each luminaire by estimating how much they would pay for the luminaire if purchased in a quantity of 100, assuming that an average product in that category would cost $200. The point was not to estimate actual price, but to determine a relative value compared to a typical industrial lighting product.
- Complete a report on both the objective performance of the luminaires as well as the subjective evaluation of the luminaires.

1.2 Criteria for ordering luminaires

The initial investigation into high-efficacy products listed in the LED Lighting Facts database began in January 2017, with a printout of the database spreadsheet, sorted by efficacy. A close look at these products found the following similarities:

- All products exhibited correlated color temperatures (CCTs) around 5000K. This is no surprise because higher CCT phosphor-converted blue LED chips are almost always higher in lumen output compared to warmer CCTs; greater Stokes losses are incurred using more phosphors to down-convert to the warmer wavelengths needed to produce 4000K and 3000K spectra.
- All products were industrial luminaires, with relatively little optical control to manage light distribution or visual comfort. There was also little lensing, gasketing, or enclosure to keep the luminaire clean in dusty or dirty industrial environments, since that, too, could reduce luminaire efficacy.
- Color rendering index (CRI) values for the high-efficacy products ranged from mid-70s to mid-80s.

The following criteria were used to select products:

- 16,000 to 22,000 lumens per luminaire, in order to duplicate the light output of a four-lamp T5HO 4' fluorescent low-bay luminaire, often specified for industrial applications. The T5HO luminaire would be expected to produce about 18,000 lumens when new.
- Luminaire efficacy of 140 lm/W or higher, according to the LED Lighting Facts database.
- CCT that would deliver 140 lm/W or higher, with CRI no lower than 70.
- Luminaire delivery within 10 weeks of ordering.
- Per-luminaire cost, ordered through electrical distributors, of less than $600. (Because only three luminaires were being purchased, the per-unit costs were very high.)

- Luminaires were selected from the LED Lighting Facts database, supplemented with two unlisted products that also claimed very high-efficacy performance.

1.3 Luminaire ordering challenges

Product ordering was initiated in March 2017, with PNNL purchasing the luminaires anonymously through electrical distribution channels, following as much as possible the catalog numbers listed in the LED Lighting Facts database. Often, the catalog numbers on the manufacturer's website did not match the catalog numbers in the database, which made it difficult to ensure the correct products were ordered. In addition, the following hurdles were encountered:

- Technical data was often missing from manufacturers' websites. It was challenging to find photometric reports on the specific luminaires, any graphical information on light distribution, actual lumen output, and/or system power use. Some manufacturers listed performance based on a single combination of CCT, CRI, light distribution, lumen output, and wattage, even though many other combinations were available.

- In some cases, the only clue to a product number and its characteristics was a luminaire photo, although in one case that photo inaccurately represented the optics of the selected high-efficacy luminaire.

- At least one luminaire in the LED Lighting Facts database was listed under one manufacturer name, but wasn't actually available from that manufacturer's website. Instead, the website led the specifier to another vendor of luminaires, which in turn led to a third vendor name and website that offered the luminaires for sale. It's not clear where the specifier would go for support on this luminaire.

- The database-listed luminaire performance values often did not match the performance claims in the manufacturer's specification sheets or test reports available from the manufacturer's website. However, it was hard to cross reference the two because catalog numbers were complex and inconsistent. For example, luminaires 17-S1 and 17-S2 theoretically range between 151 and 169 lm/W according to the database, but the ordered products performed between 140 and166 lm/W according to the specification sheet. Similarly, luminaire 17-S3 is listed at 153+ lm/W in the database, while the specification sheet shows a maximum of 150 lm/W.

1.4 Luminaires ordered

Seven luminaire types were ordered in August 2017, three samples of each. Photos from the manufacturer websites are shown in Figure 1, along with their CALiPER-assigned numbers. Table 1 shows the performance values according to the manufacturers' product literature.

Figure 1. Photos of top-efficacy luminaires from manufacturers' websites, corresponding to CALiPER product numbers. Although the specification sheets illustrate linear baffles for luminaire 17-S5, the model ordered had none. This was unexpected because there was only one model illustrated on the specification sheet, and no indication of the corresponding product options.

Table 1. Luminaires ordered for Top Efficacy Performers study, showing manufacturer catalog number and manufacturer-reported performance characteristics, where available.

CALiPER System ID	Brand	Catalog #	Manufacturer Reported Lumens	Manufacturer CCT	Manufacturer CRI	Manufacturer Wattage	Manufacturer Efficacy	LED Lighting Facts listed efficacy
17-S1B	Energy Solutions	F-14ME-EA-L4NG2-50-Y	18,727	5000	n/a	130	144	144.1
17-S1C	Energy Solutions	F-14ME-EA-L4NG2-50-Y	18,727	5000	n/a	130	144	144.1
17-S2A	Energy Solutions	F-24DT-P6LL-50-Y	19,464	5000	n/a	118	165	164.5
17-S2B	Energy Solutions	F-24DT-P6LL-50-Y	19,464	5000	n/a	118	165	164.5
17-S3A	AGC Lighting Co., Ltd	AGC HB01-100/H1-5000-120	15,000	5000	>70	100	150	175.5
17-S3B	AGC Lighting Co., Ltd	AGC HB01-100/H1-5000-120	15,000	5000	>70	100	150	175.5
17-S4A	Orion Energy Systems, Inc.	OES HBIF3C1OAUNV-NDXX-750NL	22,610	5000	77	106	213	209.7
17-S4B	Orion Energy Systems, Inc.	OES HBIF3C1OAUNV-NDXX-750NL	22,610	5000	77	106	213	209.7
17-S5A	Eaton/Cooper/Metalux	HBLED-LD5-18HE-W-UNV-L850-ED2-U-FL-1-MC6	18,835	5000	>80	115	164	Not listed
17-S5B	Eaton/Cooper/Metalux	HBLED-LD5-18HE-W-UNV-L850-ED2-U-FL-1-MC6	18,835	5000	>80	115	164	Not listed
17-S6A	Hangzhou LMenergysolution Lighting LTD	LM-HB6LAMP144W5000K	22,671	5000	83	140	162	155.0
17-S6B	Hangzhou LMenergysolution Lighting LTD	LM-HB6LAMP144W5000K	22,671	5000	83	140	162	155.0
17-S7A	Acuity Brands/Lithonia Lighting	IBG-18000LM-HEF-L/LENS-GND-120V-OZ10-50K-70CRI-CS1-DWH	18,000	5000	70	102	176	Not listed
17-S7B	Acuity Brands/Lithonia Lighting	IBG-18000LM-HEF-L/LENS-GND-120V-OZ10-50K-70CRI-CS1-DWH	18,000	5000	70	102	176	Not listed

2 Laboratory Testing, Field Testing, and Visual Evaluation

For this study, two samples of each luminaire model were photometrically tested, CALiPER samples A and B. Those same samples were shipped to PNNL's lighting laboratory for field testing and observation. In one instance, sample C was also photometrically tested because the A and B samples differed by over 10% in lumen output. The B and C samples that performed most similarly were subsequently used to represent the performance of that luminaire, and these were the units shipped to PNNL's Portland laboratory.

Figure 2. One of the Top Efficacy Performer luminaires in the process of laboratory sphere testing. Photo: PNNL.

2.1 Sphere testing methodology

Each luminaire was tested in an integrating sphere located in the LML in Richland, WA, which is NVLAP accredited.[3] (See Figure 2.) Data were collected following the IES LM-79-08 method between October 12 and November 29, 2017, following the guidelines for luminaire stabilization, ambient temperatures, and other protocols. Data included electrical characteristics, light output, and spectral power distribution, all collected at full output.

[3] National Voluntary Laboratory Accreditation Program (NVLAP # 201021-0)

2.2 Field testing methodology

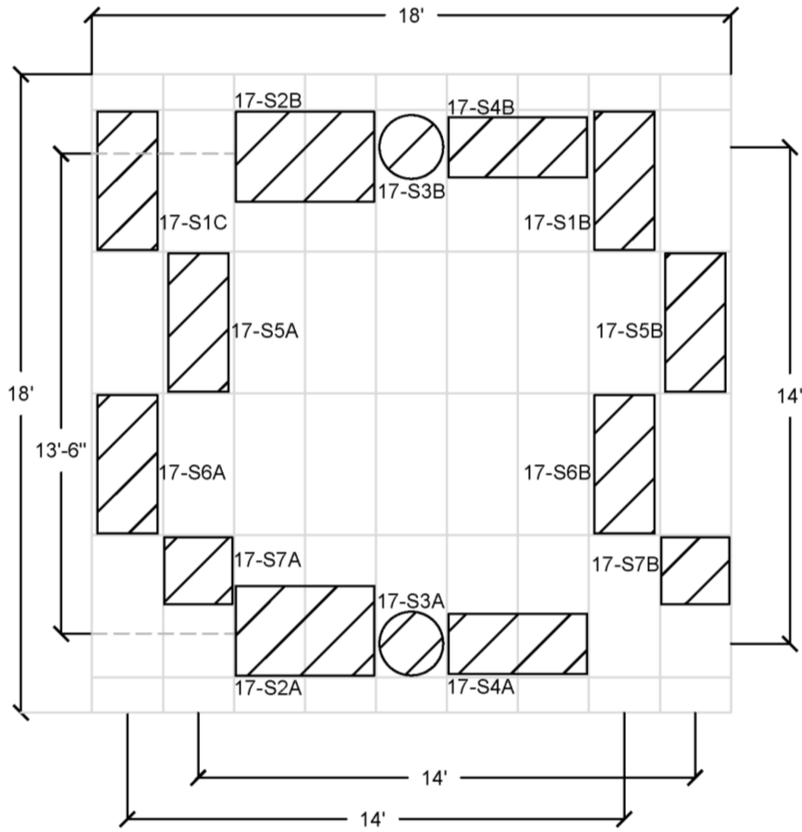


Figure 3. Layout of luminaires in 18’ x 18’ movable ceiling within laboratory mockup space, labeled with their CALiPER System IDs.

After photometric testing at the PNNL LML, two of the three samples of the seven luminaire types were shipped to Portland, OR, for installation at the PNNL Lighting Laboratory. This is a tall industrial space with a movable 18’ x 18’ grid ceiling for mockups. The luminaires were spaced 14’ on center, except for the 17-S2 luminaires, which were too large to be partially recessed in the T-bar ceiling grid, so they were installed at 13’-6” on center instead. See Figure 3. All luminaires were mounted slightly below the grid ceiling in order to achieve a common mounting height of 11’-3” above the floor. Each pair of luminaires were controlled by a single wall switch so that different pairs could be individually switched on and off.

Fluorescent striplights providing ambient lighting above and around the movable ceiling space were kept lighted during the observations, based on the assumption that actual industrial spaces would have light contribution from perimeter areas in addition to light from the overhead ceiling. Ambient light was subtracted from all lighting measurements reported here.

The following field measurements were collected:

- Horizontal illuminance at the floor, at a line of points between pairs of luminaires, using a Konica Minolta T10A illuminance meter within calibration.
- Horizontal illuminance at a 37” high movable cart, simulating a stand-up industrial task surface, at a line of points between pairs of luminaires, using the same illuminance meter.

- Luminance measurements of the luminaire from directly below (nadir), to collect either the luminance of the plastic diffuser covering the rows of LED packages or an approximate measure of the luminance of the LED package itself. The instrument used was a Konica Minolta LS-110 1/3° meter, within calibration.
- Temporal light artifacts (TLA), aka flicker. A UPRTek MF250N handheld meter was used (no calibration standards available at this time) to record metrics of modulation frequency, percent flicker, Flicker Index, and Stroboscopic Visibility Measure (SVM).

2.3 Visual evaluation methodology

Twenty-three lighting specifiers, energy efficiency specialists, and facility managers were invited to observe the mockup of seven luminaire pairs at PNNL’s Portland Laboratory in February 2018 (Figure 4). They were scheduled in groups of up to four individuals for different time slots over three days, allowing the groups to see the luminaires presented in different order. The pairs were presented, one at a time, for about three minutes, with about a minute of off time between presentations, so that observers were not immediately able to compare the performance of a pair with the previously presented pair. The presentation order was randomized, with a unique first and last luminaire for each of the seven groups in order to minimize order effects. There was no identifying information on the luminaires, and they were labeled A through G.

Instructions were given to observers before the mockup luminaires were switched on (Appendix 2). Care was taken not to prejudice the observers on what they were about to observe or influence any opinions about the luminaires’ appearance or performance. They were also specifically asked not to share their opinions with other observers in order to avoid comments that would prejudice others. Observers were handed clipboards with a questionnaire for completion (Appendix 1). The questionnaire suggested several topic areas [visual comfort, spread of light on the table top (i.e., light distribution), shadows, color quality, appearance, and functionality]. They were also asked to provide an overall quality measure by choosing how much they would pay for the luminaire, if the average price were $200 for that genre of luminaire. This was presented as not a pricing exercise, but a way to estimate the overall value relative to an average price. From this, it was possible to estimate if the luminaire was worth 50% more or 50% less than a typical luminaire, for example. Observers were also invited to note specific comments and application recommendations. After viewing seven pairs of luminaires and completing the questionnaire, observers were invited to share their observations and comments with others in an informal debriefing session.

3 Results

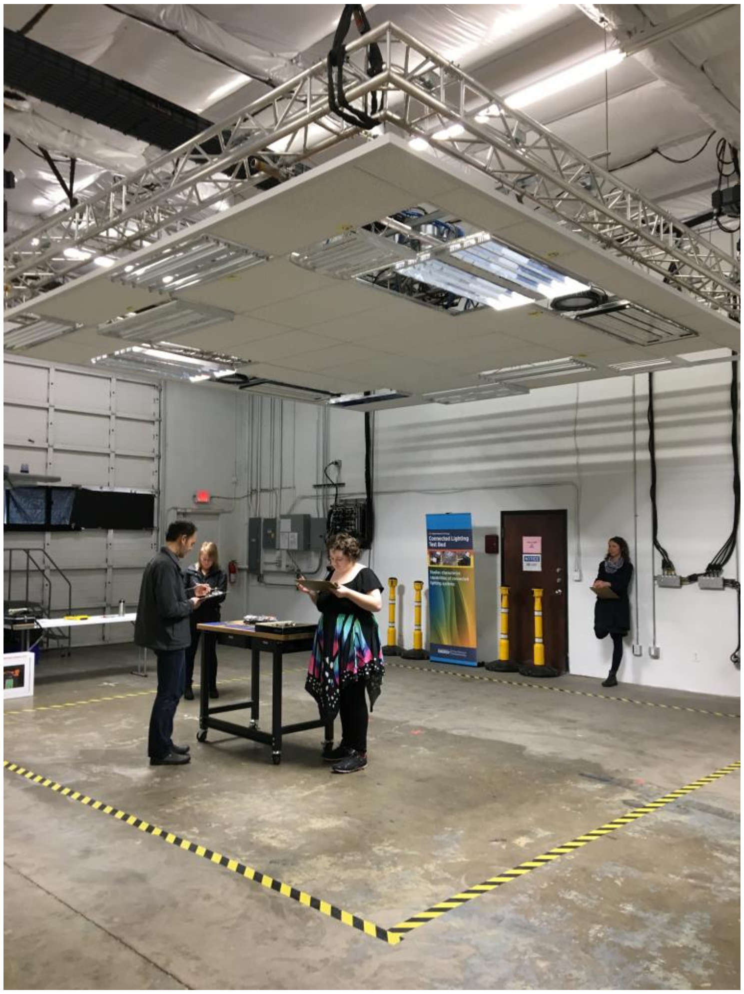


Figure 4. Photo of mockup space with one out of seven pairs of luminaires illuminated. Observers are completing questionnaires. Photo: PNNL.

The laboratory testing, field testing, and visual evaluation results follow.

3.1 Laboratory testing results

The laboratory tested performance values are summarized in Table 2. Table 3 and Table 4 present the percent and absolute differences between laboratory-tested values and the manufacturer-claimed values, respectively. (As a point of clarification, these are manufacturer claimed values as reflected in their online specification sheets, rather than what was listed in the LED Lighting Facts database.) Performance in lumen output varied within 10% of the claimed values. System power draw varied up to 7% from the manufacturer's claims. The combined lumen output and power use variations resulted in tested efficacy performance as low as 8% below claimed values, up to almost 12% above specification literature claims. For example, one of the luminaire pairs, 17-S3 performed 12% better than claimed in the online literature, although at 167 lm/W it was still lower than the 175.5 lm/W listed on the LED Lighting Facts database.

Table 2. CALiPER laboratory tested performance values.

CALiPER System ID	Brand	Catalog #	Lab Tested CRI	Lab Tested Power (W)	Lab Tested Power Factor	Lab Tested Output (lm)	Lab Tested CCT (K)	Lab Tested Efficacy (lm/W)
17-S1B	Energy Solutions	F-14ME-EA-L4NG2-50-Y	85	123.9	1.00	16,925	5143	136.6
17-S1C	Energy Solutions	F-14ME-EA-L4NG2-50-Y	84	124.9	1.00	17,018	5115	136.3
17-S2A	Energy Solutions	F-24DT-P6LL-50-Y	83	113.0	1.00	18,883	5022	167.1
17-S2B	Energy Solutions	F-24DT-P6LL-50-Y	83	112.9	1.00	18,617	5032	164.9
17-S3A	AGC Lighting Co., Ltd	AGC HB01-100/H1-120 100W	79	95.8	0.99	16,091	5218	168.0
17-S3B	AGC Lighting Co., Ltd	AGC HB01-100/H1-120 100W	79	98.2	0.99	16,234	5220	165.3
17-S4A	Orion Energy Systems, Inc.	OES HBIF3C1OAUNV-NDXX-750NL	77	106.9	0.99	21,336	4895	199.6
17-S4B	Orion Energy Systems, Inc.	OES HBIF3C1OAUNV-NDXX-750NL	77	107.3	0.99	21,178	4894	197.4
17-S5A	Eaton/Cooper/Metalux	HBLED-LD5-18HE-W-UNV-L850-ED2-U-FL-1-MC6	83	107.6	0.99	17,412	4986	161.8
17-S5B	Eaton/Cooper/Metalux	HBLED-LD5-18HE-W-UNV-L850-ED2-U-FL-1-MC6	83	107.2	0.99	17,431	4995	162.6
17-S6A	Hangzhou LMenergysolution Lighting LTD	LM-HB6LAMP144W5000K	82	138.0	0.98	21,975	4951	159.2
17-S6B	Hangzhou LMenergysolution Lighting LTD	LM-HB6LAMP144W5000K	82	138.2	0.98	21,502	4970	155.6
17-S7A	Lithonia Lighting	IBG-18000LM-HEF-L/LENS-GND-120V-OZ10-50K-70CRI-CS1-DWH	74	101.7	1.00	17,729	5062	174.3
17-S7B	Lithonia Lighting	IBG-18000LM-HEF-L/LENS-GND-120V-OZ10-50K-70CRI-CS1-DWH	74	101.1	1.00	18,127	5058	179.3

The percentage differences between the laboratory-tested and manufacturer-presented values are summarized in Table 3, with the absolute differences summarized in Table 4.

Table 3. Percentage difference between laboratory tested values and manufacturer reported values from their website specification sheets.

CALiPER System ID	Brand	% difference between lab tested values and manufacturer rating			
		Output (% lumens)	CCT (% K)	Efficacy (% lm/W)	Power (% W)
17-S1B	Energy Solutions	-9.62	2.86	-5.17	-4.69
17-S1C	Energy Solutions	-9.13	2.30	-5.42	-3.92
17-S2A	Energy Solutions	-2.99	0.44	1.31	-4.24
17-S2B	Energy Solutions	-4.35	0.64	-0.03	-4.32
17-S3A	AGC Lighting Co., Ltd	7.27	4.36	11.98	-4.20
17-S3B	AGC Lighting Co., Ltd	8.23	4.40	10.21	-1.80
17-S4A	Orion Energy Systems, Inc.	-3.02	-2.10	-3.83	0.85
17-S4B	Orion Energy Systems, Inc.	-3.73	-2.12	-4.90	1.23
17-S5A	Eaton/Cooper/Metalux	-7.55	-0.28	-1.20	-6.43
17-S5B	Eaton/Cooper/Metalux	-7.45	-0.10	-0.72	-6.78
17-S6A	Hangzhou LMenergysolution Lighting LTD	-3.07	-0.98	-1.66	-1.43
17-S6B	Hangzhou LMenergysolution Lighting LTD	-5.16	-0.60	-3.92	-1.29
17-S7A	Acuity Brands/Lithonia Lighting	-1.51	1.24	-1.22	-0.29
17-S7B	Acuity Brands/Lithonia Lighting	0.70	1.16	1.60	-0.88

Table 4. Absolute differences between laboratory tested performance and manufacturer reported values from their website specification sheets.

CALiPER System ID	Brand	Actual difference between lab tested values and manufacturer rating			
		Output (lumens)	CCT (K)	Efficacy (lm/W)	Power (W)
17-S1B	Energy Solutions	-1802	143	-7	-6
17-S1C	Energy Solutions	-1709	-115	-8	-5
17-S2A	Energy Solutions	-581	22	2	-5
17-S2B	Energy Solutions	-847	32	0	-5
17-S3A	AGC Lighting Co., Ltd	1091	218	18	-4
17-S3B	AGC Lighting Co., Ltd	1234	220	15	-2
17-S4A	Orion Energy Systems, Inc.	-664	-105	-14	1
17-S4B	Orion Energy Systems, Inc.	-822	-106	-17	1
17-S5A	Eaton/Cooper/Metalux	-1423	-14	-2	-7
17-S5B	Eaton/Cooper/Metalux	-1404	-5	-1	-8
17-S6A	Hangzhou LMenergysolution Lighting LTD	-696	-49	-3	-2
17-S6B	Hangzhou LMenergysolution Lighting LTD	-1169	-30	-6	-2
17-S7A	Acuity Brands/Lithonia Lighting	-271	62	-2	0
17-S7B	Acuity Brands/Lithonia Lighting	127	58	3	-1

3.2 Field testing results

3.2.1 Field testing results - Temporal lighting artifacts (flicker)

Two of the mockup observers reported picking up TLA (aka flicker) from one of the luminaires types, CALiPER 17-S6A and B. A handheld UPRTek MF250N flicker meter[4] was used for in situ measurements, and indeed that luminaire was the one that does not meet the IEEE Standard P1789-2015 for low risk. The low-risk standard sets a maximum allowed percent flicker of 0.08 times the modulation frequency, which for 120 Hz is 10%. At 45% flicker, this product's light modulation could be visible to some occupants, and could potentially cause responses such as headaches, migraine, malaise, and distraction. See Table 5.

[4] No calibrations standards were available for the meter at the time of this work.

Table 5. Flicker metrics of the seven installed luminaire types.

Flicker Measurements					
CALiPER System ID	Modulation Frequency	Percent Flicker	Flicker Index	SVM	Meets IEEE Standard P1789-2015 Low Risk Criteria
17-S1B	1490 Hz	33.1	0.063	0.127	Yes
17-S2A	1950 Hz	5.7	0.009	0.035	Yes
17-S3A	120 Hz	0.6	0.001	0.022	Yes
17-S4A	1100 Hz	3.9	0.006	0.022	Yes
17-S5A	1460 Hz	9.3	0.019	0.033	Yes
17-S6A	120 Hz	45.4	0.139	1.684	No
17-S7A	>2000 Hz	10.6	0.017	0	Yes

3.2.2 Field testing results – Glare

There are no reliable metrics for evaluating potential glare from luminaires with uneven luminance distributions across the aperture. Metrics such as the Unified Glare Rating (UGR) assume that the luminance is uniform across the aperture, and six of seven luminaire types installed for the mockup are extreme examples of non-uniformity because the individual LEDs are directly visible. The maximum luminance of the individual exposed LEDs may be one contributor to the glare response. One of the seven (17-S1) used a white diffuser to obscure the view of the individual LEDs and spread the luminance over a larger surface area, and this was judged to be far less glaring (see Section 3.3).

The luminaires were measured for maximum luminance using a Konica-Minolta LS-110 1/3° luminance meter. The measurements for 17-S1 are likely to be reliable because the 1/3° capture angle was completely filled by the uniform nadir luminance of the diffuser. (The meter is rated for measurements up to 990,000 cd/m^2, although the high end of the calibration range is only 13,000 cd/m^2.) However, the field luminance measurements of the other six luminaires with exposed LEDs likely underrepresent the actual luminance, because the individual LED package did not fill the entire capture angle of the meter. Therefore, some portion of the capture angle was diluted with the unlighted surfaces surrounding the LED, reducing the luminance reading. The luminances are listed in Table 6, along with the number of packages per luminaire. In general, luminaires with more packages used lower luminance packages in order to achieve roughly the same lumen output.

Table 6. Measured luminances of the seven luminaires installed at the mockup site.

CALiPER System ID	Measured luminance (cd/m^2) [a]	Area measured	Number of packages	Notes
17-S1B	40045	LEDs behind diffuse tubular cover	Not visible	Diffuse tube. Measured luminance value realistic.
17-S2A	>283700[a]	Bare LED	1080	LEDs filled less than the meter's capture angle
17-S3A	>424800[a]	Bare LED behind clear glass shield	536	LEDs filled less than the meter's capture angle
17-S4A	>400000[a]	Bare LED	756	LEDs filled less than the meter's capture angle
17-S5A	>289000[a]	Bare LED	672	LEDs filled less than the meter's capture angle
17-S6A	>154000[a]	Bare LED, behind clear acrylic cover	2862	LEDs filled less than half the meter's capture angle
17-S7A	>478000[a]	Bare LED, behind clear acrylic cover	576	LEDs filled less than the meter's capture angle

(a) Luminance meter capture angle was 1/3°. The individual LED package did not fill the full capture angle, and therefore the measured value may underrepresent the actual luminance.

3.2.3 Field testing results – Illuminance distribution on floor and workplane

As a way to evaluate lighting uniformity on the floor and the 37" work plane, horizontal illuminance values were measured, subtracting ambient illuminance from the results. The resulting values are shown in Table 7.

Table 7. Horizontal illuminances from each pair of luminaire types, with maximum-to-minimum uniformity values.

Illuminance Measurements at Floor, in lux							
CALiPER #	Under Luminaire	Quarter Point	Between Luminaires	Quarter Point	Under Luminaire	Average (weighted)	Uniformity (max/min)
17-S1B, C	748	711	648	719	746	706	1.2
17-S2A, B	725	847	732	818	668	773	1.3
17-S3A, B	595	574	535	572	594	569	1.1
17-S4A, B	677	659	622	672	704	661	1.1
17-S5A, B	472	528	502	514	552	514	1.2
17-S6A, B	834	790	709	784	792	774	1.2
17-S7A, B	701	661	616	650	657	651	1.1
Illuminance Measurements at 37" Workplane Height, in lux							
17-S1B, C	1242	962	724	940	1245	967	1.7
17-S2A, B	1401	988	811	996	1362	1044	1.7
17-S3A, B	970	787	632	830	1020	811	1.3
17-S4A, B	1131	882	719	927	1121	914	1.6
17-S5A, B	1023	849	683	889	1071	867	1.6
17-S6A, B	1362	1096	878	1035	1270	1081	1.6
17-S7A, B	1135	900	719	880	1036	896	1.6

Each of the pair of luminaires mocked up were 14’ on center, mounted 11’-3” to the lowest point on the luminaire. Although this type of luminaire is usually intended for a higher mounting height, all but 17-S1 and 17-S2 produced a cosine[5] distribution of light, appropriate for a spacing-to-mounting height of 1.7 (at the 37” tall work plane) and 1.2 (at the floor). Luminaires 17-S1 and 17-S2 both featured linear baffles that controlled glare to some extent, and these luminaires produced higher maximum-to-minimum illuminance uniformity ratios between luminaires. This would have been hard to anticipate because the manufacturer did not make photometric distribution data available on their website.

3.3 Visual evaluation results

The anonymous, completed questionnaires were processed as follows: Written comments from each participant were evaluated for the topic and whether it was positive, neutral, or negative for that luminaire. For example, “Excellent visual comfort/appearance; Minimal Shadowing; Great illumination; Nice color rendition; Good coverage on table” was translated as positive for the topics of light distribution, color, shadowing, and visual comfort. “Very even, soft shadows on floor; Bright source, kinda glary; Color seems good; Table evenly illuminated; Double shadows when writing from hand” was translated as positive for light distribution, positive for color, and negative for visual comfort and shadows. If an issue was not addressed, that luminaire received no positive, neutral or negative count in that area.

5 A cosine distribution for a downward-facing luminaire is characterized by a roughly circular pattern on the downward side of the horizontal axis on a polar plot. It is informally called a “blob distribution.” If the maximum intensity in candelas straight downward = I_0, then the intensity at 5° from nadir = I_0 * cos (5°), the intensity at 45° from nadir = I_0 * cos (45°), the intensity at 80° = I_0 * cos (80°), and so forth. The cosine distribution is useful for many applications, but more optical control is needed to produce a narrow distribution for focusing light on a surface below the luminaire, for example, or a wide distribution that would enable wider spacing of luminaires while maintaining good illuminance uniformity.

3.3.1 Visual evaluation results – by issue

The responses for all 23 participants were tallied, although not all participants addressed every issue. This is reflected in the "Sum responses" rows in Table 8. The same data are illustrated in Figure 5, a bar graph showing positive, neutral, negative, or no response to specific quality issues for luminaires. Luminaires with more green received more positive ratings; more red in the bars represents more negative ratings. Graphically, it is easy to see that the first and second luminaires, CALiPER 17-S1 and 17-S2, received the overall highest ratings, particularly in the visual comfort area. In fact, visual comfort (i.e., glare) was the strongest response to the luminaires from the observers.

Table 8. Summary of observer responses.

CALiPER System ID		Visual Comf			Distrib.			Shadows			Color			Appearance			Price (overall value)
		Pos.	Neut.	Neg.	Pos.	Neut.	Neg.	Pos.	Neut.	Neg.	Pos.	Neut.	Neg.	Pos.	Neut.	Neg.	
17-S1	# Responses	17	3	0	10	1	1	7	3	0	13	5	2	3	1	2	21
	Sum responses	20			12			10			20			6			$4,825
	Average price																**$230**
	% responses	85%	15%	0%	83%	8%	8%	70%	30%	0%	65%	25%	10%	50%	17%	33%	
17-S2	# Responses	10	4	3	9	0	2	5	0	3	6	6	4	1	0	5	20
	Sum responses	17			11			8			16			6			$3,925
	Average price																**$196**
	% responses	59%	24%	18%	82%	0%	18%	63%	0%	38%	38%	38%	25%	17%	0%	83%	
17-S3	# Responses	2	4	10	2	4	4	0	2	9	4	10	3	2	0	1	19
	Sum responses	16			10			11			17			3			$3,200
	Average price																**$168**
	% responses	13%	25%	63%	20%	40%	40%	0%	18%	82%	24%	59%	18%	67%	0%	33%	
17-S4	# Responses	1	6	12	10	2	0	2	6	4	3	7	10	0	0	4	20
	Sum responses	19			12			12			20			4			$3,450
	Average price																**$173**
	% responses	5%	32%	63%	83%	17%	0%	17%	50%	33%	15%	35%	50%	0%	0%	100%	
17-S5	# Responses	1	3	11	7	4	0	4	2	7	6	6	5	1	1	3	19
	Sum responses	15			11			13			17			5			$3,300
	Average price																**$174**
	% responses	7%	20%	73%	64%	36%	0%	31%	15%	54%	35%	35%	29%	20%	20%	60%	
17-S6	# Responses	2	7	7	14	0	0	6	4	1	8	6	3	1	1	3	21
	Sum responses	16			14			11			17			5			$4,025
	Average price																**$192**
	% responses	13%	44%	44%	100%	0%	0%	55%	36%	9%	47%	35%	18%	20%	20%	60%	
17-S7	# Responses	1	10	7	8	3	1	2	3	5	4	7	7	5	2	0	20
	Sum responses	18			12			10			18			7			$3,825
	Average price																**$191**
	% responses	6%	56%	39%	67%	25%	8%	20%	30%	50%	22%	39%	39%	71%	29%	0%	

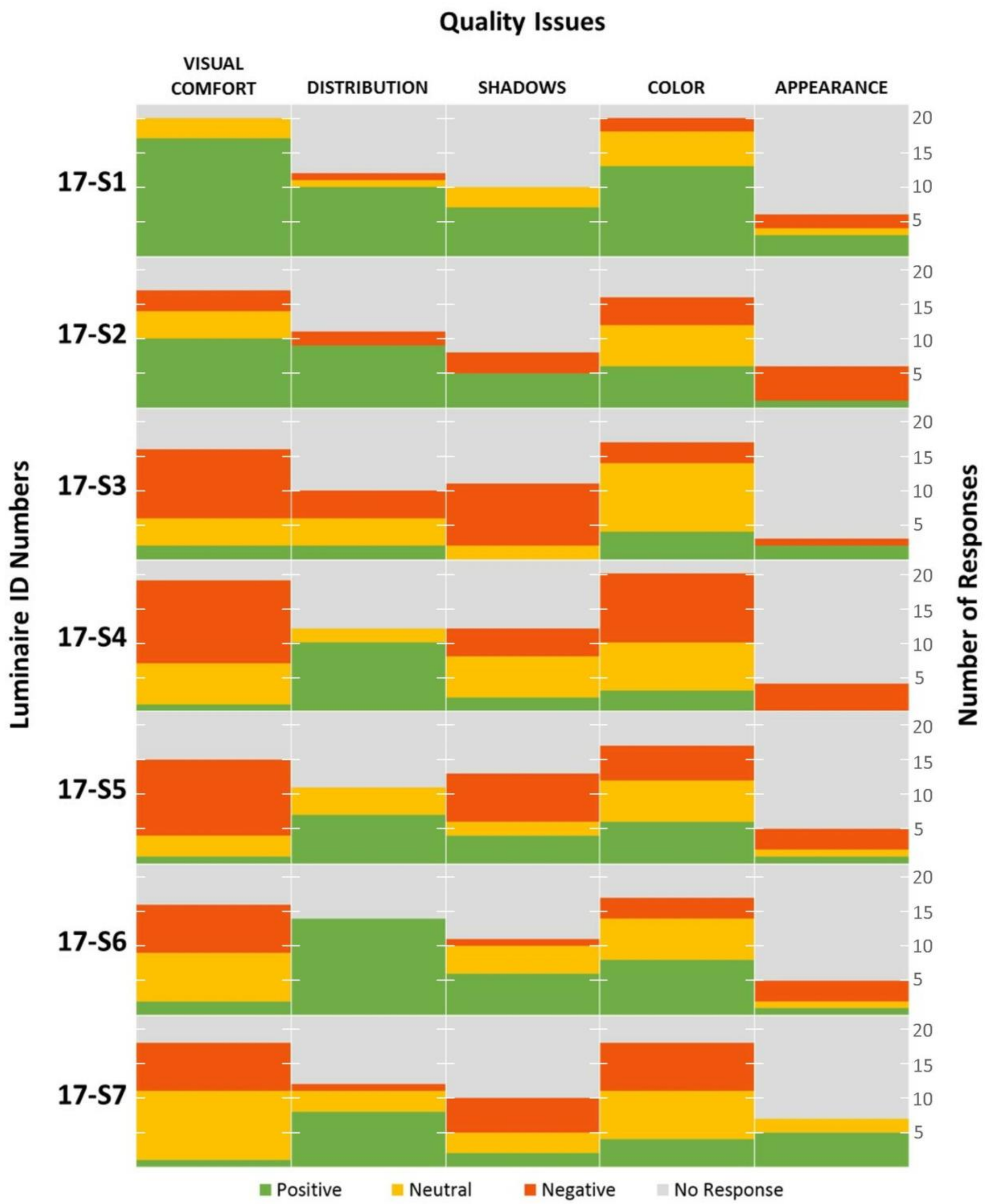


Figure 5. Bar graph showing positive, neutral, negative, or no response to specific quality issues for luminaires. Rows are CALiPER luminaire ID numbers; columns are specific quality issues. Luminaires with more green received more positive ratings; more red in the bars represents more negative ratings.

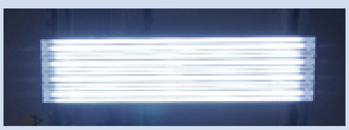
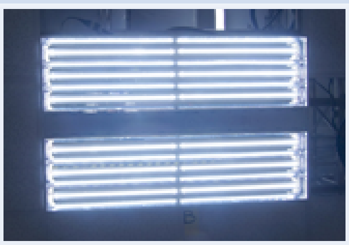
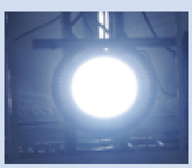
3.3.2 Visual evaluation results – Price (overall value of luminaire)

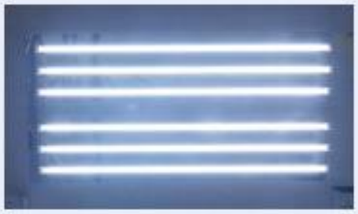
Responses to the question asking observers to choose an overall value for each luminaire type yielded results that confirmed the tallied comments. As shown in Table 8. Summary of observer responses.Table 8, the rankings of the luminaires by preference were CALiPER numbers 17-S1, 17-S2, 17-S6, 17-S7, 17-S5, 17-S4, and 17-S3. The most preferred luminaires correspond to those that received the most positive comments about glare control, and the least preferred correspond to the three luminaires that received the most negative comments about glare. Only one of these, 17-S1, is a product for which the average observer would pay more. 17-S1 is also the lowest efficacy product, demonstrating a tradeoff between visual comfort and efficacy for this particular luminaire type.

3.3.3 Visual evaluation results – Specific comments on luminaires

The following (Table 9) are a sampling of specific comments recorded by the observers for the seven luminaire types, including observer recommendations for application:

Table 9. Additional comments on luminaires from observers.

CALiPER ID and photo of lighted luminaire from mockup	Observer comments and application suggestions
	**17-S1** Soft shadows. Excellent visual comfort. Good glare control. Good shielding with lens and cutoff (from linear shielding). Only diffused product. Not terribly glary. More of a fluorescent quality. Multiple source shadows. Good for fine detail tasks. Nice appearance. Less shadowing on table top. Suitable for big box retail, warehouse, production, or manufacturing.
	**17-S2** Good cutoff. Very large fixture. Ugly. Mirrored finish might be a problem with dust or particles. Glaring until you step to far end of table, and visual comfort becomes wow! Bare LEDs burn eyeballs. Visual comfort ok above cutoff angle, not below. Nice to have deeper regress. Could use a diffuser. Suitable for industrial space or an open warehouse.
	**17-S3** High brightness, small aperture. Luminance WAY too high. High glare. Sharper shadows. Nice appearance when off. Pronounced hand shadows from writing. Looks to have robust heat sink. Visual comfort bad/bright/painful. Applications include outdoor storage space and warehouse, although several observers commented they would be unlikely to use this product because of the glare.
	**17-S4** Open strips of LEDs – more glare. Fixture aesthetic pretty raw. Quite glary, exposed diodes. Needs a diffuser. Multiple shadows. There's no good viewing angle. Pattern of LEDs is distracting. Applications include manufacturing or warehouse, or storage areas. Use in sparsely occupied spaces.

	**17-S5** Another 6 stripes of single LED points, but a white interior reflector helps make this less glaring. Terrible visual comfort. Flickers. Needs a diffuser. Too many shadows. Blob distribution. Bare diodes are distracting. Dust or particles might be an issue. Applications are warehouse or back-of-house areas only.
	**17-S6** Less glaring than some others. Designed to mimic T8/T5, but no diffusion. Chips are sealed for dust. More dots of harsh light. Glary. Bright afterimage from LEDs. More pronounced reflections on glossy task materials. Seems like very high lumen but not too terribly harsh. Stripe shadows. No optics, no regress – quite glary. Don't like the appearance of exposed sockets. Needs higher mounting height. Applications: High ceiling warehouse, industrial applications.
	**17-S7** Better optics, less shadowing. Decent visual quality. LED is covered to help with dust. Not as intense to eyes, appears less glary in most directions. Good fixture quality. LEDs not as bright. Smaller size helpful for installation. Glary. Harsh. Applications: Warehouse, gym, or big box store.

4 Discussion

4.1 Limitations of product lists

Product listings can be a useful resource for high-efficacy products. However, this should be an information-gathering step, not the only resource for selecting luminaires. It is necessary to go to the manufacturer's website to gather additional information, since the listing data may be based on the performance of a product very different from the one needed for a project. For example, among the seven luminaires procured and tested for this CALiPER project providing performance data on various options:

- Changing the CCT from 5000K to 4000K would result in up to a 13% drop in efficacy; changing from 5000K to 3000K would result in up to a 17% drop in efficacy.
- Changing the optical package from a cosine distribution (i.e., little optical control) to a narrower distribution suitable for taller ceiling heights or more focused task illumination would result in up to a 9% drop in efficacy.
- Selecting a luminaire option that provides more protection from dust and dirt (such as one with a higher ingress protection rating), OR a diffuser that reduces glare of the bare LEDs would result in up to a 16% reduction in efficacy.

(A specifier may find even greater efficacy reductions among other LED products not included in this CALiPER study.) Consequently, the efficacy value listed in the LED Lighting Facts database or similar product listings for a particular product line may be higher than the actual efficacy of many configurations of that product. It should be used as a means to identify potential products for consideration, but not for specification.

4.2 Photometric testing

The seven luminaire pairs fared well overall in photometric testing when compared to manufacturer claimed values from their website product literature (not necessarily values listed in LED Lighting Facts):

- Color performance reported with CCT and CRI was consistent with manufacturer claimed values.
- Lumen output values were no more than 9.6% above or below the manufacturer reported values.
- The power draw varied by as much as 6.8% from the manufacturer claimed values. Power factors were all above 90%.
- Efficacies (lm/W) varied by as much as 12.0% from manufacturer claimed values, although the tested efficacy values often were lower than expected, given the LED Lighting Facts listing based on top performers in a product family.

In many cases it was difficult to compare the luminaire performance with the manufacturer's claim because the manufacturer's website did not include all of the following information:

- Specific photometric performance for different combinations of CCT, light distribution, optical control options (such as lenses, diffusers, louvers and baffles, and protective covers), and light output.
- Specific drawing or photos of alternate combinations of options. It is often not clear what product a specific catalog number refers to.

4.3 Field testing, flicker and LED luminances

In general, the LED luminaires performed well in terms of TLA (i.e., flicker). Only one luminaire exhibited flicker that was outside the low-risk region of the IEEE Standard P1789-2015, or an SVM that was above 1.0. That luminaire, CALiPER 17-S6, exhibited 120 Hz frequency, 45% flicker, Flicker Index of 0.14, and an SVM of 1.68, indications that it could contribute to health consequences in sensitive individuals, or interact with moving machinery in an industrial space to create a hazardous stroboscopic effect.

Luminance measurements of the LED products revealed very high values, which likely contributed to the strong response to glare from observers, even though they were instructed not to examine the luminaire with more than a glance. The one luminaire with diffusion over the LED packages (CALiPER 17-S1) was considered by the observers to be acceptable for an industrial space, with a measured luminance of 44,000 cd/m^2. In the other luminaires, the packages were clearly visible as very bright dots, sometimes arranged so closely together that the package dots converged at a viewing distance to look like a continuous luminous line. The measured luminances ranged from 154,000 to 478,000 cd/m^2, although the actual luminances would be higher than those values because the LED did not fill the full capture angle of the meter, and thus the luminance value was diluted by the luminance of surrounding materials.

At this time there is no glare metric that takes the spatial variations in luminance into account, so current metrics are unable to distinguish between the luminance from a single tiny bright dot or a large diffuse area source if they both produce the same luminous intensity in a given direction and have the same aperture or luminaire area. That may change in the near future, with increased focus on improving glare metrics. In the meantime, it is important to communicate that the perception of bare, high-luminance LED packages seems to increase the perceived glare. This will reduce visual comfort for users in spaces with such luminaires, as opposed to those with diffusers, lenses, or other optical techniques to spread the source luminance over a larger area.

4.4 Observer responses

An analysis of questionnaire responses from the observer volunteers, combined with an informal discussion of the observer groups following the completion of the questionnaire, suggests that visual comfort/glare was a significant factor in the evaluation of product quality. The two luminaires that utilized simple optics to either diffuse glare (17-S1) or cut off view of the LEDs above a fixed viewing angle (17-S2), received the highest rankings. The third ranked luminaire (17-S6) used a large count of lower-luminance LEDs, which would effectively spread the luminance over a larger luminous area.

The same three luminaires, 17-S1, 17-S2, and 17-S6 received good comments in categories of light distribution, shadows, and color. Appearance of the luminaire received few comments.

5 Limitations of this CALiPER study

Some applications for this luminaire type have mounting heights of 20’ or higher, while other applications have mounting heights much closer to the work plane. This CALiPER study’s luminaires were mounted for observation in a ceiling that was intended to reach 15’. Because of hardware limitations, the maximum mounting height was only 11’-3” above the floor, and the average horizontal illuminances under and between pairs of luminaires ranged from 811 to 1081 lx. This lower-than-planned mounting height may have exaggerated the glare from the luminaire for the observers, although luminaires of this type and range of lumen output are sometimes mounted at similar heights to deliver 1000 lx horizontal for fine detail industrial tasks.

The volunteer observers for this study were lighting-knowledgeable. All of them were familiar with industrial lighting products and could have made mental comparisons with lighting systems they have seen and experienced in their work. Although care was taken to reduce bias and order effects through the evaluation protocol, this was not a rigorously designed human factors research study. However, it is often informative to get feedback from industry experts.

6 Conclusion and Guidance

The LED Lighting Facts database can be potentially misinterpreted because the performance of a wide range of products in a family can be reported under the tested performance of its best-performing product. The published values often mask reductions in performance from different LED color, luminaire lumen output, driver variances, and any efficiency losses due to improved optical control. A number of lessons learned can be derived from this work for the specifier:

- Luminaire efficacy is only one aspect of performance that should considered in a specification. Other attributes of performance may wind up being of greater importance to the installation and not be apparent from the values contained in such product databases. Furthermore, even the efficacy numbers may be unreliable in the sense that they represent a particular model and set of characteristics across a family of products, with significant variation within that family due to:
    - Lumen output (the highest efficacy product is often also the version with highest output).
    - Light distribution (highest efficacy usually being achieved by the product with no optics applied for glare control or anything more sophisticated than a cosine distribution. Furthermore, the product with no optical control may also come with glare issues, since there are no optics to spread the light over a larger area than the bare LEDs.)
    - Color temperature (highest efficacy generally corresponding to the version with highest CCT – dropping from 5000K to 3000K just among the seven sample products obtained for this study results in as much as a 17% loss in efficacy, for example).
- Individual attributes like efficacy should therefore be used only as a means for identifying potential candidates for consideration, followed by the collection of more detailed performance data on the particular combination of options for that product.
- Most importantly, whenever possible, see the actual products with all desired attributes in action before making a selection.

- A significant limitation to these kinds of product databases is that they do not contain products from all manufacturers, e.g., because they are not necessarily a marketing priority for all manufacturers.

However, this report also demonstrates that there are bonafide LED products that perform at *very* high levels of efficacy. The LED Lighting Facts and similar databases can be an excellent source of information, but it is incumbent on the specifier to investigate the performance of the specific product needed. With due diligence, high-performing LED products are available for virtually all architectural applications, although there are inevitably minor tradeoffs to be made for comfort, color, distribution, and other lighting quality issues.

Appendix 1. Questionnaire for Observers

Top Efficacy Performers Questionnaire

Group No.

Profession:	**Engineer**	**Lighting Designer**	**Rep or Agent**	**Architect**	**Facility Mgr**	**Contractor**	**Other**

Years of experience in lighting and/or construction:

Instructions: Pairs of industrial luminaires are mounted at 11'-3" above the floor. A table is located between the two, with a variety of objects you can use to simulate an assembly task. Take 3 minutes to walk around the tables and provide comments/observations on each type. Please do not share your thoughts with others, yet.

		Written comments **Please provide comments on the luminaires, using your knowledge and experience. Consider respond to the following issues: SPREAD OF LIGHT ON THE TABLE TOP, SHADOWS, VISUAL COMFORT, COLOR QUALITY, APPEARANCE, FUNCTIONALITY, ETC.**	**If this type of luminaire costs $200 on average, what would you pay for this one?**	**Additional comments? Where would you recommend this product?**
Luminaire Label	**A**		□ $100 □ $150 □ $200 □ $250 □ $300	
	B		□ $100 □ $150 □ $200 □ $250 □ $300	
	C		□ $100 □ $150 □ $200 □ $250 □ $300	
	D		□ $100 □ $150 □ $200 □ $250 □ $300	
	E		□ $100 □ $150 □ $200 □ $250 □ $300	
	F		□ $100 □ $150 □ $200 □ $250 □ $300	
	G		□ $100 □ $150 □ $200 □ $250 □ $300	

Appendix 2. Instructions to Observers

Top Efficacy Performers Protocol

Instructions to be read to observers

Welcome! PNNL and DOE are very grateful to have you here as observers in our CALiPER study on industrial LED luminaires. Each of you has a clipboard with a questionnaire. We have seven pairs of luminaires labeled A, B, C, D, E, F, and G mounted in this ceiling area, and we are going to switch the pairs on, one at a time. You will not see the luminaires in alphabetical order, so please be sure to fill out the questionnaire section corresponding to the luminaire letter. You will have 3 minutes to move around the space imagining yourself in the shoes of the industrial employee and the building owner. We do not advise that you stare at the luminaires, but feel free to glance at them briefly if you need to. Please complete the questionnaire on that luminaire. At the end of 3 minutes, we will turn the lights off for a few seconds, and switch on a different pair of luminaires. Each time we do this we will move a table of objects and tasks between the new pair of luminaires. VERY IMPORTANT: PLEASE DO NOT TALK WITH ANYONE ELSE ABOUT YOUR OBSERVATIONS. THERE WILL BE TIME FOR THAT WHEN WE ARE DONE.

	Presentation Order						
Group	**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**
TEP-1	G	D	C	A	F	B	E
TEP-2	C	F	E	B	D	G	A
TEP-3	F	B	G	E	A	D	C
TEP-4	B	A	F	D	C	E	G
TEP-5	A	E	G	C	B	F	D
TEP-6	D	G	C	A	F	E	B
TEP-7	E	C	B	D	G	A	F

then….

What you've been observing over the last half hour or so are high efficacy luminaires from the LED Lighting Facts database and some others that we found that claimed performance between 140 and 200 lm/W. We're going to hand out a spreadsheet that has all the product names and performance data. Now, let's talk. What did you see? What did you like? What did you not like? We are going to record the conversation so that we can transcribe your comments accurately, but we will not be sharing your identity with anyone. At the end of this discussion, you are welcome to jot down any final comments or observations on the questionnaires, and then are welcome to leave. Thanks for sharing your experience

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PNNL-27648 ▪ June 2018