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CALiPER

Application Summary Report 21:

Linear (T8) LED Lamps

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Preface

The U.S. Department of Energy (DOE) CALiPER program has been purchasing and testing general illumination solid-state lighting (SSL) products since 2006. CALiPER relies on standardized photometric testing (following the Illuminating Engineering Society of North America [IES] approved method LM-79-08[1]) conducted by accredited, independent laboratories.[2] Results from CALiPER testing are available to the public via detailed reports for each product or through summary reports, which assemble data from several product tests and provide comparative analyses.[3] Increasingly, CALiPER investigations also rely on new test procedures that are not industry standards; these experiments provide data that is essential for understanding the most current issues facing the SSL industry.

It is not possible for CALiPER to test every SSL product on the market, especially given the rapidly growing variety of products and changing performance characteristics. Instead, CALiPER focuses on specific groups of products that are relevant to important issues being investigated. The products are selected with the intent of capturing the current state of the market at a given point in time, representing a broad range of performance characteristics. However, the selection does not represent a statistical sample of all available products in the identified group. All selected products are shown as currently available on the manufacturer's webpage at the time of purchase.

CALiPER purchases products through standard distribution channels, acting in a similar manner to a typical specifier. CALiPER does not accept or purchase samples directly from manufacturer's to ensure all tested products are representative of a typical manufacturing run and not hand-picked for superior performance. CALiPER cannot control for the age of products in the distribution system, or account for any differences in products that carry the same model number.

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

To provide further context, CALiPER test results may be compared to data from LED Lighting Facts,[4] ENERGY STAR® performance criteria,[5] technical requirements for the DesignLights Consortium® (DLC) Qualified Products

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1 IES LM-79-08, *Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products*, covers LED-based SSL products with control electronics and heat sinks incorporated. For more information, visit http://www.iesna.org/.

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

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

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

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

List (QPL),[6] or other established benchmarks. CALiPER also tries to purchase conventional (i.e., non-SSL) products for comparison, but because the primary focus is SSL, the program can only test a limited number.

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

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

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

Outline of CALiPER Reports on Linear (T8) LED Lamps

This report is part of a series of investigations performed by the CALiPER program on linear LED lamps. Each report in the series covers the performance of up to 31 linear LED lamps, which were purchased in late 2012 or 2013. Summaries of the evaluations covered in each report are as follows:

Application Summary Report 21
This report focuses on the bare lamp performance of 31 linear LED lamps intended as an alternative to T8 fluorescent lamps. Data obtained in accordance with IES LM-79-08 indicated that the mean efficacy is similar to that of fluorescent lamps, but that lumen output was often much lower. This presents a situation where something must change in order for energy savings and equivalent illumination levels to be achieved simultaneously. In this case, the luminous intensity distribution of all the tested lamps was directional or semi-directional, rather than omnidirectional.

Also discussed in this report are several issues related to the electrical configuration of the lamps, such as the required socket types and power feed location. While no configuration is necessarily better, the multitude of options can make specifying and installing linear LED lamps more difficult, with the potential for safety issues. Similarly, the variety of color and power quality attributes adds a layer of complexity to the specification process. Many products offered good or excellent quality attributes, but some did not and thus could be perceived as inferior to fluorescent lamps in some installations.

Report 21.1: Linear (T8) LED Lamp Performance in a K12-lensed Troffer (Pending)
While bare-lamp attributes are often used for comparing products during the specification process, performance is best examined at the luminaire level. This report will focus on the performance of the Series 21 lamps installed in a standard troffer with a K12 (prismatic) lens. The changes in luminaire efficiency—and total luminaire efficacy—will be discussed, as well as other consequences resulting from the different luminous intensity distributions of the various lamps and their interaction with the luminaire.

Report 21.2: Linear (T8) LED Lamp Performance in Five Types of Recessed Troffers (Pending)
Although troffers using a K12 lens are numerous, there are many other types of optical systems used with luminaires in which linear LED lamps could be installed. This report will look at the performance of three different linear LED lamps—chosen primarily based on their luminous intensity distribution—compared to a benchmark fluorescent lamp in five different troffer types.

Report 21.3: Cost-effectiveness of Linear (T8) LED Lamps (Pending)
Meeting performance expectations is important for driving adoption of linear LED lamps, but cost-effectiveness may be an overriding factor in many cases. Linear LED lamps typically cost more initially than fluorescent lamps, but energy and maintenance savings may mean that the life-cycle cost is lower.

In addition to these four technical reports, CALiPER will offer a concise guidance document that describes the findings of these studies and provides practical advice to manufacturers, specifiers, and consumers. As always, the applicability of general guidance to any specific application may vary. Further, the LED market is rapidly changing, meaning today's conclusions may or may not apply to products in the future. The performance and effectiveness of every lighting system should be evaluated on its own merits.

1 Background

Linear fluorescent lamps—and the “troffers” in which they are often used—are a staple of ambient lighting in offices, classrooms, and other types of commercial spaces. They are inexpensive, can offer acceptable or good color quality, can have lifetimes in excess of 30,000 hours, and are relatively energy efficient. Thus, to be competitive, linear LED lamps must reach higher performance thresholds than for other lamps (such as PAR lamps) in categories where the primary incumbent technology is energy-inefficient incandescent or halogen lamps. Despite the challenge, linear LED lamps have become a key offering from manufacturers large and small, with dozens of options on the market. The large installed base of fluorescent lamps is undoubtedly an appealing target, and linear LED lamps have the potential for higher efficacies and longer lifetimes than fluorescent lamps.

Linear Fluorescent Lamps

The nomenclature for lamps is defined by the American National Standard Lighting Group (ANSLG) in document ANSI C79.1-2002. The first letter(s) used in a lamp designation identifies the shape classification of the bulb, such as “T” for “Tubular.” The numerical designation provides the diameter of the lamp in eighths of an inch; for example, a T8 lamp is nominally eight eighths of an inch—or one inch—in diameter. Such designations were developed around conventional technologies, and new technologies, such as LED, that became commercially available after 2002 have been adapted to fit the nomenclature. ANSI C78.81-2010 provides additional details on the dimensional tolerances for linear fluorescent lamps; for example, the overall length of a 32 W T8 fluorescent lamp must be between 47.67 and 47.78 inches, with a diameter between 0.94 and 1.10 inches. Of course, there are many types of linear fluorescent lamps, but the T8 is the most commonly specified version today, and serves as the basis of comparison throughout this report.

Fluorescent lamps are a type of low-pressure mercury-vapor gas discharge lamp. An electric current excites mercury, creating a plasma that emits ultraviolet (UV) radiation. The UV radiation is converted to visible radiation using phosphors, which are coated on the inside of the tube and give the lamps their characteristic white appearance. Early prototype fluorescent lamps date back to the late 1800s, but widespread commercial use did not occur until the middle of the twentieth century. Over the past 60 years, the technology has continued to develop, with improvements in efficacy, lumen output, color rendering, and lifetime. Notably, T8 lamps have supplanted T12 lamps—which have now been phased out of production—and offer substantially improved performance. T5 fluorescent lamps are also now available, although they are not a direct replacement for either T12 or T8 lamps.

The introduction of electronic ballasts for fluorescent lamps was important for improving lighting quality, especially flicker. Today, most fluorescent lamps operate on either instant-start or rapid-start electronic ballasts, with the former using shunted lampholders (sockets) and the latter using unshunted lampholders—meaning there is no connection between the terminals. There is also still a substantial installed base of lamps operating on magnetic ballasts, which typically connect to unshunted sockets. Shunted sockets are usually recognizable because they have a connection terminal on only one side of the lampholder. When changing lamps—or retrofitting an existing luminaire with LED lamps—it is important to know the type of lampholder used, because the electrical paths are different.

Another notable change in fluorescent lamp technology was the shift from halophosphor to triphosphor lamps, beginning in the 1970s. Halophosphor lamps relied upon broad emitting phosphors, whereas triphosphor lamps use a combination of phosphors with more distinct emissions—typically red, green, and blue. Triphosphor lamps are generally more efficient than halophosphor lamps, while maintaining or improving color quality. In general, there has been a shift to using linear fluorescent lamps with a CRI of at least 80 in typical applications, as opposed to a CRI of at least 70.

In the past decades, there has been substantial focus on trimming the wattage of fluorescent lamps, reducing mercury content, and increasing lifetime. These efforts have been successful and are continuing, but there is a finite amount of achievable improvement in fluorescent lamp technology. The introduction of LED technology as a competitor has led some fluorescent lamp manufacturers to boost performance, while others have largely shifted focus away from fluorescent technology.

Installed Base

In 2010, DOE estimated there were nearly one billion installed fluorescent luminaires, including troffers and other types of products such as linear pendants that use fluorescent lamps.[7] About 60% of those fluorescent products use T8 lamps, whereas the remainder is predominantly T12, with a small but growing percentage of T5 lamps. In contrast, in 2012 there were less than one million installed LED troffers and linear pendants—or 1% of the total market. Using these numbers, DOE estimated potential annual energy savings from converting linear fluorescent products to LED—though not necessarily to T8 LED lamps—at more than 1,000 tBtu, approximately equivalent to the electricity consumed by 27 million average U.S. homes in a year.

Linear LED Products

Although fluorescent troffers have evolved into a well-defined system of modular products, the LED market is more fragmented, especially in retrofit applications. LED products intended for use in troffer applications include lamps, retrofit kits, and dedicated LED luminaires—and sometimes the lines between these can be blurry. Expanded descriptions of these product types can be found in the CALiPER Exploratory Study *Recessed Troffer Lighting*.[8] Even considering only linear LED lamps, there can be substantial variation among products. The most apparent differences include the wiring configuration and luminous intensity distribution, as well as construction and physical appearance.

Linear LED lamps are most often given the T8 designation, although the diameters may vary. Such lamps can be used to replace both T12 and T8 fluorescent lamps in most circumstances. A vast majority of linear LED lamps uses familiar bi-pin connections at each end, but few of these operate with the existing fluorescent ballast. Rather, most include an integral driver and are powered directly by mains voltage (typically 120 V or 277 V in the U.S.). Less common are LED T8 lamps with an external driver. In addition, LED lamps may require power to be connected at one end or both ends—sometimes with an additional wire between opposite pins. Improper wiring can result in product failure and/or dangerous conditions, such as sparking, smoking, or tripping circuit breakers. Further, each lamp type may require either shunted or unshunted lampholders (sockets)—or may not use the existing sockets at all.

The combination of these three characteristics—wiring location, socket type, and driver location—creates a multitude of possible installation configurations. As such, it is rare that a fluorescent lamp—or even another type of linear LED lamp—can be used in a troffer or other luminaire that has been configured for a particular type of LED linear lamp(s). As a result, precautionary labels are required in order for the product to achieve safety certifications. The variety of potential lamp and lampholder combinations can be confusing not only for specifiers and installers during the initial installation, but also for the maintenance staff that may be changing or replacing lamps in the future.

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7 Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led-adoption-report_2013.pdf

8 Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_recessed-troffer_2013.pdf

Most linear LED lamps are also physically different from conventional fluorescent lamps. Most notably, instead of a glass tube, the cylindrical shape of linear LED lamps is partitioned to include both the driver and/or thermal management system and the LEDs. As a result, the emitting surface of linear LED lamps often covers only half of the surface area. The remainder is typically opaque, and sometimes includes ridges to aid in heat dissipation. The differences in construction are typically manifested as differences in luminous intensity distribution—and subsequent in-luminaire performance differences. Fluorescent T8 lamps have an omnidirectional distribution; that is, they emit light uniformly around the axis of the lamp. This is easily achievable, since the gas discharge responsible for the light emission is omnidirectional. In contrast, LED packages emit light directionally, so it is difficult to achieve an omnidirectional luminous intensity distribution within the confines of an existing ANSI-defined form factor while also meeting needs for thermal management and electrical regulation. Although the lamps tested by CALiPER for this report used several types of optical systems, none was able to mimic the distribution of light produced by a linear fluorescent lamp.

While directional emission may be an asset for certain product types, luminaires designed around fluorescent lamps will likely change appearance if a directional lamp is installed. Specifically, the upper reflecting surface of a recessed troffer may appear darker, and the distribution of light leaving the luminaire is likely to change, potentially affecting performance. On the other hand, using an omnidirectional lamp within a directional luminaire—such as a troffer—introduces inefficiency to the system, because some of the light must be redirected out of the aperture. Because of this, replacing an omnidirectional fluorescent lamp with a directional LED lamp that has a lower lumen output may not result in reduced illuminance at the work plane but may reduce light on adjacent walls, for example. Each product must be compared on a case-by-case basis.

This Application Summary Report focuses specifically on the performance of bare lamps—that is, lamps photometered on their own, without a luminaire. This basic level of performance is how most products are compared to one another during specification. However, bare-lamp performance may not translate when the product is operated in a luminaire, and best practice would include evaluating the performance of lamp-luminaire combinations. Subsequent reports will document the performance of each product in a typical lensed 2×4 troffer, as well as the performance of a subset of lamps in five different troffer types.

2 Results

CALiPER Linear LED Test Data

Series 21 LED Lamps

This report analyzes the independently tested performance of 31 linear LED products—sometimes referred to as T8 replacement lamps or T8 tubes. Most of the lamps were anonymously purchased in the first half of 2013, with the remainder purchased in late 2012. In this report, they are referred to as the Series 21 products. For more on the product selection parameters, both in general and as they pertain to this group of products, see Appendix A.

It is acknowledged that the products included in this dataset may have been replaced with a newer model and/or may no longer be sold. However, that does not diminish the broader relevance of the findings. In fact, the lamps generally represent a snapshot of performance at the time of purchase,[9] and serve as an effective tool for comparing LED to benchmark technologies while helping to illustrate some of the challenges of this specific application—challenges that are unlikely to abate in the near future. Further, the evaluation was not intended as a measure of the suitability of any specific lamp model, and the results should not be taken as a referendum on any product line or manufacturer.

All of the lamps were tested according to IES LM-79-08, using both an integrating sphere and a goniophotometer. For all except one of the Series 21 products, the difference in measured lumen output between the two methods was less than 3%, which is typical; the other product, 12-113, had a difference of 10%.[10] Except for color characteristics and power factor, all values included in this report were measured using the goniophotometry method. This deviates from typical CALiPER reports, but allows for more accurate calculations of luminaire efficiency when comparing the measured values for bare lamps and the lamps in luminaires. All reported values are the mean of the two samples that were tested; the exception is D_{uv}, which is reported as the value farthest from zero. Table 1 summarizes key results from CALiPER testing. Complete product descriptions are available in Appendix B.

Table 1. Results of CALiPER tests for the Series 21 linear LED lamps. Performance criteria include initial output, total input power, luminous efficacy, power factor, color rendering index (CRI), special color rendering index R_9, correlated color temperature (CCT), and distance from the Planckian locus (D_{uv}). The *Labels* column indicates whether the product was qualified by the DesignLights Consortium (DLC) or listed by LED Lighting Facts (LF).

DOE CALiPER Test ID	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	Power Factor	CRI	CCT (K)	D_{uv}	Beam Angle Across (deg)	Labels	
12-111	1,518	19.6	78	0.99	87	4137	-0.0030	129	-	-
12-113	2,191	23.3	94	0.90	73	4115	0.0027	113	-	LF
12-114	1,981	18.8	105	0.99	86	4945	0.0030	134	-	-

(continued on next page)

1. Value outside of ANSI-defined limits (ANSI C78.377).

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

[10] The exact cause of this larger difference could not be determined.

Table 1. (continued)

DOE CALiPER Test ID	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	Power Factor	CRI	CCT (K)	D_{uv}	Beam Angle Across (deg)	Labels	
12-115	1,505	16.0	94	0.92	68	4314	0.0061	134	-	-
13-01	1,686	17.7	96	0.87	74	4343	0.0070[1]	108	DLC	
13-03	1,607	18.3	88	0.99	84	3963	-0.0008	105	-	LF
13-04	1,513	16.7	91	0.99	83	3945	0.0007	144	-	LF
13-05	1,604	17.5	92	0.97	77	3998	0.0068[1]	110	-	LF
13-06	1,962	22.1	89	0.99	78	3967	0.0011	135	DLC	
13-07	1,479	18.7	79	0.42	77	4387	0.0000	111	-	-
13-09	1,819	17.4	105	0.99	72	4068	0.0036	142	-	-
13-10	2,099	19.3	109	0.99	84	4404	0.0030	114	DLC	-
13-12	2,180	21.8	100	1.00	84	5079	0.0042	130	DLC	-
13-13	1,480	13.9	106	0.89	73	4409	0.0003	114	-	LF
13-14	1,996	17.4	115	0.99	72	3131	0.0011	116	-	-
13-15	1,499	16.3	92	0.99	85	4203	0.0030	133	-	LF
13-16	1,537	17.7	87	0.99	74	5094	0.0060	138	-	-
13-17	1,380	17.5	79	0.99	73	4535	-0.0012	159	-	-
13-18	1,633	19.4	84	0.99	83	4068	-0.0005	131	-	LF
13-19	1,565	18.4	85	0.98	74	4487	-0.0029	137	-	LF
13-20	1,973	19.6	101	0.99	90	6035	0.0021	160	-	-
13-21	1,420	17.6	80	0.99	71	4428	0.0023	120	-	-
13-22	1,476	16.7	89	0.97	82	4146	0.0022	143	-	-
13-23[2]	2,052	25.5	81	0.99	85	3920	-0.0009	105	DLC	
13-24	1,655	11.5	143	0.84	76	4216	0.0012	120	DLC	LF
13-25[3]	1,357	20.6	66	(DC)	88	5261	-0.0026	126	-	-
13-26	1,731	18.6	93	0.98	81	4450	0.0003	142	DLC	LF
13-27	1,844	22.5	82	0.99	72	4099	0.0035	133	-	-
13-29	2,377	24.1	99	0.99	84	3909	0.0002	152	DLC	-
13-31	3,126	28.6	109	0.99	72	4237	0.0018	114	-	-
13-33[4]	2,265	23.7	96	0.78	82	3907	0.0015	151	DLC	LF
Minimum	1,357	11.5	66	0.42	68	3131	-	105	-	-
Mean	1,790	19.2	94	0.94	79	4329	-	129	-	-
Maximum	3,126	28.6	143	1.00	90	6035	-	160	-	-

1 Value outside of ANSI-defined limits (ANSI C78.377).

2 Data are for a single lamp operated on the supplied external driver; the results may be different if measurement was completed with another lamp connected at the same time.

3 Tested at 24 VDC; product did not come with external power supply. All other products tested at 120 VAC using external driver, if applicable.

4 Data are for a single lamp operated on the two-lamp external driver; manufacturer data provided for two-lamp system was divided by two for comparison, but some performance variation should be expected with one lamp operating on the ballast instead of two.

Figure 1 shows several of the lamps tested by CALiPER, illustrating the range of physical characteristics. The half-cylinder aperture of the vast majority of products was either diffuse or clear, and sometimes included refracting elements (e.g., ribs or ridges). Product 13-23 was the only one to take a markedly different approach—it is the bottom lamp shown in Figure 1. Other notable products were 13-33, which does not use bi-pin connectors, and 13-20, which emitted light from more than half of the surface area. Appendix C provides descriptions of the physical and electrical characteristics of each product.

Past CALiPER Data for Linear LED Lamps

The CALiPER program tested several linear LED lamps between 2007 and 2010, but the performance was generally insufficient for competing with fluorescent lamps. The dataset for those tests is available in Appendix D. A few of the lamps tested in 2010 did exceed 90 lm/W, but none of the lamps had a CRI above 77, the mean efficacy was 61 lm/W, and no lamp emitted more than 2,000 lm. As the linear LED lamp market has matured, more energy-efficient linear LED products have become available, but whether or not they compete across all performance criteria is more difficult to determine.

The CALiPER Exploratory Study on recessed troffers included four linear LED lamp products, two of which were tested further and included in Series 21; a new version of one other product from the Exploratory Study was also included in this dataset. Although it is difficult to create a consensus assessment based on four products—nor are such assessments generally appropriate, given the widespread variation in LED product performance—the linear LED lamps included in the exploratory study generally fared worse than the LED retrofit kits and dedicated LED troffer luminaires. From this baseline—and in consideration of the widespread interest in the product type—the CALiPER program determined that further investigation of linear LED lamps was appropriate.

Figure 1. A subset of the Series 21 linear LED lamp (and fluorescent benchmark, top), illustrating the range of product designs. The lamps were staggered when the photo was taken; they are all approximately the same length.

Supplemental Linear LED Lamp Data

LED Lighting Facts Data

As of October 1, 2013, LED Lighting Facts listed 534 active linear LED lamps. Summary statistics for these products are provided in Table 2. A notable statistic in the table is a maximum efficacy of 173 lm/W; however, only one product was listed at this high of a performance level, and the value was not independently verified. This product was subsequently listed by LED Lighting Facts as "not yet commercially available," and it no longer appears in the searchable database. More information on linear LED lamps listed by LED Lighting Facts can be found in a recent Snapshot Report on Interior Ambient Lighting.[11]

LED Lighting Facts data provides a broader picture of the overall market for linear LED lamps. However, LED Lighting Facts only requires basic performance information, with voluntary reporting of a wider range of metrics. The CALiPER program is intended to investigate more nuanced or difficult-to-quantify performance characteristics using a smaller sample of products. Due to the smaller sample size and selection parameters, the summary statistics for the Series 21 linear LED lamps tested by CALiPER do not necessarily match the summary data for products listed by LED Lighting Facts or any other qualification or tracking program.

DesignLights Consortium Qualified Products List

Linear LED lamps are not covered by the ENERGY STAR program, but are included on the DLC QPL. For DLC qualification, linear LED lamps must be tested alone and in a reference luminaire. The bare lamp performance criteria are as follows:

- System efficacy ≥ 100 lm/W
- Initial light output ≥ 1,600 lm
- CCT ≤ 5000 K
- CRI ≥ 80
- Power factor ≥ 0.90
- THD ≤ 20%
- Warranty ≥ 5 years

Table 3 provides summary data for the 281 "parent"[12] four-foot linear LED lamps qualified as of 12/26/2013; those lamps represent a total of 1,212 individual products. This data includes some products that were qualified under previous specifications and are still listed, but does not include products that have been delisted.

Table 2. Summary data for linear LED lamps listed by LED Lighting Facts. Includes 683 products listed as of October 1, 2013.

	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	CRI	CCT (K)
Minimum	320	4.6	58	56	2734
Mean	1,727	17.8	98	81	4356
Maximum	3,306	37.5	173	90	6881

Table 3. Summary data for DLC QPL-qualified four-foot linear LED lamps. Includes 281 parent products listed as of November 26, 2013.

	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	CRI	CCT (K)
Minimum	1,522	14.1	83.9	80	2731
Mean	1,995	18.9	104.9	83	3701
Maximum	3,006	26.4	126.6	87	5304

[11] Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lf-snapshot_ambient-lighting.pdf

[12] For DLC QPL qualification, products may be submitted in family groups, based on shared attributes.

CALiPER Testing of Conventional Product Benchmarks

The CALiPER program had previously tested three linear fluorescent products, and tested one additional benchmark product for this report. A summary of the testing results is provided in Appendix E. The four products include two F32T8s (nominally 32 W T8), one F28T8, and one F40T12 (nominally 40 W T12). All emit just over 3,000 lm, with efficacy around 100 lm/W for the T8s and 80 lm/W for the T12. Although there continues to be some development of linear fluorescent lamps, these performance characteristics remain fairly constant.

Except for the one F32T8 (BK13-30, tested for Series 21), the lamps were tested at their rated power using a reference ballast. In contrast, BK13-30 was tested using a typical two-lamp, instant start ballast with a normal ballast factor (0.87). For this test, both lamps were connected to the ballast, but only the output from one lamp was measured. This method provides data that is more comparable to in-luminaire measurements, and is most relevant to the LED T8 data obtained for this report. The difference in measurement methodology for the fluorescent benchmarks is manifested in many of the subsequent figures; for example, the lumen output of a F28T8 lamp on a ballast with a 0.87 ballast factor is notably less than that of a typical F32T8 lamp operated on a reference ballast.

There are many other types of linear fluorescent lamps that CALiPER has not tested. These include T5 lamps, some low-wattage energy-saving lamps (e.g., F25T8), and lamps with an 8-foot length, among others. Nonetheless, the basic F32T8 lamp is the most commonly used today, and remains the most appropriate benchmark for this study.

3 Analysis

Lumen Output and Efficacy

Figure 2 illustrates the lumen output and efficacy of the bare lamps tested for Series 21, as well as data from LED Lighting Facts and the DLC QPL. The Series 21 linear LED lamps had measured outputs ranging from 1,357 to 3,126 lm, with a mean of 1,790 lm—similar to typical performance for products listed by LED Lighting Facts or qualified by the DLC. In previous CALiPER testing (products purchased in 2010 or earlier), no linear LED lamps were measured above 1,951 lm, and the average output was just 1,243 lm. This contrast exemplifies a more general trend of increasing lumen output in the LED market. However, the output of a majority of the Series 21 products was less than 2,000 lm, which is much less than the typical output—approximately 3,000 lm—of a 32 W fluorescent T8 lamp (F32T8), and somewhat less than the output of BK13-30 (an F28T8 lamp with a normal ballast factor ballast, used as a baseline for this study).

Because of their lower lumen output, linear LED lamps must produce different luminous intensity distributions than fluorescent lamps in order to deliver equivalent workplane illuminance, which may in turn change the distribution of the luminaire in which they are used. In some cases, these different distributions may be more effective and more efficient, but specifiers and users should be aware of the potential changes in appearance and/or lighting quality. A given linear LED lamp may work better or worse in a given type of luminaire, a phenomenon that will be discussed in the follow-on CALiPER reports for this series of products.

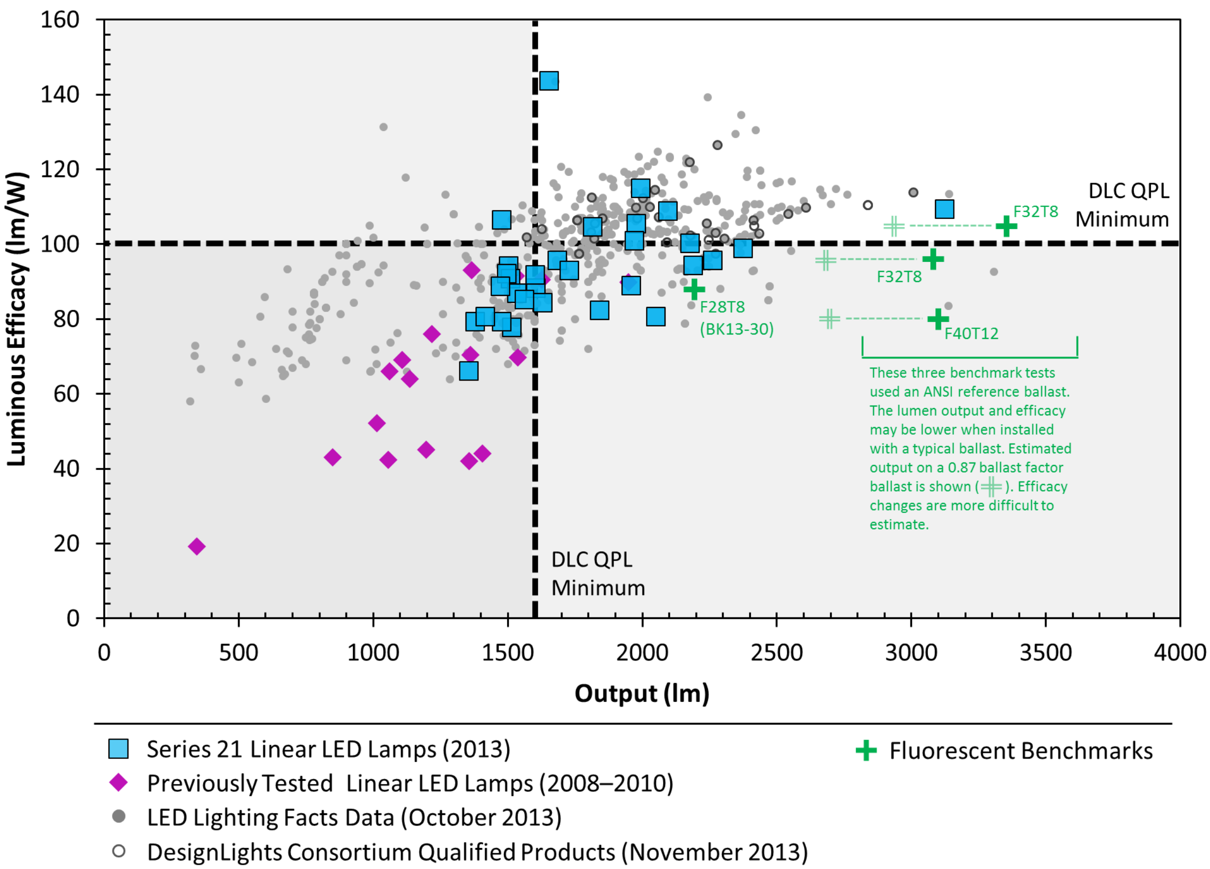


Figure 2. Luminous efficacy versus lumen output for the Series 21 linear LED lamps compared to other datasets. Compared to earlier CALiPER testing, many of the Series 21 lamps demonstrated higher lumen output and higher efficacy. However, few exceeded the efficacy of CALiPER-tested F32T8 benchmarks by a substantial amount.

In evaluating the performance of an LED lighting system compared to an incumbent, it is critical to consider the equivalency of the provided illumination. It is easy to save energy if the workplane illuminance is decreased, and the same outcome (energy savings and reduce illuminance) can be achieved by reducing the number of fluorescent lamps in a troffer, or switching to a low-output, high-efficiency ballast—simple and cost-effective solutions. However, this strategy is not an option in all instances, and some types of linear LED lamps may provide for a higher overall system efficacy with equivalent illuminance.

Nine of the 31 products in Series 21 met the 100 lm/W threshold for the DLC QPL, which is also considered a typical efficacy for F32T8 lamps—CALiPER data for fluorescent T8s ranges between 88[13] and 105 lm/W, with an F40T12 measured at 80 lm/W. However, eight of those nine products were only between 100 and 115 lm/W, which provides minimal benefit compared to bare F32T8 lamps. With the exception of one product (13-24) that was measured at 143 lm/W, all of the Series 21 products must rely on changes in luminous intensity distribution and luminaire efficiency to provide substantial energy savings at equal illuminance, compared to F32T8 lamps. Energy savings are significantly easier to accomplish when retrofitting F40T12 lamps using either T8 fluorescent lamps or LED lamps.

Distribution of Light

Figure 3 is a plot of relative luminous intensity distribution at the 90° horizontal angle (a plane perpendicular to the axis of the lamp) for each of the Series 21 lamps, including the tested fluorescent benchmark (BK13-30). The plot shows intensity versus the vertical angle from 0° (straight down) to 180° (straight up), assuming bilateral

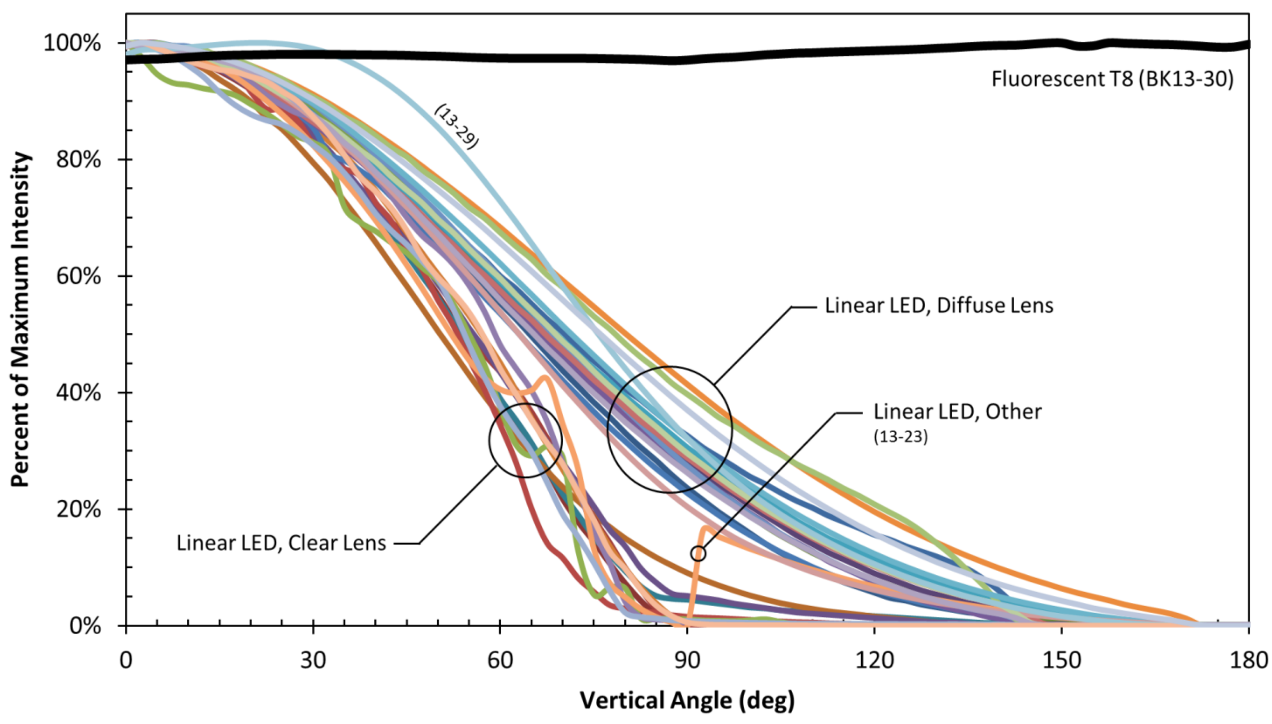


Figure 3. Relative luminous intensity distribution of the Series 21 products (90° horizontal plane). Although none of the LED products were close to matching the fluorescent benchmark—which had relatively uniform intensity at all vertical angles—the data did reveal a distinct difference between lamps with a clear lens and lamps with a frosted lens. The beam angle is twice the vertical angle at which the intensity is 50% of maximum intensity (ANSI/IES RP-16-10), assuming symmetry.

[13] Most T8 lamps have an efficacy around 100 lm/W, excluding the ballast. The lamp measured at 88 lm/W included the ballast.

symmetry.[14] This plot provides a clear illustration of the difference between the lamps, although it is different from the customary presentation of luminous intensity distribution data in a polar plot.

As shown, none of the tested linear LED lamps provides a luminous intensity distribution comparable to a linear fluorescent lamp, which offers approximately equal intensity at all angles around the lamp axis. The LED lamps offer maximum intensity straight down, and no intensity straight up. Some lamps provide little or no output at vertical angles above 90° (horizontal plane).

There are two easily distinguishable groups of linear LED lamps, which have clearly different performance. Nineteen products used a diffusing lens, which resulted in substantially more emission above 90° than the other LED products. For these 19 products, the luminous intensity at 90° was between approximately 20% and 40% of the maximum intensity. Another 11 products used a clear lens, which resulted in little or no light emitted upward. The remaining product (13-23) used a different form factor, with a correspondingly different luminous intensity distribution. Based on these results, it is probable that when linear LED lamps with a clear lens are installed in a troffer, darker interior reflecting surfaces of the luminaire will result—something observers in past CALiPER investigations have found unfavorable.

Although adding a diffuse lens over half of the cylinder allows for some upward emission, it is not without ancillary effects. Most importantly, diffusion reduces efficacy by approximately 10%, on average. The 19 diffuse products had a mean efficacy of 90 lm/W, with a minimum of 66 lm/W and a maximum of 105 lm/W. In contrast, the ten products with a predominantly clear optical system had a mean efficacy of 101 lm/W, with a range of 79 lm/W to 143 lm/W.

Color Characteristics

Linear lamps are predominantly used in office and classroom applications, with some use in retail, hospitality, institutional, industrial, and residential applications. Although some of these spaces do not require the highest standards for color quality, others host occupants for many hours at a stretch, and color appearance of skin, clothing, fabrics, finishes, and objects may affect satisfaction or performance. While a CRI in the 70s was considered standard for office and classroom applications for many years, many people now consider a minimum CRI of 80 to be typical for occupied interiors.

Over half (16 of 31) of the Series 21 linear LED lamps had a CRI of less than 80—the minimum required to meet the DLC QPL criterion—with the lowest having a CRI of 68. Except for one product with a CRI of 90, the remainder had a CRI in the 80s. Likewise, there was a large amount of variation in the CCTs of the purchased products, as shown in Figure 4. In the CALiPER selection process, a nominal CCT of 4000 K was targeted whenever possible, but not all manufacturers offered a product in that range; as a result, four products with a CCT above 5000 K were purchased.

Figure 5 demonstrates the D_{uv} values for both samples of each Series 21 product. As with CRI and CCT, the D_{uv} of the lamps in this study varied considerably. This variability was mostly from product to product, although in a few cases (e.g., 13-19, 13-22) the difference netween the two samples was large enough that it might be considered noticeable in some cases. On average, the D_{uv} was positive, indicating a slightly greenish appearance—similar to what is typical of linear fluorescent lamps. Several recent research studies have shown,

[14] The plots show data for one of the two samples for each product. The difference between the measured beam angles for the two samples was within 3% of the average for each product.

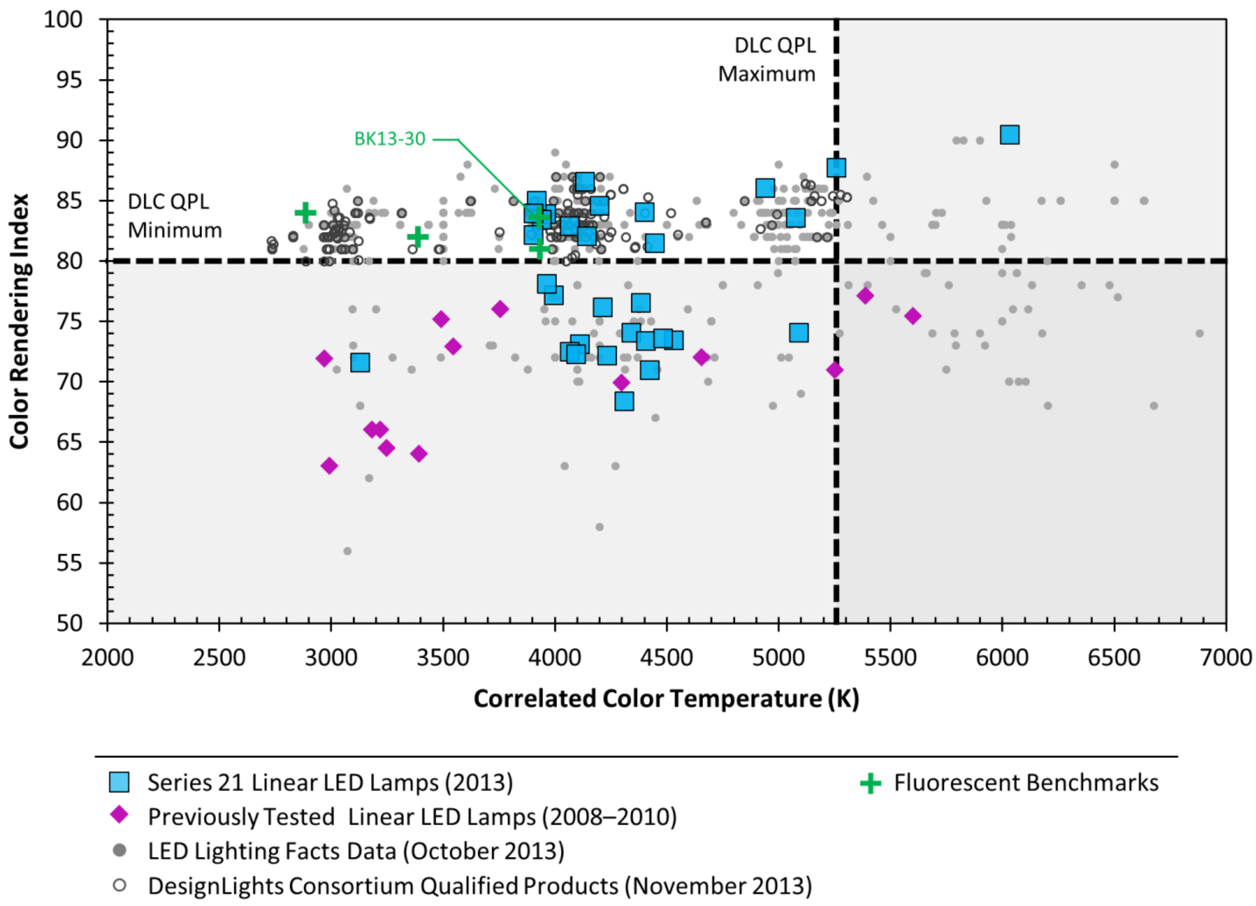


Figure 4. CRI and CCT characteristics of the Series 21 linear lamps. Of the 31 LED products tested, 14 met the DLC QPL criteria for both CRI and CCT. Compared to other product categories recently tested by CALiPER, the color quality of linear LED lamps shows more variability.

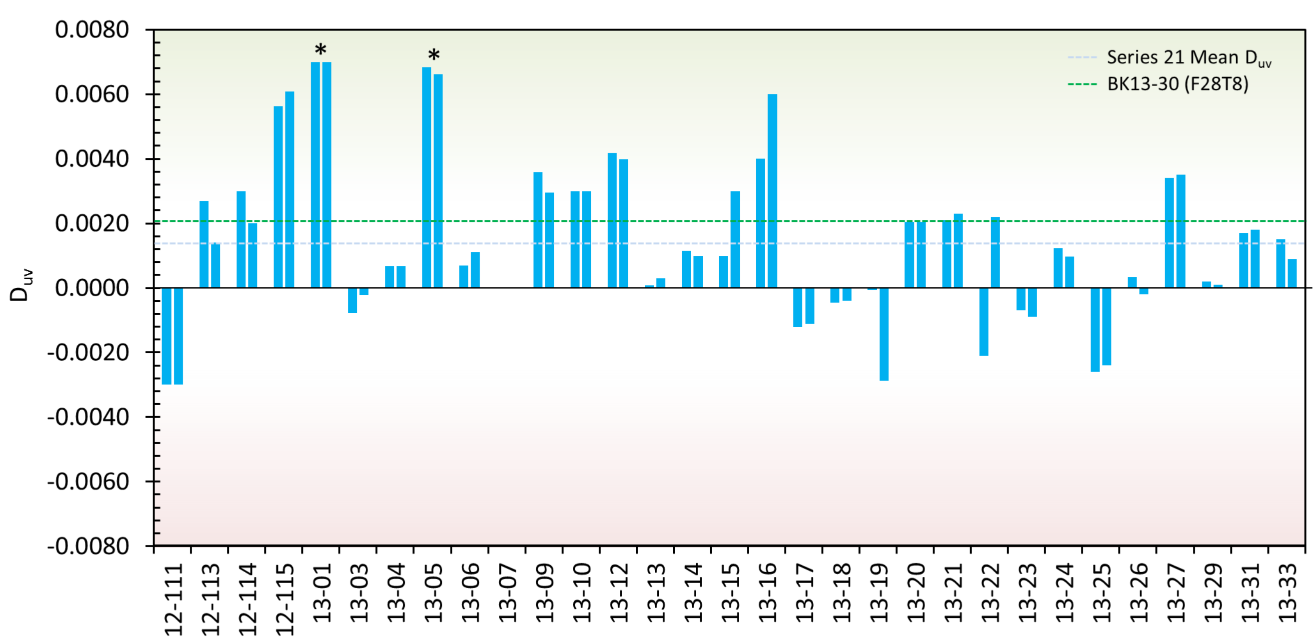


Figure 5. D_{uv} for both samples of each Series 21 linear LED lamp. The two products shown with an asterisk did not meet the ANSI criterion for nominally white light.

however, that people often prefer negative D_{uv} values, especially at CCTs below 4500 K.[15,16]

The range of performance for CRI, CCT, and D_{uv} for the Series 21 linear LED lamps was substantial enough to create potential confusion for purchasers (or occupants) who are unaware of the various metrics. With a new technology such as LEDs, it is also possible that below-average color quality—or any deviation from the existing system—could be attributed to the technology as a whole, rather than the specific product. These are real concerns, but it is also important to acknowledge that fluorescent lamps are available over the same range of performance characteristics, although non-typical lamps often must be specifically sought out.

Electrical Characteristics

For most product categories that CALiPER has investigated, there are few unique attributes related to electrical characteristics and power quality, but in the case of linear LED lamps, these attributes are very important. Input power is an important consideration, because linear LED lamps are often marketed as replacements for existing fluorescent systems. If a one-for-one replacement is made, the only way to save energy—regardless of efficacy or lighting quality issues—is if the lamp draws less power than the existing fluorescent lamp. Of the 31 lamps tested, 22 drew less than 20 W, providing approximately 38% energy savings compared to an F32T8. However, one lamp drew 29 W, which would provide (at most) less than 10% energy savings in a one-for-one replacement scenario, and would potentially draw more power if the fluorescent system used a ballast factor of less than one. Along with that product (13-31), one other product (13-23) used more energy than BK13-30, the F28T8 lamp tested by CALiPER using a typical ballast.

Power factor, as shown in Figure 6, is another performance characteristic that is frequently discussed. Aside from one product (13-07) with a power factor of 0.42, the others were generally good, with 84% above 0.90. Importantly, a lower power factor is not necessarily an indicator of system-wide poor power quality.

Beyond performance metrics, electrical characteristics are important because of the many configurations in which linear LED lamps are available (see Appendix C). Assuming that the products will be used for a retrofit, the specifier and installer must understand the wiring configuration of the existing system, as well as the proper wiring for the new LED system. In order to be made safe, unmatched systems require additional work by electricians during installation.

At this point, there appears to be little consensus emerging on the type(s) of connection used, with products included in this report having seven different configurations. Importantly, the quantity of CALiPER-tested products with each wiring type may not accurately represent the configuration's prevalence within the market. Wiring diagrams for each configuration—labelled A through G—are shown in Appendix F. They can be described as follows:

A. Integral driver, single-ended wiring with unshunted sockets (14 products)
B. Integral driver, double-ended wiring with shunted sockets (7 products)
C. Integral driver, double-ended wiring with unshunted sockets and additional connection between ends (2 products)
D. Remote driver, single-ended wiring with unshunted sockets (1 product)

[15] Rea, M.S. and J.P. Freyssinier. 2013. White lighting. *Color Research and Application* 38(2): 82–92; doi: 10.1002/col.20738.
[16] Ohno, Y and Fein, M. Vision Experiment on White Light Chromaticity for Lighting. CIE/USA-CNC/CIE Biennial Joint Meeting, Davis, CA, Nov. 7-8, 2013. http://cltc.ucdavis.edu/sites/default/files/files/publication/2-yoshi-ohno-mira-fein-white-light-chromaticity-vision-experiment.pdf

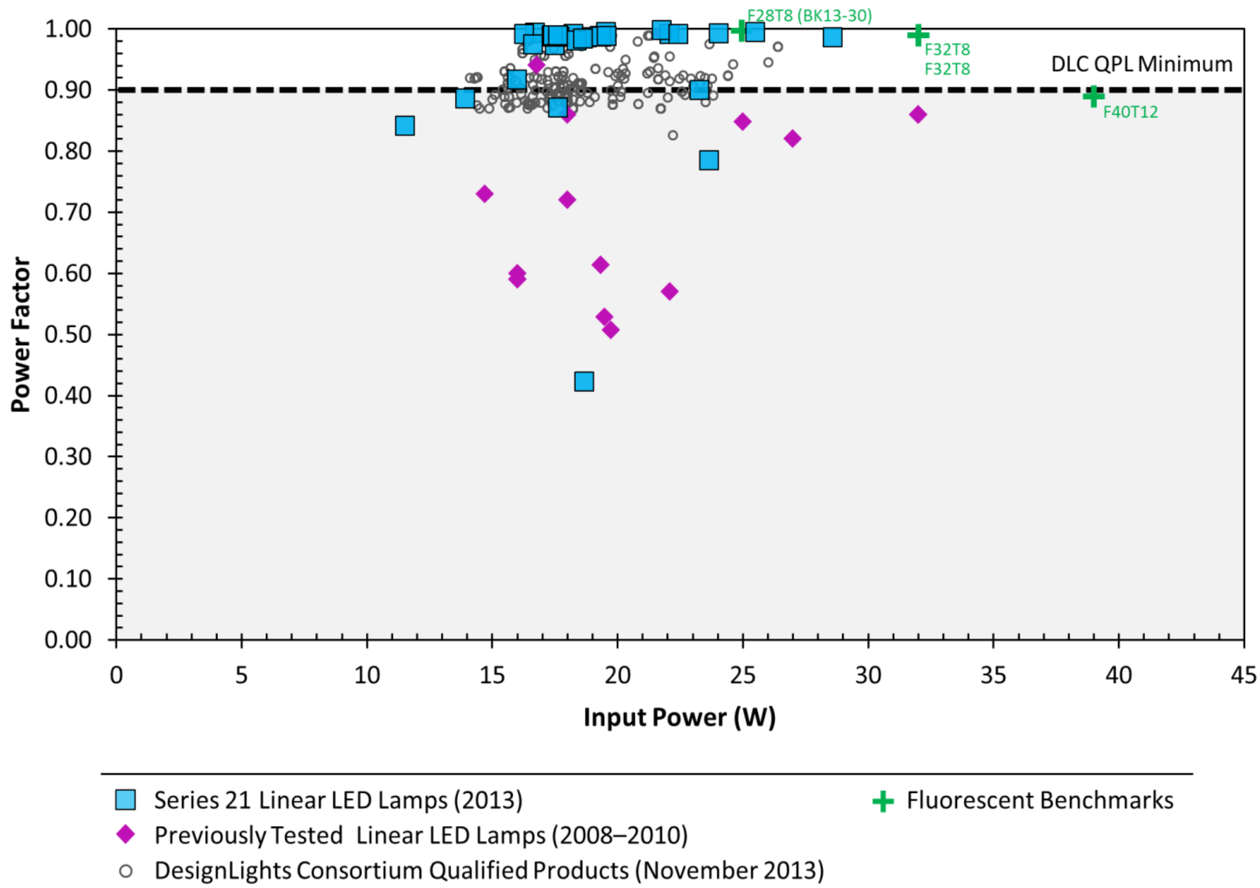


Figure 6. Power factor and input power characteristics of the Series 21 products and auxiliary data sets.

E. Remote driver, double-ended wiring with shunted sockets (4 products)
F. Existing instant-start electronic ballast with existing wiring and shunted sockets (1 product)
G. Remote driver with product powered independently from sockets (2 products)

Three products in the B category were available in multiple wiring configurations at the specifier's discretion. Of the two products that were not powered through the sockets, one did not use sockets at all (13-33), and one used the sockets for support but was powered with hardwired connections (13-31). Some manufacturers of products requiring unshunted sockets supplied them, but many did not.

Besides the potential for confusion, the many types of configurations present a safety concern if any modifications are not properly documented. For example, a fluorescent lamp could no longer be installed in a luminaire modified for LEDs. Only one product tested for this report (13-06) could be installed without removing the existing fluorescent ballast, assuming the luminaire was equipped with an instant-start electronic ballast. This can simplify installation substantially, and reduces future safety concerns of maintenance staff reinstalling fluorescent lamps into the sockets. However, performance and/or compatibility may vary based on the exact ballast, and economic calculations must consider the lifetime of the ballast and the replacement cycle. Since the time CALiPER selected and purchased this series of lamps, a couple of additional products using this system have been identified.

Two other products (13-31 and 13-33) did not use sockets for supplying power to the lamps (although 13-31 did use the sockets for supporting the lamp). Like products that can use an existing ballast, these products could reduce safety concerns related to future modifications.

Size and Shape

While all of the linear LED lamps were able to fit in a troffer typically used for T8 fluorescent lamps, the diameter of all but one lamp was larger than the nominal 1-inch T8 diameter. For the tubular products, the diameter ranged up to 1.41 inches, and the one non-tubular product had a major axis dimension of 1.46 inches. The mean diameter was 1.20 inches. Most notably, 26 of 31 products exceeded the ANSI C78.81-2010 diameter tolerances for fluorescent lamps (1.10 inches). All of the Series 21 LED lamps were also heavier than their fluorescent counterparts, sometimes weighing nearly three times as much. However, as with the dimensions, this did not cause any apparent issues during installation—although anecdotal evidence from real-world installations indicates that it may be a problem for some luminaire types, in some applications.

Manufacturer Claims

Evaluating the accuracy of manufacturers' performance claims is an important component of the CALiPER program. This task is often difficult, because different values are reported in different literature. For example, performance values listed on specification sheets are sometimes different from values listed by LED Lighting Facts or on product packaging. In some cases, these differences may be attributable to rounding to simplify visual appearance or improve legibility. In others, nominal values may be used instead of a single specific test result, to better reflect the distribution of performance that can be expected from lighting products (i.e., not every product is identical). In other cases, updates to products may not be immediately reflected in literature. In total, at least a third of the Series 21 LED products had a listed performance value that varied from one data source to another or provided a nonspecific performance range. In comparing measured values to listed values, CALiPER uses data from specification sheets or product webpages first, then data from product packaging, and if those sources are not available it uses data from LED Lighting Facts.

Most of the Series 21 LED products had data available for all of the major performance criteria (output, efficacy, power, CRI, and CCT). Of the 30 products that listed a value, 21 were measured to be within ±10% of the listed lumen output,[17] whereas one product (13-14) emitted more than 120% of the listed lumens,[18] and six products (13-06, 12-16, 13-17, 13-20, 13-21, and 13-25) emitted less than 90% of the rated lumens. The most under-performing product (13-16) was measured at 78% of the rated lumen output. In general, the level of accuracy for this group of products—in terms of lumen output—was comparable to other recent groups tested by CALiPER.

Five products failed to meet CALiPER's ±10% criterion for input power, with three drawing less than 90% of the rated input power and two drawing more than 110% of the rated power. In addition, four products had a measured efficacy greater than 110% of the listed value, and six products had an efficacy of less than 90% of the manufacturer's rating. In total, only 18 of 31 products met all three claims for input power, efficacy, and lumen output, a percentage that is similar to what CALiPER found for the Series 20 LED PAR38 lamps. In general, the manufacturer claims for color quality metrics were more accurate, although two products (12-113 and 13-21)

[17] The ±10% criterion is used by CALiPER for determining accuracy. This evaluation does not imply that conventional products meet this level of accuracy, or that the two samples tested by CALiPER represent a statistically significant sample. Regardless, it is especially important for new technologies to perform as expected.

[18] Although producing more lumens than claimed—potentially resulting in glare—is probably less likely to lead to consumer or specifier dissatisfaction, the accuracy of manufacturer data is still a fundamental concern.

had a CRI of less than 90% of the claimed value. CALiPER has rarely found CRI values to differ more than 10% from the claimed value, and measured values in the low 70s indicated substantially different performance than the manufacturers' claims of more than 80.

Beam angle is one metric used to characterize a lamp or luminaire's light distribution—although it is most appropriately used to characterize directional lamps. Beam angle is defined as the angle between the two directions for which the intensity is 50% of the maximum intensity (ANSI/IES RP-16-10) or center beam intensity (ANSI C78.379-2006), as measured in a plane through the beam axis. Of 20 products that included a claim for beam angle, eleven were measured to be more than 10% different from the manufacturer's listed value. CALiPER measured beam angles ranging from 105° to 160°, while manufacturers claimed beam angles ranging from 110° to 340°—with a majority at 120°. In some cases, the manufacturer used non-standard nomenclature, such as "LED angle," "lighting angle," or "beam spread," to characterize the distribution of the product, which is likely to create further confusion for specifiers.

Equivalency Claims

Unlike products predominantly sold through retail channels (e.g., PAR lamps, A lamps), few of the linear LED lamps tested by CALiPER made equivalency claims. As previously discussed, based on numerous performance criteria the linear LED lamps are not truly equivalent to F32T8 lamps, although in some cases they may be effective replacements.

4 Conclusions

As tested by CALiPER, the Series 21 linear LED lamps exhibited a range of performance—some good, some bad, but none truly similar to the performance of a linear fluorescent lamp across the board. Compared to previous CALiPER testing of the same product type, there have been notable performance gains, with the efficacy of many lamps now equivalent to or exceeding that of fluorescent lamps. Likewise, some of the LED lamps tested have similar color quality and power quality to the incumbent technology. However, none of the Series 21 LED products matched the luminous intensity distribution and lumen output of the lamps they are intended to replace. In order to save energy and achieve equal task plane illuminance, the linear LED lamps must rely on the directionality of the emission increasing the efficiency of the luminaire or changing its distribution to focus more light on the workplane. This premise is the subject of the reports that will follow this Application Summary. The performance of the Series 21 products can be summarized as follows:

- The lumen output of all but one of the products was substantially less than a (full-wattage) 32 W fluorescent T8 lamp. On average, the output was about half as much. One product was approximately equivalent, emitting 3,126 lm. Five products produced as much lumen output as BK13-30, a F28T8 fluorescent lamp operated on a normal ballast factor ballast.
- The Series 21 products had luminous efficacies between 66 and 143 lm/W. A majority of products had an efficacy between 78 and 115 lm/W, and the average for the group was 94 lm/W. With the exception of the one product at 143 lm/W, this range is generally not appreciably better than an 80+ CRI fluorescent T8 lamp.
- None of the linear LED lamps tested had a luminous intensity distribution similar to that of a linear fluorescent lamp. Those with a frosted lens, however, tended to provide more uplight and a wider beam angle compared to those with a clear lens.
- Although many of the products purchased were nominally 4000 K and had a CRI in the 80s, several product lines did not include that option, instead offering only a CRI in the 70s or a higher CCT, which may not be suitable for all applications.
- The power factor of most of the Series 21 lamps was very good, exceeding 0.95. This is much better than was measured by CALiPER in previous testing.
- Many of the manufacturer claims were accurate; however, 45% of products had a measured value for lumen output, input power, or efficacy that differed by more than 10% from the claimed performance.
- Many manufacturers did not accurately report beam angle for their lamps, so a specifier or customer could be surprised by the performance of the lamps inside their luminaires.

While the efficacy of linear LED lamps is higher than for many other LED product categories, the linear fluorescent lamp is a difficult incumbent to beat, on both energy efficiency and cost. However, in terms of energy savings, the tide may be starting to turn in favor of LEDs, but it remains to be seen whether the performance changes associated with the dramatically different luminous intensity distribution (e.g., luminaire appearance, glare, illuminance distribution) will be accepted. If quality limitations restrict adoption, the energy savings potential will remain theoretical. To remedy the situation, linear LED lamps with an omnidirectional distribution could be used, but at present they would be unlikely to be a cost-effective option compared to fluorescent lamps. The other alternative is to shift away from using LED products as one-for-one replacements to upgrade existing luminaires. Other solutions, such as kits or inserts that retrofit troffers with LED panels, or other solutions that move beyond the lamp-in-luminaire paradigm, would allow LEDs to capitalize on their directional emission.

Appendix A: Product Selection

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

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

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

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

- Lumen package – Products exceeding 2,000 lumens, or otherwise making equivalency claims to linear fluorescent lamps, were targeted.
- Driver location – The number of lamps with internal drivers was extensive, so some preference was given to those with external drivers or those that operated on an existing ballast.
- Luminous intensity distribution – The goal was to test lamps with a wide range of beam angles. Manufacturers/products that listed narrower or wider beam angles were given preference, as there were many products available that claimed a 120° beam angle.
- Color temperature – In general, a nominal CCT of 4000 K was preferred, although many manufacturers tended toward higher CCTS (4250-4500) as the 4100K fluorescent replacements. Some lamps with CCTs in the range of 6000–6500 K were included to accommodate other selection criteria.
- Lamp diameter/shape – The manufacturer literature (including websites) had to indicate that the lamp was intended to replace a fluorescent T8 lamp.

Other non-performance-related criteria are also considered:

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

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

Appendix B: Product Identification

Table B1. Product brand and model identification for the CALiPER Series 21 products.

DOE CALiPER Test ID	Brand	Model
12-111	OSRAM Sylvania	LED22T8L48/841/120/120-277V
12-113	RedBird LED	L4-22W-41K-132
12-114	Ohyama	LDFL2000NF-H50KNA
12-115	Clean Light Green Light	CLGL-17-342SMDS
13-01	Aleddra	LLT-4-T8-C-SW-120-110V
13-03	Toggled	MK2M-T8-48-UN19ND-4080D2-A1
13-04	American Lighting	LT8-4841-PRO
13-05	Borealis Lighting	LEDT8C-4100K-4-277V
13-06	Kumho	FL/T8-32W/22W IU-841
13-07	Advanced Control Technology	SA4120W-4500K
13-09	GoLED	L8LT84FT4500KFR18W120 LED
13-10	LED Lighting Services	LLI-T8HLO-4-4500-C-B-P2
13-12	Zytech	ZYLEDT8-12S-23
13-13	eLED	LEDFLT8-NW48-BIPARV
13-14	Enervation	EL-T8-048-288.DIP(WW)
13-15	Lumena	TB-T8-120017W-42
13-16	Lighting Solutions Group	LED-T8-48-22-NW-FR
13-17	Vivid LEDs	VVD3002-N-UNV-DM (HFL-8060N-120601-L3)
13-18	Philips	19T8/END/48-4000 UNV (421875)
13-19	SeeSmart	200204 (Tube Light, 4 foot, 19W, NWM, 120-277V, SEP, HP)
13-20	Miracle LED	T8 Cool 48"
13-21	Eco-$mart	ECO-A-4G5 (HFL-8060N-120601-L3)
13-22	Luxant LED Lighting	BT8-4/18NX1F (A0001TL018F40E)
13-23	Next Lighting	NL48-UNV2-22-840-00 (NL48-22-840-00-001)
13-24	Sunritek	ST-PT12-02
13-25	LED Smart	ALB-T10-G13-48-24-C-S-S
13-26	Green Illuminating Systems	GIS-19T8/42120 (FP-19T8/42120)
13-27	InnoGreen	IG-220DT8120-20-NW
13-29	Philips Lighting	22T8/EXT/48-4000K UNV (427203)
13-31	Independence LED Lighting	T-42940K-70-CB2
13-33	Cree	UR2-48-45L-40K-S-FD
BK13-30	Lamp: GE Ballast: Philips Advance	F28T8XLSPX41ECO IOPA2P32N

Appendix C: Product Characteristics

Table C1. Physical and electrical characteristics of the Series 21 LED products.

DOE CALiPER Test ID	Optics	Rotatable	External Driver	Requires Unshunted Sockets	Wiring Location	Configuration Type[1]
12-111	Diffuse	No	No	Yes	Both Ends, Connector	C
12-113	Clear	No	No	Yes	One End	A
12-114	Diffuse	No	No	No	Both Ends	B
12-115	Diffuse	Yes	No	No	Both Ends	B
13-01	Clear	No	No	No	Both Ends	B
13-03	Clear[2]	No	No	Yes	One End	A
13-04	Diffuse	No	No	Yes	One End	A
13-05	Clear	No	No	Yes	One End	A
13-06	Diffuse	No	No	No	Both Ends, Ballast	F
13-07	Clear	No	No	No	Both Ends	B
13-09	Diffuse	Yes	No	Yes	One End	A
13-10	Clear	No	No	No	Both Ends	B
13-12	Diffuse	No	No	Yes	One End	A
13-13	Clear[3]	Yes	No	Yes	One End	A
13-14	Clear	Yes	No	No	Multiple	(A)
13-15	Diffuse	Yes	No	No	Multiple	(C)
13-16	Diffuse	No	No	No	Multiple	(B)
13-17	Diffuse	No	Yes	No	Both Ends	E
13-18	Diffuse	No	No	Yes	One End	A
13-19	Diffuse	No	No	Yes	One End	A
13-20	Diffuse	No	No	Yes	One End	A
13-21	Clear	No	Yes	No	Both Ends	E
13-22	Diffuse	No	Yes	Yes	One End	D
13-23	Other	No	Yes	No	Both Ends	E
13-24	Clear	No	No	Yes	One End	A
13-25	Diffuse	No	No	No	Both Ends	B
13-26	Diffuse	No	No	Yes	One End	A
13-27	Diffuse	No	No	Yes	One End	A
13-29	Diffuse[4]	No	Yes	No	Both Ends	E
13-31	Clear	No	Yes	No Power	One End	G
13-33	Diffuse	No	Yes	No Sockets	One End	G

1. Configuration type corresponds with the wiring diagrams shown in Appendix F. Those listed in parentheses are the specific configuration of the lamp tested (when multiple configurations were available).
2. Lightly frosted.
3. Refractive lens.
4. In addition to diffusion, the product included a “channeled optic” to refract light.

Appendix D: Previous CALiPER Testing of Linear LED Lamps

Table D1. Summary data for previous CALiPER tests of linear LED lamps. The first two digits of the CALiPER Test ID indicate the year in which the product was purchased.

DOE CALiPER Test ID	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	Power Factor	CRI	CCT (K)
07-56	1,058	25.0	42	0.85	75	3494
08-17	849	19.7	43	0.51	71	12583
08-19	345	18.0	19	0.72	72	2971
08-37	1,016	19.5	52	0.53	76	7739
09-13AB	1,407	32.0	44	0.86	76	3758
09-13CD	1,357	32.0	42	0.86	76	3756
09-17	1,062	16.0	66	0.59	72	4657
09-39	1,108	16.0	69	0.60	66	3182
09-40	1,218	16.0	76	0.59	66	3221
09-46	1,198	27.0	45	0.82	64	3394
09-48	1,136	18.0	64	0.99	63	2993
09-107	1,539	22.1	70	0.57	73	3548
10-16	1,368	14.7	93	0.73	77	5389
10-17	1,362	19.3	70	0.61	65	3249
10-18	1,533	16.8	91	0.94	75	5602
10-19	1,951	21.8	90	0.99	71	5253
10-36	1,628	18.0	90	0.86	70	4300
Minimum	345	14.7	19	0.51	63	2971
Mean	1,243	20.7	63	0.74	71	4652
Maximum	1,951	32.0	93	0.99	77	12583

Appendix E: CALiPER Testing of Fluorescent T8 Lamps

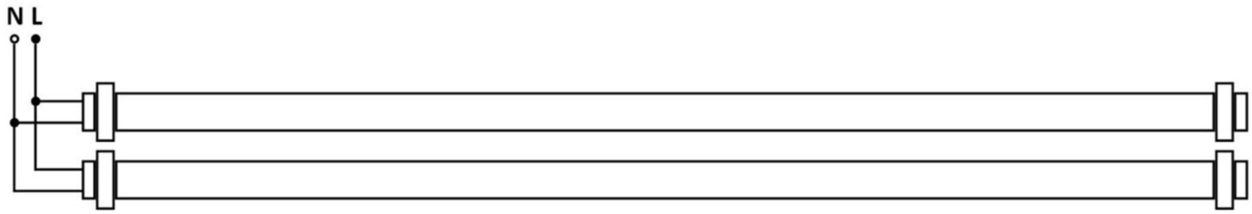
Table E1. Summary data for CALiPER tests of benchmark fluorescent T8 lamps. The first two digits of the CALiPER test ID indicate the year in which the product was purchased. Note that the most recent benchmark was tested on a commercially available ballast, whereas the older benchmarks were tested using a laboratory reference ballast. For a direct comparison, the three older benchmark products should be adjusted using a ballast factor; for T8 lamps this typically means lower input power for the lamp-and-ballast system, lower light output from the system, and slightly higher or lower efficacy depending on the ballast type..T12 systems are similar, except that they typically exhibit lower system efficacy.

DOE CALiPER Test ID	**Brand**	**Model**	**Initial Output** (lm)	**Total Input Power** (W)	**Efficacy** (lm/W)	**Power Factor**	**CRI**	**CCT** (K)
BK13-30[1]	GE	F28T8XLSPX41ECO	2,193	24.9	88	1.00	84	3929
BK08-28[2]	Philips	F32T8/TL841/PLUS/ALTO	3,081	32.0	96	0.99	81	3932
BK08-30[2]	Philips	F40T12/SOFT WHITE/84	3,101	39.0	80	0.89	84	2884
BK10-34[2]	Philips	F32T8/ADV835/ALTO	3,353	32.0	105	0.99	82	3387
Minimum			2,193	24.9	80	0.89	81	2884
Mean			2,932	32.0	92	0.97	83	3533
Maximum			3,353	39.0	105	1.00	84	3932

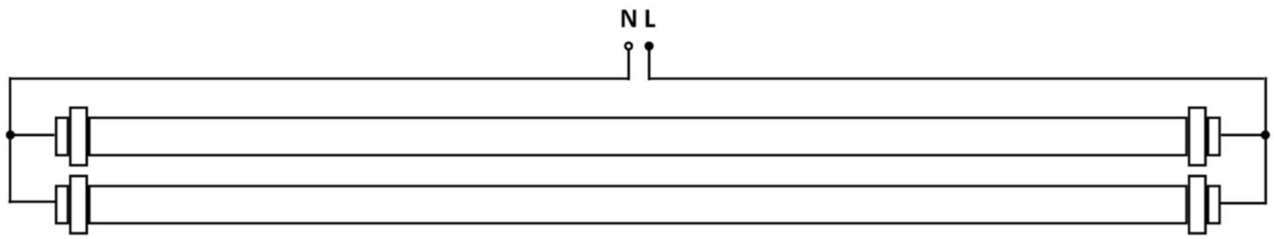
1. Operated on a Philip Advance IOPA2P32N ballast (0.87 ballast factor). Two lamps were connected at the time of measurement, but one lamp was shielded.
2. Operated on an ANSI reference ballast in accordance with IES LM-9-09.

Appendix F: Wiring Diagrams

A. Integral driver, single-ended wiring (unshunted sockets)



B. Integral driver, double-ended wiring (shunted sockets)



C. Integral driver, double-ended wiring with second pin connected (unshunted sockets)

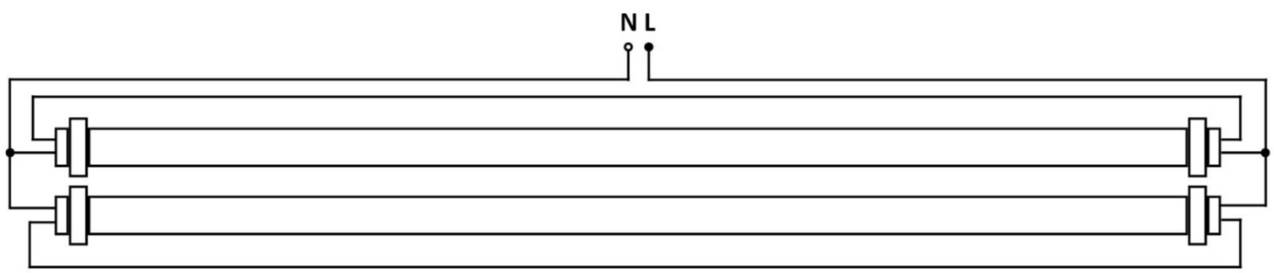
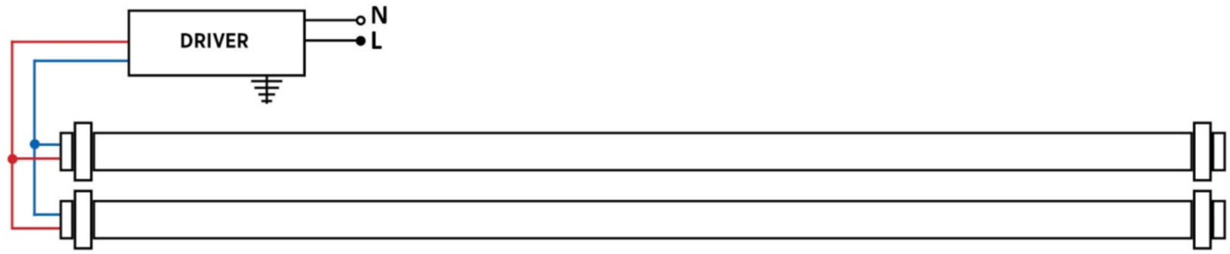
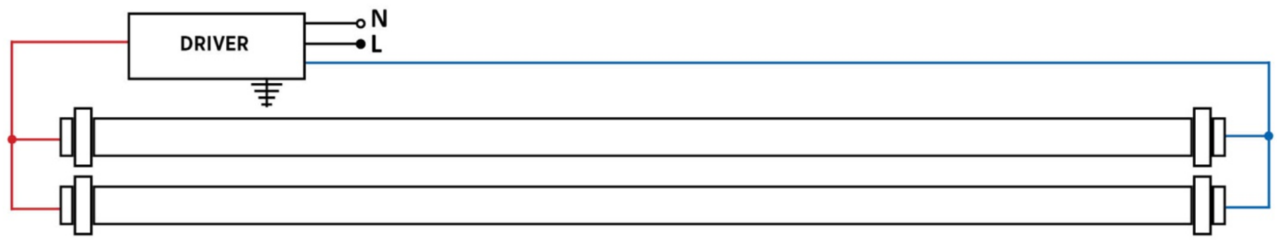


Figure F1. Typical wiring diagrams for LED T8s with an internal driver.

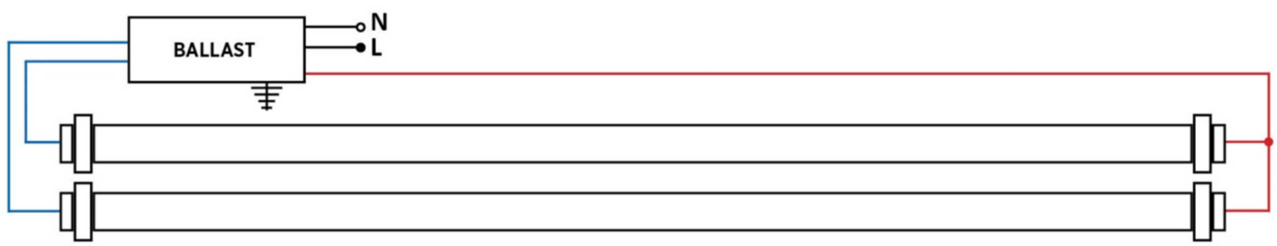
D. Remote driver, single-ended wiring (unshunted sockets)



E. Remote driver, double-ended wiring (shunted sockets)



F. Existing Instant-Start electronic ballast (shunted sockets)



G. Remote driver, no sockets

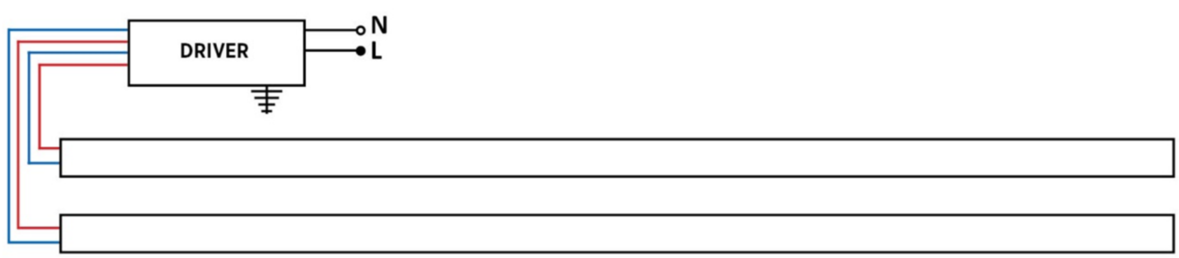


Figure F2. Typical wiring diagrams for LED T8 lamps with an external driver or ballast.

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