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CALiPER

Report 23:

Photometric Testing of White-Tunable LED Luminaires

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1 Preface

The U.S. Department of Energy (DOE) CALiPER program has been purchasing and testing general illumination solid-state lighting (SSL) products since 2006. CALiPER typically 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; investigations using these procedures 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 website at the time of purchase.

CALiPER normally purchases products through standard distribution channels, acting in a manner similar to that of a typical specifier. CALiPER cannot control for the age of products in the distribution system, nor account for any differences in products that carry the same model number.

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

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

[3] CALiPER summary reports are available at http://energy.gov/eere/ssl/caliper-application-reports. Detailed test reports for individual products can be obtained from http://www1.eere.energy.gov/buildings/ssl/caliper/default.aspx.

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

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

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

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

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

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

2 Report Summary

This report documents an initial investigation of photometric testing procedures for white-tunable LED luminaires and summarizes the key features of those products, in the hope that this nascent product category can mature quickly. Continued investigations will explore other aspects of performance and product use.

The leading goal of this study was to understand the amount of testing required to characterize a white-tunable product. In this case, determining a sufficient protocol required more extensive testing than would be feasible for widespread use. Eight white-tunable luminaires were tested at dozens of points covering the range of color tuning (correlated color temperature) and dimming (luminous intensity). This report focuses on the full-intensity measurements, which were typically at 11 color set points covering a range of correlated color temperatures (CCTs), and reveals substantial variation in input power, lumen output, efficacy, and D_{uv} over the color-tuning range for many of the products, which would not be captured with only a few test points. The results show that future test procedures will likely require at least five to seven measurement points to provide a reasonable characterization. The increase in testing burden could potentially be mitigated by specifying a relatively brief measurement stabilization process between readings at different settings, rather than requiring a lengthy warmup period between readings.

The secondary goal was to investigate and document the performance of available color-tunable luminaires that are intended for architectural lighting rather than entertainment lighting—specifically, troffers and downlights. The data demonstrate a variety of approaches used to achieve variable CCTs. A key distinction is linear (produced by two color channels) versus nonlinear (produced by three or more color channels) white tuning. Linear tuning products cannot track the blackbody locus (i.e., they cannot maintain a constant D_{uv} as CCT is adjusted), whereas the nonlinear tuning products were effective at following the blackbody locus. The importance of this distinction with regard to subjective impression requires further investigation. A second key distinction is how each luminaire manufacturer chose to treat lumen output, power draw, and efficacy over the dimming range. In some cases, one of the parameters was held constant while others varied considerably. In other cases, all three parameters were reasonably consistent. The balance of the products exhibited substantial variation across all three parameters. The different approaches are important to consider because they affect subjective impressions, as well as for practical reasons during specification or energy-efficiency program qualification.

In most cases, color-tunable LED luminaires are currently not competitive with fixed-color products (of the same type) if efficacy is the prime criterion. However, color-tunable products may offer non-energy benefits, such as the ability to shift spectrum to support human circadian cycles, affect mood and alertness, or provide a visually dynamic environment. For the downlight products, the efficacy was substantially below the ENERGY STAR qualification threshold, but in appropriate applications where aesthetics, wellness, or occupant satisfaction is very important, color-tunable luminaires are capable replacements offering features not practically available with any other lighting technology.

3 Background

The advent of SSL technology has already brought substantial change to the lighting industry, and the evolution of products is ongoing. One recent intriguing development is color-tunable luminaires. Although versions of this product type have been around for years, LEDs make color-tunable luminaires much more practical, even though they remain a niche market segment. With potential benefits including improved health and wellbeing, increased productivity, enhanced mood or alertness, and higher occupant satisfaction, there is reason to believe that color-tunable luminaires will gain market share. At this point, however, it is important to understand the tradeoffs, limitations, and issues, so that the industry can work together to maximize the rate of product maturation.

One important area of change brought on by SSL technology is photometric testing procedures. New product capabilities and performance variables have required new test methods to be developed, which is important for the industry because accurate, repeatable, and standardized test methods enable products to be appropriately compared and specified. A new challenge is measuring and reporting performance of lamps and luminaires that can change their spectral power distribution (SPD), more generically referred to as the color of the light. With a variable SPD, color metrics and other performance attributes such as lumen output, power draw, and efficacy extend across a range for any given luminaire; thus, reporting metric values is more complicated than reporting the single values that characterize other products. A single photometric test following IES LM-79-08 procedures is no longer sufficient for characterizing a color-tunable product, and in some cases, the range of possibilities is nearly limitless, complicating the development of new test procedures that do not unreasonably increase the test burden on manufacturers. To date, no standardized procedure for testing color-tunable products has been developed or proposed, but there are many ideas to consider. It is not unlike the situation that existed in 2006, prior to the adoption of IES LM-79-08, which standardized photometry of SSL products.

The number of luminaires discussed in the report (eight) is limited but is sufficient to cover important variations in product performance, such as different ways to combine two or more controllable colored LEDs, which are referred to as *LED primaries* in this report.[7] The report focuses on the differences in performance and the pros and cons of various implementations of color tunability, especially in relation to designing and implementing a photometric testing procedure for color-tunable LED products. Other issues, such as acceptability or user interfaces, are important topics that are discussed in other CALiPER documents. More information on color-tunable products is available at http://energy.gov/eere/ssl/led-color-tunable-products.

Types of LED Luminaires with Variable Color Output

Before an effective discussion of color-tunable product performance is possible, it is important to consider the types of color-tunable products that are available, and how they might be classified. The following is a brief description of three distinguishable product classes, with additional detail on what is and is not covered in this report:

- **Dim-to-warm** products automatically reduce CCT as they are dimmed. This requires at least two different LED primaries, but only one control signal (also called a channel) that adjusts both color and intensity. Dim-to-warm products were excluded from consideration for this investigation, because they present the least challenge for developing a photometric test procedure.

[7] LED primaries are sometimes called *channels*, but to avoid confusion between color channels and control channels, this report uses the term *LED primaries*—which may be either phosphor-based (i.e., polychromatic) or a dedicated color (i.e., narrowband).

- **White-tunable** products can be adjusted over a range of CCTs and can, at least theoretically, be dimmed at a constant CCT. In general, these products are not used to produce specific saturated colors of light (e.g., red or blue). Some products in this category can also be set to act as dim-to-warm products. White-tunable products require at least two LED primaries but oftentimes have more, to allow for more-precise color control. White-tunable products are the focus of this report.
- **Full-color-tunable** products can be adjusted to create white or colored light. For white light, these products are capable of performing as either dim-to-warm or white-tunable products if given appropriate control algorithms. They require at least three LED primaries (e.g., red, green, and blue), which can be mixed to create any color within their gamut. If more LED primaries are used, algorithms must be generated so that each chromaticity has a unique solution.[8] Control of full-color-tunable products is typically much more complex than for white-tunable or dim-to-warm products, requiring some type of digital interface if it is to be user-controlled and not preprogrammed. CALiPER has also tested some of these products, but they are not discussed in this report.

One point of confusion is that the term *color-tunable* is sometimes used to refer to any of the three categories described above. This report focuses on white-tunable products. However, with appropriate programming, there is a hierarchical relationship between the three categories, so that the distinction is often blurred. That is, a full-color-tunable product can typically operate as—or cover the full range of—a white-tunable or dim-to-warm product. Likewise, many white-tunable products have the potential to provide dim-to-warm functionality, and some even offer a simple way to switch between white-tuning and dim-to-warm operation. Some of the products discussed in this report had additional functionality, but were always measured when operating in white-tuning mode.

A distinguishing feature between the three categories is the number of independent control channels. This is not to be confused with the number of LED primaries available to be controlled. A dim-to-warm product requires only one control signal (e.g., a wall dimmer) that varies both color and intensity, whereas a dimmable white-tuning product requires at least two control signals: one for color and one for intensity. Full-color-tunable products usually rely on pairing each LED primary with its own control signal (e.g., one for red, one for blue, and one for green), or else employ a more complex graphical user interface combined with built-in intelligence. For this reason, full-color-tunable products typically rely on digital controls such as DMX or DALI, and are often programmed via a computer.

White-tunable products require a minimum of two independent LED primaries, with the most basic configuration being a mix of warm-white and cool-white phosphor-coated (PC) LEDs. The ratio of the two can be adjusted to mix the light to CCTs anywhere in between the minimum and maximum CCT. Mixing only two LED primaries results in a linear range of chromaticity; therefore the nomenclature *linear white tuning* is used in this report. However, the blackbody locus, which serves as a reference for CCT calculations, is not linear in a chromaticity diagram. Accordingly, two-primary white-tunable products will not follow the blackbody locus (i.e., will not have the same D_{uv}) throughout their color range; instead, they may take on a purple/pink tint in the middle of the available range (Figure 1). This deviation from the blackbody becomes larger with a wider range of possible CCTs, although it may or may not be noticeable or objectionable.

Other types of white-tunable luminaires combine more LED primaries, which allows more flexibility for changing color. All of the products tested for this investigation with more than two primaries attempted to follow the

[8] Chromaticity, the numerical representation of color, is calculated using three color matching functions. Thus, only with three (or fewer) channels is there a single solution for mixing the channels to a specified chromaticity.

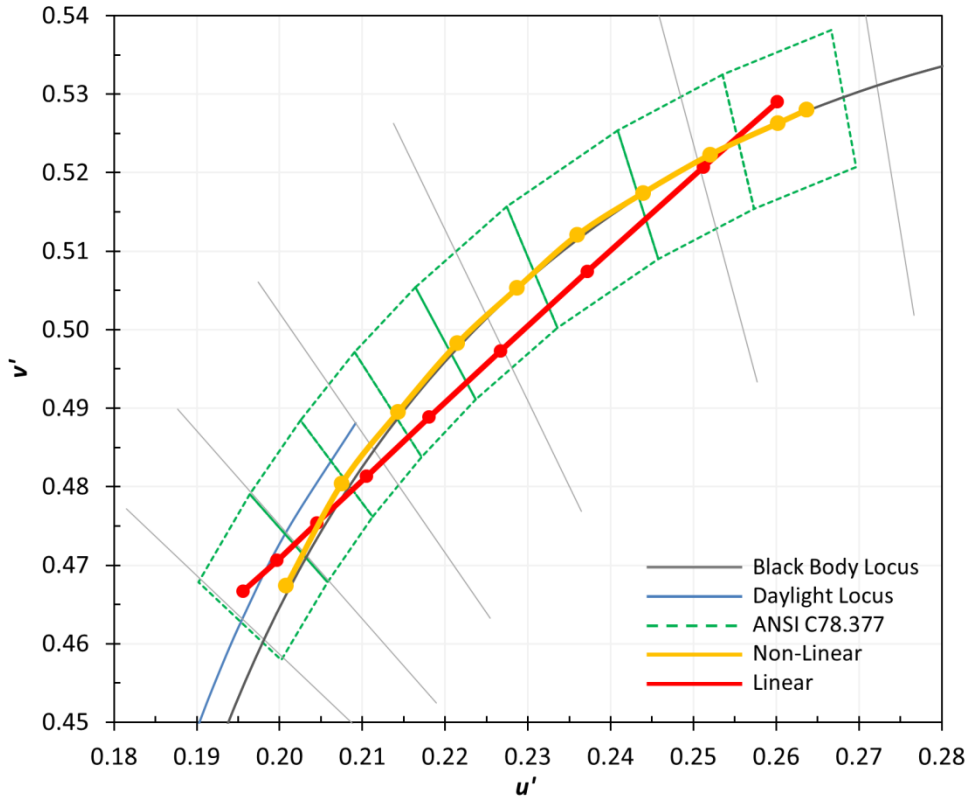


Figure 1. Examples of linear and nonlinear (blackbody) white tuning. The exact curves will vary from product to product, but the key difference is that linear (two-primary) systems can only mix to chromaticities that are directly between the two primaries, whereas products with more than two primaries can be used to create mixes that approximately follow the blackbody locus.

blackbody locus, giving rise to the classification *nonlinear white tuning* or *blackbody white tuning* (also shown in Figure 1). One approach seen in this round of testing was the combination of two white LEDs (warm-white and cool-white) with a red LED. Other products used three, four, or five independent LED primaries and preprogrammed calibrations/control-response algorithms.

Types of Controls for Color-Tunable Products

White-tunable and full-color-tunable products vary in their type of control, generally using 0–10 V, DMX, or DALI protocols. While each method allows the user to adjust the color and/or output of the product, they can be implemented in a number of ways. Some manufacturers provide proprietary control devices, which often rely on an existing protocol but provide a customized user interface/hardware. Other color-tunable lamps and luminaires rely on controls from third-party manufacturers, which provide a greater range of options but may also lead to compatibility issues.

The products tested for this investigation were controlled using DMX software, 0-10 V “dimmers,” or a proprietary control device. This provided variety, but the exact type of control system was not a focus, as long as the applicable range of output could be achieved. Nonetheless, the control interface is an important aspect of implementation for color-tunable lighting systems, and may ultimately play a large role in their acceptance by end users. Control interfaces for color-tunable luminaires will be examined in a future CALiPER report.

Beyond the user experience, the control system used may have some effect on the performance of the luminaire. For example, some LED drivers expect either a linear or a logarithmic signal over the dimming range, and performance can vary if the appropriate signal is not provided. For this report, all products were tested on an appropriate control, but the investigation did not test a given luminaire with multiple controls.

Summary of Products Tested

Table 1 provides an overview of each product type. Given the differences in form factor and tuning capability, this table is an important reference when considering subsequent performance results.

Table 1. Descriptive characteristics of the eight white-tuning products included in this report.

Product ID[1]	Luminaire Type	Control System	No. of LED Primaries	White-Tuning Type
15-01-T	Troffer (2×2)	Proprietary (DMX Based)	2	Linear
15-07-D	Downlight	(2) 0-10 V	2	Linear
15-10-S	Surface-Mounted	Proprietary (DMX Based)	2	Linear
15-12-T	Troffer (2×2)	Proprietary (DMX Based)	2	Linear
15-02-D	Downlight	(2) 0-10 V	4	Nonlinear (Blackbody)
15-05-D	Downlight	(2) 0-10 V	5	Nonlinear (Blackbody)
15-08-D	Downlight	DMX	4	Nonlinear (Blackbody)
15-09-D	Downlight	(2) 0-10 V	3	Nonlinear (Blackbody)

1. The suffix code was added for this report to distinguish between the luminaire types (D for Downlight, S for Surface, and T for Troffer).

4 Test Methods

The range of possible output for color-tunable products presents a substantial challenge for measuring and communicating performance. The advent of LED technology has already increased required testing, and the time and costs for this increased testing has become burdensome for product manufacturers, especially for smaller companies. While completing a full IES LM-79-08 test at numerous color settings would provide a very accurate characterization of performance, such an approach is impractical and excessively arduous.

A guiding principle for this initial study was to test more rigorously than was hypothesized to be ultimately necessary, at least in terms of the number of measurements made. Most products were tested at 55 points, including at least 5 intensity levels for each of the 11 separate color-control set points. Notably, the testing protocol used for this investigation covers both full-output performance and dimmed performance—something that requires more than one LM-79-08 test. Considering only full-output performance, there would be 11 tests for each product, compared to one for a standard product. Ultimately, the goal was to better understand the tradeoff between test burden and accuracy by examining if the results from fewer test points could represent the wider range of measurements that were made.

The basic procedure for each measurement point was modelled after IES LM-79-08. The key difference was in the warmup and stabilization. Given the large quantity of points, a minimum stabilization time of 30 minutes at each test point was not feasible. Instead, the output at each setting was monitored to determine mathematically when the change in predicted light output (based on a trend line) would be within 0.5% over 30 minutes. Oftentimes, the initial stabilization for a product took more than 30 minutes, whereas subsequent measurements required shorter intervals—as little as a few minutes—presumably because the luminaire had already reached thermal equilibrium. This is one potential burden-reducing method that could be considered for a formally standardized procedure. It may marginally reduce accuracy, but it reduces the time required for testing by hours, compared to using the minimum 30-minute warmup period prescribed by IES LM-79-08 for each subsequent measurement.

For this preliminary study, only one sample of each luminaire model was tested. Unlike in past CALiPER work, performance relative to manufacturer claims was not a focus of this investigation, so ensuring representative measurements with multiple samples was not deemed critical. In fact, comparisons of test and manufacturer data would have been difficult, because many of the manufacturers reported insufficient information in specification sheets. Lack of any standardized testing methods or recommended best practices on reporting performance for color-tunable products likely contributed to this shortfall, which is also troubling for specifiers.

Because of the unique nature of the required measurements, all of the photometric testing was performed at Pacific Northwest National Laboratory (PNNL) in Richland, WA, which is accredited by the National Voluntary Laboratory Accreditation Program (NVLAP). All photometric measurements were taken in an integrating sphere.

Testing Protocol

Using an appropriate control(s), the white-tuning products were operated throughout the full range of possible output (color and intensity) during testing. The more important question remains exactly how many points across the range of color options can sufficiently capture photometric performance, including luminous flux, color quality, power draw, and power quality.

Four of the white-tuning products utilized a 0–10 V control protocol. These products were controlled with a Leviton D4104 standalone multi-zone lighting control system, which provided independent control of the color

and intensity channels using push buttons. A numerical display indicated the percent of maximum control signal being delivered, which allowed for precisely achieving 11 desired set points for color (100%, 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, 10%, 0%) and up to five set points for intensity (100%, 75%, 50%, 25%, and/or minimum[9]). This resulted in 55 total tests, one for each combination of color and intensity, as shown in Table 2. Some products could not operate steadily below the 25% intensity control signal, or did not provide sufficient illumination (at least 50 lm) at lower settings to allow accurate measurement based on the available equipment. In these cases, there were only 44 total tests.

One of the eight products (15-08-D) required a third-party DMX-based controller. For this report, the product was controlled using Nicolaudie ESA2 software accompanied by a SLESA-UE7 USB-to-DMX hardware signal converter. As with the 0–10 V control, this setup was used to provide 11 set points for color (255, 230, 215, 180, 155, 130, 105, 80, 55, 30, 0) and four set points for intensity (255, 192, 130, 80). Lower set points for intensity did not provide sufficient illumination for the photometric testing.

The remaining three white-tuning products provided proprietary control hardware that utilized the DMX protocol, each with a customized user interface. Product 15-10-S provided separate control of CCT and intensity; CCT was set at 6500 K, 6000 K, 5500 K, 5000 K, 4500 K, 4000 K, 3500 K, 3000 K, and 2700 K; whereas

Table 2. Testing set points for each product. The exact number of measurements varied based on the type of control and the minimum output required by the spectroradiometer.

	Color Set Points										
15-07-D[1]	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%	0%
15-02-D[1]	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%	0%
15-05-D[1]	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%	0%
15-09-D[1]	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%	0%
15-08-D[2]	255	230	215	180	155	130	105	80	55	30	0
15-01-T[3]	7/0	7/1	6/2	5/3	4/4	3/5	2/6	1/7	0/7		
15-10-S[3]	6500K	6000 K	5500 K	5000 K	4500 K	4000 K	3500 K	3000 K	2700 K		
15-12-T[3]	6500K	5000 K	4000 K	3500 K	3000 K	2700 K					

	Intensity Set Points								Total Points
15-07-D[1]	100%	75%	50%	25%				**15-07-D[1]**	55
15-02-D[1]	100%	75%	50%	25%	15%			**15-02-D[1]**	55
15-05-D[1]	100%	75%	50%	25%	15%			**15-05-D[1]**	55
15-09-D[1]	100%	75%	50%	35%				**15-09-D[1]**	44
15-08-D[2]	255	192	130	80				**15-08-D[2]**	44
15-01-T[3]	7/7	6/6	5/5	4/4	3/3	2/2	1/1	**15-01-T[3]**	63
15-10-S[3]	100%	75%	50%	25%	3%			**15-10-S[3]**	45
15-12-T[3]	Max	75%	50%	25%	Min			**15-12-T[3]**	30

1. Controlled by Leviton D4104
2. Controlled by Nicolaudie ESA2
3. Proprietary Control

- -

intensity was set at 100%, 75%, 50%, 25%, and 3%. Product 15-12-T had similar control functionality and was tested at preset CCTs of 6500 K, 5000 K, 4000 K, 3500 K, 3000 K, and 2700 K. The intensity at each color setting was set to maximum, 75%, 50%, 25%, and minimum. Finally, product 15-01-T provided a control that allowed for separate manipulation of the warm and cool LED primary, each at eight different levels (presets of 0 through 7). This allowed for 64 different combinations of color and intensity, but it was not possible to systematically vary color or intensity while holding the other at a perfectly constant setting. The control channels were mostly independent, but the configuration did not allow the typical protocol used for the other products to be followed. As a result, two sequences were completed: nine settings for color variation (7/0, 7/1, 6/2, 5/3, 4/4, 3/5, 2/6, 1/7, 0/7)[10] and seven settings for intensity variation (7/7, 6/6, 5/5, 4/4, 3/3, 2/2, 1/1). Notably, this product's control protocol does not allow for evaluation of color stability over dimming.

The analysis focuses on the performance at maximum intensity (full output) as the color varied. This is analogous to how standard products are rated, which typically does not include any testing at dimmed levels. The dimmed performance is considered only in the context of color stability over dimming, which is an especially relevant concern for dimmable, white-tunable products. Other features, such as minimum dimmed level and dimming curve, are not discussed.

[10] The sequence is not perfectly symmetrical, as it was partially based on a manufacturer-provided matrix that listed approximately equal intensity settings across the color range. The matrix did not include the zero setting for either LED primary.

5 Product Performance

Tables 3 and 4 provide colorimetric, photometric, and electrical measurements for the eight products discussed in this report. The ranges listed all correspond to full output, spanning the color-tuning range of the product. They list the minimum and maximum points for each metric, which often do not correspond to the endpoints of the color-tuning range. This important distinction means that the values listed also do not always correspond to a single measurement point; that is, the lowest efficacy may not have occurred at the same point as the lowest input power, for example.

The tables, and several subsequent charts, are divided into two groups, based on the type of color change: linear and nonlinear. Notably, all of the nonlinear white-tuning products were downlights with apertures of 6" diameter or smaller, whereas two of the four linear white-tuning products were 2'×2' troffers, and one was a surface-mounted luminaire with 24" diameter white diffuser. The inherent differences of these product types contribute to some of the differences in the performance, such as the wide variation in efficacy. Smaller apertures generally result in lower efficacy, although the type of white tuning could also be a contributing factor.

Table 3. **Color characteristics over the tuning range.** All values except Δu'v' refer to the range as color was changed while intensity was at its maximum; the Δu'v' values describe the variability in chromaticity as intensity was changed at a constant color setting. The metrics are defined in Appendix A.

Product ID	CCT (K)	D_{uv}	R_f	R_g	CRI R_a	Δu'v'
15-01-T	3094 – 6696	-0.0028 – 0.0044	83 – 85	96 – 98	84 – 87	-[1]
15-07-D	2188 – 5691	-0.0061 – 0.0045	80 – 84	93 – 100	79 – 86	0.0002 – 0.0187
15-10-S	2742 – 6749	-0.0033 – 0.0044	82 – 84	94 – 99	81 – 86	0.0001 – 0.0030
15-12-T	2722 – 6188	-0.0030 – 0.0048	81 – 84	97 – 100	82 – 86	0.0002 – 0.0057
15-02-D	2590 – 5576	-0.0003 – 0.0022	86 – 92	102 – 104	89 – 96	0.0017 – 0.0102
15-05-D	1628 – 3833	0.0004 – 0.0013	86 – 94	96 – 102	92 – 98	0.0003 – 0.0058
15-08-D	2671 – 6359	0.0000 – 0.0009	83 – 90	101 – 106	82 – 92	0.0001 – 0.0016
15-09-D	2017 – 4437	-0.0008 – 0.0016	81 – 88	99 – 111	83 – 91	0.0001 – 0.0082

1. The proprietary control provided for product 15-01-T did not allow dimming at a constant color setting.

Table 4. **Photometric and electrical characteristics over the color-tuning range at full output.** All of the reported values are the minimum and maximum of the particular characteristic, regardless of the setting. The metrics are defined in Appendix A.

Product ID	Input Power (W)	Light Output (lm)	Efficacy (lm/W)	LER (lm/W_{rad})	Power Factor	THD-I (%)
15-01-T	18.1 – 23.5	2,153 – 2,832	110 – 122	304 – 323	0.98 – 0.99	9.7 – 12.1
15-07-D	15.2 – 15.3	735 – 891	48 – 59	311 – 316	0.99 – 0.99	5.1 – 5.3
15-10-S	47.9 – 51.8	5,457 – 5,931	108 – 124	303 – 330	0.98 – 0.98	12.8 – 24.1
15-12-T	39.2 – 41.6	4,028 – 4,588	100 – 114	310 – 320	0.99 – 0.99	11.4 – 11.7
15-02-D	16.8 – 26.1	476 – 843	28 – 32	312 – 325	0.99 – 1.00	1.8 – 2.9
15-05-D	12.2 – 28.1	263 – 905	22 – 32	285 – 301	0.96 – 0.99	10.0 – 14.0
15-08-D	21.3 – 24.2	687 – 692	28 – 32	280 – 322	0.99 – 0.99	5.9 – 7.2
15-09-D	16.6 – 19.0	703 – 868	38 – 47	306 – 331	0.98 – 0.98	9.2 – 10.0

The only reported values not corresponding to full output measurements are the ranges for Δu'v'. These values characterize the change in chromaticity as each product was dimmed at a constant color-control setting. The reference for all computed Δu'v' values is the full-intensity setting; the maximum of the Δu'v' describes the point over the dimming range where the color differed the most, compared to full-intensity operation at the same color setting, whereas the minimum Δu'v' indicates the smallest deviation from the full-intensity setting. Note that all of the products were set to the appropriate operating mode so that these two parameters were nominally independent, even though some of them could be set to other modes, such as dim-to-warm.

Efficacy, Lumen Output, and Power Draw

In contrast with previous CALiPER reports, three form factors were included in this series of testing, and as expected, their efficacies, lumen outputs, and power draws were substantially different. This included a downlight delivering as few as 22 lm/W, and a surface-mounted luminaire measured as high as 124 lm/W. It also included a downlight emitting as few as 263 lm, and a surface-mounted luminaire emitting as many as 5,931 lm. For reference, some key performance thresholds from ENERGY STAR (Luminaire Specification v2.0) and the DesignLights Consortium (DLC) Qualified Products List (QPL) are shown in Table 5, categorized based on product type. Many of the products tested failed to meet the thresholds over at least some of the tuning range—even when only considering operation at full output. This was especially true for the efficacy of the downlight products, only one of which was above the ENERGY STAR threshold of 55 lm/W for *any* part of the color-tuning range.

Note that ENERGY STAR currently has a provision for accepting color-tunable products, but DLC does not. ENERGY STAR requires testing at the least-efficient setting, the default setting, and the most-consumptive setting, as determined by the manufacturer. The product must be capable of producing at least one of the nominal CCTs specified, but color-tunable luminaires do not always have to stay within the range.

Changes over Color Range

The more unique story regarding photometric parameters that relates specifically to color-tunable products is the variation over the color-tuning range. It is practically unavoidable that the products will vary in their power draw or output over the color-tuning range, although it is possible to keep one or the other constant. Efficacy is likely to vary, and since this cannot be observed by users, it may be acceptable as long as it does not appreciably affect energy use. The products' manufacturers theoretically had the option to maintain either lumen output or power draw over the color-tuning range. These two scenarios are illustrated by products 15-08-D and 15-07-D, respectively, which varied by less than 1% over the color-tuning range in lumen output or power draw. One other product (15-10-S) exhibited near-constant power draw (8% variation[11]) and lumen output (9% variation). Product 15-12-T also performed well in terms of constant power draw (6% variation), and exhibited a 14% variation in lumen output. The remainder of the white-tuning products all exhibited substantial variation in

Table 5. Relevant performance thresholds for downlights and troffers from energy-efficiency programs. The product classification for the surface-mounted fixture, 15-10-S, is unclear based on the categories listed by DLC.

Program	Product Type	Efficacy (lm/W)	Min Output (lm)	CCT Range (K)	CRI R_a
ENERGY STAR	Downlights	≥ 55	≥ 375 (≤ 4.5" aperture) ≥ 575 (> 4.5" aperture)	2700–5000	≥ 80
DLC QPL	Troffers	≥ 85	≥1500	≤ 5000	≥ 80

[11] All variation percentages calculated as the range in performance divided by the minimum value.

lumen output, power draw, and/or luminous efficacy over the dimming range. One product, 15-05-D, varied from 12.2 to 28.1 W (131% variation), and from 263 to 905 lm (244% variation).

Figure 2 shows the input power, lumen output, and efficacy for four example products (15-07-D, 15-08-D, 15-09-D, 15-05-D) over the color-tuning range. These products illustrate the variety of approaches taken by manufacturers when trying to balance performance over the color range. Importantly, they also illustrate difficulty in fully documenting performance with only a few measurement points.

- Product 15-07-D drew constant power over the entire range. Due to the well-documented efficiency losses at lower CCTs, this resulted in reduced lumen output as the CCT was lowered, with lumen output and efficacy tracking together. The difference in efficiency was enough that output and efficacy dropped to 83% of the maximum. This may or may not be visibly noticeable or important for the application, especially given the change in color. Also important to note is that the change in performance for this

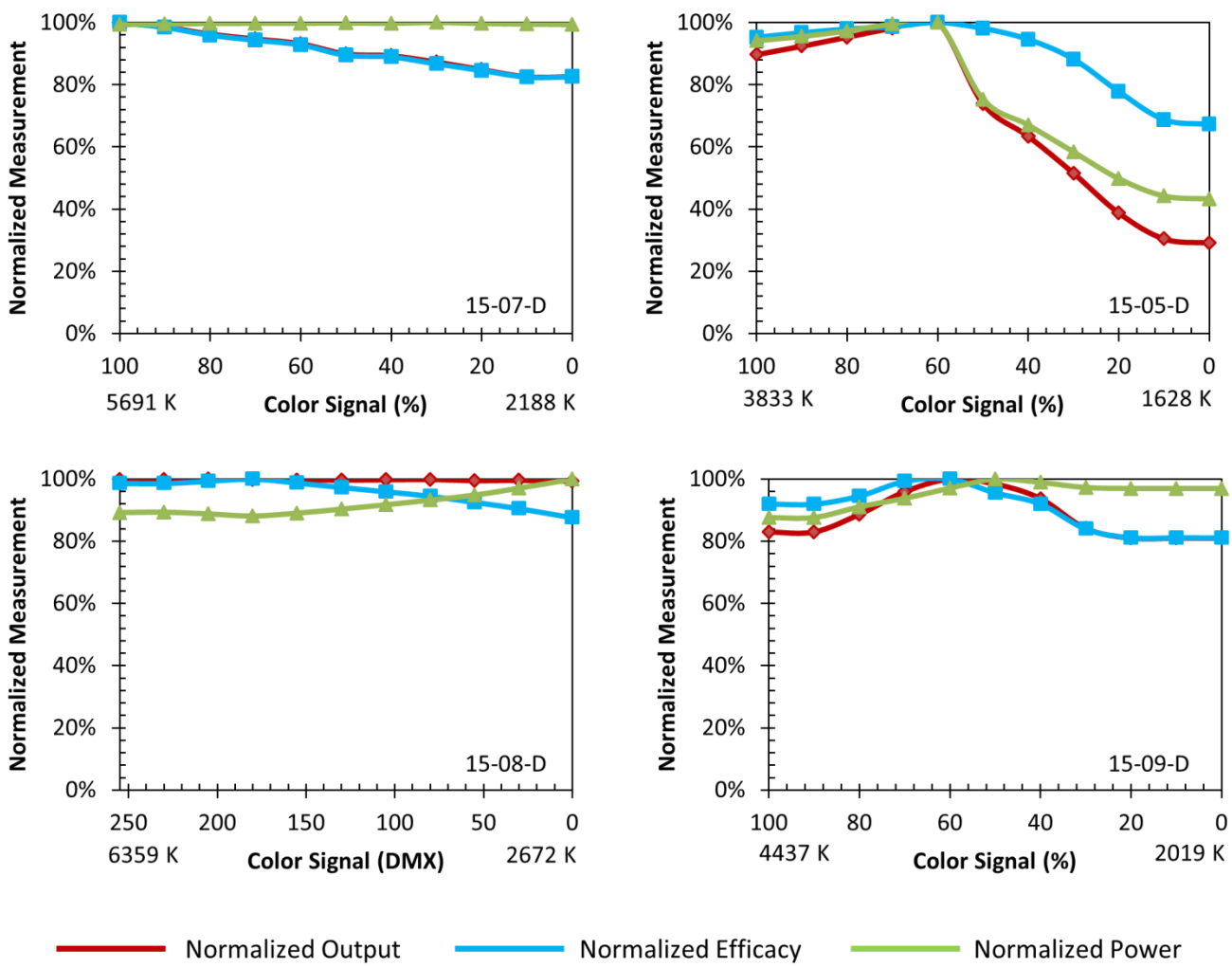


Figure 2. Output, efficacy, and power over the color-tuning range for four example products. Product 15-07-D held power constant, whereas product 15-08-D held output constant, illustrating contrasting choices made by the manufacturers. The remaining two products had somewhat unpredictable relationships between the three characteristics, which may be an issue when trying to reduce testing burden.

product was predictable and could be modelled, which would allow for testing with fewer points.

- In contrast, product 15-08-D offered constant output. As its color changed, however, the power draw ranged from about 88% to 100%. Notably, the minimum is not at one of the endpoints, which could make accurately characterizing the full range using only a few points more difficult. The relatively small range in performance means errors would be relatively small, however.

- Product 15-09-D held no parameter constant, with input power, efficacy, and lumen output all peaking somewhere in the middle of the color-tuning range, but all also having slightly different behaviors. This type of performance would be difficult to model with fewer measurement points.

- Perhaps the most striking performance variation over the color-tuning range was with product 15-05-D, for which input power and lumen output dropped precipitously when the color signal was below 60% of the maximum. (The input power, lumen output, and efficacy were at their maximum when the color signal was at 60%.) This behavior would be difficult to capture with only a few test points, and would clearly be visible to an occupant. In fact, this product essentially operates as a combination of a white-tuning product above 2700 K (i.e., output remained relatively constant) and a dim-to-warm product below 2700 K (i.e., output decreased with decreasing CCT)—perhaps intentionally. However, this product relied on two 0–10 V controls: one for color and another for intensity, similar to several other products. The data ranges shown in Table 3 resulted only from changes to the color-control signal, with intensity held at the maximum.

Even moderate unintended variation in photometric performance can be problematic. Variation in lumen output over the color range means that a user cannot maintain light output as the color changes, which may be distracting and undesirable. On the other hand, it is important that power draw never exceed the maximum listed on the product specification sheet, because that value is used for load calculations on electrical circuits and also to show compliance with building-code power-density requirements. Finally, variable efficacy could be a potential sticking point if energy-efficiency program (e.g., ENERGY STAR, DLC QPL) qualification is an issue.

Efficacy and Luminous Efficacy of Radiation (LER)

One of the key takeaways from the performance data is the low efficacy of the downlight luminaires, none of which met the ENERGY STAR minimum threshold of 55 lm/W throughout the color range, and most of which did not meet the minimum at any color setting. Four of those five products featured nonlinear white tuning. Three of those four products were measured to have efficacies in the 20 lm/w range at some point, harking back to the very earliest days of commercially available LED lamps and luminaires. In contrast, the troffer and ceiling-mounted products (all of which featured linear white tuning) tended to have much higher efficacies than the downlights. A large part of the discrepancy is due to the form factor, since downlights inherently have greater light losses and thus lower efficacies than troffers; but even considering only the five downlights, the nonlinear-tuning products all fared worse than the linear-tuning products.

Luminaire efficacy—or the lumen output of the luminaire per electrical watt input to the luminaire—does not provide the full story on efficiency of the LEDs. Luminaire efficacy is affected by the intrinsic efficiency of the LED in converting electrical energy to radiant energy, but also by thermal and optical effects of the luminaire. A different metric, the luminous efficacy of radiation (LER)—defined as the lumens produced by a certain SPD per watt of emitted radiant energy of the SPD—is a measure of the efficiency of the SPD at generating luminous flux. It can be thought of as the maximum potential efficacy of the source, if there were no optical losses or electrical inefficiencies. The LER metric shows that there was much less difference between the products than indicated

by the luminaire efficacy measurements (Figure 3). Critically, luminaire efficacy is dependent on the luminaire optical and thermal management characteristics, whereas LER is not. The differences in luminaire efficacy between the tested downlights and troffers/ceiling luminaires are typical of those luminaire types; the form factor and desired light distribution of downlights lead to inherent light losses from optical and thermal effects that result in lower luminaire efficacy compared to troffers, regardless of color tuning.

Another factor that likely contributes to the low luminaire efficacy of many of the nonlinear-tuning products is the so-called "green gap," which refers to the low efficiency of narrowband green LEDs in generating lumens from electrical power. The three products with the lowest luminaire efficacy all used a green LED emitter and, in some cases, an amber LED emitter too. While narrowband LEDs are useful for color tuning, particularly full-color-tuning, the green portion of the spectrum is highly weighted by the luminous efficiency function, meaning those sources will tend to have lower output and/or lower efficacy if a green LED is used to supply a large proportion of the lumens.

Additionally, the range in CCT for each product may also contribute to the trends seen for luminaire efficacy and LER. Some products ranged from 2700 K to 6500 K, whereas others went as low as 1600 K but only as high as 4000 K. These differences play a role in LER, as well as interacting with the efficiency of LEDs—which for PC-LEDS tends to be lower at lower CCTs, all other things equal, because more energy must be converted via phosphors. In the bigger picture, this effect may or may not be significant in relation to the other factors that contribute to differences in efficacy.

Finally, the amount of mixing required may contribute to the low efficacies of the nonlinear-tuning products comprised of multiple colored LEDs. They generate white light with good color consistency, but the light from

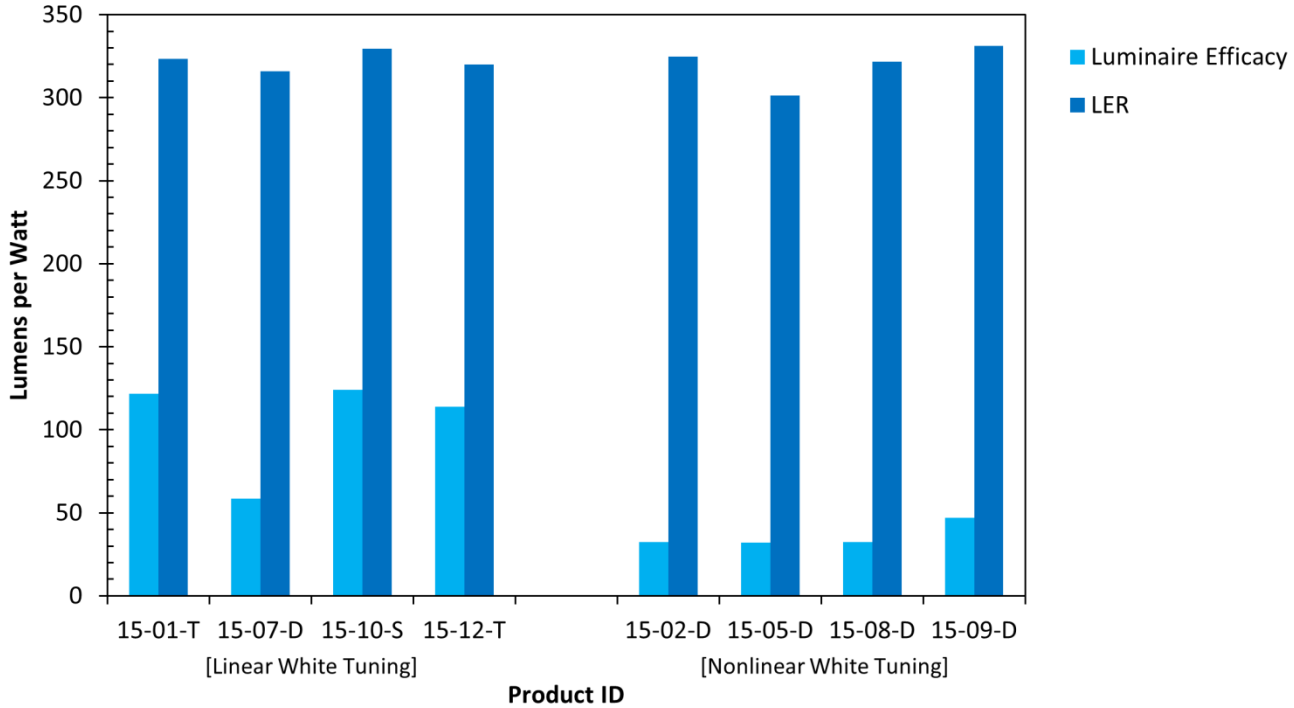


Figure 3. Luminaire efficacy and luminous efficacy of radiation (LER) for each product at full intensity. The LER for all products was relatively consistent, indicating that all of the mixes produced about the same amount of lumens per watt of emitted radiant energy. However, due primarily to form factor and secondarily to reliance on green emitters, the luminaire efficacy of the products varied substantially.

each LED must be mixed before the sum is emitted, to avoid visible color differences within the luminaire or emitted light. This mixing may be more important for nonlinear-tuning products, since they often use one or more narrowband (colored) LEDs, whereas linear tuning products mix different white LEDs with less noticeable color differences. This mixing often requires some form of secondary diffusion, which usually reduces the final efficacy. In the end, it is likely that there will always be some type of tradeoff in efficacy for the added benefit of color tunability, but as the technology advances, the differential is likely to be reduced.

Color Quality

All color metrics are calculated from the luminaire's SPD, which changes as the individual LED primaries are adjusted to provide more or less output. Appendix B provides SPDs for all color settings at full output, with one chart for each product. While color performance generally cannot be inferred just from examining an SPD, SPDs can be helpful for understanding the LED primaries that comprise each product, and how they are manipulated over the tuning range.

Chromaticity Change

Color quality is at the forefront for color-tunable luminaires. With lower efficacies than traditional LED products, the changeable color is the only distinct advantage of the products tested for this report. Notably, the two types of white-tuning products perform somewhat differently in terms of how the chromaticity changes. For the linear-tuning products, D_{uv} varies as the CCT changes, meaning that the light not only changes from warm to cool, but also becomes more green or pink at various points (Figure 4). Large values of D_{uv} may be undesirable,

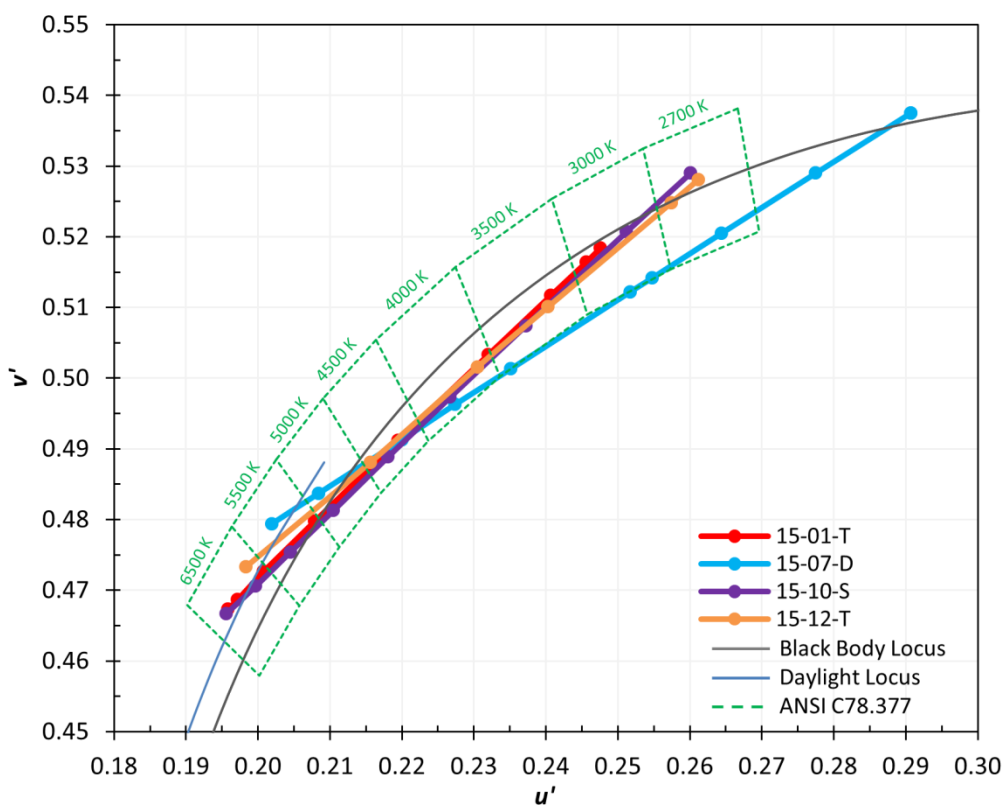


Figure 4. Change in chromaticity over the color-tuning range at full output for the linear-tuning products. The linear white-tuning products all (by definition) exhibit a range of D_{uv}s over the tuning range. The range is larger when the CCT range is increased, as with product 15-07, which actually just extends beyond the ANSI-defined nominal CCT bins.

especially if they are positive below a CCT of 4000 K, but the effect of changes in D_{uv} within a single product have not been studied, and it is unknown if they are acceptable to occupants.

All four nonlinear white-tuning products were relatively successful at following the blackbody locus, as shown in Figure 5, with small D_{uv} values across the entire range. More interesting is the fact that they employed different methods to do so. Based only on examination of the measured SPDs, it appears that three of the products used multiple narrowband LEDs—potentially combined with a white LED—whereas the fourth product used two white or near-white PC-LEDs along with a red LED. This latter product also had the highest efficacy of the nonlinear white-tuning products, potentially because it avoided using a green LED.

Color Consistency over Dimming

While dimmed performance was not the focus of this investigation, measurements were taken at multiple intensity levels for each of the color set points. The only consideration discussed in this report is the ability of each product to maintain the full-output chromaticity of a given color set point as intensity was reduced. As shown in Figure 6, a couple of the products (15-08-D, 15-10-S) performed extremely well in this area, but several others did not. Figure 6 shows two different calculated values: the maximum change in chromaticity versus full output at any given color set point as the luminaire was dimmed, as well as the average change in chromaticity versus full output for all color set points as the luminaire was dimmed. Both provide an indication of performance, and can be interpreted together to determine the significance of the inconsistency. Especially notable are the three products that exceeded a Δu'v' of 0.007 while they were dimmed at a single color set point. This is most likely noticeable.

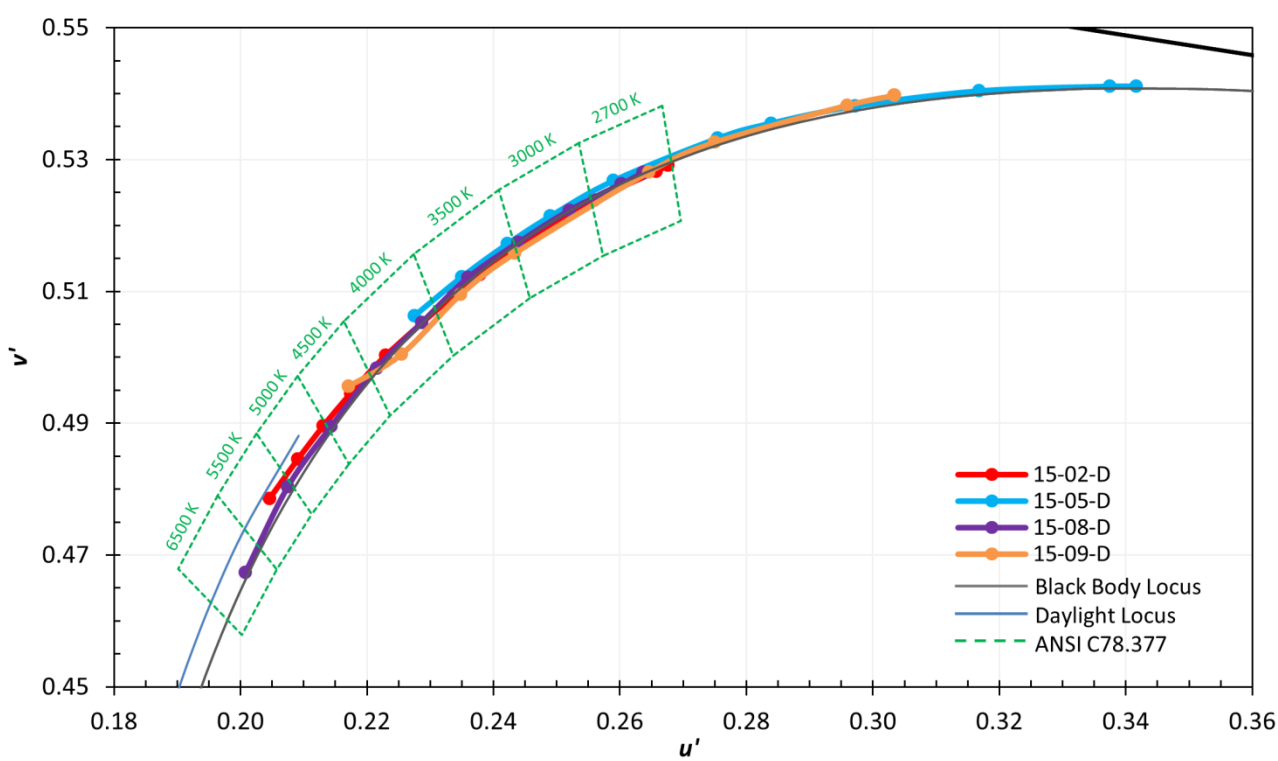


Figure 5. Change in chromaticity over the color-tuning range at full output for the nonlinear-tuning products. All four products were successful in tracking the blackbody locus. The minimum and maximum CCT of the products varied substantially.

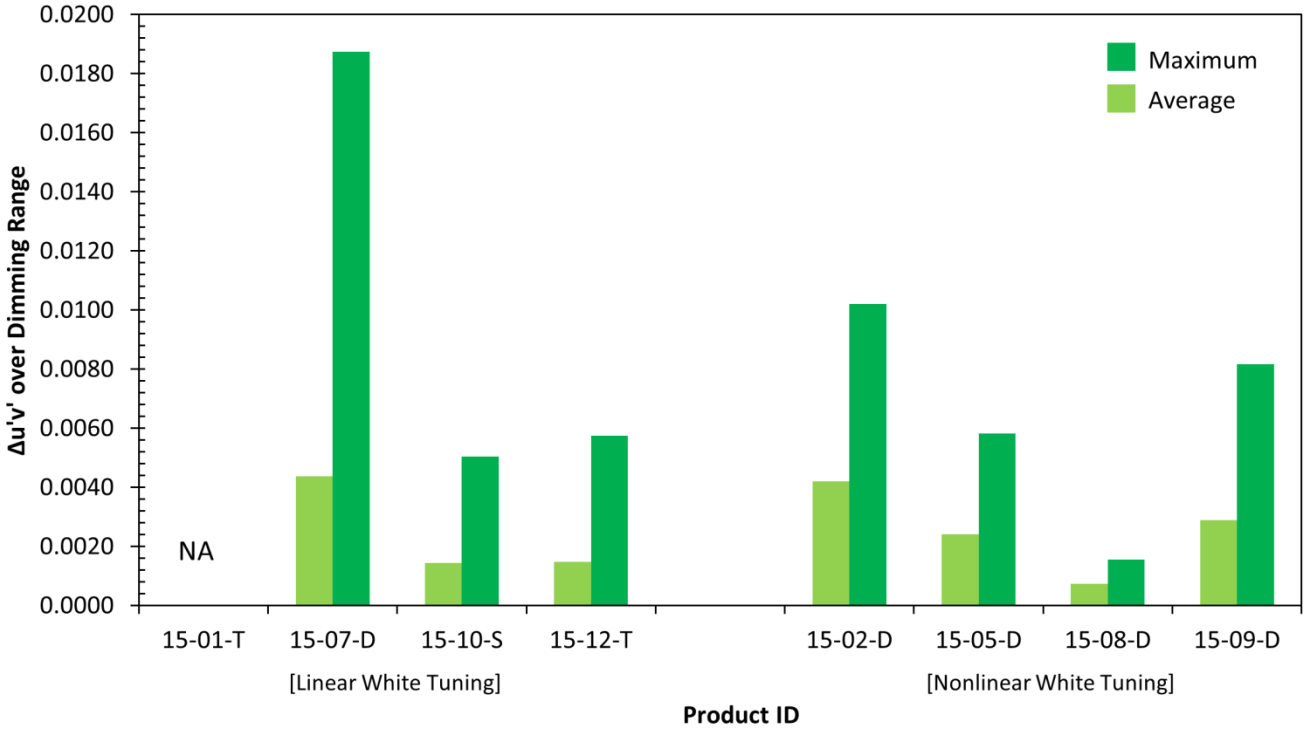


Figure 6. Maximum and average change in chromaticity at constant color setting when dimmed. There was substantial variation in the products' ability to maintain a constant color when dimmed, but it does not appear to be related to luminaire form factor or the type of white tuning.

Importantly, Δu'v' does not quantify the direction of the shift, which may have been along the path that the luminaire intended to follow, perpendicular to that path, or a combination of the two. Figure 7 shows the performance over the dimming range for four example products: 15-02-D, 15-07-D, 15-08-D, and 15-10-S. This is a more graphical way to examine the effects documented in Figure 6, and helps to show the different meaning of the maximum and average Δu'v' characterizations. First, it is clear that products 15-08-D and 15-10-S exhibit stable color-tuning performance regardless of dimmed level. Product 15-07-D performed well in general, but had several outlier points, especially at the lowest (warmest) CCTs, which led to a higher max Δu'v'. Overall, product 15-07-D performed similarly to product 15-10-S, but the worst points (at the lowest output) shifted farther. The most notable product in the group was probably 15-02-D, which had relatively high values for both average and maximum Δu'v'. At lower intensity levels, the D_{uv} became very positive, indicating a greenish appearance. In contrast with 15-07-D, the maximum Δu'v' for product 15-02-D was smaller, but the shifts occurred more along the green-pink axis than the blue-yellow axis, which may be more problematic.

Achieving perfect consistency—assuming it is a goal—requires careful calibration, because the SPD of each LED primary may change slightly as the thermal characteristics change during dimming. Under the premise that each LED is prone to small shifts in output when dimmed, one could theorize that the multi-chromatic systems used for blackbody white tuning would be more prone to chromaticity change over dimming. However, this was not always the case in this investigation, pointing to an effort by at least some manufacturers to carefully address the issue. In contrast, the similarity between all three linear-tuning systems for which these data were available may indicate a broader trend in performance. With only two LEDs, it is very difficult to maintain chromaticity

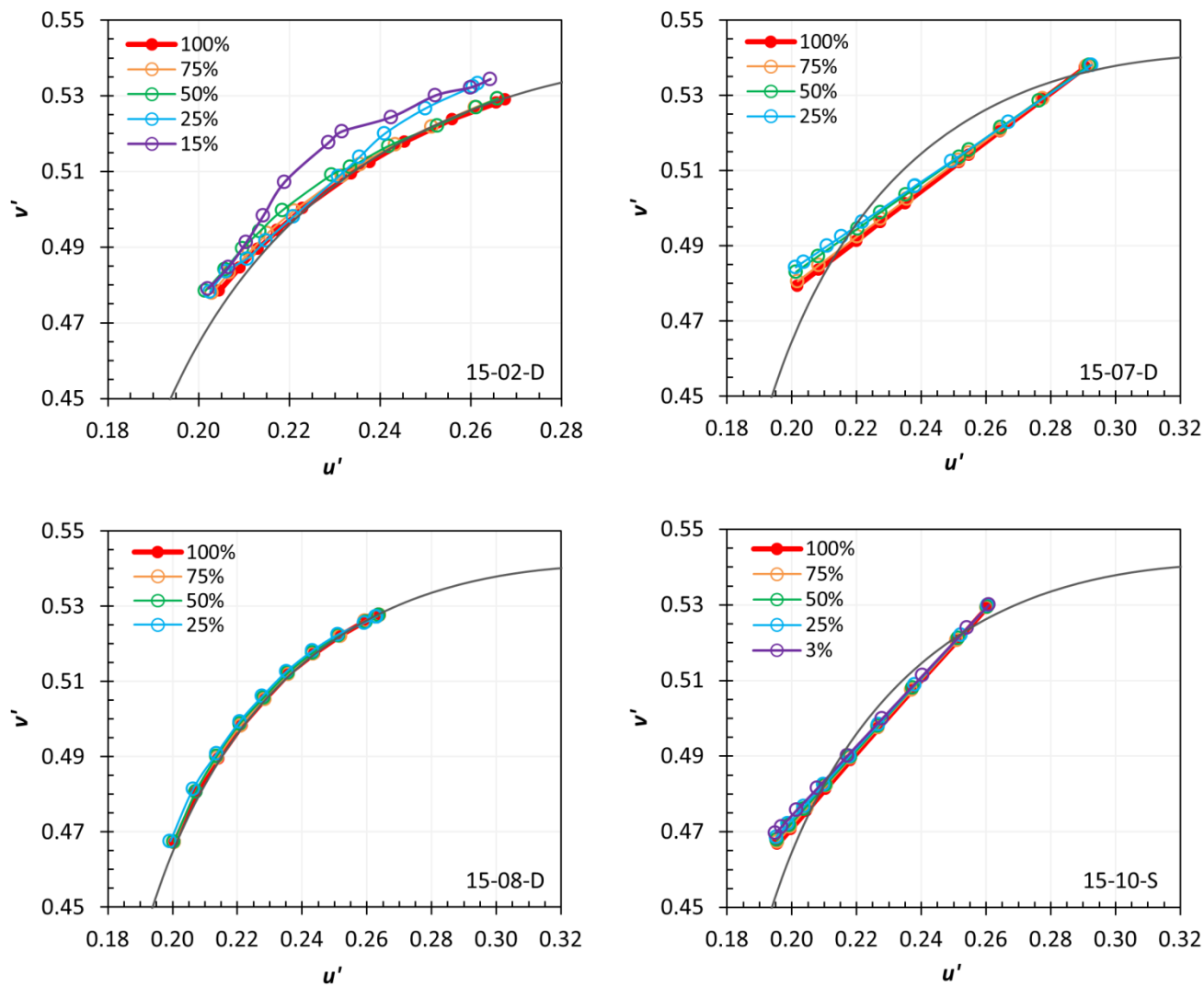


Figure 7. Color stability over the dimming range. Although these plots show lines at constant intensity settings, they also can be used to infer color stability at a constant color setting. The variation corresponds to the values seen in Figure 6.

when dimming, although the shifts were often minimal—the linear white-tuning products generally offered very good color stability during dimming.

Color Rendition

Some variation in color rendering metrics was observed over the color-tuning range, although the ranges were often small enough to not be a major issue. Still, qualification programs with color rendition thresholds should be aware of the potential for variation, which is not always easily predictable, as shown in Figure 8. For the white-tuning products, R_f values[12] were typically in the 80s and sometimes into the 90s, with R_g values near 100. CRI R_a values were generally similar to the R_f values. The four products based on PC-LEDs tended to have lower R_g scores, whereas those that more closely followed the blackbody tended to have higher R_g scores, which indicate a slight increase in saturation. This is a direct result of the inclusion of more narrowband LED emitters,

[12] R_f and R_g refer to the fidelity index and gamut index of the new *IES TM-30-15: IES Method for Evaluating Light Source Color Rendition*.

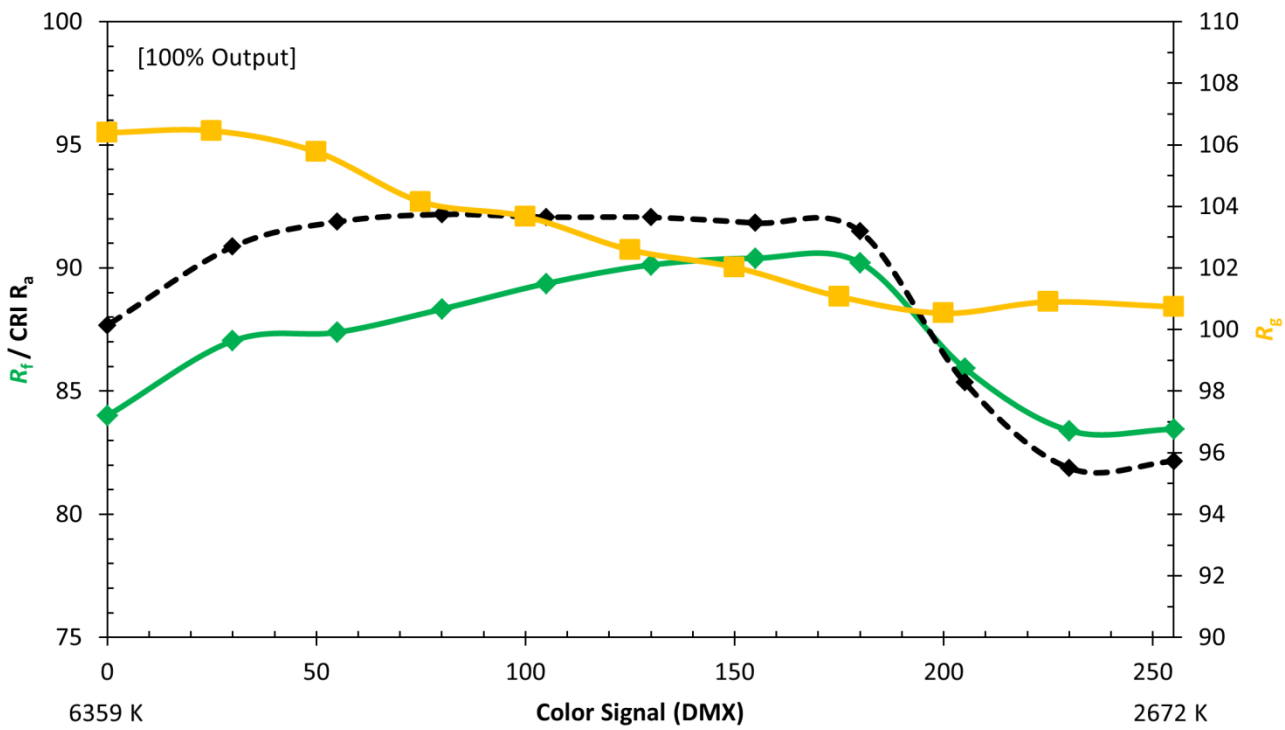


Figure 8. Change in color rendering metric values over the color-tuning range for product 15-08-D. Although the range in performance for the eight products included in this report is likely not substantial enough to affect design decisions, the variation, and its unpredictability, could nonetheless be a factor affecting qualification for energy-efficiency programs or compliance with building codes.

rather than broad-emitting phosphors, and is another reason, besides constant D_{uv}, why the four nonlinear white-tuning products may be preferred by occupants.

Another important note is that all of the nonlinear white-tuning products tested had a higher fidelity value than the linear white-tuning products, although multi-channel LED systems do not inherently have high color fidelity. This finding is just anecdotal on its own, but is important to consider within the context of the results. Products with higher color fidelity are generally less efficacious, which may be a small contributing factor in the difference in measured efficacy for the products included in this report.

Power Quality

Perhaps the most stable performance attribute over the color-tuning range was power quality. The power factor (0.96 to 1.00) of all of the products, and most of the THD values (5.1% to 24.1%), were very good. Notably, the listed values are only for operation at full output (over the color range). As expected, the variation was much more substantial over the dimming range, but that is not within the scope of this report.

6 Discussion

Recent CALiPER studies have focused on the photometric, photoelectric, long-term, and subjective performance of LED lamps and luminaires, including MR16s, PAR38s, and troffers, among others. These are all established product types that were on their second or third generation at the time of investigation. In contrast, color-tunable LED luminaires remain niche products with substantial promise but little market penetration. There is no standardized test procedure for such luminaires, and less consistency in product offerings. For these reasons, the approach to this investigation was different.

In the past, CALiPER defined focused categories so that the performance of individual products could be compared and contrasted. For this investigation, the product range was broader, with the intent to capture different approaches that attempt to realize the potential of color-tunable luminaires. Thus, direct comparison of products—in terms of efficacy, lumen output, or any other attribute—is less meaningful and less important. Rather, each product is an opportunity to learn about this emerging product category, with the end goal a collective evaluation of the issues that have already been addressed, and an identification of remaining challenges needing attention before the technology can reach maturity. The list below provides a summary of the key features of each product, along with the important lessons learned that contribute to the findings of this report. The products are grouped as in the previous tables.

- Product 15-01-T was a troffer luminaire that provided its own controller. The controller allowed for independent control of the warm-white and cool-white LED primaries, rather than control of color and intensity. In fact, it was not possible to adjust intensity while maintaining constant color, which meant the testing protocol was somewhat different for this product. Another notable limitation is a somewhat substantial range in power, which led to similar variation in output—about 25%, with the minimum input power at the midpoint of the color-tuning range.
- Product 15-07-D was the only downlight product that used a two-channel mix for linear white tuning. It was also the only product to maintain constant power throughout the color-tuning range, although that resulted in about a 20% range in lumen output, due to the difference in efficacy for the warm-white and cool-white LED primaries.
- Product 15-10-S was a surface-mounted (ceiling) luminaire with 24" diameter round diffuser that utilized two LED primaries, one warm and one cool, with linear white tuning, as well as a proprietary controller that allowed for adjustment based on CCT and intensity. The measured CCT at each point was fairly close to the value set on the controller, with slight deviation at the highest CCTs that was on the order of 200 K. Power, output, and efficacy were always above about 90% of maximum, making this product one of the more consistent over the color-tuning range.
- Product 15-12-T was very similar to product 15-10-S in terms of its control mode and performance consistency. These two products were probably the most effective implementation of a two-LED-primary linear white-tuning product, although they have the inherent limitation of changing D_{uv} across the color-tuning range. It remains to be seen if general users are familiar enough with the Kelvin scale to make proper use of the controller.
- Product 15-02-D was a module-based downlight (like all of the downlights), which seems to use four channels (it can be difficult to determine from the SPD alone). At full output, the product was able to closely track the blackbody locus, but drifted away as it was dimmed, despite inclusion of closed-loop thermal feedback (according to the module specification sheet). As with the other nonlinear white-tuning downlights, the low efficacy of this product impedes its ability to compete with fixed-color

downlights where color tunability is not a priority. There was also a substantial reduction in output as the CCT was reduced, reaching approximately 60% of the maximum at its lowest CCT.

- Product 15-05-D seems to utilize five different LED primaries and was able to closely track the blackbody locus, including at the very low CCTs that were reached. Perhaps due to the very low CCTs, the lumen-output range was the largest of all products tested, reaching less than 30% of the maximum at the lowest CCT. Efficacy and input power also varied substantially. In this sense, the product did not offer truly independent control of color and intensity, because it was not possible to achieve all intensity levels at all CCTs.
- Product 15-08-D was the only basic RGB LED primary mixture in the group, and the only nonlinear tuning product to use DMX for control. It was effective at tracking the blackbody locus, even when dimmed, which is likely the result of careful calibration. Power, output, and efficacy were all fairly stable across the tuning range. To be useful in an architectural setting, the luminaire would have to be paired with an appropriate DMX controller and user interface; the computer software used for this investigation would not work for individual users, because it requires a direct connection between the controlling computer and the lights.
- Product 15-09-D had the most unique approach to nonlinear tuning, relying on two PC- LED primaries with chromaticity above the blackbody locus, combined with a red LED. This resulted in a smaller range of possible colors than products using more LED primaries, but that is not detrimental to white tuning; in fact, it may help consistency. There was some variation in output, power, and efficacy, down to about 80% of maximum, which occurred at the midpoint of the color-tuning range. This is nearly the opposite profile to that of product 15-01-T.

Continued Development of Color Mixes

Color-tunable products remain in their infancy compared to fixed-color LED products. Currently, there is some level of tradeoff between efficacy and color performance with white-tunable products. Two PC-LED primary mixes can offer high efficacy—principally because they do not employ an inefficient green LED emitter—but they can only change color along a linear path. In contrast, mixes of three or more LED primaries often rely on a green emitter and thus often have lower efficacies, but the color change can match the blackbody or any other nonlinear curve that may be preferred. Both of these types of products were represented in this study. At this point, there is no published research focusing on the preferred chromaticity path for color tuning, although several studies[13, 14, 15] have demonstrated that observers find points below the blackbody to be preferable white points and/or neutral white points.

Within nonlinear white-tuning products, there is variation in the methods being used to generate color change following the blackbody curve. This is driven in part by different features, such as the ability to function as a full-color-tuning product in addition to operating as a white-tuning product. Whereas full-color-tuning products require the LED primaries to encompass a large gamut, this is not true of products that only offer white tuning. Using LED primaries that cover a smaller gamut may increase consistency and reduce the effects of the green gap, since they can eliminate the need for a green LED altogether. Product 15-09-D is an example of a product taking this approach, utilizing two off-white PC-LED primaries (e.g., mint) combined with a red LED. This product

[13] Rea MS, Freyssinier-Nova JP. 2013. White lighting. *Color Research and Application* 38(2): 82–92.
[14] Dikel EE, Burns GJ, Veitch JA, Mancini S, Newsham GR. 2014. Preferred chromaticity of color-tunable LED lighting. *LEUKOS* 10(2):101–115.
[15] Liu, XY et al. 2015. Assessments of White Perception in a Real Lit Room. *Proceedings of 28th CIE Session.*

had the highest efficacy of the nonlinear white-tuning products, with its minimum value exceeding the maximum value for the others.

Design Tradeoffs

Few of the tested products maintained other performance parameters while the color was changed. For example, the lumen output or power draw often changed over the color-tuning range. While such changes may be undesirable—thresholds for unacceptability have not been investigated—they may also be necessary, or at least deemed an unavoidable consequence.

With multiple LEDs, it is essentially impossible to maintain lumen output, input power, and efficacy simultaneously while changing the relative proportion of the mix (i.e., the color output). However, maintaining one of those three is readily achievable with proper consideration and product design. Of the three, lumen output is the only one that affects the visual environment, which may give its consistency priority over the other characteristics, but other considerations may also come into play. For example, maintaining constant lumen output necessitates only delivering as many lumens over the whole range as can be delivered at the point with the lowest output. Lower overall output ratings may be a marketing disadvantage, especially if only single values are reported instead of a range. Driving LEDs harder at the lower-output color settings in order to boost the minimum output may also lead to earlier chromaticity shift or lumen depreciation.

Nonetheless, some products were fairly successful at achieving relatively consistent performance. This is likely accomplished by carefully selecting components, rather than necessarily pairing best-in-class products for each primary. For example, pairing a lower-efficacy warm-white LED primary with a higher-efficacy cool-white LED primary would require additional consideration to maintain constant output. However, it may also result in the most energy-efficient product, even if the efficacy is not constant. In short, it is a careful balancing act.

Energy-efficiency programs must also consider the effects of variable power draw, lumen output, and efficacy on qualification status, and specifiers must interpret how such products are handled in building codes. All three performance parameters have specified limits in various programs, either directly or indirectly. In fact, color-tunable products have so far been excluded from some programs because it can be difficult to determine whether or not they meet performance thresholds; this is exacerbated by a lack of standardized test procedures.

Product Rating Accuracy and Reporting

CALiPER investigations have had a longstanding focus on performance relative to manufacturer claims. This becomes a much more complex task with color-tunable products, however, and rarely can effective comparisons be made. Manufacturers must decide how to distill complex information about a range of performance in order to communicate effectively; oftentimes this requires working within a framework set up around fixed-output, fixed-color products. One of the key distinctions is whether to report single values—perhaps a mean or maximum value—or the minimum and maximum value of a metric over the color-tuning range. For the products tested for this report, different manufacturers chose different approaches, and sometimes mixed the approach depending on the metric.

All the products discussed here reported a single value for input power, with little to no indication of what output setting that value corresponded to or whether it was the maximum, average, or some other value. The implication is that input power is constant, which was not the case for all but one product. In contrast, half of the products provided lumen output values tied to a specific CCT, whereas the others just provided a single value. For the nonlinear tuning products—all of which were downlights—there was the additional complication

of whether the manufacturer reported LED module lumens or luminaire lumens. All four of the products were built around a third-party module, which has its own specifications that do not match those of the luminaire. The origin of the reported values in the luminaire manufacturer's spec sheet was not always obvious. Similarly to output, efficacy values were reported as either a single value (without reference to a specific CCT) or as the value for a given CCT. Of any of the main lighting metrics beyond CCT, only CRI was ever reported as a range, but only for two products.

Many of the products had some level of discrepancy between the tested range of values and the manufacturer's listed value. Some were minor, whereas others were substantial. Some were due to the method of reporting (e.g., a single value), whereas the cause of others was indeterminate. One noteworthy product that exemplifies the challenge of accurately rating color-tunable luminaires is product 15-05-D. It was listed as emitting 891 lm at 2700 K and measured at 905 lm at 2774 K, but the full range in output was 263 to 905 lm. This product had a CCT range of 1628 K to 3833 K, and in essence functioned as a white-tuning product from 3800 K to 2700 K, then more or less as a dim-to-warm product at lower CCTs. Whether this was intentional or not is unknown, but it illustrates the struggle to identify what performance values are meaningful, since typical operation may not require full output at very low CCTs.

While color-tuning products may fare no better at matching their performance claims than traditional LED products, they also have the added complexity of trying to characterize a range of values. Based on the data in this report, best practices suggest reporting a range of values instead of a single value or a few values at specified targets. While specified targets are more informative than a single value, they still make product comparisons difficult. If reporting a range of performance is not possible, then clearly identifying whether a single value corresponds to a minimum, maximum, or average is paramount.

Prospects for Future Testing Standardization

The topic of photometric testing of color-tunable products has been under consideration in the lighting industry for some time. So far, there has been activity and conversations within the IES Technical Procedures Committee (TPC), but no agreement has been reached. Much of the debate focuses on how to establish a meaningful testing regimen that efficiently characterizes the much larger range of possible performance.

The key issue is testing burden—accuracy is not a problem, provided a large number of points are tested. Increasing the testing burden further to accommodate color-tunable products is likely to require compromises in absolute accuracy, such as limiting the number of points tested or the stabilization time between each new test condition. Hopefully, an agreement can be reached soon.

The results of this series of product testing suggest that overly limiting the number of test conditions may be detrimental to accurately characterizing a product's performance. Many of the products had nonlinear and difficult-to-predict relationships between color and power, output, or efficacy. For example, the output and efficacy of product 15-05-D (Figure 2) over the color-tuning range could not easily be modelled with only three measurement points. On the other hand, the performance of products such as 15-07-D could more readily be understood with only a few test points. Five to seven points is likely the minimum necessary to sufficiently capture the range of performance.

If a standardized test procedure for white-tunable luminaires is to be adopted, the end result will require a compromise between accuracy (more test points) and test burden (fewer test points), which will have to be debated by all stakeholders. Other considerations, such as warmup time and intervals between measurements when settings change, can be adapted from existing measurement procedures (e.g., IES LM-79-08). The

procedure becomes even more complicated for full-color-tuning products, however. These products often rely on a range of control input that is not based on a slider (e.g., a linear scale), and in some cases there is more than one way to create the same chromaticity. These issues will be discussed further in a subsequent CALiPER report.

7 Conclusions

This report discusses photometric testing and the resulting measured performance of eight white-tunable LED luminaires, including two troffers, one ceiling luminaire, and five downlights. Three of the products featured linear white tuning using two PC-LED primaries, whereas the other five products featured nonlinear white tuning (following the blackbody locus) using three, four, or five different LED primaries. The eight products demonstrate the variety of approaches that different manufacturers are taking to address the tradeoffs and compromises necessary to achieve white tuning. Two key considerations are linear versus nonlinear tuning and balancing lumen output, power draw, and efficacy:

- Linear white-tuning products may be somewhat more efficacious and intrinsically less complicated than nonlinear white-tuning products, but they exhibit a range of D_{uv} values as the CCT is adjusted, with the range increasing as the CCT range increases. This may or may not be acceptable to users. The stability of the color when dimmed is not demonstrably different from that of the nonlinear white-tuning products.
- White tuning—and all types of color tuning—requires careful consideration of lumen output, power draw, and efficacy. Without careful engineering, one or all three of the aforementioned parameters can vary in a way that is either objectionable to users or makes specification more challenging. As evidenced by this report, it is possible to strictly maintain lumen output or power draw. It is also possible to maintain all three within 10% of the maximum value.

Given the large differences in performance variation over the color-tuning range, it may be difficult to accurately capture performance by testing only a few color points. A minimum of five to seven points is suggested, with a possible reduction in testing burden achieved by not considering these as independent tests requiring separate warmup periods. After a single warmup period, as specified by IES LM-79-08, subsequent points could be measured after the minimum amount of time necessary to determine stabilization mathematically. This approach could apply to white-tuning products, but the additional complexity of full-color-tuning products likely will require a substantially different procedure.

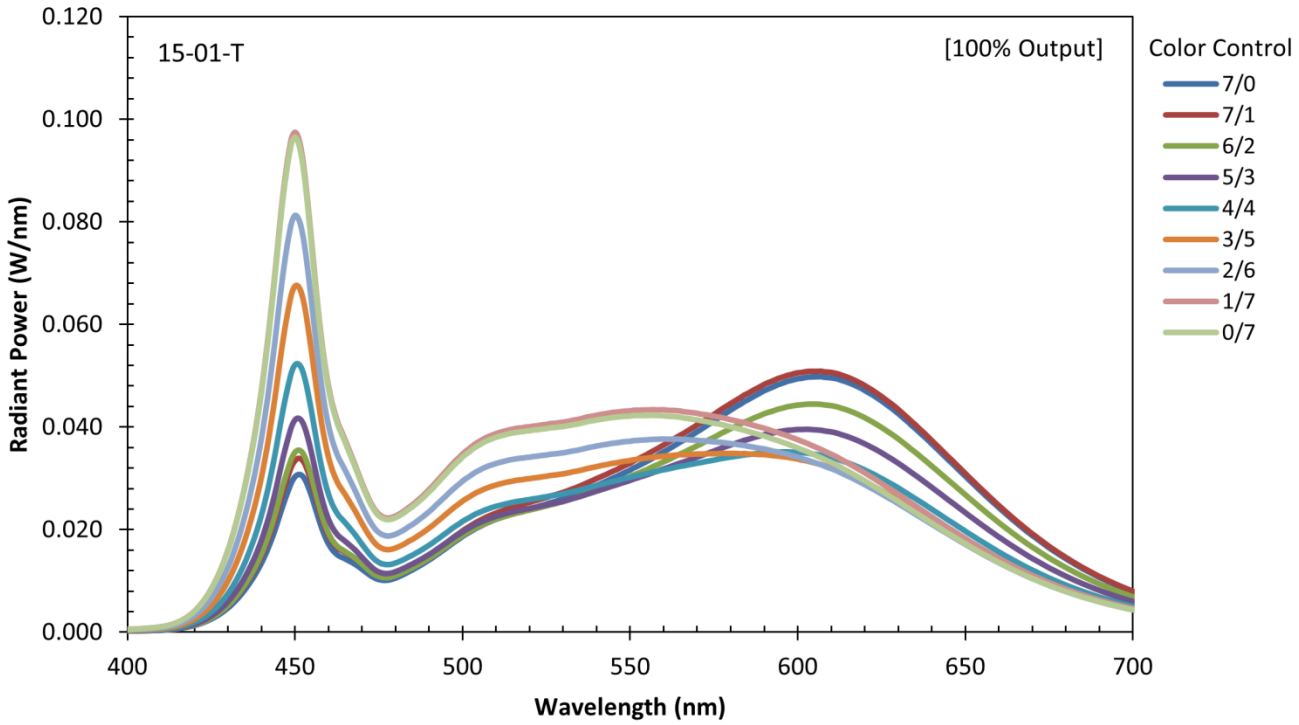
White-tuning luminaires are still in their infancy, with plenty of room to mature. While the linear-tuning troffers offered high enough efficacy to at least be considered against fixed-color products, they are still at a modest disadvantage versus the best competitors, and it remains to be seen if linear color tuning is accepted by the marketplace. On the other hand, the white-tuning downlights—linear and nonlinear tuning alike—are at a severe energy-efficiency disadvantage compared to fixed-color products, not even reaching the minimum criterion for ENERGY STAR qualification. The competitiveness of these products relies on the non-energy benefits, which can be difficult to quantify but which are also generally important in the applications where downlights are frequently specified. Engineering improvements, such as refinement of the LED primaries included or breakthroughs regarding the green gap, could change this balance in the future.

Appendix A: Definitions

Δu'v'	A measure of color difference or color changed, calculated as Euclidian distance between two chromaticity coordinate pairs in the CIE 1976 (*u*', *v*') uniform chromaticity scale (UCS).
Correlated Color Temperature (CCT) Kelvin (K)	The absolute temperature of a blackbody radiator having a chromaticity that most nearly resembles that of the light source. CCT is used to describe the color appearance of the emitted light.
Color Rendering Index (CRI or R_a)	A measure of color fidelity that characterizes the general similarity in color appearance of objects under a given source relative to a reference source of the same CCT. The maximum possible value is 100, with higher scores indicating less difference in chromaticity for eight color samples illuminated with the test and reference source. See also: *Special Color Rendering Index R_9.*
D_{uv}	The distance from the Planckian locus on the CIE 1960 (*u*, *v*) chromaticity diagram (also known as *u*', 2/3 *v*'). A positive value indicates that the measured chromaticity is above the locus (appearing slightly green) and a negative value indicates that the measured chromaticity is below the locus (appearing slightly pink). The American National Standards Institute provides limits for D_{uv} for nominally white light.
Fidelity Index (R_f)	The fidelity index from IES TM-30-15 measures the similarity of object colors under a test light source and a reference light source. The maximum value (perfect fidelity) is 100, and the minimum value is 0. For more information, see https://www.osapublishing.org/oe/abstract.cfm?URI=oe-23-12-15888
Gamut Index (R_g)	The gamut index from IES TM-30-15 measures the saturation of object colors under a test source compared to a reference source. A score of 100 indicates the same average level of saturation, a score greater than 100 indicates increased average saturation, and a score less than 100 indicates decreased average saturation. For more information, see https://www.osapublishing.org/oe/abstract.cfm?URI=oe-23-12-15888
Input Power Watts (W)	The power required to operate a device (e.g., a lamp or a luminaire), including any auxiliary electronic components (e.g., ballast or driver).
Luminous Efficacy Lumens per watt (lm/W)	The quotient of the total luminous flux emitted and the total input power.
Luminous Efficacy of Radiation (LER) (lm/W_{rad})	The quotient of the total luminous flux emitted and the total radiant flux emitted. This is a measure of the efficiency of the SPD, expressing the amount of lumens generated per watt of emitted optical radiation.
Light Output Lumens (lm)	The amount of light emitted by a lamp or luminaire. The radiant energy is weighted with the photopic luminous efficiency function, V(λ).
Power Factor	The quotient of real power (watts) flowing to the load (e.g., lamp or fixture) and the apparent power (volt-amperes) in the circuit. Power factor is expressed as a number between 0 and 1, with higher values being more desirable.
Spectral Power Distribution (SPD)	The power per unit wavelength of radiant energy. The light may be that emitted by a source or reflected from a surface.

THD-I	A measure of the level of harmonic distortion present in a current waveform, defined as the ratio of the sum of all harmonic components of the waveform to the value at the fundamental frequency.

Appendix B: SPDs



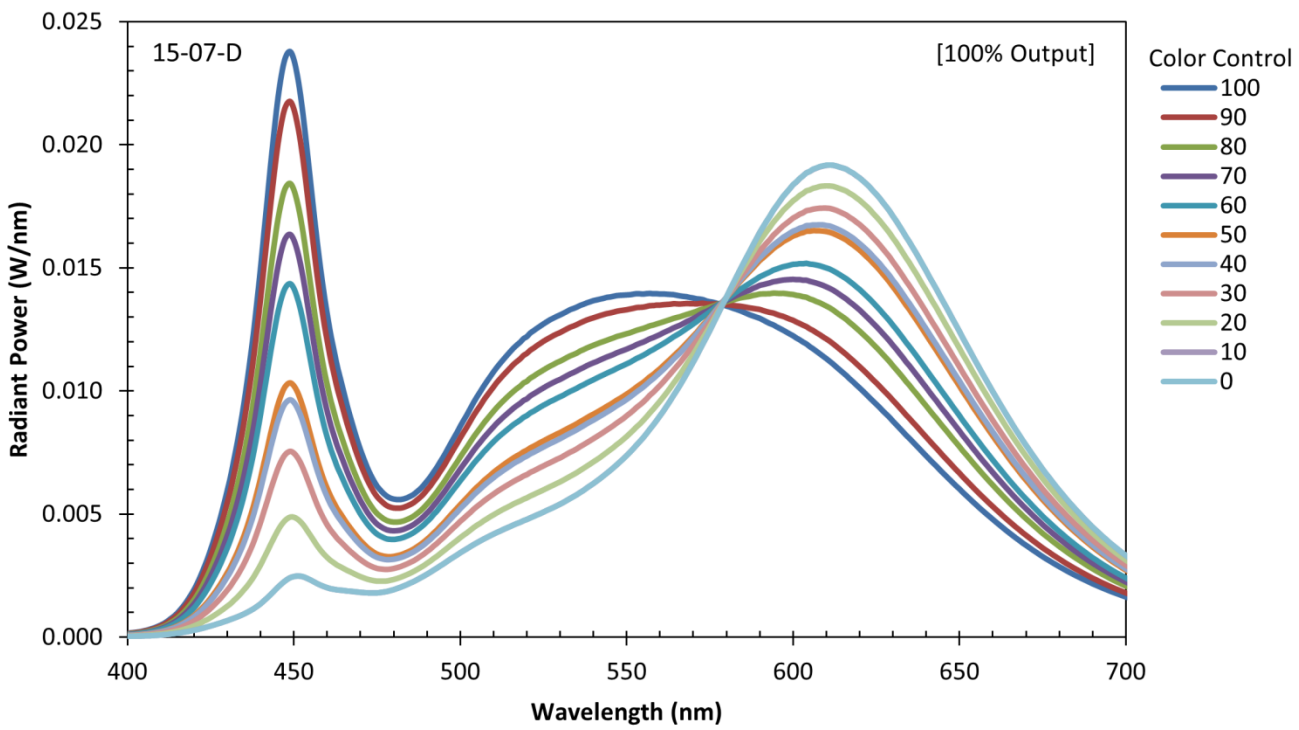


Figure B1. Change in the measured SPD as the color control was varied from minimum to maximum.

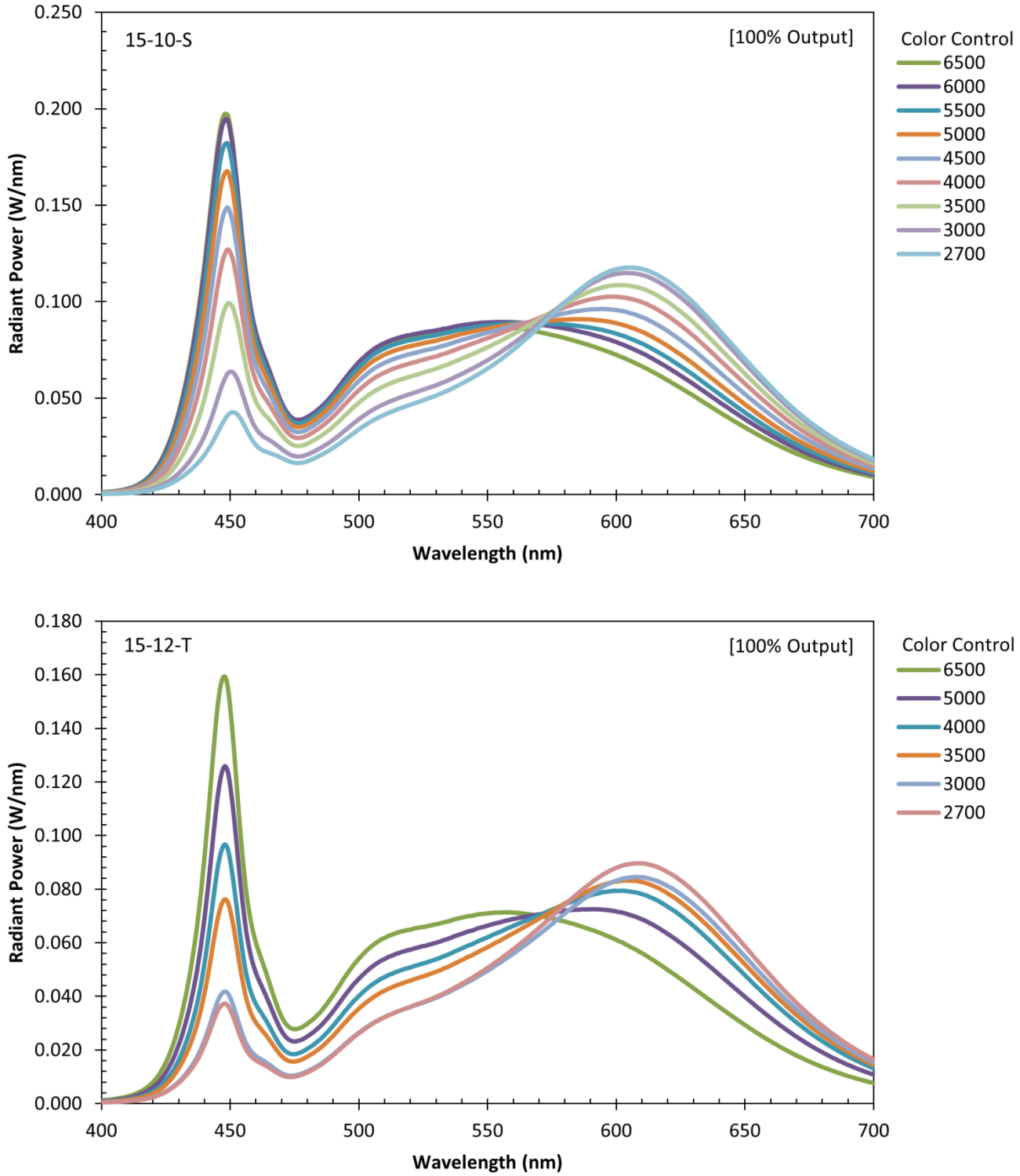


Figure B2. Change in the measured SPD as the color control was varied from minimum to maximum.

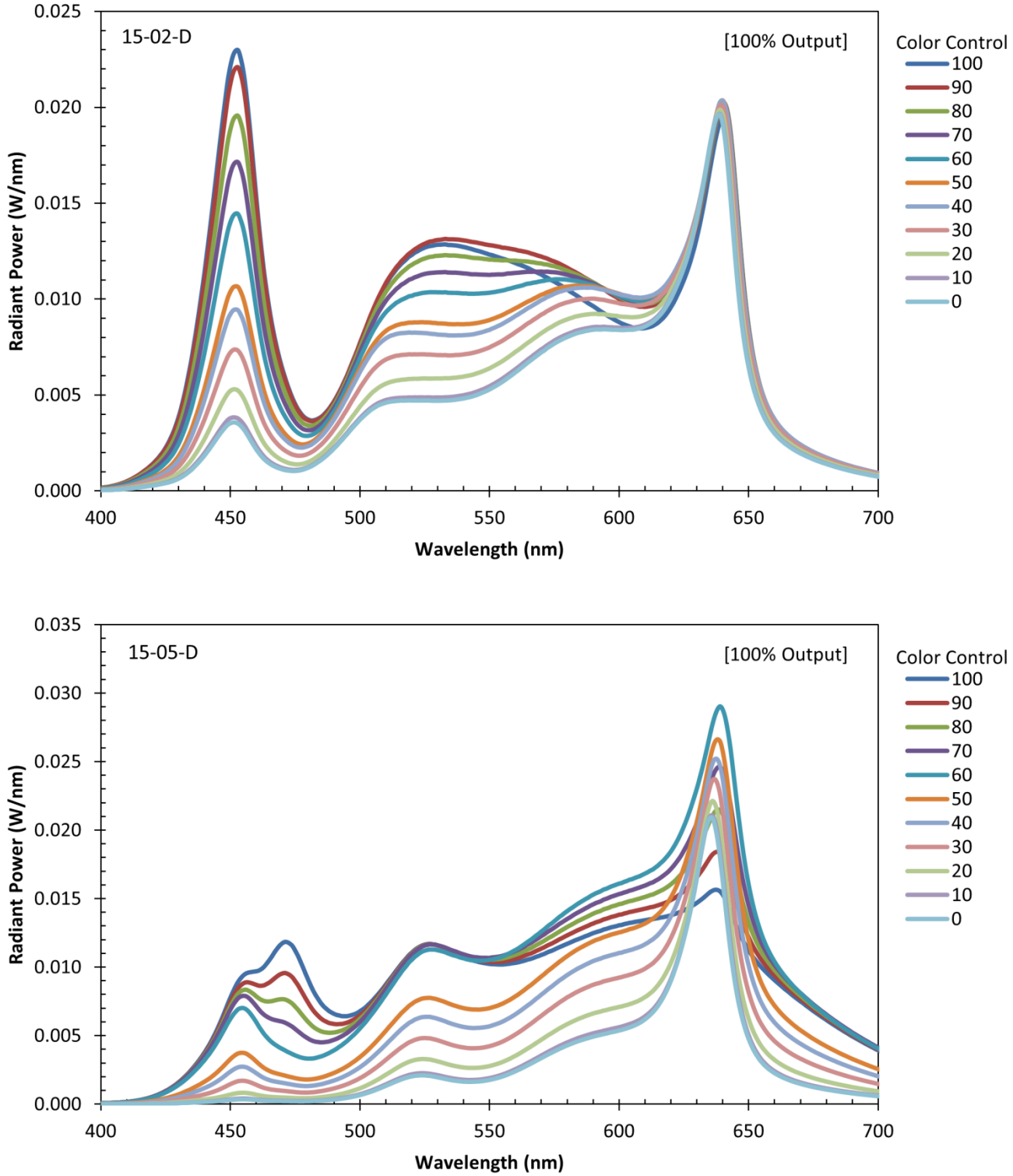
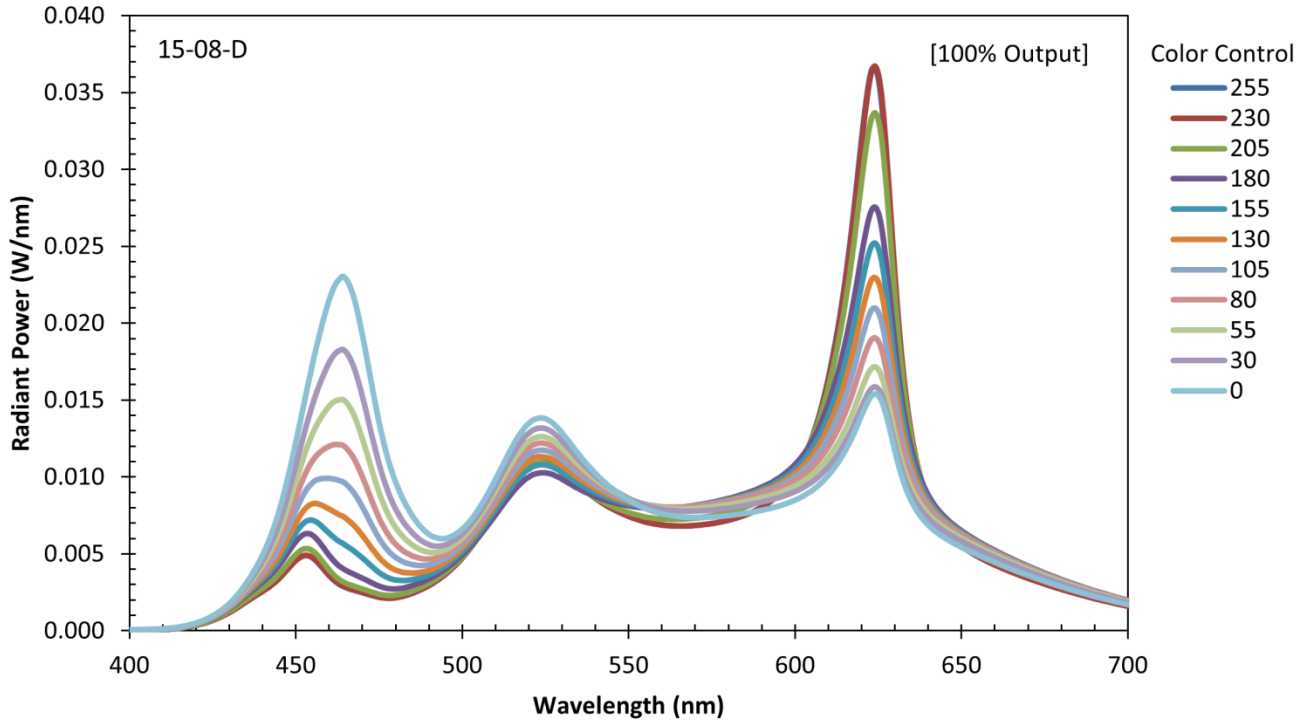


Figure B3. Change in the measured SPD as the color control was varied from minimum to maximum.



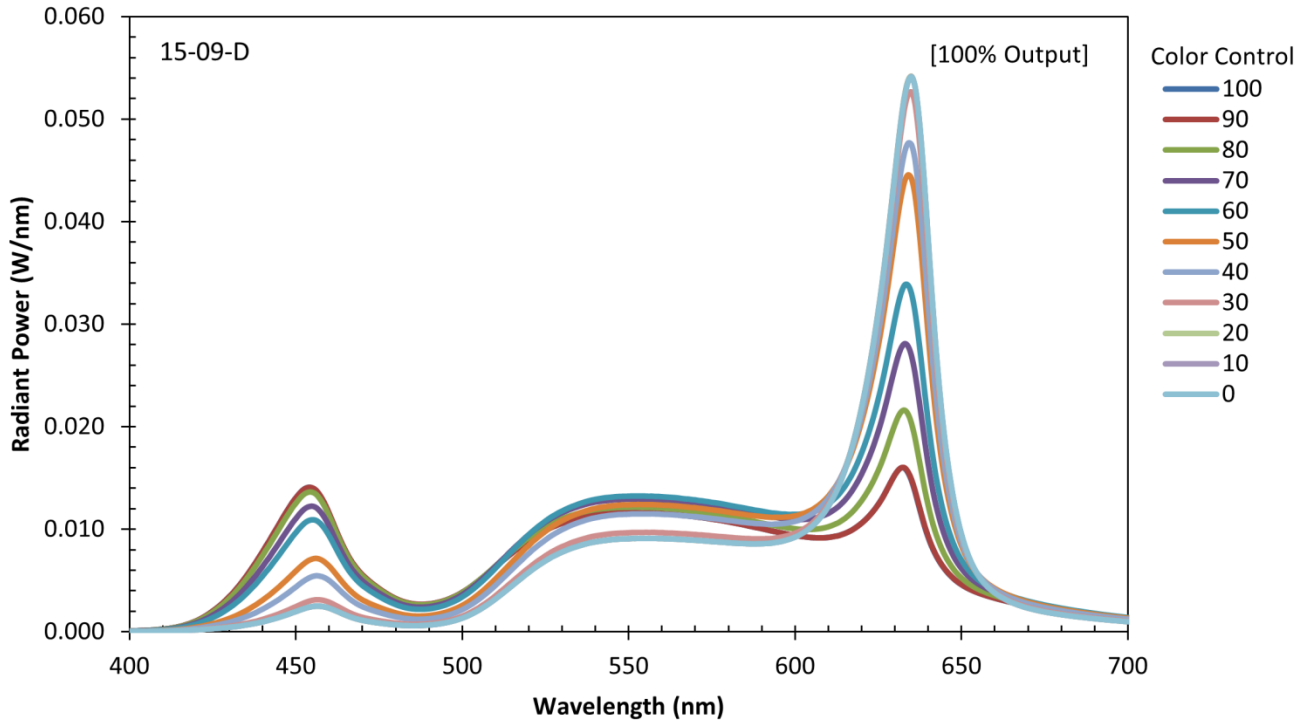


Figure B4. Change in the measured SPD as the color control was varied from minimum to maximum.

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