Addendum:
Accuracy of Photometric Testing Versus the Number of Tests Over the Tuning Range

Introduction

Lighting practice—especially testing, specification, and regulation—is built upon lamps and luminaires that offer fixed operating characteristics. Products may be paired with a dimmer to reduce intensity, but there is an obvious operating condition for characterizing the product, calculating power density, and designing for illuminance criteria: full output. Conveniently, the maximum output condition corresponds to the highest power draw, and a reportable efficacy follows.

Color-tunable luminaires do not fit perfectly into this scheme, because key operating values—such as maximum power draw, maximum or minimum lumen output, and minimum or average efficacy—typically do not occur in the same operating state (as signaled by a control system). With the ability to vary both luminous intensity and spectrum simultaneously, the number of possible operating states is nearly limitless. This presents a challenge for photometric testing: how to determine relevant performance characteristics accurately?

A key first question is: What photometric characteristics are important? In particular, it is important to understand which characteristics are related to a design criterion. The following list provides general guidelines, although some unique situations might require a different approach:

- **Input Power:** In most applications, luminaires are rated based on their maximum power draw, both for sizing of electrical circuits and for calculating lighting power density (LPD) in energy code calculations. Absent criteria based on energy use instead of power, maximum power draw is likely to be a key performance characteristic for some time.
- **Luminous Flux:** Designers often strive to meet or exceed recommended illuminance levels, which makes the minimum lumen output (at full intensity but considering different color settings) an important variable to quantify. At the same time, maximum lumen output may be an important characteristic when comparing two products.
- **Luminous Efficacy**: Minimum efficacy is likely most relevant to product qualification and energy efficiency programs. At the same time, average or maximum efficacy may be more relevant to a specifier comparing products, especially if the minimum efficacy occurs at a setting that is not expected to be used. To complicate things further, two products with different color tuning ranges may have different ranges in performance simply due to the range of spectral characteristics, which can make comparisons more difficult and less informative.

Ideally, color-tunable products would offer minimal change in power draw, lumen output, and efficacy across the color-tuning range. This would eliminate difficulty in the characterization process, and a single set of numbers could represent performance regardless of the user's choice of color temperature. However, none of the white-tunable products tested by CALiPER offered this level of performance, so characterization must consider operation of the full color-tuning range. Given that the key values do not always occur at the endpoints of the tuning range, and given that it's not possible to test every point over the color-tuning range to determine true values for maximum input power, minimum/maximum lumen output, and minimum/maximum efficacy, a fixed number of test points must be established. As is typical, there is a tradeoff between the number of points and the accuracy of the data.

This report examines the effect of the number of measurement points across the tuning range on the measured values for the previously identified key product characteristics. Only the five products that followed the standard 11-point test procedure (15-02, 15-05, 15-07, 15-08, and 15-09) were included in the analysis, which compares values derived from all 11 points to values derived from 3, 5, or 6 measurement points. For the set of three measurements, the endpoints and midpoint measurement were used, whereas for the set of six measurements, every other measurement (including both endpoints) was used. Two possible combinations of five measurements are possible, using either the third and ninth measurements in the sequence, or the fourth and eighth measurements in the sequence (in addition to the endpoint and midpoint measurements); the error values reported are the greater of the two.

The level of error attributed to each metric and each number of measurement points is derived from a relatively small number of tests. Products with greater variation in performance over the color-tuning range will have a greater level of error, especially if the variation is more erratic, as with product 15-05.

The complete test protocol is discussed in the body of this report. For this analysis, it is important to note that all measurements for a given luminaire were taken in an uninterrupted sequence. The first measurement followed an initial stabilization at the maximum intensity and maximum color settings; subsequent maximum-intensity measurements were made immediately afterward by reducing the color setting in equal increments down to the minimum—in all cases, this was going from a higher CCT to a lower CCT. This sequence was then repeated at lower intensity levels. After the initial measurement, stabilization at each measurement point was determined based on the measured and projected rate of change (< 0.5% over 30 minutes), but no rule for minimum stabilization time was applied. At no point in any of the measurement sequences was the luminaire turned off or the integrating sphere opened, which reduces the amount of measurement error that could be attributed to procedural issues.

Results

Table A1 shows the range in measurement error for the listed number of test conditions versus the baseline 11 points. While the baseline is not the true value, it is the only available reference for this calculation. A few important observations can be made. First, even with as few as three points, there was no error in determining minimum values. This is because those minimums always occurred at one of the endpoints, as shown in Figure 2. Similarly, calculated average efficacy deviated by less than 3% compared to the determination based on 11 measurement points, a level of error that is not likely to be concerning.

The most notable error in the derived values shown in Table A1 was for the maximum power draw and maximum lumen output at 6% and 10%, respectively. The error in these values can be traced to the fact that some of the products, such as 15-09, exhibited maximum output at some point in the color-tuning range—but not at the precise midpoint. Product 15-05, the attributes of which are shown in Figure 2, exhibited the highest error level for both maximum power draw and maximum lumen output. Note that based on the described

Table A1. Range in error when determining listed values based on number of color tuning (CCT) points indicated, compared to determining the listed value based on all 11 measurement points. The range is based on calculations for five products measured for CALiPER Report 23 (15-02, 15-05, 15-07, 15-08, and 15-09).

No. of Color Tuning Points	Max Power Draw	Min Output	Max Output	Min Efficacy	Average Efficacy
3	0% to 6%	0%	0% to 10%	0%	0% to 3%
5	0% to 6%	0%	0% to 5%	0%	0% to 2%
6	0% to 3%	0%	0% to 3%	0%	0% to 1%

methodology, the error always under-predicts the maximum.

In some instances, one of the five derived values in Table A1 may not be adequate for understanding a products' performance, with a model of performance over the entire tuning range being needed instead. Building a regression model with any number of points is possible, but the model will vary. Figure A1 shows third-order polynomial regression models fitted to 3, 5, 6, or 11 points of measured lumen output data for products 15-02, 15-05, and 15-08. The other two products included in this analysis have approximately linear relationships between the color setting and output, so all the models coincide.

The models in Figure A1 generally provide similar predictions with five or more points included, but a somewhat different prediction with only three points included. All the polynomial models struggle to predict performance in some cases, such as for 15-05 and 15-08, which may limit their usefulness in general. While all of the relationships between output and color setting are continuous, they do not all follow a mathematical equation.

Discussion

To reiterate, the error levels shown in Table A1 are for only a small sample of five products. Future white-tunable luminaires may exhibit substantially different characteristics, increasing the level of error induced by only testing a small number of conditions. The results also do not necessarily apply to dim-to-warm products, and cannot be applied to fully color-tunable luminaires, for which a viable test procedure has yet to be proposed.

The level of error shown in Table A1 may be acceptable in certain contexts, and must be considered alongside other tolerances in the photometric testing process. For example, there is some error associated with photometric measurement equipment, as well as product-to-product variation; it is even possible that these sources of inaccuracy are more substantial than the inaccuracy associated with limiting the number of test conditions for a white-tunable luminaire. Nonetheless, reducing error is an important goal, especially if minimal cost and effort are necessary to achieve more accurate results. This analysis shows that testing five points instead of three may reduce error. Investigation of additional products would be useful before formalizing a test procedure.

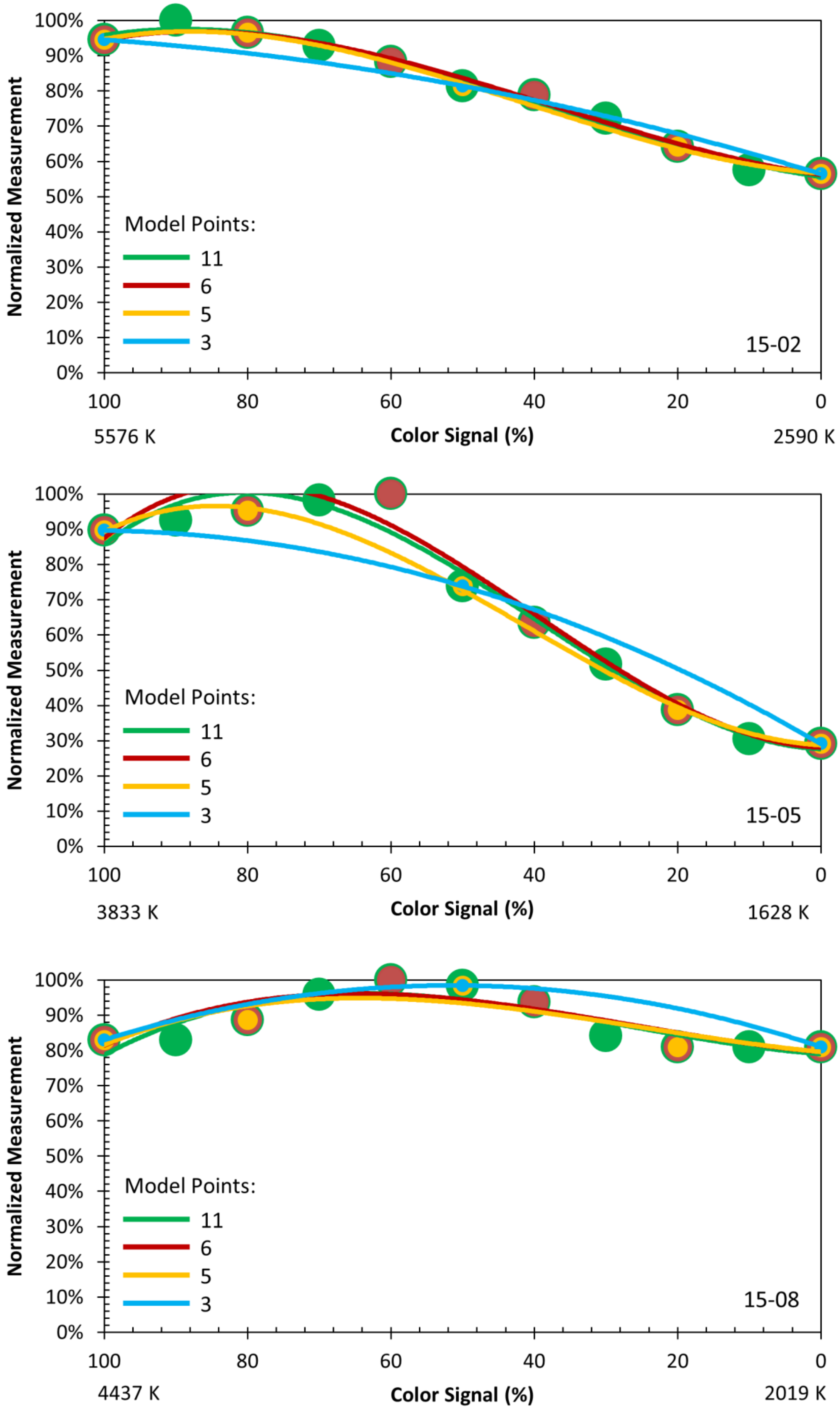

Figure A1. Third-order polynomial regression models for lumen output of three product models, based on 3, 5, 6, or 11 measurement points across the color-tuning range. The models based on 3 and 5 points are substantially different, but there is less difference between the models based on 5, 6, and 11 points.