LED Lamp Quality

Codes and Standards Enhancement (CASE) Initiative

RESPONSE TO CEC'S DRAFT STAFF REPORT AND SEPTEMBER 29, 2014 STAKEHOLDER WORKSHOP

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1 Executive Summary

The Pacific Gas and Electric Company (PG&E), Southern California Edison (SCE), Southern California Gas (SoCal Gas), San Diego Gas & Electric (SDG&E) Codes and Standards Enhancement (CASE) Initiative Program seeks to address energy efficiency opportunities through development of new and updated Title 20 standards. Individual reports document information and data helpful to the California Energy Commission (CEC), and other stakeholders in the development of these new and updated standards. The objective of this Program is to develop CASE Reports that provide comprehensive technical, economic, market, and infrastructure information on each of the potential appliance standards.

This document outlines the California investor-owned utility (IOU) CASE team response to the CEC's Draft Staff Report published in September 2014, "Analysis of Small Diameter Directional Lamp and Light Emitting Diode Lamp Efficiency Opportunities" (herein referred to as the Staff Report) and discussion in the subsequent CEC workshop on September 29, 2014. This document builds upon and supports the Codes and Standards Enhancement (CASE) Initiative entitled "Analysis of Standards Proposals for LED Replacement Lamp Quality," previously submitted to the CEC in July 2013.

We strongly support CEC's efforts to adopt quality and performance requirements for LEDs to help ensure higher levels of consumer acceptance, and believe that the Staff Report addresses several important aspects of lamp performance that will support this goal. However, there are several areas where we believe the CEC should go farther to ensure that LEDs provide a level of performance that meets or exceeds the performance of the incumbent incandescent technology. Most notably, we urge the Commission to strengthen and/or improve the specificity around the requirements for color rendering, dimming, flicker, noise, lifetime/reliability, and power factor.

We recommend that the CEC put forward a Title 20 proposal that is more consistent with other recent CEC initiatives and code requirements. Particularly with the issue of color rendering, the proposal in the September 2014 Staff Report is actually a departure from the direction the CEC has been promoting over the last few years:

- In May 2012, the CEC adopted 2013 Title 24 (the building efficiency standards) which included a requirement for 90 CRI for residential LED light sources (Appendix JA8).
- In December 2012, the CEC approved the Voluntary California Quality LED Lamp Specification (Voluntary Spec), which included a requirement for CRI of at least 90 and R_9 value of at least 50, and required lamps to be dimmable down to10%.
- In October 2014, the CEC published its draft standards proposals for 2016 Title 24, which include mandatory requirements for at least 90 CRI and 50 R_9, elevated temperature testing, and a number of other high performance requirements designed to ensure long life and consumer acceptance.

As utilities, we have been supporting the Voluntary Spec via rebate programs for the past year and have seen the market respond. Less than a year ago, there were few LED lamp products on the market that met the specification, and now there are over 40, offered from over 10 manufacturers. Likewise, since adopting the 2013 Title 24 standards in early 2012, many hundreds of JA8-compliant, 90 CRI, residential LED luminaires have been certified to the Commission's Appliance Efficiency Database and are now available to builders for installation in new homes. The semiconductor industry has responded to these strong market signals sent by the Commission; to continue this momentum we recommend that CEC strive for increased alignment with past initiatives to steer the market in a consistent direction.

In response to comments at past workshops that there are some lighting applications, such as garages and closets, that should have high efficacy options but that do not demand high performance, including high color rendering and dimmability, we would argue that CFLs are ideal options for these applications – we do not need LEDs to compete with CFLs in this space. CFLs are low cost, energy saving light bulbs that have saved a significant amount of energy in the U.S. The proposed standards apply only to LED lamps and do not affect the availability of CFLs in any way. However, the goal of the proposed standard is to ensure that LEDs are of a higher level of quality than CFLs, because despite their low prices, CFLs have fallen far short of transforming the whole market. Figure 1.1 below shows NEMA's A-line sales data from Q1 2011- Q2 2014, and demonstrates that CFL market share (represented by the green bars) has plateaued between about 25-35%.

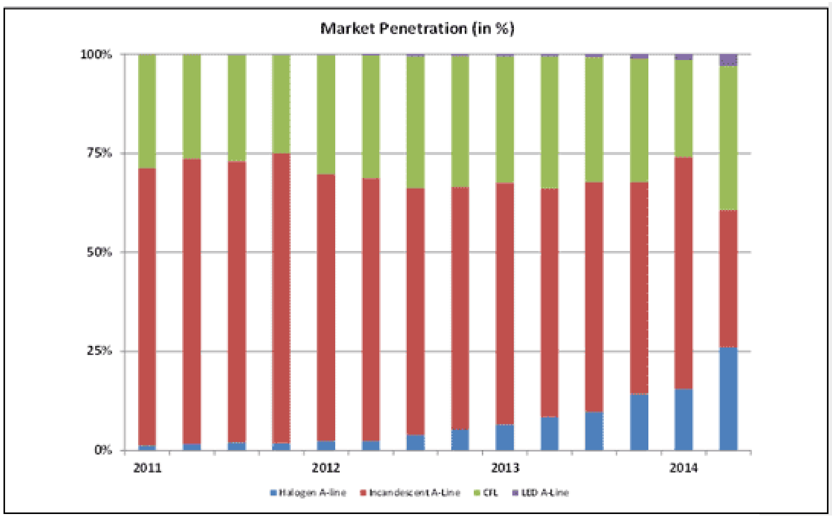

Figure 1.1 NEMA A-line sales data from Q1 2011- Q2 2014 [1]

Below is a summary of the primary specific recommendations that are made in this document:

- We recommend that CEC include LED MR16s and other LED small diameter directional lamps (specifically products with GU5.3 and GU10 bases) in the scope of coverage for the LED quality requirements. (We recommend that the CEC add all performance criteria from this LED Quality specification to the concurrent Small Diameter Directional Lamps (SDDL) regulations, or include SDDLs in both specifications so as to accomplish this result.)
- We support the CEC's proposal to require lamps to provide white light through a 4 MacAdam ellipse requirement, though we recommend specifying this requirement in more exact terms of Duv and setting the tolerance at +/- 0.0033 Duv. We encourage CEC to work with stakeholders to determine whether the target white points should be along the

[1] NEMA A-line Lamp Shipment data; http://www.nema.org/news/Pages/Incandescent-A-Line-Lamps-Decline-Sharply-in-Second-Quarter.aspx

black body locus, or the center points of the color bins in ANSI C78.377 (ANSI's white curve).

- We recommend that CEC adopt a minimum requirement of CRI (Ra) ≥ 90 and $R_9 \geq 50$ for all LED lamps addressed in this rulemaking. This recommendation is based on the following findings, all of which are laid out in detail in Section 2.2 of this document:
    - Products with low CRI can significantly distort colors and will not reliably provide consumers with accurate color rendition. Products with a CRI of at least 90 and an R_9 value of at least 50 reliably provide accurate light that is more similar to the incumbent technology we are trying to replace.
    - There is a wide range of design strategies to achieve high CRI and significant market competition across a wide array of manufacturers with 90 CRI products.
    - The average CRI of products introduced to the DOE Lighting Facts Database has been steadily increasing over the last four years, and 90CRI is no longer an aggressive target.
    - Many high CRI products are already cost-competitive with low CRI products and this trend is forecasted to continue in the near future.
    - High CRI products provide a fuller spectrum of light, requiring fewer lumens to result in equivalent perceived brightness.

- If the CEC deems that a phased-in approach is needed to allow the industry more time to comply, we recommend starting with 85CRI and R_9 of 25 in 2017, and moving to 90CRI with R_9 of 50 in 2019.

- If the CEC deems that only certain product types are appropriate or ready for a 90CRI requirement, the IOUs believe that A-lamps and MR16s are of particular importance for high color accuracy.

- We strongly support the proposed requirement for individual color samples R_1 through R_8 to all have a minimum value of 75. This will help ensure that adequate color is provided across the range of samples and that no source is allowed to provide poor rendering of one color sample while making up for it with high color rendering of another sample.

- We support the minimum efficacy requirements proposed in the Staff Report: 55 lpw in 2017 and 65lpw in 2019. We also support the concept of the efficacy/CRI trade-off equation proposed by the CEC as this acknowledges that higher CRI products may not need to provide as many photopic lumens to generate equivalent perceived brightness.

- We recommend that CEC take steps to ensure LED reliability, including the adoption of a 3,000 hour elevated temperature stress test similar to ENERGY STAR testing.

- We recommend that CEC require all LED lamps to be dimmable down to 10% or lower and that lamps designed for phase cut dimming (the majority of LED replacement lamps) be compliant with NEMA SSL7A, the recently developed phase-cut dimmer compatibility standard.

- We recommend that CEC provide more specificity around the test procedure for verification of dimming performance, including the selection of dimmer types to be used in testing.

- We support the CEC's proposal to limit flicker in LED lamps but recommend that CEC add specificity to its requirement. We propose that all lamps have an amplitude modulation (Percent Flicker) of less than 30 percent for frequencies less than 200 Hz, when tested at 100% light output and 20% light output (or at the minimum claimed dimming level of the product). We also recommend that the CEC reference the flicker test procedure that is currently being considered for adoption in Appendix JA10 of Title 24, and which is included as an Appendix to this document.

- We recommend that the CEC adopt the noise requirements from the ENERGY STAR Lamps Specification (lamps shall not emit noise above 24dBA at 1 meter or less at 100% light output and at either 20% light output or the minimum claimed dimming level).

- We recommend that CEC include a minimum power factor requirement of 0.9 at full light output, and 0.5 at 20% light output (or at the minimum claimed dimming level), for all LED lamps. Improving power factor has significant financial and greenhouse gas benefits for California consumers. Our research suggests it has minimal or negligible incremental manufacturer cost, and our analysis of thousands of online retail price points did not suggest any link between increased power factor and increased end user prices. Lastly, there is already a preponderance of products that meet these proposed levels.
- We support the CEC's proposal to require lamps marketed as incandescent replacements or equivalents to be capable of providing a CCT of 3000K or less and to provide other performance features that are comparable to incandescent (minimum light output, minimum CRI, etc.). A label could also be considered to distinguish between commercial and residential products to accomplish a similar effect (for example products clearly marked as "Intended for Commercial Use Only" might be allowed slightly lower performance values or CCTs greater than 3000K).

- We recommend that all lamp packaging include a label indicating the product's CRI, and that the date of manufacturer be permanently marked on all products in the format: MM/YYYY.

2 Specific Recommendations

2.1 Scope

We recommend that CEC include LED MR16s and other LED small diameter directional lamps (SDDLs) (specifically products with GU5.3 and GU10 bases) in the scope of coverage for the LED quality requirements (while not removing the product types from the concurrent SDDL specifications). Although the CEC is separately setting efficacy requirements for SDDLs that would ban halogens, we believe it is nonetheless important to ensure that the LED products remaining on the market provide a high level of performance such that they effectively replace the performance level of incandescents (while providing much longer life), to prevent consumer backlash to the efficacy standards. Currently there are a number of high performing SDDL products on the market, including Cree's 92 CRI dimmable MR16 Series,[2] Green Creative's 95 CRI dimmable MR16 series,[3] and Soraa's 95 CRI dimmable MR16 series.[4]

We also recommend that CEC broaden its definition of white light to ensure that only products that are truly colored lamps (e.g. party lights) are exempt from the proposed standards. In the September 2014 Staff Report, CEC proposed to exempt any lamp that is more than 7 MacAdam steps from the black body locus. This exemption as stated could invite abuse of the specifications by manufacturers allowing them to exempt products of poor quality from the performance requirements. The original ANSI standard (C78.377) for white light color bins allowed white light sources to be within 7 steps of the locus, so lamps that were 8 or 9 steps off the locus are just *barely* outside the original ANSI tolerance. CEC should not exempt these products from standards, as they could easily be marketed and sold as white lights, despite providing a quality of light with a noticeable pinkish or greenish tint. The CEC should broaden coverage to include all lamps with a D_{uv} of +/-0.02, which would translate to a distance of approximately 20 steps from the locus.

2.2 Color Rendering

We recommend CEC adopt a minimum requirement of CRI (Ra) $\geq$ 90 and $R_9 \geq 50$ for all covered LED lamps. This recommendation is based on the following findings, which will be demonstrated throughout this section:

- Products with low CRI can significantly distort colors and will not reliably provide consumers with accurate color rendition. Products with a CRI above 90 and an R_9 value of 50 reliably provide accurate color rendition that is more similar to the incumbent technology we are trying to replace.
- There is a wide range of design strategies to achieve high CRI and significant market competition across a wide array of manufacturers with 90CRI products.
- The average CRI of products introduced to the DOE Lighting Facts Database has been steadily increasing over the last four years, and 90CRI is no longer an aggressive target.
- Prices of high CRI products are coming down very rapidly. Forecasts show high CRI and low CRI products will be increasingly cost-competitive in the near future.
- High CRI products provide a fuller spectrum of light, requiring fewer lumens to result in equivalent perceived brightness.

If the CEC deems that a phased-in approach is needed to allow the industry more time to comply, we recommend starting with 85CRI and R_9 of 25 in 2017, and moving to 90CRI with R_9 of 50 in 2019.

2.2.1 Importance of Color Accuracy

High CRI products render colors more accurately and more like the way the incumbent technology renders colors. A requirement of CRI of 82 would allow light sources with significant color distortion. To our knowledge, no studies exist that prove this level of color distortion is acceptable

[2] http://www.cree.com/News-and-Events/Cree-News/Press-Releases/2014/August/MR16-bulb-intro
[3] http://www.gc-lighting.com/wp-content/uploads/GREEN-CREATIVE-LED-CRISP-SERIES-MR16-7W-High-CRI.pdf
[4] http://www.soraa.com/products/MR16-GU5.3

to consumers or that consumers will adopt this level of color rendering throughout their homes. The only real-world example we have is the example of CFLs, which provide CRI in the low 80's, and never reached market shares above 30-40% despite years of promotion and incentive dollars. If we expect consumers to replace incandescent sources with LEDs en masse, LEDs should provide accurate color rendition.

A study conducted by U.S. Department of Energy (DOE) entitled "Energy Savings Potential of Solid-State Lighting in General Illumination Applications," split out the lighting market into CRI bins based on total lumen hours and found that 60% of the total lumen hours in the residential sector is specifically high CRI light (above 90). This is the portion of the lighting market that we are aiming to replace with LED lighting in the coming years, and to do so, LED lighting must be 90 CRI.

Though the primary argument for higher CRI is increased color accuracy/fidelity, which is an objective argument, not a subjective one, we do recommend that the CEC review the consumer preference study published by Pennsylvania State University in 2014, "Perceptual Responses to LED Illumination with Colour Rendering Indices of 85 and 97."[5] The study compared participants' reactions to two LED lamps – one with high CRI, one with lower CRI, and found a clear preference for the higher CRI source.

2.2.2 Design Strategies for High CRI

There are currently more than 70 companies providing CRI of 90 or greater in a wide variety of LED luminaire types, and over 15 with 90CRI LED replacement lamp offerings, including but not limited to the following:

- Cree
- Epistar
- Feit Electric
- GE
- Green Creative
- Greenlite
- LEDnovation
- LEDshine260
- Nicor
- Soraa
- Sunrise Lighting
- Ushio

Many of these lamp manufacturers incorporate LED chips made by different LED manufacturers, including but not limited to the following:

- Seoul Semiconductors
- Samsung LED
- OSRAM Opto Semiconductors Inc.
- Philips Lumileds
- Rohm Semiconductor
- Cree Inc.

There are multiple design strategies to achieve high CRI that would not favor certain manufacturers or raise patent concerns. At a high level, most LEDs utilize some level of phosphor conversion, which entails the combination of a semiconductor chip (typically blue, violet, or UV) with

[5] M Wei MSc, KW Houser PhD, A David PhD and MR Krames PhD; Perceptual responses to LED illumination with colour rendering indices of 85 and 97; 2014 http://lrt.sagepub.com/content/early/2014/08/22/1477153514548089.abstract

converter materials (advanced phosphors), to achieve high CRI. More recent approaches add other color emitters, often red or amber, which allow for high CRI but with much higher efficacies.

At a more detailed level, individual manufacturers report using different technologies to achieve high CRI. Even within individual manufacturers, multiple design strategies are often used. New design strategies, including phosphor mixes, emitter combinations, substrate designs, and internal lamp configurations / phosphor conversion processes, are announced regularly as manufacturers continue to find ways not just to improve CRI, but to improve CRI while maintaining or improving efficacy and lowering cost.

Cree has high CRI products with warm CCT that mix red LEDs into the design, and in other products they use a different technique in which neodymium oxide is deposited on the inside of the lamp's globe to filter some portions of the color spectrum and enhance the energy produced in the red and green areas of the spectrum.[6]

Osram Opto has developed a new LED that includes four separate emitters — warm white, ultra white, green, and amber.[7] Other Osram designs achieve both high CRI and high luminaire efficiencies by combining two common existing methods – mixed color from monochromatic LEDs and phosphor converted LEDs – to create a warm white LED light source with both high CRI (> 90) and high luminous efficacy. This new approach makes total luminous efficacies of over 110 lumens per watt (lm/W) possible, producing up to up to 30 percent more light than phosphor-converted warm-white LEDs with a comparable CRI, but with similar power consumption. This approach uses red or amber monochromatic LEDs, combined with special white LEDs which have been shifted into the green range with a blue chip and green phosphor. The green phosphor has a very low conversion loss rate and makes for a very efficient light source in combination with the blue chip.[8]

Philips Lumileds (which is based in California and owned by parent company Philips) continues to expand its high CRI research as well. In July 2014, the California Energy Commission announced that Philips Lumileds Lighting Company passed into the 2nd stage of a funding solicitation process to receive Electric Program Investment Charge (EPIC) funding for a Project titled "Innovation for Disruptive Efficacy and Cost Improvements of CRI 90 LEDs and LED Lamps."[9]

Manufacturer Yuji International provides a demonstration of two methods it uses to achieve very CRIs in its products, one starting with a blue chip, and the other with a violet chip, using different phosphor mixes shown in Figure 2.1.[10]

[6] http://www.ledsmagazine.com/articles/iif/2013/09/cree-launches-high-cri-led-lamp-that-meets-california-regulatory-spec.html
[7] http://www.ledsmagazine.com/articles/2013/11/osram-opto-launches-a-95-cri-led-for-medical-lighting-applications.html
[8] http://www.mouser.com/applications/lighting-cri/
[9] http://www.energy.ca.gov/contracts/PON-13-301/PON-13-301_Stage_1_Results.pdf
[10] http://www.yujiintl.com/high-cri-led-lighting

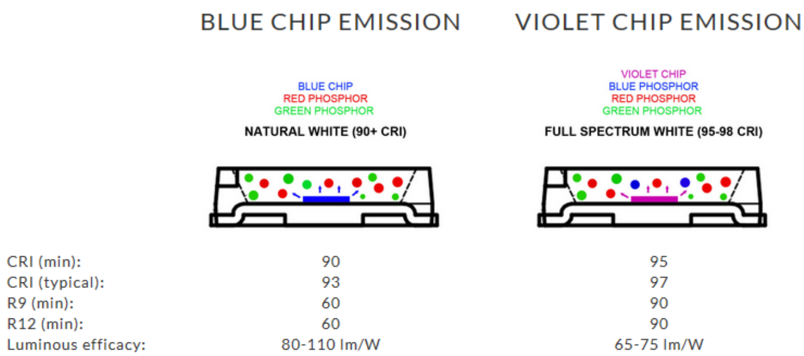

Figure 2.1 Demonstration of two design strategies for achieving 90 CRI

The specific phosphors utilized in high CRI lighting are evolving as well. Intematix Corporation, a Fremont, California-based provider of phosphor materials and components, announced that it has demonstrated a phosphor blend that provides a CRI of 98 and R9 value of 99 when applied to a reference LED package. The blend combines three separate phosphor material families.[11] Phosphor improvements can also improve the efficiency of 90 CRI LEDs – for example the introduction of a narrow (< 50nm FWHM) red phosphor. The narrower red phosphor increases the lumen efficiency by substantially reducing the emission outside the eye's sensitivity range. By optimizing the material quality, the wavelength peak, and the width of the red phosphor's emission, up to 20% gains in 90CRI LED efficiency may be achieved and thus close the gap between higher and lower CRI.[12]

As a related example, GE has been working on a red line emitting phosphor (potassium fluorosilicate) for use in white LEDs that achieves a high CRI (>90) while maintaining measured efficiency of 170 lumens per watt (lm/W). GE has begun spreading news about this development and is presenting it at industry workshops.[13]

2.2.3 Market Trends

As previously demonstrated in the CASE Report submitted on this topic, average CRI trends have been increasing among new lamp models for the last several years. In 2014 alone, over 140 new replacement lamps have been added to the DOE Lighting Facts Database with CRI's above 90, corresponding to about 15 new high CRI lamp products every month. Products are routinely introduced at 96 CRI or higher. 90CRI no longer represents a high end level of performance only achieved by specialty products. Given these trends in the market, the CASE team believes that a minimum 90CRI requirement in 2017 is not an aggressive target for the industry.

In less than one year since the implementation of our utility rebate programs that support 90CRI replacement lamps, the list of available products has increased from about 3 products to over 40 products, as shown in the figure below, and these products include A-lamps, PAR lamps, R/BR lamps, and retrofit kits (downlights). These are products that comply with the CEC's Voluntary Spec (which includes a list of rigorous performance requirements in addition to CRI). Due in large

[11] http://www.ledsmagazine.com/articles/2011/10/led-r-d-results-osram-demos-200-lm-w-red-led-at-40-ma-intematix-hits-98-cri.html
[12] http://www.allledlighting.com/author.asp?section_id=3253
[13] http://s36.a2zinc.net/clients/pennwell/sil2015/public/SessionDetails.aspx?FromPage=Calendar.aspx&SessionID=11162

part to the efforts of upstream lighting incentives, administered according to directives by the CPUC and the CEC, there will likely be millions of 90+ CRI products sold throughout California by 2017.

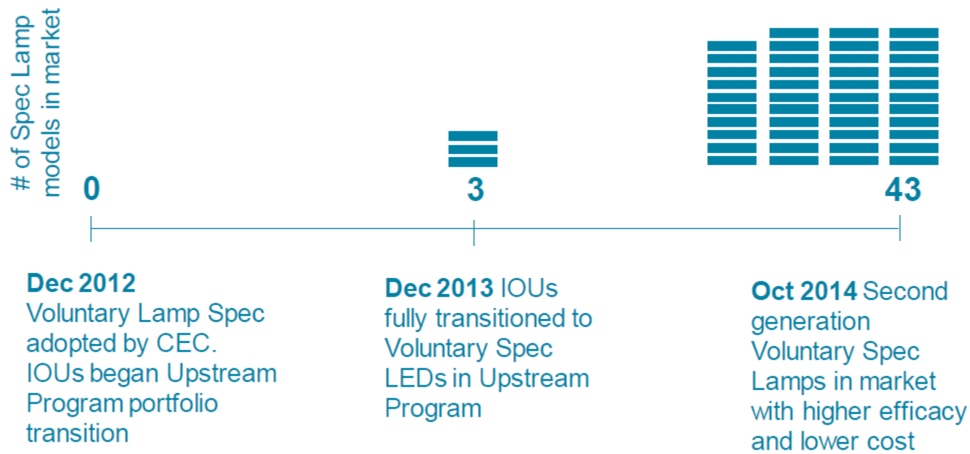

Figure 2.2 CEC Spec Products in IOU Rebate Programs

Since the adoption of 2013 Title 24, which included a 90 CRI requirement for residential LED products claiming high efficacy credit, the CEC has been collecting information on residential LED products with high CRI in its Appliance Efficiency Database.[14] This public resource now includes a list of over 5,000 90+ CRI "High Efficacy LEDs for Title 24." This list includes over 38 manufacturers and 57 brands, and represents hundreds of unique high CRI dedicated LED luminaire product lines, including downlights, track lights, wall sconces, pendants, and others. If the CEC moves to 90CRI for replacement lamps as well we expect to see a similar influx of high CRI lamp products.

2.2.4 Price Trends

Prices are falling quickly for all LEDs, but they are falling more rapidly for higher CRI products. The CASE team has been monitoring LED pricing closely using both web-crawler tools to regularly scrape hundreds of price points from online retailers, as well as tracking individual price points of high CRI products, including those that meet the CEC Voluntary Specification.

Below is a graph that shows average online pricing per kilolumen based on A-lamp prices collected from nine online retailers (including HomeDepot.com, Lowes.com, Bestbuy.com, Ace.com, 1000bulbs.com, and others), between late 2013 and Fall 2014. In less than one year, average pricing of low CRI products came down by about 25%, but the average pricing of high CRI A-lamps came down by about 36%. Exponential trend lines (dotted lines) provide a possible forecast. While other market drivers could alter the projections, the high CRI prices are projected to continue to approach the low CRI prices.

[14] http://www.appliances.energy.ca.gov/AdvancedSearch.aspx

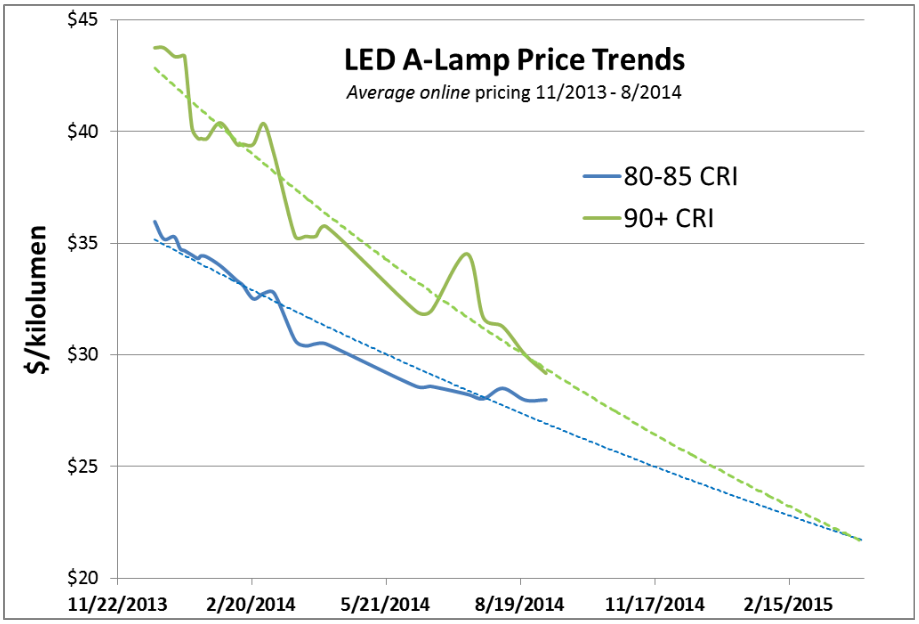

Figure 2.3 Average Online per Kilolumen Price Trends for A-lamps

These macro-level web-crawler results are corroborated by specific product launches from the past couple of years. Before the CEC Specification was passed, there were a handful of 90 CRI A-lamp products, including first the 910 lumen Philips L-Prize lamp, which sold for $40-$60, and then products from LEDnovation, such as the 810 lumen lamp at $30-40. After the adoption of the CEC Spec, other products have been introduced at lower prices, including Green Creative's 800 lumen A-lamp (~$22-25), and Cree's 800 lumen A-lamp, released at around $20 (before rebates) in late 2013 at Home Depot and other retailers. Within 6 months, in Q2 of 2014, the Cree product price was reduced by 25%, to about $15. In fall 2014, Feit released a 60Wequivalent A-lamp CEC Spec product that retails for $9 at Costco (again, before rebates). In other words, in less than one year, the price of CEC Spec 60Wequivalent A-lamp products has been cut in half. Based on conversations with manufacturers, future price points for high CRI products are expected to continue to drop rapidly.

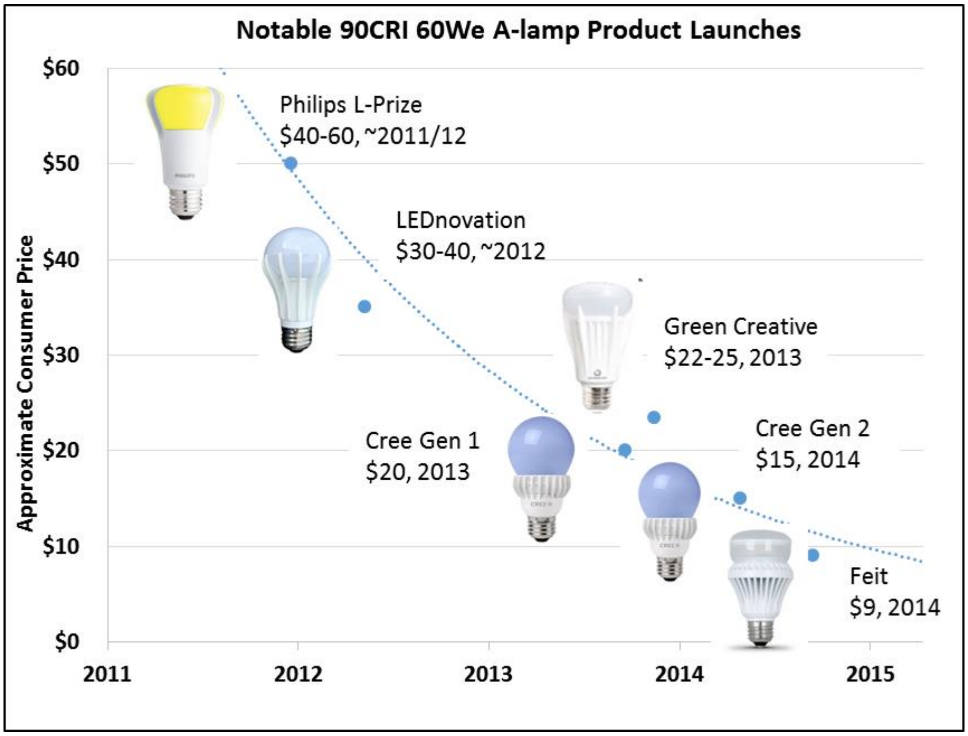

Figure 2.4 High CRI A-lamp Price History

Prices for comparable low CRI products (~80) from major manufacturers have generally been lower over the past year or two than the prices for high CRI products, but they are now very similar, since 90 CRI prices have come down so quickly. The following is a list of 60Wequivalent products from major manufacturers, with lower CRI, available currently from major retailers (before rebates).

Table 2.1 2014 Price Points for LED A-lamps with Low 80s CRI

Make	Model / Description	Lumens	Retailer	Approx. Nov. 2014 Price
Osram	8.5W LED A19 2	800	Lowe's	$10
Philips	Dimmable LED A19	830	Home Depot	$15
Philips	SlimStyle A19 Dimmable	800	Home Depot	$9
GE	60W Equivalent Soft White (2700K) A19 Dimmable	800	Home Depot	$11.50

2.2.5 Efficacy and Wattage Comparisons

It is a common misconception that high CRI sources need to draw more power than low CRI sources to be perceived by consumers to be of equal brightness. It is true that if one compares lights with excellent color rendering but different lumen output, people usually slightly prefer increased lumens, although the difference has to be quite large (roughly a factor of two) for most people to notice or care. But the situation is completely different if one compares visual satisfaction for lamps with CRI 80 to lamps with CRI 90 or greater. In that case, color rendering plays a very important role in the accurate perception of illuminated objects, and therefore in the overall satisfaction people experience with light. In other words, it is perfectly reasonable that some sources with a higher CRI can provide equivalent (or increased) lighting perception value than some sources with lower CRI and more lumens.

This concept has been demonstrated in multiple studies, including a recent paper submitted to Leukos, the quarterly journal of the Illuminating Engineering Society of North America, entitled "High Color Rendering Means Better Vision without More Power"[15] (the paper is now in the final stages of review). It examines the trade-off between CRI and the luminous efficacy of radiation, and corrects several misconceptions that have led to a disproportionate emphasis on efficacy over color. It references scientific literature that quantifies the differences in perception of the human eye in response to changes in color rendering and changes in illuminance. It demonstrates that relatively large percentage reductions in light levels are insignificant to most people, while relatively small decreases in color fidelity can be quite noticeable and objectionable. The paper goes on to discuss the "human value per watt" from a mathematical perspective associated with different lighting designs. As the title suggests, the paper demonstrates that increases in power are not needed to provide people with the high color rendering light which they prefer.

Another paper by Mark Fairchild, recently published in LD+A, the magazine of the Illuminating Engineering Society, "A Metric for the Aesthetic"[16] explained that it has "been well established that perceived brightness does not correlate directly with luminance," and that it is therefore "possible for a lighted environment to appear brighter, and therefore more colorful, in situations where the measured luminance (or illuminance) is actually lower." The author specifically calls out a comparison of two LED sources, one with higher CRI and lower lumen output, the other with lower CRI and higher lumen output, and the observation that that the lower lumen source actually appeared brighter.

This is not a new concept either – it has always been true that light sources with relatively high green and yellow content are very efficacious (considering their luminous efficacy), simply because the yellow-green wavelengths are weighted the highest in the calculation of photopic lumens and therefore luminous efficacy. But people don't want greenish lamps, so the increase in efficacy does not add value from the end user's standpoint. The situation is precisely the same for CRI – promoting lamps that appear white but which distort the colors of illuminated objects would give less useful light per Watt.

Even if one does choose to compare sources with the same lumen output, the extreme gains forecasted for all LEDs in the years ahead will render any difference in wattage between high CRI and low CRI sources virtually immeasurable. DOE's 2013 Solid State Multi-year Program Plan forecasted warm white package efficacies of 225 lpw by 2020, and luminaire efficacies of 200 lpw.[17] Although replacement lamps are generally less efficacious than luminaires, these forecasts suggest that even lamp efficacies will be around 175 lpw by 2020. Even if we assume higher CRI products

[15] Whitehead, L. et. al; High Color Rendering Means Better Vision without More Power; 2014. Leukos publication pending.

[16] Fairchild, Mark; A Metric for the Aesthetic; August, 2014. http://www.ies.org/lda/HotTopics/LED/28.cfm

[17] DOE; SSL R&D Multi-Year Program Plan; 2013. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2013_web.pdf

continue to carry a 15% efficacy penalty, we would expect to see 90CRI products at 150 lpw. For a typical 800 lumen lamp, the difference between 175 lpw and 150 lpw translates to a wattage difference of only 0.8W.

2.2.6 Importance of R_9

R_9 is important because it is an indicator of a light source's ability to accurately render red hues, where high efficacy lighting historically falls short. Red content is especially important for the accurate rendering of foods, skin tones, wood/furniture, etc. The CRI metric alone does not adequately account for the rendering of reds, because the color samples R_1 through R_8 (upon which the CRI calculation is based) are primarily pastel shades, not saturated colors. Though samples R_1 and R_8 are pink/purplish color samples with some red content, they are not saturated color samples, so high scores can be achieved without significant red content in a light source. R_9, on the other hand, is a saturated red color sample, so there is no way to achieve a high R_9 score without significant red content. The image below demonstrates this effect. It shows the relative spectral reflectivity properties (the percent reflectance at each wavelength) of all color samples R_1 through R_9, when illuminated by a reference source. It demonstrates that the samples R_1 through R_8 include a mix of many different colors, while R_9 includes high spectral reflectivity in the red region (above ~625nm) with virtually no reflectivity in other color regions (below ~600nm).

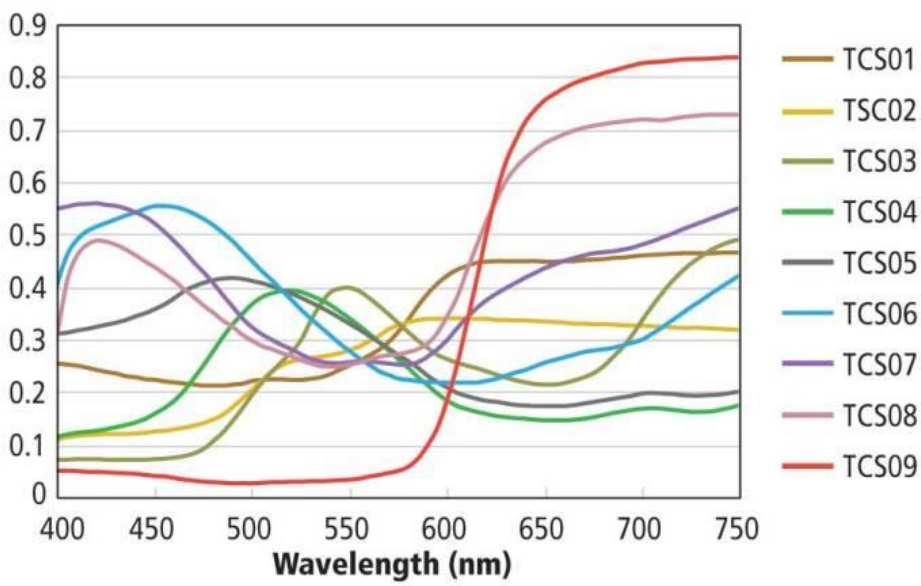

Figure 2.5 Relative Spectral Reflectivity Properties of Color Samples R1 through R9

It is also worth noting that the inclusion of an R_9 score of 50 has widespread support. Public comments submitted to the CEC in summer 2014, from NEMA[18] and from NRDC[19] and others, supported a minimum R_9 value of 50.

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[18] http://www.energy.ca.gov/title24/2016standards/prerulemaking/documents/prerulemaking_comments/NEMA_Comments_on_Staff_Workshop_on_Proposed_Lighting_Efficiency_Measures_for_Residential_and_Nonresidential_Buildings_2014-07-25_TN-73481.pdf

[19] http://www.energy.ca.gov/title24/2016standards/prerulemaking/documents/prerulemaking_comments/Natural_Resources_defense_Councils_Comments_on_the_Title_24_2016_Pre-Rulemaking_Workshops_2014-08-07_TN-73569.pdf

2.2.7 Minimum Requirements for Color Samples R_1 through R_8

We strongly support the proposed requirement for individual color samples R_1 through R_8 to all have a minimum value of 75. This will help ensure that a minimum level of color fidelity is provided across the range of color samples and that no source is allowed to provide very poor rendering of one color by making up for it with high color rendering of another sample. Though we are supportive of a minimum requirement of 90CRI, we would also note that this requirement for R_1 through R_8 in itself is not a 'back door' requirement for 90CRI. In product testing conducted by CLTC on behalf of PG&E and CLASP in 2013 at least four lamps were found that passed the proposed requirement for minimum 75 R_1 through R_8 values, but that *did not have CRI above 90*. One of those four lamps has a CRI of only 85, the other three have CRI's between 86 and 88. This demonstrates that it is possible for lamps to meet the proposed R_1 through R_8 requirement but deliver CRI in the mid-80's.

2.3 Efficacy (Including Efficacy and CRI trade-offs)

We support the minimum efficacy requirements proposed in the staff report: 55 lpw in 2017, and 65lpw in 2019. We also support the concept of the efficacy/CRI trade-off equation proposed by the CEC as this acknowledges that higher CRI products may not need to provide as many photopic lumens to generate equivalent perceived brightness. However, as discussed in the previous section, we do not support the specific levels proposed for CRI; we believe the market is ready to move to 90 CRI as soon as 2017. If the CEC prefers a phased-in approach, we would recommend an approach such as the one shown in the following graph (starting with 85 CRI as soon as possible and increasing to 90 thereafter). This alternate proposal utilizes the CEC's equations for the slope of the CRI and efficacy tradeoff, but it starts with a minimum of 85CRI in 2017 and moves to 90 CRI in 2019. For a lamp achieving the lowest allowable CRI, the required efficacy would be approximately 80lpw.

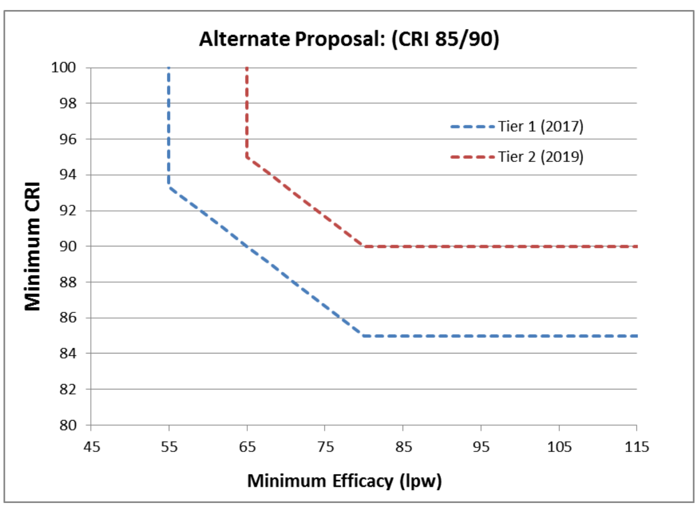

Figure 2.6 Alternate Proposal for Efficacy and CRI Trade-off Equations

2.4 Life / Early Failure / Reliability

Early failure was a significant cause for consumer dissatisfaction with CFLs and we recommend that the CEC take steps to ensure LED reliability and long product life. National testing efforts, including recent studies conducted for DOE ("LED Luminaire Lifetime: Recommendations for Testing and Reporting"[20] and "Hammer Testing Findings for Solid-State Lighting Luminaires"[21]) have found that lumen depreciation is rarely the cause of end of life in LED luminaires. Both studies found that driver failure or other electrical/component failures are most often responsible for SSL product catastrophic failure. These studies investigated multiple accelerated life test methods using various high stressors, including those based on temperature (including both high and low temperature extremes), humidity, vibration, electromagnetic irradiation, voltage, outdoor UV exposure, chemical exposure, electrical power, and ripple. The primary advantage of performing accelerated testing is to reduce test time.

Of all the accelerated stressor conditions studied, the Next Generation Lighting Industry Alliance and LED Systems Reliability Consortium concluded that temperature is perhaps the most fundamental environmental factor for electronic devices (such as drivers/power supplies). The "Hammer Test" study found failure modes that resulted from several different temperature-related accelerated tests. Furthermore, current ongoing life testing at the CLTC, being funded by PG&E and also through CEC's PIER program, is also investigating early failure rates and included elevated temperature tests. The complete analysis from the first 3,000 hours of CLTC testing of over 600 lamp samples will be available and submitted to the Commission this winter, but early results suggest that early failure is a concern for LED lamps, with over 4% of products failing in the first 3,000 hours despite lamp life claims often higher than 25,000 hours.

Heat build-up is especially common in recessed and enclosed fixtures, so these sockets are important from an LED reliability perspective. The recent Residential Lighting CASE Proposal submitted to the CEC in Fall 2014 in support of the 2016 Title 24 building efficiency standards found that about half of all the hard-wired sockets in new homes are recessed fixtures (16 out of 31). The CASE team estimates that another 10-20% may be fully enclosed fixtures. Meanwhile, over 375 products are listed in the ENERGY STAR Lamps products database as "Not for Use in Enclosed Fixtures," or "Not for Use in Recessed Fixtures." Most of these products are also labeled as such on their packaging, though this is often in the fine print, and we believe many consumers will not notice or appreciate the significance of this label.

[20] http://www1.eere.energy.gov/buildings/ssl/pdfs/led_luminaire_lifetime_guide_sept2014.pdf
[21] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/hammer-testing_Dec2013.pdf

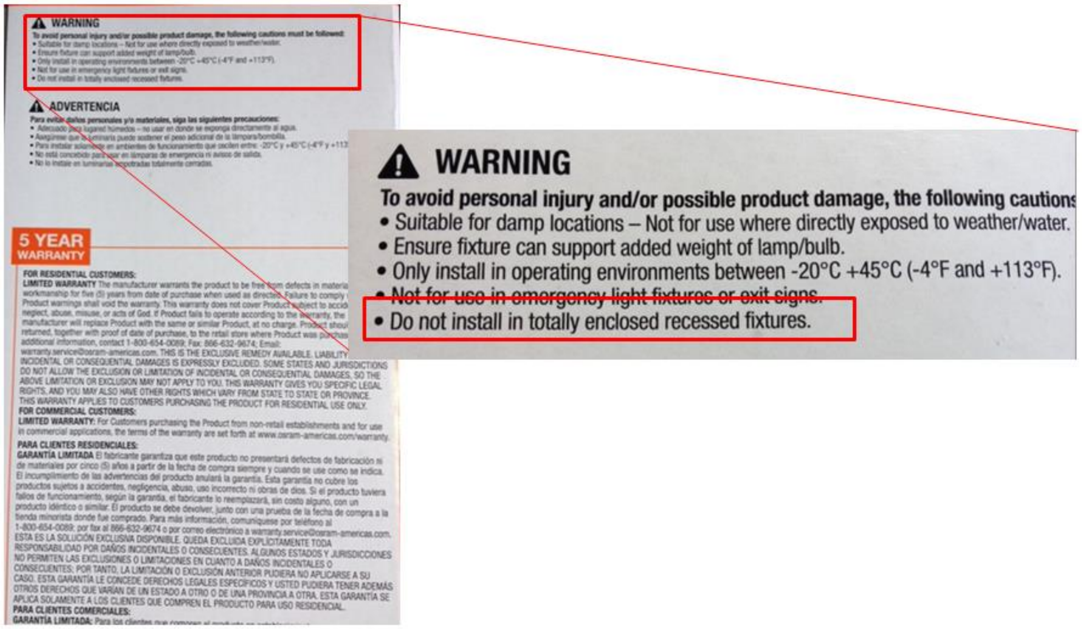

Figure 2.7 Demonstration of Fine Print Warnings about Enclosed Fixtures on Product Packaging

If bulbs die early because they are installed in recessed or enclosed fixtures, this will represent a significant obstacle to consumer satisfaction and LED adoption rates. Fortunately, DOE's Hammer Test found that most products are actually quite durable, and many products are in fact rated for these types of fixtures where heat build-up is common – almost 700 products in the ENERGY STAR database are labeled "Suitable for Use in Recessed or Enclosed Fixtures," including various A19 and floodlight products from manufacturers such as Philips, Cree, Sylvania, Green Creative, and TCP.

To ensure that replacement lamps are designed to handle the high heat conditions they are likely to experience in recessed and enclosed fixtures, we recommend that CEC include an elevated temperature test for all lamps; this test would address both lumen maintenance and early failure. We encourage CEC to engage industry stakeholders on the details of such a test procedure, and we also will appreciate an opportunity to submit further recommendations based on the final results of the ongoing testing being completed this winter at CLTC. However, based on currently available information, we recommend that CEC largely align with the ENERGY STAR elevated temperature testing protocol and requirements:

- 10 samples should be tested using ENERGY STAR's Elevated Temperature Test Procedure (Option A, B, or C) from its Lamps v1.1 Specification. For consistency with the CEC's recently published draft 2016 Title 24 standards, we recommend the following revisions:
- If using Option A, light source shall be tested in an ICAT (insulation contact, air-tight) recessed luminaire of the appropriate size for the source under test. The ICAT luminaire shall be listed for zero clearance insulation contact (IC) by Underwriters Laboratories or other nationally recognized testing/rating laboratory and have a label that certifies that the luminaire is airtight with air leakage less than 2.0 CFM at 75 Pascals when tested in accordance with ASTM E283. The sides and top of ICAT recessed luminaire shall be in direct contact of least 12" of R-38 fiberglass insulation.

- If using Options B or C, test at 45°C for sources less than 20W, and test at 55°C for sources greater than 20W.
- The average lumen maintenance of the 10 samples shall be at least 93.1% for all lamps. For lamps making rated lifetime of 25,000 hours or greater, average lumen maintenance should be at least 95.8%. Any early failures in the first 3,000 hours should be included in the average calculation as having 0% lumen maintenance.

Though ENERGY STAR requires 6,000 hours of testing for full product certification, we have proposed a minimum of 3,000 hours of testing (which aligns with ENERGY STAR's interim certification protocol) in order to allow manufacturers a shorter testing period before being able to release products to the California market. We do not recommend the Commission reduce testing time to any duration shorter than 3,000 hours, particularly given that CEC has not proposed a warranty requirement, and most product life time claims are 15,000 to 25,000 hours or longer. We do not believe 1,000 hours of testing, for example, would be sufficient to responsibly claim that a product meets a projected lifetime of 15,000 to 25,000 hours if CEC is not also proposing to require a warranty.

2.5 Dimming

We recommend that CEC require all LED lamps to be dimmable down to 10% of full light output (or lower) and that lamps designed for phase-cut dimming (the majority of LED replacement lamps) be compliant with NEMA SSL7A, the recently developed phase-cut dimmer compatibility standard.

Lack of dimmability was a major cause of consumer dissatisfaction with CFLs, and as dimming sockets become more and more prevalent in California due to building code requirements, the ability of LED lamps to dim well will be crucial for their mass adoption. The Northwest Energy Efficiency Alliance (NEEA) Residential Building Stock Assessment,[22] the first phase of which was published in late 2012, found that across their study of 1,850 homes in the Pacific Northwest, only 6.6% of the sockets controlled by dimmers had CFL lamps installed in them. For example, in dining rooms, where fixtures are commonly controlled by dimmers, CFL adoption rates were appreciably lower than in other rooms. Considering that total CFL market share is 30-40%, these results indicate that sockets on dimmers have not been converted to high efficacy sources at nearly the rate that non-dimming sockets have. Though dimming CFLs are now available, many consumers had negative early experiences when trying to install non-dimmable CFLs on dimming sockets. Distinguishing between dimmable and non-dimmable LED lamps will only create unnecessary labeling confusion for consumers and will impede the adoption of LED lamps.

Most LED lamps are already dimmable but some are not. Among the thousands of LED lamp products for which we are collecting online price data, about 85% are labeled as dimmable. In the ENERGY STAR database, over 2,000 products (about 65% of the total) are labeled as dimmable. About 75% of those are dimmable to a level of 10% or lower. Over 400 products are listed as dimmable below 5%.

[22] Northwest Energy Efficiency Alliance; 2011 Residential Building Stock Assessment: Single Family Characteristics and Energy Use, 2012. http://neea.org/docs/reports/residential-building-stock-assessment-single-family-characteristics-and-energy-use.pdf?sfvrsn=8

Section 5.4.2. of the 2013 CASE Report presented an analysis documenting savings potential for standards compliant dimmable lamps installed on dimmers (savings ranged from 4 to 14 kWh per year), and the weighted average savings for standards compliant LED lamps across the state (assuming 25% of lamps get installed on dimmers). Those tables are provided again here.

Table 2.2 Per Unit Energy Savings by Lamp Type (for lamps installed in dimming sockets)

Lamp Type	**Per Unit Energy (dimming sockets)**		
	Non-Qualifying kWh/yr	Qualifying kWh/yr	Savings (kWh/yr)
General Service A-lamp	13.8	7.6	6.2
Large Diameter Directional	37.9	24.1	13.8
Small Diameter Directional	23.2	14.8	8.4
Decorative	8.7	4.8	3.9

Table 2.3 Weighted Average per Unit Annual Energy Savings by Lamp Type (for lamps installed in all CA sockets)

		Annual Energy Savings (kWh)			
		General Service A-lamp	Large Diameter Directional Lamp	Small Diameter Directional Lamp	Decorative Lamp
Not Installed on Dimmer	75%	2.1	5.5	3.4	2.2
Installed on Dimmer	25%	6.2	13.8	8.4	3.9
Weighted Average Per Unit Annual Energy Savings		**3.1**	**7.6**	**4.6**	**2.6**

Off-the-record comments from industry contacts who are either in the driver manufacturer community or who have conducted research into dimming driver ICs suggests that the incremental cost for an LED driver to be dimmable is small and shrinking. Estimates range from $0.15 to $0.20 incremental manufacturer cost, dropping to 5 cents or less in the next few years. To verify that the incremental manufacturer cost to add dimmability is indeed small, the CASE team has conducted an analysis of thousands of retail prices collected from 9 online retailers. Based on statistical analysis of that data, there is no statistical relationship between dimmability and retail prices for A-lamps. In fact, as shown in the figure below, online prices for dimmable LED replacement lamp products (based on price points from hundreds of products collected throughout 2014) are actually slightly lower, on average, than prices for non-dimmable products. This suggests that any incremental manufacturer cost associated with making a product dimmable is negligible. It also stands in stark contrast to the CFL market, where historically few products were dimmable and they carried significant incremental retail prices.

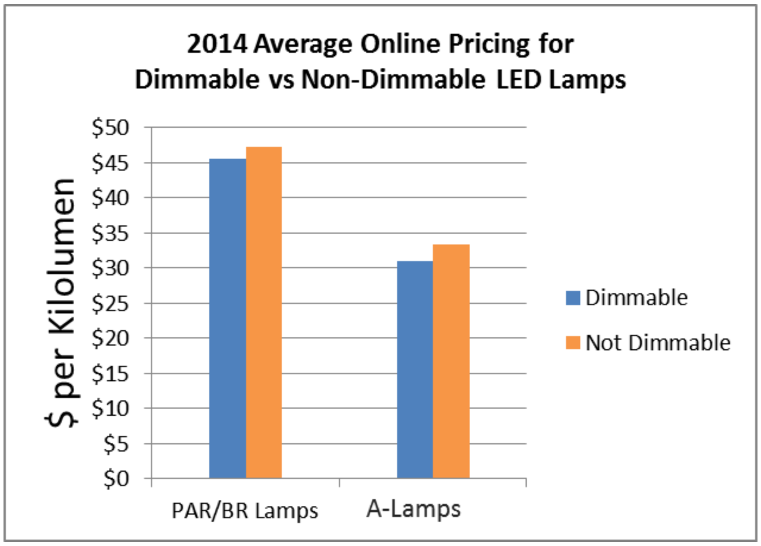

Figure 2.7 2014 Average Online Pricing for Dimmable vs. Non-Dimmable LED Lamps

2.6 Dimming Test Procedure

We recommend that CEC provide more specificity around the test procedure for verification of dimming performance. It is important for lamps to be dimmable not just with one dimmer, but with a variety. Our current recommendation is that CEC leverage the progress made by ENERGY STAR towards a test procedure for dimmability. The ENERGY STAR Lamps Specification requires that lamps be tested with five different dimmers from at least two different manufacturers. It also requires two different test configurations for each of the five dimmers—first with one sample of the lamp model on the dimmer circuit, then with four samples of the lamp model on the dimmer circuit. This provides a range of typical conditions likely to be encountered. This procedure results in a minimum of ten different test configurations per lamp model—and the lamp must pass the dimming requirements in 80% of the test configurations.

We support this general approach, but believe it could be improved. ENERGY STAR's specification explained that their "intent is for the dimmers selected to be varied in electrical construction and to represent a wide range of potential consumer situations. For example, a selection of five dimmers might include at least one dimmer specified for use with energy efficient lighting (such as CFL or LED lamps), one that has pre-set levels, one forward-phase dimmer rated 600W, and one reverse-phase dimmer." However, ENERGY STAR did not specifically require any variety in dimmer type, and we recommend that CEC do so. We also recommend that CEC require manufacturers to specify and report the dimmers used for testing by the manufacturer name, model number and load ratings when they submit their product data to the CEC Appliance Efficiency Database.

We encourage CEC to engage industry stakeholders to further specify the dimmer selection process, through a meeting with manufacturers of lamps, drivers, dimmers, and components (e.g. driver ICs) and others to discuss the test procedure options. Pending input from other stakeholders, we support the proposal submitted to the docket by California-based driver IC manufacturer Jade Sky, slightly modified as follows:

- Use at least one common digital-type dimmer, one traditional analog rotary dimmer, one occupancy sensor dimmer, and one simulated dimmer (programmable power supply).
- Of these, at least one of the dimmers tested shall be a forward phase cut dimmer and at least one dimmer shall be a reverse phase cut dimmer.

Testing completed by CLTC for PG&E included both a variety of dimmers from different manufacturers as well as a programmable power supply, and we do not believe this represents a significant incremental test burden. Most LED lamp manufacturers already test their products with far more dimmers in order to publish complete dimmer compatibility lists.

For low voltage lamps we recommend the following:

- At least one of the test configurations should include a magnetic transformer coupled with a leading edge-phase cut dimmer.
- At least one of the test configurations should include an electronic transformer coupled with a trailing-edge phase cut dimmer.

2.7 Flicker

We support the CEC's proposal to require reduced flicker operation in LED lamps but recommend that CEC add specificity to its requirement. Our proposal for the maximum allowed flicker is as follows:

- Lamps shall have an amplitude modulation (Percent Flicker) of less than 30 percent for frequencies less than 200 Hz, when tested at 100% light output and either at 20% light output or at the minimum claimed dimming level of the product.

This proposal is based on the assumption that all lamps are required to be dimmable. If the CEC proceeds with its proposal to not require all lamps to be dimmable, we would recommend that even non-dimmable lamps be required to pass a flicker test (in this case the test would be conducted at full light output only).

We also recommend that CEC adopt the Flicker Test Procedure contained in Appendix 1 for use with this Title 20 standard. This test procedure is based on the ENERGY STAR test procedure for flicker, but it includes more specificity around certain testing parameters. It also includes the methodology for filtering raw flicker data to isolate the amplitude modulation that is occurring at low frequency, which ENERGY STAR's test method does not do. The procedure in Appendix 1 is the same procedure that has been submitted to the Commission for use in the dimming fluorescent ballast measure, and for use in the Title 24 Residential Lighting measure. Because the test procedure has already been proposed by the Energy Commission to be included in Joint Appendix 10 (JA10) of Title 24, we have kept the format and section numbering consistent with the way it appears in the Title 24 documentation.

2.8 Audible Noise

We recommend that the CEC adopt the noise requirements from the ENERGY STAR Lamps Specification v1.1 (lamps shall not emit noise above 24dBA at 1 meter or less) as mandatory for all lamps. As discussed in the CASE Report audible noise is a common problem with LED lamps, particularly when installed on dimmers, and buzzing or humming is likely cause for consumer dissatisfaction. However, there are many products available that provide noise-free operation, as evidenced by the hundreds of products already certified to the ENERGY STAR database. We recommend that the Commission require noise testing at 100% and at either 20% light output or the minimum claimed dimming level of the product. If the Commission also continues to allow non-dimmable lamps, we recommend that noise requirements also apply to non-dimmable lamps (tested at 100% light output).

2.9 Directionality

We support the CEC's proposal to require lamps with ANSI standard lamp shapes of A, C, CA, or G to meet the directionality requirements of ENERGY STAR's Lamps Spec v1.1. However, ENERGY STAR's Lamps Specification contains different distribution requirements for general service omnidirectional lamps than for decorative lamps. CEC should clarify that lamps with ANSI shape A should meet the omnidirectional distribution requirements (contained in Appendix A-1 of the ENERGY STAR Lamps Specification), while lamps of shape C, CA, and G should meet the decorative lamp distribution requirements (contained in Appendix A-2 of the ENERGY STAR Lamps Specification).

2.10 Power Factor

We recommend that CEC include a minimum power factor requirement of 0.9 at full light output and 0.5 when tested either at 20% light output or at the minimum claimed dimming level of the product. Improving power factor has significant financial and greenhouse gas benefits for California consumers, it has minimal incremental manufacturer cost, no correlation to end user pricing, and there is already a preponderance of products that meet this level.

2.10.1 Technical Rationale for Power Factor

Power factor is defined as the ratio of the real power flowing to a load to the apparent power in the circuit, and is essentially a measure of how efficiently a load uses the current that it draws. A load with a low power factor draws more current than a load with a high power factor for the same amount of useful power transferred. Higher currents mean increased energy losses both on the customer side of the meter, and on the utility side (grid losses). The losses from a small load (for example an LED lamp) with a poor power factor may be small, but losses increase exponentially as the total current increases (power loss is a function of the current squared times the resistance of the wiring).Three lamps with poor power factor on a circuit result in nine times the losses of one lamp.

In comments submitted to the CEC early in 2014 in response to the Title 24 proposal for Residential Lighting,[23] NEMA suggested that poor power factor is a "utilities-based" argument, the implication being that a less efficient electrical grid is a problem for the utilities, not for consumers. To the contrary, grid efficiency (or lack thereof) is an integral part of electric rate design in California. In other words, if the California electric grid does not operate efficiently, California rate payers pay more for the energy they use. As Californians adopt LED lamps in greater numbers in the coming years (there are over 400 million sockets in the State), LED power factor will have huge implications for consumer energy bills, grid efficiency, and greenhouse gas emissions.

NEMA's comments to CEC also suggested that power factor correction is not needed because the "combination of lead and lag power factors" will cancel each other out. This is a reference to *displacement* power factor, where sinusoidal current and voltage waveforms are out of phase with each other. Displacement power factor is generally associated with capacitive and inductive loads; inductive loads, like motors, have "lagging" power factor, where current lags behind voltage, while typical capacitive loads (capacitors, electronics) have "leading" power factor (where the current leads voltage). It is true to some extent that leading and lagging power factor can cancel each other out; however, this does not apply when considering non-linear loads with *distortion* power factor, which is caused by current harmonics (distortion). LED drivers are an example of such a non-linear load (i.e. they draw current in short spikes which generally do not relate to the voltage waveform). For these types of non-linear loads, the combination of leading and lagging power factors will not cancel each other out predictably, consistently or effectively.

This is not new research; this phenomenon has been well documented through many studies over the years. The California IOU team has produced several analyses of losses from different products with poor power factor, including in our recently submitted comments (Oct. 27, 2014) on the Title 20 Dimming Ballast rulemaking, and in an analysis submitted in 2009 in support of the Title 20 Televisions rulemaking.[24] These studies documented the immediate end-user kWh savings and associated energy cost savings benefits, which were in the range of $3.50 - $7.50 for televisions and $1.20 for ballasts. Neither of these studies estimated the larger benefits to California consumers, which are the grid level inefficiencies which are eventually paid for by California rate payers through increased rates. The utilities have run many such calculations and could provide additional figures for LED lamps if needed.

Many other studies on power factor loss and its effects have been published as well, including several that specifically discuss the issue of harmonic distortion for non-linear loads. Several of these studies are provided here for the Commission's reference:

- Harmonics and how they Relate to Power Factor[25] (University of Texas with San Diego Gas & Electric)

[23] http://www.energy.ca.gov/title24/2016standards/prerulemaking/documents/prerulemaking_comments/NEMA_Comments_on_Staff_Workshop_on_Proposed_Lighting_Efficiency_Measures_for_Residential_and_Nonresidential_Buildings_2014-07-25_TN-73481.pdf

[24] http://www.energy.ca.gov/appliances/2008rulemaking/documents/comments/04-13-09_Energy_Savings_Estimate_for_Power_Factor_Correction_in_TVs_TN-51939.pdf

[25] http://www3.fsa.br/LocalUser/energia/QEE%20E%20TECNOLOGIAS%20DE%20USO%20FINAL/ARQ_10.pdf

- Power Factor, Harmonic Distortion; Causes Effects and Considerations (Northern Telecom)[26]
- Power Quality Guidelines for Energy-Efficient Device Application (Electric Power Research Institute for CEC)[27]
- Power Factor Correction: An Energy Efficiency Perspective (Ecos)[28]

2.10.1 Market Availability of High Power Factor LED Drivers

High power factor lamps are widely available. More than half of the lamps currently listed in the ENERGY STAR Lamps product database have a power factor of 0.9 or greater, offered from over 100 lamp manufacturers. Among the A-lamp product testing completed by CLTC for PG&E in 2012/2013, the *average* measured power factor was 0.9; 16 of 26 achieved 0.9 or greater, 10 were greater than 0.96. In the dimmed state, over half of the products tested (14 of 26) had a power factor greater than 0.5.

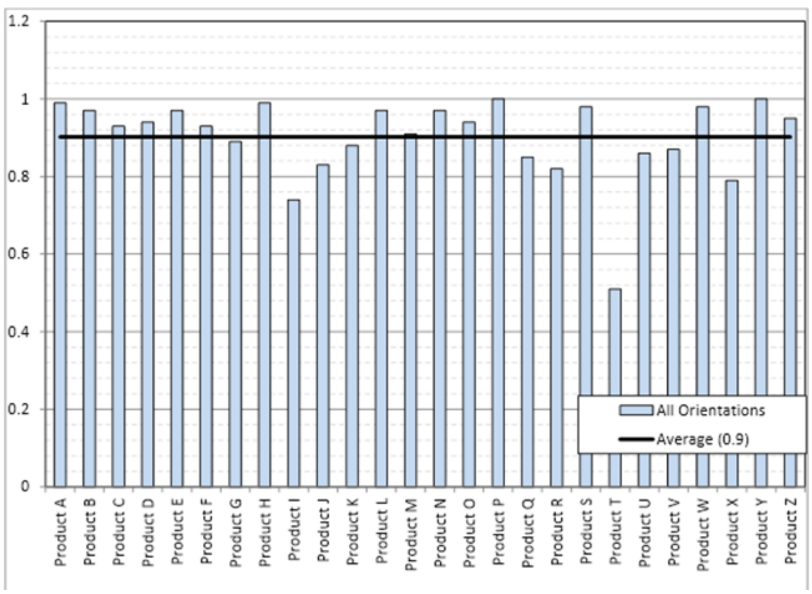

Figure 2.8 Power Factor Test Results for 26 A-lamps in 2012/2013[29]

High power factor driver performance is being provided by a wide array of driver IC manufacturers as well; there is no shortage of competition in this market. Our research found 19 different driver IC manufacturers supplying 0.90 PF drivers, including but not limited to:

- Cirrus Logic[30]
- Fairchild Semiconductor[31]

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[26] http://www.lumenteck.com/electronic_ballast/PFCHarmonics.pdf
[27] http://www.energy.ca.gov/reports/2003-09-15_500-03-073C.PDF
[28] http://standby.iea-4e.org/files/otherfiles/0000/0041/AGO_G3A_PowerFactorCorrection_FINAL_2011_0617-M.pdf
[29] http://cltc.ucdavis.edu/sites/default/files/files/publication/140609-report-omni-directional-led-replacement-lamps_rev140807.pdf
[30] http://www.cirrus.com/en/pubs/proDatasheet/CS1610-11-12-13_F6.pdf

- Infineon[32]
- NXP[33]
- Power Integrations[34]
- Texas Instruments[35]
- Toshiba[36]

Review of the product literature of these manufacturers also reveals that they are using a number of different design strategies to achieve 0.90 power factor, including both single stage and dual stage topologies, and different converters such as flyback, flyback+buck, boost, buck-boost, and many derivations. These strategies involve adding some level of control of the output current, but require minimal changes to the driver, especially compared to the control features already provided by most LED drivers. This wide availability of design strategies and IC manufacturers further indicates that there is no single pathway to achieving 0.90 power factor nor any concern about lack of access for some lamp manufacturers to obtain products at this level of performance.

2.10.2 Cost and Price Implications for 0.9 Power Factor

Based on informal conversations with manufacturers, the CASE team believes that the incremental cost to manufacturers to improve to 0.90 power factor is negligible. Depending on strategy, some estimates are as low as several cents or less, with the primary cost coming from a slight increase in the silicon area in the chip. To verify that the incremental manufacturer cost for power factor correction is indeed small, the CASE team has collected power factor data from the ENERGY STAR product database and the Lighting Facts Database, and has correlated it to over 1,000 price points from collected from online retail sites. Based on this analysis, we have not been able to identify any correlation between power factor and retail prices for replacement lamps. In fact, based on price points for over 500 lamps in the 500 – 900 lumen range, average online prices for high power factor (≥0.90) LED replacement lamp products are actually slightly lower ($22.64), than the prices for lower power factor (<.90) products ($23.47). This suggests that any incremental manufacturer cost associated with 0.90 power factor is negligible. Especially when considering the economic benefits associated with improved power factor to California consumers, power factor improvements are cost justified.

2.11 Labeling, Marking, and Reporting

We support the CEC's proposal to require lamps marketed as incandescent replacements or equivalents to have a CCT of 3000K or less. Typical incandescent lamps provide a CCT in the range of 2700K to 2900K, and most consumers expect this warm quality of light from a light bulb.

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[31] https://www.fairchildsemi.com/datasheets/FL/FLS3217.pdf

[32] http://www.infineon.com/dgdl/Datasheet_ICL8001G+vers+1.pdf?folderId=db3a304316f66ee801178c31a9af054a&fileId=db3a3043271faefd01273dce7b0e68f6

[33] http://www.nxp.com/products/lighting_driver_and_controller_ics/ac_led_driver_ics_dimmable/SSL21082T.html

[34] http://led-driver.power.com/products/lytswitch-family/lytswitch-4/

[35] http://www.ti.com/product/tps92075

[36] http://www.toshiba.com/taec/components/Datasheet/TC62D902FG.pdf

While some consumers may prefer and seek out high CCT lamps, it is misleading to market a product as a replacement for an incandescent if it provides a light color that is dramatically different. This is likely to lead to consumer dissatisfaction, similar to that experienced in the CFL market where many consumers objected to CFLs providing light that was too "cold" and "harsh." However, we recommend that the CEC require lamps *to be capable of* providing a CCT of 3000K, to accommodate color changing lamps.[37]

For the same reason, we also support the CEC's proposal to require lamps marketed as incandescent replacements or equivalents to provide a minimum light output corresponding to the claimed wattage equivalency. However, the values in the table provided by CEC should apply only to omnidirectional A lamps. Separate lumen equivalency values should be provided for directional and decorative lamps. CEC should use the ENERGY STAR values provided for lumen equivalencies for each lamp type, and should also utilize the ENERGY STAR center beam candle power equivalence tool for MR and PAR lamps.

Lastly, we would encourage the CEC to consider using the "equivalency" claims or any lamp marketing comparisons to incandescent to enforce other aspects of the CEC Voluntary Spec that are not being required of all lamps. As an example, if the CEC does not require all lamps to provide 90 CRI, it should at least require lamps claiming to be incandescent replacements to meet this level of performance. This would be consistent with the proposal to require a minimum light output (in terms of lumens) and a specific color temperature range to provide light that is similar to incandescent. The same should be done for color fidelity; lamps with CRI well below 90 are introducing a significant amount of color distortion relative to the incandescent lamp, so it is misleading to market an 80 CRI lamp as an equivalent product to an incandescent lamp (which has 100 CRI).

Another approach the CEC could consider as a way to ensure higher performance for some products would be a labeling scheme for residential or commercial products. For example, it could allow a lower CRI value for products clearly labeled "For Commercial Use Only," but require 90CRI for other products.

We support CEC's proposal that a lamp certified with a light output of less than 150 lumens for candelabra bases, or less than 200 lumens for other bases, shall be marked as "for decorative purposes only." These are such low levels of light that these products will not be useful for general lighting. We also support CEC's proposal for lamps to certify that each aspect of the California Quality LED Lamp Specification is met before making any marketing, label, or mark regarding a model's qualification for the specification. This will help our incentive programs to have a public resource of all test data for all required metrics for CEC Spec compliant lamps.

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[37] Conversely, CEC could consider exempting color changing lamps from several of the specific aspects of this standards proposal.

There are several additional marking / labeling requirements that we recommend that CEC adopt. First, we recommend that all lamp packaging include a label indicating the product's CRI, and for directional lamps, a label indicating the product's beam angle. These two metrics are not included in the Federal Trade Commission (FTC) Lighting Facts Label but they are extremely important product attributes that will help consumers. Though CEC does not have authority to revise or add to the FTC label, we recommend that California require these two product attributes be added elsewhere on the product package, for example directly below the FTC label.

Lastly, we recommend that the date of manufacturer be permanently marked on all products in the format: MM/YYYY. The Warren-Alquist Act already requires date of manufacturer be marked on covered products in Title 20, but there appears to be either low compliance with this requirement or alternate date formats/codes used that cannot be interpreted by average consumers. Having a clearly marked date of manufacturer will help consumers follow up on product warranties in the event of product failures. Date of manufacturer markings will also help with standards enforcement and compliance improvement for regulators in the State.

3 Appendix; JA10 Test Method for Measuring Flicker of Lighting Systems and Reporting Requirements

This test method quantifies flicker from lighting systems which may include all of the following components: lamps, ballasts or drivers and dimming controls. This test method measures the fluctuation of light from lighting systems and processes this signal to quantify flicker as a percent amplitude modulation (percent flicker) below a given cut-off frequency. High frequency components of the signal above the cut-off frequency are filtered out. Since this test method is measuring the relative fluctuation of light, the test can be performed using either absolute photometry or relative photometry. The flicker of lighting components shall be tested according to this method, or by a method approved by the Executive Director.

JA10.1 Equipment Combinations

Light source and dimmer combinations to be used in testing shall be determined as follows:

Light sources being tested for flicker should refer to the dimming test procedure associated with the light source for guidance on the selection of dimmers to be used in dimming testing.

Dimmers being tested for flicker should be tested with light sources as follows:

Flicker measurements of a phase cut dimmer controlling an incandescent line voltage lamp shall be considered representative of that dimmer with any line voltage incandescent lamp.

Flicker measurements of a phase cut dimmer controlling a transformer for low voltage incandescent lamps shall be considered representative of only that combination of dimmer and transformer with any incandescent lamp.

Flicker measurements of all non-incandescent lamp sources controlled by a phase cut dimmer shall be considered representative of only the specific combination of phase cut dimmer, ballast or driver, and lamp. These results cannot be applied to other combinations of dimmer, ballast, driver or lamp.

Flicker measurements of light sources controlled by a 0-10 volt control, a DALI control, other powerline carrier, wired, or wireless control protocol shall be considered representative of that combination of control protocol and ballast or driver and lamp. These results of the lamp and ballast or driver combination can be applied to other controls that utilize the same control protocol. If a proprietary protocol is used to control dimming, the results for the lamp and ballast or driver combination will be specific to that proprietary protocol only.

JA10.2 Test Equipment Requirements

Test Enclosure: The test enclosure does not admit stray light to ensure the light measured comes only from the unit under test (UUT). Provisions shall be made so that ambient air temperature and air flow rate in the test enclosure are maintained as described in JA 10.3 Test Conditions.

Photodetector: The photodetector fits the International Commission on Illumination (CIE) spectral luminous efficiency curve, V(λ)within 5% (f1'<5%) in accordance with CIE 53. The maximum deviation from linearity of response over the measurement range shall be less than 1%. The rise time of the sensor shall be 10 microseconds or less. Rise time is the time span required for the output signal to rise from a 10% to a 90% level of the maximum value when a steady input at the maximum value is instantaneously applied.

Signal amplifier: If a signal amplifier is used to increase the voltage to a range appropriate for the signal recording device, the bandwidth of the signal amplifier shall be at least 10 kHz at the amplification gain used to conduct the test and the maximum deviation from linearity of the amplifier gain over the measurement range shall be less than 3%.

Analog-to-digital converter and data storage: Digital oscilloscope with data storage capability or similar equipment able to store high frequency data from the photodetector, at a sample rate greater than or equal to 100 kHz for a minimum data record duration of greater than or equal to 2 seconds (e.g. at least 200,000 samples at 100 kHz).

JA 10.3 Flicker Test Conditions

Product wiring setup: Fluorescent ballasts shall be wired in accordance to the guidelines provided in the DOE ballast luminous efficiency test procedure in 10 CFR 430 Subpart B Appendix Q.

Product pre-conditioning: All fluorescent lamps shall be seasoned (operated at full light output) at least 100 hours before initiation of the test. Seasoning of other lamp types is not required.

Input power: Input power to the UUT shall be provided in accordance with the relevant test procedure for the UUT, as listed in JA 10.7. For technologies not listed in Section 10.7, input power to the UUT shall be provided at the rated primary voltage and frequency within 0.5% for both voltage and frequency. For technologies not listed in Section 10.7, the AC power supply while operating the UUT, shall have a sinusoidal wave shape at the prescribed frequency (typically 60 Hz or 50 Hz) such that the RMS summation of the harmonic components does not exceed 3% of the fundamental, i.e. less than 3% total harmonic distortion (THD).

Temperature: Temperature shall be maintained at a constant temperature in accordance with the relevant test procedure for the UUT, as listed in JA 10.7. For any technologies not listed in JA 10.7 temperature shall be maintained at a constant temperature of 25°C ±5°C.

Air Movement: Airflow rate shall be maintained in accordance with the relevant test procedure for the UUT, as listed in Section 10.7. For any technologies not listed in JA 10.7, airflow rate should be such that normal convective air flow induced by the UUT is not affected.

Dimming levels: Flicker measurements shall be taken within 2% of the following increments of full light output: 100%, 80%, 50%, and 20%, where 100% full light output is defined as the measured light output when operating the light source at the maximum setting provided by the control. Since this test method is interested in the relative fluctuation of light, these measurements are relative and do not require the measurement of absolute illuminance values. When the minimum light output of the systems is greater than 20% of full light output, then the flicker measurements are taken at the minimum light output. For harmonization with ENERGY STAR flicker tests, if a test lab wishes to use the labeled minimum output instead of 20% of full light output, this data can be used in lieu of the 20% light output data. For dimming fluorescent ballasts, lamp arc power may be used as a proxy for light output for the purpose of setting dimming levels for collecting test measurements.

JA10.4 Test Procedure

Light source stabilization: Light source stabilization for the initial flicker measurement of the UUT for a given equipment combination shall be determined in accordance with test procedures applicable to the UUT as referenced in JA 10.7. For any lighting technologies not listed in JA 10.7, light source output shall be considered stabilized for the initial flicker measurement of the UUT for a given equipment combination by using a test method in JA 10.7 that is applicable to a lighting technology that is most similar to the UUT. If the similar test method does not have a stabilization methodology, the light source output shall be considered stabilized for the initial flicker measurement by taking light output measurements once every fifteen minutes until three consecutive measurements over 30 minutes deviate by no more than 0.5% from the average of the three measurements.

For subsequent measurements, light source output shall be considered stabilized by taking light output measurements every minute until three consecutive measurements deviate by no more than 0.5% from the average of the three measurements.

Recording interval: Measured data shall be recorded to a digital file with an interval between each measurement no greater than 0.00005 sec (50 microseconds) corresponding to an equipment measurement rate of no less than 20kHz.

Equipment measurement period: shall be greater than or equal to 2 seconds.

For each dimming level after the lamps have stabilized, record lighting measurements from test equipment with readings taken at intervals of no greater than 50 microseconds. These readings are compiled for an equipment measurement period of no less than two seconds into a comma separated data file (*.csv) having the format specified in JA10.6.

JA 10.5 Calculations

The CEC Flicker Data Analysis Tool shall be used to perform the following data analysis on data collected at each relative dimming level (100%, 80%, 50%, 20% or minimum dimming). No calculations are required by the applicant, the CEC Flicker Data Analysis Tool will conduct the following calculations:

1. Calculate percent amplitude modulation (percent flicker) of unfiltered data over the duration of the test for a given dimming level using the following equation:

$$\text{Percent Amplitude Modulation} = \frac{(\text{Max} - \text{Min})}{(\text{Max} + \text{Min})} \times 100$$

   Where,

   Max is the maximum recorded light level or voltage from the test apparatus during the duration of the test for a given dimming level.

   Min is the minimum recorded light level or voltage from the test apparatus during the duration of the test for a given dimming level.

2. Transform the time-domain data into frequency-domain data via Fast Fourier Transform (FFT) techniques.
3. Filter frequency-domain data to create five additional data sets with the following cut-off frequencies: 40 Hz, 90 Hz, 200 Hz, 400 Hz and 1,000 Hz. For each cut-off frequency listed, all frequency domain terms above the cut-off frequency will be set to zero, effectively truncating the Fourier series.[38]
4. Transform the filtered frequency-domain data back into the time-domain using an inverse Fourier transform technique.[39]
5. Calculate percent amplitude modulation on resulting time domain data for each filtered dataset over at least half of the full sampling duration (at least one second of filtered data in the time domain).

JA 10.6 Test Report and Data Format

For all systems where reporting of flicker data is required, the data shall be submitted to the California Energy Commission in a comma separated data file (*.csv) having the format specified in Table JA-10. Applicants can submit the file with the rows for amplitude modulation information left blank. The CEC Flicker Data Analysis Tool will take the file, process the raw data, and return the same file but with the amplitude modulation filled in based on calculations performed on the raw data.

TABLE JA-10. FLICKER DATA TO BE RECORDED AND SUBMITTED TO THE CALIFORNIA ENERGY COMMISSION

[38] This filtering technique is described in Lehman, B.; Wilkins, A; Berman, S.; Poplawski, M.; Miller, N.J., "Proposing measures of flicker in the low frequencies for lighting applications," *Energy Conversion Congress and Exposition (ECCE), 2011 IEEE* , vol., no., pp.2865,2872, 17-22 Sept. 2011.

[39] Ibid, the paper above calculates "low frequency percent flicker" (filtered amplitude modulation) by a summation of the truncated Fourier series for each time step; this can more compactly be evaluated using the inverse Fourier transform.

Description	Content
Test Date (2 comma separated text strings)	Date, (mm)/(dd)/(yyyy)
Contact Type Header (5 comma separated text strings)	Contact type**,** (Company), (Contact Name), (Phone Number), (e-mail address)
Test Operator (5 comma separated text strings)	Test Operator, (Company), (Contact Name), (Phone Number), (e-mail address)
Entity submitting results (5 comma separated text strings)	Entity submitting results**,** (Company), (Contact Name), (Phone Number), (e-mail address)
Product submitted for certification (5 comma separated text strings)	Product for certification**,** (Product type – dimmer, ballast or driver, etc.), (manufacturer), (model number), (other description)
Tested lighting system component: Dimmer (4 comma separated text strings)	Dimmer, (manufacturer), (model number), (other description)
Tested lighting system component: light source (4 comma separated text strings)	Light source**,** (manufacturer), (model number), (other description)
Tested lighting system component: Ballast or Driver (4 comma separated text strings)	Ballast or Driver**,** (manufacturer), (model number), (other description)
Recording interval (1 text string and 1 number)	Recording interval (secs), (value in sec – no greater than 0.00005 seconds)
Count of data points (1 text string and 1 number)	Count of data points, (number of measurements, no less than 40,000)
Equipment Measurement Period (1 text string and 1 number)	Equipment measurement period (secs), (value in sec – no less than 2 seconds)
Nominal Percent of Max Output Header (5 comma separated text strings)	Nominal percent of maximum output, 100%, 80%, 50%, (20% or minimum)
Fraction of rated light output at 100%, 80%, 50% and the greater of 20% or minimum fraction of light output. (1 text string and 4 comma separated numbers)	Measured fraction of max output, 100%, (measured fraction of max light output at 80%), (measured fraction of max light output at 50%), (measured fraction of max light output at the greater of 20% or minimum light output).
Amplitude modulation separator (1 text string and 4 comma separated numbers)	Cut-off Frequency Hz for dimming fractions, (same 4 values from line above)
Amplitude modulation with 40 Hz cut-off for each nominal dimming level (5 comma separated numbers)	40, (calculated percent amplitude modulation with 40 Hz cut-off for 100%, 80%, 50%, and the greater of 20% or minimum fraction of light output)
Amplitude modulation with 90 Hz cut-off for each nominal dimming level (5 comma separated numbers)	90, (calculated percent amplitude modulation with 90 Hz cut-off for 100%, 80%, 50%, and the greater of 20% or minimum fraction of light output)
Amplitude modulation with 200 Hz cut-off for each nominal dimming level (5 comma separated numbers)	200, (calculated percent amplitude modulation with 200 Hz cut-off for 100%, 80%, 50%, and the greater of 20% or minimum fraction of light output)
Amplitude modulation with 400 Hz cut-off for each nominal dimming level (5 comma separated numbers)	400, (calculated percent amplitude modulation with 400 Hz cut-off for 100%, 80%, 50%, and the greater of 20% or minimum fraction of light output)
Amplitude modulation with 1,000 Hz cut-off for each nominal dimming level (5 comma separated numbers)	1,000, (calculated percent amplitude modulation with 1,000 Hz cut-off for 100%, 80%, 50%, and the greater of 20% or minimum fraction of light output)
Amplitude modulation of unfiltered data for each nominal dimming level (1 text string and 4 numbers)	Unfiltered Percent Amp Mod, (calculated percent amplitude modulation with 1,000 Hz cut-off for 100%, 80%, 50%, and the greater of 20% or minimum fraction of light output)

TABLE JA-10. FLICKER DATA TO BE RECORDED AND SUBMITTED TO THE CALIFORNIA ENERGY COMMISSION	
Description	Content
Raw data separator (5 comma separated text strings)	Unfiltered raw photometric data for the following fractions of full light output:, 100%, 80%, 50%, (20% or minimum)
Raw data column headers (5 comma separated text strings)	Time stamp (sec), 100% data, 80% data, 50% data, (20% or minimum)
Raw Photometric Flicker Waveform (unfiltered) at 100%, 80%, 50% and the greater of 20% or minimum fraction of light output. (5 comma separated data values per row, with the number of rows being the number of data points taken during the test duration)	(time stamp), (flicker waveform data at 100%, 80%, 50%, and the greater of 20% or minimum fraction of light output)

JA 10.7 Reference Test Procedures

As described in Sections JA 10.2, JA 10.3 and JA 10.4, the criteria for input voltage, ambient temperature, ambient airflow rate, and light source stabilization for the initial flicker shall be based upon criteria in the test procedure specific to the lighting technology listed in Table JA-10.7. For those technologies where the test procedure listed in Table JA-10.7 does not contain a given criteria, the tests shall use the default criteria listed in Sections JA10.2 though JA 10.4.

TABLE JA-10.7 REFERENCE TEST PROCEDURES FOR UUT-SPECIFIC TEST CONDITIONS AND LIGHT SOURCE STABILIZATION	
Technology	**Test Procedure**
Incandescent and halogen reflector lamps, Incandescent non-reflector lamps, General service fluorescent lamps	10 CFR 430 Subpart B, Appendix R
Medium base compact fluorescent lamps	10 CFR 430 Subpart B, Appendix W
Fluorescent ballasts	10 CFR 430 Subpart B, Appendix Q
Fluorescent sources that are not medium base compact fluorescent lamps or general service fluorescent lamps	IES LM-9
Induction lamps	IES LM-66
LED integral lamps, LED light engines and integral LED luminaires	IES LM-79

High intensity discharge lamps	IES LM-51