

CREE, Inc. Consultation Questionnaire Regarding Cd Exemptions

Ex. Re. No. 2013-2 for “Cadmium in colour converting II-VI LEDs ($< 10\mu\text{g Cd per mm}^2$ of light-emitting area) for use in solid state illumination or display systems” (Request for renewal of Exemption 39 of Annex III of Directive 2011/65/EU);

and Ex. Re. No. 2013-5 for “Cadmium in light control materials used for display devices”

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Summary

Lighting makes up $>15\%$ of worldwide electricity demand. LED-based solid-state lighting (SSL) offers a path towards significantly reducing electricity consumption relative to incumbent incandescent and fluorescent technologies. Elevated efficacy has direct economical and environmental benefits beyond energy savings, for example by lowering pollutant emissions associated with electricity production. Future improvements in SSL system efficacy will be made possible in part by new down-conversion materials with narrower emission than conventional phosphors. Namely, emerging quantum dot (QD) materials will raise luminous efficacy by up to 20% over conventional phosphor-downconverted LEDs, thereby resulting in lowered cost of ownership and greatly reduced pollutant emissions from electricity generation. As an example, Cree estimates that the reduction in Cd emissions enabled by QDs in LEDs used for a 10-year warranty period could be >18 times that of the Cd content sequestered in the LEDs themselves. **Cree recommends that in order to realize the efficacy-enabled benefits of QD-LEDs, the current RoHS exemption regarding the use of Cd in solid-state lighting applications should be extended by ~ 5 years.**

1. Applicant exemption requests with different wording formulations

- (a) *Do you agree that the formulation above covers the cadmium quantum dot technologies addressed in the two exemption requests?*

Due to the widely differing light output requirements between LEDs in displays vs. those in solid-state lighting products, Cree recommends a split between RoHS Cd exemption values for the two application domains. Specifically, **Cree supports the revised wording proposed in the 2013-2 application**, namely “Cadmium in II-VI color converting material ($< 10\mu\text{g Cd per mm}^2$ of light-emitting area) **for LEDs** for use in solid state illumination or display systems”. Cree proposes that the LED light-emitting area be defined as the combined surface area of region(s) on an LED component where light down-conversion may occur. Based on fabrication and testing of white LEDs containing Cd-based QDs, Cree anticipates that a maximum Cd concentration of $<10\mu\text{g per mm}^2$ of light-emitting area will be challenging but technologically feasible for LEDs which offer significantly elevated luminous efficacy with respect to incumbent technologies.

- (b) *If the exemption is to be split according to application field (SSL and display lighting) please specify what wording formulation would best cover each of the application areas.*

For SSL applications, Cree supports the use of the LED component-specific language proposed in the 2013-2 application, namely “Cadmium in II-VI color converting material (< 10 µg Cd per mm² of light-emitting area) for LEDs for use in solid state illumination or display systems”. Cree proposes that the LED light-emitting area be defined as the combined surface area of region(s) on an LED component where light down-conversion may occur.

Cree does not take a position on suggested wording for display applications.

- (c) *Please suggest an alternative wording and explain your proposal, if you do not agree with the proposed exemption wording or with the proposed split.*

N/A

- (d) *Please explain why you either support the applicant’s request or object to it. To support your views, please provide detailed technical argumentation / evidence in line with the criteria in Art. 5(1)(a) to support your statement.*

Cree supports the Cd concentration exemption value of 10 µg Cd per mm² of light-emitting area (the combined surface area of region(s) on an LED component where light down-conversion may occur). This metric provides regulators with a straightforward means of examining LED components for compliance, as surface area is readily measurable, as is the Cd content in the LED (*e.g.* via process controls and sampling at manufacturer sites, or gas discharge mass spectrometry of finished product).

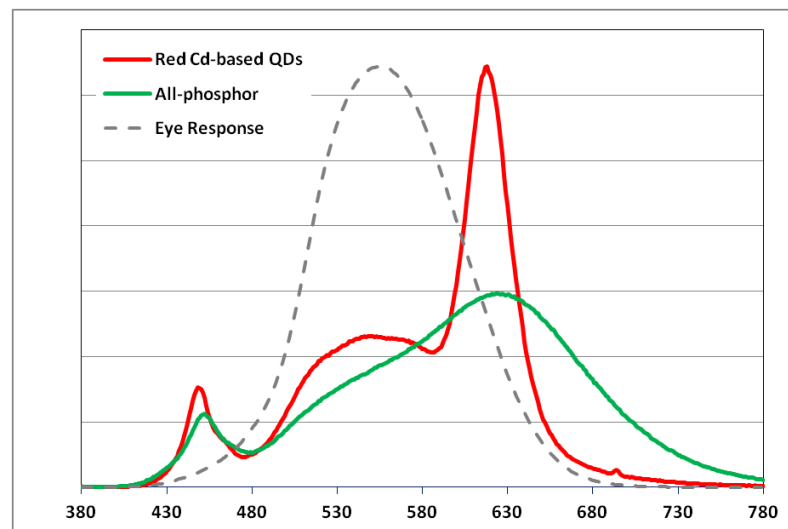


Fig. 1. Spectrum of a warm-white (2700K, 92 CRI) LED containing Cd-based QDs (red line), vs. an LED with conventional red phosphor (green line) at the same color temperature and CRI. The human eye response is overlaid for reference. The QD-containing LED has a ~18% higher spectral efficiency due to its low emission in the near-infrared.

Cree has fabricated and tested a variety of white LEDs (*i.e.* those with color points on or near the black-body locus) which contain red-emitting (600-630nm) Cd-based QDs. An example spectrum of a warm-white (~2700K) QD-LED is compared with that of a

conventional 90 CRI (color rendering index) all-phosphor LED in Fig. 1. The spectral efficiency of the QD-LED is ~18% higher than its all-phosphor counterpart, which translates into a corresponding efficacy gain when the QD quantum yield is comparable to that of the phosphors. Cree has found that the red Cd-based QD concentration in the LED varies with LED type and geometry, but can consistently amount to $<10 \mu\text{g}/\text{mm}^2$ of light-emitting area.

2. Comparison of Cd-based QDs and Cd-free QDs in display applications

(a) *Please specify if you are aware of additional display products that have become available since 2014.*

Cree declines to comment on display applications.

(b) *Please state if you agree with the detailed parameters mentioned by the three actors as relevant for enabling a comprehensive comparison of performance of the technologies.*

Cree declines to comment on display applications. However, we note that the efficacy gains enabled by QDs in LEDs for solid-state lighting will also benefit display (e.g. large-format TV) efficiency, since most LCD displays are backlit with LEDs.

(c) *Please comment as to the suitability of the NTSC, Adobe RGB and REC 2020 standards for comparing QD technologies in display applications.*

Cree declines to comment on display applications.

3. Basis of comparison of solid-state illumination technologies

Cree proposes that the best basis for comparing the economical and environmental impact of incumbent vs. emerging lighting technologies is **luminous efficacy** (lm/W), or the amount of visible light generated per unit of input electrical power. Increased efficacy benefits the lighting user via lowered recurring energy costs over the LED lamp's use lifetime (> 10 yrs.), while simultaneously benefitting the environment via lowered pollutant emissions associated with energy production. A recent report¹ to the U.S. Department of Energy estimates that SSL may reduce lighting energy consumption by 15% in 2020 and 40% in 2030, which, in absolute terms, is over 261 TWhr saved in 2030. Since lighting makes up $>15\%$ of worldwide electricity demand², replacement of inefficient incandescent and fluorescent lamps with their LED equivalents will help significantly reduce emissions of Cd, Hg, Pb, NO_x , SO_x , and CO_2 , among other pollutants. A specific emissions reduction example enabled by QD-containing LEDs is provided in section 4(b).

Existing solid-state lighting solutions are largely based on down-conversion of blue light by green-, yellow-, and red-emitting inorganic phosphors. Future improvements in SSL efficacy will rely in part on the development of new down-conversion materials, among which quantum dots are the most promising due to the high **spectral efficiency** they enable. Spectral efficiency is linked to the *visible* light generated during light down-conversion, and is linked

¹ "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications", prepared by Navigant Consulting for the U.S. Dept. of Energy (August 2014).

² Green Paper: Policy Options to Accelerate the Global Transition to Advanced Lighting, United Nations Environment Programme, Nov. 2014.

to the human eye response (Fig. 1). To realize high LED efficacy, both high spectral efficiency and high down-conversion efficiency are needed.

We note that QDs also exhibit flexibility in emission peak position and width, a feature which will enable SSL manufacturers to offer luminaires with both high color quality and high efficacy. This is expected to accelerate the displacement of lower-efficiency and low color quality lighting systems (*e.g.* compact fluorescent) with SSL, thereby increasing the benefits for consumers and the environment.

Cree has evaluated both Cd-based and Cd-free QDs which emit red light. As-synthesized Cd-based QDs currently have quantum yield (blue to red light down-conversion efficiency) values of >90%, which is on par with conventional green/yellow and red phosphors. Meanwhile, Cd-free QDs (*e.g.* InP-based) have been observed to have quantum yield values of <75%, which, combined with their broader (>45 nm FWHM) peak width, results in lower LED efficacy compared to Cd-based QDs. Given the current state of Cd-free QDs and their rate of development, Cree estimates that they will be precluded from practical use in SSL applications for the next >5 years.

4. Cd-based and Cd-free QD technologies for use in solid-state illumination applications

(a) *Have additional lighting products become available on the EU market since 2014?*

Cree is not aware of the release of new SSL products containing Cd-based QDs.

(b) *What parameters are relevant for a comprehensive performance comparison of the technologies, in particular to environmental performance?*

As described above, luminous efficacy is the most appropriate metric for evaluating the economical and environmental impacts of emerging solid-state lighting technologies. Elevated efficacy has a direct beneficial impact on both cost of ownership and the emissions of pollutants associated with electricity generation.

Table 1. Input efficacy values for calculation of Cd emissions reductions, for LEDs at 3000K CCT and 90 CRI R_a & 50 CRI R_g .

Type	Efficacy	Source
Linear Fluorescent (baseline)	75 lm/W	“Energy Savings Forecast of SSL in General Illumination Applications”, Table D.2; Prepared for U.S. DOE by Navigant Consulting, August 2014.
Phosphor-converted LED	109 lm/W	Cree XP-L datasheet, U3 flux bin at 1 W/mm ² , 3000K/90 CRI
Cd-based QD-LED	149 lm/W	Cree R&D measurement at 1 W/mm ²
Cd-free QD-LED	132 lm/W	Simulation adapted from Cd-based QD meas., with 45nm FWHM and 75% quantum yield

As an example of the positive environmental impact of emerging SSL technologies, we calculated the reduction in Cd emissions associated with electricity generation. We compared the efficacy of conventional linear fluorescent lighting with incumbent phosphor-downconverted LEDs as well as those containing Cd-based QD LEDs (see Table 1). These efficacy values, all at 3000K and 90 CRI, were drawn from representative datasheets or were directly measured. We note that for the Cd-based QD-LEDs, the Cd

content per LED was ~10 µg. We also included the *calculated* efficacy of 90 CRI LEDs containing Cd-free QDs (45 nm FWHM, 75% quantum yield), since Cree’s measurements of LEDs made with these materials have been hindered by rapid degradation of the QD quantum yield and lifetime once blended into LED encapsulant silicones.

To produce a given luminous flux of 1000 lm (typical of a T8 fluorescent tube), the input powers of luminaires based on the three LED types (including 10% efficacy discounts for non-ideal luminaire electrical and optical efficiency) were compared to the fluorescent baseline. A 5-year use period was considered, with lamps assumed to be operated for 12 hours per day (representative of linear fluorescent commercial/industrial lighting³). The total electricity consumed (in kW-hr) for each type over this period was calculated, as shown in Table 2. Drawing on published 2013 European Union electricity consumption⁴ and related Cd emissions⁵ data, we derived a value of 6.4 µg/kW-hr for Cd emissions related to electricity production (regardless of source). From this, the Cd emissions related to the operation of each lamp type over the 5 yr. period was readily calculated, as summarized in Table 2. Finally, the relative reductions in Cd emissions of each LED technology relative to linear fluorescent are plotted in Fig. 2.

Table 2. Electricity consumed and resulting Cd emissions over a 5-yr example period (@ 12 hrs/day) for the lamp types considered.

Lamp Type	Input Power (W)	Total Energy (kWhr)	Resulting Cd Emissions (mg)
Linear Fluorescent	13.3	292	1862
Phosphor-converted LED	11.3	248	1582
Cd-based QD LED	8.3	181	1157
Cd-free QD LED	9.4	205	1306

It is immediately evident in Fig. 2 that lamps made with Cd-based QD LEDs offer the largest Cd emissions reduction relative to the fluorescent baseline, owing to their superior efficacy. Importantly, their projected 5-yr Cd emissions reduction of ~705 µg is more than **9 times** the combined content of Cd in the LEDs in the lamp (~77 µg). For a 10-yr use case (the expected Cree warranty period for LED lamps), this ratio would reach **>18 times**. Finally, we note that the “payback” period – defined as the period when Cd emissions savings (relative to fluorescent) equals the Cd content sequestered in the LED lamp – is only **4 months**.

³ “Adoption of LEDs in Common Lighting Applications”, Tables D.6 and D.8; prepared by Navigant Consulting for the U.S. Dept. of Energy (July 2015).

⁴ Eurostat Table ten00087, “Total gross electricity generation”. (<http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=ten00087&plugin=1>)

⁵ European Union emission inventory report 1990–2013 under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP), European Environment Agency, published July 2nd, 2015.

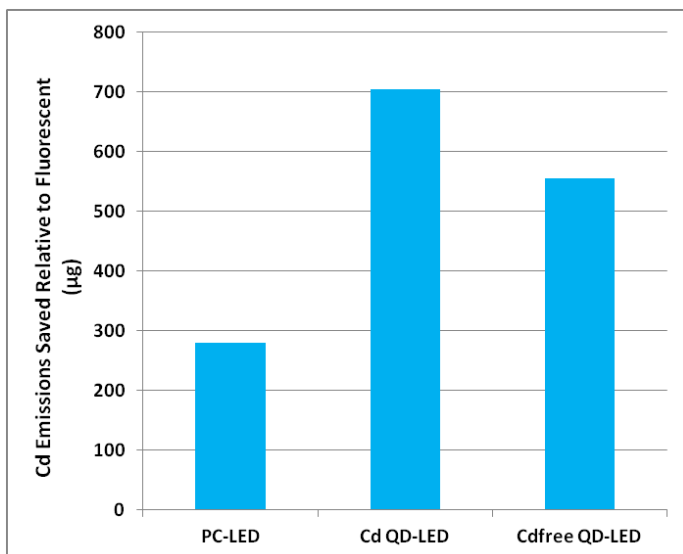


Fig. 2. Cd emissions from electricity generation saved by incumbent and emerging LED technologies relative to linear fluorescent, over a 5-yr. period (@ 12 hours/day). LEDs with Cd-based QDs clearly provide the largest reduction in Cd emissions relative to the fluorescent baseline. The amount saved is >9x that of the Cd content in the LEDs themselves.

In short, **the superior efficacy of Cd-based QD LEDs directly reduces Cd emissions associated with electricity production, at levels which dwarf the Cd content in the LEDs themselves.** Analogous reductions in Hg, Pb, NO_x, SO_x, and CO₂ emissions in electricity generation for QD-based LEDs relative to fluorescent (and even more so, incandescent) lamps can be expected.

While efficacy comparisons are of primary utility in establishing environmental benefits, we note that the useful lifetime of the SSL product must also be taken into account. Otherwise, the full economical and environmental benefits of a high-efficacy technology such as QDs may not be realized. Incumbent phosphor-converted white LEDs have a rated continuous operating lifetime of >10 years in typical application conditions (drive current, temperature, humidity). The reliability of emerging Cd-based QD materials is not yet at this level, but it is steadily improving. Meanwhile, Cd-free alternatives such as InP which Cree has measured start at a lower quantum yield (<75%), and degrade much more rapidly. Cree estimates that with further synthesis and processing improvements informed by accelerated testing results, **Cd-based QDs could be ready for use in numerous commercial SSL applications within the next 2-3 years.** In contrast, Cd-free QDs are at a much earlier stage of development – they lag Cd-based QDs in not only quantum yield maintenance but also spectral efficiency and reliability. It is not clear at this point if these challenges are temporary or may be due to fundamental rather than technological limitations. Therefore **Cree proposes that the existing RoHS Cd exemption for SSL be extended in order to allow adequate time for development of Cd-based QDs toward commercialization, and simultaneous assessment of Cd-free QDs.**

- (c) *Do you agree with the detailed parameters mentioned by the three actors as relevant for enabling a comprehensive performance comparison performance of the technologies (general and environmental performance)?*

As detailed in the sections above, Cree’s recommended metric to establish the economic and environmental benefits of emerging SSL technologies is **luminous efficacy**. The efficacy of down-converter based LEDs is impacted by the down-converter **spectral efficiency** and **quantum yield** both of which must be sufficiently high to result in high

efficacy in actual use conditions. QD reliability (specifically, quantum yield maintenance in realistic application conditions) is a key parameter in actually realizing the enhanced efficacy of QD-containing LEDs over long durations.

5. Potential hazardousness and toxicity of Cd-based and Cd-free technologies relevant to the exemption requests

Cree declines to comment on the potential hazardousness and toxicity of Cd-based vs. Cd-free technologies.

6. Research initiatives looking into the development of possible Cd-free alternatives

(a) *What part of the application range is of relevance for such initiatives?*

Recently a new type of narrow-band red phosphor, $K_2SiF_6:Mn^{4+}$ (PFS), has emerged, for example as marketed under the name TriGain[®] by General Electric. Having a narrow spectrum centered around 620-635nm, this phosphor offers higher spectral efficiency than conventional red phosphors, such that a correspondingly higher warm-white luminous efficacy can be achieved.

Unlike Cd-based QDs, PFS has a **fixed** spectrum which will limit its use in different types of warm-white lighting applications. In contrast, the peak wavelength and peak width of red-emitting Cd-based QDs are readily tunable, thereby accommodating various combinations of color temperature and CRI, as well as newer measures of color quality such as vividness (*e.g.* IES TM-30 R_g metric⁶).

An important characteristic which may limit PFS performance is the fluorescence radiative lifetime, which reflects the rate at which down-converted red photons are emitted relative to incoming blue “pump” photons. For PFS, this rate is 8-13ms,⁷ which is much slower than 50ns to 3μs for conventional green/yellow and red phosphors,⁸ respectively, and 5-100ns for Cd-based QDs.⁹ As a result, PFS exhibits “flux saturation” (a sub-linear intensity increase) as blue pump flux is raised, reducing efficacy for mid-power and high-power LED packages.¹⁰ Unless this shortcoming is solved, use of PFS in SSL will be limited to low-power LED packages – and its environmental benefits will be correspondingly limited. In contrast, QDs do not exhibit flux saturation within the anticipated LED application range. In addition, Cd-based QD optical density (concentration of light-emitting centers per unit volume) is estimated to be 15-50 times higher than PFS, requiring much less material to reach the same warm-white color point.

⁶ Illumination Engineering Society TM-30-15, “IES Method for Evaluating Light Source Color Rendition”, ISBN #9780879953126 (2015).

⁷ M. Kim *et al.*, “Radiative and non-radiative decay rate of $K_2SiF_6:Mn^{4+}$ phosphors”, J. Mat. Chem. C, **3**, 5484-5489 (2015).

⁸ Phosphor Handbook, ed. William M. Yen *et al.*, ISBN 9780849335648 (2006).

⁹ O. Chen *et al.*, “Compact high-quality CdSe–CdS core–shell nanocrystals with narrow emission linewidths and suppressed blinking”, Nature Materials, **12**, 445–451(2013)

¹⁰ A. Setlur *et al.*, “Optimized Phosphors for Warm White LED Light Engines”, Final Technical Report to U.S. Dept. of Energy, award #DE-EE-0003251 (2012).

(b) *Provide a roadmap of such on-going research. Detail the current status as well as the estimated time needed for further stages.*

As for Cd-free QDs, at this time Cree can only speculate on future advances in PFS development for SSL applications. Indications so far are that its fixed spectrum is unavoidable, which will create challenges in reaching certain combinations of warm-white color temperature and color quality. Likewise, flux saturation may be a fundamental (and not just technological) limitation of PFS luminescence; if this remains the case, Cree anticipates that use of PFS will be limited to low-power LED packages, thereby limiting the benefits of enhanced SSL efficacy for the economy and the environment. We note that if research and development eventually overcomes some of the PFS performance limitations above, it would ultimately present a complementary (rather than replacement) technology to Cd-free QDs, and would not obsolete the RoHS Cd exemption for SSL.