NLPIP Lighting Answers
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Plasma Lighting Systems

Glossary terms are shown in **boldface**; terms are defined in the Glossary section, beginning on p. 37.

Abstract

Plasma lighting systems, also known as electrodeless **high-intensity discharge (HID)**, light-emitting plasma (LEP), high-efficiency plasma (HEP), or advanced plasma lighting (APL) are emerging in the marketplace primarily for high-bay and outdoor lighting **applications**. This National Lighting Product Information Program (NLPIP) report, *Lighting Answers: Plasma Lighting Systems*, helps lighting specifiers to understand plasma lighting systems and their performance characteristics, including light output, **system efficacy**, color characteristics, **lumen maintenance**, and **rated life**. This report also provides information about operating orientation, dimming, warm-up, and **restrike times**, electromagnetic interference and compatibility (**EMI**/EMC), and **ultraviolet (UV)** radiation.

NLPIP did not make measurements of lifetime, lumen maintenance, effects of elevated temperatures or UV radiation for this report. NLPIP also did not test control methods other than analog dimming.

The key findings include:

1. Purchasing plasma lighting systems can be difficult.
2. The tested plasma lighting systems have system efficacies comparable to conventional sources used for high-bay and outdoor lighting applications.
3. The tested plasma lighting systems have **color rendering** characteristics comparable to conventional sources although they have a greenish-white tint.
4. The tested plasma lighting systems could be dimmed but dimming impacts color and system efficacy.

Introduction

From 2012 to 2013, the National Lighting Product Information Program (NLPIP) at Rensselaer Polytechnic Institute's Lighting Research Center (LRC) conducted a study of plasma lighting systems. The findings are summarized in this report, along with responses from a survey of more than 300 lighting specifiers who provided information about the plasma lighting systems they had evaluated and their opinions on the application of plasma lighting. Most of the specifiers had heard of plasma lighting systems, but did not know how this technology compared with other light sources, with regard to performance characteristics such as light output, dimming, controllability, warm-up and restrike times, color characteristics, electromagnetic interference and compatibility (EMI/EMC), lumen maintenance and cost.

What are plasma lighting systems?

Plasma lighting systems are electrodeless **metal halide lamps** that produce light directly from an arc discharge operated under high pressure. The arc discharge is powered by a high-**frequency** electromagnetic field generated externally to the **lamp**. This is different from conventional **high-intensity discharge (HID)** lamps which have **electrodes** within the **arc tube** that convey current to sustain the arc discharge.

Plasma lighting systems are also known as electrodeless HID systems. They are marketed under different names including light-emitting plasma (LEP), high-efficiency plasma (HEP), or advanced plasma lighting (APL) systems. NLPIP will use the term "plasma lighting system" throughout this report for this type of technology.

Plasma lighting systems typically have multiple components including:

- a lamp or emitter which contains the light-emitting gas that operates under high pressure
- an applicator or resonator for "coupling" the **power** to the lamp
- a high-frequency **ballast**/**driver**, such as a radio frequency (RF) generator or magnetron (microwave) generator

Many plasma lighting systems also require a separate low-voltage direct current (dc) power supply to provide power to the high-frequency driver. This dc power supply is typically supplied by an original equipment manufacturer (OEM) and the manufacturer of the plasma lighting system will typically provide specifications to **luminaire** manufacturers for dc power supplies that are suitable matches. The plasma lighting systems tested for this report include dc power supplies as part of the system.

What are the claimed and perceived advantages of plasma lighting systems?

Manufacturers claim that plasma lighting systems have longer life, higher **efficacy**, better **lumen maintenance**, improved **color rendering**, and enhanced dimming performance compared to conventional **HID** systems. In addition, manufacturers claim that plasma lighting systems have higher light output and lower overall system price than **light-emitting diode (LED)** systems while maintaining a small optical package and high system efficiency. Table 1 provides rated values of several performance metrics for comparisons of various light sources. The performance characteristics described in Table 1 include: **rated life**, efficacy, light output, **color rendering index (CRI)**, **correlated color temperature (CCT)**, **warm-up time**, **restrike time**, maximum rated dimming, and rated **lumen depreciation**. See the sidebar following the table for a discussion of some of the performance characteristics listed in Table 1.

Table 1: Rated light source characteristics for high pressure sodium (HPS) lamps, improved color HPS lamps, induction lighting systems, LED packages, low pressure sodium (LPS) lamps, metal halide (MH) lamps, mercury vapor (MV) lamps, and plasma lighting systems. HID lamps are tested with reference ballasts. Information not supplied indicated by NS.

	HPS	Improved color HPS	Induction	LED package*	LPS	MH	MV	Plasma
Rated life (1000s of hours [h])	24-40	10-15	60-100	50-60	18	5-40	16-24+	**3-50**
Rated efficacy (lm/W)	64-160	49-94	47-88	49-164	100-178	44-164	25-58	**50-110**
Rated light output (lumens [lm])	5950-140,000	3800-37,400	3500-36,000	50-8800	1800-32,000	3000-115,000	3850-58,000	**11,000-50,000**
Rated CRI	21-30	65-83	80	60-90	< 0	55-95	15-50	**70-95**
Rated CCT (K)	1900-2100	2200-2550	2700-5000	2600-9000	1700	2900-5000	3900-5900	**3200-7650**
Warm-up time (minutes [min] or seconds [s])	3-4 min	3-4 min	< 1 min	<< 1 s	7-15 min	2-5 min	5-7 min	**< 1 min**
Restrike time	1-3 min	1-3 min	< 1 s	<< 1 s	2-4 min	2-20 min	3-6 min	**2 min**
Rated Dimming (% Max Power)	Down to 35%	Down to 50%	Down to 50%	NS	Not dimmable	Down to 50%	Down to 50%	**NS**
Rated Dimming (% Max Light Output)	NS	NS	NS	Down to 1%	Not dimmable	NS	NS	**Down to 20%**
Rated lumen depreciation (%)	9-21	8-20	23-40	30	10-30	16-52	6-30	**22-30**

*Typically, multiple LED packages are integrated into an LED **luminaire**. The performance characteristics of the LED luminaire will depend on the integration of the LED packages with other components such as the driver.

Performance characteristics

The performance characteristics described in Table 1 have different criteria depending on the light source.

Rated life: For HID lamps, most lighting manufacturers define life based on the hours until median life expectancy where the lamps are operated for 10 hours (h) continuously for each start. Lamps that have a rated life of 24,000+ h are based on 65-67% of the lamps surviving at 24,000 h (General Electric 2013; OSRAM SYLVANIA 2012; Philips Lighting Company 2012). For LED packages, and typically for plasma lighting systems, rated life is based on the operating hours until 70% of the **initial light output** remains. For induction lighting systems, rated life is based on either the operating hours of the generator/driver until a certain percentage fail (10-50%) (Fulham Co. 2011; OSRAM SYLVANIA 2004) or the operating hours until 65-70% of the initial light output remains (OSRAM SYLVANIA 2004, 2013). Another manufacturer defines induction system life based on the hours until median life expectancy where the lamps are operated for 10 h continuously for each start (Philips Lighting Company 2010).

Warm-up time (run-up time): The time required for a lamp to reach 90% of its stabilized light output when it is started.

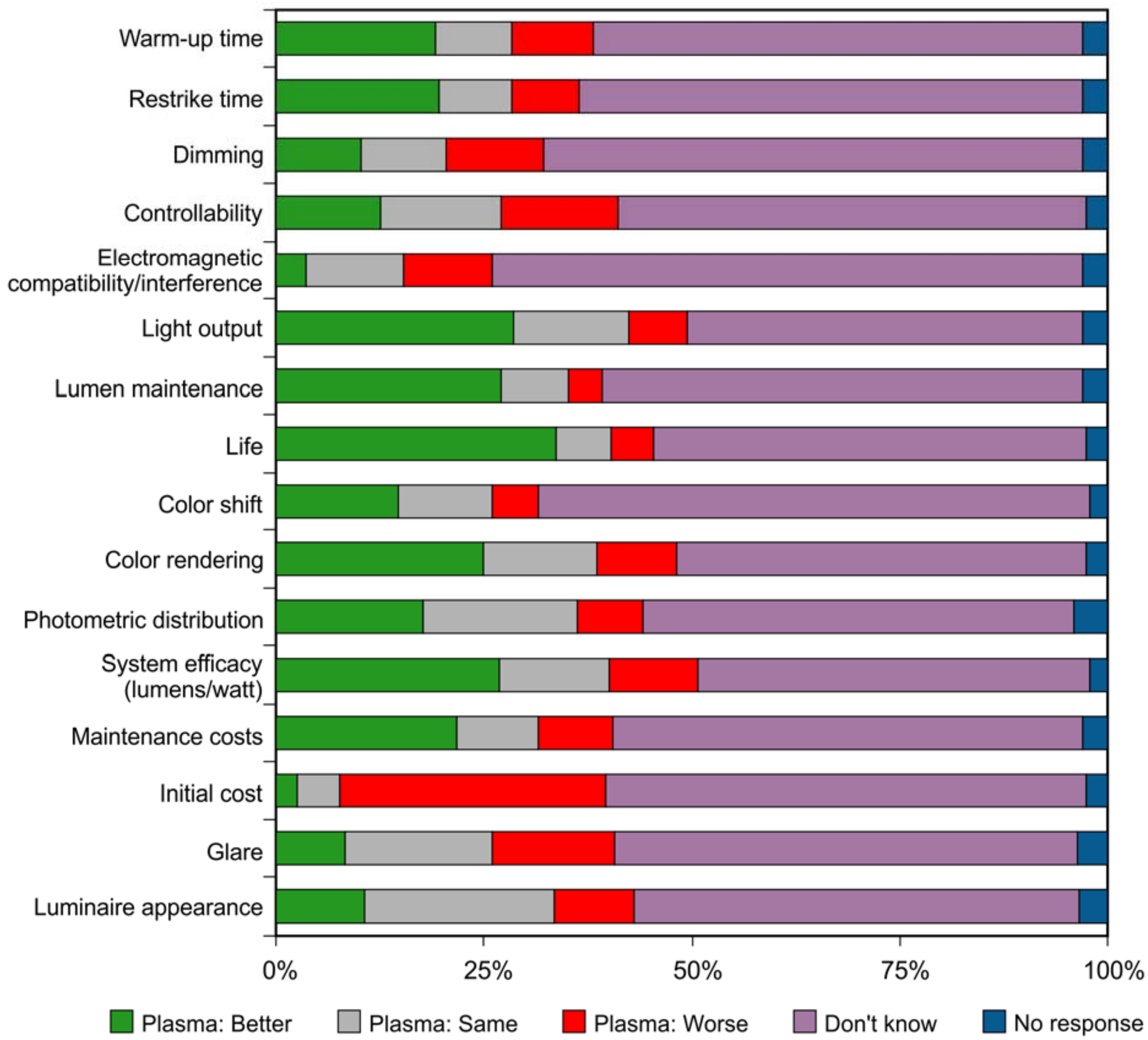
Restrike time: The time required for a lamp to start and return to 90% of its stabilized light output after the lamp is extinguished.

Rated dimming (percentage of maximum power or light output): For HID lamps and induction lighting systems, lighting manufacturers define dimming as a percentage of full power; for LED packages and plasma lighting systems, lighting manufacturers define dimming as a percentage of full light output.

Rated lumen depreciation: For HID lamps, most lighting manufacturers report mean lumens to show rated **lumen depreciation**. Typically, mean lumens are evaluated at 40% of rated life for MH and LPS lamps, at 40-50% of rated life for MV, and at 40-67% of rated life for HPS lamps (General Electric 2013; OSRAM SYLVANIA 2012; Philips Lighting Company 2012). For LED packages, induction lighting systems and plasma lighting systems, rated lumen depreciation occurs at rated life.

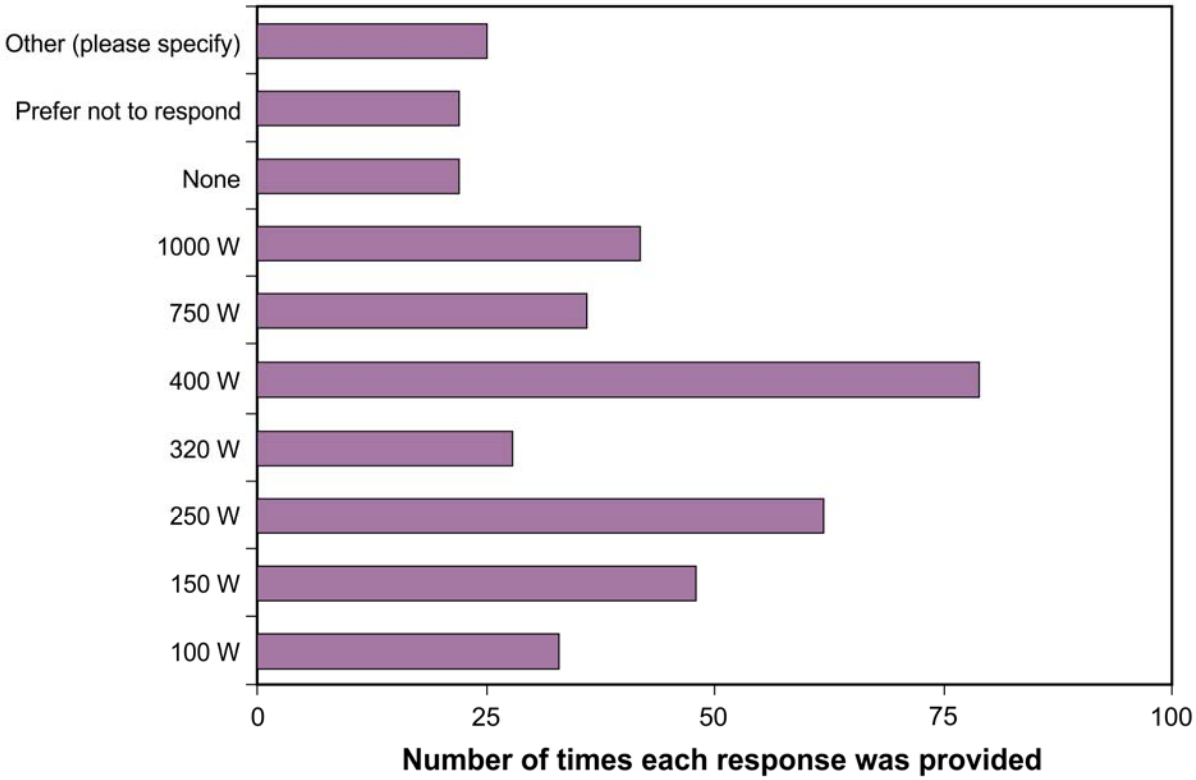
NLPIP conducted an online survey of lighting specifiers in September 2012 in order to assess their beliefs on the characteristics of plasma lighting systems. Specifiers who downloaded previous NLPIP publications were invited to participate. Manufacturers, manufacturer's representatives, and distributors were not included in the survey. The 304 survey participants provided information about the plasma lighting systems they had evaluated as well their opinions on the application of plasma lighting. Most of the survey respondents had heard of plasma lighting systems, but did not know how this technology compared to other light sources for high-bay and outdoor lighting applications (Figure 1). Of those who felt they knew enough to compare plasma lighting systems with their current lighting for these applications, plasma was perceived to be better for many characteristics, with the exceptions of electromagnetic compatibility, initial cost, controllability, dimming, and glare.

Figure 1. Responses to the survey question, "How do plasma lighting luminaires compare to your current luminaire choices for high-bay and outdoor lighting on the following performance characteristics?"



NLPIP also asked the specifiers to provide information regarding which HID lamps they would consider replacing with plasma lighting systems, shown in Figure 2. The specifiers indicated that they would consider replacing 400 watt (W) HID lamps with plasma lighting systems more than any other wattage. In the “Other” category, most specifiers responded “Don’t know” along with three responses listing other wattages: 60 W, 175 W, and 200 W.

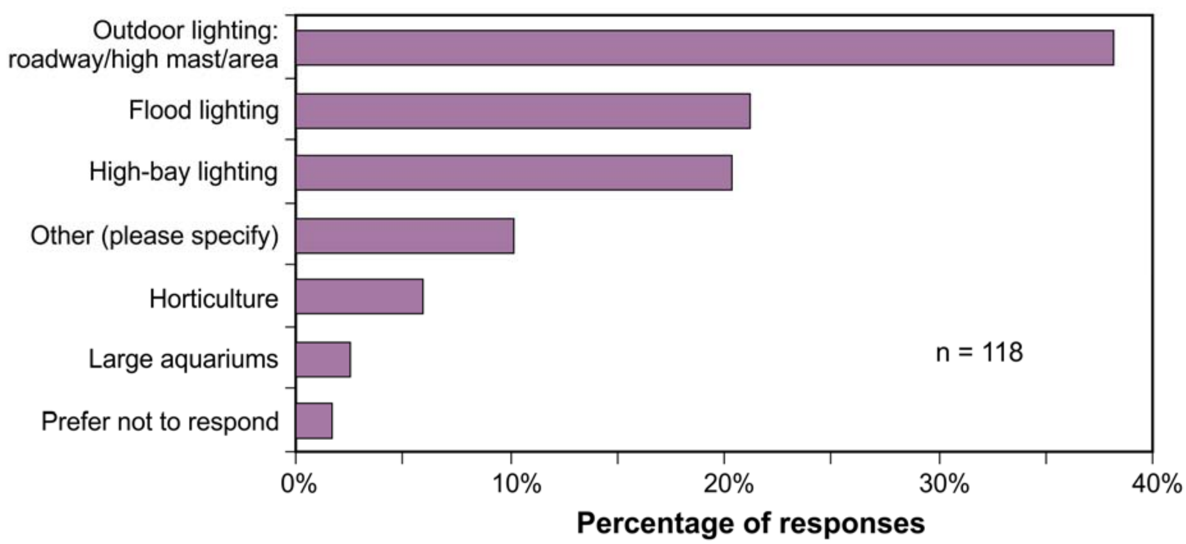
Figure 2. Responses to the question, "Which of the following wattage HID lamps would you consider replacing with plasma lighting (select as many as applicable)?"



What are potential applications for plasma lighting systems?

Manufacturers claim that plasma lighting systems are better suited for roadway, area and high mast lighting **applications** than conventional **HID** and **LED** systems because of their long life, high luminaire efficiency, and low overall system price (Neate and Lister 2012). Manufacturers also claim that plasma lighting systems are better suited for high-bay lighting applications than conventional HID systems because of their high light output, low overall system price, accurate **color rendering** (95 **CRI**) and controllability for dimming and motion sensing. In the 2012 survey of specifiers described in the section "What are the claimed and perceived advantages of plasma lighting systems?" NLPIP asked specifiers about the types of applications for which they had evaluated plasma lighting. As shown in Figure 3, specifiers had evaluated plasma lighting for outdoor lighting applications, including roadway lighting, high mast lighting, and area lighting, more than other applications. Flood lighting and high-bay lighting applications were also evaluated frequently, totaling over 40% of the responses. In the "Other" category, specifiers also mentioned the following applications: stairwells, classrooms, architectural feature lighting, accent lighting, light guides, and high-speed scientific imaging.

Figure 3. Responses to the question, "For what types of applications have you evaluated plasma lighting?"



Bullough and Radetsky (2013) found, using manufacturer's photometric data, that a 288 W plasma streetlight could meet the Illuminating Engineering Society (IES) RP-8 lighting criteria for freeways (Class B) and provide approximately the same pole spacing (225 feet [ft] [68.6 meters (m)]) and **power** demand as the median of three conventional HPS streetlights (median pole spacing: 225 ft [68.6 m]; median power: 292 W). In comparison, six types of LED streetlights demanded approximately 31% less power with comparable median pole spacing (median pole spacing: 223 ft [68.0 m]; median power: 200 W). All the streetlights had a mounting height of 40 ft (12 m). This plasma streetlight could be spaced up to 310 ft (94.5 m) apart if the mounting height was increased to 50 ft (15 m); ranking second in pole spacing behind an HPS streetlight.

What is the commercial availability of plasma lighting systems and luminaires, and how much do they cost?

Presently, there are three commercial manufacturers of plasma lighting systems. In alphabetical order, they are:

- Ceravision, based in Milton Keynes, England. Ceravision also manufactures **luminaires** incorporating their plasma lighting systems. (http://www.ceravision.com)
- LUXIM Corporation (LUXIM), based in Sunnyvale, California. LUXIM also manufactures luminaires incorporating their plasma lighting systems. (http://www.luxim.com)
- Topanga Technologies (Topanga), based in Los Angeles, California. (http://topangatech.com)

There are additional manufacturers that incorporate plasma lighting systems into luminaires.

NLPIP attempted to purchase a 400 W MH- or HPS-equivalent plasma lighting system produced by each of the three manufacturers listed, because that was the **HID** wattage most frequently mentioned in the respondent survey (as shown in Figure 2), but found that as of early 2013, plasma lighting systems are less readily available than other light sources. In order to obtain representative samples, NLPIP attempted to purchase products from online retail websites or through distributors or manufacturer representatives. However, NLPIP found that, as of early 2013, plasma lighting systems can be purchased only directly from manufacturers. NLPIP then attempted to purchase plasma lighting systems from the manufacturers through a utility representative, with the following results:

- Ceravision required a restrictive loan agreement and nondisclosure agreement that would prevent NLPIP from reporting results of the study.
- Stray Light Optical Technologies (one of several manufacturers incorporating the LUXIM plasma lighting system into luminaires) did not respond to the utility representative's request for purchasing information.
- Topanga took approximately 4 months to provide the utility representative with a plasma lighting system. However, that product was non-operational and was returned to the manufacturer.

NLPIP then attempted to purchase plasma lighting systems directly from manufacturers, instead of using a utility representative. NLPIP requested to purchase products for evaluation and informed the manufacturers that the results would be published. NLPIP had the following results:

- Ceravision was unwilling to sell a plasma lighting system or luminaire incorporating such a system to NLPIP despite many requests over 2 months.
- Stray Light Optical Technologies sold NLPIP a Tesla II streetlight which is commercially available and incorporates a 280 W (claimed as a 400 W MH- or HPS-equivalent) plasma lighting system (STA-41-01) from LUXIM (shown in Figures 4 and 5). Stray Light Optical Technologies offered no other **CCT** or **CRI** option that provided similar light output. NLPIP paid $825 for the Tesla II streetlight.

- Topanga sold NLPIP an APL400-4500-DK demonstration kit, shown in Figures 6 and 7. The kit consists of a 230 W (claimed as a 400 W HID-equivalent) plasma lighting system, but not the optics or enclosure that would be part of a commercial luminaire. NLPIP paid $500 for the demonstration kit.

For comparison, NLPIP obtained pricing for single 400 W HPS-equivalent **LED** streetlights from General Electric and Cree in the range of $725 to $1000.

Figure 4. LUXIM plasma lighting system.

Figure 5. LUXIM emitter and resonator.

Figure 6. Topanga plasma lighting system.

Figure 7. Topanga emitter and resonator.

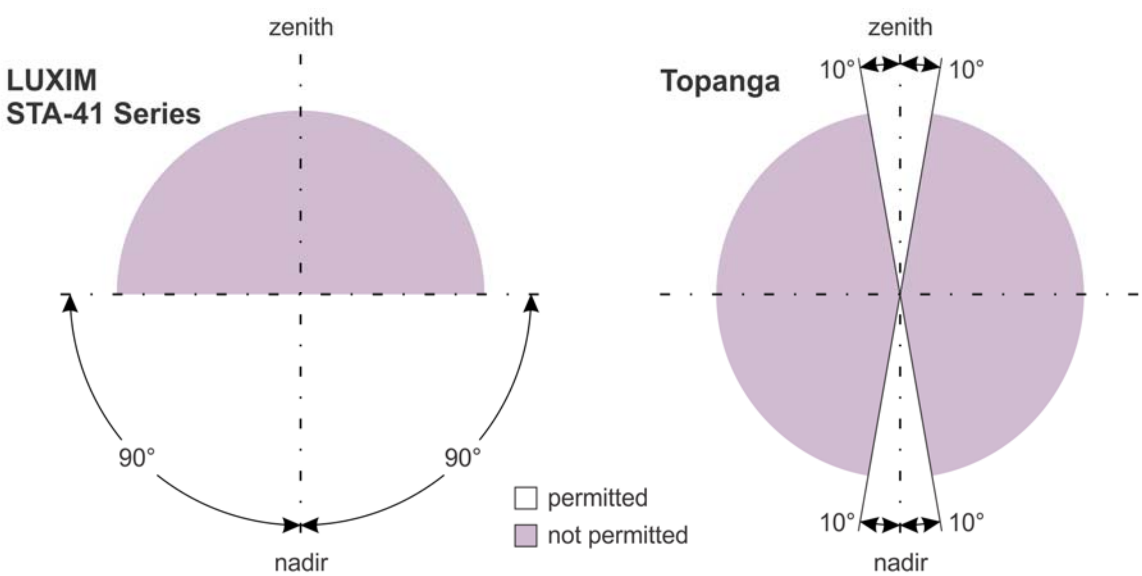
Can plasma lighting systems be operated in any orientation?

No. The allowable orientation depends on the plasma lighting system, as shown in Figure 8.

According to manufacturer specifications, the plasma lighting systems from Topanga can be oriented base up or base down within a tolerance of +/- 10° from vertical.

LUXIM's *OEM* ***Luminaire*** *Design Guide* states that its STA-40 series systems can be operated in any orientation, while its STA-41 series systems can be oriented in a vertical base-up orientation and tilted up to 90° from **nadir** (LUXIM 2010a). The Tesla II streetlight that NLPIP purchased from Stray Light Optical Technologies incorporates a LUXIM STA-41-01 series plasma lighting system. The guide from Stray Light Optical Technologies, *FM000038A Operation Bulb Orientation STA-41*, indicated that the luminaire should not be tilted more than 45° from nadir, which is more restrictive than LUXIM's guidance for the plasma lighting system (Stray Light Optical Technologies n.d.).

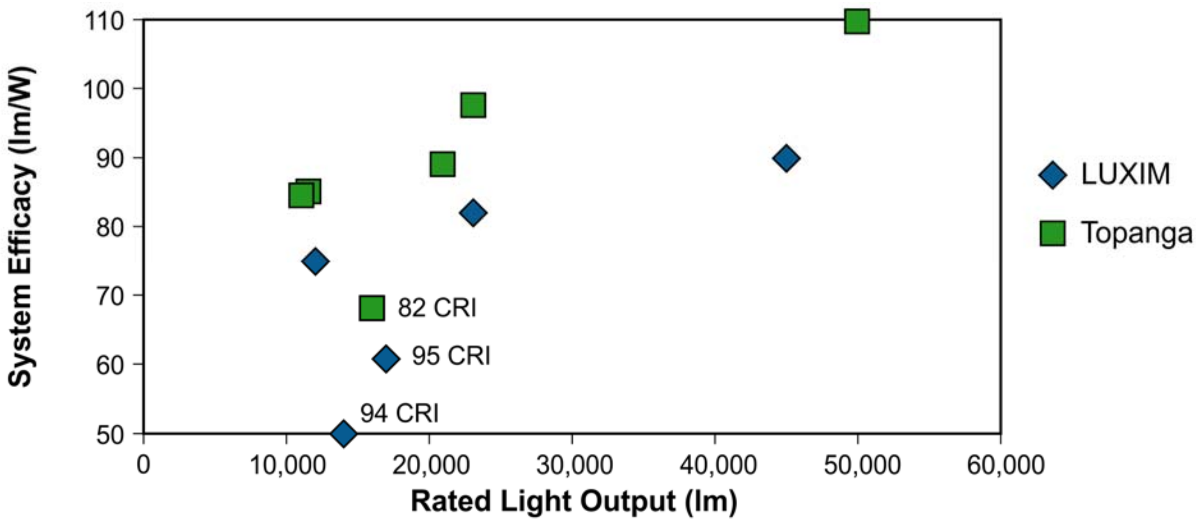
Figure 8. Permissible operating orientations of tested plasma lighting systems.



What is the light output and efficacy of plasma lighting systems?

Based on specifications provided by LUXIM and Topanga on their websites in June 2013, the **rated light output** for plasma lighting systems ranges from 11,000 **lumens (lm)** (with an input power of 130 W) to 50,000 lm (with an input **power** of 455 W), with **system efficacies** ranging from 50 lm/W to 110 lm/W, as shown in Figure 9. The system efficacies include the power demand of the commercial dc power supply. If a different dc power supply was used, the system power and efficacy could be different. Plasma lighting system specifications were not provided by Ceravision at that time. The manufacturers' specified efficacies are shown in Figure 9 as a function of rated light output. Typically, products that have a higher **CRI** have a lower lumen output and **efficacy**, and products with a higher light output typically have a higher efficacy.

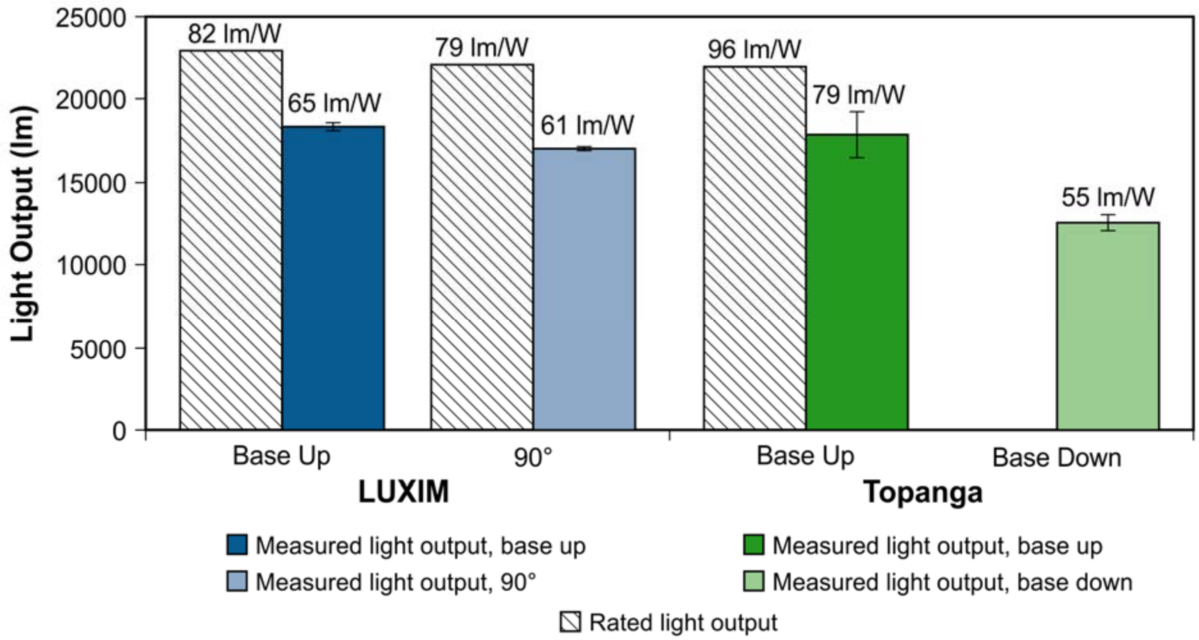
Figure 9. Rated light output and system efficacy of commercial plasma lighting systems. Products have CRI values between 70-75 except as noted.



NLPIP measured the light output and system efficacy of the two plasma lighting systems that it purchased, as shown in Figure 10. One was the STA-41-01 series LUXIM plasma lighting system extracted from the Tesla II streetlight from Stray Light Optical Technologies. (The plasma lighting system was removed by simply unscrewing bolts, and it was not modified during extraction. NLPIP then mounted a heat sink on the LUXIM RF driver and verified that its temperature was below the maximum specified temperature.) The other plasma lighting system was the APL400-4500-DK light engine demonstration kit from Topanga.

The LUXIM plasma lighting system was measured in base-up and 90° orientations at full power. NLPIP found that the light output in the base-up orientation was 18,378 lm, which is 20% lower than the rated light output. LUXIM's *LiFi STA 41 01 Data and Reliability Package* claims that the light output in the 90° orientation is 4% lower than in the base-up orientation (LUXIM 2010c). In the 90° orientation, NLPIP measured a light output of 17,013 lm, 23% less than the rated light output in this orientation and 7% lower than the measured light output in the base-up orientation.

Figure 10. Rated light output vs. measured light output of tested lamps at different operating orientations.



Notes:

1. *Rated base-down light output was not published by Topanga.*
2. *LUXIM power demand in either orientation: rated = 280 W; measured = 281 W*
3. *Topanga power demand in either orientation: rated = 230 W; measured = 227 W*

The Topanga plasma lighting system was measured in base-up and base-down orientations at full power. The results show that the measured light output was 19% lower than the rated light output in the base-up orientation. Rated light output in the base-down orientation was not provided in the Topanga datasheet, but email correspondence from Topanga personnel indicated that light output would be lower in the base-down orientation.

What is the rated life of plasma lighting systems and how well do they maintain their light output?

Manufacturers claim that plasma lighting systems have longer **rated life** than **HID lamps** because they are electrodeless. The **electrodes** in **metal halide lamps** limit useful life for multiple reasons: the tungsten on the electrodes evaporates, causing bulb wall blackening, and leading to **lumen depreciation** and elevated lamp temperatures (Lapatovich 2012); hot spots can form on the filaments accelerating evaporation and leading to filament failure (Lapatovich 2012); the glass to metal seals required to mount the electrodes weaken the bulb wall (Lister et al. 2012) leading to outgassing and failure; and the metal wires and electrodes in the lamp, which can limit the types of chemical materials used in the lamp due to chemical compatibility, can react with the other lamp chemistry and degrade over time (Zissis and Kitsinelis 2009).

The rated life of plasma lighting systems typically ranges from 30,000 to 50,000 h depending on manufacturer and product. Some specialty products geared towards entertainment lighting or instrumentation have shorter lifetimes, approximately 3000 to 10,000 h. Topanga, whose plasma lighting system allows for the replacement of the **arc tube** separately from the RF driver, specifies that the life of the emitter is 50,000 h while the life of the RF driver is 100,000 h.

The basis of rated life varies between manufacturers. For example, LUXIM specifies that life is defined as “time to 70% brightness from initial,” while Topanga uses the term “Lamp Service Lifetime,” which they do not further define. **Lumen maintenance** claims range from 70 to 90% at the end of rated life. DeVincentis et al. (2008) estimated that LUXIM LIFI4000 lamps would demonstrate lumen maintenance of 80% at 25,000 h of continuous operation, based on two prototype lamps showing 90% lumen maintenance at 16,000 h of operation. Gilliard et al. (2011) showed that lumen maintenance was approximately 95% at 4000 h for a LUXIM plasma lighting system. Hollingsworth (2012) showed that a Topanga APL400 plasma lighting system demonstrated lumen maintenance of 97% at 2000 h when operated on an 11-h on and 1-h off duty cycle.

Color shifts may also occur over the rated life. Gilliard et al. (2011) showed that CCT shifted by approximately 1000 K over 4000 h for a LUXIM plasma lighting system.

Verifying lifetime, lumen maintenance, and color shifts over rated life was beyond the scope of this NLPIP study.

What are the color characteristics of plasma lighting systems?

CRI and CCT

Specifiers regard **color rendering index (CRI)** and **correlated color temperature (CCT)** as important color metrics for light sources (NLPIP 2004). Published information, as of June 2013, from LUXIM and Topanga show that commercially available plasma lighting systems have CRI values between 70 and 95 and CCT values between 3200 and 7650 K.

NLPIP measured the **chromaticity** coordinates of the two plasma lighting systems it purchased, at full **power**, and used these chromaticities to calculate CRI and CCT. The results are shown in Table 2. The LUXIM plasma lighting system was measured in base-up and 90° orientations, while the Topanga plasma lighting system was measured in base-up and base-down orientations. NLPIP conducted all measurements in the LRC's lighting laboratories, which are accredited by the National Voluntary Laboratory Accreditation Program (NVLAP Code: 200480-0).

The measured LUXIM system has a rated CRI of 75. NLPIP measured a CRI of 71 for the LUXIM plasma lighting system when operated in a base-up orientation, and a CRI of 73 when operated at a 90° orientation. The measured Topanga system has a rated CRI of 70 in the base-up orientation. NLPIP measured a CRI of 69 for the Topanga system when operated in a base-up orientation, and a CRI of 71 when operated in a base-down orientation.

According to LUXIM's *LiFi STA 41 01 Data and Reliability Package*, the measured LUXIM system had a rated CCT of 5871 K in the base-up orientation and a rated CCT of 5815 K in the 90° orientation (LUXIM 2010c). These rated CCT values can be compared with the CCT values measured by NLPIP of 5950 ±30 K for the base-up orientation and 5860 ±30 K for the 90° orientation, considering that the uncertainty of CCT measurements is approximately ±30 K for this type of spectrum.[1] Both the rated and measured CCT values are lower for the 90° orientation by approximately similar amounts. The rated CCT of 5200 K in the base-up orientation reported in LUXIM's *Product Bulletin LEP STA Series* (LUXIM 2010b), however, is 750 K lower than that measured by NLPIP and 650 K lower than that reported in LUXIM's *LiFi STA 41 01 Data and Reliability Package* (LUXIM 2010c).

According to literature from Topanga, the measured Topanga system has a rated CCT of 4500 K in the base-up orientation (Topanga n.d.). NLPIP measured a CCT of 4930 ±30 K which was 430 K higher than the rated CCT in the base-up orientation and operating at full power. Operating the Topanga plasma lighting system in a base-down orientation increased the CCT to 5580 ±30 K, 650 K above the measured CCT in the base-up orientation, and 1080 K above the rated CCT in the base-up orientation.

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[1] This estimate of expanded uncertainty uses a coverage factor k = 2, covering two standard deviations.

Although differences as large as 1100 K in CCT for “white” light sources are noticeable, peripheral **visual performance** may not be measurably affected because the corresponding differences in scotopic/**photopic** (S/P) **efficacy** ratios can be small (ASSIST 2009).

Table 2: Rated and measured CCT and CRI values for two plasma lighting systems. Standard deviations (SD) for the measured values are also shown.

	LUXIM STA-41-01				Topanga APL400-4500-DK			
	CRI		CCT		CRI		CCT	
Orientation	**Rated**	**Measured** (+/- SD)	**Rated K**	**Measured K** (+/- SD)	**Rated**	**Measured** (+/- SD)	**Rated K**	**Measured K** (+/- SD)
Base Up	75	71 (0.2)	5871/ 5200*	5950 (80)	70	69 (0.3)	4500	4930 (70)
90°	Not specified	73 (0.1)	5815	5860 (30)	Orientation not recommended by manufacturer.			
Base Down	Orientation not recommended by manufacturer.				Not specified	71 (0.3)	Not specified	5580 (90)

*Rated CCT for base-up orientation per *Product Bulletin LEP STA Series* (LUXIM 2010b).

Table 2 shows that operating the plasma lighting systems with different orientations can change the CCT of these sources. Plasma lighting systems are not the only light sources to exhibit color shifts with different operating orientations. MH **lamps** can also exhibit color shifts when operated at different positions (NLPIP 2003). **LED** sources may also experience color shifts at different operating orientations if the orientation changes the operating temperature.

GAI

Gamut Area Index (GAI) is an adjunct measurement to CRI for assessing **color rendering**. GAI is defined as the enclosed area in the Commission Internationale de l’Eclairage **(CIE)** 1976 chromaticity space determined by the 8 CIE standard color chips used for CRI calculations relative to the enclosed area when the chips are illuminated by an equal energy spectrum (EES) (Rea and Freyssinier 2011). GAI was not reported by the plasma lighting manufacturers.

For the measured LUXIM system, NLPIP measured a GAI of 63 for the LUXIM plasma lighting system when operated in a base-up orientation, and a GAI of 64 when operated at a 90° orientation. For the measured Topanga system, NLPIP measured a GAI of 51 when operated in a base-up orientation, and a GAI of 63 when operated in a base-down orientation.

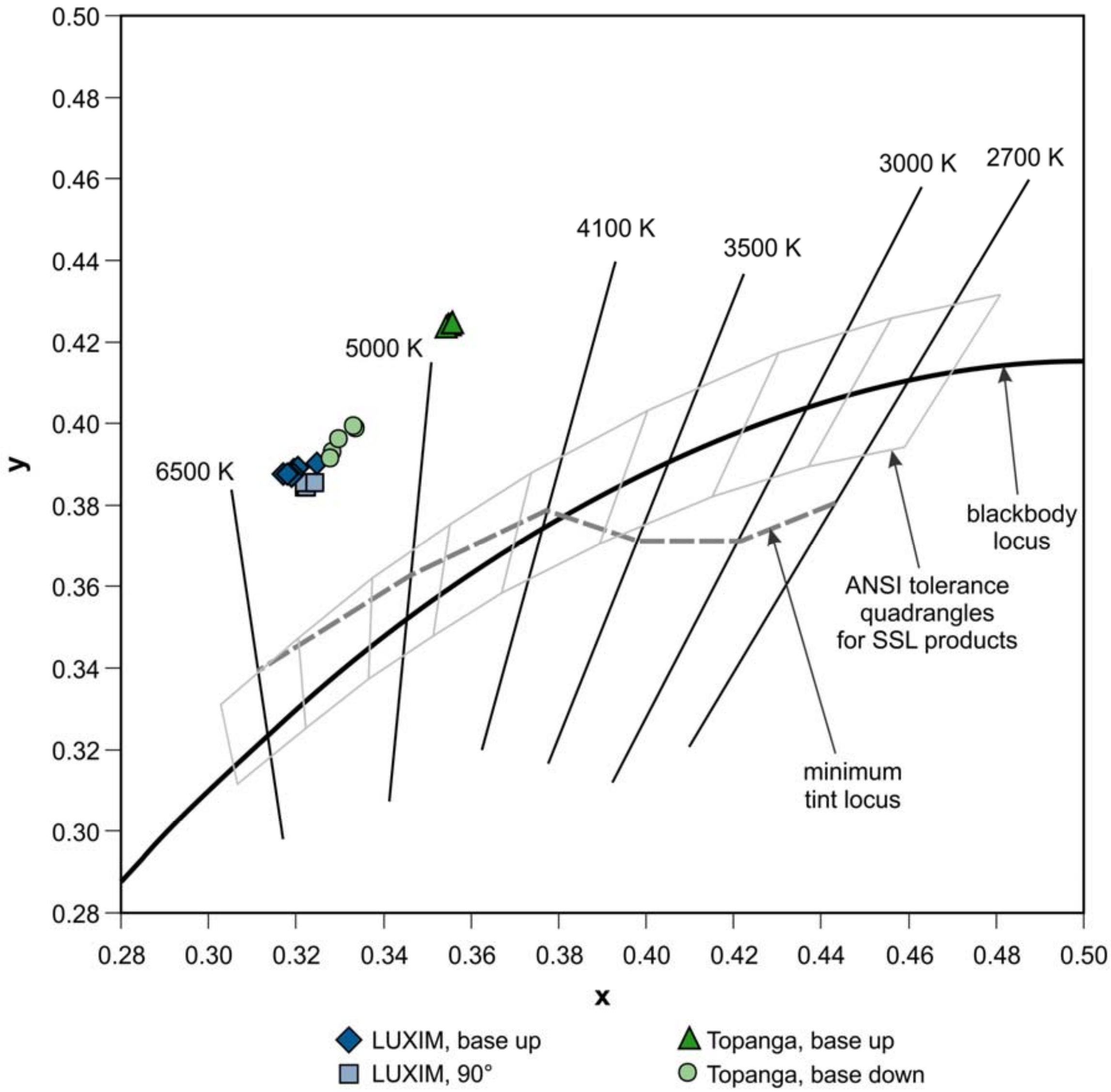
Typically, CRI values of 80 *and* higher and GAI values between 80 and 100 indicate excellent color rendering (Rea and Freyssinier 2011).

Tint

Recently, the LRC determined that light sources that provide untinted “white” illumination do not fall on the blackbody locus (Rea and Freyssinier 2013), which may be contrary to popular belief. Research shows that for CCTs greater than 4000 K, light sources perceived as minimally tinted have chromaticity coordinates that lie slightly above the blackbody locus, while for CCTs less than 4000 K, light sources perceived as minimally tinted have chromaticity coordinates that lie well below the blackbody locus. The minimum tint locus, shown in Figure 11, is described by Rea and Freyssinier (2011).

As shown in Figure 11, the chromaticity coordinates of the measured plasma lighting systems are well above the minimum tint locus, indicating that these light sources will appear greenish-white (Rea and Freyssinier 2013). NLPIP confirmed, by visual inspection, that these light sources appeared to be greenish-white. Although, light sources that appear tinted (greenish-white) are noticeably different than light sources that are untinted, their effect on peripheral visual performance may not be measurably important unless the differences in S/P efficacy ratios are large (ASSIST 2009).

Figure 11. Chromaticity coordinates of the LUXIM and Topanga lighting systems at full power. Also shown are the American National Standards Institute (ANSI) chromaticity quadrangles used to specify tolerances for solid state lighting (SSL) products used in general indoor lighting applications (ANSI 2011). The size of each quadrangle corresponds to a range from 8-step to 13-step MacAdam ellipses.



At full power, changing the orientation of the LUXIM plasma lighting system changed the chromaticity coordinates by less than a 2-step **MacAdam ellipse**. This change is less than the 4-step MacAdam ellipse tolerance allowed for **fluorescent lamps** (ANSI 2001) and the chromaticity tolerance allowed for SSL products, shown in Figure 11. Changing the orientation of the Topanga plasma lighting system at full power changed the chromaticity coordinates by more than a 6-step MacAdam ellipse.

Can plasma lighting systems be dimmed?

Yes. Plasma lighting systems can be dimmed, but dimming these systems results in **color shifts** and decreases in luminous **efficacy**, as shown in Figure 12. All three plasma lighting system manufacturers specify that their products are dimmable down to 20% of maximum light output. According to LUXIM's *LiFi STA 41 01 Data and Reliability Package*, dimming the product down to 70% of maximum light output will increase CCT from approximately 6000 K to approximately 8000 K and dimming the product down to 20% of maximum light output will increase CCT to approximately 15,000 K (LUXIM 2010c).

Similar to CCT, S/P efficacy ratios also increased when the measured plasma lighting systems were dimmed. At the same **photopic illuminance**, peripheral detection at mesopic light levels will be faster and more accurate for light sources with higher S/P efficacy ratios, than for light sources with lower S/P efficacy ratios (ASSIST 2009).

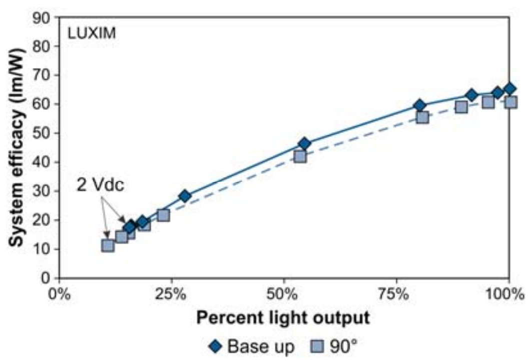
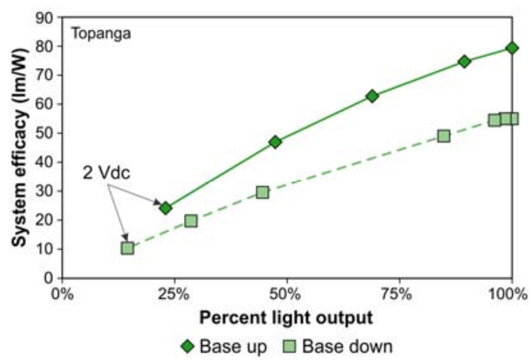
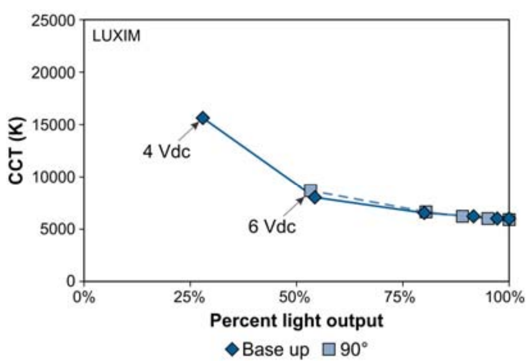
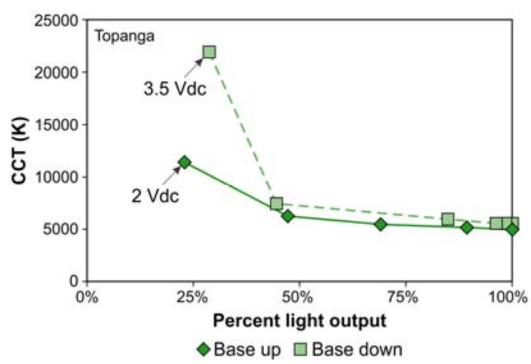
To verify these claims, NLPIP measured the light output, **system efficacy**, and color characteristics of the two plasma lighting systems that it purchased by varying the analog dimming voltage over the operating range specified by the manufacturers, which is 2 to 10 volts of direct current (Vdc). The LUXIM system was measured in base-up and 90° orientations, and the Topanga system was measured in base-up and base-down orientation. Both plasma lighting systems were measured at multiple dimming levels.

At the minimum specified analog dimming voltage of 2 Vdc, NLPIP found that the measured LUXIM system was able to be dimmed down to 16% of its maximum light output in base-up orientation and 11% of its maximum light output in the 90° orientation. The LUXIM plasma lighting system became less efficacious as it was dimmed. As suggested by the change in **chromaticity** coordinates, NLPIP observed that the light appeared greenish-white when operated at full **power**, and became bluer as it was dimmed. Its CCT shifted by more than 2000 K when it was dimmed by 50% or more. When the LUXIM plasma lighting system was dimmed to less than 25% of its maximum light output in the base-up orientation, the chromaticities were so shifted that CCT was no longer defined for its chromaticity (CIE 2004). When it was dimmed to less than 50% of its maximum light output in the 90° orientation, the chromaticities also shifted such that CCT was no longer defined (CIE 2004). This change in chromaticity corresponds to a 47-step **MacAdam ellipse** for the base-up orientation, and a 61-step MacAdam ellipse for the 90° orientation. In the base-up orientation, the **CRI** increased as the LUXIM plasma lighting system was dimmed. When the LUXIM plasma lighting system was dimmed in the 90° orientation, the CRI first increased and then decreased to approximately the same CRI as measured at full power.

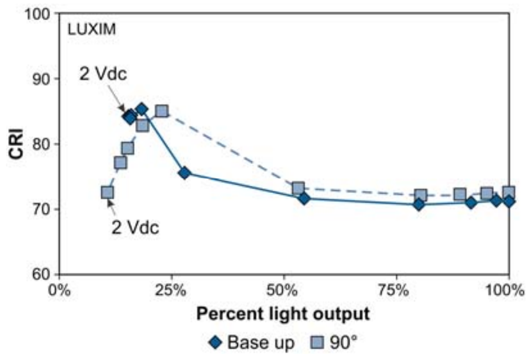
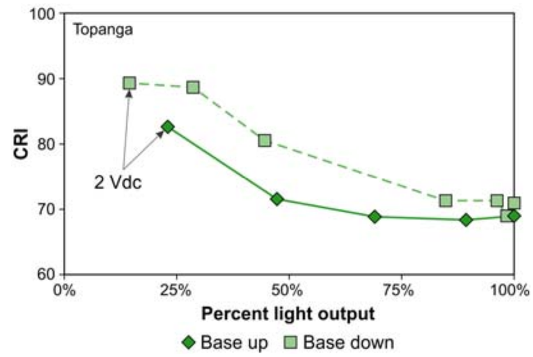
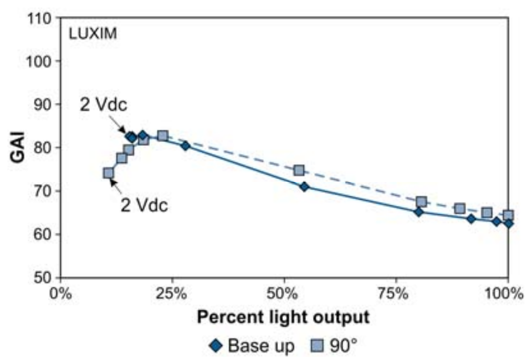
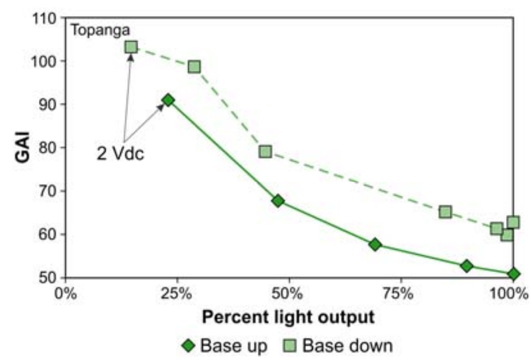
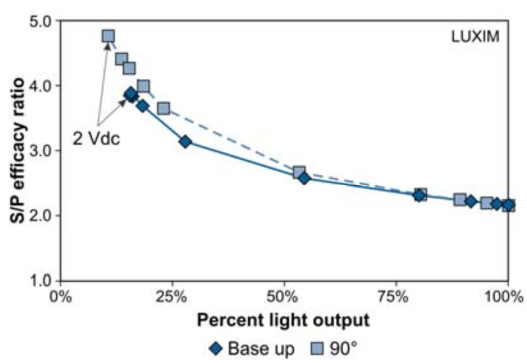
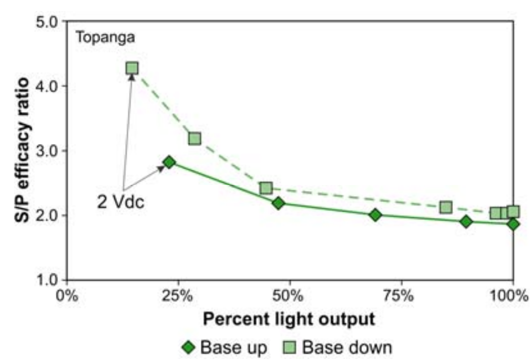
At the minimum specified analog dimming voltage of 2 Vdc, NLPIP found that the measured Topanga plasma lighting system was able to be dimmed down to 22% of its maximum light output in a base-up orientation and to 15% of its maximum light output in a base-down orientation. This product became less efficacious as it was dimmed. As suggested by the change in chromaticity coordinates, NLPIP also observed that the measured Topanga plasma lighting system appeared greenish-white when operated at full power, and became bluer as it was dimmed. The CCT shifted by more than 1000 K when it was dimmed by 50% or more. When it was dimmed to 15% of its maximum light output in the base-down position, the chromaticity of the light also shifted to such an extent that CCT was no longer defined for its chromaticity (**CIE** 2004). The change in chromaticity coordinates corresponds to a 33-step MacAdam ellipse for the base-up orientation, and a 58-step MacAdam ellipse for the base-down orientation. The CRI of this plasma lighting system increased as it was dimmed in both operating orientations.

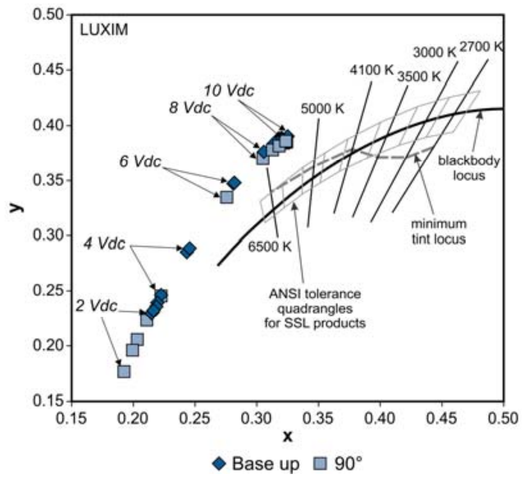
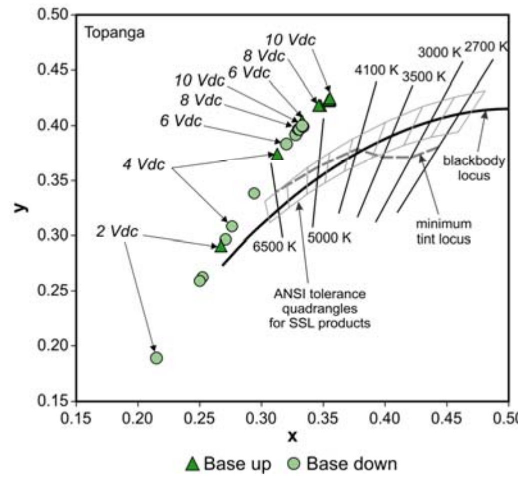
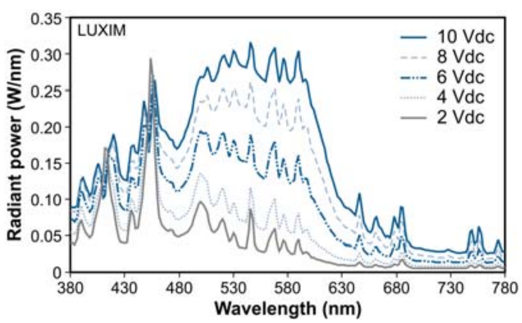
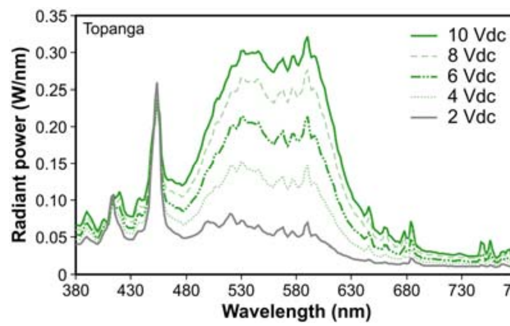
MH lamps also show a decrease in luminous efficacy when dimmed; clear MH lamps also exhibit an increase in CCT and a decrease in CRI when they are dimmed (NLPIP 1994). The measured plasma lighting systems, unlike clear MH lamps, did not demonstrate a decrease in CRI as they were dimmed, because their **SPDs** did not become discontinuous. The SPDs exhibited much larger decreases in radiant power at long **wavelengths** than short wavelengths as the plasma lighting systems were dimmed in the base-up orientation. Similar differences were seen in the other operating orientations.

Figure 12. Dimming results of LUXIM and Topanga plasma lighting systems.

<table>
<tr><th></th><th>LUXIM</th><th>Topanga</th></tr>
<tr><td>Efficacy</td><td>
</td><td>
</td></tr>
<tr><td>CCT</td><td>
</td><td>
</td></tr>
</table>

Note: CCT is undefined when dimming voltages are lower than values shown.

<table>
<tr><th></th><th>LUXIM</th><th>Topanga</th></tr>
<tr><td>CRI</td><td>
</td><td>
</td></tr>
<tr><td>GAI</td><td>
</td><td>
</td></tr>
<tr><td>S/P Efficacy Ratio</td><td>
</td><td>
</td></tr>
<tr><td></td><td colspan="2">S/P efficacy ratios of CIE standard illuminants: A – 1.41; D65 – 2.46. For examples of S/P efficacy ratios for commercially available light sources, see ASSIST 2009; NLPIP 2010, 2011.</td></tr>
</table>

<table>
<tr><th></th><th>LUXIM</th><th>Topanga</th></tr>
<tr><td>Chromaticity</td><td>
</td><td>
</td></tr>
<tr><td>SPD</td><td>
</td><td>
</td></tr>
</table>

In order to keep color shift within a 4-step MacAdam ellipse, the tolerance allowed for **fluorescent lamps** (ANSI 2001), the LUXIM plasma lighting system could not be dimmed more than 21% in the base-up orientation and more than 11% in the 90° orientation. The Topanga plasma lighting system could not be dimmed more than 12% in the base-up orientation and more than 15% in the base-down orientation and keep color shift within a 4-step MacAdam ellipse. Even though the manufacturers allow different **operating positions** (see “Can plasma lighting systems be operated in any orientation?”), when placed in these positions, NLPIP observed measurable decreases in efficacy and shifts in color. Specifiers may wish to evaluate these parameters for **applications** where the **luminaires** are aimed in a position other than base-up (such as flood lighting or architectural lighting).

How quickly do plasma lighting systems warm up and restrike?

Plasma lighting systems do not achieve their full light output immediately after starting. Rather, they require a few minutes to reach 90% of their stabilized light output. This period is called the warm-up (or run-up) time. After the plasma lighting system has been on for a period of time and then extinguished, the **lamp** cannot immediately turn back on. The lamp must have a chance to cool down before the system will restart. The period of time for the lamp to restart and reach 90% of its stabilized light output is called the **restrike time**.

According to manufacturers' literature, **warm-up times** from a cold start are less than 1 minute (min) for LUXIM and Topanga systems and 1 min for Ceravision systems (Lister et al. 2013). However, Lister et al. (2012) indicated that the measured warm-up time for the Ceravision systems was 5 min. NLPIP found that, on average, the measured LUXIM plasma lighting system achieved 90% of its stabilized light output during warm-up in approximately 3.5 min. The measured Topanga system achieved 90% of its stabilized light output within 2 min of being switched on.

All three manufacturers claim that restrike times for their plasma lighting systems are 2 min or less (with a range of 45 seconds to 2 min). NLPIP found that, on average, the measured LUXIM system achieved 90% of its stabilized light output after a restrike in approximately 5.5 min. The measured Topanga system achieved 90% of its stabilized light output after a restrike within 2 min, which meets the manufacturer’s reported restrike time.

What are the control methods available for plasma lighting systems?

Specifiers may incorporate commercial controls with plasma **luminaires**. The plasma lighting system manufacturers offer various methods of control that interface with commercial controls or their own control equipment. Testing the control methods other than analog dimming control was beyond the scope of this NLPIP study.

LUXIM offers three methods of controlling their plasma lighting systems:

- Analog dimming voltage, nominally 0 to 10 Vdc. A potentiometer or a commercial 0-10 Vdc analog dimmer can be used to manually dim the plasma lighting system.
- Serial digital controls using an external controller. LUXIM's *OEM Luminaire Design Guide* states that the external controller can consist of any wireless control technology, **power line carrier**, or other lighting control technology (LUXIM 2010a).
- A 24 Vdc serial communication interface (SCI) input is provided for controls such as occupancy/vacancy sensors or daylight harvesting sensors. A 5 Vdc wire is also provided to power the low voltage sensor from the RF driver directly. LUXIM's *OEM Luminaire Design Guide* states that preset dimming levels can be used in conjunction with occupancy/vacancy sensors (LUXIM 2010a).

According to the *Topanga APL Sample Kit Setup and Operating Instructions*, the Topanga system allows for analog dimming voltage, nominally 0 to 10 Vdc, and serial digital control, allowing for switching and scheduling control, and diagnostics (Topanga n.d.).

Ceravision claims that their system incorporates software into their power supplies which allows users to control and monitor both individual luminaires as well as complete lighting systems from one central command center. The Ceravision website shows allowable input from manual switches, occupancy sensors, and daylight sensors through a digital input module (Ceravision 2013).

What has been the experience of those who have installed HID plasma luminaires?

NLPIP interviewed an individual associated with each of four plasma lighting demonstrations and pilot studies, detailed below. These applications were either mentioned in the popular press, were funded by governmental or private agencies, or were brought to NLPIP's attention from specifiers who participated in the 2012 survey (as discussed in the section *"What are the claimed and perceived advantages of plasma lighting systems?"*).

Scottsburg Municipal Electric Utility, Scottsburg, Indiana (2009 - 2011)
Interview summary

- Scottsburg Municipal Electric Utility partnered with Stray Light Optical Technologies to replace 56 existing 400 W HPS streetlights with 40 streetlights containing plasma lighting systems, in a pilot project funded by the American Public Power Association (APPA) Demonstration of Energy and Efficiency (DEED) program (Rea 2011). A 51% reduction in total lighting power was accompanied by a 68% decrease in average **illuminance**.
- During the pilot project, many of the 40 installed plasma streetlights failed and were repeatedly replaced over the 20-month observation period (Rea 2011). One-third of the plasma streetlights did not start when the **ambient temperature** was less than approximately 15°F. Most of the 40 plasma streetlights failed due to a faulty component in the power supply. In addition, most of the 40 plasma streetlights had incompatible gaskets that caused significant off-gassing. The off-gassing created an opaque film on the plasma **arc tube**, which led to increased **lumen depreciation**, discoloration of the arc tube, and failure. All three quality issues were addressed by the luminaire manufacturer under warranty.
- Despite these issues, Scottsburg Municipal Electric Utility has since continued to replace more than 300 HPS streetlights with plasma streetlights. There have been no failures in these replacements due to cold weather (ambient temperature less than approximately 15°F) (Jim Binkley, Scottsburg Municipal Electric Utility, personal communication, 2013).
- Scottsburg Municipal Electric Utility plans to replace up to 527 HPS streetlights with plasma streetlights in total. They are satisfied with the way the manufacturer has replaced the products as needed (Jim Binkley, Scottsburg Municipal Electric Utility, personal communication, 2013).

Sacramento Municipal Utility District, Sacramento, California (2011)
Interview summary

- Sacramento Municipal Utility District (SMUD) published a technology brief on light-emitting plasma in December 2011 (SMUD 2011). One demonstration project that received a Customer Advanced Technologies program research grant is mentioned in this report. At this site, LUXIM wall-mounted luminaires replaced existing MH floodlights. SMUD also provided NLPIP with information about two other demonstration sites that received Customer Advanced Technologies program research grants. In one of the demonstration sites, LUXIM wall-mounted luminaires replaced existing MH floodlights. At the other demonstration site, LUXIM area lighting luminaires replaced existing HPS area lighting luminaires. In all three demonstration sites, **uniformity** ratios improved under the plasma luminaires.

- At one of the wall-mounted lighting demonstration sites, average light levels decreased by approximately 30% while total lighting power decreased by approximately 50%. Although there were multiple failures at this location with earlier generations of the plasma luminaires, there have been no failures at this location since November 2012. At the other wall-mounted lighting demonstration site, light levels increased even though total lighting power decreased. Although there were failures at this site, this customer plans to install more plasma luminaires and a wireless control system by December 2013 (Dave Bisbee, SMUD, personal communication, 2013).
- In the area lighting demonstration site, the decrease in total lighting power was accompanied by an even larger decrease in light level. At this site, there were multiple failures and this customer has replaced the plasma area lights with **LED** luminaires (Dave Bisbee, SMUD, personal communication, 2013).
- SMUD indicated that there was an average failure rate of 25% across the three sites with multiple generations of luminaires and noted that the manufacturer had been replacing luminaires as needed. In some cases, the luminaire replacement was not due to outright failure but due to a green **color shift** after 8000 h of use (Dave Bisbee, SMUD, personal communication, 2013).

Ports America, Oakland, California and Newark, New Jersey (2010 - 2012)
Interview summary

- Ports America is the largest terminal operator in the U.S., operating in more than 42 ports and 80 locations nationwide. Most terminal lighting is provided by 1000 W HPS high-mast luminaires (1280 W input power per luminaire) using poles that are 80 to 150 ft (24 to 46 m) in height, spaced 250 to 400 ft (76 to 120 m) apart with 8 to 12 luminaires on each pole. Some of the marine terminals are at the end of the utility **grid** distribution lines and power supply fluctuations are an ongoing issue.
- Ports America is evaluating lighting upgrades in order to reduce sky glow; meet OSHA standards of 5 **footcandles** (54 lux) average in work areas; reduce its energy use; use existing poles; augment safety and reduce maintenance costs. The HPS **lamps** and **ballasts** need to be replaced annually because of power quality issues. The HPS luminaires also have a high energy cost of $818 per luminaire per year.
- Ports America, along with the Pacific Gas and Electric Company (PG&E), evaluated successive generations of plasma luminaires for the past two years (Ward 2012, 2013 and personal communication, 2013; Douglass et al. 2013).
- In this demonstration, 12 new 1000 W HPS luminaires were replaced with twelve, ten, or eight 560 W high mast plasma luminaires from Bright Light Systems. The plasma luminaires required less power but also had lower average **horizontal illuminance** by approximately the same ratio (Douglass et al. 2013; Ward 2013). The measured uniformity was better under the plasma luminaires (Douglass et al. 2013; Ward 2013), and the plasma luminaires produced higher light levels at some key locations, such as the wharf “bull rail” (Thomas Ward, personal communication, 2013).
- The plasma luminaires were able to be individually dimmed and switched in groups, although the 50% dimming setpoint produced approximately 35% of the full light output and used approximately 60% of the full power demand (Douglass et al. 2013).

- Ports America investigated the potential visual benefits of white light (Ward 2012; Douglass et al. 2013). However, light levels at these sites were high enough that there would be very little, if any, improvement in peripheral **visual performance** due to spectral effects (ASSIST 2009; Douglass et al. 2013). The improved **color rendering** capabilities of the plasma luminaires make it easier for workers to see ground striping, to differentiate container edges, and to read container markings, and the workers prefer the "whiter" light source (Thomas Ward, personal communication, 2013). In some situations, there was a direct view of the plasma luminaires and **glare** was an issue. Ports America is considering adjusting the task locations to overcome this problem (Thomas Ward, personal communication, 2013).
- Over the course of the evaluation, Ports America found that the plasma luminaires were also sensitive to power supply fluctuations and the luminaires were replaced under warranty. Recent generations of the luminaire include updated electronics that have stabilized the luminaire's output (Thomas Ward, personal communication, 2013). Ports America believes that the Bright Light Systems luminaires produce less sky glow, compared to the base case, likely due to luminaire **shielding** and lower light levels.
- Ports America has determined that the plasma luminaires meet the OSHA illumination criteria (Thomas Ward, personal communication, 2013). Ports America has determined that the plasma luminaires are suitable for the Outer Harbor installation, and is working with the manufacturer to use the plasma luminaires in other port installations. Ports America is also evaluating LED systems for this application, but has found the proposed luminaires to be too heavy to be suitable (Thomas Ward, personal communication, 2013).

Hydro One, Leamington, Ontario, Canada (2010)

Interview summary (David Forgione, Hydro One, personal communication, 2013)

- Hydro One, a utility in Ontario Canada, incentivized the replacement of 370 existing 1000 W HPS luminaires with 295 W Plasmalyte plasma luminaires on a one-for-one basis for a greenhouse application. The luminaires were incentivized under the Ontario Power Authority *saveONenergy* RETROFIT program administered by Hydro One's conservation demand management department.
- Hydro One was interested in the energy and demand savings provided by the retrofit, whereas the client is interested in produce growth, particularly that of green peppers.
- The client has indicated that there are no major differences in the growth rate of the green peppers under the HPS or the plasma luminaires.
- When the plasma luminaires were cycled on and off, there were problems with the electronic drivers due to voltage fluctuations. The drivers were replaced and there have been no further problems with the plasma luminaires.

What is the effect of ambient temperature on plasma lighting systems?

Operating the plasma lighting systems in hotter **ambient environments** will decrease light output and increase **CCT**. LUXIM's *LiFi STA 41 01 Data and Reliability Package* states that there is a 3% decrease in light output and a 100 K increase in CCT at 50°C relative to the light output and CCT measured at 20°C (LUXIM 2010c). The publication states that the decrease in light output is due to a decrease in the RF driver efficiency, and the shift in color temperature is due to a decrease in the bulb wall temperature at the cold spot; the same publication also claims that light output will increase by approximately 7% at -40°C relative to the light output measured at 20°C and that the color shift is less than 20 K for temperature ranges between -40°C and 20°C (LUXIM 2010c). Hollingsworth (2012) showed that light output decreased by a maximum of approximately 3% for a Topanga plasma lighting system operated in a temperature range of 40°C to 55°C. Hollingsworth (2012) also indicated that there was no reduction in light output at temperatures between -30°C to 40°C and that operating this plasma lighting system at -40°C would decrease light output by approximately 3%. Verifying temperature effects on plasma lighting systems was beyond the scope of this NLPIP study.

Is electromagnetic compatibility a concern for plasma lighting systems?

Yes. Plasma lighting systems operate at high **frequencies** and can be a source of both radiated and conducted **electromagnetic interference (EMI)** (Lapatovich 2012). If the **luminaire** containing the plasma lighting system is not shielded, the luminaire can cause interference with other electronic equipment. Controlling a device's EMI so that it can operate satisfactorily alongside other electronic devices is known as electromagnetic compatibility (EMC).

The Federal Communication Commission (FCC) specifies limits for conducted and radiated emissions for radio frequency (RF) digital devices (Part 15) and for industrial, scientific and medical equipment (Part 18) which includes RF lighting devices. FCC Part 15 includes two classes: Class A covers digital devices that are marketed exclusively for use in business, industrial and commercial environments; Class B covers digital devices that are marketed for use anywhere, including residential environments. FCC Part 18 covers two types of usage: non-consumer equipment and consumer equipment. The FCC limits only pertain to electromagnetic radiation at distances of 3 m (10 ft) and greater from the luminaire. To NLPIP's knowledge, there are no requirements from the FCC or other governing bodies that would cover EMC for devices less than 3 m (10 ft) from the RF device, such as a wireless sensor placed on the luminaire. Therefore, luminaires and other electronic devices that meet the FCC requirements for radiated emissions could still be sources of EMI for devices nearer than 3 m (10 ft).

NLPIP sent the Stray Light Optical Technologies Tesla II streetlight to Underwriters Laboratories (UL) in Melville, New York for EMC testing. The measured Topanga system was not tested for EMI, because it was a demonstration kit and the manufacturer indicated that it was not adequately shielded to prevent EMI. The Tesla II streetlight was tested to determine if it complied with FCC Part 15 Class A and B and FCC Part 18 non-consumer and consumer limits. According to FCC, residential environments are not limited to property lines and would include city streets in residential neighborhoods (FCC 2013). As a guideline, streetlights installed within 250 ft (76 m) of a residential property line are considered to be operating in a residential environment (FCC 2013). Streetlights installed in a residential area would need to meet the consumer limits for Part 18 RF lighting devices or the Part 15 Class B limits as applicable. The radiated emissions were measured at 3 m (10 ft) and 10 m (33 ft). The luminaires were measured at 3 m (10 ft) over a frequency range of 30 to 10,000 megahertz (MHz), and at 10 m (33 ft) over a frequency range of 30 to 1000 MHz. FCC Part 15 Class B and FCC Part 18 limits were compared to the radiated emissions measured at 3 m (10 ft), the FCC Part 15 Class A limits were compared to the radiated emissions measured at 10 m (33 ft). In addition, the radiated emissions measured at 3 m (10 ft) were compared to the FCC Part 15 Class A limits translated to 3 m (10 ft) using an inverse relationship between field strength and distance. The Tesla II datasheet indicated that the luminaire is in compliance with FCC Part 18 Class A and CISPR 22, an international EMC standard from the International Electrotechnical Commission (IEC). FCC allows digital devices to comply with the radiated emissions limits in CISPR 22, third edition, as an alternative to the radiated limits given in FCC Part 15.

NLPIP asked UL to verify that the Tesla II streetlight met FCC limits when the luminaire was operated at full power, and also when the luminaire was dimmed to 50% light output and 20% light output. NLPIP attached a rotary dimmer that was provided by Stray Light Optical Technologies to dim the streetlight during EMC testing. NLPIP marked the dimmer at 100%, 50%, and 20% of full light output to indicate how much UL was to dim down the luminaire during testing.

Results of the EMC testing showed that the Tesla II streetlight exceeds the maximum allowable radiated emissions set by the FCC Part 15 Class A and B limits, and Part 18 consumer and non-consumer limits at full **power** and at both measured dimming levels. Figure 13 shows the measured radiated emissions at 100% light output at 3 m (10 ft) and 10 m (33 ft), compared to the FCC Part 15 Class A limits at 3 m (10 ft) and 10 m (33 ft) and the FCC Part 18 non-consumer limits scaled to the 3 m (10 ft) testing distance. Figure 14 shows the measured radiated emissions at 100% light output at 3 m (10 ft) compared to the FCC Part 15 Class B limit of at 3 m (10 ft) and Part 18 consumer limits scaled to the 3 m (10 ft) testing distance. The Tesla II streetlight exceeded the FCC limits by up to 13 times the maximum allowable radiated emissions, when operated at full power. Even when the luminaire was dimmed down to 20%, it exceeded FCC limits by up to 7 times the maximum allowable radiated emissions.

Figure 13. Radiated emissions from a Tesla II streetlight compared to the FCC commercial limits (FCC Part 15 Class A and FCC Part 18 non-consumer limits) at 100% light output, measured 3 m (10 ft) from the luminaire and 10 m (33 ft) from the luminaire. The Y-axis in decibels (dB) indicates the electric field strength relative to 1 microvolt (μV) per meter. Emissions in the shaded area of the figure exceed the maximum allowable FCC limits.

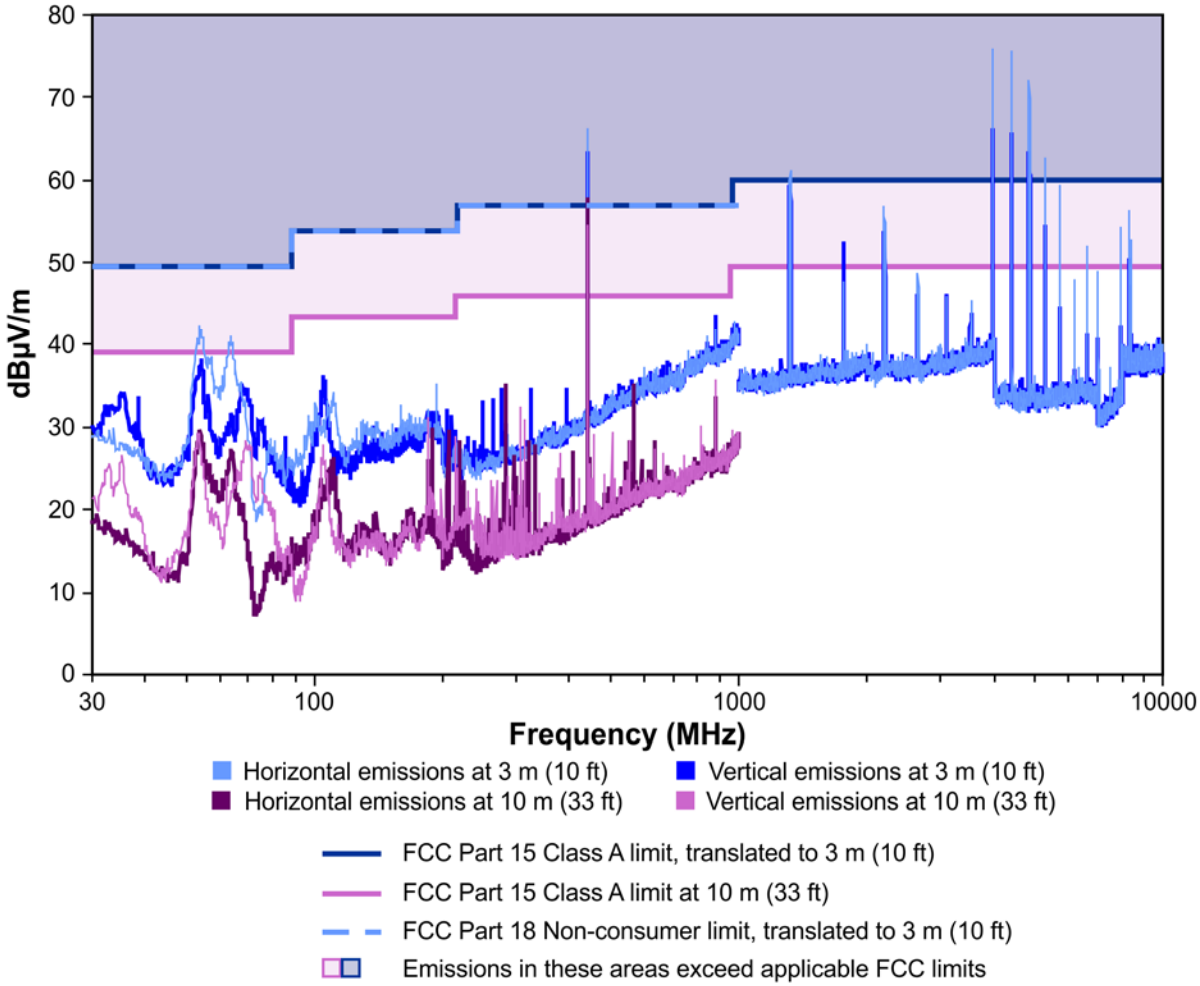
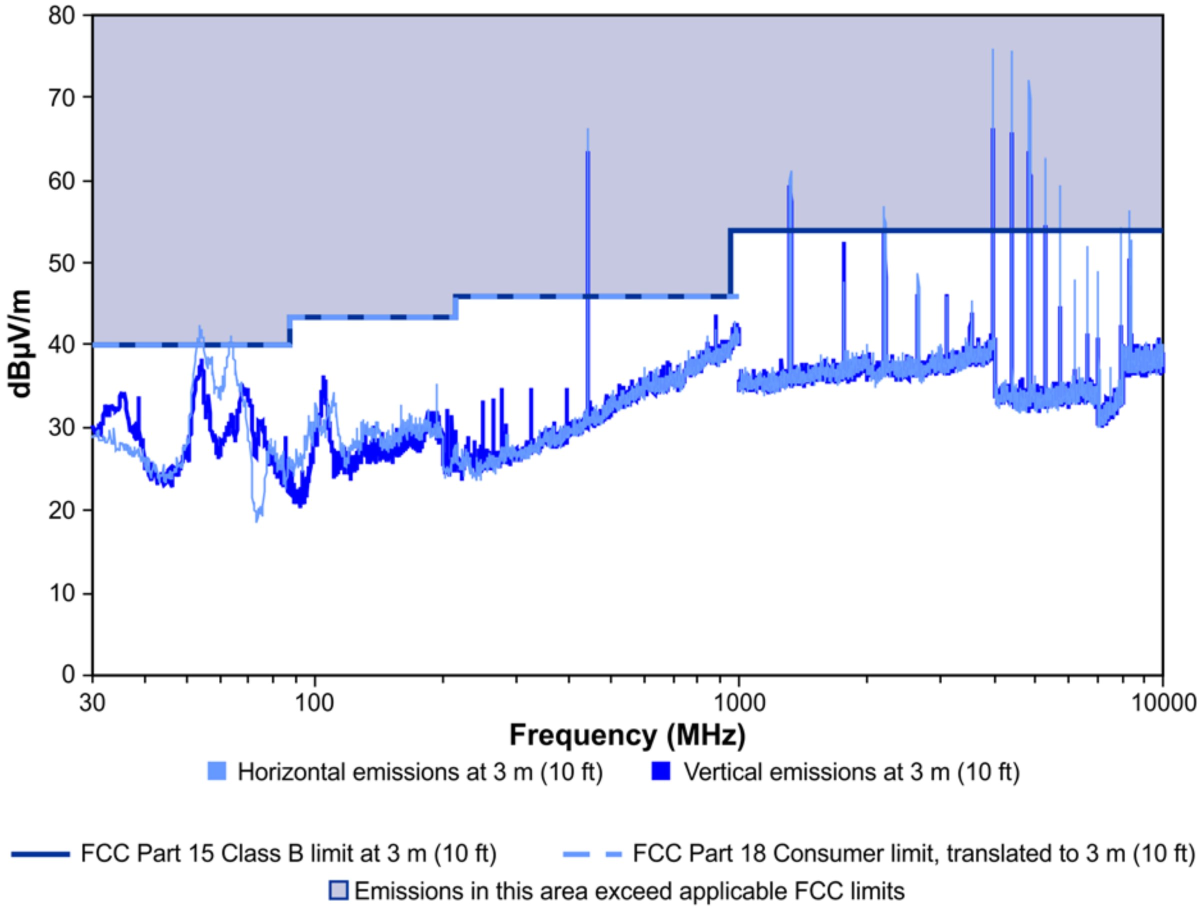


Figure 14: Radiated emissions from a Tesla II streetlight compared to the FCC residential limits (FCC Part 15 Class B and FCC Part 18 consumer limits) at 100% light output, measured 3 m (10 ft) from the luminaire. The Y-axis in decibels (dB) indicates the electric field strength relative to 1 microvolt (µV) per meter. Emissions in the shaded area of the figure exceed the maximum allowable FCC limits.



Is ultraviolet radiation a concern for plasma lighting systems?

No, not if used as recommended. Plasma lighting systems produce **ultraviolet (UV)** radiation in addition to light, and **luminaire** manufacturers should use UV-absorbing glass to shield people and objects from radiated UV. Some manufacturers of plasma lighting systems provide recommendations on the specification of glass to be used (LUXIM 2010a).

NLPIP did not measure UV radiation from the tested plasma lighting systems because it was beyond the scope of this study.

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Glossary

Sources of term definitions: National Lighting Product Information Program (NLPIP), Lighting Research Center's Lighting Education Online, the IEEE Standard Dictionary of Electrical and Electronics Terms (IEEE Std 100-1996).

ambient temperature	The temperature of the surrounding air that comes into contact with the lamp and ballast. Ambient temperature affects the light output and active power of fluorescent lamp/ballast systems. Each fluorescent lamp-ballast system has an optimum ambient temperature at which it produces maximum light output. Higher or lower temperatures reduce light output. For purposes of lamp/ballast tests, ambient temperature is measured at a point no more than 1 meter (3.3 feet) from the lamp and at the same height as the lamp.
application	The use to which a lighting system will be put; for example, a lamp may be intended for indoor residential applications.
arc tube	An envelope, usually quartz or ceramic that contains the arc of a discharge light source.
ballast	A device required by electric-discharge light sources such as fluorescent or HID lamps to regulate voltage and current supplied to the lamp during start and throughout operation.
chromaticity	The dominant or complementary wavelength and purity aspects of the color taken together, or of the aspects specified by the chromaticity coordinates of the color taken together. It describes the properties of light related to hue and saturation, but not luminance (brightness).
CIE	Abbreviated as CIE from its French title Commission Internationale de l'Eclairage, the International Commission on Illumination is a technical, scientific, and cultural organization devoted to international cooperation and exchange of information among its member countries on matters relating to the science and art of lighting.
color rendering	A general expression for the effect of a light source on the color appearance of objects in conscious or subconscious comparison with their color appearance under a reference light source.
color rendering index (CRI)	A rating index commonly used to represent how well a light source renders the colors of objects that it illuminates. For a CRI value of 100, the maximum value, the colors of objects can be expected to be seen as they would appear under an incandescent or daylight spectrum of the same correlated color temperature (CCT). Sources with CRI values less than 50 are generally regarded as rendering colors poorly, that is, colors may appear unnatural.

color shift	The change in a lamp's correlated color temperature (CCT) at 40% of the lamp's rated life, in kelvin (K).
correlated color temperature (CCT)	A specification for white light sources used to describe the dominant color tone along the dimension from warm (yellows and reds) to cool (blue). Lamps with a CCT rating below 3200 K are usually considered warm sources, whereas those with a CCT above 4000 K usually considered cool in appearance. Temperatures in between are considered neutral in appearance. Technically, CCT extends the practice of using temperature, in kelvins (K), for specifying the spectrum of light sources other than blackbody radiators. Incandescent lamps and daylight closely approximate the spectra of black body radiators at different temperatures and can be designated by the corresponding temperature of a blackbody radiator. The spectra of fluorescent and LED sources, however, differ substantially from black body radiators yet they can have a color appearance similar to a blackbody radiator of a particular temperature as given by CCT.
driver	For light emitting diodes, a device that regulates the voltage and current powering the source.
efficacy	The ratio of light output (in lumens) to input power (in watts), expressed as lumens per watt (LPW).
electrodes	The structure that serves as the electric terminals at each end of electric discharge lamps.
electromagnetic interference (EMI)	The interference of unwanted electromagnetic signals with desirable signals. Electromagnetic interference may be transmitted in two ways: radiated through space or conducted by wiring. The Federal Communications Commission (FCC) sets electromagnetic interference limits on radio frequency (RF) lighting devices in FCC Part 18.
fluorescent lamp	A low-pressure mercury electric-discharge lamp in which a phosphor coating on the inside of the glass tubing transforms most of the ultraviolet energy created inside the lamp into visible light.
footcandle (fc)	A measure of illuminance in lumens per square foot. One footcandle equals 10.76 lux, although for convenience 10 lux commonly is used as the equivalent.
frequency	The number of cycles completed by a periodic wave in a given unit of time. Frequency is commonly reported in cycles per second, or hertz (Hz).

gamut area	A measure of color rendering based upon volume in color space. It is the range of colors achievable on a given color reproduction medium (or present in an image on that medium) under a given set of viewing conditions.
glare	The sensation produced by luminances within the visual field that are sufficiently greater than the luminance to which the eyes are adapted, which causes annoyance, discomfort, or loss in visual performance and visibility.
grid	The combination of electric power plants and transmission lines operated by an electric utility.
heat sinking	Adding a material, usually metal, adjacent to an object in order to cool it through conduction.
high-intensity discharge (HID)	An electric lamp that produces light directly from an arc discharge under high pressure. Metal halide, high-pressure sodium, and mercury vapor are types of HID lamps.
high-pressure sodium (HPS)	A high-intensity discharge lamp type that uses sodium under high pressure as the primary light-producing element. HPS lamps produce light with a correlated color temperature (CCT) of approximately 2000 kelvins, although CCTs for lamps having higher CRI values range from 2200 to 2700 kelvins. Standard lamps have a CRI value of 22; others have CRI values from 60 to 80. HPS lamps are among the most efficacious light sources, with efficacies as high as 150 lumens per watt, although those with higher CRI values have efficacies as low as 25 lumens per watt.
horizontal illuminance	The average density of luminous flux incident on a horizontal surface, measured in footcandles (fc) or lux (lx). One fc equals 10.76 lx.
illuminance	The density of luminous flux incident upon a surface. Illuminance is measured in footcandles (lumens/square foot) or lux (lumens/square meter). One footcandle equals 10.76 lux.
initial light output	A lamp's light output, in lumens, after 100 hours of seasoning.
lamp	A radiant light source.
lamp life	The number of hours at which half of a large group of lamps have failed when operated under standard testing conditions.

light-emitting diode (LED)	A solid-state electronic device formed by a junction of P- and N-type semiconductor material that emits light when electric current passes through it. LED commonly refers to either the semiconductor by itself, i.e. the chip, or the entire lamp package including the chip, electrical leads, optics and encasement.
lumen (lm)	A unit measurement of the rate at which a lamp produces light. A lamp's lumen output rating expresses the total amount of light the lamp emits in all directions per unit time.
lumen depreciation	The decrease in lumen output that occurs as a lamp is operated, until failure. Also referred to as lamp lumen depreciation (LLD).
lumen maintenance	The lumens produced by a light source at any given time during its operating life as a percentage of its lumens at the beginning of life.
luminaire	A complete lighting unit consisting of a lamp or lamps and the parts designed to distribute the light, to position and protect the lamp(s), and to connect the lamp(s) to the power supply. (Also referred to as fixture.)
MacAdam ellipse	Researcher David L. MacAdam showed that a just noticeable difference (JND) in the colors of two lights placed side-by-side was about three times the standard deviation associated with making color matches between a reference light and a test light (MacAdam 1942, Wyszecki and Stiles 1982). These JNDs form an elliptical pattern of "constant discriminability" in a chromaticity space, centered on the chromaticity of a reference light, known as MacAdam ellipse.
mercury vapor (MV) lamp	A high-intensity discharge lamp type that uses mercury as the primary light-producing element. Mercury vapor lamps produce light with a CCT from 3000 to 7000 K. Mercury vapor lamps with clear outer bulbs have CRI values from 15 to 25, whereas phosphor-coated lamps have CRI values from 40 to 55. Mercury vapor lamps are less efficacious than other HID lamp types, typically producing only 30 to 65 LPW, but they have longer lamp lives and lower initial costs than other HID lamp types.
metal halide (MH) lamp	A high-intensity discharge lamp type that uses mercury and several halide additives as light-producing elements. Metal halide lamps have better color properties than other HID lamp types because the different additives produce more visible wavelengths, resulting in a more complete spectrum. Metal halide lamps are available with CCTs from 2300 to 5400 K and with CRI values from 60 to 93. Efficacies of metal halide lamps typically range from 75 to 125 LPW.

nadir	In the lighting discipline, nadir is the angle pointing directly downward from the luminaire, or 0°. Nadir is opposite the zenith.
operating position	The manufacturer-recommended operating position for a lamp.
phosphors	Materials used in a light source to produce or modify its spectral emission distribution. In fluorescent and high intensity discharge lamps, the phosphors fluoresce (emit visible light) when excited by ultraviolet radiation produced by mercury vapor inside the lamp when energized by an electric arc. In a light emitting diode, phosphors convert short-wavelength light or ultraviolet radiation produced by a semiconductor die into longer-wavelength light, usually with the goal of producing white illumination.
photopic	Vision mediated essentially or exclusively by the cones. It is generally associated with adaptation to a luminance of at least 3.4 cd/m^2.
power	The power used by a device to produce useful work (also called input power or active power). In lighting, it is the system input power for a lamp and ballast or driver combination. Power is typically reported in the SI units of watts.
power line carrier (PLC)	A system that transmits high-frequency (50 to 500 kHz) analog or digital signals via the power lines of a building. These signals control devices such as luminaires or contain voice transmissions such as intercom messages. Some commercial and residential energy management systems also use power line carrier systems.
power quality	The degree to which current and voltage wave forms conform to a sinusoidal shape and are in synchronous phase with each other. Poor power quality results when the wave forms are distorted and/or out of phase and can interfere with data communications, cause inefficient operation or failure of other electrical equipment on the same supply line, and result in excessive current in electrical distribution lines.
rated lamp life	The number of hours at which half of a group of product samples fail. The rated life is a median value of life expectancy; any lamp or group of lamps may vary from the published rated life. Rated life is based on standard test conditions.

rated lumen	Also referred to as rated light output from lamp in lumens. Lumen refers to a unit measurement of the rate at which a lamp produces light. A lamp's light output rating expresses the total amount of light emitted in all directions per unit time. Manufacturers rate their lamps' initial light output after 100 hours of operation.
restrike time	The time required for a lamp to restrike, or start, and to return to 90% of its initial light output after the lamp is extinguished. Normally, HID lamps need to cool before they can be restarted.
sky glow	Brightening of the sky caused by outdoor lighting and natural atmospheric and celestial factors.
spectral power distribution (SPD)	A representation of the radiant power emitted by a light source as a function of wavelength.
standard deviation	A measure of the average distance of a set of data points from their mean. A set of data points that are all close to their mean will have a smaller standard deviation than a set of points that are further from their mean.
system efficacy	Also referred to as relative system efficacy, system efficacy is a measurement of a system's ability to convert electricity into light. Measured in lumens per watt (LPW), system efficacy is the ratio of the light output (in lumens) to the active power (in watts).
ultraviolet	Any radiant energy within the wavelength range 100 to 400 nanometers is considered ultraviolet radiation (1 nanometer = 1 billionth of a meter, or 1 X 10^{-9} m).
uniformity	The degree of variation of illuminance over a given plane. Greater uniformity means less variation of illuminance. The uniformity ratio of illuminance is a measure of that variation expressed as either the ratio of the minimum to the maximum illuminance or the ratio of the minimum to the average illuminance.
visual performance	The quantitative assessment of the performance of a visual task, taking into consideration speed and accuracy.
warm-up time	The time it takes for a lamp to produce 90% of its initial light output when it is started, unless otherwise indicated.
wavelength	The distance between two corresponding points of a given wave. Wavelengths of light are measured in nanometers (1 nanometer = 1 billionth of a meter, or 1 X 10^{-9} m)

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