Xenon Lighting – Technology Evaluation & Testing

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LEGAL NOTICE

ABBREVIATIONS AND ACRONYMS

CCT	Color Correlated Temperature
CIE	International Commission on Illumination
CLTC	California Lighting Technology Center
CMH	Ceramic Metal Halide
CRI	Color Rendering Index
ELF	Effective Luminance Factor
HPS	High Pressure Sodium
IES	Illuminating Engineering Society
LED	Light Emmiting Diode
LM	Lighting Memorandum
MH	Metal Halide
PGE	Pacific Gas and Electric Co.
TM	Technical Memorandum
USIGT	United States Innovative Green Technologies

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Project Goal

Due to the potential use of Xenon lamps in exterior applications, CLTC in collaboration with PG&E will develop and complete an evaluation and testing program for Xenon technology used in general illumination, exterior applications. The research included under this project will establish a program to evaluate the performance and reliability of Xenon lamps against comparable Light Emitting Diodes (LED), induction or other appropriate parking and area lighting solutions. This program will identify available Xenon products, evaluate manufacturers' product literature to estimate their performance against other exterior luminaires, and quantify their photometric and energy performance in a laboratory setting using industry-standard test methods. This information will be used to develop and document the current state-of-the-art for Xenon lamps, and provide PG&E with a broad data set that it may use to determine the viability of the technology for its current or future incentive programs.

Project Description

This evaluation project is divided into two phases. The first phase consists of product evaluation and comparison against traditional exterior source technologies using published manufacturer's data. The second phase of this project consists of a rigorous laboratory evaluation of select Xenon products marketed for the exterior sector. Labortory testing will measure actual product performance with respect to power consumption, luminous flux, luminous efficacy, color, life, dimming, and light distribution.

Project Findings/Results To Date

During 2012, the project team completed Phase I analysis and Phase II test methodology. CLTC collected performance data of representative examples of both traditional and emerging technologies from manufacturers' product catalogs. For each lamp type, products are grouped based on luminous output. Within each group, CLTC calculated the average percent difference of luminaire efficacy between incumbent (high pressure sodium baseline) and replacement luminaire. Positive values represent savings.

Table 1 – Percent energy saved over the average of incumbent technologies

Luminous Flux (lm)	Percent difference in luminaire efficacy			
	Induction	LED	MH Ceramic	Xenon
2500-5000				
5000-7500	-0.5%	33%	28%	21%
7500-12500	-6	26%	28%	18%
12500-17500	-12%		24%	14%
17500-22500		16%	24%	10%

PROJECT RECOMMENDATIONS

These results will contribute towards development of the minimum performance specification for xenon luminaires. This specification may be used as starting point for PG&E to develop an incentive program for xenon luminaires used in the commercial outdoor lighting sector. CLTC will recommend minimum performance levels for luminaire efficacy, CCT, CRI, and luminaire life including dimming and other labeling requirements.

INTRODUCTION

Due to the potential energy savings attributed to the use of Xenon lamps in exterior applications, CLTC in collaboration with PG&E will develop and complete an evaluation and testing program for Xenon technology used in general illumination, exterior applications. The research included under this project will establish a program to evaluate the performance and reliability of Xenon lamps against comparable Light Emitting Diodes (LED), induction or other appropriate parking and area lighting solutions. This program will identify available Xenon products, evaluate manufacturers' product literature to estimate their performance against other exterior luminaires, and quantify their photometric and energy performance in a laboratory setting using industry-standard test methods. This information will be used to develop and document the current state-of-the-art for Xenon lamps, and provide PG&E with a broad data set that it may use to determine the viability of the technology for its current or future rebate and incentive programs.

BACKGROUND

The goals of outdoor area lighting include providing adequate illumination for the application without producing extraneous light or glare. Luminaire density and distribution patterns are chosen to maximize the use of light. Light trespass (such as street lights shining into windows) and light pollution (sky glow) are mitigated with reflector designs. High pressure sodium and metal halide with magnetic ballasts are the most common types of luminaires being used (Table 2). Replacement technologies include: induction, LED, ceramic metal halide, and xenon.

TABLE 2 – INSTALLED BASE FOR VARYING LUMINAIRE TECHNOLOGIES USED FOR OUTDOOR LIGHTING IN THE U.S.[1]

Source Type	Installed Base	Market Share
Incandescent	17,814,000	10%
Halogen	4,021,000	2%
Compact fluorescent	12,053,000	7%
Linear fluorescent	29,124,000	16%
Mercury vapor	4,177,000	2%
Metal halide	29,514,000	17%
High pressure sodium	57,941,000	32%
Low pressure sodium	1,455,000	1%
LED	19,219,000	11%
Miscellaneous	3,056,000	2%

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[1] Navigant Consulting, Inc., Building Technologies Program, U.S. Department of Energy. *2010 U.S. lighting market characterization*. January 2012.

Options for outdoor xenon lighting in the United States are overwhelmingly offered as retrofit lamps for existing fixtures. Interviews with xenon distributors established that the most common retrofits were for shoe-box style luminaires. The retrofit for shoe-box style luminaires was chosen as to be representative of the xenon market as a whole.

Xenon lamps have been used extensively for niche applications such as movie projection and automobile headlights. Recently, some industry groups have begun to incorporate Xenon lamps into exterior general illumination applications such as parking and area lighting. This is a very new application for Xenon lamps, and very limited test or demonstrated performance data exists for the technology when used in exterior spaces.

ASSESSMENT OBJECTIVES

The assessment objectives of the Xenon Technology Evaluation Program include full characterization of product performance with respect to multiple parameters commonly used in the general illumination, exterior luminaire market. Individual metrics and brief discussions are included below. Each of the metrics listed below will be first collected from manufacturer's product literature and used to prepare an initial product comparision. The second phase of the assessment will consist of laboratory measurement and evaluation of select Xenon products in order to verify manufacturer's claims and document actual product performance. Phase I results are provide in the Results section of this report. Phase II laboratory test methods are provided in the Product Testing and Evaluation section.

ASSESSMENT METRICS

CLTC examined the performance characteristics of representative examples of commercially available luminaires for general outdoor lighting. This included an example for each technology and over a range of luminous flux. Data was collected from lamp manufactures' product catalogs and online websites. All performance metrics and product information provided were recorded into a database, in spreadsheet format. Metrics include power, light output, CRI, CCT, lifetime, and manufacturer. Performance was quantified with lamps integrated into a shoebox fixture with a luminaire efficiency of around 70%. The Induction and LED lamps considered are integrated into their own fixtures with luminaire efficiencies considered accordingly. The performance metrics are described below. Discussions on color and spectral sensitivity are also included.

- Power (W) – The maximum amount of power required to operate the luminaire (measured in watts).
- Light Output (lm) – The amount of visible light output by a light source independent of direction, and weighted to the sensitivity of human vision (measured in lumens).
- Correlated Color Temperature (CCT), Duv – CCT correlates a luminaire's color to the color of a black body radiator at a given temperature and is measured in degrees kelvin (K) (for more details see the section on color). A tight

tolerance on the color temperature and Duv of luminaires ensures that luminaires in close spatial proximity appear to be the same color.

- Color rendering index – CRI compares a light source's rendering of a set of pastel colors with that of a blackbody radiator of the same CCT (for more details see the section on color). CRI (Ra) is the most widely used standard to establish the ability of a luminaires to render colors correctly.
- Lifetime – The lifetime of each lamp, expressed in hours. For metal halide and xenon this was defined as the number of hours that on average 50% of lamps would fail by (67% for high pressure sodium). For LED and induction lamps, this is the point at which lumen output has reduced to 70% of its initial rated output (L70).
- Dimming – The ability to dim luminaires allows for more flexibility in lighting levels and allows for energy savings during times of reduced occupancy or lighting needs.

COLOR

Color, as a lighting metric, is multifaceted. Traditionally, two metrics are used to identify color: correlated color temperature (CCT), and color rendering index (CRI). CCT correlates a lamp's color to the color of a black body radiator at a given temperature and is measured in degrees Kelvin (K). The spectrum of color that is visible to the human eye is defined by the International Commission on Illumination (CIE) color space (Figure 1). Illustrated on Figure 1 is the blackbody locus, a line representing the spectrum of color that is radiated from an *ideal* black body radiator. To date, industry consensus has been that reproducing the chromaticity (hue and saturation) of an ideal black body radiator is most desirable for maximizing user satisfaction with respect to color rendering. However, no scientific data exists to support this claim. Recently, researchers have begun to study this theory, in order to validate the hypothesis, but no conclusive results have been published to date.

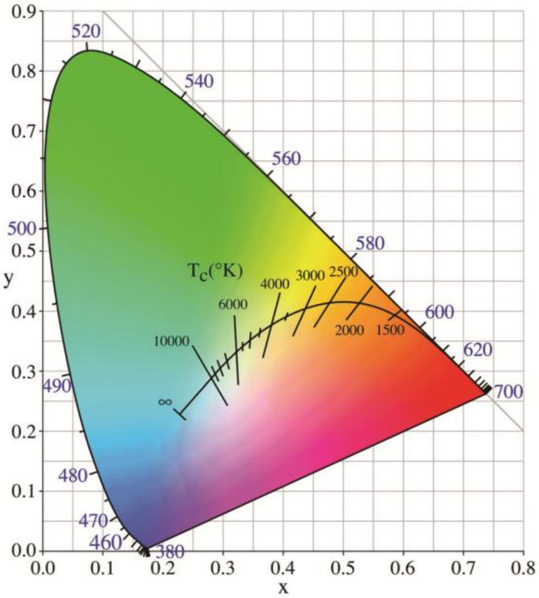


FIGURE 1 – CIE COLOR SPACE WITH BLACK BODY LOCUS

The second metric, CRI, compares a light source's rendering of a set of pastel colors with that of a blackbody radiator of the same CCT (Figure 2). CRI is typically given as a single rating from 0-100. Color rendering is an important aspect of lighting quality, but it is important that specifics of the metric be well understood. Where CCT represents color output as a weighted average of spectral power distribution, CRI attempts to quantify the variation in spectral power distribution from that of a black body radiator.

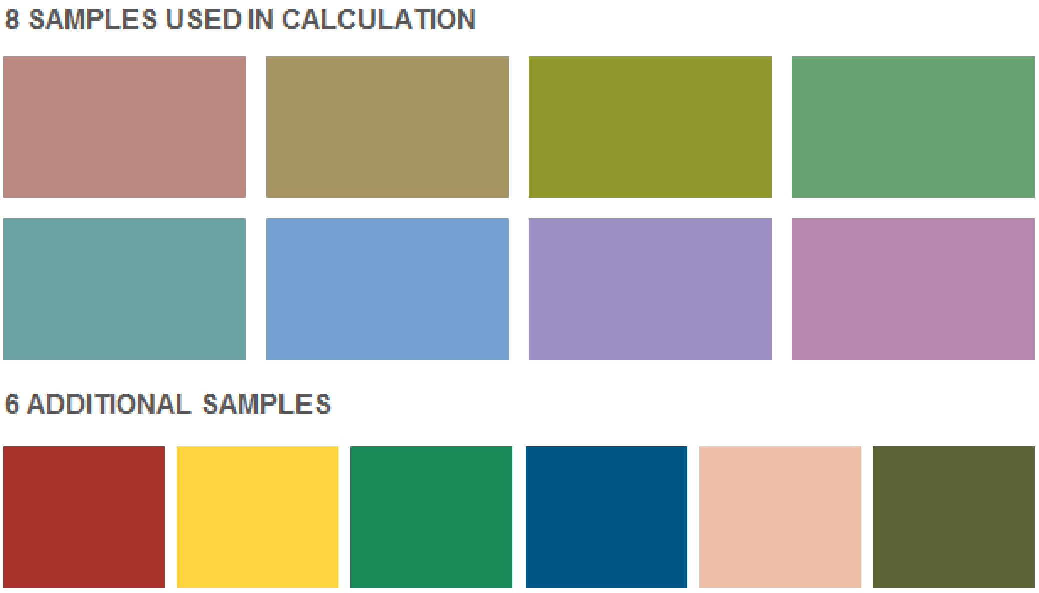
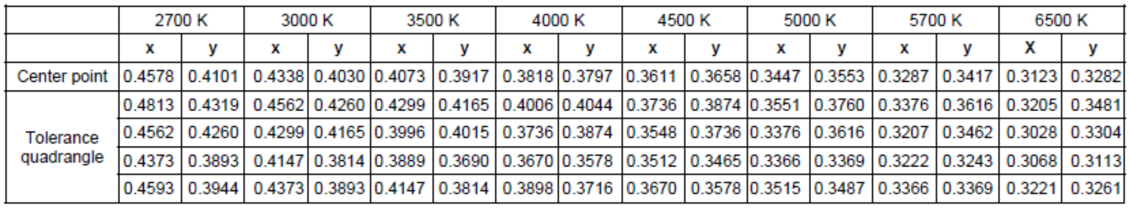


FIGURE 2 – COLOR RENDERING INDEX (CRI R_A) COLOR SAMPLES

There are several inadequacies with quantifying color using CCT and CRI. First, CCT does not indicate distance from the black body locus. This can lead to undesirable and unaccounted for color-shifts. An additional metric, Duv, fixes this problem by adding a second piece of information in regard to how far, and in which direction, the lamp deviates from the black body locus (Figure 3). Some specifications, like Energy Star, require color performance based on chromaticity quadrangle specifications. Figure 4 shows the quadrangles for the LED specification and the correlating 7-step MacAdam ellipses. Macadam ellipses represent regions on the chromaticity chart where a certain portion of the population cannot differentiate color. The steps refer to the number of standard deviations the radius of the ellipse corresponds to. provides the coordinates for the quadrangles in Figure 4. Currently the industry's best in class products are designed for a 2-step ellipse with 4-step ellipse being more common.

TABLE 3 – CHROMATICITY COORDINATES DEFINING CCT QUADRANGLES FOR ENERGY STAR LED SPECIFICATION. SOURCEERROR! BOOKMARK NOT DEFINED.



	2700 K		3000 K		3500 K		4000 K		4500 K		5000 K		5700 K		6500 K	
	x	y	x	y	x	y	x	y	x	y	x	y	x	y	X	y
Center point	0.4578	0.4101	0.4338	0.4030	0.4073	0.3917	0.3818	0.3797	0.3611	0.3658	0.3447	0.3553	0.3287	0.3417	0.3123	0.3282
Tolerance quadrangle	0.4813	0.4319	0.4562	0.4260	0.4299	0.4165	0.4006	0.4044	0.3736	0.3874	0.3551	0.3760	0.3376	0.3616	0.3205	0.3481
	0.4562	0.4260	0.4299	0.4165	0.3996	0.4015	0.3736	0.3874	0.3548	0.3736	0.3376	0.3616	0.3207	0.3462	0.3028	0.3304
	0.4373	0.3893	0.4147	0.3814	0.3889	0.3690	0.3670	0.3578	0.3512	0.3465	0.3366	0.3369	0.3222	0.3243	0.3068	0.3113
	0.4593	0.3944	0.4373	0.3893	0.4147	0.3814	0.3898	0.3716	0.3670	0.3578	0.3515	0.3487	0.3366	0.3369	0.3221	0.3261

CRI is also limited as a metric for several reasons. CRI only considers color fidelity and not color saturation, it is based only on a small number (8 for R_a) of color samples, and it does not account for the direction of color shift. A partial solution, adopted by the lighting industry, is to also include the measure of performance for a specific color palate R9 (not included in the R_a calculation).

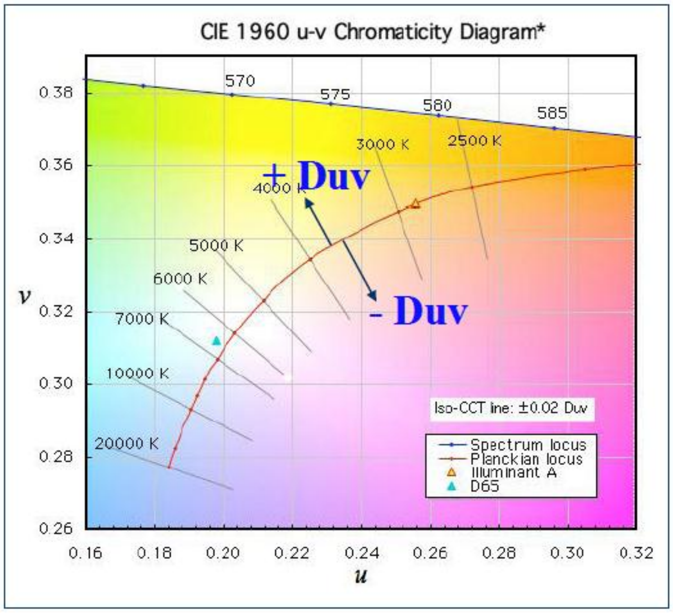


FIGURE 3 – CIE 1960 WITH BLACKBODY LOCUS AND VECTORS INDICATING POSITIVE AND NEGATIVE DUV. SOURCE[2]

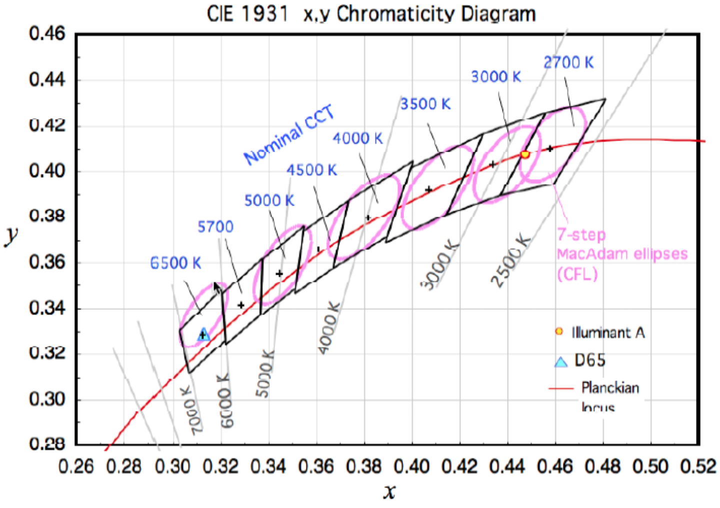


FIGURE 4 – CCT QUADRANGLES FOR THE ENERGY STAR LED SPECIFICATION. SOURCE[3]

SPECTRAL SENSIVITY

In this report, spectral sensitivity describes how humans perceive different wavelengths of light. This is represented by a curve relating the sensitivity of the eye (lumens per watt) to varying wavelengths of light (Figure 5). It has been found that this spectral sensitivity curve shifts based upon the level of light. Humans sense light from two general types of sensors in the eyes: rods and cones. Cones allow the perception of colors and are active under bright lighting ($\geq 3 cd/m^2$) known as photopic vision, while rods sense light level and are active under dim lighting ($\leq 0.001 cd/m^2$) known as scotopic vision. As the level of light changes from high to low, the cones become less active, the rods become more active, and the peak sensitivity shifts from a green 555 nm to a more green-blue 498 nm. The region for light levels in between ($0.001 \geq L_v \geq 3$ cd/m^2), where both cones and rods are active, is known as mesopic vision.

Traditionally, lighting efficacy standards are based on luminous flux. However, designing lights to emit spectra targeting the photopic region of vision at low light levels would be less efficient than targeting the spectra corresponding most with that low light level (mesopic or scotopic vision depending upon the level). To account for this the IES recommends a technique for calculating effective luminance in TM12[4]

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[2] Thompson, M. *Defining quality of Light*. Voices for SSL efficiency 2011 – DOE SSL market introduction workshop. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/thompson_quality_sslmiw2011.pdf.

[3] Energy Star Program Requirements for Integral LED Lamps. Version 1.4. http://www.energystar.gov/ia/partners/product_specs/program_reqs/Integral_LED_Lamps_Program_Requirements.pdf?b3b3-6932

[4] IES Spectral effects of lighting on visual performance at mesopic lighting levels (TM-12-12)

based upon CIE 191[5]. The IES recommendation calculates an effective luminance based upon a desired illuminance on a target, that target's reflectance, and the effective luminance factor (ELF). The ELF is a ratio between mesoptic and photopic luminance calculated based upon light level, and the ratio of scotopic to photopic luminance.

The consequence of the spectral shift for low light levels is that lamps that emit light that has more blue content will effectively be more efficacious than those that emit warmer colors. When combined with conversion efficiency, technologies such as induction, LED, metal halide, and xenon will be effectively more efficacious than their photopic efficacies, while high pressure sodium will fare much worse than its photopic efficacy (Table 5).

TABLE 4 – SCOTOPIC/PHOTOPIC LUMINANCE RATIOS FOR CORRELATING EFFECTIVE LUMINANCE AT LOW LIGHT LEVELS (SOURCE) [6]

Lamp Type	S/P ratio
Induction (5000K)	1.96
Metal Halide	1.49
High pressure sodium	0.62
LED (cool white)	2.14
LED (warm white)	1.5
Xenon	1.65

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[5] CIE Recommended system for mesopic photometry based on visual performance (CIE 191:2010)

[6] Berman S. *The coming revolution in lighting practice*.

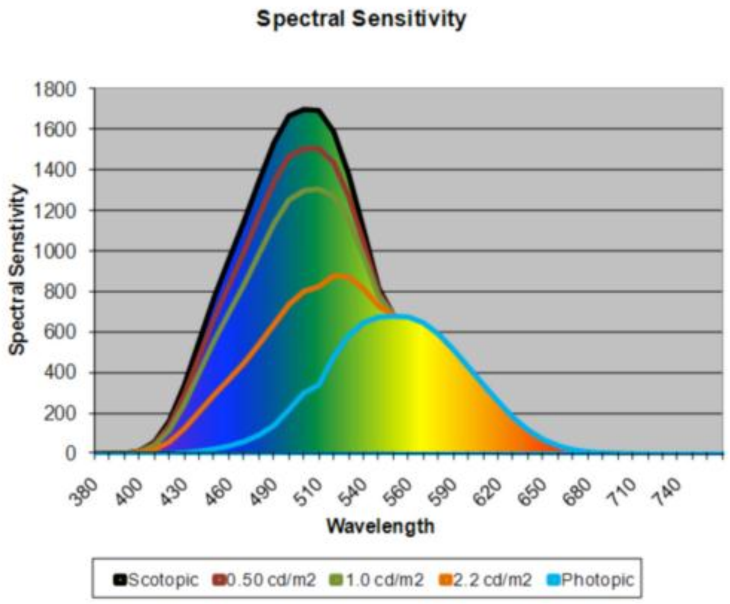

FIGURE 5 – SPECTRAL SENSITIVITY FOR VARYING LIGHT LEVEL (SOURCE) [7]

ENERGY CONSUMPTION AND LIFECYCLE COST

Once minimum lighting performance requirements, such as luminous flux, lifetime and color are established, energy efficiency and product cost can be evaluated to fully characterize a particular replacement luminaire. Luminous efficacy is a measure of a luminaire's light output per unit of electrical power consumed. In addition, the product's overall lifecycle cost is directly affected by its lamp life. Lifetime for metal halide, and xenon lamps is quantified as time to 50% failure rate (67% for high pressure sodium) while for solid state and fluorescent lamps, it is rated in terms of lumen maintenance, or the amount of time the lamp can sustain a minimum level of delivered flux (70% of initial).

The product evaluation included in this report considers the performance characteristics of the luminaire only, without consideration of the particular application. This is appropriate for establishment of equipment specifications. Selection of a replacement luminaire for a specific application should consider a comparison of the luminaire performance characteristics, as well as an evaluation of the application efficacy, the illumination delivered on the task surface relative to the luminaire power consumption. Through this process, an efficient luminaire for a given application can be selected.

Table 5 illustrates the specifications for efficiency by the DesignLights Consortium for outdoor pole/arm-mounted area and roadway solid state luminaires.

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[7] US Department of Energy Solid State Lighting Program, *Light at night: the latest science*.

TABLE 5 – EFFICIENCY SPECIFICATIONS FOR THE DESIGNLIGHTS CONSORTIUM BENCHMARK

	DesignLights Consortium
Luminous efficacy	≥ 60lm/W
Lumen maintenance	70% of initial after 50,000h

System cost over time is a function of initial lamp cost, initial installation cost, energy cost, and lamp lifetime. Energy saved is determined from the difference in the wattage of the incumbent and replacement luminaires (Eq. (1)).

$$W_{saved\ per\ luminaire} = \left(W_{incumbent} - W_{replacement}\right) \qquad (1)$$

The annual operating cost per luminaire is determined from the average electricity rate multiplied by the product of the wattage rating of the lamp and the average operating hours per year (Eq. (2)).

$$Cost_{operating\ per\ luminaire}/_{yr}$$

$$= \left(electricity\ rate\left(\$/_{kWh}\right)\right)\left(W_{luminaire}\right)\left(\frac{1kW}{1000W}\right)\left({}^{operating\ hours}/_{yr}\right) \qquad (2)$$

The basic lifecycle cost is then a function of the lamp cost, lamp life time (replacements per lifecycle), and the number of years over which the cost is considered (Eq. (3)). The cost or savings associated with a particular lamp replacement is equal to the cost calculated in Eq.(3)[8].

$$Cost_{total}(yr) = Cost_{energy}(yr) + Cost_{initial\ and\ replacement}(yr)$$

$$= \left(Cost_{operating\ per\ luminaire}/_{yr}\right)(yr) \qquad (3)$$

$$+ \left\lceil \left(Cost_{initial}\right)\left(\frac{1}{lifetime(hr)}\right)\left(operating\ hours/_{yr}\right)(yr)\right\rceil$$

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[8] The brackets with no bottoms represent the floor function

PHASE I: INITIAL PERFORMANCE

In order to characterize Xenon performance relative to other standard lighting technologies, CLTC collected performance data of representative examples of both traditional and emerging technologies from manufactures' product catalogs. Comparison of Xenon products to other exterior sources with respect to luminous flux, luminous efficacy, color and life are provided below. This information was collected in order to provide a clear picture of where Xenon technology appears to currently fall in relation to other exterior source technologies.

LUMINOUS FLUX AND EFFICACY

CLTC segmented its data set on commercially-available luminaires into groups based upon luminous flux. Using this data, CLTC analyzed luminous efficacy with respect to lumen output for each luminaire type (Figure 6). Multiple xenon and LED luminaires were considered, and the average of their performance is presented in Table 6.

TABLE 6 – AVERAGE LUMINOUS EFFICACY FOR DIFFERENT LUMINAIRE TYPES AND LUMEN RANGES

Luminous Flux (lm)	Luminous Efficacy – average (lm/W) (photopic)						
	HPS	induction	LED	MH Ceramic	MH Magnetic pulse start	MH Magnetic probe start	xenon
2500-5000		46.4	71.5	81.1			68.1
5000-7500	57.6	46.1	79.5	74.4	49.2		67.6
7500-12500	65.5	51.6	73.7	76.0	50.7	48.3	66.9
12500-17500	63.8	51.0		75.6	56.3	51.8	66.7
17500-22500	65.4		71.6				66.7

Table 7 shows the percent difference of efficacy between the average of the incumbent technologies for each replacement technology and flux bin. Efficacies were seen to be generally constant for varying light levels. LED and ceramic metal halide luminaires were found to be the most efficacious with the magnetic metal halides and induction near the bottom, and xenon and HPS in the middle.

TABLE 7 – PERCENT DIFFERNCE IN EFFICACY OVER THE AVERAGE OF INCUMBENT TECHNOLOGIES

Luminous Flux (lm)	Percent difference in luminaire efficacy			
	Induction	LED	MH Ceramic	Xenon
2500-5000				
5000-7500	-0.5%	33%	28%	21%
7500-12500	-6	26%	28%	18%
12500-17500	-12%		24%	14%
17500-22500		16%	24%	10%

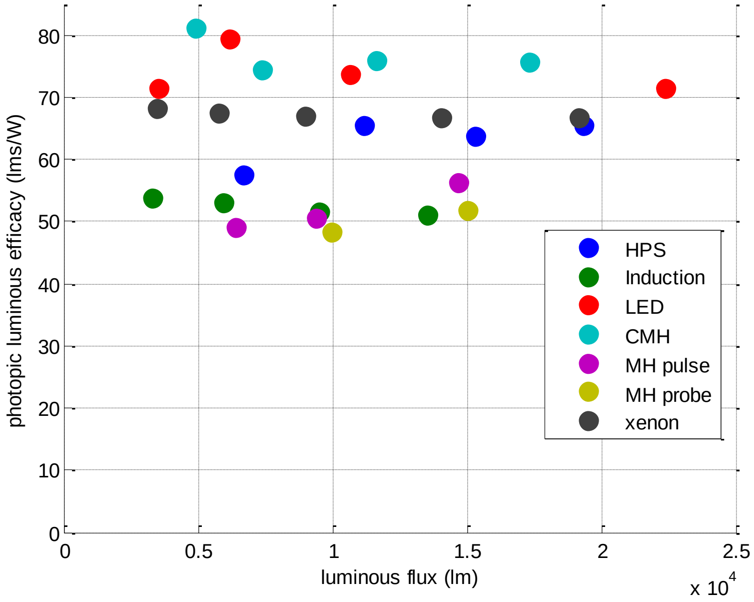

FIGURE 6 – LUMINAIRE EFFICACY VS. LUMINOUS FLUX FOR PHOTOPIC FLUX

COLOR

CLTC analyzed available information on CRI values for a selection of commerically available outdoor luminaires from major manufacturers. The results are shown in Figure 7. It should be noted that for LED luminaires there is typically a correlation between CCT, CRI, and efficacy. LEDs with higher CCT are more efficacous than those that are warmer colored, but also have lower values for CRI. Xenon and induction had the highest CRI levels followed by LED, and the metal halides, with HPS at the bottom. There is an increase in the CRI of CMH for the highest lumen level due to a different, more advanced, model being investigated compared to that used for the lower lumen levels.

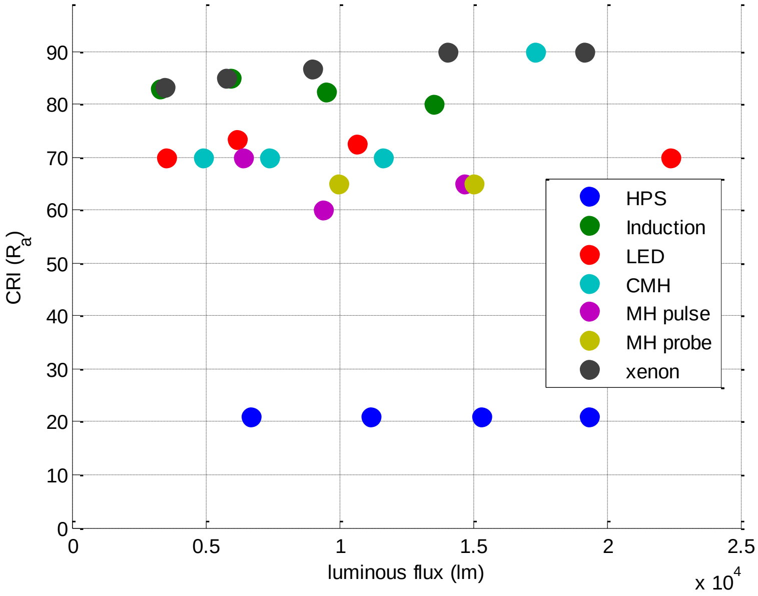

FIGURE 7 – CRI VS. LUMINOUS FLUX FOR ALL LUMINAIRES CONSIDERED

LIFETIME

Lifetimes for the LED and induction luminaires were significantly higher than for the high intensity discharge (HID: high pressure sodium, metal halide, and xenon) luminaires (50,000-100,000h as opposed to 10,000-30,000h). Of the HID luminaires, the newer ceramic metal halide and xenon, in addition to the high pressure sodium luminaires, have longer lifetimes than the magnetically ballasted metal halide luminaires. The variation in LED lifetime is solely due to the ratio of one company's 100,000 h luminaire to the other's 50,000h luminaire included in each luminous flux range.

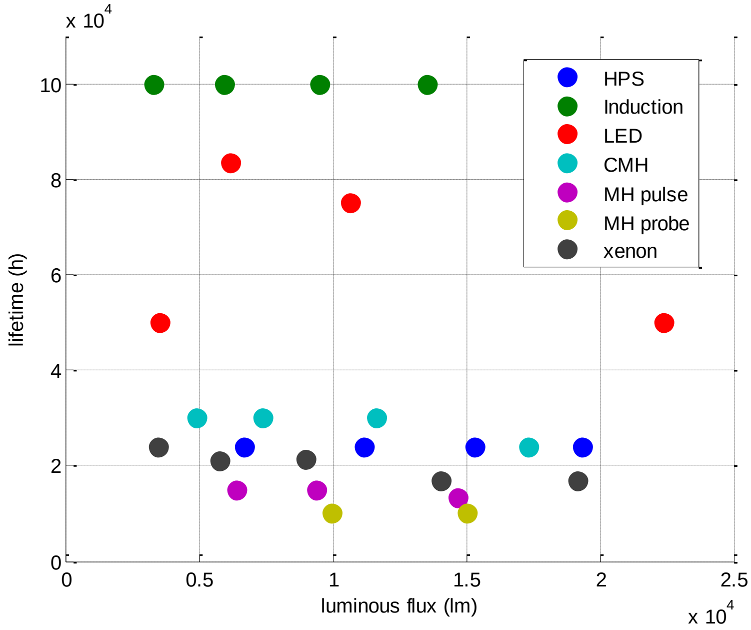

FIGURE 8 – LIFETIME VS. LUMINOUS FLUX FOR LUMINAIRES CONSIDERED

PHASE II - PRODUCT TESTING & EVALUATION

The test methodology developed for this project includes selection criterion and descriptions of test specimens, test metrics, and test procedures employed to fully characterize xenon lamps used in exterior applications. Whenever available, these test procedures are based on industry-standard test procedures. The xenon test plan includes a description of the test methodology that will be employed over the course of the next 30-months. CLTC will test xenon lamps both in fixtures and as a bare system, in order to characterize the technology with respect to multiple performance parameters including luminous flux, correlated color temperature (CCT), color rendering index, and angular light distribution. Both photometric and life testing will be conducted at the CLTC facilities and in accordance with industry standard test procedures. Information on test specimens, data acquisition systems and test procedures are included in this plan.

TEST SPECIMEN SELECTION

Based on the initial product review, CLTC pursued procurement of test specimens from all xenon lamp outlets available in the U.S. Three manufactures are included in this category, two that distribute from within the United States, and a third based in China. The Chinese manufacturer was unresponsive to communication attempts, and will therefore not be included in product testing and evaluation.

CLTC surveyed the remaining distributors, Innertech, Inc. and US Innovative Green Technologies (USIGT), to understand how their products are used in exterior applications. It was found that all products sold are for luminaire retrofits, with the most common retrofit being for a shoebox-style fixture operating with an HID lamp. The most common xenon replacement lamp, by lamp wattage, ranged near 100W, and operated in a horizontal orientation. This product was selected as the representative case for product testing. It was deemed better to test one product category with statistically significant sample sizes over a number of less utilized product categories with smaller, less statistically significant sample sizes. Sample size was limited by product availability and cost.

Xenon retrofit offerings for lamp sizes greater than 70W are composed of arrays of smaller, standard-sized xenon lamps. Innertech offers lamps in multiples of 35W, while USIGT offers lamps in multiples of 60W[9]. To produce approximately a 100W lamp, xenon systems are actually arrays of three-35W lamps totaling 105W or two-60W lamps totaling 120W.

To account for multi-lamp arrays, and various beam distribution patterns, the array geometry is chosen by application, and in some cases, modifications are made to the luminaire reflector, as well. Distributors will be given the opportunity to assist with the retrofit design to make the test units resemble a typical luminaire geometry found in the field. In addition to testing 100W lamp arrays, individual lamps will also be tested. This will provide information on the differences between the arrays and the individual source with respect to photometric performance and longevity.

The quantity of test samples for luminaire and individual lamp testing was selected to ensure an appropriate level of statistical significance, while also adhering to cost constraints. CLTC received 14 donated fixtures, which set the fixture test sample size at 7 for each brand. Nine bare lamps from each distributor are included in the testing. This sample size was selected to maximize use of data acquisition channels available on the data acquisition system.

TEST AND PRODUCT INVENTORY

- Test Set-up: Sterner executive square 19" shoebox fixture (type 3H reflector)
    - (7) Innertech 105W xenon lamp array system
    - (7) USIGT 120W xenon lamp array system
- Test Set-up: Open lamp
    - (9) Innertech 35W xenon lamp and ballast system
    - (9) USIGT 60W xenon lamp and ballast system

TEST METRICS

CLTC will measure nine individual performance characteristics of xenon lamps. A majority of these performance metrics are detailed below. CLTC will include three additional metrics, which are listed last in the following list. These metrics are angular light distribution, lamp temperature, and ballast temperature. Angular distribution will give insight into how well the retrofit lamps work with the reflector to produce the desired light pattern. Temperature measurements will be taken of the

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[9] 40W lamps were also available from USIGT, however they are much less popular than the 60W option

ambient environment, lamp's base, and ballast to ensure that components stay within manufacturer specifications.

Each of the following metrics is standard in evaluating lamp performance, and allows for comparison with other lighting technologies.

- Lumen maintenance
- Luminous flux
- Scotopic luminous flux
- Color correlated temperature (CCT)
- Color rendering index (CRI)
- Chromaticity
- Angular light distribution
- Lamp temperature
- Ballast temperature

INSTRUMENTATION

LIFE TESTING DATA ACQUISITION

Luminaires and lamps will be held in a custom testing rack made out of standardized strut channel (unistrut). The luminaires will have sections of unistrut bolted onto their backs that will allow the fixtures to hang across two cross-pieces with the luminaire reflectors facing down. Luminaires will have standard 3-prong electrical plugs to tie into the main switch. Bare lamps will be held horizontally by their sockets from the rack.

The lamps and luminaires will be electrically connected to the main power through a digitally controlled switch. Depending upon the capabilities of the electrical panel, several branch circuits may be required to allow for the total current required by the test. Branches will all be switched on or off at once using a multi-pole, single throw switch controlled through the digital output port on the data acquisition system. Power will be monitored and recorded with a power analyzer.

The data acquisition system will be centrally located, and have leads reaching out to sensors at each lamp. The system consists of a desktop computer running LabVIEW software, which connects to a data acquisition chassis that holds modules for communication with voltage and temperature sensors. For each lamp, one voltage and two thermocouple lead wires will be strung from the chassis to the thermocouples and light sensor/amplifier. The thermocouples will be attached to the ballast, at the temperature measurement point, and at the base of the lamp. The light sensor will be placed in a tube aimed at the lamp so as to restrict stray light from being picked up.

- Data acquisition
  - National instruments compact DAQ chassis (cDAQ-9178)
    - (1) 32channel voltage module (NI9205)

    - (6) 16-channel thermocouple modules (NI9940)
  - Desktop computer running LabVIEW software by National Instruments and Windows 7 operating system

- Sensors
  - Light
    - (32) photometric cosine corrected photosensors LI-COR (LI-210SA)
    - (32) transconductance LI-COR amplifiers EME Systems UTA
  - Temperature
    - (67) 40 gage K-type thermocouples Omega 5TC-TT-K
  - Main line voltage
    - (1) Eagle 120 power analyzer

- Control
  - Power
    - (1) digital out (NI6008)
    - (1) digitally controlled multi-pole single throw relay

PHOTOMETRIC TESTING DATA ACQUISITION

For photometric testing in the integrating sphere and goniophotometer, luminaires and lamps will be held by special brackets that interface with either the unistrut on the fixture, or the lamp base. The source is held in the center for optimal measurements in both the sphere and goniophotometer.

- Integrating sphere
  - Spectral power distribution - SMS-500 spectrometer, 2m integrating sphere

- Goniophotometer – Type C
  - Photopic luminance measurements – T-10 Konica Minolta Illuminance meter

PHOTOMETRIC TESTING PROCEDURES

INTEGRATED LIGHT

Metrics related to light, without respect to angle, such as luminous flux, CCT, CRI, and chromaticity, are measured in an integrating sphere (Figure 9). The special coating in the sphere allows for the light to be distributed diffusely and evenly over the interior surface of the sphere. A photosensor on the surface of the sphere and shielded from direct light takes the photometric measurements. The photosensor used for these tests is a spectrometer, which determines the spectral power distribution of the lamp. The spectrometer used in this testing is capable of measuring light with wavelengths between 360 nm and 1000 nm.

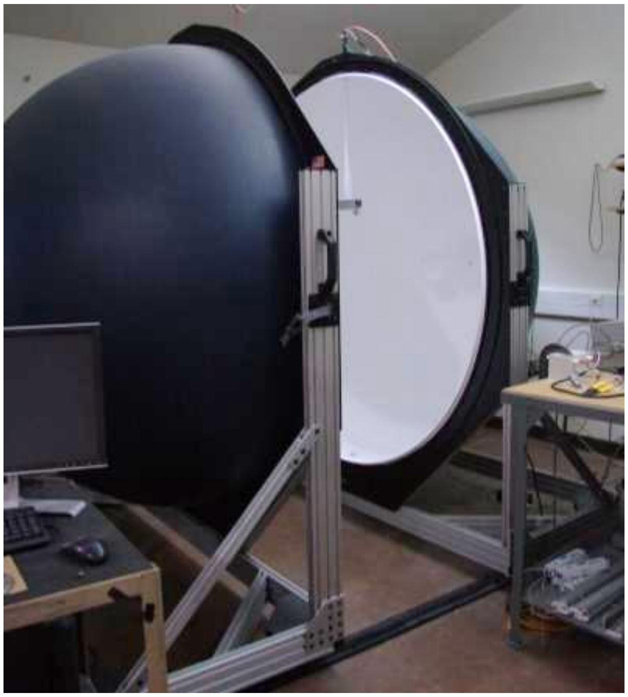

FIGURE 9 – TWO METER INTEGRATING SPHERE

PROCEDURES

The procedures for making measurements are detailed in IES LM-51 Electrical and Photometric Measurements of HID Lamps[10] and LM-79 Photometric Measurements for Solid State lighting[11]. References to specific sections are listed below.

- Lamp preparation and seasoning: LM-54, LM-51 §2.1
- Power source characteristics: LM-51 §3.1-3.3
- Lamp stabilization: LM-51 §6.0
- Ballasts are lamp specific, so no reference ballasts will be used
- Lamp orientation will be horizontal
- Photometric measurement: LM-51 §9.0 and LM-79 §9.0

ANALYSES

Analysis software included with the spectrometer converts the raw spectral power distribution into the metrics of interest: luminous flux, color correlated temperature (CCT), color rendering index (CRI), and chromaticity coordinates. Scotopic flux will be calculated using an algorithm coded in MATLAB using the scotopic efficacy

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[10] LM51 Electrical and Photometric Measurements of HID. Illumination Engineering Society of North America. 2000

[11] LM79 Photometric Measurements for Solid State Lighting. Illumination Engineering Society of North America. 2008

equation, and spectral power distribution . The spectral power distribution gives radiance (power in W) as a function of the component wavelength (nm) of the light.

ANGULAR LIGHT DISTRIBUTION

Angular light distribution is measured using a c-type goniophotometer as shown in Figure 10. A c-type goniophotometer works by holding a luminaire translationally fixed in a central location, moving a mirror around it, and recording the light intensity from a remote location. The luminaire can also be rotated to measure light distribution in spherical coordinates. The light sensor used for these tests is a photopic cosine corrected photosensor.

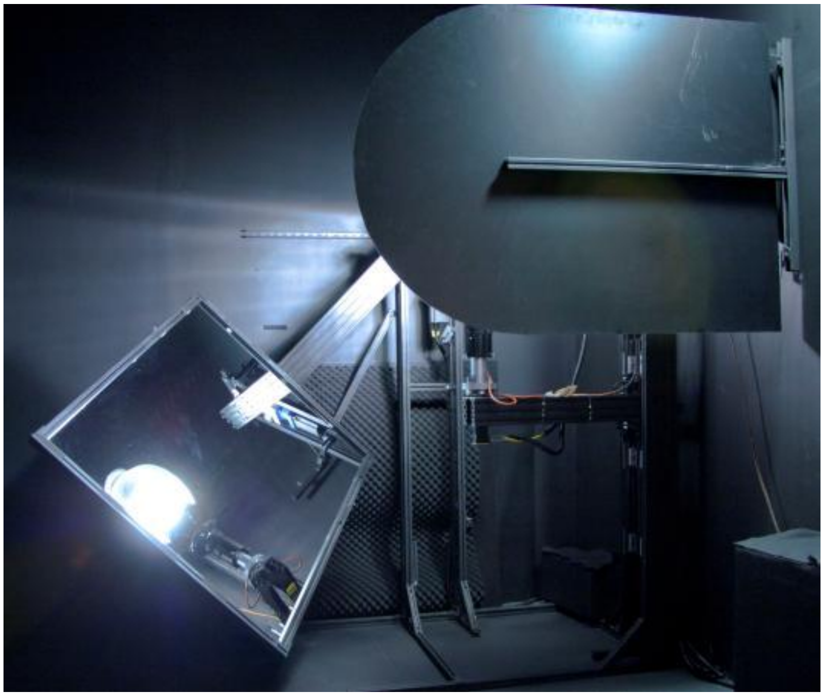

FIGURE 10 – GONIOPHOTOMETER (TYPE C)

PROCEDURES

The procedures for taking angular distribution measurements are detailed in IES LM-51 Electrical and Photometric Measurements of HID10 Lamps and LM-79 Photometric Measurements for Solid State Lighting[11] References to specific sections are listed below.

- Lamp preparation and seasoning: LM-54, LM-51 §2.1
- Power source characteristics: LM-51 §3.1-3.3
- Lamp stabilization: LM-51 §6.0
- Ballasts are lamp specific, so no reference ballasts will be used
- Lamp orientation will be horizontal
- Photometric measurement: LM-51 §9.0 and LM-79 §9.0

ANALYSES

The raw data output from the system provides luminous intensity (in candelas) as a function of angular rotation in the vertical and horizontal planes (in degrees). These values will be provided in a table with the horizontal and vertical plane cross sections graphed.

LIFE TESTING

Life testing will be done with lamps and luminaires placed in a custom rack to ensure ballast temperatures stay within the manufacturers specifications. Lamps will be controlled through a central switch that turns all units on or off. Photo sensors will be placed next to each lamp or luminaire to determine how many hours each has been on, and measure relative light depreciation over time. A data acquisition and control system (described above) records temperature and voltage data and controls the on/off switch.

PROCEDURES

Life testing will follow procedures from LM-47 Life Testing for HID Lamps[12.] First, lamps will be run for 100 hours of seasoning time as recommended by LM-54 Lamp Seasoning[13]. Luminaires will then be moved for initial photometric measurements. Due to the large number of measurements to be made, and the limited measurement equipment, these measurements will be spread out over several days. Both integrating sphere and goniophotometer measurements will be taken initially. The luminaires will then be returned to the testing racks in a temporally staggered manner to run for the rest of the first 1000 hours. After 1000 hours of run time, and for every multiple of 1000 hours thereafter, luminaires will be removed from the testing racks and tested in the integrating sphere. It should be noted that goniophotometer measurements will only occur once for the initial measurement. Life

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[12] LM47 Life Testing for HID Lamps. Illumination Engineering Society of North America. 2012

[13] LM54 Lamp Seasoning. Illumination Engineering Society of North America. 1999

testing is deemed complete once all lamps have failed or 30 months of testing have passed, whichever comes first.

- Lamp preparation: LM-47 §4.1
- Spacing: LM-47 §4.5
- Power source characteristics: LM-47 §5.1-5.3
- Run time instrumentation: LM-47 §5.5
- Operating cycle: LM-47 §6.4

ANALYSES

Luminous flux, scotopic luminous flux, chromaticity, CCT, and CRI (all measured incrementally by the integrating sphere) in addition to ballast and lamp temperatures will be graphed as a function of lamp run time to understand behavior over time.