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GATEWAY
Demonstrations

Technical Feasibility Assessment of LED Roadway Lighting on the Golden Gate Bridge

September 2012

Prepared for:

Solid-State Lighting Program
Building Technologies Program
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Prepared by:

Pacific Northwest National Laboratory

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Technical Feasibility Assessment of LED Roadway Lighting on the Golden Gate Bridge

JR Tuenge

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Preface

This document is a report of observations and analysis performed in preparation for a potential lighting demonstration project to be conducted in cooperation with the U.S. Department of Energy (DOE) GATEWAY Demonstration Program. The program supports demonstrations of high-performance solid-state lighting (SSL) products in order to develop empirical data and experience with in-the-field applications of this advanced lighting technology. The DOE GATEWAY Demonstration Program focuses on providing a source of independent, third-party data for use in decision-making by lighting users and professionals; this data should be considered in combination with other information relevant to the particular site and application under examination. Each GATEWAY Demonstration compares SSL products against the incumbent technologies used in that location. Depending on available information and circumstances, the SSL product may also be compared to alternate lighting technologies. Though products demonstrated in the GATEWAY program have been prescreened for performance, DOE does not endorse any commercial product or in any way guarantee that users will achieve the same results through use of these products.

Executive Summary

Following is an assessment of the technical feasibility of LED roadway lighting on the Golden Gate Bridge. Economic feasibility is beyond the scope of this report. The analysis was supported by these organizations and individuals:

- The Golden Gate Bridge Highway & Transportation District (GGB), represented by Kevin Raddatz
- Pacific Gas & Electric (PG&E), represented by Dave Alexander and Jack D'Angelo
- The DOE GATEWAY Demonstration program, represented by Bruce Kinzey and Jason Tuenge of the Pacific Northwest National Laboratory (PNNL).

Subsequent to preliminary investigations by the GGB, in coordination with PG&E, the GATEWAY Demonstration program was asked to evaluate the feasibility of replacing existing roadway lighting on the bridge with products utilizing LED technology. GGB and PG&E also indicated interest in induction (i.e., electrodeless fluorescent) technology, since both light source types can feature rated lifetimes significantly exceeding those of the existing high-pressure sodium (HPS) and low-pressure sodium (LPS) products. Regardless of the technology chosen, the goal of the study was to identify solutions which would reduce maintenance and energy use without compromising the quantity or quality of existing illumination.

It is assumed that existing light levels must be preserved. A new analysis would need to be performed if the GGB ultimately determines reduced illumination would be acceptable. For example, if a product which reduces existing light levels by over 50% is deemed adequate, LED products matching this reduced illumination should be sought. This would enable the use of lower wattage products, thereby increasing energy savings and improving the feasibility of LED technology in this application.

Photometric and colorimetric analyses were performed based on manufacturer-provided data for commercially-available alternatives to the existing roadway luminaires, supplemented by laboratory testing of the special bridge paint and the historic amber-lensed shoebox luminaire type. It was determined that induction technology does not appear to represent a viable alternative for the roadway luminaires in this application; any energy savings would be attributable to a reduction in light levels. Although no suitable LED retrofit kits were identified for installation within existing luminaire housings, several complete LED luminaires were found to offer energy savings of 6-18%, suggesting custom LED retrofit kits could be developed to match or exceed the performance of the existing shoeboxes. Luminaires utilizing ceramic metal halide (CMH) were also evaluated, and some were found to offer 28% energy savings, but these products might actually increase maintenance due to the shorter rated lamp life.

Color is a primary consideration for this project. Whereas the light emitted by the existing luminaires is yellow or very yellowish in appearance, the light emitted by the alternative technologies considered can be more accurately described as white in appearance. Based on the findings of this assessment, it is recommended that relatively inexpensive mock-ups of CMH products be performed to determine whether a whiter light would be appropriate in this application. If whiter light is deemed acceptable—or even preferable—this will increase the viability of LED alternatives by allowing for the use of more efficacious products. Performance criteria would then need to be developed to inform the design and evaluation of custom retrofit kits; guidance is offered in the Conclusions section to assist in the development of such specifications.

Although no suitable commercially-available LED product was identified, it appears feasible to develop an LED retrofit kit which would save energy while maintaining HPS light levels. However, the following issues will present challenges for manufacturers of custom retrofit kits and will require substantial coordination with the GGB project team:

- A carefully selected mixture of differently-colored LEDs may be required to avoid a greenish hue when operated behind the amber lens
- Since different types of LEDs may degrade at different rates, products incorporating more than one type of LED may require specialized electronics to prevent color shift over time
- Retrofit kits must be tested in situ (in the existing shoebox housing) to capture thermal effects on photometry, colorimetry, and ISTMT
- Retrofit kits must be securely mounted in the existing housing and demonstrate adequate resistance to vibration
- The added weight of retrofit kits must be determined and approved by GGB to ensure the existing poles and mounting arms are not overloaded.

There does not yet appear to be a simple means of reducing energy use and maintenance while preserving the quality and quantity of illumination for this historic landmark. Analysis provided in this report was completed in May 2012; although LED technologies are expected to become increasingly viable over time, and product mock-ups may reveal near-term solutions, some options not currently considered by GGB may ultimately merit evaluation. For example, it would be preferable in terms of performance to simply replace existing luminaires (some of which may already be nearing end of life) with fully-integrated LED or CMH luminaires rather than replacing internal components. Among other benefits, this would allow reputable manufacturers to offer standard warranties for their products. Similarly, the amber lenses might be reformulated such that they do not render white light sources in a greenish cast, thereby allowing the use of off-the-shelf LED or CMH products. Last, it should be noted that the existing amber-lensed shoeboxes bear no daytime resemblance to the LPS luminaires originally used to light the roadway.

Acronyms and Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ANSI	American National Standards Institute
ANSLG	American National Standard Lighting Group
avg:min	Average-to-minimum ratio
BUG	Backlight, Uplight, and Glare
CALiPER	Commercially Available LED Product Evaluation and Reporting
CCT	Correlated color temperature
cd	Candela(s)
CIE	International Commission on Illumination
CMH	Ceramic metal halide
CQS	Color Quality Scale
CRI	General Color Rendering Index
DLC	DesignLights™ Consortium
DOE	U.S. Department of Energy
DSS	Downward street-side
Duv	Distance from the Planckian locus on the CIE 1960 (u, v) diagram
eHID	HID lamp developed for use with an electronic ballast
fc	Footcandle(s)
GGB	Golden Gate Bridge Highway & Transportation District
HID	High-intensity discharge
HPS	High-pressure sodium
IES, IESNA	Illuminating Engineering Society of North America
IR	Infrared
ISTMT	In Situ Temperature Measurement Testing
K	Kelvin
LCL	Light center length
LCS	Luminaire Classification System
LDD	Luminaire Dirt Depreciation
LED	Light-emitting diode
LLD	Lamp Lumen Depreciation
lm	Lumen(s)
L_{XX}	Hours of operation before output diminishes to XX% of initial
LPS	Low-pressure sodium
MOL	Maximum overall length
NEMA	National Electrical Manufacturers Association
NGLIA	Next Generation Lighting Industry Alliance

NIST	National Institute of Standards and Technology
NRTL	Nationally Recognized Testing Laboratory
NVLAP	National Voluntary Laboratory Accreditation Program
pcLED	Phosphor-converted LED
PG&E	Pacific Gas & Electric Co.
PNNL	Pacific Northwest National Laboratory
Q_{GG}	Q_i modified for GGB paint
Q_i	CQS individual score
R_9	Special Color Rendering Index for Test Color Sample "Strong Red"
R_{10}	Special Color Rendering Index for Test Color Sample "Strong Yellow"
R_a	General Color Rendering Index
R_{GG}	R_i modified for GGB paint
R_i	Special Color Rendering Index
S/P	Scotopic/Photopic
SPD	Spectral power distribution
SRD	Spectral reflectance distribution
STD	Spectral transmittance distribution
SSL	Solid-state lighting
TCS	Test Color Sample
T_s	In situ case temperature for the device under testing
UV	Ultraviolet
$V(\lambda)$	Photopic luminous efficiency function
W	Watt(s)

Contents

1.0 Introduction

The original roadway luminaires on the bridge, visible in the photo which precedes the Preface, incorporated low-pressure sodium (LPS) lamps.[1] These LPS luminaires, which featured curved reflectors resembling the wings of a bird in flight, were replaced in 1972 with the shoebox-style luminaires shown in Figure 1.0.

Figure 1.0. Existing HPS luminaire with amber lens (Photo credit: PG&E)

The yellowish-white light emitted by the high-pressure sodium (HPS) lamps used in the shoeboxes was somewhat broader in spectrum than the essentially monochromatic yellowish-orange light emitted by LPS. Consequently, an amber lens was incorporated into the shoebox housings to filter light and thereby more closely match the light emitted by post-top LPS luminaires still bounding the sidewalk around each tower base. HPS floodlighting luminaires with spectrally neutral (rather than amber) lenses were subsequently installed for decorative tower lighting in 1987.[2] Due to their combined function in above-roadway bridge illumination, these three existing luminaire types—shown together in Figure 1.1—must be considered as a system:

1. Floodlights with 400 W HPS lamps for decorative up-lighting of the two towers, indicated with a green arrow
2. Post-tops with 35 W LPS lamps for diffuse fill lighting of tower bases and adjacent sidewalks, indicated with a magenta arrow
3. Shoeboxes with 250 W HPS lamps and amber lenses for illumination of the roadway and sidewalks, indicated with a yellow arrow.

[1] The website (http://www.goldengatebridge.org/research/factsGGBLighting.php) was accessed on December 30, 2011, and archived in Appendix A. Note that a horizontal plate appears to have been installed immediately above the lamp sometime after the original construction.

[2] The color of the floodlight lenses varies from neutral to slightly yellowish. It is assumed any yellowness of these lenses is attributable to deterioration from exposure to UV and IR radiation.

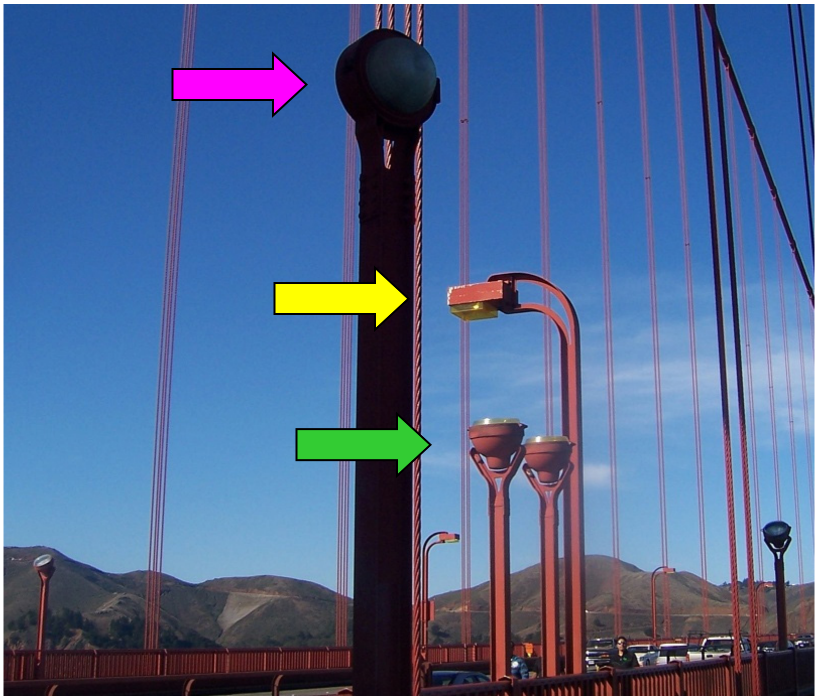

Figure 1.1. Three existing above-roadway luminaire types
(Photo credit: PG&E)

Figure 1.2 shows the combined effect of the bridge lighting system, alongside a photograph of an earlier mock-up using searchlights. The bridge was designated as California Historical Landmark No. 974 in 1990, effectively precluding future replacement of visible luminaire components such as the amber lens on the shoeboxes.[3]

[3] For more information, visit http://ohp.parks.ca.gov.

Photo credit: San Francisco History Center, San Francisco Public Library

Photo credit: © Ron Niebrugge

Figure 1.2. Tower floodlighting mock-up in 1947 (left) and current installation (right)

The ten cobrahead-style roadway luminaires at the south end of the bridge—pictured in Figure 1.3—cast light onto the painted guardrails and thus are also considered as part of the analysis. This fourth luminaire type utilizes 250 W HPS lamps.

Figure 1.3. First ten cobraheads at south end of bridge (Photo credit: Google)

2.0 Color Considerations

Color is a primary concern for this national landmark, and must be considered when evaluating lighting products. According to a report issued by the bridge architect prior to completion of construction, darkness would be preferable to poor color quality:

> *"The color of the bridge is unhesitatingly put forward as of more importance than the illumination [of the painted structure]. If this possible economy in current [i.e., electricity] consumption is a controlling consideration, then the recommendation is to abandon decorative illumination and preserve the right color [of paint as viewed under daylight]." (GGB 1935)*

Roadway lighting is primarily directed at the drivelanes and sidewalks, but some light from roadway luminaires can and should illuminate the specially painted surfaces of the bridge, including the handrails and the bases of the two towers. Even the utilitarian cobraheads at the south end of the bridge will illuminate the painted guardrails, and thus should be evaluated for color characteristics.

> *"While the roadway lighting is installed for practical purposes, it will have decorative value as well. The long line of yellow glow marking the roadway will serve as the one constant bond uniting the various parts of the structure." (GGB 1935)*

Care should be taken to ensure the apparent color of the towers is acceptably close to the rest of the like-painted surfaces of the bridge. However, differences in color characteristics between the four existing luminaire types are likely mitigated somewhat by the inevitable variation in paint color across the bridge, attributable to manufacturing tolerances and weathering.

> *"the irregular variation in tone due to repaintings will have positive value as picturesqueness […] the magnitude of the structure and the great distances separating its parts could absorb considerable of the kind of variation of tone and 'weathering' that we admire in the great monuments of the past." (GGB 1935)*

Basic color criteria can be summarized as follows:

- Products must render the color of the bridge paint in a uniform and appealing manner
- The luminous portions of luminaires should appear similar in color when viewed at night.

Two metrics are commonly applied to lighting products when evaluating color: the Color Rendering Index (CRI) and correlated color temperature (CCT).[1] CRI is poor for HPS (rated at ~ 21 out of a possible score of 100) and terrible for LPS (often reported as zero but actually negative in value), so other technologies such as LED and induction generally represent improvements in this aspect. CCT, reported in kelvin (K), provides an indication of hue for white light sources. Lower CCTs (e.g., 2100 K for HPS) indicate a yellowish-white appearance, whereas higher CCTs (e.g., 6500 K for daylight) indicate a bluish-white appearance. CRI and other color rendering metrics should not be compared between products differing widely in CCT.

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[1] For more on these and other color metrics, see the "LED Color Characteristics" fact sheet, available online at www.ssl.energy.gov/factsheets.html.

CCT is often supplemented with another metric, Duv, to ensure products do not shift toward greenish or pinkish hues (ANSLG 2008). It is not clear whether Duv is relevant at very low CCTs beyond the typical range of light sources considered white in appearance. Although CCT and Duv do not perfectly capture the color appearance of a light source when viewed directly, these metrics serve as a good starting point in preliminary product evaluation. By contrast, the CRI metric may not be particularly relevant for this application, given the current acceptance of very low values on this and most other roadways (DOE 2011).

To ensure consistent color across the bridge, CCT should be fairly consistent across all four luminaire types, and—depending on the direction of drift—Duv generally should not be allowed to fall far outside ANSI tolerances (ANSI 2011).[2] This is significant in terms of energy savings because within any given LED product family, and given equal drive current and CRI, efficacy is largely a function of CCT. Figure 2.0 summarizes sample data from Philips-Hadco (see Appendix I), showing minimal differences in efficacy between 4000 and 5700 K. By contrast, the efficacy for this product family at 3000 K is on average 26% lower than at 4000 K, outweighing other factors such as the choice of optical system (spatial distribution of light). Consequently, the ability of LED products to outperform HPS may greatly depend on the range of CCTs deemed appropriate for this application.

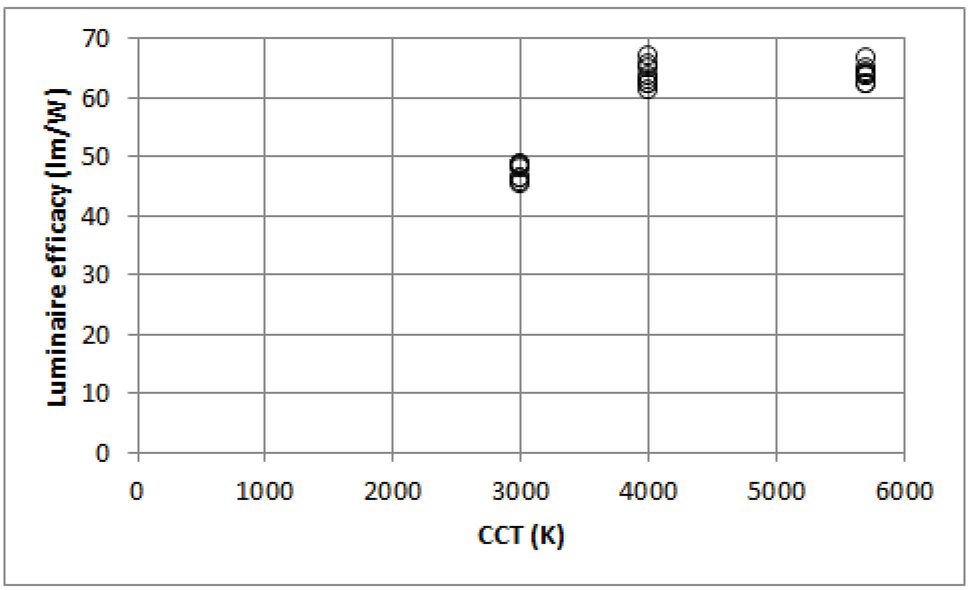

Figure 2.0. Hadco LED efficacy as a function of CCT

The perceived color of the painted surfaces is a function of the spectral power distribution (SPD) of incident light and the spectral reflectance distribution (SRD) of the paint. Whereas the SPDs of the LPS post-top and HPS floodlights were estimated by assuming spectrally neutral lenses, laboratory testing was performed as part of this study to determine the effect of the amber lens on the HPS shoebox. The series of tests is summarized in Table 2.0 and the test reports are compiled in Appendices D-G.[3] To ensure the

[2] Although ANSI C136.37 incorporates the ANSI C78.377 tolerances, less stringent criteria may be adequate in many roadway lighting applications.

[3] Note that due the compromised surface area ratio between luminous opening and sphere interior, the lumen output values derived from luminaire goniophotometry are to be used in lieu of those from integrating sphere photometry.

equipment selected for testing was representative of the other luminaires on the bridge, additional data from other sources was also evaluated for comparison.

Table 2.0. HPS shoebox test configurations

Testing (apparatus)	Lens A	Lens B	No lens	Bare lamp
Photometry (goniophotometer)	✓	✓	✓	
Photometry (integrating sphere)	✓	✓	✓	✓
Colorimetry (integrating sphere)	✓	✓	✓	✓

Testing was performed using two amber lenses differing slightly in appearance, perhaps due to deterioration and/or the material used. The variety of tests allows for determination of lens spectral transmittance distribution (STD), luminaire SPD, luminaire output, and spatial distribution of light. Figure 2.1 illustrates the STD of the amber material used by GGB staff to fashion the five-sided lens; manufacturer-provided data is shown alongside test data for comparison.[4] Whereas nearly all light is transmitted for wavelengths above 550 nm, most light below 500 nm is effectively blocked by the lens. It is assumed that the intermediate curve, obtained by averaging the STDs for samples A and B, is representative of other lenses installed on the bridge. The segmented reflector SRD is also shown to demonstrate that, being in essence spectrally neutral, its effect on calculated lens STD (due to interreflected light) can be assumed to be negligible. It is not clear whether the apparent trend of increasing transmittance for wavelengths around and below 400 nm may be attributed to near-UV measurement error.

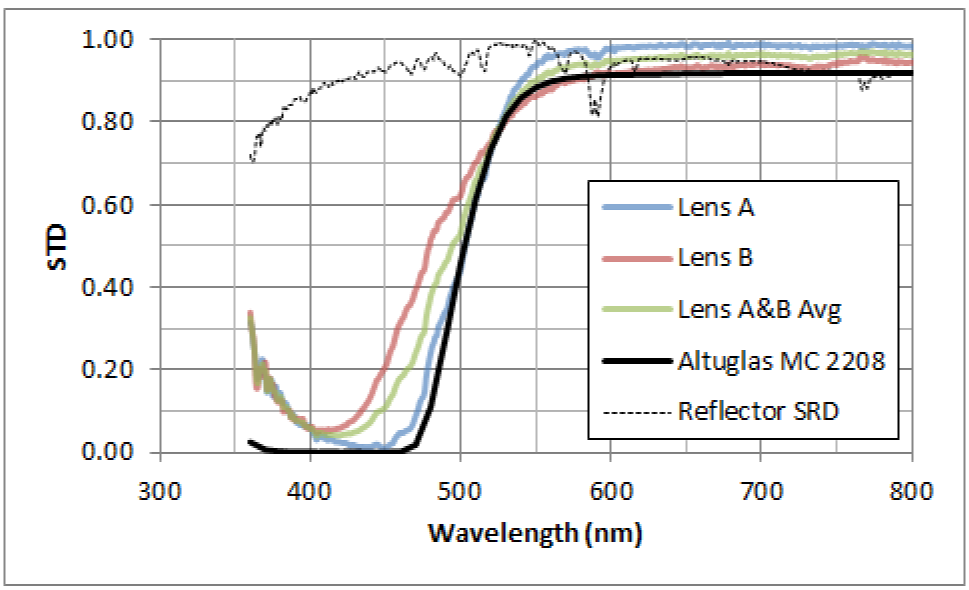

Figure 2.1. Rated and measured STDs for amber lens material

[4] The specification for this product is provided in Appendix C for reference. According to a Dow Chemical Co. representative, the Plexiglas product formerly sold by Rohm & Haas is now manufactured by Altuglas International under product code MC 2208.

Very little of the HPS lamp output is filtered-out by the amber lens since most of the light is produced at wavelengths greater than 550 nm. Figure 2.2 illustrates the unique SPDs of each of the existing luminaire types under consideration:

- Floodlights and cobraheads—HPS without amber lens
- Shoeboxes—HPS with amber lens
- Post-tops—LPS without amber lens.[5]

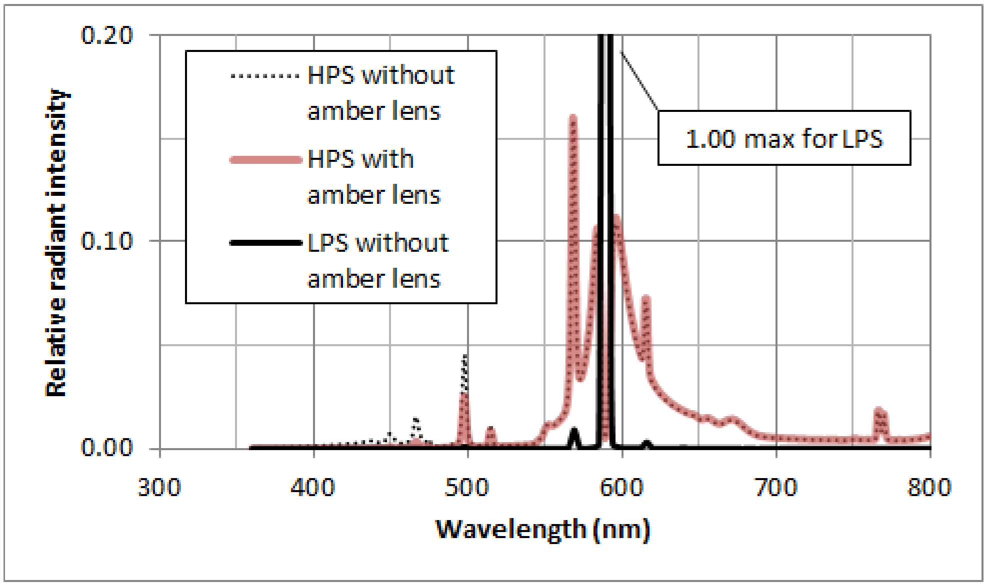

Figure 2.2. Estimated SPDs for the four existing luminaire types
(scale is normalized for equal lumen output)

The optical transmittance of the amber lens is lower for sources emitting a significant proportion of radiant energy at wavelengths below 500 nm. SPDs for two LED products tested by the DOE Commercially Available Lighting Product Evaluation and Reporting (CALiPER) program are shown in Figure 2.3.[6]

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[5] LPS data courtesy of Osram Sylvania.
[6] For details of the CALiPER testing, visit www.ssl.energy.gov/caliper.html.

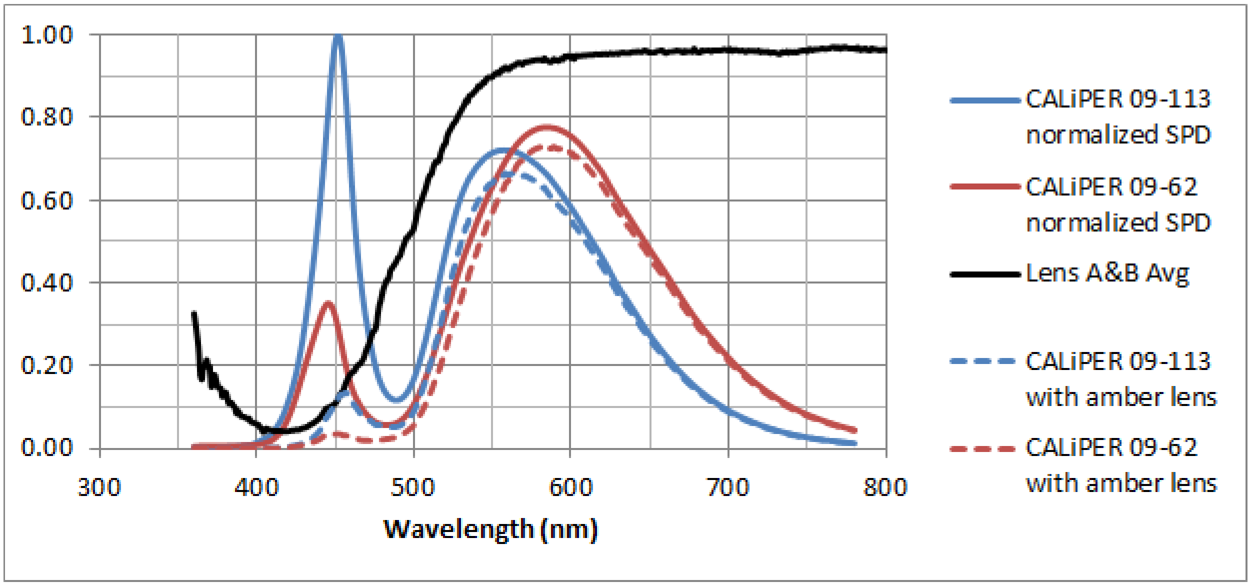

Figure 2.3. Effect of amber lens on warm-white and cool-white LED products

Product 09-62 was nominally 3000 K and product 09-113 was nominally 5000 K. The SPDs were first normalized for equal lumen output, and then scaled-down by applying the STD of the amber lens to demonstrate that the overall effect generally decreases with decreasing CCT. Note that the peak below 500 nm, characteristic of phosphor-converted LED (pcLED) products and most prominent for cool-white products exhibiting high CCT, is nearly eliminated by the amber lens and is thus largely wasted in this application. However, the photopic luminous efficiency function, V(λ), mitigates the relative impact of losses at shorter wavelengths. Whereas optical transmittance is calculated by taking the ratio of radiant energy in the visible spectrum (optical radiation) with/without lens, luminous transmittance is calculated by taking the ratio of lumens with/without lens. Thus, the relationship between CCT and efficacy losses associated with Stokes' shift (DOE 2011) appears to be much stronger than the relationship between CCT and the luminous transmittance of the lens, as illustrated in Figure 2.4.[7] Luminous transmittance of the amber lens is estimated at 93% for HPS, as shown in Figure 2.5.

[7] Manufacturer-provided induction SPDs courtesy of the QL Company and Osram Sylvania.

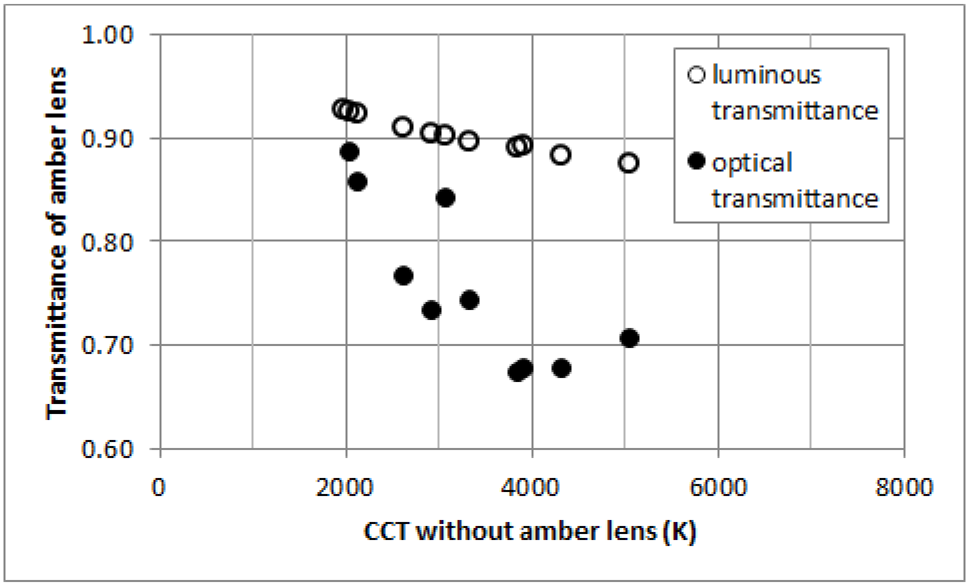

Figure 2.4. Optical and luminous transmittance across product types

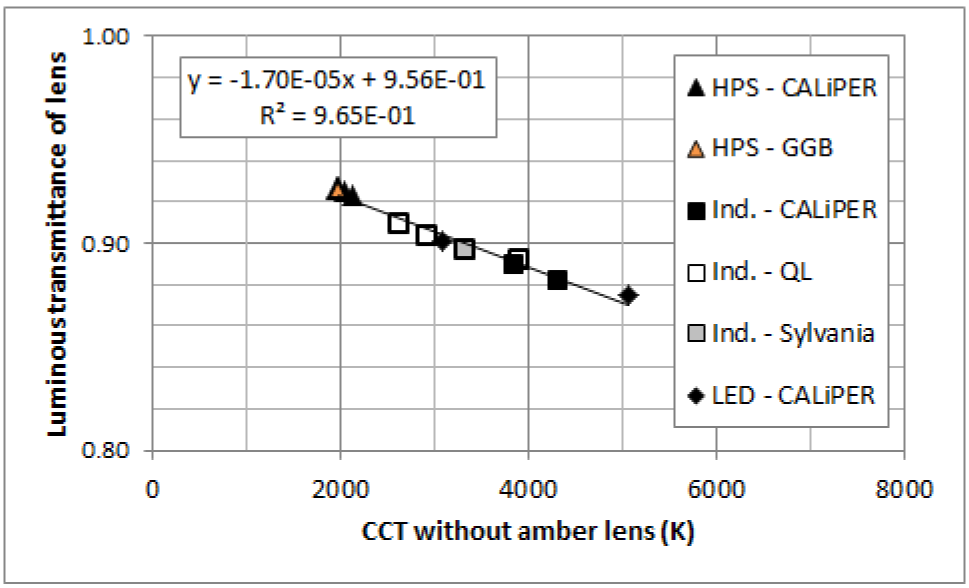

Figure 2.5. Luminous transmittance by product type

According to the GGB website, the bridge is painted “Golden Gate Bridge International Orange,” inspired by the “orange vermillion” color of the red lead primer which had been applied by the steel fabricator prior to shipping.[8] The CMYK color mixing formula is 0% cyan (C), 69% magenta (M), 100% yellow (Y), and 6% black (K). To enable more detailed analysis, three paint samples were mailed to a laboratory for SRD testing. Of these, only two—designated B and C in Figure 2.6—proved mechanically compatible with the test apparatus.

[8] The website (http://goldengatebridge.org/research/factsGGBIntOrngColor.php) was accessed on January 3, 2012, and archived in Appendix A.

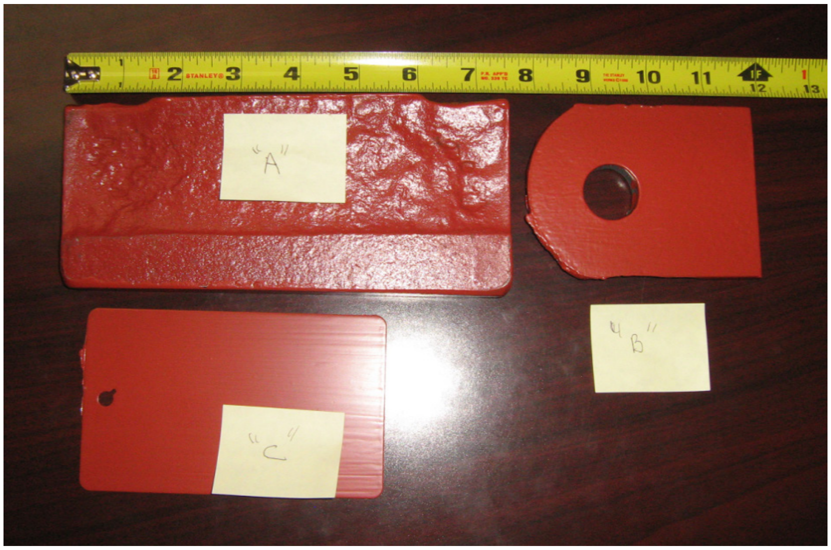

Figure 2.6. Paint samples used for testing (Photo credit: GGB)

The complete test report is included in Appendix B, and the averaged SRD (designated SRD_{GG}) is illustrated in Figure 2.7.[9] Similar SRDs defined by the International Commission on Illumination (CIE 1995) and the National Institute of Standards and Technology (NIST 2010) are also shown for reference.

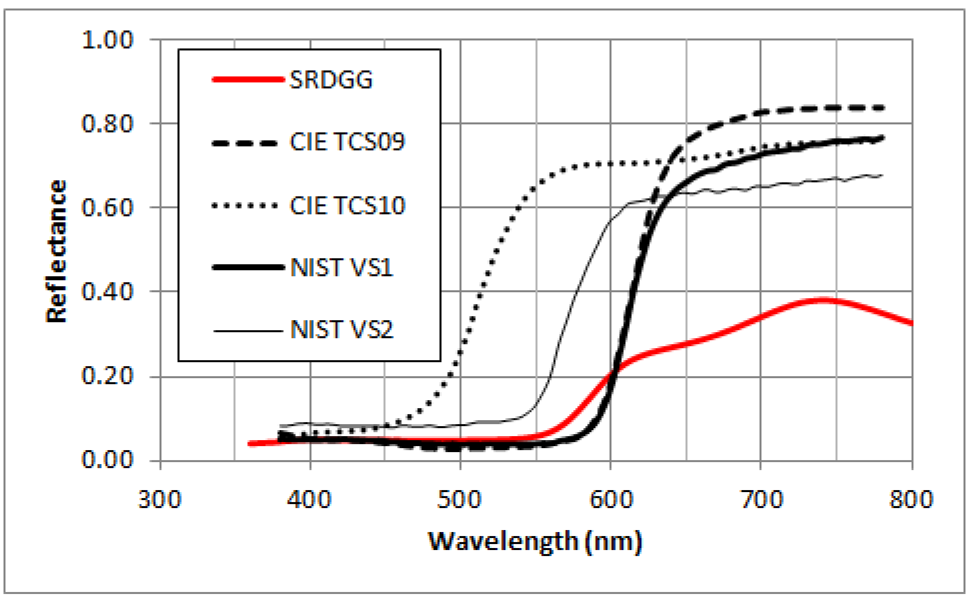

Figure 2.7. SRDs for test samples

The CIE Test Color Method defines a number of Special Color Rendering Indices (R_i) which are each a function of an associated Test Color Sample (TCS), along with the more commonly used CRI which is calculated as the average of scores R_1 through R_8. Whereas CRI addresses a set of pastel colors, special indices R_9 through R_{12} address saturated colors; TCS 09 is used to calculate R_9 (strong red) and TCS 10 is

[9] It was assumed that the specular reflection component should be excluded from the total hemispherical reflectance measurement to better represent typical (diffuse reflection) viewing conditions. Total reflectance (including the specular component) would be more appropriate for indoor applications such as office lighting, where interreflected light is more substantial.

used to calculate R_{10} (strong yellow). These metrics are useful for general purposes, but knowledge of the GGB paint SRD allows for more refined evaluation of bridge color. An analogous special color rendering index—designated R_{GG}—was calculated by arbitrarily replacing TCS 14 with SRD_{GG} and then evaluating the resulting R_{14} score.[10] Another metric—designated Q_{GG}—was calculated in a similar manner as an alternative to R_{GG}. This metric is analogous to the individual scores used in the Color Quality Scale (CQS), a system developed by NIST as an alternative to the CIE Test Color Method. Whereas R_{GG} is expected to characterize color fidelity relative to the reference source, blackbody radiation, Q_{GG} is expected to serve as a better predictor of color preference.

The V(λ) function is applied to the SPD of a lighting product to calculate its lumen output; similarly, an SRD must be applied to the SPD of incident light to accurately determine the lumens reflected from surfaces painted a color which is not spectrally neutral. The product of V(λ) and SRD_{GG}—designated $V(\lambda)\cdot SRD_{GG}$ and normalized in Figure 2.8—indicates SPDs peaking near 600 nm will be most effective in terms of generating paint luminance.

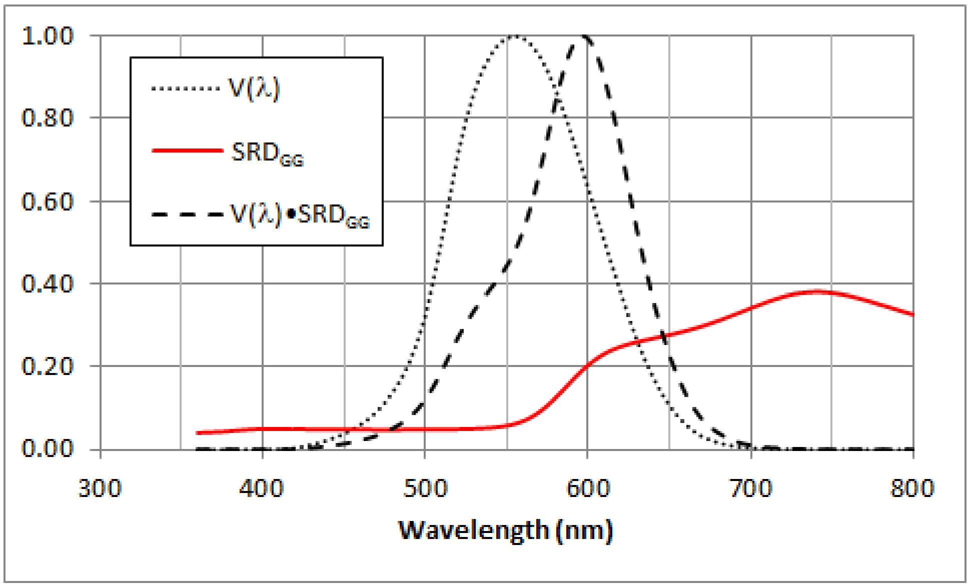

Figure 2.8. V(λ), SRD_{GG} and their product

The light emitted by LPS is nearly monochromatic, with a dominant wavelength near 590 nm. The selection of a light source having an SPD which aligns with the $V(\lambda)\cdot SRD_{GG}$ peak was likely coincidental, given the limited technology options available at the time of bridge construction. The 1000 W flood lights originally specified by the bridge architect for decorative tower illumination were presumably intended to be lamped with incandescent, given that he characterized LPS as a light source known for "destroying all colors" (NPS 1935).

Table 2.1 suggests the amber lens can be expected to reduce CCT, increase Duv, and compromise color rendition for most white light sources. Red text indicates SPDs outside tolerances for white light or deficient in the red portion of the spectrum; LPS is shown without lens for comparison.

[10] Calculations were performed by PNNL using a modified version of a spreadsheet provided by Yoshi Ohno of NIST (CQS 9.0.b 1 nm version (Win).xls).

Table 2.1. Color characteristics for LPS, HPS, and amber-filtered HPS

Product	Lens	CCT (K)	Duv	CRI	R_9	R_{GG}	Q_{GG}
HPS (CALiPER BK 09-105)	neutral	2131	0.000	11	-261	-63	45
	amber	2020	0.008	7	-269	-70	32
HPS (CALiPER BK 08-122)	neutral	2043	0.001	21	-208	-42	53
	amber	1951	0.007	17	-215	-49	34
HPS (GGB shoebox)	neutral	1977	0.000	26	-182	-32	57
	amber	1887	0.006	22	-189	-38	37
LPS (Sylvania)	neutral	1776	0.007	-45	-495	-170	0

Due to distortions in the red portion of the color space used for calculation of the R_9 metric, a positive value (greater than zero) is generally considered acceptable for most indoor applications.[11] Given the similarity between SRD_{GG} and CIE TCS09, it might be assumed that this criterion for R_9 is also applicable to the R_{GG} metric. However, in spite of R_{GG} scores as low as -32 for standard HPS (well below zero), this light source is already considered acceptable for the purpose of tower floodlighting. It is assumed that Q_{GG} will serve as a more meaningful metric for this application since standard HPS can be expected to receive a suitably moderate score in the 50's. However, note that the current use of LPS lamps for fill lighting at sidewalk level around the base of each tower suggests the value could be as low as zero for the cobraheads and shoeboxes.[12]

Table 2.2 suggests both LED and induction can generally be expected to receive Q_{GG} scores above 60, even with the amber lens. However, the amber lens greatly increases Duv for both LED and induction, yielding values which far exceed ANSI tolerances; this effect tends to be more pronounced at higher CCTs, as illustrated in Figure 2.9. This is attributable to the higher proportion of short-wavelength (blue) content in the broad spectrum, and may result in an unacceptably greenish hue.

[11] There is no standard for minimum R_9 in outdoor applications. A positive R_9 value is required for ENERGY STAR® qualification of LED integral replacement lamps; see http://www.energystar.gov/lightbulbs for details.

[12] Given the acceptance of LPS, it is assumed that application of more sophisticated metrics is not warranted. For example, Δu'v' could be calculated for the light reflected from the paint for each pair of SPDs considered.

Table 2.2. Effect of amber lens on color characteristics for white LED and induction

Product	Lens	CCT (K)	Duv	CRI	R_9	R_{GG}	Q_{GG}
LED (CALiPER 09-113)	neutral	5058	0.003	70	-28	47	78
	amber	3582	0.032	61	-70	24	72
Induction (CALiPER BK 08-153)	neutral	4323	-0.002	80	25	86	94
	amber	3252	0.026	72	-16	67	80
Induction (QL 4000K)	neutral	3910	-0.002	76	13	88	94
	amber	3121	0.025	72	-20	73	76
Induction (CALiPER BK 08-152)	neutral	3847	-0.009	78	15	83	91
	amber	2992	0.021	72	-24	64	78
Induction (Sylvania 3500K)	neutral	3335	-0.001	80	12	93	97
	amber	2825	0.020	77	-14	81	74
LED (CALiPER 09-62)	neutral	3080	0.006	69	-20	45	81
	amber	2729	0.020	64	-36	36	62
Induction (QL 3000K)	neutral	2939	-0.005	79	-3	90	96
	amber	2567	0.016	78	-25	79	68
Induction (QL 2700K)	neutral	2636	0.001	78	-23	80	93
	amber	2400	0.015	76	-37	73	57

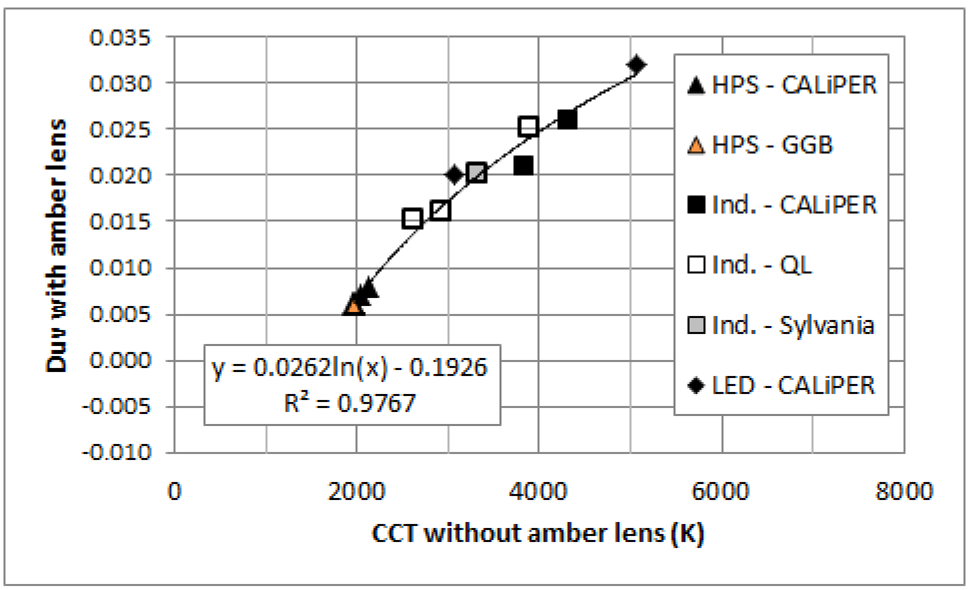

Figure 2.9. Effect of amber lens on Duv for different source types

Amber-colored LEDs featuring an SPD peak near 600 nm may also merit consideration, although few manufacturers offer roadway luminaires which utilize these light sources. The SPD of an amber luminaire from BetaLED is illustrated in Figure 2.10, with and without amber lens.

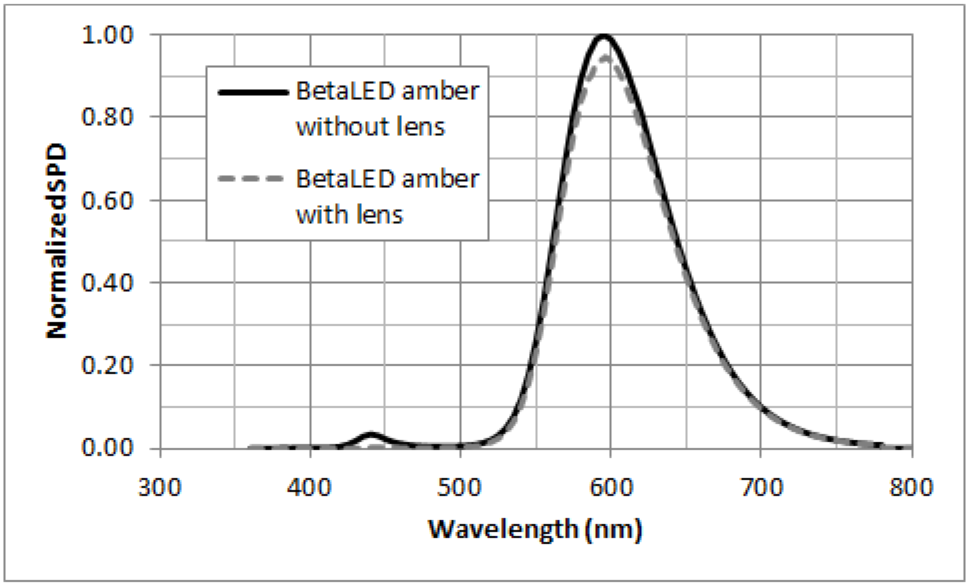

Figure 2.10. Normalized SPD for amber LED luminaire from BetaLED

A comparison of this and another luminaire by BetaLED suggests that, holding other parameters equal (including wattage and spatial distribution), a 4300 K luminaire might be expected to produce nearly twice as much light as a luminaire having only amber LEDs.[13] Considering this apparent difference in efficacy, the improvement in luminous transmittance of the amber lens would be negligible. However, the overall luminous reflectance of the paint would be higher for these amber LEDs (16%) than for the 3000 K LED product designated CALiPER 09-62 (13%) when contained by the amber lens, thereby yielding 24% higher exitance for equal illuminance. Furthermore, the Duv of 0.007 (see Table 2.3) suggests this light source would not be perceived as greenish in hue after being filtered by the amber lens.

Table 2.3. Effect of amber lens on color characteristics for amber LED

Product	Lens	CCT (K)	Duv	CRI	R_9	R_{GG}	Q_{GG}
BetaLED	neutral	1825	0.005	39	-109	-7	48
	amber	1790	0.007	38	-110	-9	9

It might be argued that nighttime illumination should replicate daytime illumination from the sky and sun, which is broad in spectrum and features a relatively cool bluish-white appearance. However, the greater proportion of long-wavelength spectral content exhibited by warmer-appearing light sources can offer an interesting contrast between daytime and nighttime bridge appearance.

> *"The object is to reveal aspects of a great monument which are unsuspected under the conditions of natural, or day lighting." (GGB 1935)*

There appears to be a widely held belief that yellowish light performs better in fog by scattering less than white light. However, fog scatters light independent of wavelength—this is why clouds appear neutral in color (white or gray) in broad daylight. Thus, any preference for yellowish light in foggy conditions is likely attributable to differences in perceived brightness rather than disability glare. Still, it

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[13] Based on catalog numbers ARE-EDG-3M-DA-24-C-UL-xx-AMB-350 (amber) and ARE-EDG-3M-DA-24-C-UL-xx-43K-350 (4300 K), from cutsheets dated 2010-11-09.

is assumed that light sources should remain relatively warm in appearance in order to preserve the desired contrast between the daytime and nighttime appearance of the bridge. Additional support for this approach is offered by the higher paint reflectance at longer wavelengths, which generally translates to higher luminous reflectance for lower CCT light sources.

Given its use in floodlighting the primary luminous elements at night—the two towers—the CCT of HPS with neutral lens (nominally 2100 K) is clearly deemed appropriate for this application. Further, given that LPS (nominally 1800 K) is also deemed acceptable in this outdoor application, it appears likely that a nominally 2400 K luminaire would similarly prove compatible, provided the LPS post-tops were also retrofitted as part of the project. A review of CALiPER data for a variety of LED products suggests the amber lens would reduce the CCT of a 3000 K warm-white LED light source to roughly 2600 K, as illustrated in Figure 2.11. By comparison, a 4200 K light source would be expected to appear roughly 3200 K when viewed through the amber lens. LED products above 3500 K are generally not characterized as being warm in appearance (ANSI 2011).

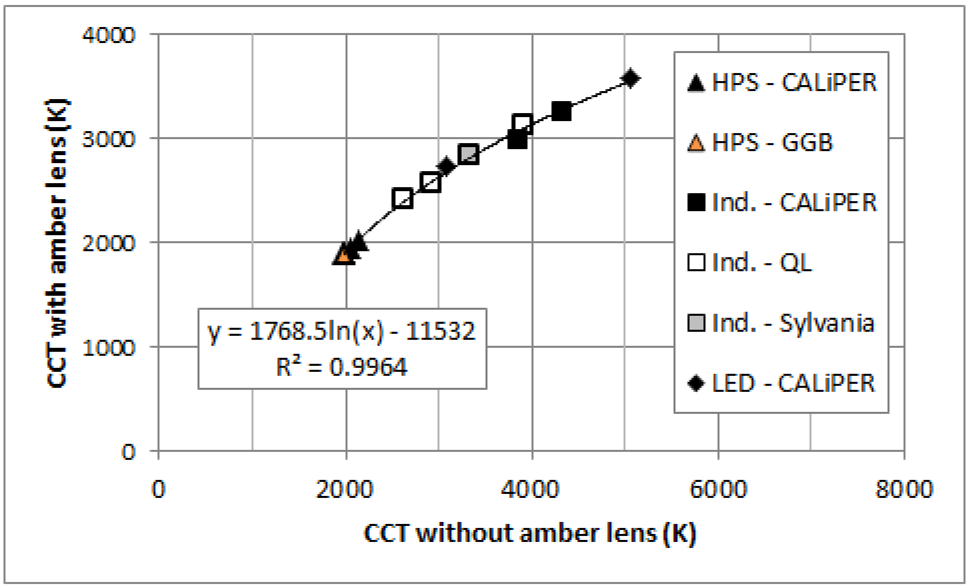


Figure 2.11. Effect of amber lens on CCT for different source types

The following analysis assumes a luminaire CCT of approximately 3000 K would be acceptable, particularly if utilized for all four luminaire types. However, the exact threshold for acceptably warm appearance can only be determined through visual evaluation, and simple CCT could ultimately prove to be an inadequate metric for this purpose.

> *"There is only one sure way to select colors for anything, and that is to see fairly extensive samples of the actual materials which are to be used, in the actual place where they are to be used." (GGB 1935)*

If the CCT of any of the four luminaire types is increased substantially the others should also be replaced or modified to maintain uniform color. A broader spectrum could improve safety and security by increasing the visual contrast of pedestrians and obstacles against a background of different color. LED and induction appear to offer improved color rendition of the bridge paint. However, a custom SPD may be required to ensure a greenish hue is not produced when these light sources are placed behind the amber lens.

3.0 Shoebox Performance—HPS (Existing)

Following is the set of AGi32 inputs representing the typical luminaire layout between the two towers, as illustrated in Figure 3.0:

- Opposite pole arrangement
- 150' between poles in the direction of traffic flow
- 23'-3" from pavement to luminaire aperture (mounting height)
- 5' from center of luminaire aperture to center of pole (arm length)
- 11' sidewalk width and distance from pole to road (setback)
- 6 drivelanes each 11' wide.

Figure 3.0. Typical four-pole layout with illuminance grids (plan view)

Dimensions were based on Google Maps data; scaled drawings of the bridge were not available according to GGB staff. Pole spacing is considerably shorter for the north-most 26 poles (i.e., 13 poles on either side of the road). Calculation grids were defined as follows:

- Horizontal illuminance at pavement in each drivelane per IES RP-8 (IES 2000)
- Veiling luminance per IES RP-8
- Horizontal illuminance at pavement for two lanes on sidewalk
- Vertical illuminance 4.9' above pavement for both lanes on sidewalk, oriented in both directions of travel per IES RP-8
- Vertical illuminance normal to a vertical grid above the outer guardrail, which spans the area from 5 to 23' above pavement, as illustrated in Figure 3.1.

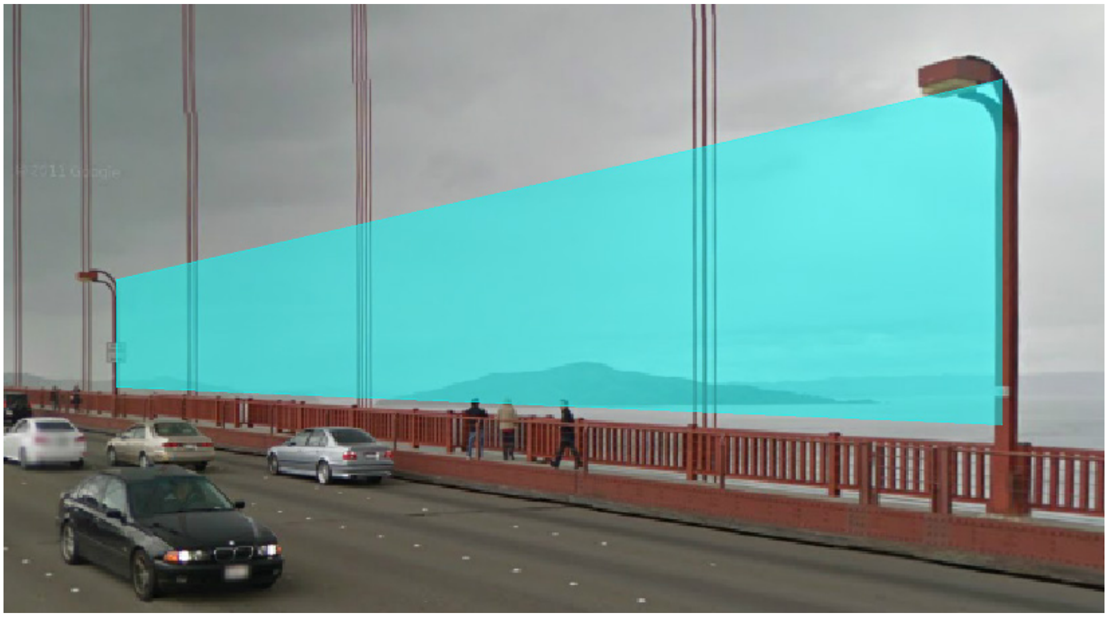


Figure 3.1. Location of calculation grid for spill light
(adapted from Google photography)

The reflector pans used in the existing luminaires were reportedly manufactured by Philips-Gardco Lighting. Table 3.0 shows good agreement between values calculated using the manufacturer-provided IES file for their type "3" distribution Form 10 optic (having a spectrally-neutral flat glass lens) and the IES file generated by the laboratory for the luminaire tested with no lens.[1] The greatest discrepancies are found in comparing the uniformity ratios; this may merely be attributable to sensitivity to the minimum (darkest) point.

Table 3.0. Simulated shoebox illumination without light loss factors

Test	Input power (W)	Drivelanes			Sidewalks		
		Avg horiz illum (fc)	Avg:Min uniformity ratio	Max veiling lum ratio	Avg horiz illum (fc)	Avg:Min uniformity ratio	Min vert illum (fc)
Gardco (neutral lens)	-	1.88	2.2	0.55	2.99	4.8	0.01
No lens	314	1.89	3.2	0.62	2.93	8.1	0.01
Lens A	319	1.66	3.4	0.63	2.76	8.4	0.02
Lens B	315	1.39	3.4	0.68	2.38	7.7	0.05
Avg Lens A&B	317	1.53	3.4	0.66	2.57	8.0	0.04

The luminaire housing, shown with Lens A in Figure 3.2, was considered to be in good condition and typical of luminaires in service on the bridge. Lenses A and B were selected to approximately represent

[1] Data file "EH19-3-250H.IES" downloaded 2011-11-15 from www.sitelighting.com.

newer and more weathered assemblies, respectively. The lamp sample was seasoned for 100 hours before testing to ensure stable operation (IES 1999). The luminaire, which was not removed from service but rather had been stored for prior testing, was tested as delivered.

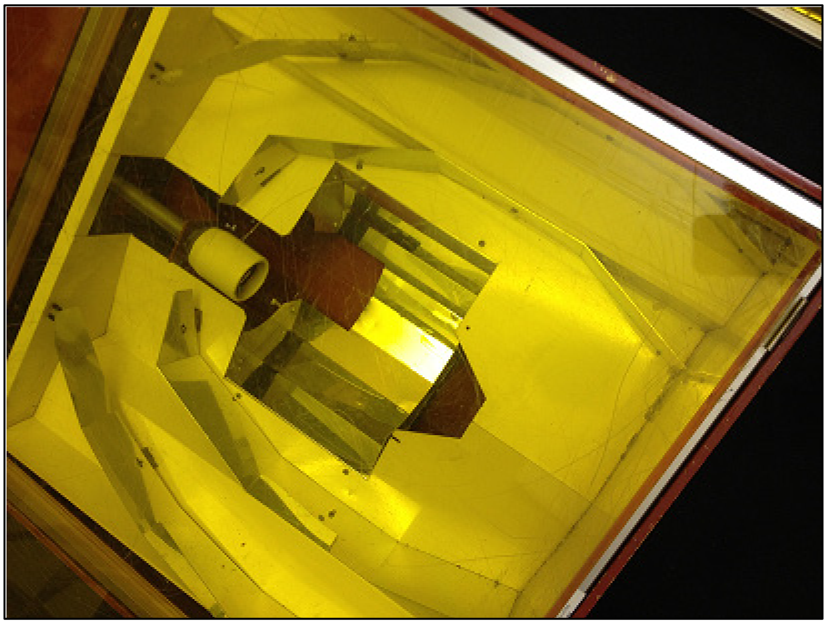


Figure 3.2. View into tested shoebox with lens A
(Photo credit: Luminaire Testing Laboratory)

Table 3.1 uses the Luminaire Classification System (LCS) to illustrate how the amber lens creates uplight and increases the percentage of light emitted just below horizontal (IES 2011a). The weathered lens B exacerbates these spatial effects, which combine with spectral effects (luminous transmittance) to further reduce average illuminance on the roadway. Conversely, the slight increase in vertical illuminance for pedestrians is likely attributable to the increased high-angle brightness.

Table 3.1. High-angle and upward-directed light

LCS zone(s) ≥ 80° from nadir	Percentage of luminaire output		
	No lens	Lens A	Lens B
FVH	0.1	0.4	1.3
BVH	0.1	0.4	1.1
UL	0.0	0.2	1.7
UH	0.0	2.4	4.8
FVH+BVH+UL+UH	0.2	3.4	8.9

Stray light should be evaluated in terms of initial uplight and average illuminance on the vertical plane above the outer guardrail; averaging tests for lenses A and B yields 830 lm of uplight and 1.9 fc of spill light, respectively.[2] In many roadway lighting applications with adjacent pedestrian ways, use of simple luminaire metrics such as house-side lumens and the Backlight portion of BUG Ratings can result in inadvertent penalization of useful flux. However, due to the relatively short distance to edge of sidewalk behind the shoeboxes in this application (0.2 to 0.3 mounting height), it is clear that intensity

[2] Grid spacing was 3' by 3' across 50 columns and 7 rows, for a total of 350 spill light calculation points.

distributions being essentially symmetric front-to-back (equal flux street-side and house-side) will invariably waste an excessive amount of light behind the pole. Thus, preliminary evaluation on the basis of downward street-side (DSS) output is helpful in this particular application by distinguishing intensity distributions being asymmetric front-to-back.

Most luminaires exhibit a gradual reduction in lumen output over time and thus must be effectively oversized initially to ensure adequate maintained illumination for the duration of operation. The primary light loss factors associated with outdoor lighting are lamp lumen depreciation (LLD)—also known as lumen maintenance—and luminaire dirt depreciation (LDD). Because different luminaires generally degrade in output at different rates, it is standard practice to assign a specific LLD and LDD to each luminaire type.

LLD for HPS is commonly determined by taking the ratio of rated mean lumens to rated initial lumens, where the mean value is set by the lamp manufacturer at 40 or 50% of rated life, depending on the manufacturer and specific lamp (IES 2011c). By contrast, IES DG-4 recommends streamlining maintenance by proactively group relamping and cleaning at approximately 70% of rated lamp life. However, the GGB estimates one third of luminaires are relamped each year, meaning that if luminaires are operated 11 hours per day on average the actual service life is roughly 12,000 hours—just half of the rated value.[3] Consequently, assuming HPS lumen maintenance follows the curve provided in Figure 1 of IES DG-4 (for a clear 400 W HPS lamp operated horizontally), LLD is estimated at 90% prior to relamping. The abbreviated service life may be attributable to bridge vibration (IDOT 2002).

Luminaire dirt depreciation is a function of luminaire design, time between cleanings, and ambient particulate level. According to data published by the Environmental Protection Agency (EPA), concentrations of airborne particulate matter in San Francisco appear to be well below 150 $\mu g/m^3$, indicating a “very clean” environment.[4] Whereas an earlier models assumed linear degradation (IES 1971), current recommendations assume the effect is exponential (IES 2003); these estimates are illustrated in Figure 3.3. LDD is estimated at 91% prior to relamping, given a cleaning interval of three years, and assuming the luminaire can be accurately characterized as “enclosed and gasketed.”

[3] The GGB standard 250 W HPS lamp is GE #85377 (rated 24,000+ hours). It is not clear whether newer alternatives such as Sylvania #67578 (rated 30,000 hours), non-cycling, or dual arc tube “standby” HPS would offer greater vibration resistance and service life.

[4] Based on “coarse” particles between 2.5 and 10 μm in diameter (PM10) at site 060750005. Data is available online at http://www.epa.gov/airtrends/pm.html.

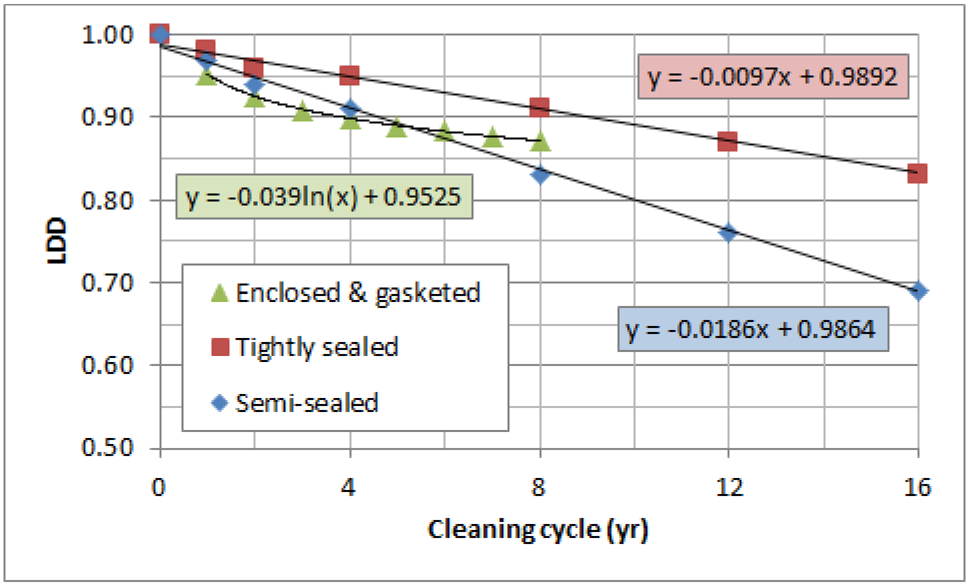


Figure 3.3. Luminaire Dirt Depreciation for < 150 μg/m^3 environment

Applying the LLD and LDD multipliers yields a maintained illuminance value comparable to the IES-recommended illuminance for undivided Major roadways and the AASHTO-recommended illuminance for Other Principal Arterials, as shown in Table 3.2. For comparison, the 93% HPS luminous transmittance is applied to the "no lens" IES file to separate spectral effects from spatial effects.[5] It is worth noting that driver veiling luminance (a disability glare metric), sidewalk uniformity, and pedestrian vertical illuminance appear inadequate by current industry standards. However, this is based on a single test sample (which may not represent all existing luminaires), and GGB is not obligated to meet either set of recommendations.

Table 3.2. Simulated shoebox maintained illumination

Test	Drivelanes			Sidewalks		
	Avg horiz illum (fc)	Avg:Min uniformity ratio	Max veiling lum ratio	Avg horiz illum (fc)	Avg:Min uniformity ratio	Min vert illum (fc)
No lens x 93%	1.4	3.2	0.62	2.2	8.1	0.01
Avg Lens A&B	1.2	3.4	0.66	2.1	8.0	0.03
IES RP-8 Maj-Med-R3	1.3	3.0	0.30	0.5	4.0	0.20
AASHTO OPA-Int-R3	1.2	3.0	0.30	-	-	-

For the purposes of this report, the criteria listed in Table 3.3 are offered as targets for preliminary screening of LED and induction alternatives. Manufacturer-provided photometry (performed without the amber lens) will be evaluated after application of suitable multipliers for luminous transmittance, LLD,

[5] Ray tracing of light propagation within luminaires is outside the scope of this study; it is assumed that distortion of spatial distribution of light by the amber lens will be comparable across manufacturers and light source types.

and LDD. Note that the sidewalk appears to be overlit relative to IES recommendations; however, illumination here should remain comparable to the roadway illumination for monitoring purposes.

Table 3.3. Suggested criteria for maintained shoebox performance

Application	Metric	Target
Drivelanes	Avg horizontal illum (fc)	≥ 1.4
	Avg:Min uniformity ratio	≤ 3.0
	Veiling luminance ratio	≤ 0.6
Sidewalks	Avg horizontal illum (fc)	≥ 1.4
	Avg:Min uniformity ratio	≤ 6.0
	Min vertical illum (fc)	≥ 0.02

With its release in July 2011, IES HB-10 introduced guidance for the use of scotopic/photopic (S/P) ratios to calculate mesopic multipliers for streets with a speed limit of 25 mph or less. Given the posted speed limit of 45 mph, only photopic quantities—rather than mesopic or scotopic—are applicable to roadway lighting on the bridge. Similarly, whereas improved uniformity can give LED products a competitive edge in parking lot applications (which use *minimum* illuminance as the criterion), improved uniformity is not necessarily of any benefit in roadway applications (which use *average* illuminance as the criterion). Hence, barring an improved utilization factor (percentage of luminaire output delivered to the roadway), LED luminaires must produce maintained output comparable to HPS. Assuming LED and induction luminaires would feature a service life greatly exceeding HPS, their LLDs and LDDs must likely be lower (harsher) than for HPS. Given the desire for energy savings, products drawing no more than 315 W of input power are targeted for this analysis.[6]

If no commercially-available LED or induction luminaire can be found which produces illumination equivalent to HPS in terms of quality and quantity, it is doubtful any commercially-available LED or induction retrofit kit would prove adequate, either. Luminaire manufacturers have the ability to integrate electrical, thermal, and optical components for optimal system performance. By contrast, commercially-available retrofit kits are generally designed for installation in a variety of housings, and thus are not optimized for any given housing. However, it may be possible to develop a custom retrofit kit which approaches or exceeds the performance of commercially-available luminaires in this particular application.

[6] HPS lamp voltage and ballast input wattage vary with time but are expected to remain within ANSI tolerances (ANSLG 2009).

4.0 Shoebox Performance—Induction

Induction luminaire manufacturers were considered on the basis of IES-format photometric files being available for download from their websites (IES 2002).[1] In addition, manufacturers with products eligible for incentives from BC Hydro as replacements for 250 W HPS luminaires were asked to provide this data if it was not available online.[2] It was determined that some files by some manufacturers were identical to files by other manufacturers; in such cases only data by the manufacturer publishing more data online was used in the analysis. No verification testing of product samples was performed as part of this analysis.

Normalization of the IES files required an understanding of the lamps and ballasts used in each luminaire.[3] Whereas cutsheets for luminaires utilizing QL or Sylvania lamps usually made this clear, cutsheets for other products generally did not specify the manufacturer of the lamp-ballast system. Table 4.0 provides an overview of lamp wattages and shapes considered. The Fulham lamp-ballast product line bears a striking resemblance to product lines offered by Global, Think, and others; however, performance claims vary between these manufacturers.

Table 4.0. Common induction lamp wattages

Manufacturer (Min. CCT)	Shape/format		
	Arbitrary/Globe	Circle	Rectangle
Fulham* (2700 K)	35, 55, 85, 100, 120, 165, 200, 250	40, 70, 80, 100, 120, 150, 200, 250, 300, 400	40, 70, 80, 100, 120, 150, 200, 250, 300, 400
QL** (2700 K)	55, 85, 165	n/a	n/a
Sylvania* (3500 K)	n/a	40	40, 70, 100, 150
* Values shown exclude ballast losses. ** Values shown are nominal—actual values are a function of nominal line voltage.			

DSS output is a particularly useful metric for induction luminaires in this application since, due to lamp-reflector proximity, it is difficult to control the spatial distribution of light without incurring undesirable losses.[4] Table 4.1 shows that of the induction luminaires considered, none appear likely to match initial HPS illumination while also providing energy savings. Of these manufacturers, only Kim and Visionaire offered IES files for distributions being asymmetric front-to-back at these wattages. The Deco luminaire incorporates two 150 W lamps. Although 1st Source does not offer IES files on their website, products by the company were already under consideration by GGB before PNNL became involved in the project, and IES files were provided upon request.

[1] IES-format files are required to calculate uniformity and veiling luminance ratios, etc. Although some manufacturers may claim otherwise, such data is not proprietary in nature.
[2] The website www.bchydro.com/ecatalog was accessed 2012-01-13.
[3] IES files for induction luminaires are usually based on relative photometry, allowing adjustment of rated lamp lumens when using lighting software. The IES does not offer a recommended test method for induction luminaires.
[4] Downward street-side lumens are calculated by summing lumens in LCS zones FL, FM, FH, and FVH.

Table 4.1. Initial luminaire performance characteristics excluding amber lens

Product (Lamp)	Lamp output (lm)	Luminaire output (lm)	DSS output (lm)	Input power (W)	DSS efficacy (lm/W)
Shoebox (HPS) without amber lens	28890	20493	12139	314	39
GE Lighting Solutions (Sylvania) MSCL-15T-4E21-GSC2	12000	10536	5237	156	34
Hubbell Kim (QL) 1A-AR3-165-IF-277	12000	5886	3828	165	23
Visionaire (QL) AME-2-I-T3-165G-IND-3K-4	12000	7015	4476	165	27
Philips Wide-Lite (QL) EALQL-165-5V-277	12000	8364	4188	165	25
Neptun 37250	20000	16717	7420	250	30
Everlast ESB-EC-250W-120-4000K	21000	14132	7056	265	27
1st Source (Sylvania) UISB-IT-2-150-150-35K-M4-2	24000	17130	8568	312	27
Deco (Sylvania) D828i-300-35-277	24000	15471	7728	312	25

Induction lamp-ballast systems are generally rated for 100,000 hours of service life, but published lumen maintenance data indicates 60,000 hours (60% of rated life) may be a better estimate for design purposes:

- QL only publishes LLD to 60,000 hours (78% LLD at that point)
- Sylvania, Fulham, and Think are rated for 70% LLD at 60,000 hours
- Documentation provided by Everlast indicates 78% LLD at 60,000 hours.

Assuming cleaning accompanies the replacement of components, LDD is estimated at 85%. For simplicity, luminous transmittance is somewhat liberally estimated at 91% regardless of CCT.

Table 4.2 shows that the higher luminous transmittance, LLD and LDD values for HPS only broaden the expected performance gap. Red text indicates values which miss the mark by more than 10%. Horizontal illuminance on the roadway is less than half the target for all luminaires, and uniformity is substantially worsened. The reduced disability glare is directly attributable to light being effectively contained to the areas around poles, leaving intermediate areas relatively dark. Consequently, it is deemed highly unlikely an induction retrofit kit could be developed which could maintain HPS illumination levels while also providing energy savings.

Table 4.2. Maintained illumination including luminous transmittance of amber lens

Test	Drivelanes			Sidewalk		
	Avg horiz illum (fc)	Avg:Min uniformity	Max veiling lum ratio	Avg horiz illum (fc)	Avg:Min uniformity	Min vert illum (fc)
Target	≥ 1.4	≤ 3.0	≤ 0.60	≥ 1.4	≤ 6.0	≥ 0.02
GE Lighting Solutions (Sylvania) MSCL-15T-4E21-GSC2	0.4	9.5	0.41	0.9	15.8	0.01
Hubbell Kim 1A-AR3-165-IF-277	0.4	10.3	0.28	0.4	13.8	0.00
Visionaire AME-2-I-T3-165G-IND-3K-4	0.4	6.6	0.41	0.5	11.3	0.01
Philips Wide-Lite EALQL-165-5V-277	0.4	6.6	0.33	0.6	11.2	0.01
Neptun 37250	0.6	7.9	0.36	1.4	16.8	0.02
Everlast ESB-EC-250W-120-4000K	0.6	6.3	0.44	1.2	12.6	0.02
1st Source UISB-IT-2-150-150-35K-M4-2	0.6	8.6	0.32	1.5	20.2	0.01
Deco D828i-300-35-277	0.6	6.5	0.44	1.2	13.0	0.03

5.0 Shoebox Performance—LED

Given the low sensitivity of its luminous transmittance to the SPD of the light source, preliminary screening of LED shoebox alternatives was performed without consideration of the amber lens. Candidate luminaire manufacturers were identified by searching the following product listings:

- LED Lighting Facts products listed under the "outdoor area/roadway" fixture type [1]
- DesignLights Consortium (DLC) Qualified Products List (QPL) "outdoor pole/arm-mounted" categories.[2]

Table 5.0 lists a number of manufacturers offering LED luminaires which—in this application—produce illumination comparable to HPS while requiring less input power.[3] In an attempt to normalize the data, only luminaires featuring a nominal CCT below 5000 K (without amber lens) were considered, as the amber lens would be expected to decrease such CCTs to 3500 K or lower.

Table 5.0. Initial luminaire performance characteristics excluding amber lens

Product	CCT (K)	DSS output (lm)	Input power (W)	DSS efficacy (lm/W)
Shoebox (HPS) without amber lens	-	12139	314	39
Acuity Lithonia CSX2LED4-30B700-40K-SR3	4000	17393	294	59
Cooper McGraw-Edison VTS-C11-LED-E1-T3-7040	4000	13733	279	49
Cree BetaLED ARE-EDG-3M-16-D-UL-525-43K	4300	12207	256	48
GE Lighting Solutions ERS4-0-TX-CX-5-40	4000	15169	258	59
Leotek GC2-120E-MV-NW-3-GY-700	4300	12085	271	45
Philips Gardco RL-1-4V3-260LA-NW-UNIV	4000	14085	258	55
Philips Hadco RX2160-X-3-N-A-5-X-X-N	4000	12791	278	46
Philips Roadway RVM-270W160LED4K-LE3-277	4100	14255	271	53
Philips Wide-Lite ASA-128G1-700-NW-2L0-120	4125	16243	277	59

[1] Accessed www.lightingfacts.com on 2012-04-24.
[2] Accessed http://designlights.org on 2012-04-24.
[3] Visionaire was in the process of updating their product and photometry at the time this report was published.

Of these manufacturers only Hadco published lumen output for a nominal CCT at or below 3000 K, indicating efficacy at 3000 K is 75% of the efficacy at 4000 K for this particular configuration (data for others is provided in Appendix I). The other manufacturers were asked whether CCTs at or below 3000 K were available (if this was not already indicated on product cutsheets) and, if so, what multiplier should be applied to accurately adjust available data for higher CCTs. Claimed multipliers varied widely among manufacturers, ranging from 63 to 85% of efficacy at the higher CCT, but were roughly centered around the Hadco multiplier. Lower values are reportedly due in part to the use of warm white LED packages designed for interior applications, where efficacy is compromised to some extent in the pursuit of higher CRI. Conversely, LED packages marketed as "outdoor white"—which usually target 4100 K—generally compromise CRI somewhat in order to increase efficacy. In other words, multipliers are generally lowest (greatest penalty) when CRI is higher at the lower CCT.

IES TM-21 (IES 2011b) offers two methods of determining LLD and LED lumen maintenance life: Either LLD is specified and extrapolation is used to determine LED lumen maintenance life, or LED lumen maintenance is specified and extrapolation is used to determine LLD. TM-21 also defines two different designations for characterization of LED lumen maintenance life, namely "Reported" or "Calculated" values, indicated in hours.[4] Whereas Reported values must not exceed six times the IES LM-80 (IES 2008b) test duration,[5] Calculated values are unrestricted and consequently may have little or no statistical basis.

IES HB-10 differs from TM-21 in its recommendation that LLD be no higher than 70% for LED products, based on the conservative assumption that these products will be allowed to operate until they have visibly diminished in output (IES 2011c). However, L_{70} values (hours of operation until output diminishes to 70% of initial) often greatly exceed the so-called "six times" limit prescribed by TM-21 for Reported lumen maintenance life. Thus, this approach effectively encourages manufacturers to emphasize the less substantiated Calculated values.

The TM-21 methodology allows for determination of unique LLD values for each LED product, rather than simply applying an assumed value of 70% to all products; this can potentially result in reduced LED quantity, product cost, and energy use. However, estimates based solely on LM-80 data are liberal when applied directly to luminaires, even when combined with In Situ Temperature Measurement Testing (ISTMT) data, since other unaccounted-for failure mechanisms may accelerate lumen depreciation (EPA 2010, NGLIA 2011).

For the purpose of this report, LED components are assumed to require replacement after approximately 50,000 hours of operation (over 12 years when operated 11 hours every night),[6] accompanied by cleaning of the luminaire for an LDD of 87%. Implicit in this assumption is that the LED light sources will also be replaced at this time, to reduce labor costs and to ensure compatibility with the new drivers. It seems unlikely that the LED light sources would be allowed to continue operating until they visibly diminish in output, given that the currently high initial cost of LEDs is expected to continue to decrease over time. By the time a driver or another component fails, LEDs will likely be replaced proactively—just as HPS lamps are often replaced when their ballasts fail.

[4] The term "Projected" is used interchangeably with the term "Calculated."
[5] Extrapolation is limited to 5.5 times the test duration if fewer than 20 samples are tested.
[6] The DLC currently requires an L_{70} of 50,000 hours for associated product categories ("Outdoor Pole/Arm-Mounted Area and Roadway Luminaires", and "Retrofit Kits for Outdoor Area and Roadway Luminaires").

TM-21 calculations were performed using the ENERGY STAR TM-21 spreadsheet tool,[7] based on nominal LED drive current, LM-80 reports, and ISTMT documentation provided by each manufacturer. For simplicity, ambient temperature effects were assumed negligible in terms of instantaneous and long-term performance. In addition, it was assumed that other variables such as bridge vibration will not compromise service life. Table 5.1 summarizes LLD values calculated per TM-21; following is a summary of adjustments and assumptions made while performing these calculations:

- Although LED Lighting Facts allows LM-80 drive current to differ by 5% from nominal (i.e., rated by luminaire manufacturer), for conservative calculation no such tolerance was used.[8]
- The ENERGY STAR calculator does not report values if one of the LM-80 lumen maintenance curves (at a given T_s and drive current) has positive slope; in such scenarios only the curve with negative slope was used.
- Time points within 50 hours (1% of 5,000 hours) of the last LM-80 measurement were adjusted slightly as needed to be considered by the ENERGY STAR calculator; for example, if the last measurement was after 6,048 hours of operation and a prior measurement had been performed after 1,008 hours of operation, these values were changed to 6,028 and 1,028 respectively.
- The LM-80 reports for the BetaLED and GE Lighting Solutions products included 6,048 hours of test data for 25 samples, with additional data to 10,080 hours of operation for 20 of these samples. The five samples not included in the 10,080 hour set were among the lowest six in terms of lumen maintenance at 6,048 hours. Values shown are based on the 20 samples operated 10,080 hours, yielding LLDs approximately 3-4% higher than LLDs based on 25 samples operated 6,048 hours.

[7] Available for download at www.energystar.gov/TM-21calculator.
[8] From the LED Lighting Facts Partner Participation Manual, Version 3.1, available at www.lightingfacts.com.

Table 5.1. Lamp lumen depreciation (LLD) estimates

Product	Nominal LED drive current (mA)	T_S from ISTMT (°C)	LLD at 36,000 h	LLD at 50,000 h *	Reported L_{80} (h)
Acuity Lithonia CSX2LED4-30B700-40K-SR3	700	83.0	0.95	0.93	> 60,000
Cooper McGraw-Edison VTS-C11-LED-E1-T3-7040	1000	76.0	0.99	0.97	> 54,000
Cree BetaLED ARE-EDG-3M-16-D-UL-525-43K	525	73.9	0.96	0.94	> 60,000
GE Lighting Solutions ERS4-0-TX-CX-5-40	525	74.0	0.96	0.94	> 60,000
Leotek GC2-120E-MV-NW-3-GY-700	700	72.2	0.72	(0.65)	25,000
Philips Gardco RL-1-4V3-260LA-NW-UNIV	530	66.0	0.91	(0.87)	> 36,000
Philips Hadco RX2160-X-3-N-A-5-X-X-N	530	74.6	0.91	(0.88)	>36,000
Philips Roadway RVM-270W160LED4K-LE3-277	530	88.4	0.85	0.80	50,000
Philips Wide-Lite ASA-128G1-700-NW-2L0-120	700	88.5	0.86	(0.80)	>42,000
* LLD values at 50,000 h are shown in parentheses if the extrapolation exceeds TM-21 limits for Reported values.					

The available data and calculation methods indicate most of these integrated luminaires will exhibit excellent lumen maintenance, with all but Leotek ranging from 85% to 99% of initial output after 36,000 hours of operation. This duration corresponds to 9 years of service when operated 11 hours every night, and also serves as the Reported extrapolation limit for some of the luminaires considered. Predicted and actual lumen maintenance can be expected to vary from luminaire to luminaire depending on product design. However, for the purpose of this report, a single LLD of 0.80 was artificially applied to all LED luminaires considered to simply strike a balance between the 0.70 LLD recommended in IES HB-10 and the generally higher LLDs calculated using IES TM-21. This value also roughly corresponds to the lowest estimated LLDs at 50,000 hours (excluding Leotek). Table 5.2 compares performance against the target criteria in this scenario, assuming 88% luminous transmittance for nominally 4000-4300 K LEDs. Red text indicates values which miss the mark by more than 10%.

Table 5.2. Maintained illumination including luminous transmittance of amber lens

Product	Drivelanes			Sidewalk		
	Avg horiz illum (fc)	Avg:Min uniformity	Max veiling lum ratio	Avg horiz illum (fc)	Avg:Min uniformity	Min vert illum (fc)
Target	≥ 1.4	≤ 3.0	≤ 0.60	≥ 1.4	≤ 6.0	≥ 0.02
Acuity-Lithonia CSX2LED4-30B700-40K-SR3	1.8	2.6	0.63	1.3	4.3	0.07
Cooper McGraw-Edison VTS-C11-LED-E1-T3-7040	1.4	2.1	0.57	1.5	2.6	0.06
Cree-BetaLED ARE-EDG-3M-16-D-UL-525-43K	1.3	3.3	0.40	1.1	3.6	0.05
GE Lighting Solutions ERS4-0-TX-CX-5-40	1.5	4.0	0.43	1.8	5.2	0.01
Philips-Gardco RL-1-4V3-260LA-NW-UNIV	1.4	4.9	0.55	1.5	6.3	0.01
Philips-Hadco RX2160-X-3-N-A-5-X-X-N	1.2	3.1	0.48	1.8	6.0	0.01
Philips Roadway RVM-270W160LED4K-LE3-277	1.4	2.9	0.42	1.9	6.0	0.02
Philips Wide-Lite ASA-128G1-700-NW-2L0-120	1.6	7.5	0.80	1.8	4.4	0.01

Several of the luminaires appear to satisfy or nearly satisfy all of the photometric targets; others might prove adequate depending on finalized GGB criteria and the planned maintenance program. Some of these manufacturers have expressed interest in developing a custom retrofit kit, but would require additional information and coordination before committing to the project. These results suggest it may be technically feasible to develop an LED retrofit kit which saves energy while matching HPS light levels.

Another item not yet considered is the thermal management limitations imposed by the existing HPS shoebox housings, which—unlike many LED luminaire housings—are neither ventilated nor finned for passive heat dissipation. The existing shoebox housing weighs approximately 85 pounds (excluding remote ballast) and measures approximately 26" wide by 39" long by 12" tall (excluding the protruding amber lens).[9] By comparison, the Lithonia LED luminaire shown in Figure 5.0 is rated to weigh 59 pounds (driver included) and measure less than 19" wide by 36" long by 6" tall. The larger form factor of the existing housing suggests it could enable adequate heat dissipation, depending on its material content and thermal characteristics.

[9] The weight of internal components which would be removed during a retrofit has not yet been determined.

Figure 5.0. Lithonia LED luminaire without visible heat fins

Once it is confirmed a given retrofit kit—presumably somewhat smaller than a complete luminaire—would physically fit in the existing housing, the following tests should be performed with the product installed in the existing housing (in situ) and enclosed by the amber lens:

- IES LM-79, to verify initial performance parameters such as lumen output, input power, color characteristics, and spatial distribution of light (IES 2008a).
- ISTMT, to enable estimation of long-term performance by capturing actual LED operating temperature.

This methodology is used by the DLC to ensure retrofit kit performance is not overstated by manufacturers, as described in Appendix H. Perhaps due to such thermal management limitations, only two retrofit kits on the DLC QPL were listed for more than 12,000 lm of total output.

- A 4500 K product offered by Noribachi (Qnuru) was listed at 16,400 lm and 250 W.
- A 4900 K retrofit kit offered by Xeralux was listed at 12,300 lm and 168 W.

No photometry or cutsheet was available on the Noribachi website, but an LM-79 report and IES file were provided upon request. This product was only offered in an axially symmetric (Type VS) distribution, which would broadcast excessive illumination behind the luminaire, yielding an initial DSS efficacy of just 33 lm/W (comparable to the induction luminaires). Uniformity would also be poor.

Xeralux was one of a handful of LED manufacturers already under consideration by GGB prior to DOE involvement in the project. Photometry was available online, and according to the cutsheet the DLC-approved product was the highest-output version offered. In addition to data for this standard product (intended for broad application), Xeralux provided PNNL with photometry for a custom LED module which had been designed specifically for the bridge. Although both products were tested in shoebox housings to roughly capture thermal effects, they have not yet been tested in one of the existing housings with amber lens. Table 5.3 summarizes lumen maintenance characteristics of the 4000 K version of the standard DLC-listed product, and Table 5.4 gives an estimate of maintained light levels, again applying 0.80 LLD (consistent with the LED luminaires). Red text indicates values which miss the mark by more than 10%.

Table 5.3. Lamp lumen depreciation (LLD) estimate for 4000 K version of standard Xeralux kit

Product	Nominal LED drive current (mA)	T_s from ISTMT (°C)	LLD at 36,000 h	LLD at 50,000 h *	Reported L_{80} (h)
Xeralux XLE-L2S-418-40P7	700	64.8	92	(90)	> 36,000
* LLD values at 50,000 h are shown in parentheses if the extrapolation exceeds TM-21 limits for Reported values (provided in the next column).					

Table 5.4. Maintained illumination including luminous transmittance of amber lens

Product	Drivelanes			Sidewalk		
	Avg horiz illum (fc)	Avg:Min uniformity	Max veiling lum ratio	Avg horiz illum (fc)	Avg:Min uniformity	Min vert illum (fc)
Target	≥ 1.4	≤ 3.0	≤ 0.60	≥ 1.4	≤ 6.0	≥ 0.02
Xeralux XLE-L2S-418-40P7	0.8	5.1	0.51	1.3	12.2	0.00

The standard Xeralux retrofit kit would fall well short of the target light levels while also compromising uniformity. Table 5.5 summarizes the anticipated effect of the amber lens on color characteristics for the module developed by Xeralux specifically for the bridge. This product was designed to eliminate any greenish hue, and the results suggest careful mixing of differently-colored LEDs can indeed improve Duv in this manner. In addition, Q_{GG} would be compromised but still acceptable. However, Xeralux estimates the existing shoebox housings could accommodate no more than four of the 40.5 W modules. Consequently, initial illuminance would be reduced by at least 38% relative to the already inadequate standard retrofit kit, greatly outweighing any improvement in luminous transmittance of the amber lens. LM-80 data was not available for the differently-colored LEDs used in the mix.

Table 5.5. Effect of amber lens on color characteristics for custom Xeralux module

Product	Lens	CCT (K)	Duv	CRI	R_9	R_{GG}	Q_{GG}
Xeralux	Neutral	1819	-0.002	70	-7	44	82
	Amber	1730	0.005	67	-15	38	46

Although no suitable commercially-available LED product was identified, it appears feasible to develop an LED retrofit kit which would save energy while maintaining HPS light levels. However, the following issues will present challenges for manufacturers of custom retrofit kits and will require substantial coordination with the GGB project team:

- A carefully selected mixture of differently-colored LEDs may be required to avoid a greenish hue when operated behind the amber lens
- Since different types of LEDs may degrade at different rates, products incorporating more than one type of LED may require specialized electronics to prevent color shift over time

- Retrofit kits must be tested in situ (in the existing shoebox housing) to capture thermal effects on photometry, colorimetry, and ISTMT
- Retrofit kits must be securely mounted in the existing housing and demonstrate adequate resistance to vibration
- The added weight of retrofit kits must be determined and approved by GGB to ensure the existing poles are not overloaded.

6.0 Shoebox Performance—Other Technologies

In addition to LED and induction, two high-intensity discharge (HID) light source technologies also merit discussion due to their compactness (enabling optical control) and high lamp-ballast efficacies:

- Next-generation ceramic metal halide (CMH) lamps optimized for use with electronic ballasts, often referred to as eHID. A number of major manufacturers offer eHID lamp-ballast systems, e.g., the Philips Elite product family, which is offered in CCTs of 3000 or 4200 K at lamp wattages of 210 and 315 W.[1]
- An electrodeless HID technology commonly denoted plasma. Luxim and Topanga are the only known manufacturers of plasma lamp-ballast systems.[2] As of May 2012, Luxim did not offer a nominal CCT below 5200 K, and although Topanga offered 4000 K this light source was not yet offered in any commercially available roadway luminaire.

Table 6.0 below summarizes performance for commercially available luminaires incorporating a 210 W Elite lamp, which features luminaire input power of 227 W—lower than any of the LED products considered. Red text indicates values which miss the mark by more than 10%. Ballast input power is rated at 341 W for the higher output version of the lamp and thus would not represent an energy saving alternative to the existing HPS lamp-ballast system, which was measured at 317 W. Assuming that—as with HPS—lamps would fail at 50% of rated life, LLD is estimated at 85% after 14,000 hours of operation (just over three years) and LDD is estimated at 90%. At 3000 K, luminous transmittance of the amber lens would be approximately 90%.

Table 6.0. Maintained illumination including luminous transmittance of amber lens

Product	Drivelanes			Sidewalk		
	Avg horiz illum (fc)	Avg:Min uniformity	Max veiling lum ratio	Avg horiz illum (fc)	Avg:Min uniformity	Min vert illum (fc)
Target	≥ 1.4	≤ 3.0	≤ 0.60	≥ 1.4	≤ 6.0	≥ 0.02
Acuity-AEL * 125-21-MC-ELBD-277-R2-FG	1.1	3.0	0.61	1.9	7.1	0.01
Hubbell-Kim 1SA-WP9LE3-210CMH-277	1.5	2.8	0.39	1.4	3.6	0.01
Philips-Gardco EH19-1-3-210MCE-3K-QUAD	1.1	2.7	0.47	1.4	7.5	0.01
Philips Wide-Lite OPP-210-A-277E-Sx	0.8	3.3	0.41	0.4	2.3	0.02
* A 315 W IES file was scaled by PNNL to approximate 210 W performance.						

Although the expected service life would not be appreciably greater than the existing HPS, the rated performance of the Elite lamp in the Kim luminaire suggests this configuration (not yet catalogued)

[1] For reference, the City of Chicago began installing luminaires utilizing the Elite and related Cosmopolis lamp-ballast systems in late 2011.
[2] The terms "plasma" and "solid-state" are used in marketing material by both companies. Note that "plasma" is actually applicable to any gas-discharge source (such as fluorescent), and "solid-state" is actually applicable to any electronic ballast.

merits consideration; Kim has expressed interest in developing a custom induction retrofit kit for this project. However, similar to white LED and induction, the amber lens may render CMH lamps somewhat greenish in appearance by increasing Duv outside ANSI tolerances; Table 6.1 summarizes color characteristics based on data provided by Philips.

Table 6.1. Effect of amber lens on color characteristics for CMH

Product	Lens	CCT (K)	Duv	CRI	R_9	R_{GG}	Q_{GG}
Philips MasterColor CDM-T Elite 210W/930	neutral	2911	-0.004	92	74	99	98
	amber	2471	0.012	89	47	85	78

7.0 Cobrahead Alternatives

The first 10 cobraheads south of the bridge are evenly spaced at approximately 160' along the road, and the cross-section here is essentially identical to the center of the bridge, with a span of approximately 88' between poles. By contrast, heading south from this 2x5 array of poles the roadway rapidly widens to 14 lanes—a span of approximately 213' between poles—and pole spacing along either side of the road is reduced to as little as 80' in places, as shown in Figure 7.0. These six luminaires just north of the tollbooths, which would merit different treatment in terms of criteria for spatial distribution of light, are considered outside the scope of this analysis since they do not cast light on any of the specially painted bridge surfaces. Luminaires are approximately 35'-6" above pavement on mast arms 6' to 8' in length; input power is rated at 305 W (less than for the shoeboxes) and wiring is 277 V.

Figure 7.0. Cobraheads just north of the tollbooths (Photo credit: Google)

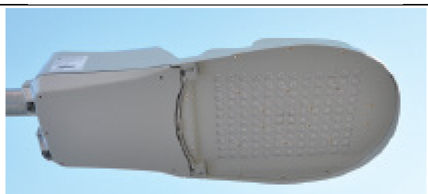
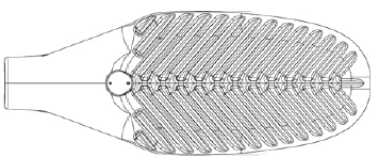
Table 7.0 summarizes estimated maintained performance for the HPS cobraheads, using an IES file obtained from the manufacturer website and the measured output of the lamp sample which was used to test the shoebox. No amber lens is used for these luminaires; LLD and LDD are assumed equal to the shoebox values. Unfortunately, uplight cannot be evaluated since the manufacturer did not measure intensity at angles above horizontal.

Table 7.0. Estimated maintained illumination produced by existing HPS cobraheads

Product	Drivelanes			Sidewalk		
	Avg horiz illum (fc)	Avg:Min uniformity	Max veiling lum ratio	Avg horiz illum (fc)	Avg:Min uniformity	Min vert illum (fc)
GE Lighting Solutions M2AR-25S-0A1-GMS2-2	2.0	1.6	0.33	1.6	2.2	0.25

Note that illumination appears to be better under the cobraheads than under the shoeboxes in every aspect but horizontal illuminance on the sidewalks, which is still comparable to the roadway illumination and adequate per IES. It is not clear whether this discrepancy is accidental (merely attributable to use of the same lamp in a more cost-effective luminaire) or deemed necessary for transitional lighting to and from the bridge. Consistent with section 4.7 of IES RP-8, it is assumed that transitional lighting is not necessary in this application; consequently, the less stringent shoebox criteria are considered adequate for cobrahead replacements. It is not clear whether historical status is strictly applicable to these luminaires; PNNL was directed by GGB to restrict the product search to those luminaires resembling HID cobraheads in terms of daytime appearance. Products were further filtered on the basis of availability in a nominal CCT below 3500 K, as shown in Table 7.1.

Table 7.1. HPS cobrahead alternatives

Manufacturer (light source)	Appearance	< 3500 K available?
Acuity-AEL (Philips Elite eHID)		✓ (3000 K)
Cooper-Lumark (LED)		✓ (3000 K)
Cree-BetaLED (LED)		
GE Lighting Solutions (LED)		
GE Lighting Solutions (QL induction)		✓ (2700 or 3000 K)
Leotek (LED)		
Philips-Hadco (LED)		✓ (3000 K)

Note that whereas the LED alternatives would produce no direct uplight, the existing HPS luminaires and the eHID and induction alternatives emit some light upward due to the protruding lens. Table 7.2 summarizes maintained performance for commercially available cobrahead-style luminaires utilizing induction, LED, and eHID light sources. Red text indicates values which miss the mark by more than 10%. The same LLD and LDD values were applied here as in preceding sections of this report.

Table 7.2. Estimated maintained illumination for HPS cobrahead alternatives

Product (source)	Drivelanes			Sidewalk		
	Avg horiz illum (fc)	Avg:Min uniformity	Max veiling lum ratio	Avg horiz illum (fc)	Avg:Min uniformity	Min vert illum (fc)
Target	≥ 1.4	≤ 3.0	≤ 0.60	≥ 1.4	≤ 6.0	≥ 0.02
Acuity-AEL 125-21-MC-ELBD-277-R2-DG (CMH 3000 K)	1.6	2.5	0.26	1.3	3.2	0.08
Cooper-Lumark* LDRL-T3S-B06-E-8030 (LED 3000 K)	1.1	2.0	0.22	0.6	1.8	0.03
GE Lighting Solutions MSRL-64Q-4EX1-RSS3 (induction 3000 K)	0.5	3.2	0.22	0.4	3.2	0.03
Philips-Hadco RX2160-X-3-W-A-5-X-X-N (LED 3000 K)	1.0	2.0	0.18	1.0	2.8	0.04
* IES file for 4000 K was scaled by 0.63 per manufacturer to approximate 3000 K performance.						

It is assumed that, given the relatively low initial cost of HPS cobraheads, complete luminaire replacements will be preferable to retrofit kits. Induction does not perform as well in this application due to the lower luminaire efficiency, and LED performance is greatly compromised by the criterion of less than 3500 K for nominal CCT.

Although the 227 W eHID product from Acuity-AEL may not represent a desirable long-term alternative to the existing HPS cobraheads due to the comparable expected life, this luminaire offers energy savings and a simple means of exploring the acceptability of ~3000 K light sources on the bridge. If this option is pursued, lamps should be seasoned in situ (operated in luminaires which are oriented as they will be installed) for 100 hours prior to visual evaluation. Given the high profile of the bridge and associated public scrutiny, bench-top or off-site seasoning would be preferable to on-site seasoning.

8.0 Experimenting with CCT

If the HPS floodlights and LPS post-tops were retrofitted to yield 3000 K output, this would enable retrofitting of the amber-lensed shoeboxes with 4200 K LED light sources. Higher efficacy would be achieved than for LEDs at 3000 K, and the amber lens would yield roughly 3200 K with minimal impact on lumen output. Further, the replacement of HPS and LPS with such warm-white broad spectrum sources would be expected to result in improved color rendition of the bridge paint. However, the acceptability of 3000 K illumination should be confirmed via careful mock-ups before committing to any large-scale retrofit project. In addition, it is likely that many off-the-shelf white light sources will yield some degree of greenish hue after being filtered by the amber lens; this could be resolved by tuning the SPD—possibly by mixing LEDs of different colors—or by replacing the existing lenses with a similar material which does not cause this green shift.

Assuming an efficiency of approximately 60-70% for the tower floodlights, the rated 51,000 lumens (51,000 lm) of the 400 W HPS lamps would translate to an initial luminaire output of roughly 30,000-36,000 lm for approximately 465 W of input power. This appears to be beyond the reach of commercially available floodlights and retrofit kits below 3500 K, regardless of the light source used—LED, induction, or eHID. However, a variety of HID alternatives merit consideration as direct replacements for the existing HPS lamps. By allowing the HPS ballast to remain, such products present an opportunity for relatively simple and inexpensive exploration of higher CCTs and the possible benefits of broad spectrum illumination—likely without any compromise to the spatial distribution of light.

It appears CMH replacements would be preferable to color-enhanced super HPS due to differences in lumen output and rated life, as shown in Table 8.0. Further, the greater maximum overall length (MOL) and light center length (LCL) may cause the super HPS lamp to be misaligned relative to the optical system or to simply not fit in the luminaire. The rated life of the CMH lamp is slightly lower than standard HPS, but it is not clear which would fare better in this reportedly high-vibration application. Possibly of greater significance is the reduction in lumen output relative to standard HPS, but this may be mitigated by the improved color rendition (CSJ 2010, CSJ 2011). Further, unlike illumination of the road and sidewalks, a slight reduction in tower illumination would be unlikely to pose a safety issue. If reduced output is then deemed acceptable, other lower-output HID or LED alternatives might be considered.

In any case, HID lamps should be allowed to operate in situ for 100 hours (10 days if operated 10 hours each day) to ensure they have stabilized before their color characteristics or light output are evaluated. Existing lamp orientation must also be determined to ensure compatibility of proposed alternatives; for example, a number of high-wattage CMH lamps are only rated for operation in a base-up (axis vertical) position. Lenses which have yellowed over time should also be replaced with newer lenses to allow for direct comparison of lamp CCTs.

Table 8.0. Comparison of standard HPS and alternative HID lamps for floodlights[1]

Parameter	GE # 85379 (standard HPS)	EYE # 67365 (super HPS)	GE # 93295 (CMH)	Philips # 130948 (CMH)
CCT (K)	2100	2500	3000 [2]	4000
CRI	22	85	80	80
Mean output (lm)	45,000	22,000	31,000	29,000
Life (h)	24,000+	9,000	20,000	20,000
Bulb shape	ED18	T15	ED18	ED18
MOL (in)	9.7500	11.1875	9.7500	9.7500
LCL (in)	5.7500	6.7188	5.7500	5.7500

It is doubtful any currently available lamp-ballast replacement could match the initial LPS lamp-ballast efficacy of over 140 lm/W. Assuming an efficiency of 50% and one 35 W LPS lamp rated 7800 lm per dual-lensed luminaire, initial post-top output is estimated at 3900 lm for approximately 54 W of input power. A custom LED or induction solution may merit consideration since, as with the floodlights, it may be determined that improved color rendition allows for some reduction in output. However, sidewalk illumination must be preserved. In addition, coordination with manufacturers would be required to address spatial restrictions and the thermal environment in the existing housings. Resistance to bridge vibration would also need to be reviewed.

[1] All lamps are universal-burn with clear envelope and mogul base. Comparable alternatives to these products may be offered by other manufacturers such as Sylvania, Venture, etc. Note that basis for calculation of mean lumens and lifetime can vary somewhat from manufacturer to manufacturer.

[2] The CCT of this CMH lamp is a function of operating position: 3000 K if lamp axis is oriented horizontally and 3600 K if vertical.

9.0 Conclusions

The historic status and high efficacy of the existing HPS and LPS luminaires present challenges for any energy-saving alternatives. In addition, the already-accepted color characteristics of these limited-spectrum light sources further limit the breadth and efficacy of suitable alternatives. Four luminaire types are currently used to illuminate the roadway, the two walkways, and the two towers; the CCTs of these luminaires range from approximately 1800 to 2100 K. By contrast, most white light alternatives (including LED, induction, and CMH) are offered in nominal CCTs of 2700 K or higher. Although the efficacy of other technologies is not strongly tied to CCT, the efficacy of pcLED products generally diminishes substantially at CCTs below 4000 K. All of the white light sources considered are expected to improve color rendition of the special bridge paint, but preliminary analysis suggests many of these sources may appear somewhat greenish in hue when installed in the amber-lensed shoebox luminaires.

Viability of the various technologies can be summarized as follows:

- Due to its relatively limited efficacy once integrated into luminaires, induction does not appear to be a viable alternative for the HPS shoeboxes, cobraheads, or floodlights. This technology may, however, merit consideration in the post-top LPS luminaires if sidewalk illumination is not overly compromised.
- LED technologies may merit consideration in the shoeboxes and the post-tops, offering approximately 6-18% energy savings for the former. Few luminaires resemble the daytime appearance of cobraheads, and efficacy at 3000 K is currently inferior to HPS. The substantial size and limited lumen packages of currently-available products further reduces the viability of LEDs as an alternative for the floodlights. However, LED may ultimately prove viable for all four luminaire types as technologies continue to improve.
- Although it would likely increase maintenance costs somewhat, CMH merits consideration as an energy-saving alternative for the cobraheads, and may also merit consideration for the shoeboxes—offering approximately 28% energy savings in either case. It also offers a relatively inexpensive means of evaluating higher CCT in the floodlights, and its improved color may demonstrate the acceptability of reduced tower illumination.

It is assumed that existing light levels must be preserved. A new analysis would need to be performed if the GGB ultimately determines reduced illumination would be acceptable. For example, if a product which reduces existing light levels by over 50% is deemed adequate, LED products matching this reduced illumination should be sought. This would enable the use of lower wattage products, thereby increasing energy savings and improving the feasibility of LED technology in this application.

It is similarly assumed that all four luminaire types should remain comparable in CCT, and that the allowable CCT range should remain centered at a fairly low value—probably no higher than 3000 K. CCT should be supplemented by other metrics (e.g., Duv and Q_{GG}) since it does not capture all color characteristics. Although the various metrics and criteria can help in preliminary product screening and selection, it is well established that lighting systems cannot be truly optimized using numerical methods alone. Final product selection should be preceded by physical mock-ups, as there is no substitute for visual evaluation. In addition, given that color preference is highly subjective and varies from individual to individual, all key stakeholders should be given an opportunity to voice opinions.

Based on the findings of this preliminary analysis, it is suggested that GGB begin with relatively straightforward and inexpensive replacements of HPS lamps and luminaires to explore the acceptability of CCTs higher than currently used on the bridge. The goal of these mock-ups is not to verify a color match with the remaining 1800 to 2100 K luminaires on the bridge, but rather to ascertain whether the bridge paint would retain an acceptably warm appearance if all four luminaire types were changed to approximately 3000 K. The following approaches balance associated costs and benefits:

1. Merely relamp all six floodlights up-lighting one side of a tower (as indicated in Figure 9.0) with the 3000 K CMH lamp from GE identified in Table 8.0. This retrofit would be relatively inexpensive but very high profile. Note that the remaining LPS post-tops at the base of the tower will be expected to visibly differ in color during this temporary evaluation.
2. Completely replace most or all of the 10 cobraheads at the south end of the bridge with the 3000 K CMH luminaire from Acuity-AEL identified in Table 7.2. This retrofit would be somewhat more costly but relatively low profile in comparison with the floodlights.

Figure 9.0. One of four possible sets of six floodlights to relamp with CMH (adapted from Google photography)

These mock-ups would either result in approval or rejection of 3000 K as the new target CCT for the four luminaire types. If 3000 K is not deemed acceptable, it is unlikely that LED products of 4000 to 4300 K—approximately 3100 to 3300 K after filtering through the amber lens—would be appropriate for the shoeboxes. In this possible scenario, it might eventually be determined that light sources installed in the shoeboxes can be no higher than perhaps 2700 K; the CCT produced after filtering by the amber lens would then be at or below approximately 2400 K—quite close to the current range of 1800 to 2100 K. This would effectively preclude the use of currently available LED products, since their efficacy is significantly diminished at CCTs below 4000 K. A restriction of 2700 K would also limit options for other technologies; for example, the Philips CDM product is not currently offered in a nominal CCT below 3000 K.

If instead 3000 K is accepted (or even preferred), retrofit kits for the shoeboxes and post-top luminaires might be developed to produce a cohesive appearance across all four luminaire types. Although it may seem obvious, it bears mentioning that it would not be difficult to produce retrofit kits which reduce input power while also reducing light output; this could be achieved most cost-effectively by simply replacing existing lamp-ballast systems with lower-wattage versions (i.e., still HPS or LPS).

This illustrates the importance of developing a set of specifications to guide manufacturers and to enable apples-to-apples comparison of alternatives.

A model specification was recently developed by the DOE Municipal Solid-State Street Lighting Consortium to serve as a template, and PNNL could assist the GGB in tailoring this document to meet the particular needs of this project.[1] Items which should be addressed in a specification and coordinated with manufacturers include:

- Photometric and colorimetric criteria such as those utilized in this assessment. Retrofit kits should be tested (LM-79 and ISTMT) in an existing amber-lensed shoebox to accurately capture thermal effects, spectral effects, and the impact on spatial distribution of light.
- Warranty requirements and criteria for maintained performance over time.
- Criteria for electrical immunity and interference.
- Criteria for testing to demonstrate resistance to bridge vibration.
- Criteria for resistance to the elements in this coastal environment.
- The loading capacity of the poles—the weight of existing components to be removed and the weight of retrofit kits must both be ascertained.
- Precise space constraints and other mechanical compatibility considerations.

The GGB will need to determine whether an open RFP should be issued using such a specification, or if it would be preferable to instead begin by coordinating with a small set of preferred manufacturers such as those identified in this assessment. Following is a summary of the manufacturers not already in contact with GGB which—based on the screening process implemented for this assessment—currently appear best suited to developing retrofit kits for the amber-lensed shoeboxes or complete replacements for the cobraheads:

- Acuity-AEL, www.americanelectriclighting.com (CMH cobrahead)
- Acuity-Lithonia, www.lithonia.com (LED shoebox)
- Cooper-McGraw, www.cooperindustries.com/content/public/en/lighting/brands/mcgraw-edison.html (LED shoebox)
- Cree-BetaLED, www.betaled.com (LED shoebox)
- Hubbell-Kim, www.kimlighting.com, (CMH shoebox)
- Philips Roadway, www.usa.lighting.philips.com/us_en/subsites/roadway (LED shoebox).

Of the luminaire manufacturers listed above for shoebox alternatives, none are accustomed to developing custom retrofit kits, but indicated interest due to the unusually high profile of this project. This interest may diminish as more information is gleaned through coordination with GGB staff, and in time these and other manufacturers will likely develop products superior to those evaluated in this assessment. For these reasons, the manufacturers identified in this assessment are merely offered for reference—providing a realistic sense of current technological capabilities—and as a suggested starting point.

Although no suitable commercially-available LED product was identified, it appears feasible to develop an LED retrofit kit which would save energy while maintaining HPS light levels. However, the

[1] The model specification can be downloaded at www.ssl.energy.gov/specification.html. Of the two versions posted online, the "System" version is recommended to more directly address illuminance levels, uniformity, etc.

following issues will present challenges for manufacturers of custom retrofit kits and will require substantial coordination with the GGB project team:

- A carefully selected mixture of differently-colored LEDs may be required to avoid a greenish hue when operated behind the amber lens
- Since different types of LEDs may degrade at different rates, products incorporating more than one type of LED may require specialized electronics to prevent color shift over time
- Retrofit kits must be tested in situ (in the existing shoebox housing) to capture thermal effects on photometry, colorimetry, and ISTMT
- Retrofit kits must be securely mounted in the existing housing and demonstrate adequate resistance to vibration
- The added weight of retrofit kits must be determined and approved by GGB to ensure the existing poles are not overloaded.

There does not yet appear to be a simple means of reducing energy use and maintenance while preserving the quality and quantity of illumination for this historic landmark. Although LED technologies are expected to become increasingly viable over time, and product mock-ups may reveal near-term solutions, some options not currently considered by GGB may ultimately merit evaluation. For example, it would be preferable in terms of performance to simply replace existing luminaires (some of which may already be nearing end of life) with fully-integrated LED or CMH luminaires rather than replacing internal components. Among other benefits, this would allow reputable manufacturers to offer standard warranties for their products. Similarly, the amber lenses might be reformulated such that they do not render white light sources in a greenish cast, thereby allowing the use of off-the-shelf LED or CMH products. It also bears repeating that the amber-lensed shoeboxes bear no resemblance to the LPS luminaires originally used to light the roadway.

10.0 References

ANSI 2011. ANSI C136 Committee. ANSI C136.37-2011, “American National Standard for Roadway and Area Lighting Equipment – Solid State Light Sources Used in Roadway and Area Lighting.” National Electrical Manufacturers Association, Rosslyn, VA.

ANSLG 2008. American National Standard Lighting Group. ANSI_NEMA_ANSLG C78.377-2008, “American National Standard for Electric Lamps – Specifications for the Chromaticity of Solid State Lighting (SSL) Products.” National Electrical Manufacturers Association, Rosslyn, VA.

ANSLG 2009. American National Standard Lighting Group. ANSI_ANSLG C78.42-2009, “American National Standard for Electric Lamps: High-Pressure Sodium Lamps.” National Electrical Manufacturers Association, Rosslyn, VA.

CIE 1995. CIE Division 1, Vision and Colour. CIE 13.3-1995, “Technical Report: Method of Measuring and Specifying Colour Rendering Properties of Light Sources.” International Commission on Illumination, Vienna, Austria.

CSJ 2010. Mutmansky, M., et al. “Advanced Street Lighting Technologies Assessment Project – City of San Jose.” San Jose, CA.

CSJ 2011. City of San Jose. “Public Streetlight Design Guide.” San Jose, CA.

DOE 2011. Bardsley Consulting, et al. “Solid-State Lighting Research and Development: Multi-Year Program Plan.” March 2011. Lighting Research and Development, Building Technologies Program, Office of Energy Efficiency & Renewable Energy. U.S. Department of Energy, Washington, D.C.

EPA 2010. ENERGY STAR Manufacturer’s Guide for Qualifying Solid State Lighting Luminaires – Version 2.1. April 2010. Office of Air and Radiation. U.S. Environmental Protection Agency, Washington, DC.

GGB 1935. Morrow, I.F. “Report on Color and Lighting for the Golden Gate Bridge, San Francisco.” Golden Gate Bridge Highway & Transportation District, San Francisco, CA.

IDOT 2002. Dunker, K.F. et al. “Report on Vibration Monitoring of Luminaires on the Burlington Cable-Stayed Bridge.” Iowa Department of Transportation, Ames, IA.

IES 1971. Van Dusen, H. A. Jr. “Maintenance and Adjustment Factors in Street Lighting Design Calculations.” Journal of the Illuminating Engineering Society, October 1971, p. 62. Illuminating Engineering Society of North America, New York, NY.

IES 1999. IESNA Testing Procedures Committee, Subcommittee on Photometry of Light Sources. IESNA LM-54-99, “IESNA Guide to Lamp Seasoning.” Illuminating Engineering Society of North America, New York, NY.

IES 2000. IESNA Roadway Lighting Committee, Standard Practice Subcommittee. ANSI / IESNA RP-8-00, “American National Standard Practice for Roadway Lighting.” Illuminating Engineering Society of North America, New York, NY.

IES 2002. IESNA Computer Committee, Subcommittee on Photometry. ANSI/IESNA LM-63-02, "IESNA Standard File Format for the Electronic Transfer of Photometric Data and Related Information." Illuminating Engineering Society of North America, New York, NY.

IES 2003. IESNA Roadway Lighting Committee, Subcommittee on Lighting Maintenance & Light Sources. IESNA DG-4-03, "Design Guide for Roadway Lighting Maintenance." Illuminating Engineering Society of North America, New York, NY.

IES 2008a. IES Testing Procedures Committee, Subcommittee on Solid-State Lighting. IES LM-79-08, "Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products." Illuminating Engineering Society of North America, New York, NY.

IES 2008b. IES Testing Procedures Committee, Subcommittee on Solid-State Lighting. IES LM-80-08, "IES Approved Method for Measuring Lumen Maintenance of LED Light Sources." Illuminating Engineering Society of North America, New York, NY.

IES 2011a. IES Luminaire Classification Task Group. IES TM-15-11, "Luminaire Classification System for Outdoor Luminaires." Illuminating Engineering Society of North America, New York, NY.

IES 2011b. IES Testing Procedures Committee, Subcommittee on Solid-State Lighting. IES TM-21-11, "Projecting Long Term Lumen Maintenance of LED Light Sources." Illuminating Engineering Society of North America, New York, NY.

IES 2011c. DiLaura et al. IES HB-10-11, "The Lighting Handbook, Tenth Edition, Reference and Application." Illuminating Engineering Society of North America, New York, NY.

NGLIA 2011. "LED Luminaire Lifetime: Recommendations for Testing and Reporting," Second Edition, June 2011. U.S. Department of Energy, Washington, D.C.

NIST 2010. Davis, W., and Ohno, Y. "Color quality scale." Optical Engineering, Vol. 49(3), 033602-1, March 2010.

Appendix A

Excerpts from the GGB Online Research Library

Golden Gate Bridge, Highway & Transportation District

Bridge Lighting

Consulting Architect, Irving F. Morrow, wrote *Report on Color and Lighting* to Chief Engineer, Joseph B. Strauss, on April 6, 1935. In his report, he indicated that the two most important factors in lighting the Golden Gate Bridge are: 1) the enormous size of the project; and, 2) the tremendous scale and dignity of the project. Morrow carefully weighed these considerations as he designed his lighting scheme, one which would even further accent the uniqueness of the Golden Gate Bridge.

Because of the Bridge's great size, Morrow did not want the same intensity of light on all of its parts. The effect would seem too artificial. The towers, for example, were to have less light at the top, so they would seem to soar beyond the range of illumination. further, because of the scale and dignity of the Bridge, Morrow believed tricky, flashy or spectacular lighting would be unworthy of the structure's magnificence. Thus, he selected low pressure sodium vapor lamps with a subtle amber glow for the roadway, providing warm, non-glare lighting for passing motorists. The lamps were the most modern available in 1937.

Forty-five years later in 1972, the original low pressure sodium roadway lights were replaced with high-pressure sodium vapor lamps. These modern lamps provide improved lighting at a lower cost. To preserve the original warm glow, the new lampheads have a plastic amber lens.

The tower lighting, as originally envisioned by Morrow, was not installed during the construction of the Bridge due to budgetary constraints. However, in 1987, shortly after the 50th Anniversary, the Bridge towers came to life with light on June 22, 1987. Just as Morrow had envisioned, the new lighting made the towers seem to disappear into the evening darkness, further accenting their great height. The tower lighting was installed at a cost of nearly $1.2 million, funded in part, through a generous grant from Pacific Gas & Electric Company. The lighting was installed by Abbett Electric Company, who under-bid the original construction estimates by nearly $1 million.

- **Main Cable Lights:** There are eight 116 watt lights on each of the two main cables.
- **Roadway Lights:** There are 128 lamp posts that line the roadway. In 1972, the original low pressure sodium (LPS) lighting (90 watts each) within the lamp posts were changed to high pressure sodium (HPS) lighting (227 volt and 250 watt each). *(See photo of original light below)*
- **Tower Sidewalk Lights:** There are 6 lights at the sidewalk level at each of the tower's two legs (shafts) making a total of 24 lights at the sidewalk level at the main towers. These are LPS lights, 35 watts each.
- **Tower Decorative Lighting:** These are HPS, 400 watt decorative floodlights; with 12 at the sidewalk level pointed upward on each tower. There are also 12 HPS lights below the roadway for each tower; four are 150 watts, four are 250 watts, and four are 400 watts.
- **Aircraft Beacons:** Installed in 1980, each tower now has a 360 degree flashing red aircraft beacon at the very top of the tower. Each beacon has two 750 watt lamps. Originally, the aircraft beacons had a single rotating red light; with a built-in "back-up" light.

Navigation Beacons: The San Francisco tower pier has one 1,000 watt beacon facing northward, with four 116 watt lights on the tower fender. The Marin tower pier has three 116 watt lights on three sides facing the water.

- **Midspan Navigation Lighting:** For seafaring vessels, there are eight lights that mark the center of the Bridge below the deck at midspan; four on each side in a vertical column. The top three lights are white, the bottom light green.

Original Lighting with the Roadway Lamp Post

Golden Gate Bridge, Highway & Transportation District

Why the International Orange Color?

The Short Story:
When the steel for the Golden Gate Bridge was fabricated by Bethlehem Steel at its foundries in PA and NJ, the steel was coated with a red lead primer. As the bridge towers began to rise for the Golden Gate Bridge, Consulting Architect Irving F. Morrow was commuting to the construction site from his home in the East Bay via ferry. He became inspired by the red lead color. Morrow undertook color studies, which resulted in the specification of the unique Golden Gate Bridge International Orange because it blended well with the nearby hills and contrasted with the ocean and sky.

Morrow recognized very clearly that the Bridge color was a very important influence on its appearance in relationship to its surroundings. As the Bridge stands today, the color blends perfectly with the changing season tints of the spans' natural setting against the San Francisco skyline and the Marin hills. Morrow concluded, "The effect of International Orange is as highly pleasing as it is unusual in the realm of engineering."

The color dubbed "International Orange" existed before the Bridge (and still exists) and is a color used in the aerospace industry to set things apart from their surroundings, similar to safety orange, but deeper and with a more reddish tone. You can see this, the "other" International Orange color here:
http://en.wikipedia.org/wiki/International_orange

The Longer Version:
The Golden Gate Bridge is painted Golden Gate Bridge International Orange which was selected by Consulting Architect Irving F. Morrow.

In his April 1935 *Report on Color and Lighting*, Morrow defined the approach to the color section, "Preliminary to discussion of particular colors, a decision must be made on a matter of policy – is it desired to emphasize the bridge as an important feature of the landscape, or to make it as inconspicuous as possible."

The final color was inspired by studies undertaken by Morrow in cooperation with other architects, engineers, painters, sculptors, and others. Morrow also included black, grey, and aluminum in the studies, ruling each out for a range of reasons. Black would be unattractive and would reduce the scale of the bridge more than any other color. Proponents for the aluminum color reported that this color would give beauty as the beauty of a dirigible aircraft. Morrow rejected it as the towers would be deprived of substance and made tiny. Battleship grey and warm grey were studied. Warm grey was named as the distant second to orange vermillion.

Italian American sculptor Beniamino Benvenuto Bufano submitted his comments to Morrow, " I have been watching very closely the progress of the towers on the Golden Gate Bridge in its structural beauty its engineering and architectural simplicity – and of course its color that moves and molds itself into the great beauty and contours of the hill – let me hope that the color will remain the red terracotta because it adds to the structural grace and because it adds to the great beauty and the colorful symphony of the hills—and it is because of this structural simplicity that carries to you my message of admiration."

Morrow envisioned that different bridge structures would be painted with slightly different tones of the International Orange. He stated that whatever the color chosen, several closely related tones should be used, according to the following general principle –

(a) Basic tone – towers throughout their height, except the diagonal bracing below deck.
(b) Slightly darker than (a) – diagonal tower bracing below deck, stiffening trusses, floor framing, arch over Fort Winfield Scott (Fort Point)
(c) Slightly darker than (b) – approach viaducts and cables
(d) Slightly darker than (c) or a contrasting color – hand rail and electroliers (lampposts)

Later in his report, these colors are defined as:
(a) Orange Vermillion or the color of shop red lead
(b) Orange Vermillion, slightly tinged with burnt sienna
(c) Burnt Sienna leaning toward orange vermillion
(d) Burnt Sienna

As far as we know, Morrow' suggested paint tone variations may have happened, but we do not know for certain. The only exterior areas of the bridge that would have been painted the darker colors have all been subsequently repainted International Orange. So, was it done? We can't be sure. We know that it does not happen today.

Color Formula

The Golden Gate Bridge International Orange color is mixed to our requirements. The Bridge has maintained our formula for GGB International Orange through the years. Our requirements are in no way proprietary, anyone can formulate and use the color – in fact we provide the color percentages on the website. What passes for International Orange is going to vary by manufacturer or standard of which there are many. When purchasing paint for the Golden Gate Bridge, it is done through a competitive bidding process. Currently, the paint is supplied by Sherwin Williams and is made to match the GGB International Orange color formula. For compliance purposes we use ASTM D 2244 – Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates.

When purchasing paint for the Golden Gate Bridge, it is done through a competitive bidding process. Currently, the paint is supplied by Sherwin Williams and is made to match the Bridge International Orange color formula. The closest off-the-shelf paint color that Sherwin Williams has available is "Fireweed" (color code SW 6328).

Many people ask about the formula for the Bridge's unique International Orange paint color. Paint stores can mix it with the following information:

CMYK colors are: C= Cyan: 0%, M =Magenta: 69%, Y =Yellow: 100%, K = Black: 6%.

The closest existing color codes to GGB International Orange color are:
PMS 173 (CYMK = 0%, 80%, 94%, 1%),

PMS 174 (CYMK 8%, 85%, 100%, 34%)
Pantone 180 (CYMK 19.4%, 77.9%, 79.6%, 3.6%)

Appendix B

Paint Sample Test Data

Avian Technologies LLC
Measurement # AT-20111222-1
8°/Hemispherical Reflectance Factor
Specular Component Excluded
for
Pacific Northwest National Laboratory

Avian TECHNOLOGIES LLC
Optical Spectroscopy
Materials, Coatings, & Standards

P.O. Box 716
Sunapee, NH
03782-0716

603.526.2420 (P)
603.526.2729 (F)
www.aviantechnologies.com

Customer Name: Pacific Northwest National Laboratory
Order no: PO 170940
Sample(s): Two (2) Paint Samples on Tile

Measurement Instrument: Perkin-Elmer Lambda-9/19 UV-Vis-NIR Spectrometer Ser. No. 1099, Reflectance Accessory Ser. No. 1991

Traceability of measurement to: ASTM Test Method E 1331-96, Test Method E903-96
NIST SRM 1920/SRM 2035/SRM 2036 (Wavelength Calibration Accuracy Standards)
NRC Certificate Cal PAR-2008-2614 (Holmium Oxide Filter)
NRC Certificate PA-2011-2879 (Diffuse Reflectance Standards) and/or
NRC Certificate PA-2011-2881 (Specular Reflectance Standard)

Measurement Conditions:
Mean Temperature: 23°C
Relative Humidity: 23%
Instrument Parameters:
Bandpass: 4 nm (UV-Vis)
NIR Sensitivity: 4
Recording Interval: 1.0 nm.
Scan Speed: 240 nm/min
Number of measurements averaged: 3

Procedure: The Total Hemispherical Reflectance measurements were performed on a Perkin-Elmer Lambda 9/19 UV-Vis-NIR Spectrophotometer. The instrument was set up in total hemispherical reflectance geometry (8°/t) using a Labsphere 150 mm integrating sphere accessory. The measurement beam is well collimated (maximum angle of convergence is ±4°). The reflectance factor measurements were relative to freshly packed PTFE (Dupont 7A) powder per ASTM Practice E259-98 and CIE 15.2 at ambient temperature (23° ±1°) and humidity (23±5%).

The measurement of the sample was performed at 1.0 nm. intervals over the wavelength 300-1100 nm. for 8°/hemispherical geometry, with the specular component excluded. A deuterium source (300-320 nm) and tungsten-halogen (320-2500 nm) were used in combination with a photomultiplier detector in the UV-Vis and a lead sulfide detector in the NIR.

Certified by: T.M. Ricker
T.M. Ricker

Date: 12/22/11
22 December 2011

Other Pertinent References:
ASTM Standard Practice E 275-93 "Standard Practice for Describing and Measuring Performance of UV, Vis, and NIR Spectrophotometers"
ASTM Standard Practice E 925-94 "Standard Practice for Periodic Calibration of Narrow Band-Pass Spectrophotometers"
CIE 15.2 Colorimetry

Avian Technologies LLC
General Statements of Measurement Uncertainty
Based on Perkin-Elmer Lambda-9/19 Spectrophotometers
and Byk-Gardner ColorView 45:0 Spectrophotometer

Wavelength Accuracy

Precision of measurement of < 0.2 nm from 250 to 850 nm is based on repeated measurement of a Corning holmium oxide filter (melt 3131). Accuracy, determined by comparison with a holmium oxide filter calibrated by the National Research Council, Canada, is ±0.2 nm over the same range. Uncertainty in the near-IR range has been calculated to be <±1.5 nm by repeated measurements of NIST SRM-1920a and the NRC calibrated holmium oxide filter in total hemispherical reflectance and normal transmittance mode.

Transmittance/Photometric Scale

Precision of measurement of <0.001A between 400-700 nm at 50% transmittance, <0.001A between 400-700 nm at 3% transmittance, and ≈0.002 between 400-700 nm has been determined by multiple readings of neutral density filter glasses (Starna Inc. Serial No. 5688). Accuracy in the visible range (400-700 nm) has been determined to be <±0.005A for a 50% filter, <±0.010A for a 3% filter, and <±0.010A for a 1% filter. Accuracy in the UV is better than ±0.005A for a nominal 10% transmissive filter. (NRC UV-Vis ND Filters, Certificate PAR2007-2532). Accuracy in the NIR and in the UV on filters over 2A has not been determined.

8°/Hemispherical Reflectance Factor

Precision of measurement was determined at 11 wavelengths between 360-760 nm using three CERAM Research tiles. A series of measurements over a three week period showed the overall precision to be no worse than 0.0025 at any wavelength on all three tiles. Accuracy was determined by multiple measurements of a calibrated sintered PTFE plaque (ser. #PO2115, Calibration date 7-20-2002) and calibrated CERAM tiles (PA-2007-2535) from the National Research Council, Canada. Measurements at ten wavelengths showed a variance from the mean NRC values of <0.006. The overall uncertainty of measurement has been calculated to be <0.0045 at 500 and 750 nm and, by interpolation, approx. 0.005 at 300 nm. These are comparable with the uncertainties stated by the National Laboratories of the United States (NIST) and Canada (NRC).

45:0 Directional Radiance Factor

For samples measured using this methodology, a separate uncertainty statement is provided.

Specular Reflectance (7.5° Absolute Reflectance)

The uncertainty has been determined to be <0.4% for the range 400-2000 nm, as determined by multiple measurements of a first surface aluminum mirror calibrated by National Research Council Canada, Certificate #AVIAN-17947-5-2).

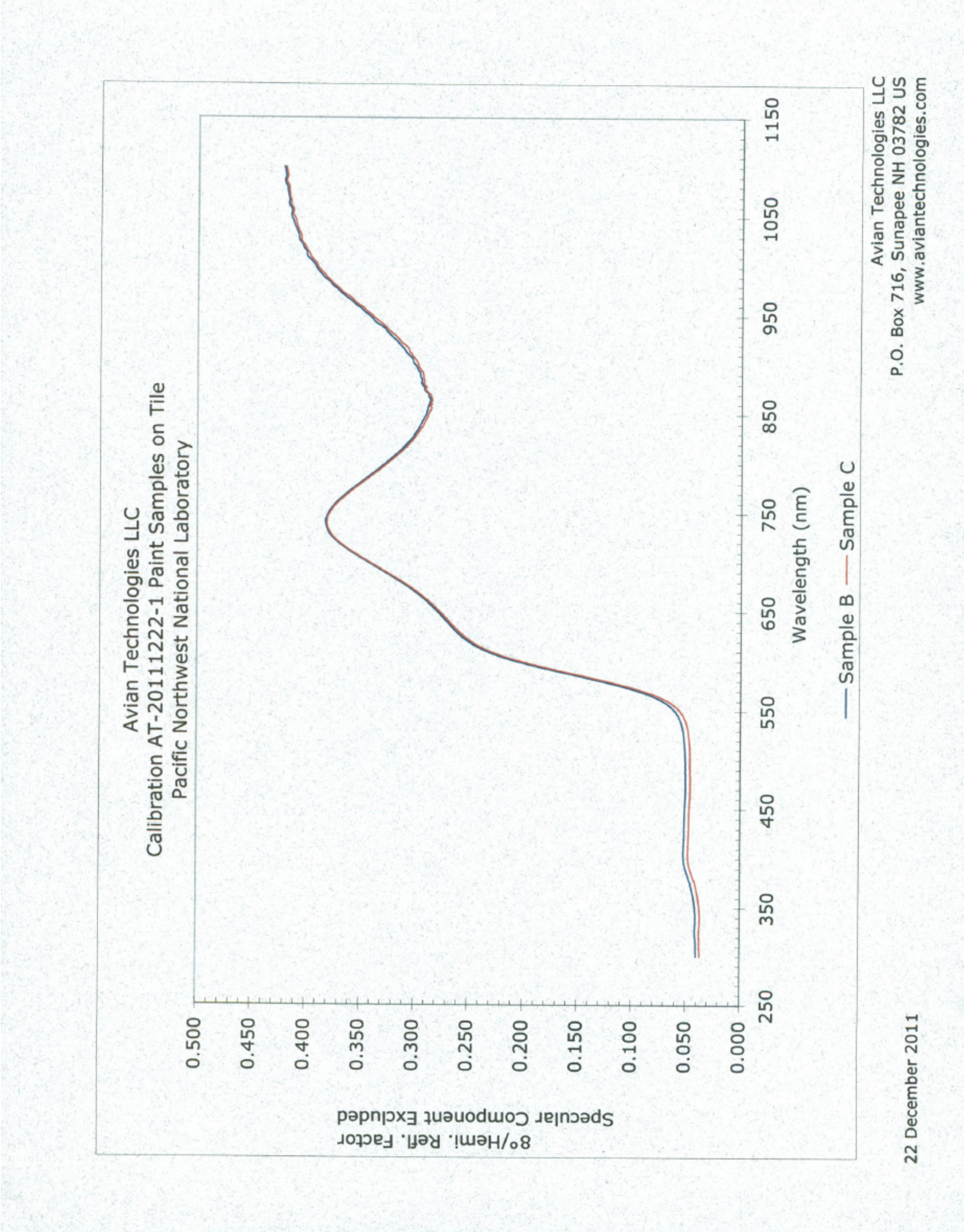
(Revised 10-16-08)

Avian Technologies LLC
Paint Samples on Tiles
Calibration AT-20111222-1
for
Pacific Northwest National Laboratory

8°/Hemi. Reflectance Factor					
Wavelength (nm)	Sample B	Sample C	Wavelength (nm)	Sample B	Sample C
300	0.040	0.037	700	0.343	0.341
310	0.041	0.037	710	0.357	0.356
320	0.041	0.037	720	0.370	0.369
330	0.041	0.037	730	0.379	0.378
340	0.041	0.037	740	0.382	0.381
350	0.042	0.037	750	0.380	0.378
360	0.043	0.039	760	0.373	0.372
370	0.045	0.040	770	0.363	0.362
380	0.047	0.043	780	0.351	0.350
390	0.050	0.046	790	0.340	0.338
400	0.052	0.048	800	0.328	0.326
410	0.052	0.048	810	0.317	0.315
420	0.052	0.048	820	0.308	0.306
430	0.051	0.047	830	0.300	0.298
440	0.051	0.047	840	0.295	0.292
450	0.051	0.047	850	0.290	0.288
460	0.051	0.046	860	0.288	0.286
470	0.050	0.046	870	0.288	0.286
480	0.050	0.046	880	0.294	0.292
490	0.050	0.046	890	0.295	0.293
500	0.051	0.046	900	0.299	0.297
510	0.051	0.046	910	0.305	0.303
520	0.052	0.047	920	0.313	0.309
530	0.053	0.048	930	0.322	0.318
540	0.055	0.051	940	0.331	0.328
550	0.060	0.056	950	0.341	0.339
560	0.072	0.067	960	0.352	0.349
570	0.094	0.089	970	0.364	0.360
580	0.128	0.123	980	0.374	0.372
590	0.169	0.165	990	0.384	0.382
600	0.206	0.203	1000	0.391	0.390
610	0.233	0.230	1010	0.399	0.396
620	0.250	0.248	1020	0.403	0.401
630	0.262	0.259	1030	0.408	0.406
640	0.270	0.268	1040	0.411	0.409
650	0.279	0.277	1050	0.415	0.412
660	0.288	0.286	1060	0.415	0.414
670	0.299	0.298	1070	0.417	0.416
680	0.313	0.311	1080	0.419	0.417
690	0.327	0.326	1090	0.420	0.418
			1100	0.422	0.420

Avian Technologies LLC
P.O. Box 716, Sunapee NH 03782 US
www.aviantechnologies.com

22 December 2011


Avian Technologies LLC
Calibration AT-20111222-1 Paint Samples on Tile
Pacific Northwest National Laboratory
8°/Hemi. Refl. Factor
Specular Component Excluded
0.500
0.450
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
250
350
450
550
650
750
850
950
1050
1150
Wavelength (nm)
Sample B
Sample C
22 December 2011
Avian Technologies LLC
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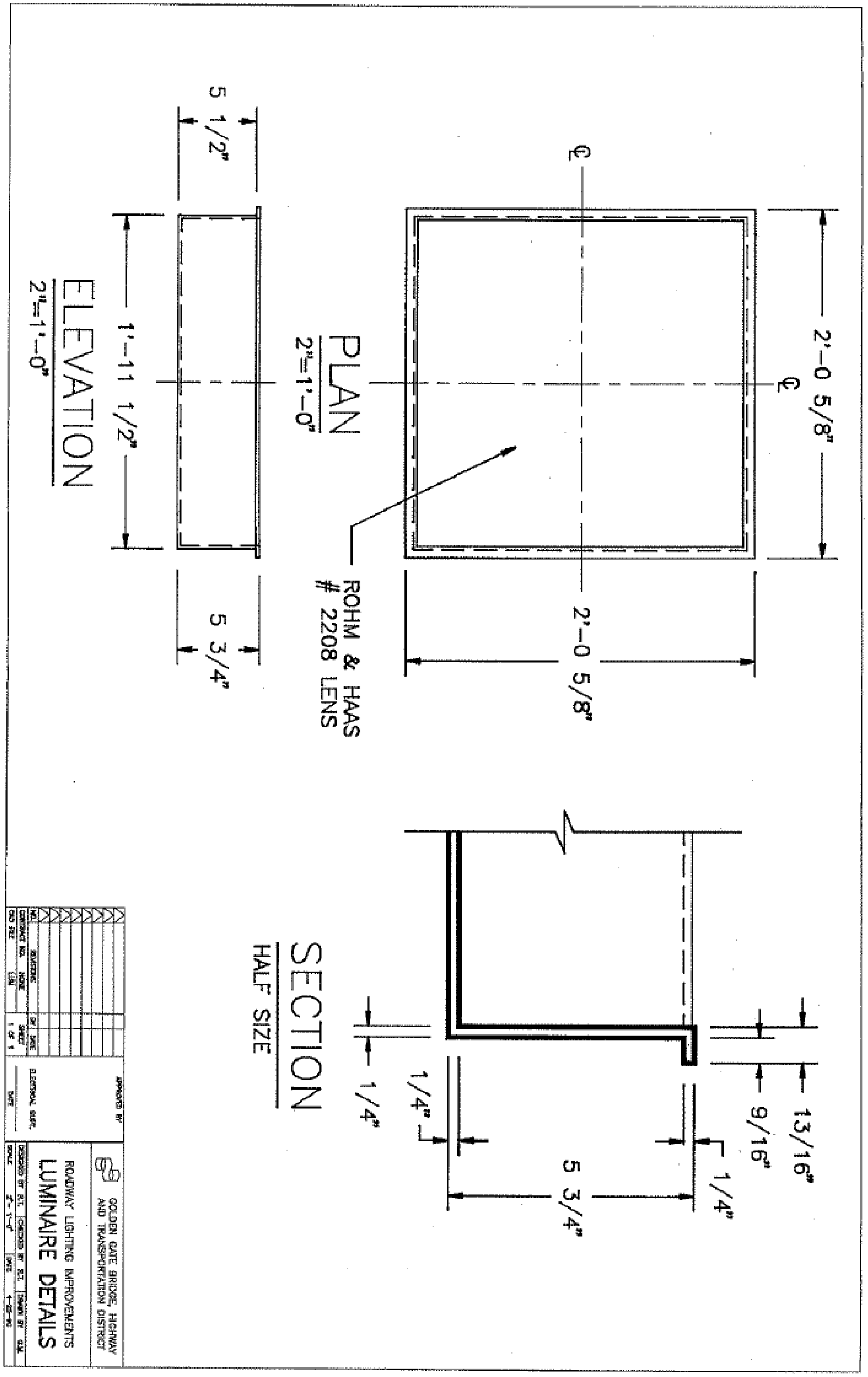
Appendix C

Amber Lens Specification


2'-0 5/8"
2'-0 5/8"
PLAN
2"=1'-0"
ROHM & HAAS
2208 LENS
5 1/2"
1'-11 1/2"
5 3/4"
ELEVATION
2"=1'-0"
SECTION
HALF SIZE
13/16"
9/16"
1/4"
1/4"
1/4"
5 3/4"
APPROVED BY
ELECTRICAL SUPT.
GOLDEN GATE BRIDGE, HIGHWAY
AND TRANSPORTATION DISTRICT
ROADWAY LIGHTING IMPROVEMENTS
LUMINAIRE DETAILS

Appendix D

HPS Shoebox Test Data—Lens A

Integrating Sphere Test Report

Relevant Standards
LM-51-2000 (Withdrawn), IES LM-31-1995 (Withdrawn), IES LM-46-2004
ANSI C82.6-2005
CIE 13.3-1995, CIE 15-2004

Prepared For
Leonardo Technologies, Inc.
Timothy Porco
Suite 610
2000 Oxford Drive
Bethel Park, PA 15102

Catalog Number
Caliper TD 11-85 (LENS A)

LTL Test Number
27706

Test Date

2012-02-06

Prepared By	Approved By
Eric Gaudreau, Technician III	Brian Moyer, Engineer

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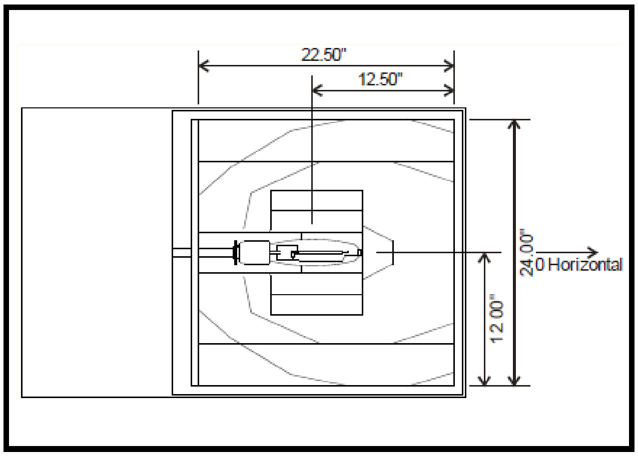
Luminaire Description:	Cast aluminum housing, formed white enamel aluminum reflector with specular aluminum upper reflector and specular aluminum side reflectors, formed yellow plastic enclosure
Catalog Number:	Caliper TD 11-85 (LENS A)
Lamp:	One clear horizontal S50 250 watt ED18 high pressure sodium lamp
Lamp Catalog Number:	GE LucaLox LU250/H/ECO
Mounting:	Horizontal
Ballast/Driver:	One unmarked ballast
Note:	This test does not follow the sample to sphere surface area suggestion in IESNA LM-79-2008

Luminaire



Summary of Results

Radiant Flux:	86970	mW
Luminous Flux:	25680	Lumens
Luminaire Efficacy:	80.9	Lumens/Watt
CCT:	1875	K
CRI (Ra):	21.0	
Chromaticity (x):	0.5588	
Chromaticity (y):	0.4337	
Chromaticity (u):	0.3154	
Chromaticity (v):	0.3672	
Duv:	0.0073	

Test Conditions

Test Temperature:	25.2	°C
Voltage:	120.0	VAC
Current:	2.839	A
Power:	317.4	W
Power Factor:	0.932	
Frequency:	60	Hz
Current THD:	10.2	%

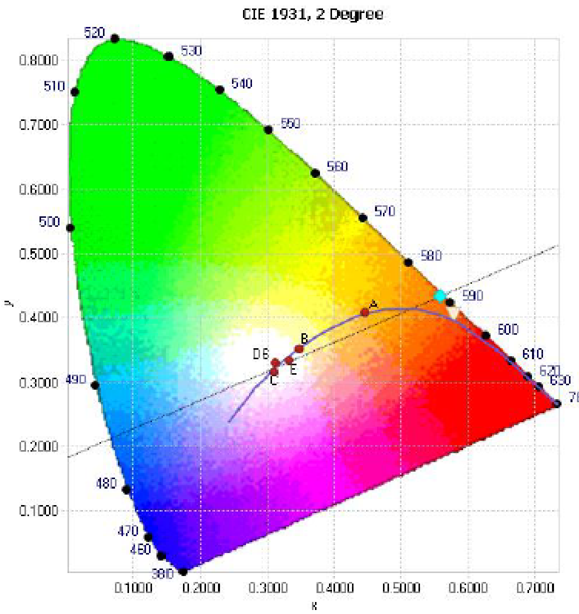
Testing was performed in a Labsphere SLMS7650 two meter integrating sphere using the 4π geometry method, a Labsphere CDS 1100 spectrometer, and LightMtrX software.
Absorption correction was employed for this measurement.

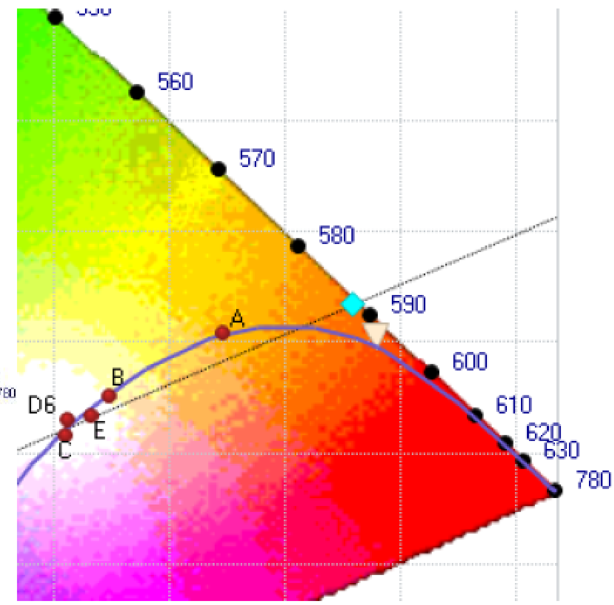
Chromaticity Coordinates

x	y	u	v	u'	v'	Duv
0.5588	0.4337	0.3154	0.3672	0.3154	0.5508	0.0073

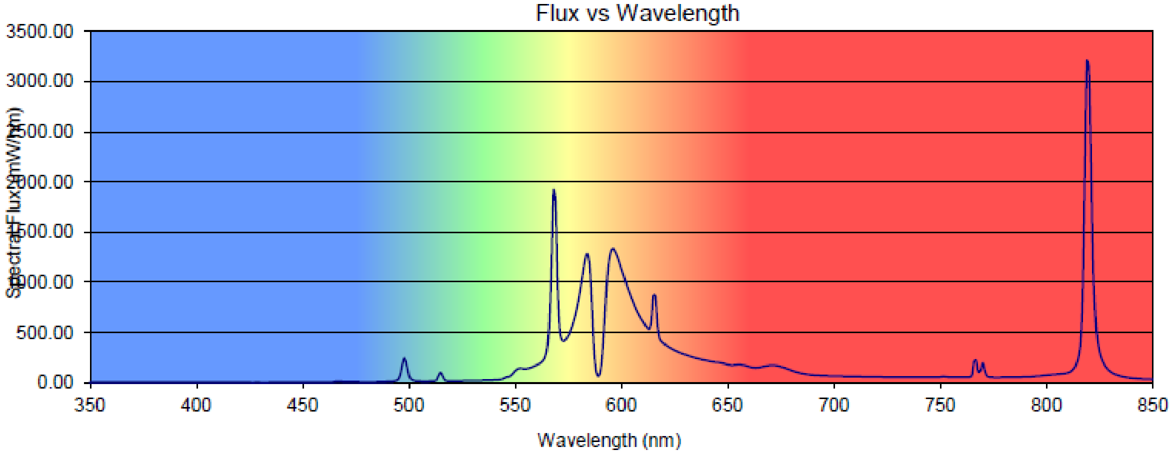
Color Rendering Index Detail

Ra (CRI)	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14
21.0	11.2	59.8	61.9	-10.8	4.3	44.1	41.0	-43.6	-190.7	32.1	-42.9	2.5	15.1	75.2





Flux vs Wavelength



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Spectral Power Distribution

λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm
350	1.53	422	0.686	494	17.2	566	564	638	229	710	59.1	782	51.1
351	1.56	423	0.735	495	31.5	567	1150	639	224	711	58.5	783	50.6
352	1.34	424	0.686	496	83.5	568	1920	640	220	712	58.2	784	50.7
353	1.45	425	0.660	497	185	569	1810	641	215	713	57.8	785	51.4
354	1.29	426	0.579	498	243	570	969	642	210	714	57.4	786	52.1
355	1.38	427	0.530	499	171	571	530	643	207	715	57.0	787	53.1
356	1.31	428	0.646	500	73.4	572	422	644	203	716	56.6	788	53.8
357	1.41	429	0.635	501	33.5	573	411	645	201	717	56.1	789	54.5
358	1.43	430	0.577	502	20.4	574	433	646	200	718	55.6	790	55.4
359	1.41	431	0.556	503	15.5	575	468	647	197	719	55.3	791	56.3
360	1.39	432	0.578	504	13.3	576	518	648	192	720	55.0	792	57.2
361	1.37	433	0.553	505	12.3	577	576	649	184	721	54.8	793	58.2
362	1.23	434	0.543	506	11.7	578	648	650	177	722	54.4	794	60.0
363	1.26	435	0.612	507	11.4	579	737	651	173	723	54.1	795	62.0
364	1.47	436	0.664	508	11.5	580	841	652	172	724	53.8	796	63.4
365	1.35	437	0.603	509	11.8	581	966	653	173	725	53.5	797	65.4
366	1.22	438	0.707	510	12.1	582	1100	654	176	726	53.0	798	68.0
367	1.22	439	0.659	511	12.4	583	1230	655	178	727	52.7	799	70.8
368	1.35	440	0.667	512	13.9	584	1280	656	178	728	52.7	800	72.9
369	1.22	441	0.641	513	23.8	585	1170	657	175	729	52.6	801	75.1
370	1.12	442	0.672	514	72.0	586	803	658	170	730	52.4	802	76.5
371	0.997	443	0.658	515	97.9	587	358	659	163	731	52.0	803	78.2
372	1.08	444	0.688	516	59.9	588	121	660	157	732	51.7	804	79.6
373	1.27	445	0.727	517	21.3	589	61.8	661	152	733	51.5	805	81.5
374	1.30	446	0.733	518	15.6	590	93.1	662	148	734	51.6	806	83.8
375	1.04	447	0.713	519	14.6	591	258	663	146	735	51.6	807	86.1
376	1.18	448	0.836	520	14.1	592	580	664	147	736	51.8	808	88.1
377	1.30	449	0.905	521	14.1	593	948	665	150	737	52.2	809	91.2
378	1.05	450	1.00	522	14.3	594	1190	666	154	738	52.1	810	95.6
379	1.15	451	0.961	523	14.8	595	1310	667	159	739	51.9	811	103
380	1.27	452	1.02	524	15.2	596	1340	668	164	740	51.6	812	117
381	1.13	453	1.08	525	15.6	597	1310	669	168	741	51.4	813	141
382	1.14	454	1.22	526	15.8	598	1260	670	170	742	51.2	814	182
383	1.17	455	1.16	527	16.1	599	1200	671	171	743	51.0	815	253
384	1.19	456	1.20	528	16.6	600	1130	672	171	744	51.0	816	407
385	1.11	457	1.24	529	17.2	601	1070	673	168	745	51.2	817	896
386	1.04	458	1.24	530	17.7	602	1000	674	164	746	51.4	818	2080
387	0.960	459	1.45	531	18.0	603	939	675	158	747	51.6	819	3200
388	1.11	460	1.56	532	18.3	604	883	676	151	748	51.9	820	3150
389	1.10	461	1.81	533	18.8	605	827	677	144	749	52.6	821	2230
390	0.981	462	2.22	534	19.1	606	775	678	136	750	54.4	822	1170
391	0.911	463	2.89	535	19.8	607	729	679	128	751	58.5	823	666
392	0.922	464	3.95	536	20.5	608	686	680	120	752	58.6	824	429
393	0.878	465	6.68	537	21.2	609	645	681	113	753	55.3	825	303
394	0.927	466	10.7	538	22.0	610	612	682	106	754	53.4	826	233
395	0.887	467	12.0	539	22.9	611	579	683	99.8	755	52.7	827	186
396	0.903	468	9.49	540	24.0	612	552	684	94.5	756	52.2	828	153
397	0.960	469	7.18	541	25.1	613	532	685	89.7	757	52.0	829	128
398	0.978	470	6.19	542	26.7	614	609	686	85.3	758	51.8	830	110
399	0.907	471	5.61	543	28.7	615	869	687	81.7	759	51.5	831	95.8
400	0.933	472	5.11	544	32.8	616	869	688	78.6	760	51.7	832	84.5
401	0.864	473	5.27	545	44.1	617	580	689	76.2	761	51.6	833	75.3
402	0.825	474	7.20	546	52.0	618	442	690	74.1	762	51.8	834	68.0
403	0.787	475	8.02	547	56.8	619	406	691	72.5	763	52.3	835	62.1
404	0.718	476	5.58	548	69.7	620	388	692	70.9	764	54.1	836	57.4
405	0.770	477	3.33	549	92.4	621	372	693	69.8	765	73.7	837	53.1
406	0.861	478	2.96	550	116	622	357	694	68.8	766	214	838	49.6
407	0.742	479	2.99	551	133	623	345	695	67.6	767	220	839	46.6
408	0.771	480	3.17	552	142	624	332	696	66.6	768	106	840	44.0
409	0.704	481	3.38	553	141	625	322	697	65.9	769	118	841	41.4
410	0.822	482	3.56	554	136	626	313	698	65.2	770	198	842	39.4
411	0.661	483	3.90	555	136	627	303	699	64.6	771	116	843	37.8
412	0.687	484	4.13	556	140	628	294	700	64.0	772	62.2	844	36.1
413	0.738	485	4.55	557	146	629	286	701	63.5	773	54.0	845	34.9
414	0.738	486	4.92	558	154	630	278	702	62.9	774	51.5	846	34.0
415	0.740	487	5.39	559	163	631	271	703	62.5	775	50.4	847	32.9
416	0.699	488	6.19	560	172	632	263	704	61.8	776	50.0	848	32.2
417	0.651	489	7.45	561	183	633	258	705	61.3	777	49.7	849	31.6
418	0.693	490	9.31	562	195	634	250	706	60.8	778	49.9	850	30.8
419	0.709	491	11.0	563	215	635	245	707	60.4	779	51.1		
420	0.697	492	11.4	564	251	636	239	708	59.9	780	53.3		
421	0.696	493	12.4	565	337	637	234	709	59.5	781	52.6		

LTL

LUMINAIRE TESTING LABORATORY, INC.

SUSTAINING MEMBER of the IESNA

905 Harrison Street · Allentown, PA 18103 · 610-770-1044 · Fax 610-770-8912 · www.LuminaireTesting.com

LTL NUMBER: 27705 DATE: 2012-01-10

PREPARED FOR: LEONARDO TECHNOLOGIES, INC.

CATALOG NUMBER: CALIPER TD 11-85 (LENS A)

LUMINAIRE: CAST ALUMINUM HOUSING, FORMED WHITE ENAMEL ALUMINUM REFLECTOR WITH SPECULAR ALUMINUM UPPER REFLECTOR AND SPECULAR ALUMIUM SIDE REFLECTORS, FORMED YELLOW PLASTIC ENCLOSURE

LAMP: ONE CLEAR HORIZONTAL S50 250 WATT ED18 HIGH PRESSURE SODIUM LAMP

BALLAST: ONE UNMARKED BALLAST

ELECTRICAL VALUES: 120.0VAC, 2.826A, 319.1W, PF=0.941

LUMINAIRE EFFIACY: 60.7 LUMENS/WATT

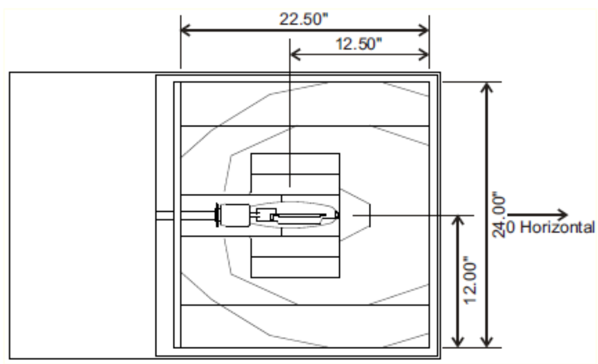
NOTE: THIS TEST WAS PERFORMED USING THE CALIBRATED PHOTODETECTOR METHOD OF ABSOLUTE PHOTOMETRY.*

IES CLASSIFICATION: **TYPE III**

LONGITUDINAL CLASSIFICATION: **SHORT**

CUTOFF CLASSIFICATION: **SEMI- CUTOFF****

**CUTOFF DESIGNATION IS NOT DEFINED FOR ABSOLUTE PHOTOMETRIC TESTS. THIS CUTOFF RATING IS BASED ON THE MAXIMUM CANDELA READING PER LUMINAIRE RATED AT 1000 LUMENS.



FLUX DISTRIBUTION

LUMENS	DOWNWARD	UPWARD	TOTALS
HOUSE SIDE	8111.93	165.72	8277.64
STREET SIDE	10740.21	343.00	11083.21
TOTALS	18852.14	508.71	19360.85

Approved By: [signature]

*DATA WAS ACQUIRED USING THE CALIBRATED PHOTODETECTOR METHOD OF ABSOLUTE PHOTOMETRY. A UDT MODEL #211 PHOTODETECTOR AND UDT MODEL #S370 OPTOMETER COMBINATION WERE USED AS A STANDARD. A SPECTRAL MISMATCH CORRECTION FACTOR WAS EMPLOYED BASED ON THE SPECTRAL RESPONSIVITY OF THE PHOTODETECTOR AND THE SPECTRAL POWER DISTRIBUTION OF THE TEST SUBJECT.

TESTING WAS PERFORMED IN ACCORDANCE WITH IES LM-79-08.

TEST ANGULAR INCREMENTS AND REPORT FORMATTING WAS BASED ON IES LM-31-95 (WITHDRAWN).

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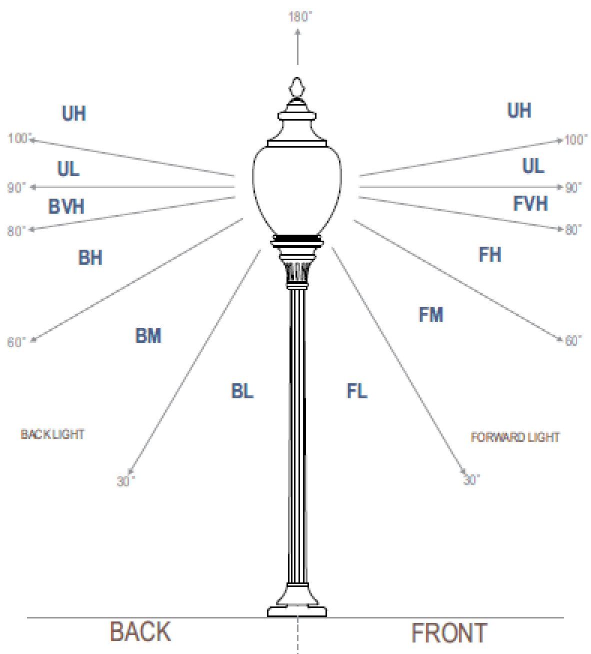
FLUX DISTRIBUTION TABLE BASED ON THE IESNA LUMINAIRE CLASSIFICATION SYSTEM



ZONE	FLUX LUMINAIRE LUMENS	FLUX % OF LUMINAIRE LUMENS
FORWARD LIGHT	10740	55.5
FL (0°-30°)	1471	7.6
FM (30°-60°)	5310	27.4
FH (60°-80°)	3882	20.1
FVH (80°-90°)	77	0.4
BACK LIGHT	8112	41.9
BL (0°-30°)	1414	7.3
BM (30°-60°)	4436	22.9
BH (60°-80°)	2185	11.3
BVH (80°-90°)	78	0.4
UPLIGHT	509	2.6
UL (90°-100°)	38	0.2
UH (100°-180°)	471	2.4
TRAPPED LIGHT	NA	NA

BUG (**B**acklight, **U**plight, **G**lare) Rating	
Asymmetrical Luminaire Types (Type I, II, III, IV)	B3 U3 G3
Quadrilateral Symmetrical Luminaire Types (Type V, Area Light)	B3 U3 G2

Appendix E

HPS Shoebox Test Data—Lens B

LTL LUMINAIRE TESTING LABORATORY, INC.

SUSTAINING MEMBER of the IESNA

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Integrating Sphere Test Report

Relevant Standards
LM-51-2000 (Withdrawn), IES LM-31-1995 (Withdrawn), IES LM-46-2004
ANSI C82.6-2005
CIE 13.3-1995, CIE 15-2004

Prepared For
Leonardo Technologies, Inc.
Timothy Porco
Suite 610
2000 Oxford Drive
Bethel Park, PA 15102

Catalog Number
Caliper TD 11-85 (LENS B)

LTL Test Number
27704

Test Date

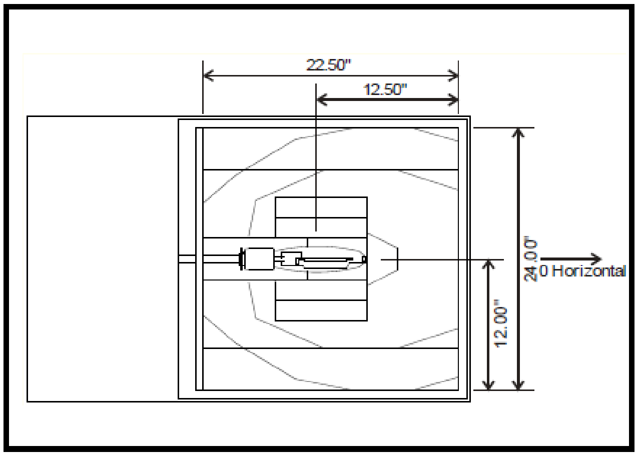
2012-02-06

Prepared By	Approved By
Eric Gaudreau, Technician III	Brian Moyer, Engineer

LTL LUMINAIRE TESTING LABORATORY, INC.
SUSTAINING MEMBER of the IESNA
905 Harrison Street · Allentown, PA 18103 · 610-770-1044 · Fax 610-770-8912 · www.LuminaireTesting.com

Luminaire Description:	Cast aluminum housing, formed white enamel aluminum reflector with specular aluminum upper reflector and specular aluminum side reflectors, formed yellow plastic enclosure
Catalog Number:	Caliper TD 11-85 (LENS B)
Lamp:	One clear horizontal S50 250 watt ED18 high pressure sodium lamp
Lamp Catalog Number:	GE LucaLox LU250/H/ECO
Mounting:	Horizontal
Ballast/Driver:	One unmarked ballast
Note:	This test does not follow the sample to sphere surface area suggestion in IESNA LM-79-2008

Luminaire



Summary of Results

Radiant Flux:	83560 mW
Luminous Flux:	24180 Lumens
Luminaire Efficacy:	75.9 Lumens/Watt
CCT:	1898 K
CRI (Ra):	22.9
Chromaticity (x):	0.5507
Chromaticity (y):	0.4275
Chromaticity (u):	0.3134
Chromaticity (v):	0.3649
Duv:	0.0052

Test Conditions

Test Temperature:	25.8 °C
Voltage:	120.0 VAC
Current:	2.836 A
Power:	318.7 W
Power Factor:	0.937
Frequency:	60 Hz
Current THD:	10.4 %

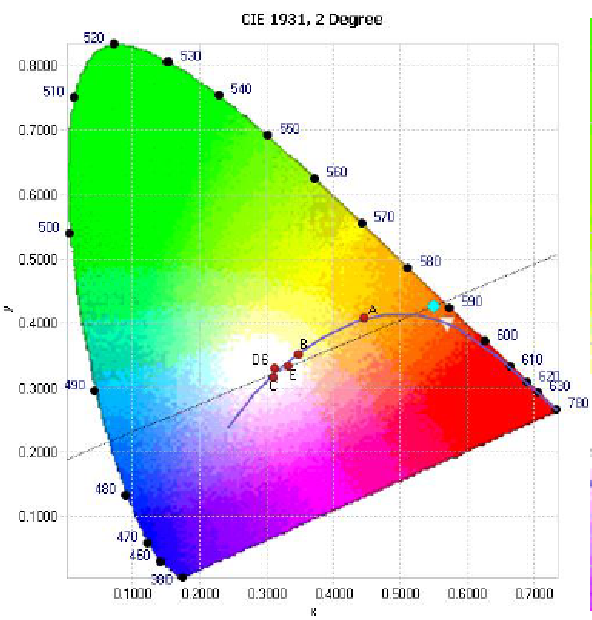
Testing was performed in a Labsphere SLMS7650 two meter integrating sphere using the 4π geometry method, a Labsphere CDS 1100 spectrometer, and LightMtrX software.
Absorption correction was employed for this measurement.

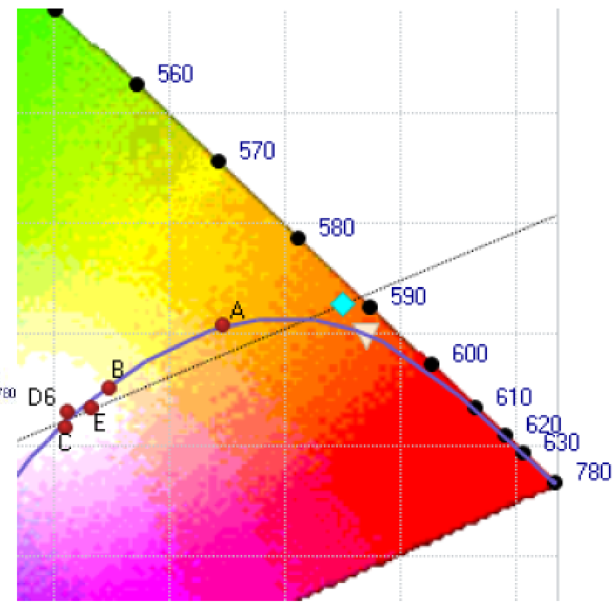
Chromaticity Coordinates

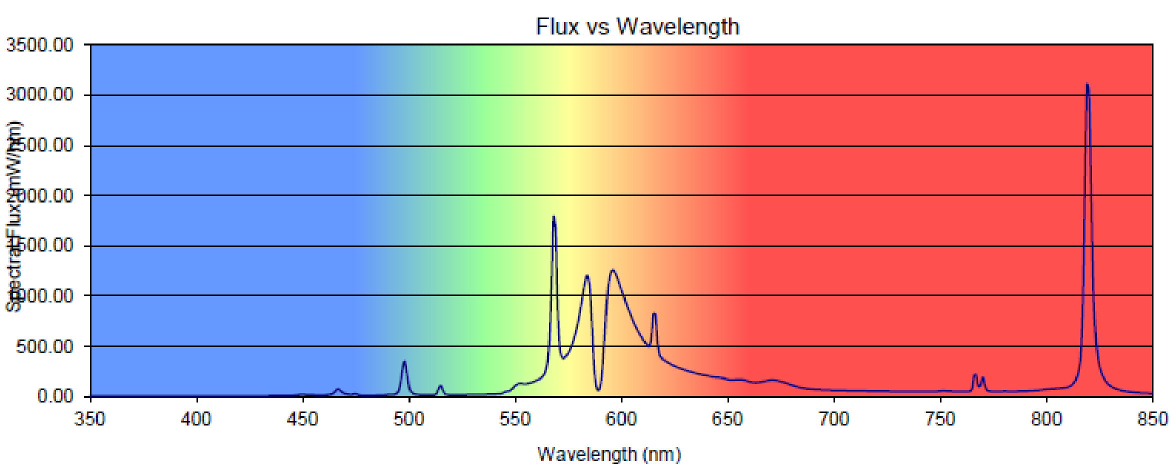
x	y	u	v	u'	v'	Duv
0.5507	0.4275	0.3134	0.3649	0.3134	0.5474	0.0052

Color Rendering Index Detail

Ra (CRI)	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14
22.9	13.9	63.2	59.0	-7.6	8.6	50.3	39.3	-43.3	-186.9	39.7	-36.5	16.1	18.6	73.3







Spectral Power Distribution

λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm
350	1.91	422	1.91	494	26.7	566	525	638	216	710	56.3	782	49.2
351	1.74	423	1.96	495	48.0	567	1070	639	211	711	55.8	783	48.6
352	1.49	424	2.06	496	125	568	1790	640	208	712	55.4	784	48.7
353	1.63	425	2.25	497	272	569	1680	641	203	713	55.1	785	49.5
354	1.53	426	2.39	498	353	570	897	642	199	714	54.6	786	50.0
355	1.49	427	2.50	499	245	571	491	643	196	715	54.3	787	50.9
356	1.33	428	2.59	500	103	572	390	644	192	716	53.8	788	51.6
357	1.30	429	2.76	501	45.8	573	380	645	190	717	53.4	789	52.4
358	1.50	430	3.01	502	27.4	574	401	646	189	718	53.0	790	53.1
359	1.14	431	3.39	503	20.3	575	433	647	186	719	52.5	791	53.9
360	1.50	432	3.72	504	17.0	576	479	648	181	720	52.3	792	54.8
361	1.34	433	3.85	505	15.3	577	534	649	174	721	52.1	793	55.9
362	1.30	434	4.24	506	14.2	578	600	650	168	722	51.6	794	57.6
363	1.21	435	4.87	507	13.8	579	683	651	164	723	51.3	795	59.4
364	1.14	436	5.41	508	13.6	580	781	652	163	724	51.0	796	60.8
365	1.18	437	5.42	509	13.7	581	898	653	164	725	50.6	797	62.8
366	1.28	438	6.10	510	13.8	582	1020	654	166	726	50.3	798	65.2
367	1.05	439	6.77	511	14.1	583	1150	655	168	727	50.1	799	68.0
368	1.22	440	6.76	512	15.5	584	1200	656	168	728	50.0	800	70.0
369	1.23	441	6.23	513	26.5	585	1100	657	166	729	49.9	801	72.2
370	1.36	442	5.96	514	79.4	586	759	658	161	730	49.6	802	73.6
371	1.05	443	5.64	515	107	587	339	659	155	731	49.3	803	75.2
372	1.17	444	5.83	516	65.1	588	115	660	149	732	49.0	804	76.6
373	1.29	445	6.84	517	22.8	589	58.8	661	143	733	48.9	805	78.4
374	1.15	446	8.47	518	16.4	590	89.5	662	140	734	48.9	806	80.6
375	1.26	447	10.5	519	15.2	591	249	663	138	735	48.9	807	82.9
376	1.12	448	13.7	520	14.5	592	556	664	139	736	49.3	808	84.9
377	1.06	449	17.9	521	14.4	593	903	665	142	737	49.6	809	87.9
378	1.01	450	19.3	522	14.6	594	1130	666	146	738	49.5	810	92.4
379	1.05	451	16.3	523	15.1	595	1230	667	151	739	49.4	811	100.0
380	1.12	452	13.9	524	15.3	596	1260	668	155	740	49.1	812	113
381	1.13	453	13.7	525	15.5	597	1230	669	159	741	48.8	813	137
382	0.941	454	14.2	526	15.6	598	1190	670	162	742	48.6	814	177
383	0.988	455	12.8	527	15.7	599	1130	671	162	743	48.6	815	246
384	1.05	456	10.3	528	16.2	600	1060	672	162	744	48.5	816	397
385	1.04	457	9.38	529	16.7	601	1000	673	160	745	48.8	817	874
386	1.10	458	9.23	530	17.1	602	940	674	155	746	49.1	818	2030
387	0.929	459	9.44	531	17.3	603	881	675	149	747	49.3	819	3110
388	1.08	460	10.4	532	17.6	604	827	676	143	748	49.6	820	3050
389	0.987	461	12.3	533	17.9	605	775	677	136	749	50.3	821	2160
390	0.964	462	15.1	534	18.1	606	727	678	129	750	52.0	822	1130
391	1.05	463	18.8	535	18.7	607	683	679	122	751	56.2	823	646
392	1.07	464	25.7	536	19.3	608	643	680	114	752	56.1	824	416
393	1.06	465	42.9	537	19.9	609	605	681	107	753	52.9	825	294
394	0.993	466	66.9	538	20.7	610	574	682	101	754	51.3	826	226
395	1.11	467	71.4	539	21.4	611	543	683	94.8	755	50.5	827	180
396	0.946	468	51.9	540	22.4	612	518	684	89.7	756	50.0	828	148
397	0.889	469	35.0	541	23.5	613	500	685	85.2	757	49.8	829	124
398	0.874	470	27.4	542	24.9	614	573	686	81.2	758	49.6	830	107
399	0.960	471	22.9	543	26.7	615	822	687	77.6	759	49.5	831	92.8
400	0.924	472	19.1	544	30.6	616	821	688	74.9	760	49.5	832	81.9
401	1.04	473	18.1	545	41.2	617	545	689	72.4	761	49.6	833	72.9
402	0.996	474	24.0	546	48.4	618	415	690	70.6	762	49.7	834	66.1
403	1.09	475	26.0	547	52.6	619	382	691	69.0	763	50.2	835	60.2
404	1.11	476	16.7	548	64.3	620	365	692	67.5	764	51.9	836	55.5
405	1.11	477	8.52	549	85.1	621	349	693	66.4	765	71.5	837	51.5
406	1.08	478	7.05	550	107	622	336	694	65.5	766	209	838	48.0
407	1.04	479	6.63	551	122	623	324	695	64.3	767	213	839	45.1
408	1.10	480	6.76	552	130	624	313	696	63.5	768	103	840	42.7
409	1.13	481	6.85	553	130	625	303	697	62.7	769	115	841	40.2
410	1.10	482	7.19	554	125	626	294	698	62.1	770	192	842	38.2
411	1.15	483	7.45	555	125	627	285	699	61.6	771	112	843	36.6
412	1.28	484	7.90	556	128	628	277	700	60.9	772	59.8	844	35.0
413	1.21	485	8.35	557	134	629	270	701	60.4	773	51.9	845	33.7
414	1.29	486	8.84	558	141	630	262	702	59.9	774	49.5	846	32.8
415	1.35	487	9.55	559	150	631	255	703	59.4	775	48.4	847	31.9
416	1.41	488	10.7	560	158	632	248	704	58.9	776	48.0	848	31.0
417	1.44	489	12.6	561	168	633	242	705	58.2	777	47.8	849	30.3
418	1.56	490	15.8	562	180	634	236	706	57.9	778	48.0	850	29.7
419	1.59	491	18.3	563	198	635	231	707	57.5	779	49.3		
420	1.71	492	18.3	564	232	636	226	708	57.1	780	51.2		
421	1.79	493	19.5	565	312	637	221	709	56.6	781	50.5		

LTL LUMINAIRE TESTING LABORATORY, INC. SUSTAINING MEMBER of the IESNA
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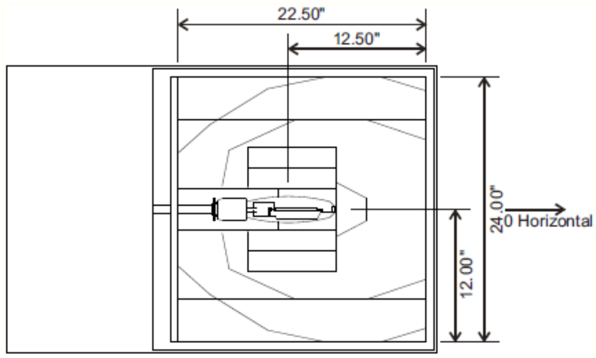
LTL NUMBER: 27703 DATE: 2012-01-10
PREPARED FOR: LEONARDO TECHNOLOGIES
CATALOG NUMBER: CALIPER TD 11-85 (LENS B)
LUMINAIRE: CAST ALUMINUM HOUSING, FORMED WHITE ENAMEL ALUMINUM REFLECTOR WITH SPECULAR ALUMINUM UPPER REFLECTOR AND SPECULAR ALUMIUM SIDE REFLECTORS, FORMED YELLOW PLASTIC ENCLOSURE
LAMP: ONE CLEAR HORIZONTAL S50 250 WATT ED18 HIGH PRESSURE SODIUM LAMP
BALLAST: ONE UNMARKED BALLAST
ELECTRICAL VALUES: 120.0VAC, 2.783A, 315.4W, PF=0.944
LUMINAIRE EFFICACY: 56.5 LUMENS/WATT
NOTE: THIS TEST WAS PERFORMED USING THE CALIBRATED PHOTODETECTOR METHOD OF ABSOLUTE PHOTOMETRY.*

IES CLASSIFICATION: **TYPE III**
LONGITUDINAL CLASSIFICATION: **SHORT**
CUTOFF CLASSIFICATION: **SEMI-CUTOFF****

**CUTOFF DESIGNATION IS NOT DEFINED FOR ABSOLUTE PHOTOMETRIC TESTS. THIS CUTOFF RATING IS BASED ON THE MAXIMUM CANDELA READING PER LUMINAIRE RATED AT 1000 LUMENS.



FLUX DISTRIBUTION

LUMENS	DOWNWARD	UPWARD	TOTALS
HOUSE SIDE	7397.20	428.07	7825.27
STREET SIDE	9261.86	719.97	9981.84
TOTALS	16659.07	1148.04	17807.11

Approved By: Brian Morgan

*DATA WAS ACQUIRED USING THE CALIBRATED PHOTODETECTOR METHOD OF ABSOLUTE PHOTOMETRY. A UDT MODEL #211 PHOTODETECTOR AND UDT MODEL #S370 OPTOMETER COMBINATION WERE USED AS A STANDARD. A SPECTRAL MISMATCH CORRECTION FACTOR WAS EMPLOYED BASED ON THE SPECTRAL RESPONSIVITY OF THE PHOTODETECTOR AND THE SPECTRAL POWER DISTRIBUTION OF THE TEST SUBJECT.

TESTING WAS PERFORMED IN ACCORDANCE WITH IES LM-79-08.
TEST ANGULAR INCREMENTS AND REPORT FORMATTING WAS BASED ON IES LM-31-95 (WITHDRAWN).

LTL LUMINAIRE TESTING LABORATORY, INC.

SUSTAINING MEMBER of the IESNA

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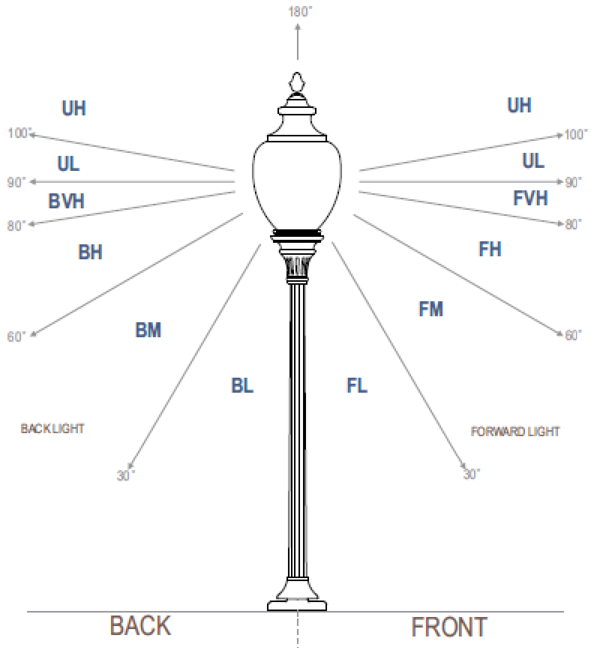
FLUX DISTRIBUTION TABLE BASED ON THE IESNA LUMINAIRE CLASSIFICATION SYSTEM



FLUX

ZONE	LUMINAIRE LUMENS	% OF LUMINAIRE LUMENS
FORWARD LIGHT	9262	52.0
FL (0°-30°)	1435	8.1
FM (30°-60°)	4483	25.2
FH (60°-80°)	3122	17.5
FVH (80°-90°)	223	1.3
BACK LIGHT	7397	41.5
BL (0°-30°)	1384	7.8
BM (30°-60°)	3874	21.8
BH (60°-80°)	1938	10.9
BVH (80°-90°)	202	1.1
UPLIGHT	1148	6.4
UL (90°-100°)	295	1.7
UH (100°-180°)	853	4.8
TRAPPED LIGHT	NA	NA

BUG (**B**acklight, **U**plight, **G**lare) Rating	
Asymmetrical Luminaire Types (Type I, II, III, IV)	B3 U4 G3
Quadrilateral Symmetrical Luminaire Types (Type V, Area Light)	B3 U4 G2

Appendix F

HPS Shoebox Test Data—No Lens

LTL LUMINAIRE TESTING LABORATORY, INC.

SUSTAINING MEMBER of the IESNA

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Integrating Sphere Test Report

Relevant Standards
LM-51-2000 (Withdrawn), IES LM-31-1995 (Withdrawn), IES LM-46-2004
ANSI C82.6-2005
CIE 13.3-1995, CIE 15-2004

Prepared For

Leonardo Technologies, Inc.
Timothy Porco
Suite 610
2000 Oxford Drive
Bethel Park, PA 15102

Catalog Number

Caliper TD 11-85 (NO LENS)

LTL Test Number

27708

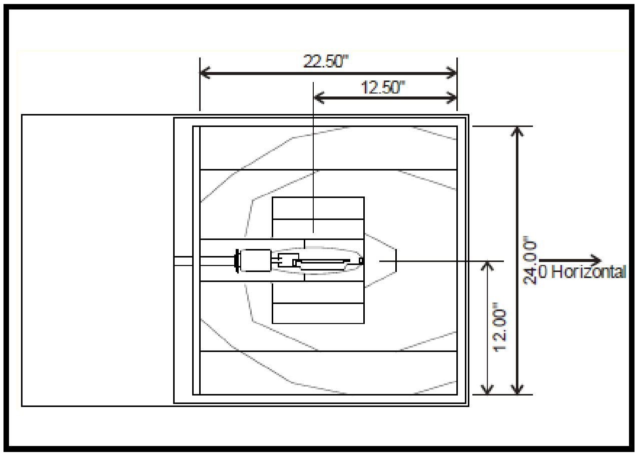
Test Date

2012-02-06

Prepared By	Approved By
Eric Gaudreau, Technician III	Brian Moyer, Engineer

Luminaire Description:	Cast aluminum housing, formed white enamel aluminum reflector with specular aluminum upper reflector and specular aluminum side reflectors, no enclosure
Catalog Number:	Caliper TD 11-85 (NO LENS)
Lamp:	One clear horizontal S50 250 watt ED18 high pressure sodium lamp
Lamp Catalog Number:	GE LucaLox LU250/H/ECO
Mounting:	Horizontal
Ballast/Driver:	One unmarked ballast
Note:	This test does not follow the sample to sphere surface area suggestion in IESNA LM-79-2008

Luminaire



Summary of Results

Radiant Flux:	94490 mW
Luminous Flux:	26930 Lumens
Luminaire Efficacy:	85.0 Lumens/Watt
CCT:	1976 K
CRI (Ra):	25.6
Chromaticity (x):	0.5281
Chromaticity (y):	0.4114
Chromaticity (u):	0.3070
Chromaticity (v):	0.3588
Duv:	-0.0005

Test Conditions

Test Temperature:	25.5 °C
Voltage:	120.0 VAC
Current:	2.835 A
Power:	316.8 W
Power Factor:	0.931
Frequency:	60 Hz
Current THD:	10.3 %

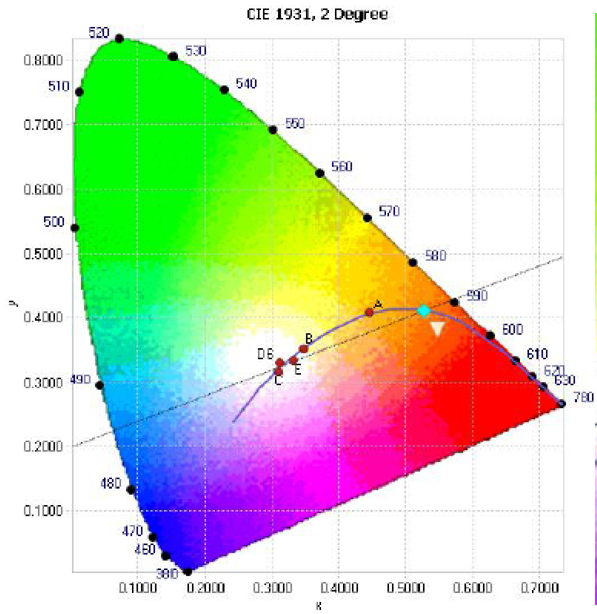
Testing was performed in a Labsphere SLMS7650 two meter integrating sphere using the 4π geometry method, a Labsphere CDS 1100 spectrometer, and LightMtrX software.
Absorption correction was employed for this measurement.

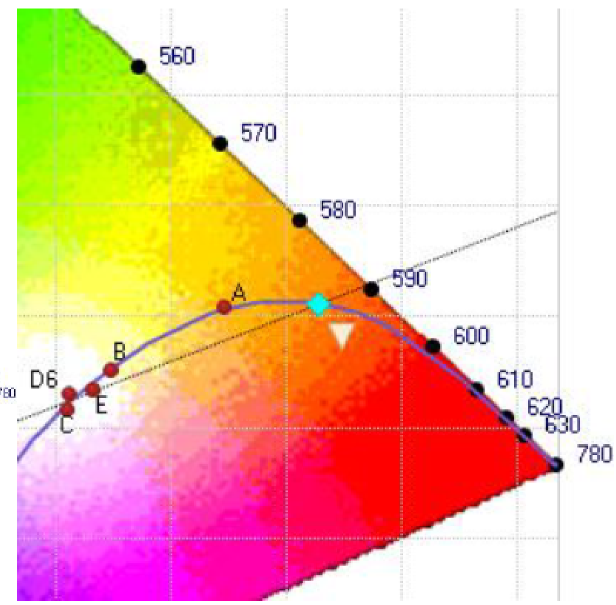
Chromaticity Coordinates

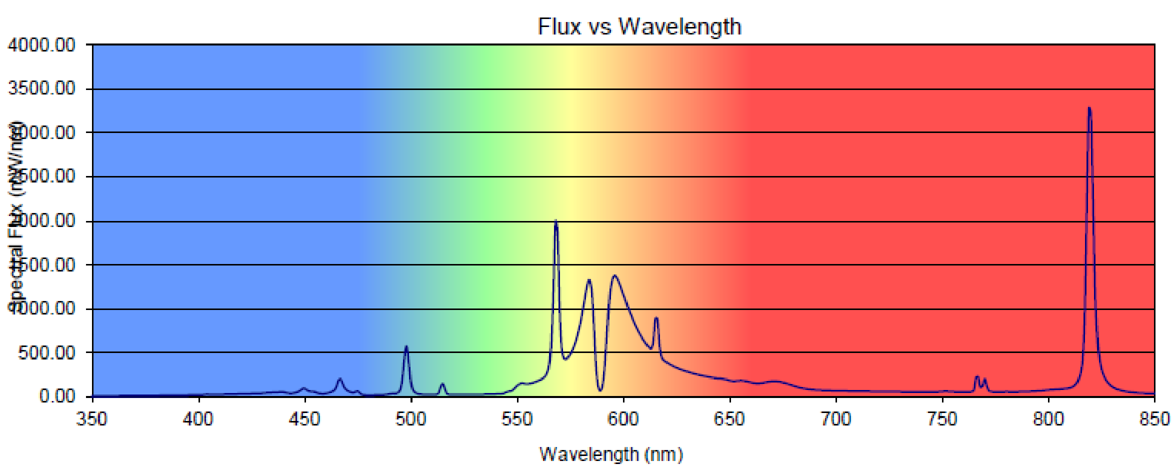
x	y	u	v	u'	v'	Duv
0.5281	0.4114	0.3070	0.3588	0.3070	0.5381	-0.0005

Color Rendering Index Detail

Ra (CRI)	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14
25.6	17.9	67.7	54.8	-3.9	15.0	58.5	36.8	-42.1	-181.9	49.3	-29.5	37.3	23.7	70.9







Spectral Power Distribution

λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm
350	3.69	422	29.4	494	44.1	566	584	638	232	710	60.1	782	51.7
351	3.68	423	30.1	495	78.3	567	1190	639	227	711	59.6	783	51.3
352	3.81	424	30.9	496	204	568	1990	640	223	712	59.0	784	51.6
353	4.04	425	31.3	497	443	569	1880	641	218	713	58.7	785	52.2
354	4.05	426	32.3	498	572	570	1000	642	213	714	58.2	786	52.9
355	4.17	427	33.1	499	397	571	546	643	210	715	57.9	787	53.7
356	4.30	428	33.7	500	165	572	434	644	206	716	57.4	788	54.7
357	4.22	429	34.3	501	72.0	573	423	645	204	717	57.0	789	55.4
358	4.36	430	35.6	502	42.0	574	445	646	202	718	56.5	790	56.4
359	4.29	431	38.3	503	30.8	575	481	647	199	719	56.0	791	56.9
360	4.42	432	40.2	504	25.5	576	531	648	194	720	56.0	792	58.0
361	4.51	433	40.3	505	22.9	577	591	649	187	721	55.7	793	59.1
362	4.64	434	41.0	506	21.1	578	664	650	180	722	55.2	794	60.9
363	5.23	435	45.9	507	20.2	579	756	651	176	723	55.0	795	63.0
364	7.31	436	48.8	508	19.7	580	862	652	175	724	54.6	796	64.5
365	7.55	437	46.3	509	19.6	581	992	653	176	725	54.2	797	66.5
366	6.28	438	50.0	510	19.6	582	1130	654	178	726	54.0	798	69.1
367	5.73	439	52.8	511	20.0	583	1260	655	180	727	53.7	799	71.9
368	5.98	440	49.8	512	21.7	584	1320	656	180	728	53.6	800	74.2
369	6.19	441	43.3	513	36.6	585	1210	657	177	729	53.5	801	76.6
370	6.24	442	38.6	514	109	586	835	658	172	730	53.3	802	77.9
371	6.82	443	34.4	515	148	587	373	659	166	731	53.0	803	79.5
372	6.78	444	33.4	516	89.7	588	126	660	160	732	52.8	804	81.2
373	7.15	445	38.4	517	30.9	589	64.0	661	154	733	52.6	805	83.1
374	7.39	446	45.9	518	22.1	590	97.3	662	150	734	52.4	806	85.0
375	7.61	447	54.9	519	20.3	591	270	663	148	735	52.5	807	87.6
376	7.86	448	69.4	520	19.4	592	606	664	149	736	52.8	808	89.6
377	8.07	449	88.3	521	18.9	593	983	665	152	737	53.0	809	92.6
378	8.18	450	92.1	522	18.9	594	1230	666	156	738	53.1	810	97.4
379	8.60	451	74.8	523	19.4	595	1350	667	161	739	52.8	811	105
380	8.74	452	60.0	524	19.6	596	1370	668	166	740	52.5	812	119
381	8.94	453	56.3	525	19.8	597	1340	669	170	741	52.3	813	144
382	9.53	454	56.4	526	19.9	598	1290	670	173	742	52.0	814	185
383	9.68	455	49.4	527	20.0	599	1230	671	174	743	52.0	815	257
384	10.1	456	37.6	528	20.4	600	1160	672	173	744	51.9	816	414
385	10.4	457	32.6	529	20.9	601	1090	673	171	745	52.0	817	913
386	10.7	458	30.7	530	21.3	602	1030	674	166	746	52.3	818	2130
387	11.1	459	30.6	531	21.4	603	959	675	160	747	52.4	819	3280
388	11.9	460	32.9	532	21.6	604	900	676	153	748	52.7	820	3230
389	12.3	461	38.0	533	21.8	605	844	677	146	749	53.5	821	2280
390	12.4	462	46.0	534	22.2	606	791	678	137	750	55.4	822	1190
391	12.6	463	55.3	535	22.6	607	743	679	130	751	59.4	823	677
392	12.9	464	73.9	536	23.3	608	699	680	122	752	59.4	824	436
393	13.1	465	121	537	24.0	609	658	681	115	753	56.2	825	308
394	13.3	466	188	538	24.8	610	623	682	108	754	54.3	826	237
395	13.5	467	196	539	25.6	611	590	683	101	755	53.4	827	189
396	14.1	468	140	540	26.7	612	562	684	95.8	756	53.0	828	155
397	14.4	469	91.1	541	27.7	613	542	685	90.9	757	52.7	829	130
398	14.9	470	69.4	542	29.5	614	621	686	86.5	758	52.5	830	112
399	15.3	471	56.9	543	31.5	615	887	687	82.7	759	52.2	831	97.6
400	15.9	472	46.3	544	35.8	616	886	688	79.8	760	52.3	832	85.9
401	16.4	473	42.6	545	48.2	617	590	689	77.4	761	52.4	833	76.6
402	17.5	474	55.0	546	56.2	618	450	690	75.1	762	52.5	834	69.0
403	19.4	475	59.3	547	61.0	619	413	691	73.5	763	53.0	835	63.3
404	23.0	476	37.3	548	74.6	620	395	692	71.8	764	54.8	836	58.2
405	21.9	477	18.1	549	98.9	621	378	693	70.8	765	74.9	837	53.8
406	19.5	478	14.4	550	124	622	363	694	69.8	766	218	838	50.4
407	19.7	479	13.3	551	141	623	351	695	68.5	767	223	839	47.4
408	20.0	480	13.1	552	150	624	338	696	67.5	768	108	840	44.8
409	20.7	481	13.1	553	149	625	327	697	66.6	769	120	841	42.2
410	21.3	482	13.4	554	144	626	318	698	66.0	770	201	842	40.3
411	21.9	483	13.9	555	143	627	308	699	65.5	771	118	843	38.4
412	22.4	484	14.6	556	146	628	299	700	64.9	772	62.9	844	36.9
413	22.9	485	15.0	557	153	629	291	701	64.1	773	54.7	845	35.7
414	23.7	486	15.8	558	160	630	283	702	63.9	774	52.0	846	34.5
415	24.3	487	16.9	559	170	631	275	703	63.3	775	51.0	847	33.6
416	24.8	488	18.9	560	180	632	267	704	62.6	776	50.6	848	32.8
417	25.7	489	22.1	561	191	633	261	705	62.0	777	50.4	849	32.1
418	26.5	490	27.2	562	203	634	254	706	61.7	778	50.6	850	31.4
419	27.4	491	31.5	563	223	635	249	707	61.3	779	51.9		
420	28.4	492	31.2	564	261	636	243	708	60.8	780	54.0		
421	29.0	493	32.7	565	349	637	238	709	60.3	781	53.4		

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SUSTAINING MEMBER of the IESNA
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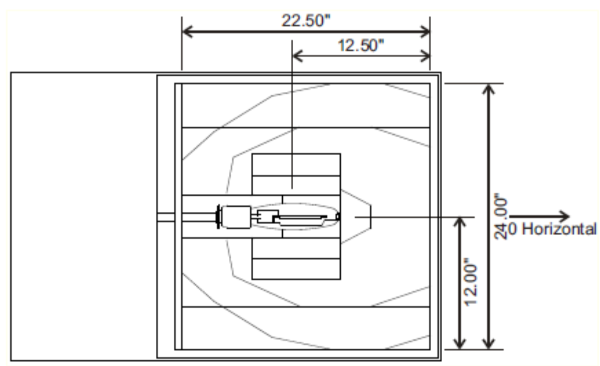
LTL NUMBER: 27707 DATE: 2012-01-10
PREPARED FOR: LEONARDO TECHNOLOGIES
CATALOG NUMBER: CALIPER TD 11-85 (NO LENS)
LUMINAIRE: CAST ALUMINUM HOUSING, FORMED WHITE ENAMEL ALUMINUM REFLECTOR WITH SPECULAR ALUMINUM UPPER REFLECTOR AND SPECULAR ALUMIUM SIDE REFLECTORS, NO ENCLOSURE
LAMP: ONE CLEAR HORIZONTAL S50 250 WATT ED18 HIGH PRESSURE SODIUM LAMP
BALLAST: ONE UNMARKED BALLAST
ELECTRICAL VALUES: 120.0VAC, 2.775A, 314.0W, PF=0.943
LUMINAIRE EFFICACY: 65.3 LUMENS/WATT
NOTE: THIS TEST WAS PERFORMED USING THE CALIBRATED PHOTODETECTOR METHOD OF ABSOLUTE PHOTOMETRY.*

IES CLASSIFICATION: **TYPE III**
LONGITUDINAL CLASSIFICATION: **MEDIUM**
CUTOFF CLASSIFICATION: **FULL-CUTOFF****
**CUTOFF DESIGNATION IS NOT DEFINED FOR ABSOLUTE PHOTOMETRIC TESTS. THIS CUTOFF RATING IS BASED ON THE MAXIMUM CANDELA READING PER LUMINAIRE RATED AT 1000 LUMENS.



FLUX DISTRIBUTION

LUMENS	DOWNWARD	UPWARD	TOTALS
HOUSE SIDE	8317.92	0.00	8317.92
STREET SIDE	12184.82	0.00	12184.82
TOTALS	20502.74	0.00	20502.74

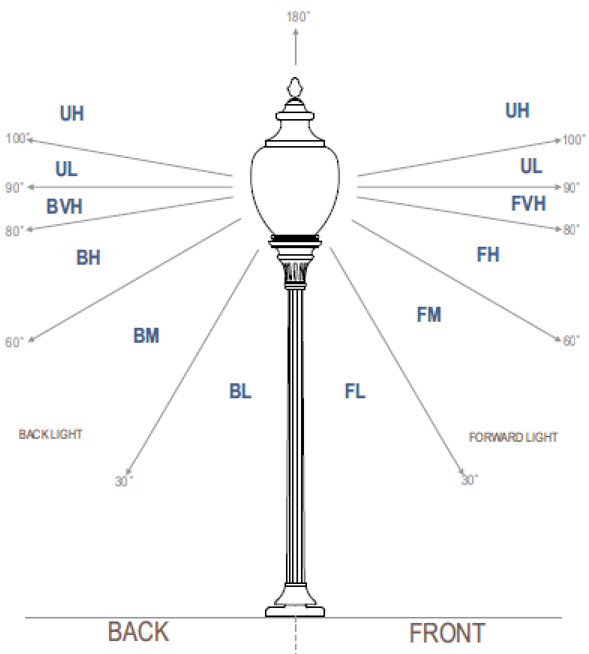
Approved By: [signature]

*DATA WAS ACQUIRED USING THE CALIBRATED PHOTODETECTOR METHOD OF ABSOLUTE PHOTOMETRY. A UDT MODEL #211 PHOTODETECTOR AND UDT MODEL #S370 OPTOMETER COMBINATION WERE USED AS A STANDARD. A SPECTRAL MISMATCH CORRECTION FACTOR WAS EMPLOYED BASED ON THE SPECTRAL RESPONSIVITY OF THE PHOTODETECTOR AND THE SPECTRAL POWER DISTRIBUTION OF THE TEST SUBJECT.

TESTING WAS PERFORMED IN ACCORDANCE WITH IES LM-79-08.
TEST ANGULAR INCREMENTS AND REPORT FORMATTING WAS BASED ON IES LM-31-95 (WITHDRAWN).

LTL LUMINAIRE TESTING LABORATORY, INC.
SUSTAINING MEMBER of the IESNA
905 Harrison Street · Allentown, PA 18103 · 610-770-1044 · Fax 610-770-8912 · www.LuminaireTesting.com

FLUX DISTRIBUTION TABLE BASED ON THE IESNA LUMINAIRE CLASSIFICATION SYSTEM



FLUX

ZONE	LUMINAIRE LUMENS	% OF LUMINAIRE LUMENS
FORWARD LIGHT	12185	59.4
FL (0°-30°)	1486	7.2
FM (30°-60°)	5864	28.6
FH (60°-80°)	4807	23.4
FVH (80°-90°)	27	0.1
BACK LIGHT	8318	40.6
BL (0°-30°)	1433	7.0
BM (30°-60°)	4797	23.4
BH (60°-80°)	2068	10.1
BVH (80°-90°)	20	0.1
UPLIGHT	0	0.0
UL (90°-100°)	0	0.0
UH (100°-180°)	0	0.0
TRAPPED LIGHT	NA	NA

BUG (**B**acklight, **U**plight, **G**lare) Rating	
Asymmetrical Luminaire Types (Type I, II, III, IV)	B3 U0 G3
Quadrilateral Symmetrical Luminaire Types (Type V, Area Light)	B3 U0 G2

Appendix G

HPS Shoebox Test Data—Bare Lamp

LTL LUMINAIRE TESTING LABORATORY, INC.

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Integrating Sphere Test Report

Relevant Standards
LM-51-2000 (Withdrawn), IES LM-31-1995 (Withdrawn), IES LM-46-2004
ANSI C82.6-2005
CIE 13.3-1995, CIE 15-2004

Prepared For
Leonardo Technologies, Inc.
Timothy Porco
Suite 610
2000 Oxford Drive
Bethel Park, PA 15102

Catalog Number
Caliper TD 11-85 (LAMP ONLY)

LTL Test Number
27709

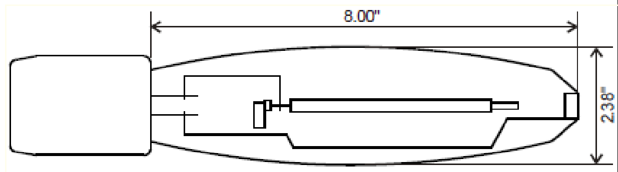
Test Date

2012-02-06

Prepared By	Approved By
Eric Gaudreau, Technician III	Brian Moyer, Engineer

Catalog Number:	Caliper TD 11-85 (LAMP ONLY)
Lamp:	One clear horizontal S50 250 watt ED18 high pressure sodium lamp
Lamp Catalog Number:	GE LucaLox LU250/H/ECO
Mounting:	Horizontal
Ballast/Driver:	One unmarked ballast

Luminaire



Summary of Results

Radiant Flux:	102500 mW
Luminous Flux:	28890 Lumens
Luminaire Efficacy:	91.0 Lumens/Watt
CCT:	1968 K
CRI (Ra):	24.5
Chromaticity (x):	0.5285
Chromaticity (y):	0.4107
Chromaticity (u):	0.3076
Chromaticity (v):	0.3586
Duv:	-0.0007

Test Conditions

Test Temperature:	25.4 °C
Voltage:	120.0 VAC
Current:	2.791 A
Power:	317.6 W
Power Factor:	0.948
Frequency:	60 Hz
Current THD:	11.2 %

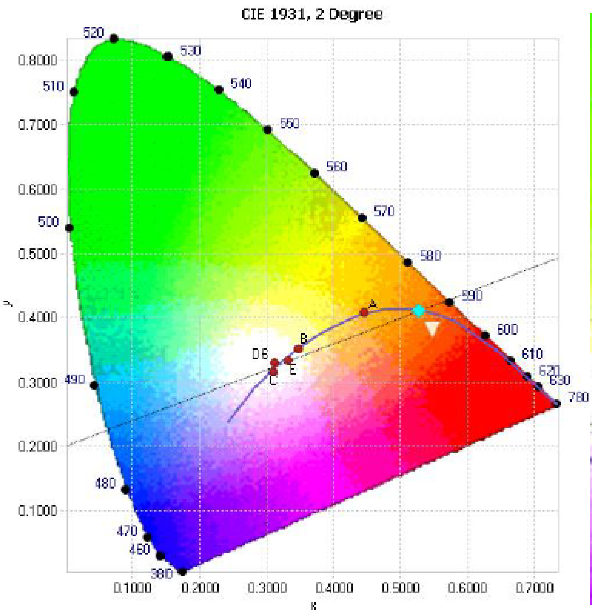
Testing was performed in a Labsphere SLMS7650 two meter integrating sphere using the 4π geometry method, a Labsphere CDS 1100 spectrometer, and LightMtrX software.
Absorption correction was employed for this measurement.

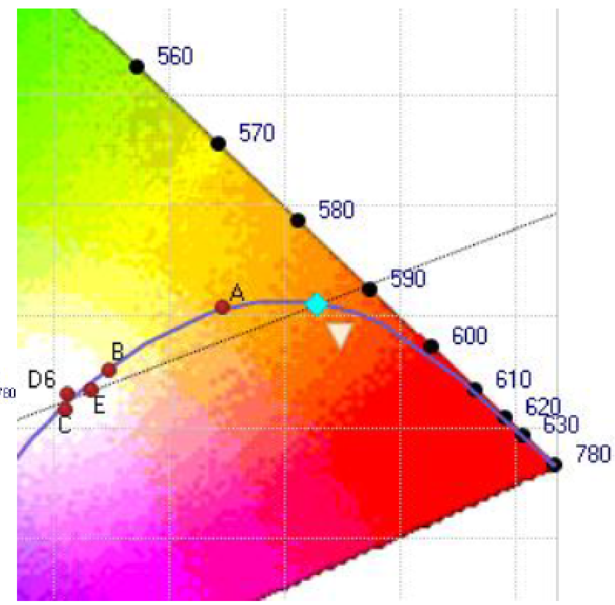
Chromaticity Coordinates

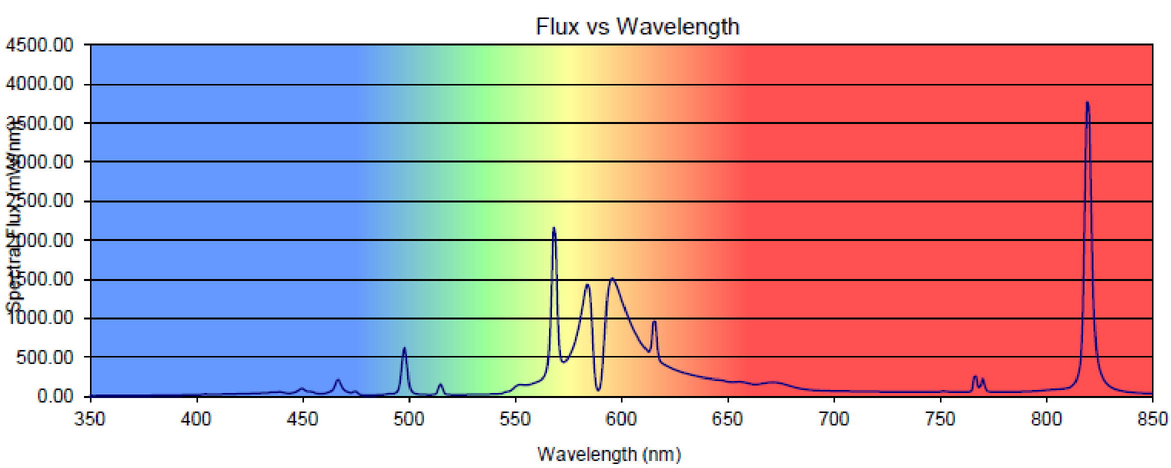
x	y	u	v	u'	v'	Duv
0.5285	0.4107	0.3076	0.3586	0.3076	0.5379	-0.0007

Color Rendering Index Detail

Ra (CRI)	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14
24.5	16.8	67.7	53.4	-5.4	14.1	58.8	35.4	-44.6	-186.7	49.6	-30.8	38.0	22.9	69.9







Spectral Power Distribution

λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm	λ(nm)	mW/nm
350	5.22	422	32.6	494	47.4	566	625	638	244	710	63.9	782	56.9
351	5.58	423	33.2	495	84.8	567	1280	639	239	711	63.3	783	56.4
352	5.50	424	34.1	496	221	568	2150	640	234	712	63.0	784	56.6
353	5.71	425	34.6	497	480	569	2040	641	229	713	62.6	785	57.3
354	5.71	426	35.6	498	623	570	1090	642	224	714	62.2	786	57.9
355	5.91	427	36.5	499	434	571	580	643	221	715	61.9	787	58.9
356	6.03	428	37.0	500	181	572	452	644	217	716	61.5	788	59.7
357	6.16	429	37.7	501	78.4	573	438	645	214	717	61.1	789	60.5
358	6.25	430	39.4	502	45.3	574	459	646	212	718	60.6	790	61.4
359	5.89	431	42.0	503	32.8	575	496	647	209	719	60.2	791	62.3
360	6.13	432	43.7	504	27.0	576	547	648	204	720	60.2	792	63.2
361	6.40	433	43.7	505	23.9	577	610	649	196	721	59.9	793	64.5
362	6.58	434	44.9	506	21.8	578	686	650	189	722	59.6	794	66.3
363	7.26	435	50.4	507	20.8	579	783	651	184	723	59.2	795	68.5
364	9.60	436	53.7	508	20.4	580	896	652	183	724	59.0	796	70.0
365	9.84	437	50.5	509	20.3	581	1040	653	184	725	58.6	797	72.1
366	8.12	438	54.2	510	20.3	582	1190	654	186	726	58.3	798	74.9
367	7.74	439	57.4	511	20.5	583	1340	655	189	727	58.0	799	78.1
368	7.63	440	54.1	512	22.4	584	1440	656	188	728	57.9	800	80.6
369	7.88	441	46.9	513	38.5	585	1350	657	185	729	57.9	801	82.8
370	8.01	442	41.9	514	117	586	976	658	180	730	57.6	802	84.5
371	8.60	443	37.2	515	159	587	454	659	173	731	57.2	803	86.4
372	8.62	444	36.1	516	97.2	588	154	660	167	732	57.1	804	88.1
373	8.94	445	41.2	517	32.7	589	74.8	661	161	733	56.8	805	90.4
374	9.34	446	49.4	518	22.7	590	117	662	157	734	56.7	806	92.9
375	9.44	447	59.6	519	20.7	591	332	663	155	735	56.8	807	95.6
376	9.80	448	75.1	520	19.7	592	726	664	156	736	57.1	808	98.2
377	9.96	449	95.7	521	19.2	593	1140	665	159	737	57.5	809	102
378	10.3	450	100	522	19.2	594	1400	666	164	738	57.4	810	107
379	10.6	451	80.9	523	19.6	595	1500	667	169	739	57.2	811	116
380	10.8	452	64.5	524	19.9	596	1510	668	175	740	57.0	812	132
381	11.1	453	60.1	525	20.0	597	1460	669	179	741	56.5	813	160
382	11.4	454	60.3	526	20.1	598	1400	670	182	742	56.3	814	207
383	11.7	455	52.7	527	20.2	599	1320	671	183	743	56.2	815	288
384	12.1	456	39.9	528	20.7	600	1240	672	182	744	56.1	816	464
385	12.5	457	34.5	529	21.1	601	1170	673	180	745	56.2	817	1030
386	12.7	458	32.5	530	21.6	602	1090	674	175	746	56.5	818	2420
387	13.2	459	32.4	531	21.7	603	1020	675	169	747	56.7	819	3760
388	14.1	460	34.8	532	21.9	604	958	676	162	748	57.1	820	3700
389	14.4	461	40.4	533	22.2	605	895	677	154	749	58.0	821	2610
390	14.5	462	49.1	534	22.5	606	837	678	146	750	60.0	822	1350
391	14.7	463	59.2	535	23.1	607	786	679	137	751	64.8	823	770
392	15.0	464	79.4	536	23.7	608	738	680	129	752	64.9	824	495
393	15.2	465	131	537	24.3	609	693	681	121	753	61.1	825	349
394	15.6	466	203	538	25.2	610	656	682	114	754	58.9	826	269
395	15.9	467	214	539	26.0	611	620	683	107	755	58.0	827	214
396	16.6	468	152	540	27.1	612	591	684	101	756	57.4	828	176
397	16.9	469	97.7	541	28.2	613	570	685	96.1	757	57.2	829	147
398	17.3	470	73.4	542	29.8	614	658	686	91.5	758	57.0	830	127
399	17.7	471	59.8	543	32.0	615	957	687	87.4	759	56.8	831	110
400	18.2	472	48.6	544	36.5	616	960	688	84.4	760	56.9	832	97.0
401	18.9	473	44.9	545	50.1	617	633	689	81.6	761	56.9	833	86.3
402	19.8	474	58.9	546	58.4	618	474	690	79.3	762	57.2	834	77.9
403	22.2	475	63.8	547	62.4	619	433	691	77.5	763	57.8	835	71.3
404	26.4	476	40.2	548	75.2	620	414	692	75.8	764	59.9	836	65.7
405	25.0	477	19.2	549	99.4	621	396	693	74.7	765	82.8	837	60.9
406	22.1	478	15.2	550	124	622	381	694	73.7	766	246	838	56.7
407	22.3	479	13.9	551	142	623	368	695	72.3	767	254	839	53.3
408	22.6	480	13.7	552	152	624	354	696	71.3	768	121	840	50.3
409	23.1	481	13.7	553	151	625	343	697	70.5	769	134	841	47.5
410	23.9	482	14.1	554	145	626	333	698	69.8	770	228	842	45.2
411	24.5	483	14.4	555	144	627	323	699	69.1	771	133	843	43.2
412	25.3	484	15.1	556	148	628	314	700	68.6	772	69.6	844	41.2
413	25.7	485	15.7	557	155	629	305	701	68.0	773	60.1	845	39.9
414	26.4	486	16.6	558	163	630	296	702	67.5	774	57.3	846	38.6
415	27.3	487	17.8	559	174	631	288	703	67.0	775	56.1	847	37.5
416	27.8	488	19.9	560	183	632	280	704	66.4	776	55.6	848	36.6
417	28.6	489	23.5	561	195	633	274	705	65.9	777	55.4	849	35.8
418	29.5	490	29.1	562	208	634	267	706	65.4	778	55.6	850	35.0
419	30.4	491	33.8	563	230	635	261	707	65.0	779	57.1		
420	31.4	492	33.5	564	270	636	255	708	64.5	780	59.6		
421	32.3	493	34.9	565	367	637	250	709	64.2	781	58.9		

Appendix H

Excerpts from PG&E and DLC QPL Websites

LED Street Light Rebates

Program Components
Pacific Gas and Electric Company's (PG&E) LED Street Light Program will offer street light customers on our LS-2 rate two ways to save energy and money when replacing traditional street lighting.

Rate Change
Customers who have installed or replaced existing street light fixtures after May 1st, 2009 with LED fixtures will be able to switch to a lower billing rate under the LS-2 rate schedule.

Potential LED Replacement Savings
Customers who have purchased and installed pre-qualified LED fixtures after May 1, 2009, may be eligible for rebates. Read below to learn more about which fixtures qualify.

Rebate/fixture	
Replace 70 watt fixture with new LED fixture	$50
Replace 100 watt fixture with new LED fixture	$75
Replace 150 watt fixture with new LED fixture	$100
Replace 200 watt fixture with new LED fixture	$125
Replace 250 watt fixture with new LED fixture	$150
Replace 310 watt fixture with new LED fixture	$175
Replace 400 watt fixture with new LED fixture	$200

Please email led@pge.com to request a street light rebate and rate change application.

Qualified LED Street Light Fixtures

Only well-designed LED products using the latest in LED technology that are appropriate for the application will offer the energy savings, lighting quality, and lifetime benefits sought. To help customers select quality LED street light fixtures, PG&E has worked with the U.S. Department of Energy and other utility partners to develop stringent performance standards. To qualify for the PG&E LED Street Light Program rebate, LED products must provide a variety of independent tests that help ensure they will deliver as promised.

The Design Lights Consortium (DLC) maintains a listing of all non-Energy Star LED

Additional Info

- LED Street Light Case Studies & Fact Sheets

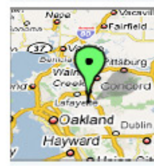
Related Links

- LS-2 Rate Schedule
- Table of Pre-Qualified LED Fixtures/Luminaires and Qualification Process
- ENERGY STAR® Learn About LEDs
- Department of Energy Solid State Lighting
- Department of Energy - Technology Fact Sheets (LEDs)
- Designlights Consortium - Manufacturer Application Overview

Carbon Calculator

What's your carbon footprint?

→ Learn more



Find Outages in Your Area

Visit the electrical system outage map.

→ View Map

Money-Back Solutions for Pre-K—12 Schools

→ Learn more

products meeting the performance standards required of our programs. In addition to these specifications, PG&E requires that LED Street Light products also meet the following service requirements:

- Photo Controls: Fixtures must be socket ready for electronic type photo controls meeting American National Standards Institute (ANSI) standard C136.10 with a turn on value of 1.0 foot-candles and a turn off value of 1.5 foot-candles. Electro-mechanical or thermal type photo controls are not acceptable.
- Manufacturer Labeling: Wattage Stickers identifying the fixture technology (LED) and total fixture wattage that follows ANSI Standard C136.15, already used by nearly all manufacturers and customers for identification of light types currently included in the standard.

If you are a manufacturer wishing to submit LED Street Light products for inclusion in PG&ampE's program, please review information on the DLC's Manufacturer Application Overview and then follow the requirements as outlined on the DLC's Manufacturer Application Process.

Customers who install non-qualified LED fixtures will still be able to switch to the lower LS-2 rate schedule, but will not be eligible for the rebates.

Customer wishing to install Induction Street Lighting may be eligible for both the lower LS-2 rate as well as a calculated incentive. See information on our Customized Retrofit Incentives page for information.

If you have any questions please contact us at led@pge.com.

Outdoor Retrofit Kits

DLC will accept QPL applications for SSL Outdoor Retrofit Kits. The testing and reporting requirements described below are intended to subject the retrofit kits to worst-case thermal conditions in order to assure confidence in lumen maintenance.

For testing purposes DLC specifies typical fixture housings for retrofit products to be tested in. These typical fixture housings are intended to provide testing results of the most common worst case conditions that the retrofit kits would be installed in. In providing this list of typical fixture housings, DLC does not endorse or exclude any particular make or model frame for use in energy efficiency programs. Note that in each recommended variation we state, "or approved other". In selecting a fixture for testing the applicant shall consider the purpose of subjecting the tested kit to extreme confinement for thermal endurance.

Applicants shall test and report fixture performance under the following restrictions and conditions.

- Required Tests & Reports All DLC QPL testing and reporting requirements that apply to new fixtures shall also apply to any outdoor retrofit kit application e.g.: LM79, ISTMT, IES file, product data sheet, etc. (Note that for lumen maintenance testing, the source manufacturer is responsible for light package's LM80 test).

Fixture Level Tests

LM79, ISTMT and Option 2 of LM80, shall be conducted in a fully functional DLC approved fixture with the kit properly installed per manufacturer's instructions.

Only *one* LM79, ISTMT, IES file is needed for the retrofit kit to be tested on *one* of the fixtures approved below. Depending on which option you choose to use for LM80 will determine how many tests you need. If you choose Option 1: one LM80 report is needed. If you choose Option 2: you will need two LM79 reports to test the retrofit kit for 0hrs and then 6,000hrs on the fixture.

Manufacturer shall select a fixture for these tests among the following:

- Area & Roadway Luminaires
  - Cobrahead Fixture Retrofit Kits:
    - Kits shall be tested in
      - American Electric Roadway Series 115 Fixture
      - GE M250R2 fixture
      - Kim Archetype SAR
      - Cooper OVH Series or
      - Pre-approved equal
    - Kits must replace all reflectors and optical systems of existing fixture
- Shoebox Fixtures
  - If the kit may be applied to both cobraheads and shoebox fixtures, choose a fixture from among those listed herein under shoebox and cobrahead
  - If the kit is specific to shoebox fixtures (not applicable to cobraheads) the kit shall be tested in:
    - WideLite XL Excel-Lyte 400
    - Lithonia KAD Contour Series
    - Lumark TR Tribute
    - Kim Archetype SAR or
    - Pre-approved equal
  - Kits must replace all reflectors and optical systems of existing fixture
- Decorative Luminaires
  - Acorn, globe, etc. The kit shall be tested, fully and properly mounted in a glass or polymer globe with optics as similar as possible to the kit's intended use
    - King Luminaire K400 series
    - Lexalite Lindy Model 424
    - GE Patriarch Luminaire
    - Holophane GV Luminaires Washington PostLite or
    - Pre-approved equal
  - Kits must replace all reflectors and optical systems of existing fixture

Application Review

DLC shall log, analyze and evaluate outdoor retrofit kit applications in accordance with procedures followed for any individual fixture application: 1) for completeness and accuracy of the filed application data and 2) for qualification according to DLC category specifications.

For outdoor retrofit kit applications DLC will apply the appropriate category and the specification values which are in effect as of the date of application submission. These categories are the following:

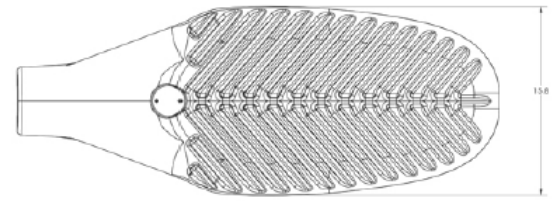
- Outdoor Pole or Arm Mounted Area and Roadway Luminaires
- Outdoor Pole or Arm Mounted Decorative Luminaires

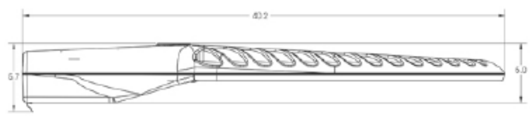
Appendix I

Sample LED Efficacies at 3000 and 4000 K

RX2 LEDGINE (160 LED's) (RX2160) Specification Sheet

Project Name:	Location:	MFG: Philips Hadco
Fixture Type:	Catalog No.:	Qty:





Ordering Guide

Example: RX2160 A 2 W A 5 N N S N

Product Code	RX2160	RX2 LEDGINE (160 LED's)	
Finish	A B H I	Black White Bronze Gray	
Optics	2 3 4 5	Type II Type III Type IV Type V	
Color Temperature	W N C	3000K 4000K 5700K	
Voltage	A B	120-277 VAC 347-480 VAC	*2
Drive Current	5	530 mA	
Photo Control	N R	None Twist-lock Receptacle	
Dimming Control	N DA DB DC DD DE DF DG DH DJ DZ W	None 4 Hrs 25% Reduction 4 Hrs 50% Reduction 4 Hrs 75% Reduction 6 Hrs 25% Reduction 6 Hrs 50% Reduction 6 Hrs 75% Reduction 8 Hrs 25% Reduction 8 Hrs 50% Reduction 8 Hrs 75% Reduction Custom Dimming Schedule Wireless Controls	 *3 *1
Surge Suppression	S A	Standard Built In <3kV Additional 10kV/10kA	
House Side Shield	N H	None House Side Shield	

*1 Consult Factory for W Wireless Controls.
*2 Dynadimmer Dimming Control (DA-DZ) only available with 120-277 VAC.
*3 Consult Factory for DZ Custom Dimming Schedule.

Specifications

TOTAL PHILIPS HADCO SYSTEM:

Total end-to-end, vertically integrated Philips Hadco System – Philips Lumileds LEDs, Philips LEDGINE LED platform, Philips Lighting Electronics Advance driver, integral Philips dimming / controls, Philips Hadco luminaire. Our comprehensive extended warranty covers the entire luminaire as shipped from factory.

APPLICATIONS:

The RX2 is the perfect LED solution for roadway lighting and is the ideal luminaire for both new and retrofit installations. Other application locations include: residential streets, city streets, campuses and parking lots. The performance, energy savings, and uniformity of this luminaire allow for it to be a one to one replacement for standard HID cobra-head style luminaires.

CONSTRUCTION:

The housing is constructed of low copper die-cast aluminum with a traditional cobra-head style, low profile and EPA. The housing is a unique thermal dissipating design with wide angular channels that allow for natural removal of dirt and debris. Two tool-less clips allow for access to the driver and wiring compartment. The hinged door is removable for serviceability and upgradability. The Philips LEDGINE LED platform has precision designed, injection molded optic plates behind a single tempered glass lens. The lens and lens frame gaskets are robotically applied. The LED optics chamber is IP66 rated. The luminaire is designed to mount to a 1.5" to 2.5" O.D. or 1.25" to 2" NPS horizontal tenon or arm, minimum 6" long. Complies with ANSI C136.3 and ANSI C136.14. A bubble level is built in as well as mounting steps that allow for a +5° to -5° tilt, in 2.5° increments. There is a dual clamp mounting system. Mounting clamps are made of HSLA steel and are zinc plated. Fasteners are made of stainless steel. A large terminal block is directly in line with incoming power wires and accepts up to 6 gauge wire. There is an option for a 360° rotatable twist lock photocell receptacle. Tenon guard protects against birds and similar intruders.

LED SPECIFICATIONS:

RX2 LEDGINE (160 LED's) (RX2160) Specification Sheet

Project Name:	Location:	MFG: Philips Hadco
Fixture Type:	Catalog No.:	Qty:

Refer to IES files for energy consumption and delivered lumens for each option. Based on in-situ thermal testing and data from Philips Lumileds and Philips Advance, expected to reach 80,000 hours with >L70 lumen maintenance @ 25°C. The Philips LEDGINE uses Philips Lumileds Rebel LEDs. Color temperatures available are ANSI Bins 3000K, 4000K, and 5700K CCT. Multiple distributions are available including Type 2, 3, 4 and 5.

ELECTRONIC DRIVER:
Integral Philips Lighting Electronics Advance XITANIUM LED drivers (2 per luminaire). Standard drivers provide 0-10V dimming capability and universal voltage input from 120-277VAC or 347-480VAC, 50-60Hz. All XITANIUM LED drivers are RoHS compliant. The LED drivers have <3kV surge suppression built in, 10kV is an additional option (see Ordering Guide). The LED drivers are installed on the enclosure door, keeping it mechanically and thermally separated from the canopy which doubles as the LED array heat sink. This allows LED driver case temperatures to remain well below the maximum rated temperature for enhanced reliability and lifetime. IP66 rated.

FINISH:
Thermoset polyester powdercoat is electrostatically applied after a five-stage conversion cleaning process and bonded by heat fusion thermosetting. Laboratory tested for superior weatherability and fade resistance in accordance with ASTM B117 specifications. Powdercoat is 3.0 - 6.0 mil thickness. Textured finish.

OPTIONS:
Optional integral surge suppression device tested in accordance with ANSI/IEEE C62.45 per ANSI/IEEE C62.41.2 Scenario I Category C High Exposure 10kV/10kA waveforms for Line-Ground, Line-Neutral and Neutral-Ground. Enclosure for surge suppression device is constructed of high temperature, flameproof material with an 85°C maximum surface temperature rating. The device consists of a thermally protected transient overvoltage circuit and is designed for use with universal voltage ballasts and drivers. There is an option for a 360° rotatable twist lock photocell receptacle. The Philips Dynadimmer (120-277 VAC only) is an option with the RX2. There are 9 standard factory set dimming schedules available. A custom schedule (DZ) is available by contacting the factory. As an alternative, Wireless Controls options are also available - contact the factory for details.

IP RATING:
IP66: Dust-tight and sealed against direct jets of water. No Ingress of dust. Will withstand 26.4 gallons of water per minute. Water projected in powerful jets shall not enter the enclosure in harmful quantities. The LED optics chamber is IP66 rated. The LED drivers are IP66 rated.

CERTIFICATIONS:
UL8750 and UL1598 compliant. ETL listed to U.S. safety standards for wet locations. cETL listed to Canadian safety standards for wet locations. Manufactured to ISO 9001:2008 Standards. Vibration tested to ANSI C136.31 for Bridge Applications. Luminaire photometric testing performed in accordance with IESNA LM-79 guidelines. Photometric .ies files that include "LM79" in the file name are verified by an independent NVLAP accredited lab. LEDs tested in accordance with LM-80 guidelines.

WARRANTY:
5 year extended warranty

AWARDS & RECOGNITIONS:
Buy American and ARRA Compliant - commercially available off-the-shelf (COTS) product proudly designed and Made in the U.S.A. Listed on the DesignLightsTM Consortium (DLC) Qualified Products List (QPL) - see certification letter(s) for details.

ACCESSORIES:
House Side Shield - can be ordered as an accessory, see RX2-HSS specification sheet. Replacement lens - contact factory.

Width:
15.8"

Height :
5.0"

Length:
40.2"

EPA:
.82 sq. ft.

Max. Weight:
32 lbs

IESNA Classifications:
See .ies files. Deprecated: Refer to BUG Ratings.

BUG Ratings:
See photometric .ies files for details.

RX2 LEDGINE - IES FILE DATA

Model Number	mA	Wattage	Delivered Lumens	LPW	Color Temp	BUG (per TM-15-11)
RX2120 2H W A 5	530	203	9907	49	3000	B2-U0-G2
RX2120 3H W A 5	530	202.8	9819	48	3000	B2-U0-G2
RX2120 4H W A 5	530	205.7	9531	46	3000	B2-U0-G2
RX2120 5H W A 5	530	203.1	9214	45	3000	B3-U1-G2
RX2160 2H W A 5	530	277.7	13487	49	3000	B3-U0-G2
RX2160 3H W A 5	530	278	13387	48	3000	B3-U0-G2
RX2160 4H W A 5	530	274.3	12708	46	3000	B3-U0-G2
RX2160 5H W A 5	530	277.6	12648	46	3000	B4-U1-G2
RX2120 LM79 2H N A 5	530	207.6	13886	67	4000	B3-U1-G2
RX2120 3H N A 5	530	207.9	13117	63	4000	B3-U1-G2
RX2120 4H N A 5	530	203.7	12708	62	4000	B3-U0-G2
RX2120 5H N A 5	530	209.7	13329	64	4000	B4-U1-G2
RX2160 LM79 2H N A 5	530	274.1	18014	66	4000	B3-U1-G2
RX2160 3H N A 5	530	275.3	17850	65	4000	B3-U0-G2
RX2160 4H N A 5	530	271.6	16944	62	4000	B3-U0-G2
RX2160 5H N A 5	530	274.8	16864	61	4000	B4-U1-G2
RX2120 2H C A 5	530	209.4	13950	67	5700	B3-U0-G2
RX2120 3H C A 5	530	206.9	13256	64	5700	B3-U0-G2
RX2120 4H C A 5	530	207.8	12962	62	5700	B3-U0-G2
RX2120 5H C A 5	530	211.4	13444	64	5700	B4-U1-G2
RX2160 2H C A 5	530	279.7	17943	64	5700	B3-U0-G2
RX2160 3H C A 5	530	280.8	18207	65	5700	B3-U0-G2
RX2160 4H C A 5	530	277	17283	62	5700	B3-U0-G2
RX2160 5H C A 5	530	281.8	17925	64	5700	B4-U1-G2

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