Advanced Lighting Systems for Externally Lit Billboards

ET 08.12 Report

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ABBREVIATIONS AND ACRONYMS

CCD	Charge Coupled Device
CMH	Ceramic Metal Halide
CCT	Correlated Color Temperature[1]
CRI	Color Rendering Index
EB	Electronic Ballast
fc	Footcandle
HID	High Intensity Discharge
HPS	High Pressure Sodium
IES	Illuminating Engineering Society of North America
ILC	Integrated Lighting Concepts, Inc.
LED	Light Emitting Diodes
LDD	Lamp Dirt Depreciation
LLD	Lamp Lumen Depreciation
LLF	Light Loss Factor
lm	Lumen
LPD	Lighting Power Density
LPW	Lumens per watt
MH	Metal Halide
mW	milliwatt
kW	kilowatt
kWh	kilowatt-hour
nm	nanometer
NPV	Net Present Value
PSMH	Pulse Start Metal Halide
ROI	Return on Investment
SCE	Southern California Edison Company
SCLTC	Southern California Lighting Technology Center
W	watt

FIGURES

TABLES

CONTENTS

EXECUTIVE SUMMARY

Southern California Edison's (SCE) Emerging Technology Program assesses technologies that have the potential to reduce electric energy use. This report assesses the energy savings potential and attendant visual impacts of four advanced lighting sources and systems used to externally light billboards.

The main objectives of this project are to determine:

- Available lighting energy savings from the new and improved systems vs. baseline metal halide systems.
- Light levels and uniformity provided by the new systems.
- Visual impacts, as determined by a subjective survey of users of various new systems.
- Correlation of the subjective survey results to the objective energy and photometric results.

In September 2009 12 sign lighting systems, baseline and new source, were designed, procured, prepared, and assembled for lab, field, and subjective survey tests.

A cross-section of manufacturers was invited to participate. Each was given requirements for meeting benchmarks for target light levels and uniformities based on the recommendations of Illuminating Engineering Society of North America (IES) as well as the present baseline of the customer. This yielded 15 lab and 15 field tests, which produced a baseline as well as five source class winners. The visual impacts of the baseline and source class winners were surveyed in late November 2009, completing the project.

One hundred and sixty-eight footcandle (fc) measurements were taken, per field test, uniformly on a 14'h x 48'w billboard. The billboard was lit at various times by several metal halide, linear fluorescent, induction fluorescent, and LED light-sets. One lighting solution had the highest visual impact, best average and maintained illuminance levels as well as the lowest 20-year lifecycle cost. This lighting solution consisted of two fixtures, each housing a 400 watt (W) Ceramic Metal Halide (CMH) source and magnetic ballast. This solution resulted in approximately 951 kilowatt hour (kWh) annual energy savings per billboard compared to the most likely Baseline lighting configuration, and 1,283 kWh annual energy savings against the Title 24 requirement. In addition to identifying a market-available lighting solution that may save 951 kWh per billboard in SCE service territory, two other worthy candidates were discovered in this report. The first is a lighting configuration that uses 16 amalgam fluorescent lamps (four lamps per fixture and four fixtures) and provides comparable performance and energy savings to the aforementioned CMH configuration at a similar cost. The second is a LED-based system that can outperform all candidate lighting systems in most categories except cost. The abundance of market-available and cost-effective (or, soon to be cost-effective) lighting solutions suggests that the California Title 24 lighting power density allowance of 2.3 watts per square foot of signage can be reduced to 2.0 W/ft^2 or even lower with minimal economic impact on the operators of lighted billboards in California. Economic life cycle cost analyses conducted in support of this study indicate that the efficient lighting solutions are cost-effective for newly constructed billboards and also can act as a retrofit to existing billboards.

INTRODUCTION

The purpose of this study is to characterize the performance of the baseline and various new sources to externally lit billboards. Probe start metal halide (MH), standard color rendering and high color rendering index (CRI)[2], quartz pulse start metal halide (PSMH), and ceramic metal halide (CMH), a high CRI source, all were tested with magnetic ballasts. Electronic ballasts (EB), standard CRI, PSMH, and linear fluorescent amalgam T5HO systems, were tested. Induction fluorescent and LED systems were also tested. Finally, new 330W CMH lamps are available to directly replace (no ballast change required) 400W MH or PSMH lamps. These 330W lamps were lab and field tested.

BACKGROUND OF BILLBOARD ILLUMINATION

The primary purpose of billboard lighting is to capture attention and deliver a product or idea message to motorists. Billboard illumination strives to maintain, at nighttime, the same impression that a billboard imparts to motorists during daytime. It does so by maintaining the juxtaposition of the typically bright, bold colors that comprise most billboard signage. Additional important design considerations are:

- Minimizing maintenance costs by reducing the frequency of lamp replacement and increasing the ease of accessing the fixture.
- Minimizing any potential shadows that may be cast on the billboards during daytime by the light fixtures.
- Minimizing light trespass to the sides of the sign and upward light pollution.
- Preventing excessive light from billboard (a light source itself) to the observer's eye
- Improving energy efficiency

Due to their extended life and low operating costs (energy efficiency); high intensity discharge (HID) sources have dominated the outdoor illumination market. Initially, high pressure sodium (HPS) lamps dominated most of the outdoor lighting market, but because of poor CRI they weren't often used for signage. MH lamps, with their much improved light quality, were restricted to high-end applications due to their shorter life, and lower luminous efficacy. Billboard illumination is one of the "high-end" markets, where the need for high color rendering has naturally led to a market dominated by MH lamps. The MH lamps have several notable drawbacks, such as an undesirable shift in light color and poor lumen maintenance. Most light sources grow dimmer with age, and an illumination metric called lumen maintenance describes the severity of this effect. MH lamps achieve 48% of initial light levels at the end of their service lives and their lumen maintenance is 0.48. Much of the billboard lighting market relies on first generation MH lamps. Other sources, and newer generations of MH lamps (PSMH, CMH, and high CRI PSMH) demonstrate marked improvement in lumen maintenance.

ALTERNATIVES TO FIRST GENERATION METAL HALIDE LAMPS

Advancements in lighting technologies allowed for several alternatives to standard probe-start MH lamps that are appropriate for illuminating billboards. These include:

- Pulse-Start Metal Halide (PSMH) Lamps: These are second generation MH lamps that provide higher luminous efficacies and better lumen maintenance than probe start MH lamps. PSMH lamps are approaching 100 lumens per watt (lm/W) in luminous efficacy. High CRI versions are also available and were tested.
- Ceramic Metal Halide (CMH) and high CRI quartz PSMH (HPSMH) Lamps: These are third generation MH lamps, have the highest CRI of all gas discharge lamps, and retain light levels and color stability better than other gas discharge lamps. Moreover, the luminous efficacies of CMH and PSMH lamps have luminous efficacies at or near 90 lm/W. With these attributes, the duo is poised to supplant HPS, MH, and PSMH as the dominant HID light sources where high CRI is important.
- Light Emitting Diodes (LED): LED has recently entered the outdoor lighting market and is rapidly improving. LED has a long lifetime (50,000 to 150,000 hours[3]), design lumen depreciation of about 30% in the 40,000 to 50,000 hours range, high bare-chip luminous efficacy (85 to 108 lumens per watt (LPW)), and high CRI (70 to 80+).
- High Efficiency T5HO Fluorescent Light Fixtures: These have similar efficacies and better color rendering than LED, and at a fraction of the cost. The lamps also feature lifetimes from 20,000 to 35,000 hours, and low lumen depreciation.
- Induction Fluorescent Lamps: These were invented by Nikola Tesla in 1891 but the design was not used for almost 100 years. Modern induction lamps came to market in the early 1990's and boasted luminous efficacies of about 70 lm/W, having good color rendering at about 80, and system lifetimes of 100,000 hours.

ENERGY EFFICIENCY REGULATIONS

Both 2005 and 2008 California Title 24 regulations require that all externally illuminated outdoor signage either comply with a maximum wattage allowance of 2.3 W/ft^2 or limit the usage lighting technology to a short list of efficient technologies (e.g. LED, Fluorescent) which excludes probe start metal halide lamps. Moreover, CA Title 20 regulations limit all probe start ballasts manufactured after January 1, 2009 to have a minimum ballast efficiency of 94 percent. This essentially phases out probe start ballasts as they do not achieve 94 percent efficiency.

PROJECT OBJECTIVES

The main objectives of this project are to determine the:

- Lighting energy savings that can be achieved by using various new and/or improved signage systems in lieu of 400W baseline probe start metal halide with magnetic constant wattage autotransformer (CWA) ballasts.
- Light levels and attendant uniformities provided by the various systems.
- Cost/benefit comparisons of baseline versus the new systems.

- Visual impact, as determined by a subjective survey, of the various new systems against baseline.
- Correlation of the subjective responses to the subjective parameters listed above.

The following sections describe the tests and analyses used to achieve these main project objectives.

METHODOLOGY

This study strives to consider a wide range of potential lighting solutions and to obtain both field and lab measurements, focus-group survey data, and economic analysis for the most competitive lighting technologies in the billboard lighting market. As a result, it was necessary to have a two-stage filtering system for consideration of candidate technologies. During the first stage of filtering, SCE technical staff made a survey of all market-available lighting technologies and distilled a list of the light sources that were likely to meet the billboard lighting criteria. Several representatives from each category were contacted and invited to enter their lighting solutions for further study. During the second stage of filtering, field photometric measurements, lab photometric and power measurements, as well as AGI32 computer models were employed to identify the most competitive lighting solutions from several competing technologies. These included HID, LED, and Induction and Linear Fluorescent. Further studies, such as an economic life cycle cost analysis and a customer focus-group survey, supported by full-scale billboard demos, were conducted for the resulting “short-list” of lighting solutions.

TEST SITES

There were three test sites used in this study. Integrating Sphere tests were conducted at SCE’s Southern California Lighting Technology Center (SCLTC) in Irwindale, CA. Photometric measurements were taken at an outdoor facility in Los Angeles, CA as shown in Figure 1. After the direct measurements, six full size billboards (one the MH baseline and the others source class winners as determined by the lab, computer and field tests) were shown to a walk-by audience of over 320 in a movie studio in Studio City; all 320 individuals surveyed completed a questionnaire.

FIGURE 1. PHOTOMETRIC TESTING AT THE OUTDOOR FACILITY

LIGHTING RECOMMENDATIONS AND BASELINE LIGHTING CHARACTERISTICS

RECOMMENDED ILLUMINATION LEVELS

The IES Lighting Handbook[4] recommends illuminance levels between 20 and 100 footcandles (fc) and uniformity, defined as the ratio of maximum to minimum light levels, of 4.0 or less for billboards. The 20 fc level is most applicable for billboards since they are reflective surfaces with dark surrounds. The IES Lighting Handbook also recommends that light fixtures should not cause much glare or obstruct the view of the billboard. It is important to note that, in the case of billboards, the IES guidelines are not legal requirements as they often are for other lighting applications. The IES recommendations for uniformity in billboard lighting are considered unrealistic versus most of the technologies studies since only one of the tested technologies achieved a maximum to minimum light level ratio under 4.0. The current industry standard practice of four 400W Probe Start MH fixtures, however, does not achieve a maximum to minimum uniformity ratio of 4.0, but is able to achieve an average to minimum uniformity ratio of 4.0. As a result, we base our recommended illumination characteristics on current standard practice. The recommended lighting characteristics are a minimum in-service illumination of 20 fc, and uniformity, defined as the ratio of *average* light level to minimum light level, of 4.0 or less.

POWER REQUIREMENTS

California Title 24[5] limits outdoor signage lighting power density (LPD) based on lighting application. In particular, the 2008 Non-residential Compliance Manual allows up to 2.3 watts per square foot of externally illuminated signage. According to the guidelines in the manual, the illuminated area attributable to the 12 lights is 48'h x 14'w = 672 ft^2, and the corresponding lighting power allowance is 1,546W. The current industry practice of four 400W MH fixtures does not comply with the California 2005 Title 24 code. However, a number of market-available lighting solutions that can exceed the current standard baseline and comply with California Title 24 have been identified. Table 1 lists the illumination and power usage recommendations for billboard lighting.

TABLE 1. RECOMMENDED BILLBOARD ILLUMINANCE AND POWER USAGE

LIGHTING PARAMETER	RECOMMENDED LEVEL
Minimum In-Service Illuminance (fc)	20
Uniformity Ratio, Maximum-to-Minimum	4:1
Maximum Power Usage watts/ft^2	2.3

ACHIEVING THE LIGHTING RECOMMENDATIONS

In lighting design it is customary to specify an initial illuminance that exceeds the design illumination goal in order to compensate for lumen depreciation that occurs over time. Typically, the minimum in-service illumination is estimated, and the initial lumens are specified such that the minimum in-service illumination meets or exceeds the design illumination goal.

Two distinct lumen depreciation factors are used to estimate the minimum in-service illumination levels, based on initial photometric measurements. The product of the two factors is called the systemic light loss factor (LLF).

The first depreciation factor is the lamp lumen depreciation (LLD), which is the ratio of a lamp's illuminance at re-lamping time to a lamp's initial illuminance.

The second factor is luminaire dirt depreciation (LDD), which is the gradual decrease in fixture light output caused by dirt accumulation. LDD is the ratio of a lamp fixture's illuminance at replacement or cleaning time to initial illuminance, assuming that lamp sources are of equal illuminance at both times.

The overall loss of light is the product of the two aforementioned factors and is determined individually for each source/fixture combination listed in this report. The determination of the LLFs is discussed in Appendix E: Determination of Light Loss Factors.

BASELINE TECHNOLOGY

The predominant lighting configuration consists of four fixtures, each housing a 400W probe start MH lamp. This lighting configuration exceeds the 2.3 W/ft^2 lighting power density allotted by current California 2008 Title 24 requirements. The following three lighting configurations closely most resemble the existing market solution yet comply with the upcoming Title 24 regulation:

1. Four with 320W standard or high CRI quartz PSMH lamps (326W and 368W connected respectively),

2. Four 330W (380W connected) high CRI CMH lamps that require no new ballast and can work with either probe-start or pulse-start ballasts.
3. Three 400W (455W connected) PSMH lamps

In this report, the 4 x 400W MH setup will be referred to as the United States Baseline configuration, while a 3 x 400W (455W connected) PSMH setup will be referred to as the California Baseline lighting configuration.

The United States Baseline MH fixture/source combination has the following ratings:

- A bare-lamp initial light output of 32,000 lm
- A fixture efficiency of 59%
- A power requirement of 400W (without ballasts) and 455W (with ballasts)
- A rated bare lamp initial luminous efficacy of 80 lm/W (32,000 lm/400W) and a combined fixture, lamp, and ballast initial luminous efficacy of 41.5 LPW (18,880 lm/455W)
- A CRI of 62
- A rated lifetime of 15,000 hours
- A ratio of light output at 15,000 hours (spot re-lamping time) to initial light output is 0.50
- Four fixtures per 14'h x 48'w billboard

The California Baseline Fixture has the following ratings:

- A bare-lamp initial light output of 31,000 lm
- A fixture efficiency of 59%
- A power requirement of 400W (without ballasts) and 455W (with ballasts)
- A rated bare lamp initial luminous efficacy of 78 lm/W (31,000 lm/400W) and a combined fixture, lamp, and ballast initial luminous efficacy of 40.2 LPW (18,290 lm/455W)
- A CRI of 65
- A rated lifetime of 15,000 hours
- The ratio of light output at 15,000 hours (suggested group re-lamping time) to initial light output is 0.81
- Three fixtures per 14'h x 48'w billboard

This configuration is called the California Baseline because it conforms to Title 24 requirements and has a LPD of 2.03W/ft^2; it is the configuration that is most similar to the newly constructed (post-2005) billboard lighting stock in SCE service territory.

ALTERNATIVE LIGHTING SOLUTIONS

There were 13 separate lighting configurations field-tested (15 total including 2 retests) at the outdoor facility in Los Angeles. Additionally, five lighting configurations were simulated, but not tested. The various lighting solutions can be placed in broad categories including:

- Systems that employ three or four MH fixtures
- Systems that employ two MH fixtures
- Systems that employ four linear fluorescent fixtures
- Systems that employ three or four induction fixtures
- Systems that employ four LED fixtures
- Systems that provide a continuous linear LED source.

METAL HALIDE SYSTEMS

The MH systems included the United States Baseline probe start source, standard and high CRI PSMH sources on magnetic ballasts, a standard PSMH on electronic ballasts, and CMH sources on magnetic ballasts. The study also included novel CMH sources that can be used with both pulse-start and probe-start ballasts. There were two types of fixtures used, both from the same manufacturer, for all the MH/PSMH/HPSMH/CMH tests. The standard fixture is designed so that three or four ballasts are required per 48'h x 14'w billboard; additionally, a newer fixture by the same manufacturer satisfies the task with just two fixtures per billboard. Source wattages ranged from 295 to 400 nominal watts; one manufacturer's lamp, the quartz high CRI, has a 320W nominal but 295W spec sheet. There were 10 configurations of MH-type lighting systems considered in this study.

INDUCTION SYSTEMS

The induction systems in this study used 165W and 200W sources. A four-fixture 150W system was also simulated, but never made it to the lab or field tests because it failed to start after its successful 100-hour burn-in. Repeated attempts to revive it failed and we pronounced it dead. Sources were provided by three manufacturers, and there were two types of fixtures tested. However, only one fixture type was specifically designed for billboard lighting. There were four configurations of induction lighting systems in this study.

LED SYSTEMS

Two LED lighting systems were tested. The first system was essentially a roadway fixture, while the second system was designed solely for illuminating outdoor signage. The two systems varied significantly in ease of installation, LED source quality, and performance.

LINEAR FLUORESCENT SYSTEMS

One manufacturer submitted four- lamp T5HO fluorescent fixtures for study. These fixtures are an area light derivative with asymmetric reflectors designed to meet the required duty. They use amalgam lamps that provide more light over a wider range of ambient temperatures than standard lamps. These lamps are discussed briefly in Appendix D: Amalgam Linear Fluorescent Lamps. A major outdoor signage provider's previous experience with these fixtures suggests that minor design improvements are necessary to strengthen fittings and mountings and also improve water tightness.

TECHNICAL APPROACH

Comparative measurements of the lighting systems were taken. Laboratory measurements included:

- Light output levels
- Light quality
- Power usage
- Power quality factors

Field measurements included:

- Determining the average light levels delivered on the test billboard,
- Determining the light uniformity on target
- Surveying 320 observers' reactions to six billboards illuminated by several competing fixtures

LAB TESTS AT THE SCLTC

The total light outputs, spectral compositions, and power were measured at SCLTC for the various fixtures.

All tests used a Labsphere SLMS LED 76506 integrating sphere, as shown in Figure 2. The integrating sphere is equipped with a 2048 pixel charge-coupled device (CCD) spectrometer with a calibrated spectral range sensitivity of 350 nanometer (nm)-850nm and a photometric range of 30 to 100,000 lm.

Each light fixture was placed in the integrating sphere, one at a time, and left on for at least 25 minutes. After the start of each of the ten tests, two measurements were taken at 0.5, 1, 1.5, 2, 2.5, 5, 10, 15, 20, 25, 45, 55, and 65 minutes. These results included:

- The total light output (measured in lumens)
- The spectral composition measured in milliwatt (mW)/nm for the range 350 nm $< \lambda <$ 850 nm, where λ is the wavelength of the light. This range spans the visible spectrum (400 nm $< \lambda <$ 700 nm).

In addition to the photometric measurements, the power usage and power factors were measured at one-second intervals throughout the test.

Power measurements were taken with an AEMC® PQL120 power meter that, for the wattages of interest, is accurate to 3%[7].

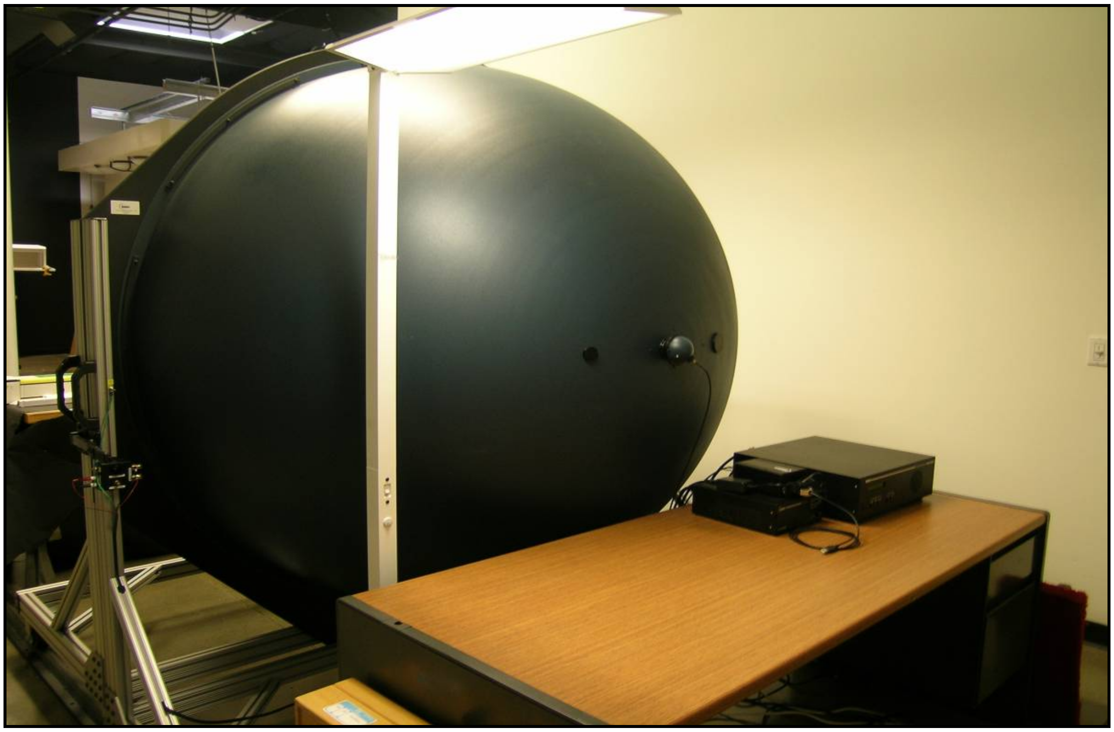


FIGURE 2. INTEGRATING SPHERE USED FOR LIGHT OUTPUT MEASUREMENTS AT SCLTC

FIELD MEASUREMENTS

In addition to the laboratory tests conducted at SCLTC, light-level measurements were made over a uniform vertical grid on the billboard at the test site. Lighting measurements were made at the site in September and October 2009 for the various configurations of lights. The measurements were taken in full darkness, between 1 ½ hours to 4 ½ hours after sunset.

A custom billboard was constructed from 12 standard billboard graphics showing a wide spectrum of color, contrast, and value. The luminaires were placed on the billboard's outriggers with the lighting placed upward from the base of the billboard in accordance with United States billboard lighting standards. Each test began by setting up a light meter and measuring system for recording point-by point illuminance on the billboard. A 2'h × 2'w measurement grid was employed, resulting in a total of 168 measurements for the 14'h x 48'w foot billboard.

To test the illuminance of each lamp at its full operation, the warm-up times of the different lamps were considered. The warm-up time of each tested lamp type is listed in Table 2.

TABLE 2. WARM-UP TIMES FOR VARIOUS LIGHT SOURCES

LAMP TYPE	WARM-UP TIME (MINUTES)
Metal Halide	20
Induction Fluorescent	10-15
T5HO Fluorescent	10-15
LED*	10

*LED lamps essentially have zero warm-up time.

LIGHT LEVEL SIMULATIONS

The lighting levels at the billboard were also simulated using AGI lighting analysis software[8]. The simulation output included light levels at the billboard on a 168-point 2'h x 2'w grid similar to that used during the actual light level measurements, enabling direct comparison between simulated and measured data. The simulations use data from ".ies" files, provided by the manufacturers that describe the light outputs of the fixtures. The light level simulation helped to identify ideal placement of the light fixtures. The AGI32 computer simulations were also used to estimate the light trespass for each lighting configuration.

HOURS OF OPERATION

In SCE service territory, most billboards are lit shortly after dusk and shut off at midnight. The annual hours of operation are determined by using light turn-on times from monitored streetlights controlled by a photocell in Inglewood, CA[9], and a light turn-off time of midnight. The resulting hours of operation are 1,839 hours. A small portion of the lights in SCE service territory may have an additional hour of operation, from one hour before dawn until dawn. This control scheme results in 2,204 annual hours of operation. Standard dusk to dawn photocell operation is rare but results in 4,314 hours per year.

VISUAL IMPACT SURVEY

A large indoor studio was fitted with six full-size (14'h x 48'w) billboards. Each billboard was set up in an individual viewing chamber, and all viewing chambers were separated by thick blackout style diffuse curtains. Each billboard contained the same image, but was lit by one of six competing lighting solutions. Over 320 observers participated in a survey that was designed to rate the six lighting technologies. The observers completed a survey questionnaire that asked them to rate the vividness, clarity, brightness, evenness of color, contrast, and overall look and impact of the billboard on a five-point scale. The observers were given instructions that directed them through the six billboards in varying orders, so that any bias in the ratings that may arise from ordering would be minimized, recognized during the analysis of the results, and, if necessary, corrected. The survey participants were instructed to avoid communication with other observers during the course of the survey, and the tours were staggered so there was a sole observer at any given billboard at most times. A more detailed description of the visual impact survey, including the survey instrument, is provided in Appendix B: Visual Impact Survey.

ILLUMINANCE RECORDINGS

According to IES publication TM-11-00, the recommended illuminance for a 14’h x 48’w electronic billboard at 250 ft is not more than .3 fc. A Nikon COOLPIX E5400 digital camera with a fisheye lens was used to take numerous pictures of the lighted billboard at various exposures. The Photo-Lux 2.0 luminance software was used to analyze the illuminance from the tested billboards at the camera position of 25-30 ft. These field-measured values were then used as a reference for AGI32 computer simulations, which, once verified with the field-measurements, were able to measure the highest illuminance from the lighted billboards at a distance of 250 ft. The analysis process is described in more detail in Appendix C: Luminance Camera Study.

RESULTS

This section presents and discusses the data collected from the lab tests, the field measurements, and the AGI simulations. First, a summarization of the manufacturer's specifications for the source lights is presented in Table 3.

TABLE 3. MANUFACTURERS' SPECIFICATIONS FOR THE VARIOUS SOURCES AND BALLASTS

LAMP / WATTS	BALLAST TYPE	CRI	CONNECTED LOAD	LIGHT OUTPUT (BARE LAMP LUMENS)	LAMP LIFE	LAMP ORIENTATION (AS REQUIRED BY FIXTURE)
MH-400	Probe Start Magnetic	62	455	32,000	15,000	Horizontal
High CRI PSMH 320[10]	PSMH Magnetic	90	368	22,500	20,000	Horizontal
CMH 330	PSMH Magnetic	90	380	33,000	20,000	Horizontal
PSMH 400	PSMH Magnetic	65	455	31,000	15,000	Horizontal
PSMH 400	PSMH Magnetic	65	455	40,000	20,000	Base Down Vertical
CMH 400	PSMH Magnetic	90	455	36,000	20,000	Base Down Vertical
PSMH 320	Electronic(E)	65	346	30,000	15,000	N/A
Induction 200 A	E Genset	90	210	15,695*	80,000	N/A
Induction 200 B	E Genset	82	210	16,000*	80,000	N/A
Induction 165	E Genset	80	177	12,000	80,000	N/A
F54T5HO Amalgam	E program Start	85	234	19,600	35,000	N/A
LED A	E Solid State	70	227	12,652*	50,000	N/A
LED B	E Solid State	70	61	2,359*	50,000	N/A

* Light output ratings include fixture efficiency.

RESULTS FROM SCLTC

The results from the lab testing at SCLTC are summarized in Table 4. The HID, LED, and fluorescent lamps and fixtures performed similarly to their ratings. Two of the three induction lamps tested had significantly lower light output and color rendering than claimed by the manufacturers.

TABLE 4. SCLTC MEASUREMENT RESULTS FOR LAMP/BALLAST/FIXTURE COMBINATIONS

LAMP / WATTS (NOMINAL)	BALLAST TYPE	CRI	CONNECTED LOAD	LIGHT OUTPUT (FIXTURE)	LPW
MH 400	Probe Start Magnetic	56	435	21,389	49
High CRI PSMH 320[10]	PSMH Magnetic	91	326	14,144	43
CMH 330	PSMH Magnetic	90	373	16,906	45
PSMH 400	PSMH Magnetic	58	447	19,574	44
PSMH 400**	PSMH Magnetic	63	456	31,261	69
CMH 400**	PSMH Magnetic	87	424	27,462	65
PSMH 320**	E	63	356	23,948	67
Induction 200 A	E Genset	73	208	12,335	59
Induction 200 B	E Genset	75	220	9,957	45
Induction 165	E Genset	77	177*	7,440*	42
F54T5HO Amalgam 218	E Program start	79	234	12,436	53
LED 180	E Solid State	74	227	12,652	56
LED 51	E Solid State	76	61	2,359	39

* Measured in a separate Integrating Sphere test in Orange, CA.

** These sources were in new and more efficient fixtures.

RESULTS FROM FIELD LIGHT LEVEL MEASUREMENTS

Table 5 shows the measured vs. simulated average light levels and uniformity ratios for various lighting configurations over the 48'h x 14'w measurement area. Some fixtures were tested or simulated in more than one configuration. The configurations are described in the Configuration column of this table. In this column, the numbers represent distance in feet, while the dashes represent fixtures. Table 5 includes some unexpected and noteworthy findings. For instance, the best four-fixture configurations tend to have worse uniformities than the best three-fixture or two-fixture lighting configurations. The three-fixture configurations had the best uniformity among the HID and induction sources, while the four-fixture sources were generally worse than two-fixture configurations. This is due to the fact that two-fixture or three-fixture configurations have more potential spacing, while the four-fixture configurations are constrained and cannot be placed further than 12 feet apart without losses in light delivered to the billboard, coupled with unacceptable levels of light trespass. The three-fixture setups performed remarkably better when the fixtures were spaced 16 feet apart. Simulations predicted and measurements confirmed that two fixtures can provide sufficient uniformity if spaced 24 feet apart. Of all the tested fixtures, the continuous linear LED fixtures cast the most uniform light on the billboards. Appendix A: Photographs of Lit Billboards contains photographs of identical billboards as illuminated by the various lighting configurations during the visual impact survey portion of this study.

TABLE 5. MEASURED AND SIMULATED LIGHT OUTPUTS AND UNIFORMITIES

LAMP / WATTS (NOMINAL)	BALLAST TYPE	CONFIGURATION	MEASURED MEAN ILLUMINATION	MEASURED UNIFORMITY	SIMULATED MEAN ILLUMINATION	SIMULATED UNIFORMITY
PSMH 400	PSMH Magnetic	Three-lamp, 12-12-12-12	32	7.9	58	6.2
PSMH 400	PSMH Magnetic	Three-lamp, 8-16-16-8	38	2.6	55	2.7
MH 400	Probe Start Magnetic	Four-lamp, 6-12-12-12-6	51	3.7	82	2.8
PSMH 400	PSMH Magnetic	Two-lamp, 12-24-12	70	3.4	64	3.9
CMH400	PSMH Magnetic	Two-lamp, 12-24-12	54	4.0	58	3.9
PSMH 320	Electronic	Two-lamp, 12-24-12	54	3.9	48	3.9
Induction 200 A	E Genset	Four-lamp, 6-12-12-12-6	38	6.5	41	5.2
Induction 200 A	E Genset	Three-lamp, 12-12-12-12	19	27.6	35	9.4
Induction 200 A	E Genset	Three-lamp, 8-16-16-8	N/A	N/A	37	6.1
Induction 200 B	E Genset	Three-lamp, 12-12-12-12	29	20.4	24	8.4
Induction 200 B	E Genset	Three-lamp, 8-16-16-8	N/A	N/A	24	6.6
F54T5HO Amalgam-54	Electronic	Four-lamp, 6-12-12-12-6	36	3.9	39	4.0
High CRI PSMH 320	PSMH Magnetic	Three-lamp, 12-12-12-12	33	7.8	41	6.2
High CRI PSMH 320[10]	PSMH Magnetic	Three-lamp, 8-16-16-8	N/A	N/A	39	2.7
LED 180	Solid State	Four-lamp, 6-12-12-12-6	21	5.7	30	3.2
Induction 165	E Genset	Four-lamp, 6-12-12-12-6	13	3.7	17	3.7
LED 51	Solid-State	Continuous (6-connected-sections	19	2.3	22	2.1
CMH 330	PSMH Magnetic	Three-lamp, 12-12-12-12	N/A	N/A	61	6.2
CMH 330	PSMH Magnetic	Three-lamp, 8-16-16-8	39	2.6	58	2.7

VISUAL IMPACT SURVEY RESULTS

Table 6 summarizes the survey results. The six lighting configurations finished in the same order for five of the six results. The Overall Impact and Overall Look categories are the key metrics used in judging the survey results. All values represent averages from over 320 individual ratings that range from one to five.

TABLE 6. VISUAL IMPACT OF THE BASELINE AND FIVE "CLASS WINNER" FIXTURE CONFIGURATIONS

LIGHTING CONFIGURATION	OVERALL IMPACT	OVERALL LOOK	COLOR VIVIDNESS	BRIGHTNESS	COLOR EVENNESS	CONTRAST
2 × CMH 400	4.15	4.35	4.39	4.26	4.08	4.22
4 × 4 F54T5HO 216	3.97	4.10	4.13	4.16	4.02	4.12
Continuous LED String 610	3.71	3.80	3.80	3.59	3.76	3.87
3 × High CRI PSMH 320[10]	3.56	3.61	3.58	3.36	3.60	3.78
4 × Induction 165	3.39	3.46	3.39	2.99	3.48	3.59
United States Baseline 4 × MH 400	3.10	2.97	2.81	3.13	3.11	3.26

DISCUSSION

SHORT LIST OF MOST COMPETITIVE FIXTURES

The five selected fixtures, along with the United States and California Baseline Configurations, are summarized in Table 7 and Table 8. In Table 7, the connected loads and CRIs are direct measurements from SCLTC. The minimum in-service illumination levels result from scaling the actual measured values by the systemic light loss factors. The fractions of light delivered to the billboard are determined through calibrated AGI32 simulations.

TABLE 7. PERFORMANCE OF THE TWO BASELINE AND SIX "CLASS WINNER" FIXTURE CONFIGURATIONS

LIGHTING CONFIGURATION	CRI	CONNECTED LOAD (W)	MINIMUM IN-SERVICE ILLUMINATION (FC)	UNIFORMITY RATIO	LIFETIME (HOURS)	FRACTION OF LIGHT DELIVERED TO BILLBOARD
2 × CMH 400	87	848	38	4.0	20,000	54%
4 × 4 F54T5HO 216	79	936	30	3.9	35,000	34%
Continuous LED String 610	73	732	13	2.3	50,000	51%
3 × High CRI PSMH 320[10]	91	978	23	2.7	20,000	39%
4 × Induction 165	77	708	8	3.7	50,000	36%
United States Baseline 4 × MH 400	56	1,740	23	3.7	15,000	39%
California Baseline 3 × PSMH 400	65	1, 368	28	3.7	15,000	54%
3 × High CRI 330	87	1,119	28	2.7	20,000	39%

The fixture costs, lamp costs, and ballast costs shown in Table 8 represent quotes from distributors obtained in the fourth quarter of 2009. The installation costs assume a $50 per hour labor rate and a two-man crew, although the LED fixtures (six eight ft sections making one continuous piece) took a team of three, 6.5 hours to install. Certain ballast and lamp costs are shown to be included in the fixture cost.

TABLE 8. COSTS FOR TWO BASELINE AND SIX "CLASS WINNER" FIXTURE CONFIGURATIONS

LIGHTING CONFIGURATION	FIXTURE COST ($)	LAMP COST ($)	BALLAST COST ($)	INSTALLATION COST ($)
A: 2 × CMH 400	1,154	109	112	400
B: 4 × 4 F54T5HO 216	1,506	Included	Included	500
C: Continuous LED String 610	2,985	Included	Included	1,200**
D: 3 × High CRI PSMH 320[10]	975	98	Included	500
E: 4 × Induction 165	3,480	Included	Included	500
F: United States Baseline - 4 × MH 400	1,300	113	224	500
G: California Baseline 3 × PSMH 400	975	85	168	500
H: 3 × High CRI 330	975	273	168*	500
* These lamps can be used with existing probe-start ballasts.				
** Due to recent design improvements, the installation cost for this fixture is now expected to be $450.				

The costs of the following lighting configuration are listed in Table 8:

- Lighting Configuration A: This configuration represents high CRI 400W CMH sources in new and efficient fixtures specifically designed to provide sufficient uniformity and illumination with just two fixtures per billboard. The fixtures were measured at approximately 80% efficiency in the SCLTC, compared to 62% for the traditional fixtures. The fixtures cost $577 each, but due to a reduction in the number of fixtures, the overall cost is extremely competitive. This lighting configuration was the overall winner of the visual impact survey.
- Lighting Configuration B: This configuration consists of four 4-lamp F54T5HO fixtures with amalgam lamps. These lamps boast extended lives (35,000 hours) and excellent lumen maintenance. The fixture had a strong second place finish in the visual impact survey. A major national provider of lighted billboards has experimented with these fixtures and found issues with water collecting in the fixtures. As previously mentioned, these fixtures were not specifically designed for billboard lighting, but performed surprisingly well in all measurements. It is likely that a fixture redesign involving heavier duty materials and gaskets will provide the desired level of protection against the elements.
- Lighting Configuration C: This configuration consists of six eight ft. linear sections that contain LED sources. The fixtures proved difficult to install in the field, but delivered illumination of unparalleled uniformity. LEDs have long lifetimes, similar to induction sources, and may be the most rugged of all sources. It is important to note this particular implementation used older and more economical LED chips that have low luminous output and low luminous efficacy. It is possible to double the light output at the same wattage by replacing the older generation LED chips with newer ones from the same manufacturer. The additional cost associated with the newer LED chips is not known at this time. The LED lighting configuration came in third place in the visual impact survey despite the low light output.

- Lighting Configuration D: This configuration consists of high CRI PSMH 320W[10] sources in three of the traditional 62% efficiency fixtures spaced 16' apart. The fixtures cost approximately $325 each. This lighting configuration had the best color rendering and the second best uniformity of all tested lighting configurations. The visual impact study, however, placed this configuration in fourth place, behind the LEDs and just ahead of the induction lamps.

- Lighting Configuration E: This configuration consists of 165W induction sources in a four-fixture configuration, using standard fixtures. The induction source comes in a retrofit kit which includes a lens specifically designed to work with the relatively large induction source. The first cost for the retrofit kit is quite high, at approximately $520 per fixture. (This is in addition to the nominal $325/fixture.) The induction source has a long lifetime (up to 100,000 hours) and has a 10-year warranty. This particular induction source is from a reputable manufacturer and is the only one out of the three tested, that has a good correspondence to its rated qualities. Induction sources tend to be more resilient to vibration, and this may be an important attribute to consider in specifying illumination sources for outdoor billboards. The induction source came in second to last in the visual impact survey and had the lowest light output in the field.

- Lighting Configuration F: This configuration consists of standard probe start MH sources in four of the traditional, 62% efficiency fixtures. This configuration is the prominent lighting setup in the lighted billboard market and is called the United States Baseline in this report. This configuration, despite requiring approximately twice the electric power as most other configurations in the study, finished in last place in the visual impact survey. The configuration scored especially poor in the Color Vividness category, likely due to its poor color rendering. This lighting configuration breaches the current Title 24 2.3 W/ft^2 lighting power density allowance.

- Lighting Configuration G: This is a 2008 Title 24 compliant proposed alternative to the United States Baseline; the California Baseline, consists of replacing the probe start sources with PSMH lamps and ballasts, and converting from four fixtures per billboard to three.

- Lighting Configuration H: This configuration consists of high CRI CMH 330W sources in three of the traditional 62% efficiency fixtures spaced 16' apart. The fixtures cost approximately $325 each. This lighting configuration was not included in the visual impact survey because the lighting characteristics would be nearly identical to that of lighting configuration D, though with approximately 20% higher light output. The likely result of the visual impact study would be a tie with configuration D for fourth place, behind the LEDs and just ahead of the induction lamps. These novel sources were tested at the SCLTC. The test results are summarized in Appendix G: Results of Bare Lamp Tests at SCLTC.

- Honorable Mention: The PSMH/Electronic Dimmable Ballasts (EDB) combination performed satisfactorily in field measurements and had an excellent luminous efficacy (67 lm/W), but was not chosen as a finalist due to a lack of extensive field experience with EB. However, recent laboratory tests at CLTC suggest that EBs are durable and energy efficient alternatives to standard magnetic ballasts[11].

ECONOMICS

As shown in Table 8, there is substantial variation in fixture costs, source and ballast costs, and fixture installation costs. To make a meaningful economic comparison of the competing lighting configurations, the 20-year operating costs are calculated for the aforementioned fixtures.

To estimate 20-year total operating costs for the candidate lighting configurations, the following technological and economic considerations are applied. The lifecycle cost calculations are explained in more detail in Appendix F: Economic Analysis.

- The costs associated with fixture installation are taken from Table 8 except that an additional cost of $100 per fixture has been added to the T5HO fixtures. This additional cost, presumably, would be sufficient to upgrade the fixtures to robust, all-weather fixtures that are appropriate for billboard lighting.
- The cost of electricity is $0.112/kWh.
- A real discount rate of 3% (e.g., 5.0% investment interest rate minus 2.0% inflation) is applied to costs associated with maintenance costs. Energy cost increases are assumed to outpace general inflation by 1%.
- The lights are operated 1,839 hours per year.
- There are two scenarios considered for lamp lifetimes.
    - The first scenario, the Nominal Lifetime Scenario, uses lamp lives as summarized in Table 7.
    - The second scenario, the Short Life Scenario, uses a two-year lifespan for HID lights and a shortened, 10-year (18,390 hours – about half the lamp life) lifespan for the fluorescent lamp.

The second scenario is motivated by reports from a major national provider of lighted billboards that state the typical 15,000 hour horizontal MH lamp tends to last only two years, (4,000 hours) in the field. The reasons behind the shorter lamp lives observed in the field are not understood with certainty. However, it is known that the lamps are cycled shorter than the standard "10 hours per start", with an average on-time of just five hours per start and are subject to high and low frequency vibrations from winds. In this context, the non-HID sources are expected to be more robust with respect to vibration-induced failure modes and resistant to "short cycling".

Table 9 lists the net present values (NPV) of the annual expenditures associated with the various fixture configurations over the next decade. The two highest-rated configurations from the visual impact survey are quite competitive from a cost perspective in both scenarios. Two alternate scenarios are presented. The Nominal scenario assumes 20,000-hour longevity for HID fixtures while a Short-Life scenario assumes that the HID fixtures must be replaced every other year.

TABLE 9. 20-YEAR NET PRESENT VALUE COSTS FOR THE VARIOUS CANDIDATE FIXTURES

LIGHTING CONFIGURATION	NOMINAL SCENARIO 20-YEAR COST	SHORT LIFE SCENARIO 20-YEAR COST	ANNUAL ENERGY SAVINGS VS. CA BASELINE (KWH)
A: 2 × CMH 400	$5,173	$7,167	951
B: 4 × 4 F54T5HO 216	$5,828	N/A	741
C: Continuous LED String 610	$6,700	N/A	1,114
D: 3 × High CRI PSMH 320[10]	$5,398	$7,317	664
E: 4 × Induction 165	$6,419	N/A	1,154
F: United States Baseline - 4 × MH 400	$8,604	$10,622	N/A
G: California Baseline 3 × PSMH 400	$6,873	$8,708	N/A
H: 3 × High CRI CMH 330	$6,333	$9,384	406

In addition to 20-year net present values (essentially lifecycle cost) comparisons, the simple returns on investment (ROI) are calculated for the various lighting configurations. The ROI is calculated as the ratio with the numerator as the first-year maintenance and energy cost savings, as calculated by the same assumptions as for the net present value calculations above, without the discount rate. The denominator is taken as the additional installed cost of the alternative lighting configurations. For example, if a lighting configuration costs $100 more to install, yet saves $200 over the first year, the simple ROI would be 200%. The aforementioned nominal and "short life" scenarios are used in the ROI calculations. The ROI are also calculated for new construction and for retrofit scenarios. In the new construction scenario, the marginal cost used in the denominator is the cost difference between the installation of the CA baseline and the given fixture configuration on a new billboard. In the retrofit scenario, the marginal cost used in the denominator is the cost difference between the modifications needed to convert a "US Baseline" lighting configuration to the CA baseline or to a particular fixture configuration on an existing billboard.

Note that the ranking in the ROI test, shown in Table 10, are different than the rankings in the net present value tests. The highest ROI does not correspond to the lowest 20-year cost of ownership. Generally, the ROI metric favors low initial costs or high initial rates of return, while the net present value metric favors the best long-term investment.

TABLE 10. 20-YEARSIMPLE ANNUALIZED RETURN ON INVESTMENT FOR THE VARIOUS CANDIDATE FIXTURES

LIGHTING CONFIGURATION	NEW CONSTRUCTION ROI	NEW CONSTRUCTION ROI (SHORT LIFE)	RETROFIT ROI	RETROFIT ROI (SHORT LIFE)
A: 2 × CMH 400	220%	199%	10%	9%
B: 4 × 4 F54T5HO 216	37%	N/A	8%	N/A
C: Continuous LED String 610	7%	N/A	5%	N/A
D: 3 × High CRI PSMH 320[10]	613%	573%	613%	573%
E: 4 × Induction 165	7%	N/A	5%	N/A
G: California Baseline 3 × PSMH 400	N/A	N/A	N/A	N/A
H: 3 × High CRI CMH 330	159%	-210%	159%	-210%

OPERATION OF EXTANT BILLBOARD LIGHTING STOCK

In addition to the economic lifecycle cost estimates, three scenarios were compared in order to identify the best approach to minimizing the operating costs for the existing billboard stock in CA[12]. The scenarios included the following:

- Spot Re-lamping Probe Start MH: This involves spot re-lamping of existing MH lamps.
- Retrofit at First Opportunity: This involves switching an entire billboard to configuration "A", "B", or "D" listed in Table 9 at the first opportunity. For example, if a billboard must be serviced for any reason, all the probe-start ballasts and lamps are removed and one of the efficient lighting configurations is implemented. The CMH sources in lighting configuration "H" are capable of working with probe-start or pulse-start ballasts. Because a relatively high percentage of the billboards are visited each year (over 50%, according to a major operator of lighted billboards in SCE service territory), this scenario is naturally compatible with localized group-re-lamping (e.g. all billboards in a localized geographic region on a similar re-lamping schedule).
- Retrofit at Last Opportunity: This scenario uses the existing probe-start ballasts for as long as possible, but achieves operating cost savings and energy savings by gradually converting the billboards from having four probe-start sources to three PSMH fixtures. Billboards with burnt out MH lamps (or any other service calls) are converted to a three-fixture configuration. All three MH lamps are replaced with universal (probe-start or pulse-start ballast) CMH lamps[13], and the probe-start ballasts are replaced with pulse-start ballasts upon ballast failure. The final outcome is a gradual transformation from configuration "F" into configuration "D" in Table 9.

The Retrofit at First Opportunity is the most cost-effective scenario, regardless of the efficient lighting configuration that is chosen.[14] This scenario is the most cost-effective because it yields immediate cost reductions associated with energy savings and reduces the need for spot re-lamping. The Retrofit at Last Opportunity is second but is not as cost-effective as the Retrofit at First Opportunity because the maximal energy savings are delayed until the probe-start ballasts fail. The Spot Re-lamping Probe Start scenario is the most expensive scenario due to the high energy costs associated with the 4 × MH 400 lighting configuration. Compared to the Spot Re-lamping Probe Start scenario, the Retrofit at First Opportunity approach will save approximately $2,000 per billboard (net present value of savings) over the next 20 years.

DURABILITY CONSIDERATIONS

Among the most promising fixture configurations, the two 400W CMH fixtures have the lowest nominal 20-year operating cost and the best visual impact. The fixtures may provide annual electric energy savings of 951 kWh per billboard for the typical control scenario (dusk to midnight) used in SCE service territory. The one potential drawback to this scheme, however, is that the design does not have sufficient redundancy.

Half the poster will be poorly lit if one of the two fixtures fails. Table 11 lists the percentage of billboards that will be in need of service in the event of a lamp failure for various lamp failure likelihoods. The figures in the table assume the following:

- If either of the lamps from a two-fixture billboard burn out, a lamp must be replaced.
- Billboards lit with three fixtures can operate normally if the center light burns out, but they need prompt servicing if any peripheral lights burn out.
- Billboards lit with four fixtures can operate normally if any single one, the center two lights or the outer two lights burn out, but any other burnout scenario requires prompt servicing.

It should be noted that linear fluorescent fixtures have the marked advantage that they can provide sufficient illumination even with one or two inoperable lamps per fixture (two lamps per ballast, and series-parallel ballasts are recommended to enhance redundancy). Only LED fixtures have a higher degree of redundancy. According to basic statistical calculations summarized in Table 11, the odds of having to service a billboard rise dramatically as the number of fixtures diminishes. The disparity in the number of required visits to billboards for four-fixture configurations and two-fixture configurations increases dramatically with the lamp failure rate.

TABLE 11. THE PERCENTAGE OF BILLBOARDS THAT WILL NEED SERVICING VS. THE NUMBER OF FIXTURES PER BILLBOARD AND THE AVERAGE LAMP LIFE

TYPICAL LAMP LIFE (IN YEARS)	PERCENTAGE OF TWO-FIXTURE BILLBOARDS THAT NEED RE-LAMPING EACH YEAR	PERCENTAGE OF THREE-FIXTURE BILLBOARDS THAT NEED RE-LAMPING EACH YEAR	PERCENTAGE OF FOUR-FIXTURE BILLBOARDS THAT NEED RE-LAMPING EACH YEAR
20	5%	3%	0%
10	10%	7%	0%
5	20%	13%	1%
2	50%	33%	8%

This table does not apply to LED fixtures, which are assumed to be fail-proof for at least 50,000 hours. Induction lamps are also quite durable, and have a limited ten-year warranty.

As mentioned, concerns regarding redundancy and durability seem to be the main drawbacks for the two-fixture lighting configurations tested in this report. The fixtures, however, tend to be economically competitive even if they must be re-lamped every other year. To the extent that there is a problem with the perception that a two-fixture solution requires excessive lamp replacements, a warranty against lamp failure will assuage potential customers' concerns regarding HID lamp longevity, particularly for the two-lamp configurations. This is an unlikely scenario, however, as it is difficult to assess whether the party responsible for the warranty is the lamp maker or the fixture maker.

One indication that the fixture manufacturer has attempted to compensate for this shortfall in redundancy, however, is that the new two-fixture lighting systems use vertical burning lamps which tend to outlast horizontal lamps.

OVERALL COMPETITIVENESS

The rankings of the five lighting designs in various aspects of this study are listed in Table 12. The two-fixture CMH lighting configuration is the most cost-effective lighting solution for billboards in SCE territory. This lighting configuration outperformed the other contenders in the following areas:

- Total light delivered to billboard (both initial and maintained values)
- Overall visual impact, as determined from a survey of over 320 observers
- Cost-effectiveness (This system outperformed competitors in the nominal 20-year scenario, and came in second place even if the lamps burn out every other year. The system also has a relatively low initial cost.)

TABLE 12. RANKINGS FOR TWO BASELINE AND FIVE "CLASS WINNER" FIXTURE CONFIGURATION

LIGHTING CONFIGURATION	VISUAL IMPACT RANKING	ECONOMIC (NPV) ANALYSIS RANK	LIGHT LEVEL RANK	ENERGY SAVINGS RANKING	UNIFORMITY RANK
A: 2 × CMH 400	1	1	1	3	5
B: 4 × 4 F54T5HO 216	2	3	2	4	4
C: Continuous LED String 610	3	6	5	2	1
D: 3 × High CRI PSMH 320[10]	4	2	4	5	2
E: 4 × Induction 165	5	4	6	1	3
H*: 3 × High CRI CMH 330	4*	5	3	6	2
*The 330W CMH lamps were not included in the visual impact tests, but their performance would be similar to that of the high CRI 320W lamps					

It is important to recognize that the economic analysis presented above pertains to usage patterns in SCE service territory. If the lights operated from dusk to dawn, for example, and if the billboards tended to be relatively far apart such that maintenance costs were higher, the LED fixtures will likely be the most economically competitive lighting solution in the study.

OTHER CONSIDERATIONS

The continuous string of LEDs ranked third in the visual impact study. This configuration has several noteworthy advantages:

- Superior Uniformity: This lighting configuration had the highest measured uniformity ratio in the study.
- Extended Service Life: This lighting configuration should provide almost service-free operation for 50,000 hours or longer.
- Maximal Energy Savings: At just 1.1 W/ft^2, this lighting solution requires less than half of the current Title 24 power allowance. The potential energy savings are approximately 14% compared to configuration "A", 22% compared to configuration "B", and 55% compared to the California Baseline.

However, there were several notable drawbacks with this system:

- High Installation Cost: The fixtures took 18 man hours to install and align.
- Low Light Output: The minimum in-service light levels are about 50% lower than the United States Baseline configuration.
- High Initial Cost: The fixture cost is about three times the cost of the California Baseline.

The high fixture and installation costs, coupled with the low light output prevent this fixture from being the natural choice in billboard illumination. This study included direct dialogue with all the manufacturers. One result was that this continuous string LED manufacturer provided practical upgrade solutions.

The overall installation time has been reduced to just two man hours, based on the following improvements:

- Un-necessary end-caps have been removed and a quick disconnect has been added to ease electrical coupling of fixtures during installation.
- Other electrical connections that were previously connected during installation are now pre-connected in the factory.
- Nuts and bolts that required open-ended wrenches have been replaced by bolts and nuts that may be quickly secured with power tools.
- The fixture aiming and alignment mechanism has been improved.
- The LED drivers are now remotely mounted to ease service and installation.

Additionally, this manufacturer is able to increase light output by 25% with no added cost. This particular fixture is now poised to capitalize on the continuing trend toward more efficacious and less costly LED chips. These design improvements are a direct result of the LED manufacturer's participation in SCE's Emerging Technology (ET) program. This highlights an important function of the ET program research and development feedback. The California Evaluation Protocols identify a "chasm" that separates early adopters of a technology from the mass market[15]. The ET programs are tasked with being both a gatekeeper and a bridge for deserving technologies over the metaphorical chasm to market. ET programs have traditionally been evaluated on the basis of market transformation, uptake of technologies to resource acquisition programs, dissemination of information, and on casting a wide enough net to capture and identify the most promising emerging technologies. However, we have here a clear example of research and development feedback resulting in a more competitive product with strong energy savings potential.

CONCLUSION

The main objectives of this project are to determine the:

- Lighting energy savings available from the new/improved systems versus baseline MH systems.
- Light levels provided by the new systems.
- Visual impacts, as determined by a subjective survey among the winners by source, of the various new systems.
- Correlation of the subjective results to the objective (energy and photometric) results.

Five alternative lighting configurations were identified as viable candidates representing the best available market lighting solutions from the CMH, PSMH, LED, Induction Fluorescent, and Linear Fluorescent light sources. The CMH, PSMH, and Linear Fluorescent sources provided more illumination than the baseline 4 × 400W MH lighting configuration. The LED and Induction Fluorescent sources had dramatically lower light output, although the LED fixture could achieve adequate light levels if newer LED chips were used in the fixture.

Of these five candidates, a lighting configuration that consisted of two high efficiency fixtures housing 400W CMH lamps proved to be the most economical solution with the highest maintained light levels. This promising alternative to the existing MH systems will result in approximately 951 kWh annual energy savings per billboard as compared to the baseline lighting system that will comply with the California Title 24 regulation regarding energy usage density for externally lit signage. The visual impact survey results were well-correlated with the field photometric measurements and laboratory spectral analysis results. The two clear winners in the visual impact survey, the 2 × CMH and 4 × T5HO fixtures were also clear winners in the economic analysis. These findings tend to support these two fixtures as the best present alternatives to the traditional probe start technology. The CMH lighting solution tends to have slight advantages in visual impact, energy efficiency, and economic costs, while the T5HO configuration, containing 16 lamps compared to just two for the CMH setup, has an advantage in redundancy and expected duration between re-lampings. Regardless of the final choice in energy efficient alternatives, the greatest savings in both energy and operating costs are achieved if the billboards are retrofit with the efficient configurations at the first possible opportunity. That is, the next routine spot-re-lamping service should be replaced with a systemic lighting upgrade.

RECOMMENDATIONS

Based on the findings of the objective lab and field tests, and the subjective visual impact study, the following lighting configurations or sources are recommended for lighted billboards.

1. **Lighting configuration A** is the overall leader in both the objective and subjective categories. This is largely due to the new high efficiency fixtures that are specifically designed to light a full-size billboard with just two fixtures.
2. **Lighting configuration B** is a close competitor to A. The T5HO fixtures provide a high visual impact and low maintenance costs due to their excellent redundancy in sources (4 sources per fixture).
3. **Lighting configuration C**, poised to become a leader in the lighted signage market, ranks not far below A and B. As mentioned, the fixtures are much improved due to feedback that resulted from this study. They achieve the most uniform, and the second most efficient delivery of light onto the billboard. Solid state lighting is experiencing marked improvements in luminous efficacy coupled with decreases in cost.
4. **Honorable mention:** This study considered 330W (380W connected) high CRI CMH lamps that require no new ballast and can work with either probe-start or pulse-start ballasts. These lamps are a relatively low-wattage, high CRI alternative to replace 400W probe and pulse start lamps, and may provide substantial energy savings for the existing stock of 400W probe start ballasts.

As this study identified several economically viable lighting configurations with LPDs well beneath the Title 24 limit, it is recommended to consider a downward revision of the CA Title 24 LPD requirement.

APPENDIX A: PHOTOGRAPHS OF LIT BILLBOARDS

The pictures in this appendix were taken with a digital camera that automatically adjusted exposure to the light levels. As such, these pictures should not be used to judge the total illumination delivered by the lighting systems, but are adequate to enable comparisons of color rendering and uniformity of light. The letters P,Q,R,S,T,U correspond to letters A,E,C,B,D,G in the report, respectively.

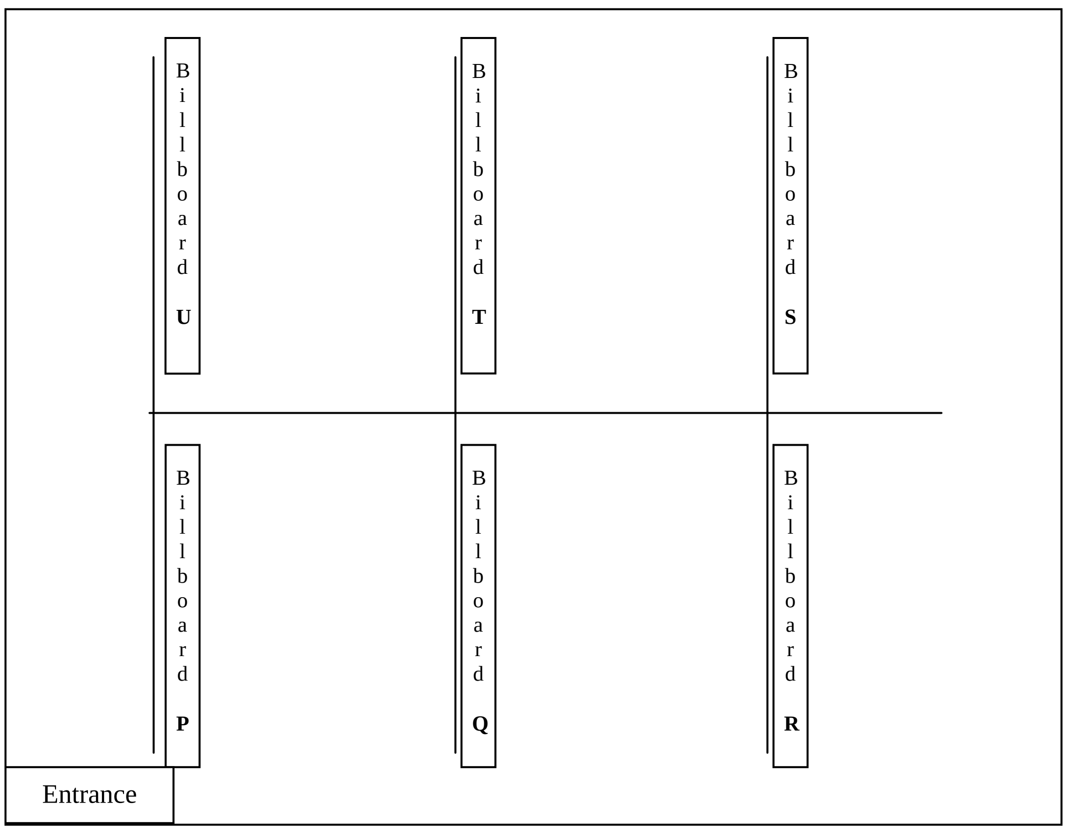
FIGURE 3. SIX SURVEYED BILLBOARDS ILLUMINATED BY VARIOUS LIGHTING SOLUTIONS

APPENDIX B: VISUAL IMPACT SURVEY

SCE Billboard Lighting Survey – Purpose and Methodology

Purpose: To test consumer reaction to six billboard lighting options. The goal of this survey is to learn which billboard consumers liked best without letting them know that we were testing the lighting.

Methodology: Six identical billboards were placed in the soundstage as seen in the sketch below. The billboards were for Halloween at Disneyland and contained a large picture of Captain Hook from Peter Pan. Black curtains were hung between the boards so a respondent could only look at one at a time.



The billboards were labeled **P, Q, R, S, T, and U** as shown above. Respondents were given instructions at the entrance and were not told that the only difference between the boards was the lighting. They were handed a seven page survey that included one page for each billboard and one for personal demographic information. Each person was randomly assigned to start at one of the billboards and to rate it based on a series of attributes including vividness of color, brightness, clarity, etc., as well as on the overall impact of the message and look of the billboard.

When respondents finished rating each billboard, they returned the completed survey which was placed in a box. The respondent then received a ticket for a free lunch as an incentive for completing the survey.

Nearly all respondents were employees from a large film/television studio in Los Angeles, and tended to be younger than average, with 47% under 35 years old and 1% 65 years old or older (compared to random studies of LA market adults which show about 15% under 35 and 25% 65 and over). However, the respondent group was generally in the target market for commuters (who would most likely see billboards) with 81% commuting every day and 92% commuting at least once a week. Also, 88% of the respondents travel at night during this time of year (when billboard lighting is important) at least a few times per week and 98% of those by automobile.

A copy of the survey instrument is included below.

Thank you for taking the time to help us with our project. Today, we will be showing you 6 versions of the same billboard. We would like you to rate each version across a series of characteristics such as color and clarity. There are no right or wrong answers. We are only interested in how **you** perceive each version, **not** how you think others would see them.

Please visit the billboards **in the order that they are presented in the questionnaire** you are holding. Each version of the billboard is lettered. Find the letter of the billboard first on your questionnaire and visit that one first. When finished, move to the version with the letter presented next on your questionnaire and rate that one. Please continue until you have visited all 6 versions.

BILLBOARD "P"

Please take a minute to look at Billboard "P" and read it. When finished, please rate the following characteristics of Billboard "P". Please check the appropriate box from 1 to 5, with 1 meaning the billboard is poor on that characteristic and 5 meaning the billboard rates excellent on that characteristic.

	1	2	3	4	5
The **vividness** of the colors	Washed out ☐	☐	☐	☐	Vivid ☐
The **clarity** of the pictures and text	Blurry ☐	☐	☐	☐	Clear ☐
The **brightness** of the billboard	Dim ☐	☐	☐	☐	Bright ☐
The **evenness** of color, clarity and intensity across the whole billboard	Uneven ☐	☐	☐	☐	Even ☐
The ability to **distinguish** similar colors from each other	Hard to distinguish ☐	☐	☐	☐	Very Distinct ☐
The **overall look** of the billboard	Poor ☐	☐	☐	☐	Excellent ☐
The **overall impact** of the message as presented on the billboard	Low Impact ☐	☐	☐	☐	High Impact ☐

BILLBOARD "Q"

Please take a minute to look at Billboard "Q" and read it. When finished, please rate the following characteristics of Billboard "Q". Please check the appropriate box from 1 to 5, with 1 meaning the billboard is poor on that characteristic and 5 meaning the billboard rates excellent on that characteristic.

	1	2	3	4	5
The **vividness** of the colors	Washed out ☐	☐	☐	☐	Vivid ☐
The **clarity** of the pictures and text	Blurry ☐	☐	☐	☐	Clear ☐
The **brightness** of the billboard	Dim ☐	☐	☐	☐	Bright ☐
The **evenness** of color, clarity and intensity across the whole billboard	Uneven ☐	☐	☐	☐	Even ☐
The ability to **distinguish** similar colors from each other	Hard to distinguish ☐	☐	☐	☐	Very Distinct ☐
The **overall look** of the billboard	Poor ☐	☐	☐	☐	Excellent ☐
The **overall impact** of the message as presented on the billboard	Low Impact ☐	☐	☐	☐	High Impact ☐

BILLBOARD "R"

Please take a minute to look at Billboard "R" and read it. When finished, please rate the following characteristics of Billboard "R". Please check the appropriate box from 1 to 5, with 1 meaning the billboard is poor on that characteristic and 5 meaning the billboard rates excellent on that characteristic.

	1	2	3	4	5
The **vividness** of the colors	Washed out ☐	☐	☐	☐	Vivid ☐
The **clarity** of the pictures and text	Blurry ☐	☐	☐	☐	Clear ☐
The **brightness** of the billboard	Dim ☐	☐	☐	☐	Bright ☐
The **evenness** of color, clarity and intensity across the whole billboard	Uneven ☐	☐	☐	☐	Even ☐
The ability to **distinguish** similar colors from each other	Hard to distinguish ☐	☐	☐	☐	Very Distinct ☐
The **overall look** of the billboard	Poor ☐	☐	☐	☐	Excellent ☐
The **overall impact** of the message as presented on the billboard	Low Impact ☐	☐	☐	☐	High Impact ☐

BILLBOARD "S"

Please take a minute to look at Billboard "S" and read it. When finished, please rate the following characteristics of Billboard "S". Please check the appropriate box from 1 to 5, with 1 meaning the billboard is poor on that characteristic and 5 meaning the billboard rates excellent on that characteristic.

	1	2	3	4	5
The **vividness** of the colors	Washed out ☐	☐	☐	☐	Vivid ☐
The **clarity** of the pictures and text	Blurry ☐	☐	☐	☐	Clear ☐
The **brightness** of the billboard	Dim ☐	☐	☐	☐	Bright ☐
The **evenness** of color, clarity and intensity across the whole billboard	Uneven ☐	☐	☐	☐	Even ☐
The ability to **distinguish** similar colors from each other	Hard to distinguish ☐	☐	☐	☐	Very Distinct ☐
The **overall look** of the billboard	Poor ☐	☐	☐	☐	Excellent ☐
The **overall impact** of the message as presented on the billboard	Low Impact ☐	☐	☐	☐	High Impact ☐

BILLBOARD "T"

Please take a minute to look at Billboard "T" and read it. When finished, please rate the following characteristics of Billboard "T". Please check the appropriate box from 1 to 5, with 1 meaning the billboard is poor on that characteristic and 5 meaning the billboard rates excellent on that characteristic.

	1	2	3	4	5
The **vividness** of the colors	Washed out ☐	☐	☐	☐	Vivid ☐
The **clarity** of the pictures and text	Blurry ☐	☐	☐	☐	Clear ☐
The **brightness** of the billboard	Dim ☐	☐	☐	☐	Bright ☐
The **evenness** of color, clarity and intensity across the whole billboard	Uneven ☐	☐	☐	☐	Even ☐
The ability to **distinguish** similar colors from each other	Hard to distinguish ☐	☐	☐	☐	Very Distinct ☐
The **overall look** of the billboard	Poor ☐	☐	☐	☐	Excellent ☐
The **overall impact** of the message as presented on the billboard	Low Impact ☐	☐	☐	☐	High Impact ☐

BILLBOARD "U"

Please take a minute to look at Billboard "U" and read it. When finished, please rate the following characteristics of Billboard "U". Please check the appropriate box from 1 to 5, with 1 meaning the billboard is poor on that characteristic and 5 meaning the billboard rates excellent on that characteristic.

	1	2	3	4	5
The **vividness** of the colors	Washed out ☐	☐	☐	☐	Vivid ☐
The **clarity** of the pictures and text	Blurry ☐	☐	☐	☐	Clear ☐
The **brightness** of the billboard	Dim ☐	☐	☐	☐	Bright ☐
The **evenness** of color, clarity and intensity across the whole billboard	Uneven ☐	☐	☐	☐	Even ☐
The ability to **distinguish** similar colors from each other	Hard to distinguish ☐	☐	☐	☐	Very Distinct ☐
The **overall look** of the billboard	Poor ☐	☐	☐	☐	Excellent ☐
The **overall impact** of the message as presented on the billboard	Low Impact ☐	☐	☐	☐	High Impact ☐

Again, thank you for taking the time to help us with our project. Finally we would like to ask you a few questions about yourself:

Are you:
- ☐Male
- ☐Female

Do you commute to work during the week?
- ☐Do not commute
- ☐Commute every day
- ☐Commute a few times a week
- ☐Commute once or twice a week
- ☐Less than once a week

How often do you travel at night this time of year?
- ☐Every day
- ☐A few times a week
- ☐Once or twice a week
- ☐Less than once a week

How do you usually travel at night?
- ☐Car
- ☐Bus
- ☐Train
- ☐Other

What is your age?
- ☐Under 24 years old
- ☐25 to 34 years old
- ☐35 to 44 years old
- ☐45 to 54 years old
- ☐55 to 64 years old
- ☐65 years old or older

How would you describe your vision?
- ☐Excellent
- ☐Good
- ☐Fair
- ☐Poor

Do you wear glasses or contact lenses?
- ☐Yes
- ☐No

Are you at all colorblind?
- ☐Yes
- ☐No

Thank you. That concludes our survey. Have a wonderful day!

APPENDIX C: LUMINANCE CAMERA STUDY

Overview of Luminance Camera Recording Functions and Procedures

- Camera Name: Nikon E5400 Digital with Nikon Fisheye Lens
- Camera Settings: Manual setting with series of 14 specific F stop & shutter Speed combinations as prescribed by the luminance program
- Camera Placement: Approximately 25 - 30 feet in front of the billboard, slightly above eye -level and mounted to camera tri-pod
- Luminance Program: Photo Lux 2.0
- Calculation Process: Outlined below are the parameters for recording luminances on the 15 billboard tests that were conducted from September 16, 2009 to October 21, 2009.
    - Fourteen images were processed with a combination of exposures as defined by the Photo Lux 2.0 program.
    - Average luminance recorded in cd/m^2 was taken on the billboard surface by masking billboard area in the image program in order to obtain the appropriate average luminance on the billboard surface.
    - Maximum cd/m^2 was found by manually surveying (scaling) the surface of the billboard image to find the highest local value. This method was used as the automatic calculation process records the highest value on the image even though the area has been excluded from the mask.
    - Illuminance, recorded in Lux, is taken at the camera position of 25 - 30 feet from the billboard surface.
- Illuminance Reference: Illuminance from the billboards tested at the camera position of 25-30 feet ranged from a low of 11.03 Lux (1.1 fc) to a high of 48.85 Lux (4.88 fc). The recommended illuminance for a 14 ft X 48 ft electronic billboard at 250 feet is not more than .3 fc or 3 Lux. AGI32 computer simulation determined that even the highest illuminance from the tested front lighted billboards produce significantly less illuminance at 250-feet than the maximum allowed for electronic billboards.

Prepared by Integrated Lighting Concepts on November 22, 2009.

APPENDIX D: AMALGAM LINEAR FLUORESCENT LAMPS

Amalgam linear fluorescent lamps tend to operate at near-optimum light outputs over a wide range of ambient temperatures. The amalgam tends to prevent the vaporized mercury from condensing on the coldest spot of the lamp tube. The improved operational characteristics with respect to temperature are shown in Figure 4. This figure has been adapted from a major manufacturer's sales literature.

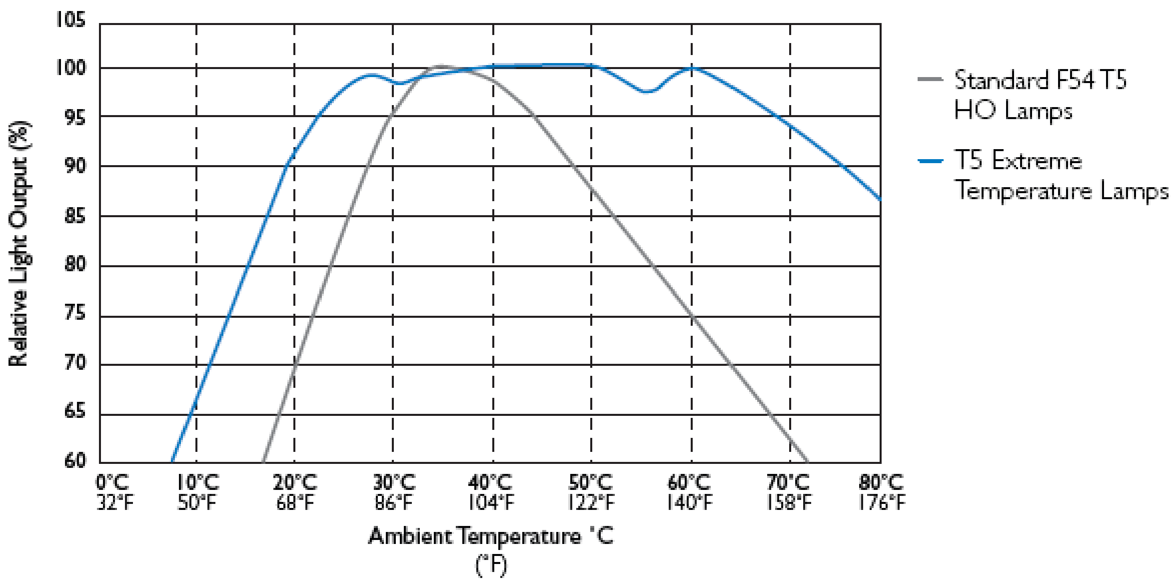


FIGURE 4. LIGHT OUTPUT VS. AMBIENT TEMPERATURE FOR STANDARD AND AMALGAM T5 LINEAR FLUORESCENT LAMPS

APPENDIX E: DETERMINATION OF LIGHT LOSS FACTORS

ACHIEVING THE LIGHTING RECOMMENDATIONS

In lighting design it is customary to specify an initial illuminance that exceeds the design illumination goal in order to compensate for lumen depreciation that occurs over time. Typically, the minimum in-service illumination occurs just before group re-lamping is estimated, and the initial lumens are specified in order that the minimum in-service illumination meets or exceeds the design illumination goal.

Two distinct lumen depreciation factors are used to estimate the minimum in-service illumination levels, based on initial photometric measurements. The product of the two factors is the systemic LLF.

The first depreciation factor is the LLD, which is the ratio of a lamp's illuminance at re-lamping time to a lamp's initial illuminance. According to the manufacturer's cut sheet, a source will experience a specified decrease in light output after a given number of hours of operation. The lumen depreciation curve for LEDs has been shown to behave like an exponential function[16]. In fact, an exponential function seems to be an accurate descriptor of lumen depreciation for most known light sources. The lumen depreciation after any number hours is calculated as shown in Equation 1.

EQUATION 1. CALCULATION OF LUMEN DEPRECIATION AFTER 70,000 HOURS OF BI-LEVEL OPERATION

$$\mathrm{LLD} = \exp(\ln(\textit{rated lm}) \times \frac{\textit{hours}}{\textit{hours at rating}})$$

Where, *rated lm* corresponds to the rated lumen maintenance at a given number of hours. For example, if a LED source is rated to maintain 70% of initial lumens after 50,000 operating hours, the lumen maintenance (or equivalently, LLD) at 20,000 hours would be given by:

$$\mathrm{LLD}_{20} = \exp(\ln(0.7) \times \frac{20000}{50,000}) = 0.867$$

Where, LLD_{20} is the lumen maintenance at 20,000 hours, the LLDs for the various light sources are calculated in this fashion.

The second factor is LDD, which is the gradual decrease in fixture light output caused by dirt accumulation. LDD is the ratio of a lamp fixture's illuminance at replacement or cleaning time to initial illuminance, assuming that lamp sources are of equal illuminance at both times. We use LDD values determined by ILC, with the derivation of the LDD factors described by ILC as follows:

"IESNA recommended dirt depreciation taken from Edition-9 Lighting Handbook, 2000 for luminaires similar to those used for sign lighting suggest a dirt depreciation factor at 36-48 month of operation is between .70 and .60 (measured at re-lamping cycle). However more recently The International Association of Lighting Management Companies (NALMCO) completed a three-year, EPA-funded study of luminaire (lighting fixture) dirt depreciation. This study projects significantly less dirt depreciation than stated in the IESNA Addition-9 handbook. IESNA has adopted the LDD study results which are incorporated into a new IESNA Recommended Practice (RP) on maintenance (RP-36) and will be included in the next IESNA Handbook Addition 10 to be issued within 18 to 24 months."

The findings of the National Association of Lighting Management Companies (NALMCO®) study are shown in Figure 5. Clearly, the trend is towards smaller dirt depreciation factors. The dirt depreciation factors used in this study are 0.9 for all fixtures except the LED fixtures, which receive a dirt depreciation factor of 0.95.

The overall systemic LLF is simply the product of the LDD and the LLD for each fixture.

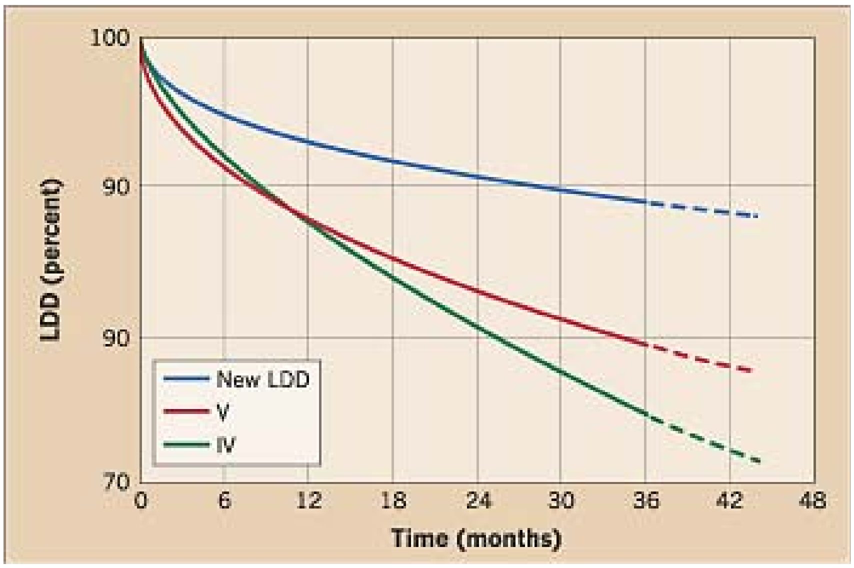


FIGURE 5. THE LATEST LUMEN DIRT DEPRECIATION CURVE FOR OUTDOOR FIXTURES

APPENDIX F: ECONOMIC ANALYSIS

To estimate a 20-year total operating cost for the candidate's lighting configurations, the following technological and economic considerations are applied.

- The costs associated with fixture installation are taken from Table 8 except that an additional cost of $100/fixture has been added to the T5HO fixtures. This additional cost, presumably, would be sufficient to upgrade the fixtures to robust, all-weather fixtures that are appropriate for billboard lighting.
- The cost for electricity is $0.112/kWh.
- A real discount rate of 3% (e.g., 5.0% investment interest rate minus 2.0% inflation) is applied to costs associated with maintenance costs. Energy cost increases are assumed to outpace general inflation by 1%, which means that energy costs in year *n* are discounted by a factor of 1.02^{-n}, and all other costs in year *n* are discounted by a factor of 1.03^{-n}.
- The lights are operated 1,839 hours per year.
- There are two scenarios considered for lamp lifetimes.
    - The first scenario, the Nominal Lifetime Scenario, uses lamp lives as summarized in Table 7.
    - The second scenario, the Short Life Scenario, uses a two-year lifespan for HID lights and a shortened, 10-year (18,390 hours which is approximately half the lamp life) lifespan for the fluorescent lamp.
- The cost of lamp repair is calculated on a time and material basis. The material cost in the n^{th} year is the net present value of the replacement light sources in year *n*. The fixture replacement cost is taken to be the net present value of $200 per billboard. It is assumed that all lamps on a billboard are replaced at the same time; this assumption is used because the goal of this exercise is to make an economic comparison between a two-fixture solution (for which double-relamping is likely to be cost-effective given the relatively small cost of the light source, compared to the labor and travel involved in re-lamping) and two other fixtures (the T5HO and LED) which have such long lives that re-lamping is not a factor in their lifecycle costs.

ROI Investment Calculations:

The installation and operational costs used to compute the simple ROI are included in the table below.

Lighting Configuration	20 Year Energy + Maintenance	20-Year Energy + Maintenance Alternate	Installed Cost	Retrofit Cost
A: 2 × CMH 400	$ 4,112	$ 6,585	$ 775	$ 1,775
B: 4 × 4 F54T5HO 216	$ 4,160	$ 4,464	$ 2,006	$ 2,006
C: Continuous LED String 610	$ 3,015	$ 3,015	$ 4,185	$ 4,185
D: 3 × High CRI PSMH 320[10]	$ 4,624	$ 7,004	$ 1,741	$ 766
E: 4 × Induction 165	$ 2,925	$ 2,925	$ 3,980	$ 3,980
G: California Baseline 3 × PSMH 400	$ 6,204	$ 8,481	$ 1,728	$ 753
H: 3 × High CRI CMH 330	$ 5,556	$ 9,340	$ 1,748	$ 773

APPENDIX G: RESULTS OF BARE LAMP TESTS AT SCLTC

Items were tested for total light output (luminous flux), correlated color temperature, color rendering index, power, and total power factor. All values are steady state averages taken at 25 minutes after cold start.

ITEM 01 – 330W PULSE START / PROBE START CERAMIC METAL HALIDE

- Luminous flux: 30965.48 lumens
- Claimed Luminous flux: 33000
- Claimed mean flux: 26400
- Correlated color temp.: 3971.672 Kelvin
- Claimed CCT.: 4000 Kelvin
- Color rendering index: 87.65562
- Claimed CRI: 90
- Measured System Power: 361.7 Watts
- Claimed Lamp Power: 330 Watts
- Total power factor: 0.95
- Current THD: 22.3%
- Efficacy: 85.61 lumens per Watt
- Claimed Efficacy: 100 lumens per Watt

ITEM 02 – 400W PULSE START METAL HALIDE

- Luminous flux: 43084.740 lumens
- Claimed Luminous flux: 40000
- Claimed mean flux: 32000
- Correlated color temp.: 3667 Kelvin
- Claimed CCT.: 4000 Kelvin
- Color rendering index: 62.3
- Claimed CRI: 68
- Measured Power: 436.0 Watts
- Claimed Lamp Power: 400 Watts
- Total power factor: 0.96
- Current THD: 16.0%
- Efficacy: 98.82 lumens per Watt
- Claimed Efficacy: 100 lumens per Watt

REFERENCES

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[1] The Correlated Color Temperature corresponds to the temperature of a blackbody that would radiate a spectrum with a mean wavelength as measured for a particular light source. For example, 5500 K corresponds to daylight, and 3500 K corresponds to sunlight at dusk or dawn. Higher temperatures correspond to spectra that favor blue or white light, while lower temperatures correspond to yellow or red light.

2 The CRI ranges from 0 to 100 and characterizes the ability of a light source to render the colors of an object lighted by the source. The benchmark is blackbody radiation. Incandescent lights have CRIs near 100 as they are blackbody radiators to a good approximation. Fluorescent lamps typically have CRIs in the 60-90 range. One can compare CRIs directly only for light-sources with similar CCTs. CRIs above 75 are considered to be excellent. For more information, see the Environmental Protection Agency Publication 430-B-95-007 "Lighting Fundamentals", p. 4 http://www.cleanaircounts.org/Resource%20Package/A%20Book/EE%20Lighting/manual/lightingfund.pdf

3 The LED L_{70} lifetime depends on the LED chip semiconductor junction temperature, which is a factor of the LED chip's driving current, ambient conditions, and the LED fixture's heat dissipation capability. Phillips has recently published test results that range from 50,000 hours to 150,000 hours depending on the junction temperature. For more information, see http://www.philipslumileds.com/pdfs/DR06.pdf

4 IES Lighting Handbook 9th Addition Copyright © 2000 by the Illuminating Engineering Society of North America

5 California's Energy Efficiency Standards for Residential and Non-residential Buildings (Title 24) 2008. "Non Residential Compliance Manual," p. 7-3, Table 7-1

6 The manufacturer's spec sheet is available online: http://labsphere.com/data/userFiles/SLMS%20LED_Large1.pdf,

7 The spec sheet on the power meter is available online: http://www.microdaq.com/aemc/power-quality/pql-100.php#specs

8 For more information on this lighting simulation software, see http://www.agi32.com

9 For the full description of the monitoring of the hours of operation at Inglewood, see SCE emerging Technology report ET 05.09.

10 This quartz high CRI lamp is nominally a 320W lamp but is rated at 295W in the spec sheet.

11 For the full description of the EDB performance under long-term thermal and power cycling tests, see SCE emerging Technology report ET 07.16.

12 The financial, labor and material cost assumptions in this analysis are identical to the lifecycle cost analysis described in the appendix. See detailed calculations in the ET 08.12 Data file also attached.

13 These lamps are also available in 205W and may be appropriate for smaller lighted signage http://www.lighting.philips.com/us_en/applicationsolutions/industrial/allstart/index.php?main=us_en&parent=0&id=us_en_application_solutions&lang=en

14 The LEDs are not considered at this point due to high initial costs and unknown additional costs associated with increasing light output. Likewise, induction fixtures are not considered due to high initial cost and low light output.

15 *California Energy Efficiency Evaluation Protocols: Technical, Methodological, and Reporting Requirements for Evaluation Professionals*, Prepared for the CA Public Utilities Commission by the TecMarket Works Team, April 2006. p. 74

16 See equation 1, p. 5, of IES Paper #52, "What is Useful Life for White Light LEDs?", A. Bierman, *et al.*, Lighting Research Center, Rensselaer Polytechnic Institute, Troy, NY

http://www.lrc.rpi.edu/resources/pdf/NN_ies1.pdf