USING LIGHT EMITTING DIODES IN TRAFFIC SIGNALS

Final Report

An FHWA PTP Funded Project

by

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16. Abstract

In 1993, the Oregon Department of Transportation (ODOT) began testing red light emitting diodes (LED's) as a replacement to the incandescent lamps in vehicular and pedestrian signals. Field performance was found to be reliable and subsequently ODOT began replacing all red incandescent lamps. In 1995, an implementation program was created to introduce Oregon cities and counties to the LED lamps. The program installed 2,212 red LED lamps used in 12" balls, 12" arrows, 8" balls and pedestrian "hand" symbol.

The red LED lamps reduced power consumption by 88%. Operating costs, including power and annualized lamp replacement costs, were reduced 26%. The LED lamps are warranted to last 5 years and have an estimated payback of 3.6 years. The 12" lamps, which typically have about 620 individual LED's, continue to operate after several of the LED's have failed -- thus making the LED lamp more reliable. The higher reliability and longer life has reduced the number of emergency calls for lamp failures.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8 + 32	Fahrenheit	°F

* SI is the symbol for the International System of Measurement

(4-7-94 jbp)

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PREFACE

It should be noted that light emitting diode (LED) technology is rapidly changing, such that the information presented in this report may be, or is already, obsolete. As an example, the LED's used in this study were constructed of an aluminum gallium arsenide material (a.k.a.: AlGaAs, pronounced \'al-gas\), but most LED's now use an aluminum indium gallium phosphide material (a.k.a.: AlInGaP, pronounced \'al-in-gap\).

Readers of this report who are interested in using LED lamps in traffic signals should contact their sales representatives to learn about the latest products available for traffic signal use.

LIGHT EMITTING DIODES IN TRAFFIC SIGNALS

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1.0 INTRODUCTION

1.1 OBJECTIVES

The Oregon Department of Transportation (ODOT) tested the efficiency of light emitting diodes (LEDs) for potential use in traffic signals. Successful results prompted ODOT to establish a program to encourage the use of LEDs by local governments as well. The objectives of this program were to introduce local governmental agencies to the light emitting diode (LED) traffic signal lamp, to demonstrate its benefits and to promote the implementation of the lamp. Implementation was funded in part by the Federal Highway Administration (FHWA) Priority Technology Program (PTP).

1.2 BACKGROUND

Before 1993, the vehicular and pedestrian lamps used in Oregon were all incandescent. The lamps were typically rated for 8,000 hours life and operated on 120 volts AC. Characteristics of the red, yellow and green lamps are shown below.

Table 1.1: Characteristics of Incandescent Traffic Signal Lamps

Type	Wattage	Lumens	Approximate "ON" time *	Percent of Total Energy *
12" Red	158	1950	17 hrs/day	71%
12" Yellow	100-116	1260	1 hrs/day	2%
12" Green	158	1950	7 hrs/day	27%
8" Green/Red	66	665		
Pedestrian wait	66	665	19-23 hrs/day	

* Average for an intersection with 12 signal heads (8 "through" and 4 left-turn signals)

The red phase of traffic signals is the most critical in avoiding preventable accidents and liability claims. They operate the longest, require annual group relamping and need immediate response to lamp failures. Work zone lane closures for relamping contribute to congestion problems at major intersections and increase the risk of accidents, a situation ODOT wants to avoid. Finding a longer lasting, reliable, cost-effective lamp was important.

Early production LEDs were expensive and limited in quantity and color. As demand increased, LED technology improved, the supply increased and production costs dropped. The reduced price has made LEDs cost effective for a greater variety of applications including traffic signal lamps.

Red and yellow LEDs are the brightest and cheapest to manufacture. Yellow LEDs were once more expensive than red, but the cost is now about the same. While relatively cheap in cost, the yellow LED is still not cost effective for use in traffic signal installations due to the limited hours of yellow light operation. At four seconds per phase, the yellow LED could potentially last over 100 years, far beyond the design life of an intersection and of the equipment.

Green LEDs initially produced a yellow-green color, which was not acceptable for traffic signal use. At the time of this report, a blue-green color has become available, but its cost is a deterrent, at about 2 ½ times the cost of the red LED. Continued advances in technology and increased demand may soon make this LED cost effective for traffic signal use.

In 1993, ODOT began testing red LED lamps as a replacement to the red lens incandescent lamp. Field performance was found to be reliable. Subsequently, ODOT began replacing the incandescent lamps as funds became available. The LED is now the specified lamp for ODOT's 12-inch red-ball, 12-inch red-arrow and pedestrian red-orange "hand" symbol (see appendix C).

2.0 LED IMPLEMENTATION PROGRAM

2.1 LOCAL GOVERNMENT INVOLVEMENT

In 1995, ODOT contacted city and county government agencies to introduce them to the LED lamps and set up an implementation program. The PTP program provided $130,000 for ODOT to help implement the use of the LED lamps. Per the program agreement, participating agencies were reimbursed 30% for the cost of the lamps, using the PTP funds. The cost of the lamps ranged from $80 to $180, producing a reimbursement of $24 to $54 per lamp.

In addition to the reimbursement, agencies were eligible to participate in energy rebate programs offered by electric utility companies as shown below.

Table 2.1: Energy Rebates Offered for Each Retrofit Kit

Utility Company	Red Ball	Red Arrow	Pedestrian Hand Symbol
Portland General Electric	$40	$30	$20
Pacific Power and Light	$40	$30	$20
Eugene Water & Electric Board	70%	70%	70%

The Oregon Department of Energy also offered loans through their Small-Scale Energy Loan Program to help the agencies off set the high initial cost of the LED lamps.

The cities that participated in the LED implementation program are shown in Table 2.2 below.

Table 2.2: List of Oregon Cities Participating in LED Implementation Program

City	Number of lamps installed			
	Red 12" balls	Red 12" arrows	Red 8" balls	Pedestrian hand symbol
Eugene	500	46		522
Medford	293	41		
Beaverton	106	30		
Corvallis	196	2		130
Tigard	83	3		10
Lake Oswego	86	19		24
North Bend	17	4		16
Klamath Falls	22		62	
Total	**1303**	**145**	**62**	**702**

Two cities, Salem and Portland, did not participate in this program. Salem had already converted most of their lamps to LED before this program got underway. Portland chose not to participate, due to their lower electric rates and experiences with poor lamp lumen depreciation.

2.2 ENERGY COMPARISON

The estimated energy and costs differences between incandescent and LED lamps are shown in Table 2.3. Actual metered energy usage was not available for this comparison; therefore, the differences are calculated using technical data sheets and basic electrical fundamentals.

Table 2.3: Estimated Energy and Costs: Incandescent vs. LED

	Red 12" balls	Red 12" arrows	Red 8" balls	Pedestrian "hand" symbol	Total
Incandescent lamps					
Specified lamp lumens	1950	1950	665	665	
Typical lamp wattage at 120 v	158	158	66	66	
No of lamps	1303	145	62	702	
Total lamp wattage	**205,874**	**22,910**	**4,092**	**46,332**	**279,208**
Operating hours/day	15	21	15	19	
Days/year	365	365	365	365	
Kilowatt hours/year (kWh/yr)	1,127,160	175,605	22,404	321,312	1,646,481
$/kWh (approx.)	$ 0.06	$ 0.06	$ 0.06	$ 0.06	
Annual kWh cost	**$ 67,630**	**$ 10,536**	**$ 1,344**	**$ 19,279**	**$ 98,789**
Lamp cost, each	$ 1	$ 1	$ 1	$ 1	
Approximate lamp life	1 yr	1yr	1 yr	1 yr	
Annual lamp cost	**$ 1,303**	**$ 145**	**$ 62**	**$ 702**	**$ 2,212**
Total annual cost	**$ 68,933**	**$ 10,681**	**$ 1,406**	**$ 19,981**	**$ 101,001**
LED lamps					
Typical lamp wattage	20	9	8	8	
No of lamps	1303	145	62	702	
Total lamp wattage	**26,060**	**1,305**	**496**	**5,616**	**33,477**
Operating hours/day	15	21	15	19	
Days/year	365	365	365	365	
Kilowatt hours/year (kWh/yr)	142,679	10,003	2,716	38,947	194,345
$/kWh (approx.)	$ 0.06	$ 0.06	$ 0.06	$ 0.06	
Annual kWh cost	**$ 8,561**	**$ 600**	**$ 163**	**$ 2,337**	**$ 11,661**
Lamp cost, each	$ 179.25	$ 79.50	$ 125	$ 89.75	
Total lamp cost	$ 233,563	$ 11,528	$ 7,750	$ 63,005	$ 315,846
Estimated lamp life	5 yr	5 yr	5 yr	5 yr	
Annual lamp cost	**$ 46,713**	**$ 2,306**	**$ 1,550**	**$ 12,601**	**$ 63,170**
Total annual cost	**$ 55,274**	**$ 2,906**	**$ 1,713**	**$ 14,938**	**$ 74,831**

Annual power (kWh) cost is $98,789 for incandescent lamps and $11,661 for LED lamps. This is a saving of $87,128 or an 88% reduction for the red LEDs (note: the energy savings for the entire signalized intersection including the green, yellow and red lamps are estimated to be 65%). The estimated payback for an initial $315,846 investment of LED lamps is 3.6 years.

The total annual cost including annualized lamp replacement cost is $101,001 for incandescent lamps and $74,831 for LED lamps. The total annual saving is $26,170 or a 26% reduction in costs. This amount does not include labor for the initial conversion, group relamping or emergency response calls. If these costs are included, the annual savings would be greater.

3.0 LED PERFORMANCE AND EVALUATION

3.1 PHYSICAL CHARACTERISTICS

LEDs come in a variety of colors, beam widths and luminous intensities. They also have a long rated life. To assure the long life, ODOT requires the LEDs to be operated at no more than 50% of their rated wattage and requires a written warranty for 5 years on parts and materials. To achieve the rated life, a 50-milliampere rated LED may operate at only 25-milliampere.

The individual LEDs typically used in ODOT's red vehicular signals emit a luminous intensity of 1,500 to 2,000 millicandelas (mcd), have a 30 degree viewing angle and a dominant wavelength of 644 nanometers (nm). The face of the lamp is covered with a red non-prismatic impact-resistant polycarbonate lens. The polycarbonate helps to resist impact damage and the red color helps to maintain a red appearance when the lamp is de-energized during the yellow or green signal phases. LEDs for the pedestrian signal emit a luminous intensity of 650-mcd and have a 30-degree viewing angle.

To obtain the desired brightness, a 12-inch red-ball signal lamp may contain as much as 620 LEDs. The red-arrow and pedestrian hand symbol lamps use 250 and 220 LEDs, respectively.

For retrofit applications, circuitry is included in the lamp to convert the 120-volt AC supply voltage to a DC voltage. This is necessary to power the DC operated LED lamps.

LEDs produce mostly a monochromatic color, that is, the emitted light occurs within a relatively narrow wavelength (see Figure 3.1). Over 95% of the red LED radiant energy is emitted between 620 and 670 nm. This is within the sensitivity of the human eye, which is sensitive from 380 to 780-nm. This makes the LED a very efficient source in producing visible light.

In comparison, incandescent lamps emit most of its radiant energy between 330 and 3,500-nm (see Figure 3.2). About 95% of the energy is radiated as heat which is beyond the visible spectrum. The remaining 5% is then filtered through a red lens to obtain the proper color. Consequently, the incandescent lamp is much less efficient at producing a red light.

The difference in lamp efficacy is quantified when comparing the lumens per watt (lm/w). The incandescent is rated at 13 lm/w, whereas, the LED is 85 lm/w or 6.5 times more efficient.

Incandescent arrow lenses are even less efficient. Arrow backgrounds use a black non-reflecting surface that absorbs the light. This absorbed light is energy wasted as heat instead of radiant visible light.

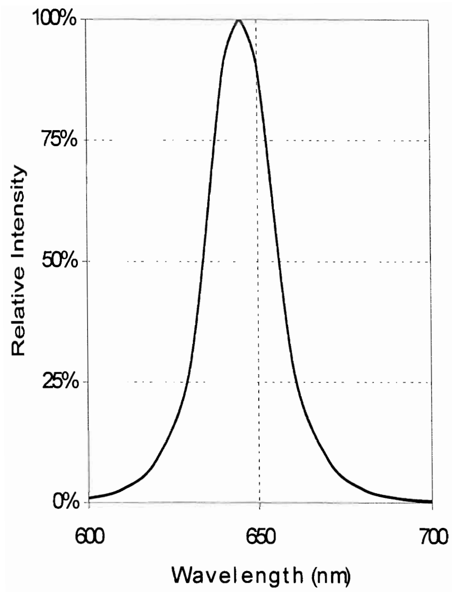

Figure 3.1: $LED_{644\ nm}$ Relative Intensity

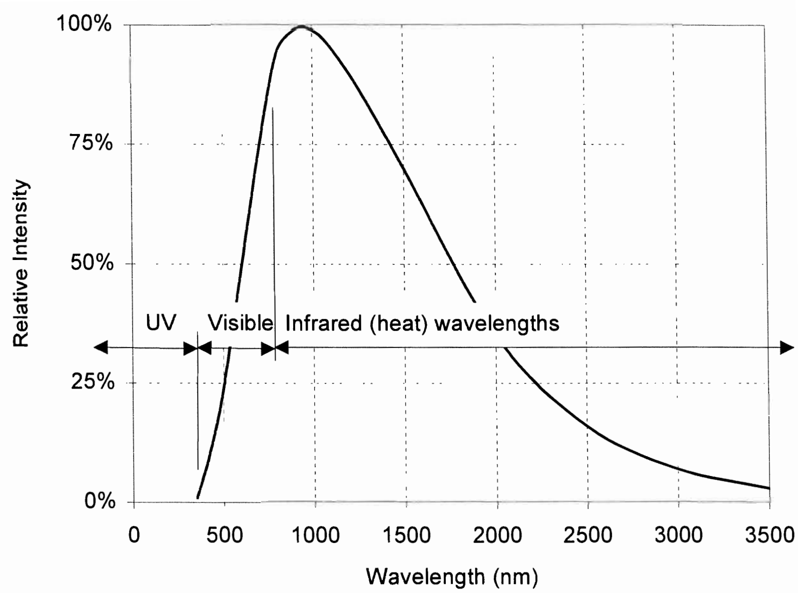

Figure 3.2: Incandescent Relative Intensity

3.2 RETROFITTING

LED retrofit kits are usually installed when the incandescent requires relamping. The initial installation required the old reflector, socket, lens and gaskets to be removed. The retrofit lamp was then mounted with the same hardware that held the old lens and the lamp leads were wired directly to the terminal block. This work required a few extra minutes to perform.

Newer retrofit kits are now available that can mount in the same socket as the incandescent lamp. Removal of the reflector, socket, lens and gasket is no longer required. The new kit is preferred over the older kit since the relamping time is shorter. Unfortunately, the old retrofit kits will need to be replaced in-kind or the original reflector, socket, lens and gasket must be reinstalled before the new retrofit kits can be installed.

Photographs of the retrofit kits can be found in appendix A.

3.3 SAFETY ASPECTS

LED lamps provide several safety advantages over incandescent lamps.

First, LED lamps typically consist of several parallel and series circuits. When an LED fails, it usually maintains continuity in the circuit and does not affect the other LEDs. However, in a few cases the LED may fail in an open mode causing all LEDs on the same series circuit to extinguish. Fortunately the lamp has many other circuits that are unaffected, so that 96% of the LEDs would remain lighted. Although the loss of an LED will result in a slight reduction in brightness, the remaining LEDs will still provide sufficient brightness to control traffic. This is a much safer condition than a single filament incandescent lamp, which extinguishes completely when it fails. Redundant traffic signals are vital in this situation.

Second, the LED circuit design is also effective against vandalism, specifically with firearms. If a bullet damages a circuit, the remaining circuits continue to operate. An exception is when the main power lead or converter is damaged; causing all the LEDs to extinguish.

Maintenance crews have commented that a damaged LED lamp is often difficult to detect until a lift-truck is used to inspect the traffic signal up close. Due to the close spacing of the LEDs, a few burned out LEDs or an extinguished circuit go largely unnoticed until a planned relamping is performed.

3.4 VISUAL DIFFERENCES

Since the LED wavelength is similar to the incandescent with red lens, the color differences are nearly imperceptible. The cluster of LEDs in the lamp under normal viewing conditions is largely unnoticed by the motorist. When viewed up close, the lamp appears to have numerous bright spots as emitted by the individual LEDs, but the refracting prisms on an incandescent lens creates a similar appearance. Although the differences are noticeable, they are insignificant and largely unnoticed by the motorist. This difference is even less noticeable with the newer retrofit kits, which retain the same prismatic lens as the incandescent lamp.

Differences in visibility are more apparent in fog conditions. In heavy fog, observers have noticed the incandescent system produces a large "halo" affect around the lens. This may be caused by the wide beam light distribution that reflects off the moist air similar to a rainbow. This reflection can be distracting and reduces the ability to recognize and identify the traffic signal. In comparison, the LED lamp does not produce as strong a halo and is much easier to recognize. This effect is assumed to be due to the narrower LED beam width.

3.5 RELAMPING SCHEDULES

At the time of this report, the LED lamps have been in operation for four years, from 1993 to 1997. During this period, it is estimated that less than one percent of the LED lamps have failed. By comparison, ODOT experienced a 5 to 8 percent annual failure rate for the incandescent lamps. If the LED failure rate stays low, it will have significantly reduced the road crews' exposure to traffic, preventable accidents and maintenance costs. The planned group relamping cycle is currently five years, but this could be extended if the failure rates stay relatively low and lamp brightness remains high.

Although the group relamping of the LED may occur on a five-year or greater cycle, the incandescent group relamping for the green and yellow lenses will still occur every two years. As such, the two-year cycle is still a large improvement from the one-year cycle that previously occurred with the red incandescent lamp. The two-year visit also gives opportunity for the maintenance crews to inspect and clean the signal to maintain its light output.

3.6 LAMP OUTPUT AND DEPRECIATION

Age and the operating environment can affect lamp output. A decrease in brightness could be a concern if it reduces the motorists' ability to identify the traffic signal, increasing their response time. Therefore, it is important that the lamps maintain a sufficient brightness during its life.

This study did not test lamp performance, but tests performed by others report the LED output decreased 30% after two years of operation in a traffic signal when tested at temperatures over 38° C (100° F). By comparison, incandescent lamps typically depreciate 10 to 20% after reaching 70% of its rated life. At this time, it is unknown what the retrofit LED lamp output will be after five years.

Lamp output test results are shown in Appendix D, but it should be noted that these tests were not substantiated by this study.

Although it appears the LED depreciation is greater than the incandescent, new advances in LED technology have produced brighter LEDs that could have a better end-of-life output.

3.7 FUTURE DEVELOPMENTS

As more traffic signals are converted nationwide to LEDs, the increased demand should result in greater technological advances, producing brighter, longer life, lower cost lamps. Such changes will have a beneficial effect on LED costs and performance.

Since this program began, brighter LEDs have been marketed and better retrofit kits have become available. As mentioned in the preface of this report, the LEDs used in this initial relamping program were constructed of an aluminum gallium arsenide material (AlGaAs). Improved LED's now use an aluminum indium gallium phosphide material (AlInGaP). Advances in LED technology will undoubtedly continue.

The Institute of Transportation Engineers' specifications for LED lamps are currently under development. These LEDs could some day redefine the standard color and brightness in vehicular and pedestrian signals.

4.0 CONCLUSIONS

LED lamps have performed well since first installed in traffic signals in 1993. ODOT has converted to the red LED lamps for all "stop-ball", "stop-arrow" and pedestrian "hand" symbol installations. The cities that participated in the implementation program plan to continue using the LED lights. The energy saved has helped reduce demand for energy and the need for local power companies to construct additional power generation plants. The benefits of LED lamps include the following:

1. LED lamps will lower energy demand and operating cost. For this project, 1,452,000 kWh and $87,128 will be saved each year, an 88% reduction for the red LEDs (note: the energy savings for the entire signalized intersection including the green, yellow and red lamps are estimated to be 65%). The saving with LED lamp costs factored in reduces the savings to $26,170 saved each year, or a 26% annual reduction.

2. The longer lamp life of LEDs reduces maintenance relamping costs, traffic congestion caused by relamping and crew exposure to work zone hazards.

3. LEDs reduce emergency calls for lamp failures and vandalism. Reducing the emergency response calls from 6% to 1% provides significant savings to the road crews. It saves maintenance costs and time, allowing road crews to allocate their time to other needs. It also reduces risk of preventable accidents and liability.

4. Future advancements in LED technology will continue to make the LED a cost-effective lamp. As the lamps become more efficient, the annual savings should continue to increase.

5.0 REFERENCES

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Kaufman, John, ed. *IES Lighting Handbook: the Standard Lighting Guide.* 5th ed. New York. Illumination Engineering Society. 1972.

Lighting Handbook. rev.ed. Bloomfield, NJ. Westinghouse Electric Corporation, Lamp Division. January, 1976.

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Tech Update TU-94-1. Boulder, CO. E Source, Inc. February 1994.

APPENDIX A

PHOTOGRAPHS OF LED RETROFIT KITS

The lamp with black housing is the original LED retrofit kit. It is designed to replace the existing lens and reflector. Note the wire leads for wiring directly to the terminal block. The lamp with the white housing is the newer retrofit kit. The Kit includes a medium base lamp socket for retrofitting in existing signal heads. Removal of lens, reflector and socket is not required.

Figure A.1: Retrofit Kits.

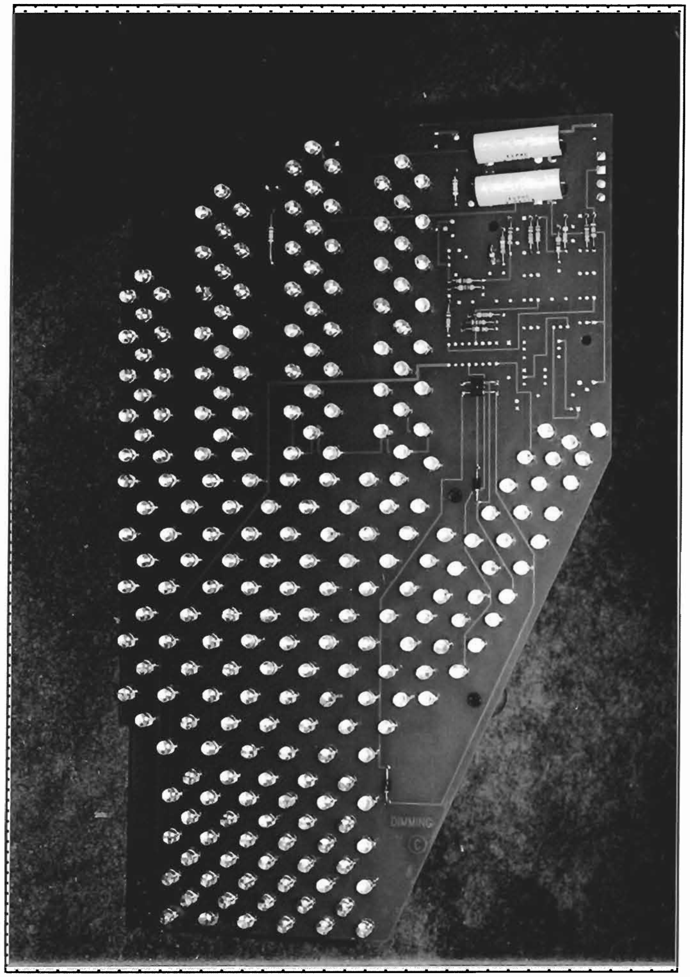


Figure A.2: LED Pedestrian Hand Symbol

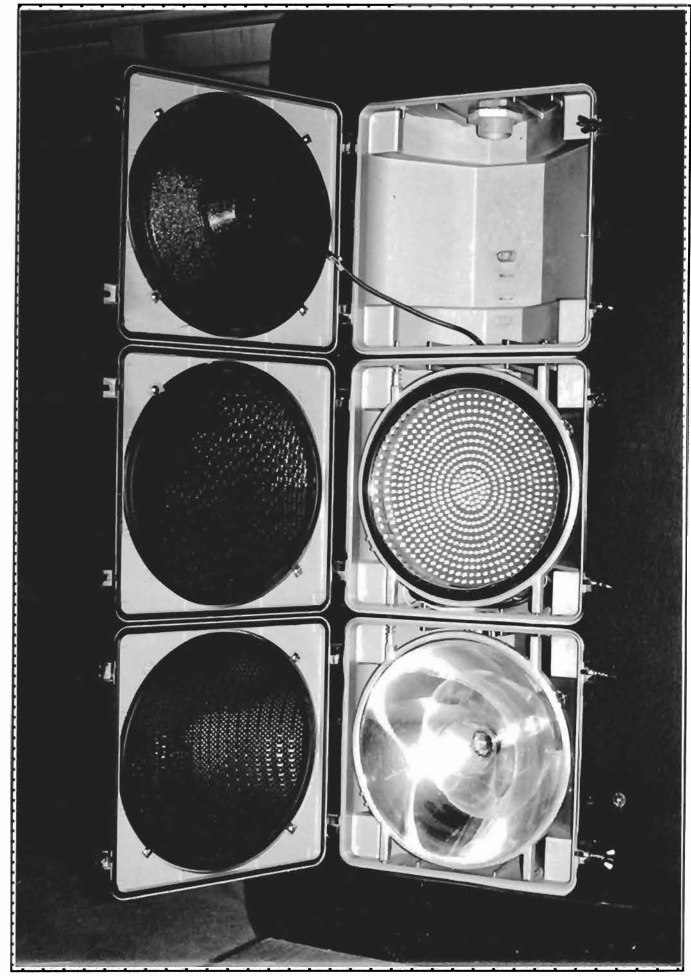


Figure A.3: Retrofit Kits Mounted in Signal Head. Top to bottom: Original LED kit, newer LED kit, and incandescent lamp

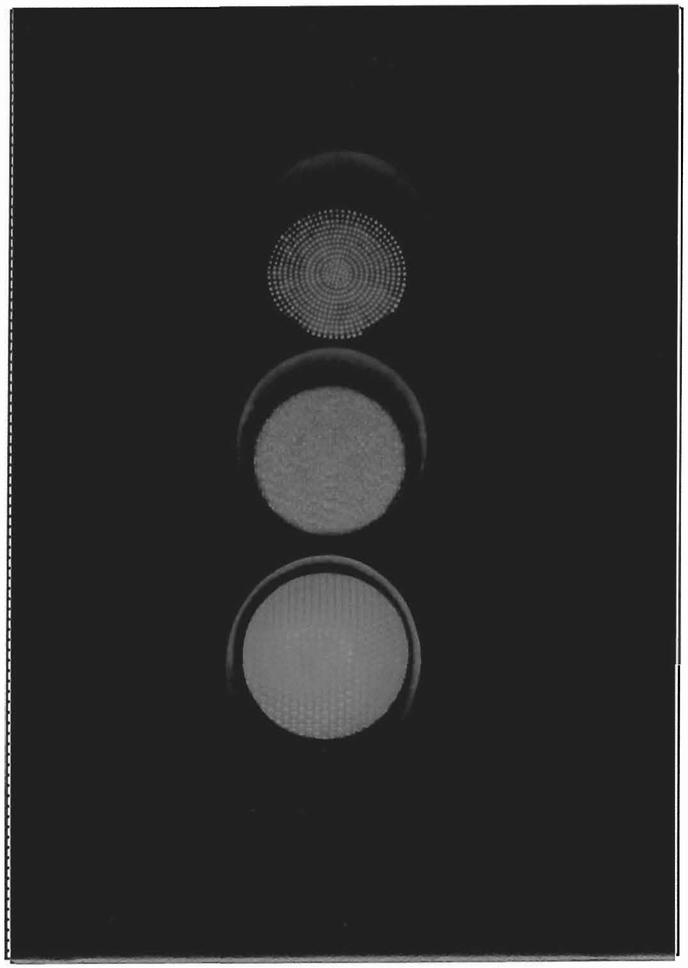


Figure A.4 and A.5: Illuminated and Non-Illuminated Views of Retrofit Kits (top 2 lights) and Incandescent Lamps (bottom light).

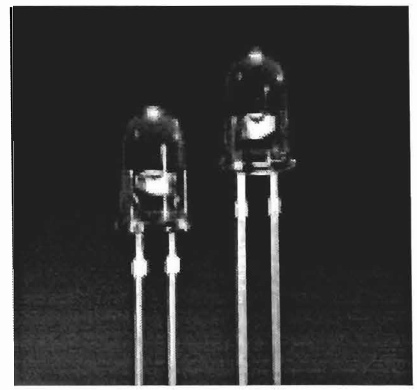
APPENDIX B

HLMP-C100 TECHNICAL DATA SHEET

T-1¾ (5 mm) High Performance TS AlGaAs Red LED Lamps

Technical Data

HLMP-810X Series
HLMP-C100
HLMP-C110



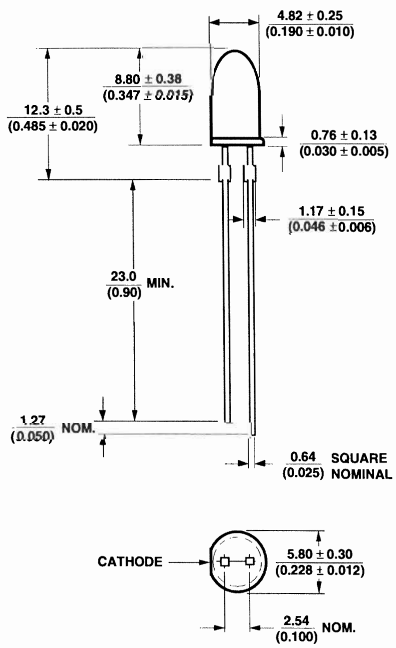
Features

- **Exceptional Brightness**
- **Outstanding LED Material Efficiency**
- **High Light Output Over a Wide Range of Drive Currents**
- **Viewing Angle: Narrow or Wide**
- **Low Forward Voltage**
- **Low Power Dissipation**
- **CMOS/MOS Compatible**
- **Red Color**

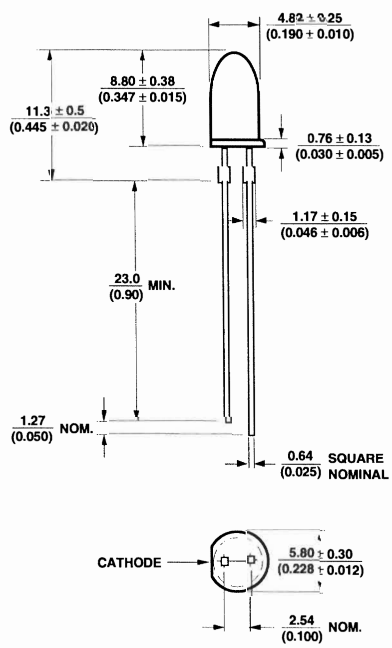
Description

These T-1¾, untinted, nondiffused lamps utilize a highly optimized LED material technology, transparent substrate aluminum gallium arsenide (TS AlGaAs). This LED technology has a very high luminous efficiency, capable of producing high light output over a wide range of drive currents (500 µA to 50 mA). The color is deep red at a dominant wavelength of 644 nm. TS AlGaAs is a flip-chip LED technology, die attached to the anode lead and wire bonded to the cathode lead.

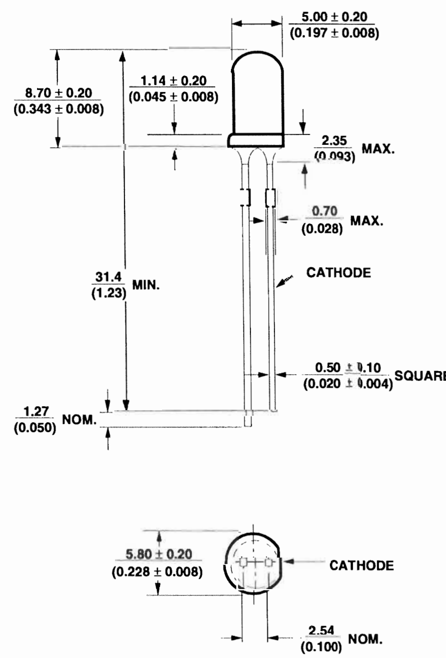
Package Dimensions



HLMP-8100



HLMP-8102/-8103



HLMP-C100/-C110

NOTES:
1. ALL DIMENSIONS ARE IN MILLIMETERS/INCHES.
2. THE LEADS ARE MILD STEEL, SOLDER DIPPED.
3. AN EPOXY MENISCUS MAY EXTEND ABOUT 1 mm (0.040") DOWN THE LEADS, UNLESS OTHERWSE NOTED.

Axial Luminous Intensity and Viewing Angle at T_A = 25°C

Part Number HLMP-	Minimum Intensity (mcd) @ 20 mA	Typical Intensity (mcd) @ 20 mA	Typical Radiant Intensity (mW/sr) @ 20 mA	$2\theta^{1/2}$ [1] Degrees
8103	2000	3000	35.3	7
8102	1400	2000	23.5	7
8100	290	1000	11.8	19
C100	290	750	8.8	30
C110	200	400	4.7	40

Note:
1. θ1/2 is the off axis angle from optical centerline where the luminous intensity is 1/2 the on-axis value.

Absolute Maximum Ratings at T_A = 25°C

Peak Forward Current[2] .... 300 mA
Average Forward Current (@ I_{PEAK} = 300 mA) [1,2] .... 30 mA
DC Forward Current[3] .... 50 mA
Power Dissipation .... 100 mW
Reverse Voltage (I_R=100 µA) .... 5 V
Transient Forward Current (10 µs Pulse)[4] .... 500 mA
Operating Temperature Range .... -55 to +100°C
Storage Temperature Range .... -55 to +100°C
LED Junction Temperature .... 110°C
Lead Soldering Temperature
[1.6 mm (0.063 in.) from body] .... 260°C for 5 seconds

Notes:
1. Maximum I_{AVG} at f = 1 kHz, DF = 10%.
2. Refer to Figure 6 to establish pulsed operating conditions.
3. Derate linearly as shown in Figure 5.
4. The transient peak current is the maximum non-recurring peak current the device can withstand without damaging the LED die and wire bonds. It is not recommended that the device be operated at peak currents above the Absolute Maximum Peak Forward Current.

Electrical/Optical Characteristics at $T_A = 25°C$

Description	Symbol	Min.	Typ.	Max.	Units	Test Conditions
Forward Voltage	V_F		1.85	2.4	V	$I_F = 20$ mA
Reverse Voltage	V_R	5.0	20.0		V	$I_R = 100$ μA
Peak Wavelength	λ_{PEAK}		654		nm	
Dominant Wavelength[1]	λ_d		644		nm	
Spectral Line Halfwidth	$\Delta\lambda 1/2$		18		nm	
Speed of Response	τ_S		45		ns	Exponential Time Constant, $e^{-t/\tau}$
Capacitance	C		20		pF	$V_F = 0$, f = 1 MHz
Thermal Resistance HLMP-810X	$R\theta_{J\text{-}PIN}$		210		°C/W	Junction-to-Anode Lead
HLMP-C1X0			237			
Luminous Efficacy[2]	η_v		85		lm/W	

Notes:
1. The dominant wavelength, λ_d, is derived from the CIE chromaticity diagram and represents the color of the device.
2. The radiant intensity, I_e, in watts per steradian, may be found from the equation $I_e = I_V/\eta_V$, where I_V is the luminous intensity in candelas and η_V is luminous efficacy in lumens/watt

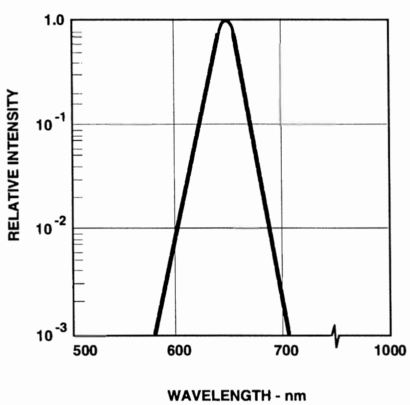


Figure 1. Relative Intensity vs. Wavelength.

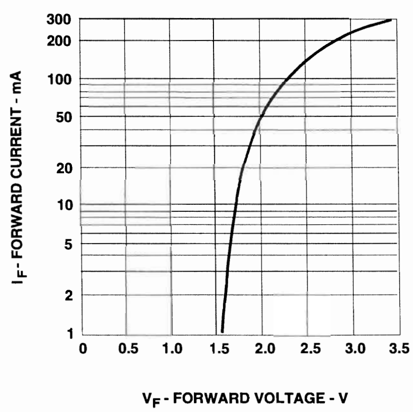


Figure 2. Forward Current vs. Forward Voltage.

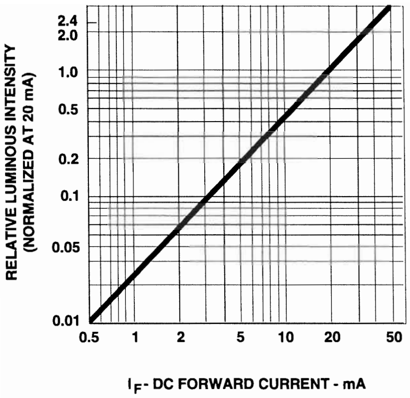


Figure 3. Relative Luminous Intensity vs. DC Forward Current.

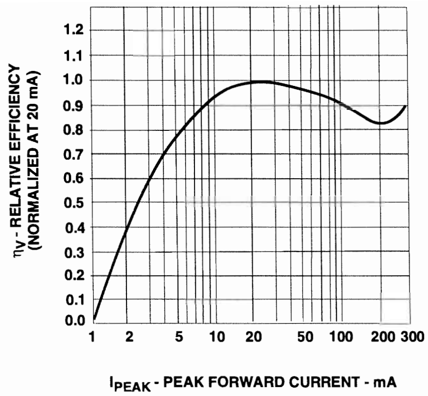


Figure 4. Relative Efficiency vs. Peak Forward Current.

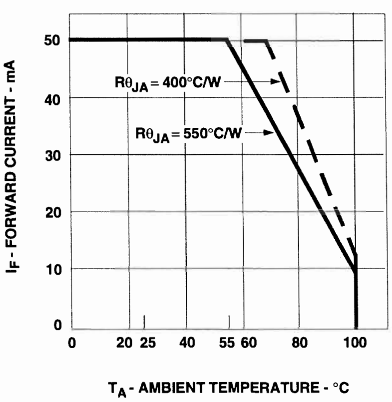


Figure 5. Maximum Forward DC Current vs. Ambient Temperature. Derating Based on TJMAX = 110°C.

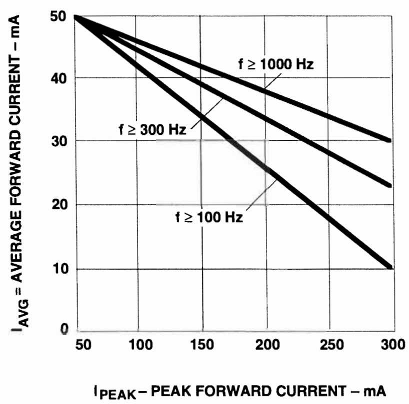


Figure 6. Maximum Average Current vs. Peak Forward Current.

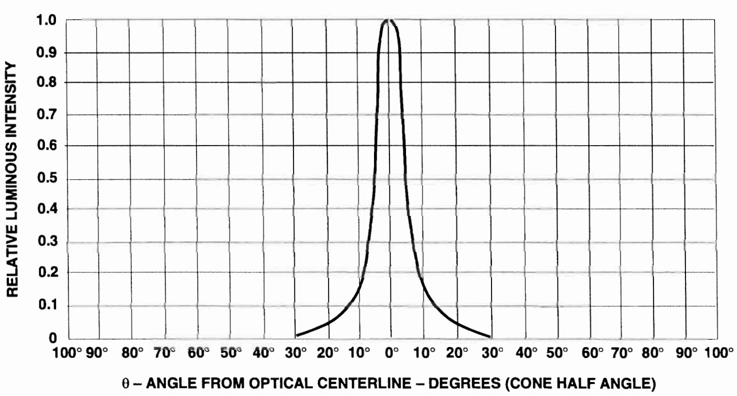


Figure 7. Relative Luminous Intensity vs. Angular Displacement. HLMP-8103 and HLMP-8102.

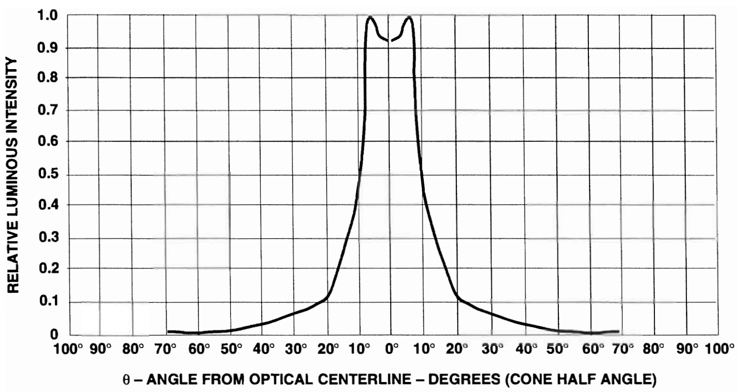


Figure 8. Relative Luminous Intensity vs. Angular Displacement. HLMP-8100.

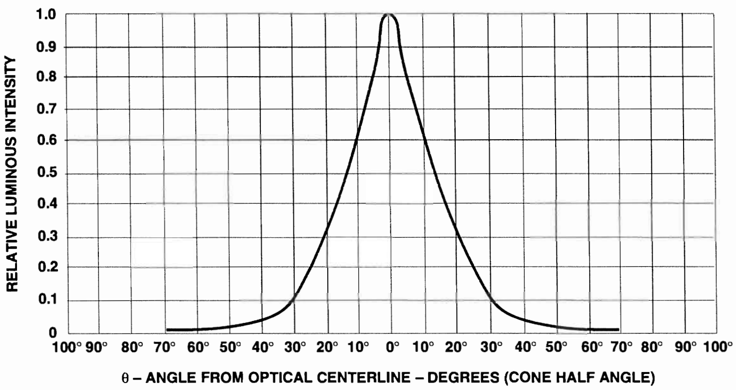


Figure 9. Relative Luminous Intensity vs. Angular Displacement. HLMP-C100.

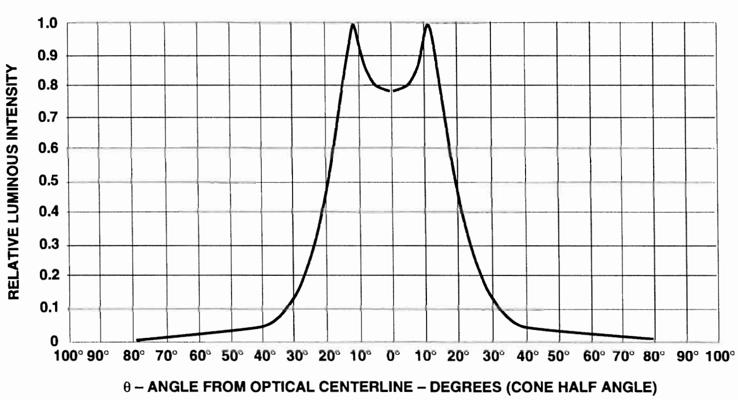


Figure 10. Relative Luminous Intensity vs. Angular Displacement. HLMP-C110.

APPENDIX C

ODOT SPECIFICATIONS

ODOT 1996 Standard Specifications for Highway Construction

SECTION 02920 - HIGHWAY ILLUMINATION AND TRAFFIC SIGNAL MATERIALS

02920.51 Traffic Signal Lamps - Vehicular signal lamps shall be rated for 130 V AC operation, and shall have a rated life of at least 6000 hours.

The light distribution and candle power intensity from the combination of lamp, reflector, and lens for signal heads shall conform to the current ITE Standards for Adjustable Face Vehicle Traffic Control Signal Heads.

The signal lamps shall be rated in either watts or lumens. The following are recommended signal lamp ratings. Certification of compliance with ITE Standards shall be submitted on lamp rated for other than the recommended values.

Indication	**200 mm Lens**		**300 mm Lens**	
Color	**Watts**	**Lumens**	**Watts**	**Lumens**
Red	67-69	665	See 02920.51(a)	
Yellow	67-69	665	100-116	1260
Green	67-69	665	150	1950

Light center length for 300 mm signal lenses shall be 75 mm and for 200 mm signal, lenses shall be 62 mm or as recommended by the Manufacturer. Lamps shall be of the type designed to withstand vibration and intended for use in traffic signal heads. Each lamp receptacle shall be equipped with heat and moisture resistant thermoplastic insulated, color coded or marked leads of stranded wire of sufficient length to allow full movement of the hinged reflector without breaking the lighting circuits. Lamp sockets shall be of weatherproof molded construction and capable ofwithstanding, without deterioration, the operating temperatures encountered during operation. Design the sockets so the lamps will not become loose due to vibration.

(a) Light Emitting Diode (LED) Retrofit Kits

(1) Wattage - Maximum wattages shall be:

- 25 W for 300 mm red ball
- 15 W for 300 mm red arrow
- 20 W for pedestrian hand symbol

LEDs are to be driven at no more than 50% of their rated wattages.

(2) Voltage - Operating voltages shall be between 85 V AC and 130 V AC.

(3) Temperature - The operating temperature range shall be -35 °C to +75 °C.

(4) LED Types - The red ball and arrow shall be Hewlett Packard HLMPC100 , or equal. The pedestrian hand symbol shall be Hewlett Packard HLMA-CH00, or equal. LED type and brand must be approved. All LEDS must be approved as to type and brand. All LEDs are to be driven at no more than 50% of their rated amperage.

(5) Number of LEDs - The minimum number of LEDs shall be:

- 300 mm ball - 620 LEDs
- 300 mm arrow - 250 LEDs
- pedestrian hand symbol - 220 LEDs

(6) Circuit Configuration:

- **300 mm Ball -** The LEDs shall be connected to form multiple series circuits, with a minimum of 7 such circuits provided. All series circuits shall be interconnected at intervals, forming subcircuits not exceeding 15 LEDs each. These subcircuits shall limit the number of extinguished LEDs to no more than 4% of the total on the signal lamp in the event of a single LED failure.

- **300 mm Arrow -** The LEDs shall be connected to form multiple series circuits, with a minimum of 3 such circuits provided. All series circuits shall be interconnected at intervals, forming subcircuits not exceeding 14 LEDs each. These subcircuits shall limit the number of extinguished LEDs to no more than 6% of the total on the signal lamp in the event of a single LED failure.

- **Pedestrian Hand Symbol -** The LEDs shall be connected to form multiple series circuits, with a minimum of 4 such circuits provided. All series circuits shall be interconnected at intervals, forming subcircuits not exceeding 10 LEDs each. These subcircuits shall limit the number of extinguished LEDs to no more than 4% of the total on the signal lamp in the event of a single LED failure.

(7) **Color and Light Output** - The red ball and red arrow shall meet ITE incandescent lamp standards for color (640 nm - 660 nm) and light output. The pedestrian hand symbol shall have a color of 600 nm - 621 nm and a minimum light output of 650 mcd per LED at 20 mA. Color and light testing shall be performed after 30 minutes of continuous unit operation.

(8) **Enclosure -** The enclosure shall be dust and water resistant.

(9) **300 mm Ball and Arrow Lens -** The lens shall be clear, "Hard Coated", polycarbonate (UV stabilized "Lexan") and convex with a minimum thickness of 3 mm. It shall have a minimum light transmittance of 92% and free from bubbles, flaws and other imperfections. It shall not be diffused. The hard coating shall be tested as follows and shall meet the specified results:

Abrasion Test:	Taber Abrasion Test (with 500 g load on each wheel @ 1000 cycles). Haze percent measured per ASTM D 1003.
Results:	3.0 - 7.0 Δ Haze
Environmental Testing:	Water Immersion Test (in tap water @ 6.5 °C).
Results:	500+ hours with no cracking or loss of adhesion.
QUV Exposure Testing:	(On QUV instrument manufactured by Q Panel Corp.) Cycle = 8 hours UV @ 70 °C and 4 hours cond. humidity @ 50 °C.
RS Sunlamp Exposure Results:	800+ hours with no cracking or loss of adhesion.
Yellowness Index Test Results:	(After 500 hours of QUV) Index = 1 - 4

(10) **Printed Circuit Boards -** Shall have acrylic resin base conformal coating. ("Loctite Shadow Cure" item 18893 or equivalent.) Pedestrian hand symbol printed circuit board shall be no larger than 178 mm X 279 mm.

(11) **Options -** The kits shall have the following options:

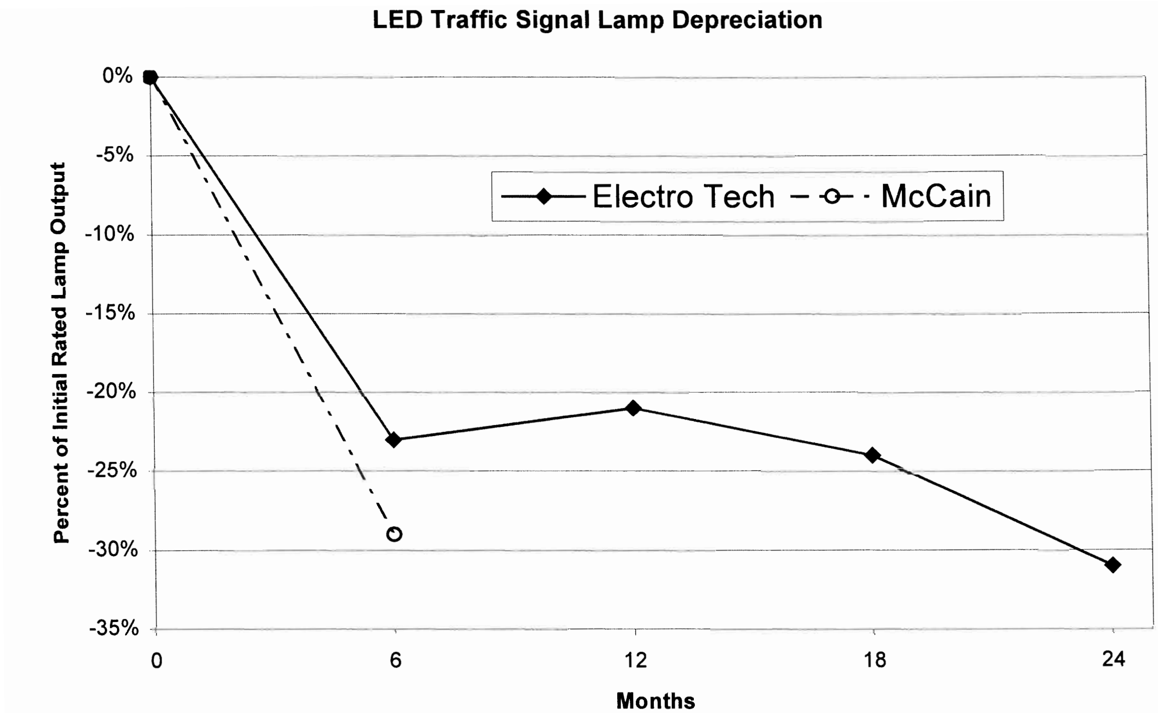
- red tinted replacement lens
- increased lens thickness

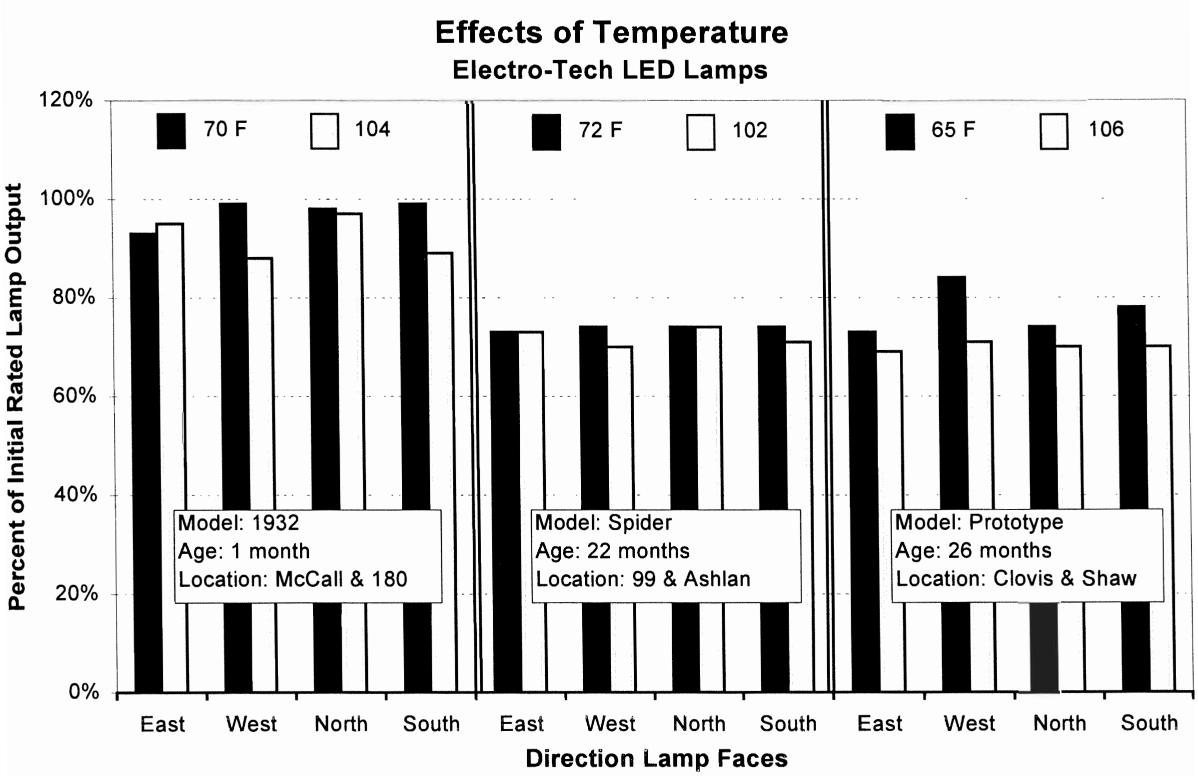
(12) **Prior Field Experience Required** - Each model submitted for approval shall have a minimum of 6 months field experience as part of a documented test program administered by a public agency.

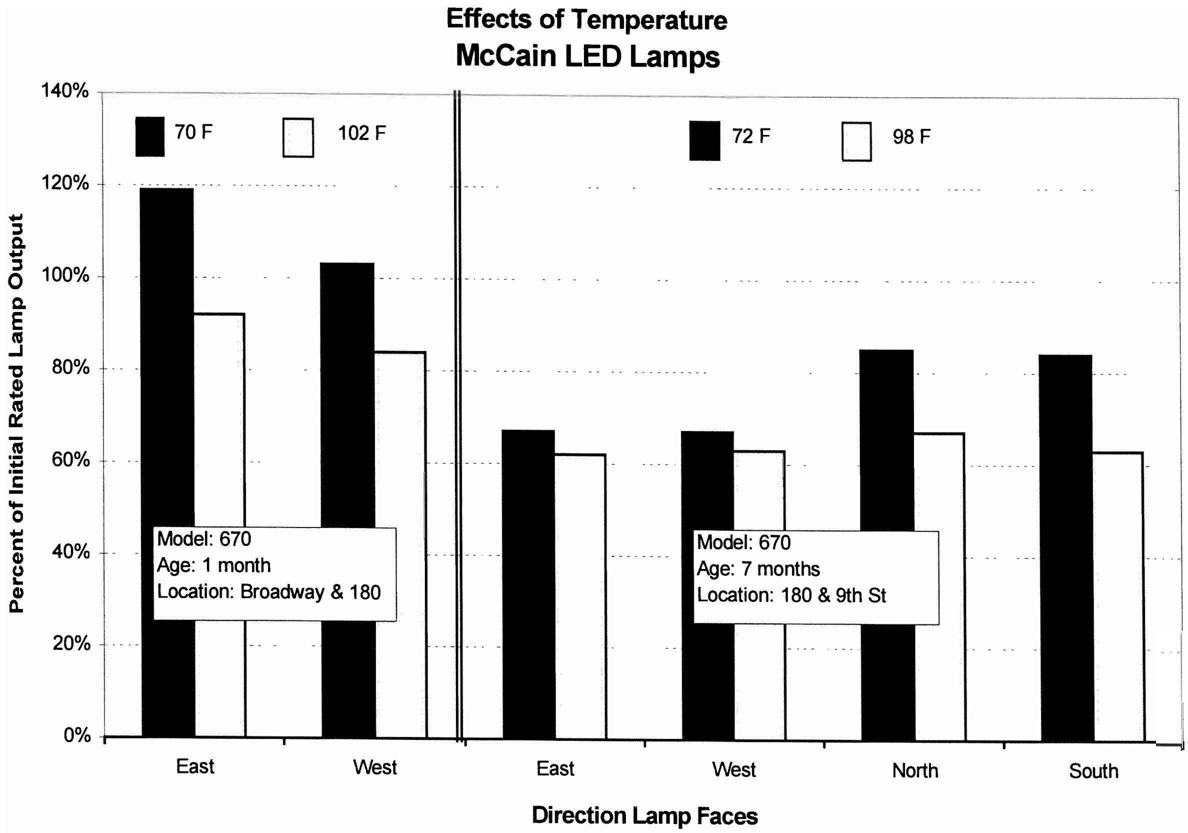
(13) **Warranty** - A five (5) year written manufacturer's warranty on parts and materials will be required on these products: red ball, red arrow and pedestrian hand symbol.

APPENDIX D

LAMP OUTPUT TESTS


LED Traffic Signal Lamp Depreciation
Electro Tech
McCain
0%
-5%
-10%
-15%
-20%
-25%
-30%
-35%
Percent of Initial Rated Lamp Output
0
6
12
18
24
Months


Effects of Temperature
Electro-Tech LED Lamps
70 F
104
72 F
102
65 F
106
120%
100%
80%
60%
40%
20%
0%
Percent of Initial Rated Lamp Output
Model: 1932
Age: 1 month
Location: McCall & 180
Model: Spider
Age: 22 months
Location: 99 & Ashlan
Model: Prototype
Age: 26 months
Location: Clovis & Shaw
East
West
North
South
East
West
North
South
East
West
North
South
Direction Lamp Faces


Effects of Temperature
McCain LED Lamps
140%
120%
100%
80%
60%
40%
20%
0%
Percent of Initial Rated Lamp Output
70 F
102 F
72 F
98 F
Model: 670
Age: 1 month
Location: Broadway & 180
Model: 670
Age: 7 months
Location: 180 & 9th St
East
West
East
West
North
South
Direction Lamp Faces