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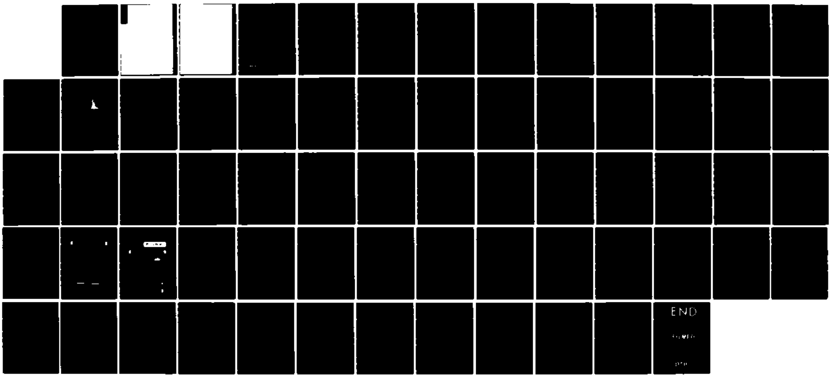

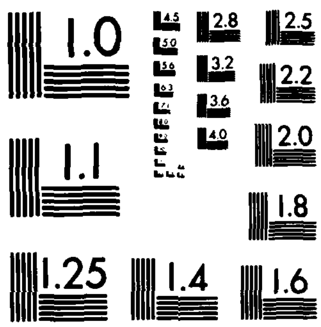

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A RAND NOTE

ASTRONOMY AND SODIUM LIGHTING

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PREFACE

The rapid growth of street and commercial lighting in urban areas has historically confounded, and in some cases even prohibited, scientific measurements at astronomical observatories. Several cities are currently in the process of replacing incandescent and mercury vapor lights with lower cost, more efficient sodium lamps. Community decisionmakers are choosing between two options--low- and high-pressure sodium. Astronomers favor low-pressure lamps because they cause least interference with the electromagnetic spectrum, while some community residents prefer the more natural color rendition offered by high-pressure lamps.

Because of the growing importance of this public policy issue, The Rand Corporation, with its own funds, supported a case study of the sodium lighting decision facing the City of San Diego, California. The study addresses the technical questions most likely to be raised in the course of the decisionmaking process. Most of the research presented here was completed before the February 6, 1984, San Diego City Council vote in favor of low-pressure sodium lighting. The authors are grateful for the comments and review offered by individuals both in the City of San Diego and at the Palomar Observatory. Photometric data drawn from catalog and journal sources, included in several figures and tables, are used with permission.

SUMMARY

In the last decade, lighting in the City of San Diego and its suburbs has increased substantially. Astronomers at Palomar Observatory are concerned that the encroaching light will make many of their measurements impossible. San Diego will soon convert its street lights to one of the more efficient sodium systems. Astronomers prefer low-pressure sodium lights because they do not interfere with the detection of distant stars. Other groups prefer high-pressure sodium lights because they have fair color rendition.

Many of the issues surrounding this choice have become controversial. The function of this Note is to identify and analyze some of the important factors in this public policy question. The first purpose of the research is to assess the significance of light pollution to astronomers. The second purpose is to focus on methods of mitigating the effects of light pollution. The third purpose is to compare the costs and efficiency of low- and high-pressure sodium lighting.

Our findings reveal that light pollution indeed presents a problem for many types of astronomical measurements. Although a number of methods of reducing the impacts of lighting might be adopted, the most promising is conversion to low-pressure sodium lights. Costs of the low- and high-pressure systems in San Diego are comparable, and the final decision on the type of lighting should be based on other factors.

CONTENTS

FIGURES

TABLES

I. INTRODUCTION

Recent years have brought significant increases in population, urbanization, and street and commercial lighting levels in urban areas. One consequence of this growth, little known to the general public, is disastrous to astronomers. Light pollution near highly populated areas is contributing significantly to the artificial sky glow. Since many galaxies and star systems are already near limits of detectability, light pollution may eventually prevent them from being studied.

The problem of light pollution has become so widespread that locations for new observatories are few. The most serious concern, however, is the encroachment of urban lighting on existing observatories. The American Astronomical Society and the Astronomical Society of the Pacific have organized committees to deal with the issue of environmental pollution. In 1972, Tucson passed the first ordinance requiring the use of downward shields and filters on lights to decrease the sky brightness at Kitt Peak National Observatory. At Mt. Wilson Observatory near Los Angeles, the sky brightness is now so high that the telescope is useless for detecting distant stars. The sky brightness around Palomar has increased by about 25 percent because of the growth of San Diego and its suburbs (Faber, 1980).

The mercury vapor lamp has been the common source of outside lighting for many years. Increasing energy prices have prompted some conversion to the more energy efficient high-pressure sodium (HPS) and low-pressure sodium (LPS) lamps. Indeed, many communities are examining the characteristics and costs of the sodium lights that will ultimately replace the mercury vapor type. Each type of sodium lamp offers specific advantages and disadvantages and the life-cycle costs are roughly comparable.

Astronomers across the country are working to encourage communities near observatories to adopt the LPS rather than the HPS lamps for street lighting. They are motivated by the fact that HPS lamps emit a great deal of light in the visible range that interferes with astronomical observations. LPS lamps, on the other hand, are favored by astronomers, since they emit light in only a narrow band of the visible spectrum. Some communities have accommodated the observatories and installed LPS lamps and others have adopted HPS lighting, citing cost and aesthetics as the reason for their preference.

The City of San Diego will shortly adopt sodium lighting in place of incandescent and mercury vapor street lamps. The San Diego City Council has changed its mind several times on the type of lighting to adopt and a vote in 1984 is expected to decide the issue.[1] This choice will heavily influence the quality of future astronomical measurement that can be performed at Palomar Observatory. Because the lighting decision involves substantial public resources, The Rand Corporation supported a study of the San Diego lighting choice to provide an analysis of the pertinent issues. This document summarizes the results of our investigation. Although we focused on only one locality, and other situations may present different features to some extent, parts of the analysis can apply to other locations as well.

Our investigation confirms that astronomers have adequate reason for concern. Adoption of HPS lighting in many expanding communities in the region of observatories may ultimately signal the demise of certain land-based observations. Although there are many methods of mitigating the influence of light pollution, one of the most effective is the adoption of LPS for street lights and similar applications. Our results show that the costs of LPS and HPS lighting are comparable. Although the capital and maintenance costs of HPS lamps are lower, the lower energy requirements of LPS lighting somewhat offset that advantage. The overall cost difference is always small and can be shifted to either type by a change in the light level required or by differences in pole spacing or luminaire location. Opponents of LPS claim that the yellow light emitted prevents color discrimination. Since the costs of the two lighting types are so close, the tradeoff becomes one between public acceptance and continued astronomical measurements.

Because our resources were limited, we made cost comparisons on only a few of the many cases of interest. It was not possible to treat quantitatively many of the other issues. Nonetheless, the approach and

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[1] On February 6, 1984, the San Diego City Council voted in favor of low-pressure sodium lighting.

methods are illustrative of those needed to analyze the light pollution issue at other observatories. We identify important variables and suggest some areas of development remote from astronomy, but which nevertheless may have an important impact on it. Decisions on lighting type are important: They affect both urban life and astronomical research.

In Section II, we present some general background information on city lighting.

In Section III, we discuss the issues that make up the controversy. We briefly describe the requirements for performing astronomical measurements and discuss several methods for reducing light pollution. We then compare the costs and efficiency of LPS and HPS systems. Finally, we describe other issues of public acceptance that can influence the choice of lighting.

In Section IV, we summarize our findings.

II. BACKGROUND

For many years, outdoor lighting in the United States was primarily incandescent. These lamps emit most of their radiation at wavelengths longer than about 555 nm and operate at approximately 2700°K. In Fig. 1, we show the spectrum of a typical incandescent lamp, together with the human visual response curve (Riegel, 1973). Most of the radiation emitted by these lamps evokes no visual response, and therefore, their efficiency is low.

More recently, most communities have replaced these incandescent lamps with high-intensity gas discharge (HID) lamps, generally mercury vapor. By 1970, although there were approximately equal numbers of

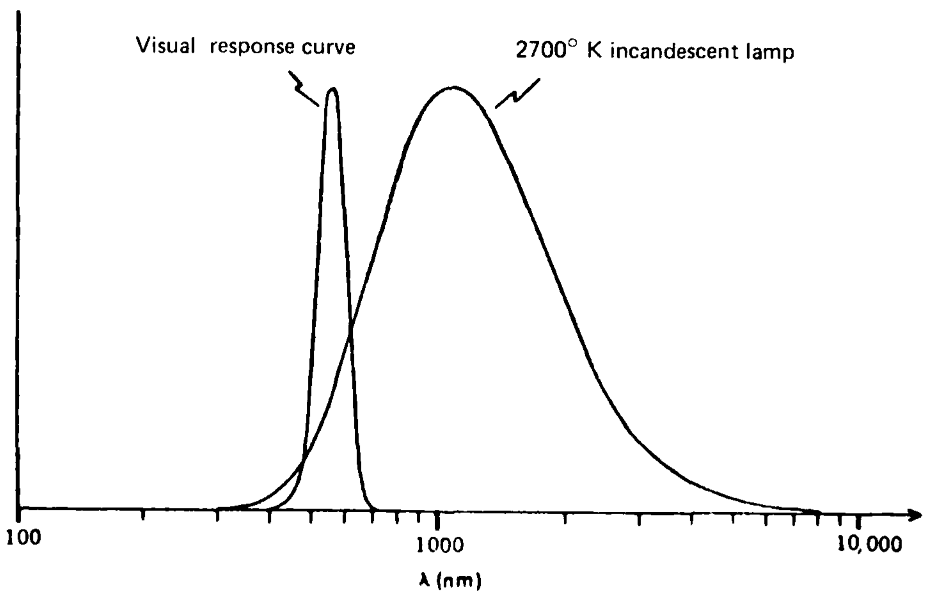

Fig. 1 -- Wavelength response of the human eye and spectrum of a typical incandescent lamp

outdoor incandescent and vapor lamps, about 85 percent of the total luminous radiation in the United States was produced by the vapor lamps (Riegel, 1973). In Fig. 2, we portray the spectrum of the mercury vapor lamp. The emission lines at 365.0, 404.7, and 435.8 nm[1] especially interfere with astronomical observations because they lie in the long wavelength blue end of the visible spectrum, a sensitive range for photographic emulsions. The remaining lines at longer wavelengths are troublesome to astronomers as well.

In Fig. 3, we show the spectral distribution of HPS and LPS lamps across the visible region. For comparison, this spectrum is drawn to the same scale as the mercury vapor spectrum in Fig. 2. Sources for the spectra are given in Plankenhorn (1981). From Figs. 2 and 3, it is

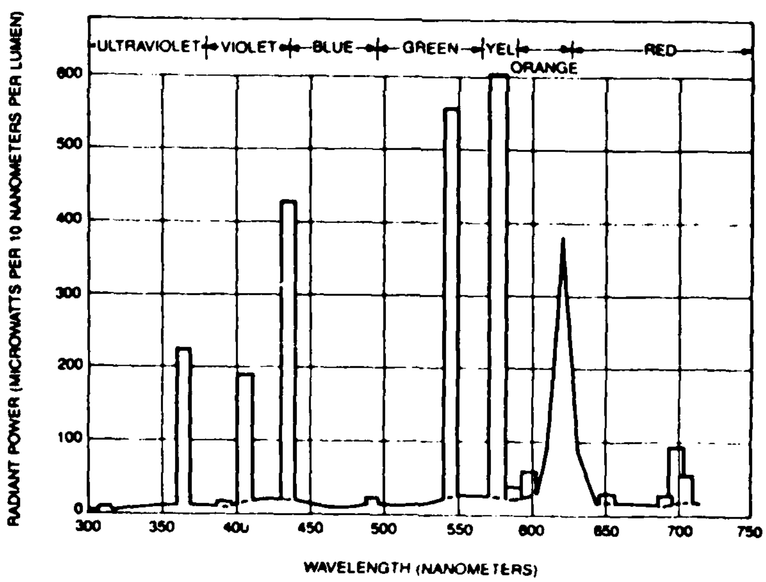

Fig. 2 -- Spectral distribution curve for deluxe white mercury lamp

[1]Metal halide and fluorescent lamps emit at these wavelengths as well.

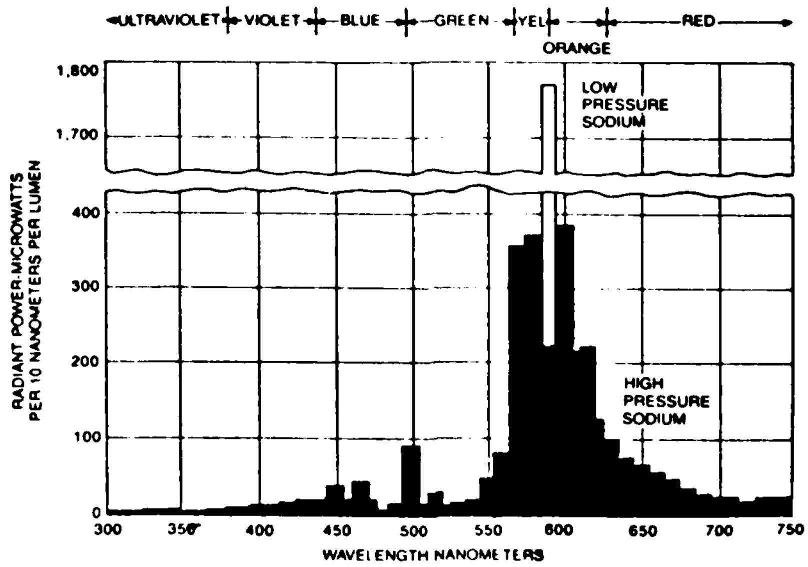

Fig. 3 -- Spectral distribution curve for high-pressure, low-pressure sodium lamps

obvious that the HPS light emits a strong continuum radiation and contains a much richer line spectrum than the cleaner mercury vapor lamp spectrum. The HPS lamps emit strongly over a significant portion of the visible range and will interfere drastically with astronomical measurements. On the other hand, the spectrum of the LPS light shown in white on Fig. 3 will interfere only minimally with astronomical observations. The very strong single line centered around 589.8 nm and the three small bands at 498, 569, and 616 nm (not visible in Fig. 3) are discrete, and measurements can generally be made around them.

Many communities, like San Diego, are now converting or considering converting their remaining incandescent and mercury vapor lamps to the more energy efficient HPS or LPS lighting. Figure 4 shows a comparison of the efficacy[2] of various lighting types (*Public Works*, 1980). The

[2]Lighting engineers measure light source efficiency in lumens per watt and call this quantity efficacy.

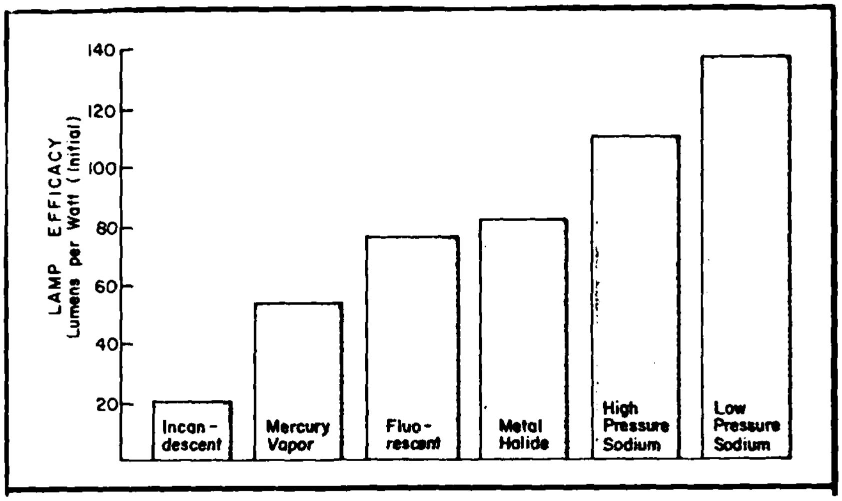

Fig. 4 -- Efficacy of various lighting systems

figure illustrates that both HPS and LPS lights are significantly more efficacious than other lighting.

Palomar, site of the 200-inch telescope, was established in the 1930s; the location was chosen, in part, because it was remote from human settlement and had dark sky characteristics. Since 1970, the population of San Diego, the nearest large urban center, 45 miles away, has grown by about 29 percent. Since population levels and lighting are correlated, there has been an increase in night sky illumination as well. This "light pollution" has effectively reduced the scope of the 200-inch telescope to the equivalent of a 140-inch aperture, which is only half as efficient.

In San Diego, 17,453 of the existing street lights are owned by the city. Of these, 7,142 are mercury vapor, incandescent, metal halide, or fluorescent; of the balance, 10,034 have been converted to HPS and 277 to LPS. The utility serving the San Diego area, SDG&E, owns an additional 10,277 street lights, the majority of which are mercury vapor. The 17,419 lights that are presently neither HPS or LPS are candidates for conversion. SDG&E is known to favor HPS. Although the

City of San Diego does not currently own these lights, it has made a move to purchase them. Regardless of ownership, however, in principle, the City Council does have the power to mandate a conversion to LPS. The utility would then submit a proposed conversion rate schedule to the Public Utilities Commission (PUC), which would decide whether or not it was equitable.

The history of San Diego's conversion decisions is somewhat involved. Initially, the City Manager recommended conversion to HPS. In November 1982, after hearing presentations by personnel from Palomar Observatory on light pollution and cost, the council voted 7 to 1 in favor of LPS. In June 1983, the council vote was 5 to 4, this time in favor of HPS. Another vote to approve the contracts for HPS is scheduled for early 1984, and presumably, it will decide the issue once and for all.

The conversion decision is surrounded in controversy and has become contentious. Astronomers claim that HPS lights will strongly interfere with their measurements and that LPS lighting is cheaper, at any rate. Opponents of LPS insist that HPS is the cheaper lighting system and complain about the poor color rendition of LPS. In what follows, we have attempted to sort out the issues that are important in a choice between LPS and HPS lighting. Although we focus specifically on the San Diego/Palomar decision, much of the discussion applies to other locations as well.[3]

[3]In particular, the San Diego decision will also directly affect Mt. Laguna Observatory, 45 miles east of San Diego. That observatory, owned by San Diego State University, is the site of a one-meter telescope moved from the University of Illinois.

III. ANALYSIS

In this section, we discuss a number of issues that are fundamental to the controversy surrounding the choice in lighting. First, we describe some features of astronomy that can be influenced by the encroaching "light pollution." Second, we discuss the influence of street lighting. Third, we identify and evaluate various methods for mitigating the effects of artificial lights. Fourth, we provide a comparative analysis of the costs of LPS and HPS lighting in the San Diego area. Fifth, we briefly mention some of the other issues affecting the choice of lighting type.

ASTRONOMICAL REQUIREMENTS

The astronomer would like to have access to as much of the electromagnetic spectrum as possible because different physical processes emit radiation at widely varying wavelengths. Our eyes respond most strongly to light in the optical region, which ranges from 400 to 700 nm. Although there are astronomical objects that emit radiation at other wavelengths, most solar-type stars emit a significant amount of their radiation in the visible region.

Two types of measurements made by astronomers are broad band (continuum), which includes high-resolution spectroscopy of stars, and narrow band, which includes photographing galaxies, quasars, and other very distant bodies. Many basic constituents of the universe have been discovered using broad band methods, and it remains an important technique for observing new phenomena. Interference can be narrow band, in which case the spectrum remains relatively uncluttered; as long as the body of interest does not emit at exactly the frequency of the interfering body, then observation is still possible. If the interference is broad band, or is composed of many lines, however, then the interference may be more serious. Narrow band measurement will still be possible as long as the region of concern falls between the interfering spectral lines.

There are two sources of sky glow. The first, the natural sky glow, is a result of moonlight, zodiacal light, lightning, light from background stars, meteors and comets, atmospheric scattered light, ground reflections, aurora borealis, and aurora australis. The second, the artificial sky glow, includes upward light from recreational facilities, amusement parks, parking lots, advertising signs, industrial and commercial buildings, houses, vehicles, road signs and signals, street lights, and indirect light reflected from ground level surfaces. The sky glow from natural sources cannot be controlled and astronomers have always had to take it into account when making measurements. The artificial sky glow can be controlled to some extent, and the options for doing so are discussed later in this section.

A value for the natural sky brightness can serve as a standard against which we can compare the contaminating effect of artificial skylight. A value for this brightness, in this case taken from a spectrum at Kitt Peak, is of the order of 20×10^{-9} stilb (candelas[1] per square centimeter). This is equivalent to one star of magnitude 22 per square arc second determined as follows (Riegel, 1973; Cayrel et al., 1980):

$$B = \frac{14.35 \times 10^{-0.4m}}{S^2}$$

where B is the sky brightness (stilbs); S is the seeing circle diameter (arc sec); and m is the apparent magnitude (per square arc second)[2].

[1]A candela is the luminous intensity in the perpendicular direction of a surface of 1/600,000 m^2 of a blackbody at the temperature of freezing platinum under a pressure of 101,325 N/m^2.

[2]The astronomical definition of magnitude is that a star of magnitude m is 2.512, or $\sqrt[5]{100}$ times as bright as a star of magnitude m + 1. In the equation above, 0.4 in the exponent is equal to log 2.512.

When the Kitt Peak Observatory was originally sited in 1960, it was a dark sky site and was expected to remain so for decades. In fact, there has been a drastic increase in the sky brightness from Tucson, some 45 miles away. Other observatories have been affected by artificial light pollution as well. At Mt. Wilson, near Los Angeles, observation of sources below the twentieth magnitude are no longer possible. At Palomar Observatory in California, stars of magnitude 24, two magnitudes lower in luminance than at Kitt Peak, can still be recorded (Finch, 1978). Light pollution from San Diego and other sources, however, is beginning to affect the sky brightness around Palomar, and measurements may become more difficult in the near future.

CITY LIGHTING

The sky glow that results from city lighting is made up of contributions from a number of different sources. The fraction that street lights contribute to the total city lighting is in dispute. Various published estimates claim that it represents between 15 and 50 percent of the total (Finch, 1978); other sources contend that street lighting is responsible for no more than 5 percent. Indeed, depending upon the characteristics of the lighting in a particular location, a huge range in the contribution of street lighting is possible.

Several factors can influence the city sky glow seen from an adjacent observatory. First, it will depend on the actual makeup of the lighting, which includes emissions from parking lots, billboards, parks, and theaters, as well as street lights. The sky glow is a heterogeneous halo made up of continuous and line radiation sources spanning the visible range. In San Carlos, California, for example, the results of a lighting inventory showed that street lighting accounted for 1.200 million lumens per square kilometer, whereas other city lighting accounted for 1.203 million lumens per kilometer (Finch et al., 1979).

A second factor that affects the sky glow is the fraction of lighting that is emitted into the upper hemisphere and the fraction emitted downward. Light emitted downward reaches an observatory telescope only after it has been reflected from various surfaces. In the analysis of San Carlos, for instance, it was assumed that 5 percent of the light from street lights was emitted upward and 95 percent downward. For the other lights, 30 percent was assumed to be emitted upward, and 70 percent downward. In general, the greater the shielding of the lighting luminaire, the lower the fraction directed upward (Finch et al., 1979).

A third factor that influences the amount of light that reaches an observatory telescope is scattering by atmospheric particles. At increasing altitudes, there is less light scattered because, as the density of the atmosphere decreases, there are fewer particles and the particles change from larger to smaller size.

Assuming a scattering function together with a relationship describing the intensity distribution, the luminance arriving at the telescope contributed by the various types of lighting can be calculated. In one such calculation, the luminance seen by the Mount Laguna telescope outside San Diego was estimated using the lighting inventory of San Carlos, California. The largest contribution in this case was from the direct upward light originating from both street lights and other city lighting. It represented about half the total light reaching the telescope. The next most important source was the halo of scattered light over the city. The forward scattered light and the reflected light were of only minor significance. The total contribution by street lights amounted to about 20 percent (Finch et al., 1979). In another calculation performed for an Australian city, the contribution of the direct and reflected radiation each represented about half of the total[3] (Fisher and Turner, 1977).

The contribution of street lighting to the artificial sky glow and to the total (artificial plus natural) will depend on several factors, and will vary greatly from location to location. There is no definitive method for calculating the fraction represented by street lighting. For most cities, it is safe to conclude that street lights are likely to be the largest single source of lighting. Many of the methods suggested for reducing light pollution involve decreasing street lighting and the effectiveness of such methods cannot be determined without at least a reasonable estimate of the contribution. In what follows, we have assumed that San Diego street lights represent 35 percent of total city

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[3] The average of all bearings over 30 degrees elevation.

lighting. This value may be too high but we believe it will serve as an upper bound to the reduction that can be achieved through measures that mitigate light pollution.

There are two basic factors about the interaction between city lighting and observatories to keep in mind. First, the higher the level of city lighting, including both street and other sources, the higher the artificial sky glow. This follows from the San Carlos and Australian city examples, where the direct emissions represented about half the light reaching the telescope. Because of the heterogeneous mixture of lighting in most cities, the direct contribution will probably always be fairly large. Second, the type of lighting, and therefore its emission spectrum, can have a significant influence on whether or not the astronomer will be presented with interfering light. This is simply another way of saying that it is the emission spectrum rather than the lighting intensity that matters most to the astronomer. For example, the astronomer would like a very intense light that emits radiation in one small window of the visible spectrum, even if much of its radiation were emitted upward. On the other hand, astronomers would not like a less intense light that emits radiation across a large portion of the visible spectrum even if more of its radiation is reflected rather than emitted upward.

METHODS FOR MITIGATING LIGHT POLLUTION

Below, we discuss seven techniques that could reduce the effects of increased sky brightness. They fall into two categories. The first three, generally suggested by those opposing LPS lighting, place the burden on astronomers. The last four would require changes in current lighting practices.

Relocate Observatories

Relocating observatories to new dark sky sites is an obvious method of reducing the impact of light pollution. This is not a practical option, however, for a number of reasons. First, the cost of such moves is large. One astronomer estimates that relocating an observatory with a large telescope would require tens of millions of dollars, approximately as much as it would cost to construct a new observatory

(Faber, 1980). Second, a relocation effort might take several years, and valuable time for making astronomical measurements would be lost. Third, the requirements of a good optical telescope site are stringent. The location, for example, must have a high percentage of clear nights, low humidity, moderate wind speeds, high altitude, remoteness from jet routes, low air pollution, and laminar air flow over the telescope to insure steady images. An additional requirement is that the site be accessible by maintenance workers and trained personnel; therefore, it should not be too remote.

When these requirements are combined with that of low light pollution, there are very few potential new observatory sites within the United States. In 1975, an analysis of California sites showed that in much of the state, the artificial sky brightness already exceeded 25 percent of normal. These sites are, therefore, not suitable for future observatories. When these bright areas are eliminated from consideration, there remains only one California peak, Junipero Serra, that is appropriate for an observatory. Indeed, one astronomer claims that she knows of no other such site in the United States (Faber, 1980).

Another related suggestion is that all future observatories will ultimately be space-based, making ground-based observatories obsolete. Astronomers maintain, however, that the extremely high cost and inaccessibility of space observatories make it unlikely that they will ever be a substitute for ground-based ones. In particular, many different types of observations, like those requiring new experimental methods and equipment, or especially bulky apparatus, cannot be done in orbit (Riegel, 1973). Furthermore, it is a poor use of the limited astronomy resources to perform measurements in space that can be done on the ground.

Increasing the Telescope Size

The limit of large telescopes for detecting faint bodies is set directly by the square root of the night sky brightness. Therefore, if the sky brightness increases by a factor of four, a large telescope has the equivalent detection capability of an instrument half its diameter operating at a dark sky site. Many people have suggested that astronomers can deal with the light pollution simply by increasing the size of their telescopes.

There are two reasons this approach is not a panacea. First, the cost of a 60-inch telescope amounts to approximately $2 million; the cost of a 120-inch telescope like that at Lick Observatory is about $12 million (Faber, 1980). Doubling the diameter of a telescope is clearly an expensive endeavor. Second, it is not obvious that increasing the telescope diameter would provide a solution. Although a larger instrument would collect the light more efficiently (increase the signal) and allow the observation of fainter objects, it would increase the interference (noise) as well. The limiting factor in astronomical measurements is, in effect, the detector.

Improve Measurement Efficiency

In the last decade, astronomers have adopted techniques that allow them to make more efficient measurements. These include photoelectric photometry and multiple exposure photography, which give longer integration times and better signal-to-noise ratios. These techniques will not solve the fundamental problem of light pollution, however, because the *signal-to-noise ratio is inversely* proportional to the square root of the background light. Thus, an increase in the sky glow from artificial sources will always act to decrease the signal-to-noise ratio regardless of the measurement efficiency.

Filtering

As mentioned in the last section, street lighting is the largest single source of city lighting; the balance is contributed by various other sources. Other outside sources, like automobiles and parks, use primarily incandescent sources. Interiors of commercial and industrial buildings are generally lit by fluorescent lights. Parking lots are lit by a variety of lighting types. Advertising signs vary in spectral distribution over the entire visual range. Promotional lights are commonly carbon arc sources that emit many lines as well as a continuum. Street lighting until recently was generally mercury vapor. The composite spectrum in a city that contributes to the artificial sky glow virtually covers the entire visible range.

Fluorescent, mercury vapor, and metal halide lamps emit strongly at 365.0, 404.7, and 435.8 nm. Although these lines contribute very little to increased visibility, they interfere significantly with astronomical measurements because they lie in the blue end of the visible and the long wavelength ultraviolet spectrum, an area important for photographic emulsions. The interfering far blue and ultraviolet components can be removed from lights by substituting a luminaire constructed of a material that incorporates dyes. The enclosure itself can serve as a filter that absorbs the blue and ultraviolet components before they are emitted to the atmosphere. This is called filtering at the source, and materials appropriate for this purpose are available in glass or plastic (Cayrel et al., 1980). Requirements for such filtration techniques have been adopted in some city ordinances, notably Tucson, Arizona. The ordinance was largely designed to minimize the impacts of light pollution from mercury vapor lamps. Indeed, it is apparent from Fig. 2 that the discrete emission lines of the mercury vapor lamps are especially amenable to source filtration.

In contrast, although the HPS lamp does not interfere as much as the mercury vapor lamp with the blue and ultraviolet regions of the spectrum, it does contribute a large continuum component in the red and yellow range. In Fig. 3, for instance, there is a strong continuum emission in the 550 to 750 nm range. Astronomers particularly need access to this spectral region for studying the features of distant quasars and galaxies. Source filters that remove the light in this range are inappropriate, since the HPS lights would then emit virtually no light in the visible range, rendering them useless for street lighting.

The emission spectrum of LPS lights, also shown in Fig. 3, is essentially monochromatic with a strong, discrete band at 589 nm. There are also three smaller bands at 498, 569, and 616 nm that are not visible in Fig. 3. In general, the LPS light is preferable to the astronomer because for most measurements, the discrete lines on a spectrograph would not interfere with lines from the body of interest; furthermore, in those instances where they did interfere, they could be eliminated easily by filtering. This is called filtering at the telescope.

In general, filtering existing mercury vapor lamps at the source is feasible. If these lamps are replaced with HPS street lighting, filtering is not appropriate because of the strong continuum component emitted. If the mercury vapor lamps are replaced with LPS lights, filtering at the telescope would be possible, but probably unnecessary.

Restricting Lighting Levels

Limiting the hours of use or levels of use could reduce light pollution measurably. The City of Tucson, for example, has adopted an ordinance in which advertising searchlights, aesthetic exterior building illumination, and outdoor public lighting are prohibited after midnight. Although such prohibitions for some lighting are certainly to be encouraged, a corresponding prohibition on street lighting might be dangerous. Furthermore, though the option might be effective in reducing light pollution, the uses and requirements of outdoor lighting vary so widely that a blanket regulation covering all aspects seems impractical.

Shielding of Lights

Many people have suggested that shielding street lights above the horizontal can reduce light pollution significantly. Others dispute this, claiming that very little light is emitted above the horizontal to begin with, so that controls to reduce emissions will not accomplish a great deal. Efficient shielding will limit the light that enters the upper hemisphere for all wavelengths. It will not eliminate that component of the light that is reflected from ground surfaces, however. Although street lighting may emit only a few percent of the luminous flux in the upper hemisphere, because there are so many luminaires with relatively high wattage, shielding might prevent at least some fraction of the sky glow.

In the case of San Diego, the City Council will shortly choose between adopting LPS or HPS lighting in place of the current incandescent and mercury vapor lighting. If the city adopts the HPS, its plan is to use them together with cutoff luminaires that will shield the light emitted upward. To estimate the effects of shielding the HPS lights, we assume, first, that there is no advantage to shielding LPS lights, since their emissions are virtually monochromatic and, as such, not troublesome to astronomers. We, therefore, compare two cases of shielding for illustrative purposes. The first is the case where 27,453 San Diego street lights are HPS and 277 are LPS (these have already been converted); the second is the case where 10,034 of the street lights are HPS (these have already been converted) and 17,696 are LPS. The calculations are summarized in Tables 1 and 2.

The characteristics of the LPS and HPS lights that are candidates to replace the current San Diego lights are described below. For this analysis, we briefly mention them here. The LPS is a 55 watt light with 8,000 initial lumens. There are two types of HPS lights under consideration: a 100 watt light with 8,800 initial lumens and a 70 watt light with 5,400 initial lumens. For purposes of this comparison, we selected the HPS lighting of the 100 watt type. Both the HPS and LPS light sources depreciate over time because of dirt; if this effect is included, the average luminous efficiency of the lights is only 95 percent of the initial lumens. Each LPS light gives off 7,600 lumens, and each HPS light gives off 8,360 lumens.

If we assume that 27,453 San Diego street lights are HPS and 277 are LPS, then there are 229.51 million HPS bulb lumens and 2.11 million LPS bulb lumens generated. According to values given in Figs. 9 and 10, 12 percent of the bulb lumens are lost in the fixture for LPS and 26 percent for HPS. Therefore, there are 169.84 million lumens given off by HPS lights, and 1.86 million by LPS lights. Four percent of the HPS bulb lumens are directed into the upper hemisphere and 70 percent are directed downward (see Fig. 10); comparable values for LPS are 9 percent and 79 percent (see Fig. 9). The light that falls on the street is determined from the product of bulb emissions and the coefficient of utilization, which is 0.39 for HPS and 0.318 for LPS. Nonstreet light is the difference between downward and street emissions.

In Table 3, we display the reflectance of various kinds of materials. We assume that the light directed onto the street will fall on somewhat worn asphalt, with a reflectance of 15 percent. The remaining nonstreet light will fall on a combination of concrete, grass, and other vegetation; for this light, we assume an average reflectance

Table 1

SAVINGS IN STREET LIGHT FROM SHIELDING WITH 100 PERCENT HPS

Item	HPS (LUCALOX/D)	LPS
Nominal watts	100	55
Initial lumens	8,800	8,000
Dirt depreciation	0.95	0.95
Number of lights	27,453	277
Bulb lumens	229.51×10^6	2.11×10^6
Emitted lumens[a]	169.84×10^6	1.86×10^6
Upper hemisphere light[b]	9.18×10^6	0.19×10^6
Downward light[c]	160.66×10^6	1.67×10^6
Street light[d]	89.51×10^6	$.67 \times 10^6$
Nonstreet light[e]	71.15×10^6	1.00×10^6
Reflected light[f]	34.77×10^6	0.40×10^6
Total light[g]	43.95×10^6	0.59×10^6
Total shielded light[h]	36.76×10^6	NA
Percent savings[i]	16	NA

[a] Assuming that 26 percent is lost in the fixture for HPS and 12 percent for LPS.

[b] Using a rate of 4 percent of the bulb lumens for HPS and 9 percent for LPS.

[c] Using a rate of 70 percent of the bulb lumens for HPS (from Table 10) and 79 percent for LPS (from Table 9).

[d] Street light = bulb light × coefficient of utilization. Assuming a coefficient of utilization of 0.39 for HPS and 0.318 for LPS (see Table 4).

[e] Nonstreet light = downward light - street light.

[f] Assuming the light falling on the street has a 15 percent reflectance and the light falling elsewhere has a 30 percent reflectance (see Table 3).

[g] Total light = upper hemisphere light + reflected light.

[h] Assuming upper hemisphere light converted to downward light. Street light represents 55.7 percent at a reflectance of 15 percent; nonstreet lights represent 44.3 percent at a reflectance of 30 percent. Total shielded light = reflected light + converted upper hemisphere light.

[i] Percent savings = (total light - total shielded light)/total light.

Table 2

SAVINGS IN STREET LIGHT FROM SHIELDING WITH MIX OF HPS AND LPS

Item	HPS (LUCALOX/D)	LPS
Nominal watts	100	55
Initial lumens	8,800	8,000
Dirt depreciation	0.95	0.95
Number of lights	10,034	17,696
Bulb lumens	83.88×10^6	134.49×10^6
Emitted lumens[a]	62.07×10^6	118.35×10^6
Upper hemisphere light[b]	3.36×10^6	12.10×10^6
Downward light[c]	58.72×10^6	106.25×10^6
Street light[d]	32.71×10^6	42.77×10^6
Nonstreet light[e]	26.01×10^6	63.48×10^6
Reflected light[f]	12.71×10^6	25.46×10^6
Total light[g]	16.07×10^6	37.56×10^6
Total shielded light[h]	13.44×10^6	NA
Percent savings[i]	16	NA

[a] Assuming that 26 percent is lost in the fixture for HPS and 12 percent for LPS.

[b] Using a rate of 4 percent of the bulb lumens for HPS and 9 percent for LPS.

[c] Using a rate of 70 percent of the bulb lumens for HPS (from Table 10) and 79 percent for LPS (from Table 9).

[d] Street light = bulb light × coefficient of utilization. Assuming a coefficient of utilization of 0.39 for HPS and 0.318 for LPS (see Table 4).

[e] Nonstreet light = downward light - street light.

[f] Assuming the light falling on the street has a 15 percent reflectance and the light falling elsewhere has a 30 percent reflectance (see Table 3).

[g] Total light = upper hemisphere light + reflected light.

[h] Assuming upper hemisphere light converted to downward light. Street light represents 55.7 percent at a reflectance of 15 percent; nonstreet lights represent 44.3 percent at a reflectance of 30 percent. Total shielded light = reflected light + converted upper hemisphere light.

[i] Percent savings = (total light - total shielded light)/total light.

Table 3

REFLECTIVITY OF SUBSTANCES

Substance	Reflectance (percent)
Grass	6
Asphalt[a]	7
Gravel	13
Granolite pavement	17
Macadam	18
Vegetation	25
Concrete	40

[a] The value given is for new asphalt. As the material wears, its reflectance will increase.

of 30 percent. This results in 34.77 million lumens from reflected components of the street lights for HPS. This can be compared with 9.18 million lumens directed above the horizontal into the sky. Summing the two contributions, we obtain a total street light flux of 43.95 million lumens. Assuming we can convert all of the light directed into the upper hemisphere downward, and apportion it to street and nonstreet light as before through shielding, we could save 7.19 million lumens. This represents about 16 percent of total street lighting and a much smaller percentage of total city lighting. We assume no shielding of the LPS lights, since they do not represent a problem to astronomers.

These calculations are summarized in Table 1. We also show the calculations for the system with more LPS lighting in Table 2. As expected, the percentage savings for the mix of lights in Table 2 is the same as in the case of all HPS lights, but the absolute value of the savings is smaller.

It is apparent from the data of Tables 1 and 2 that shielding HPS lights provides only modest reductions in the total sky glow.[4] This is because very little light is directed upward from the HPS luminaires. Although we have not evaluated the costs of the shielding option, it is doubtful that they could be justified on the basis of the small reduction in light pollution that could be achieved.

Restricting the Types of Light Sources

Conversion of San Diego's street lighting to HPS would immediately increase the artificial sky glow in the yellow/red end of the visible spectrum. Alternatively, conversion to LPS would increase the artificial sky glow only in a small band of the spectrum because the light emitted would be primarily monochromatic. In Fig. 5, we show a computer plot of the sky glow from Mt. Hamilton where Lick Observatory is located, 10 miles from downtown San Jose (Turturici, 1981). In this plot, all street lighting is assumed to be LPS. We show a comparable plot in Fig. 6, where all street lighting is assumed to be HPS (Turturici, 1981). In Fig. 6, we also show the increase in spectral intensity that will occur over the next few decades according to one set of population projections (Turturici, 1981).

Of particular note in Figs. 5 and 6 is the line entitled "Light Level Limit," which represents a 50 percent increase in the night sky pollution measured presently at Lick Observatory. Although the observatory staff employs powerful computer-assisted instrumentation, the signal processing techniques cannot compensate for the increased light pollution. Once the light level increases beyond the "light level limit," much of the valuable research will no longer be possible.

In a comparison of Figs. 5 and 6, which are drawn to the same scale, it is clear that HPS lighting virtually obscures the yellow/red range of the spectrum, making it inaccessible for astronomical

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[4]As mentioned earlier, the contribution of street lights to the total upward lumens is estimated at between 15 and 50 percent for the San Jose area. This issue is the subject of much debate in the literature. See, for example, Faber (1980) and Finch (1978) and attached letters. A more precise calculation of the effects of shielding would require better estimates of the relative contributions to sky glow.

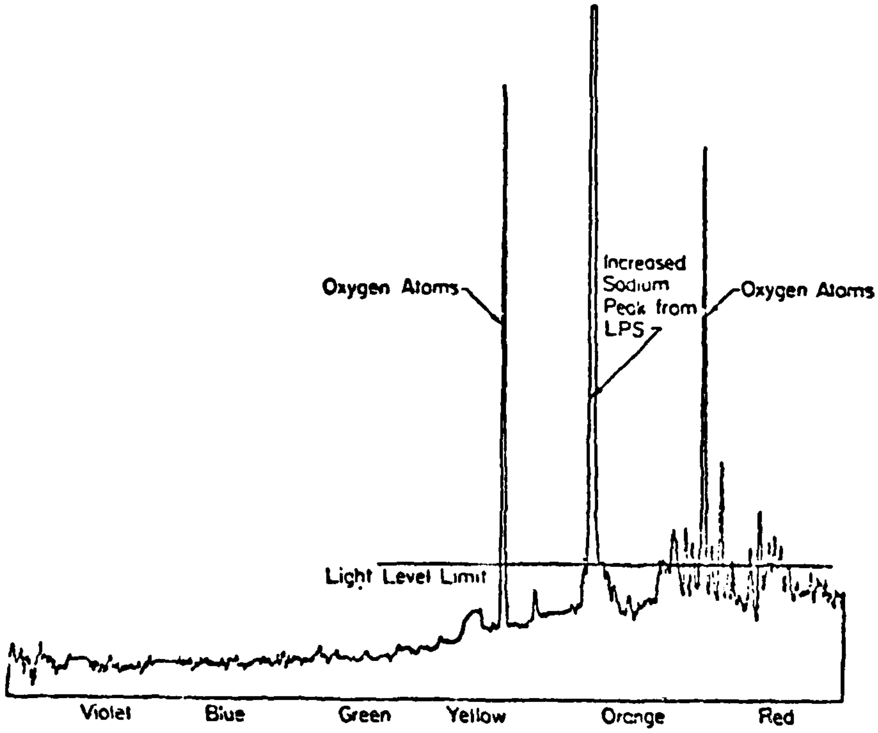

Fig. 5 -- San Jose 1979 with LPS street lights

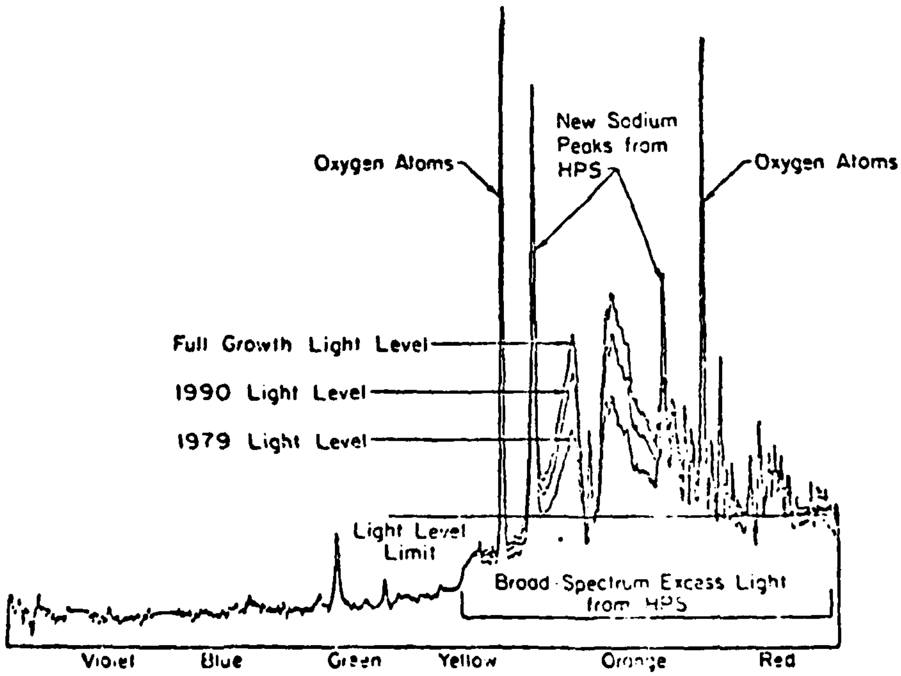

Fig. 6 -- San Jose with HPS street lights

measurement. Under these conditions, several Lick research programs would no longer be possible. Examples include the detection of distant radio galaxies and clusters of galaxies at the edge of the observable universe, spectroscopic investigations of faint stars and galaxies, and polarization measurement of violently variable quasars (Turturici, 1981). In contrast, LPS lighting leaves this spectral region relatively free of light pollution, and virtually the entire visible range remains accessible to astronomers.

In Fig. 7, we show a computer plot of mixed LPS and HPS systems (Turturici, 1981). This figure illustrates that even with partial LPS lighting, the presence of HPS lighting causes the sky glow spectrum to exceed the light level limit in the yellow/red end of the spectrum.

We do not have comparable spectra for the Palomar Observatory. For a rigorous analysis of the differences between LPS and HPS street lighting in the San Diego area, such data would be required. Nevertheless, some of the qualitative conclusions from the Mt. Hamilton data apply to Palomar as well. The Palomar observatory is located about

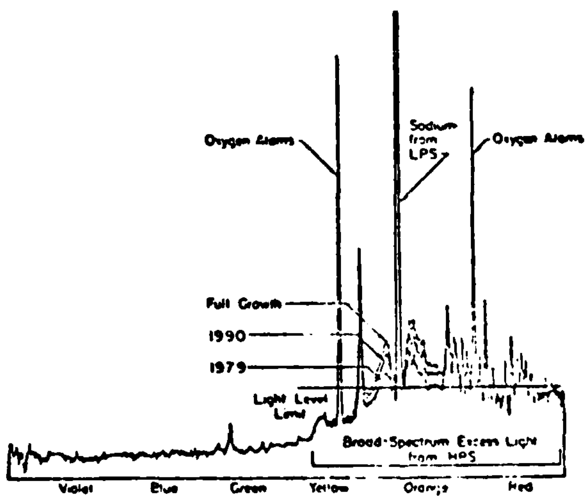

Fig. 7 -- San Jose with LPS--Residentials,
HPS--Arterials (Alum Rock, Evergreen, and Edenvale)

45 miles from downtown San Diego and is therefore farther than San Jose is from Lick Observatory. The artificial light pollution over Palomar is therefore probably less intense. This will simply have the effect of delaying severe light pollution. It is safe to conclude that adoption of LPS street lighting could reduce the sky glow at Palomar significantly.

LIGHTING SYSTEM COSTS

It is widely appreciated that the efficacy of LPS lighting is very substantially better (50 percent or more) than that of HPS lighting. The possibility exists that LPS lighting could be significantly cheaper, especially where (as in San Diego) energy costs are very high. Below, we first discuss some general background information. We then present a cost comparison of the two sodium lighting systems.

Background

LPS lighting was developed relatively early, and was (and is) extensively used in Europe,[5] where higher energy costs have been an issue longer than in the United States. In this country in the same period, mercury vapor lighting was widely used for street lighting. The monochromatic nature of LPS light is a drawback. That led to the development of HPS lighting which has a higher efficacy than mercury vapor lighting, and a spectral characteristic that is acceptable to the general public.

The cost comparison given here is intended to model the possibilities that exist in a real-world retrofit decision facing the City of San Diego and affecting the observatory at Palomar. Costs are estimated for retrofitting existing commercial hardware for high- and low-pressure sodium lights, in place of existing mercury vapor lights. The fact that existing poles and wiring are to be used precludes re-optimizing the dimensions (height, location, spacing) of the installation to adapt to one lamp type or another. Moreover, there is not a precise match of lumen output and distribution available. Where this is critical, we investigate costs for more than one size.

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[5] Also in Canada, South America, and in scattered locations in the United States.

Although the Illuminating Engineering Society (IES) has formulated recommended levels for street lighting, and these recommendations are widely used as design guides, they have not officially been adopted by the City of San Diego. Instead, San Diego (like most other cities) has a "safety" standard, intended essentially to assure the public well-being. In any case, the combination of fixed installation type (i.e., pole rather than wire suspended) and dimensions and the absence of absolute standards precludes making a cost comparison in which all other parameters are held at desired values. Instead, we estimate costs for several reasonable possibilities, as in a real-world situation.

Although we have scrupulously considered only commercially available equipment in the cost comparisons, it is evident that the development of ancillary equipment (ballasts and luminaires) for LPS lighting has not kept pace with that for HPS lighting. Evidently this is because of the relatively restricted use of LPS lighting in the United States in recent years. The high cost of electrical power now gives more incentive for LPS lighting, entirely aside from astronomical pollution aspects, and appears to justify efforts to improve the efficiency of ballasts and to improve the light distribution from luminaires.

The essentially monochromatic light that is characteristic of LPS is much less damaging to astronomical work at the limit of detectability than is the nearly continuum spectrum of HPS. The monochromatic nature of LPS light is also responsible for the resistance to its widespread adaptation. Objects are rendered visible in shades of yellow, but there is no evidence that that results in a hazard.[6] The unnatural appearance of objects to drivers and pedestrians in LPS light is somehow to be weighed against the disadvantages to research astronomers because of HPS lights. The aim of this section is not to make that comparison but rather to compare narrower cost issues that bear (perhaps heavily) on it. The high lumens/watt efficiency of low-pressure sodium lighting may make it possible to produce both light with spectral characteristics acceptable to astronomers and a cost saving to the municipal budget.

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[6] Indeed, this characteristic may be valuable as reducing scattering in fog.

In making these cost comparisons, an important secondary aim is to show explicitly the input assumptions and methods, and to make the comparison so transparent that the effect of a change in input data can be readily found.

Knowledgeable people have made divergent cost estimates.[7] In part that is traceable to vested interests of various kinds. In part it may simply be that the cost comparison is sufficiently complex, and the results sufficiently close, that differences in assumptions or circumstances (such as an assumption of continuous inflation of energy costs or federal funding of capital costs) can alter the results. Although our estimates may be no more "true" than others, we point out that we have no commercial or other vested interest. Our first aim is to present as complete and balanced a comparison as we know how. Our second aim is to show and discuss in detail the basis of our estimates, so they can be evaluated by interested parties. We also discuss variations in results resulting from changes in equipment and cost inputs. Finally, we are wary of putting too much reliance on cost comparisons; in most situations, other factors commonly weigh heavily in policy decision.

There are roughly 20 pieces of input data required to make a cost estimate for a retrofit lighting installation. Many of them can be--indeed already have been--the subject of acrimonious debate, as perhaps is to be expected where commercial interests and already-hardened positions are involved. The following paragraphs discuss the major inputs and areas of contention in connection with Table 4, which summarizes the light output and energy calculations, and Table 5, which gives the cost comparisons for a representative mercury vapor lighting installation, and three more efficient possible retrofits.

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[7] A draft version of this Note was reviewed in detail by representatives of the San Diego City Engineer's Office, of the utility (San Diego Gas and Electric), and of Palomar Observatory. We benefited greatly from these discussions, and previously unavailable data were made available to us. On some points, however, two reviewers suggested inputs that were in conflict (for instance, on lamp life and relamping man-hour requirements) and we relied on our own estimates. We are grateful to our reviewers, but the present cost estimates are our responsibility, not theirs.

Table 4

LIGHT OUTPUT AND ENERGY CALCULATIONS FOR STREET LIGHTING RETROFITS OF 175 W MERCURY VAPOR LAMPS (RESIDENTIAL)

Item	Hg (clear)	HPS (LUCALOX)		LPS
Nominal watts	175	100	70	55
Nominal life, hr	24,000	24,000	24,000	18,000
Lamp lumen depreciation (mean)	.94	.90	.90	1
Initial lumens	7,950	8,800	5,400	8,000
Replacement interval, yr	4	4	4	3
Dirt depreciation	.95 ------------------------------->			
Lamp power (avg), w	175	100	70	59
Ballast power, w	40	30	18	25
Power to fixture, w	215	130	88	84
Utilization coefficient	<---------- .39 --------->			.318
Fixture	<-------- GE M250A ----->			Norelco SRX114
Maintained, utilized lumens	2769	2934	1800	2416
Maintained, utilized lumens/w	12.9	22.6	20.4	28.4
Average illumination,[a] lumens/ft^2 (=footcandles)	.62	.65	.40	.54
EFFECT OF USING CUT-OFF LUMINAIRES				
Utilization coefficient	--	.40	.40	.16
Fixture	--	GE M250R ----->		Norelco -501
Maintained, utilized lumens	--	3010	1847	1216
Maintained, utilized lumens/w	--	23.1	21.0	14.5
Average illumination,[a] lumens/ft^2	--	.67	.41	.27

[a] IES recommended illumination for local residential streets is 0.4 lumens/ft^2.

Table 5A

ESTIMATED COST PER FIXTURE OF
RESIDENTIAL STREET LIGHTING RETROFITS

Item	Hg CLEAR	HPS (LUCALOX/D)		LPS
Nominal watts	175	100w	70w	55
Installation labor and overhead, $	0	75	75	75
Hardware cost, $	0	69	68	81
Capital increment, $	0	144	143	156
Actual watts (avg)	215	130	88	84
Yearly energy cost, 4165 hr, .12 $/kw-hr	107.5	65.0	44.0	42.0
Yearly maintenance cost, $ (cleaning & rebulbing)	10.6	12.9	12.6	16.5
Yearly capital charge, $ (charge rate = .14)	0	20.1	20.0	21.8
Total yearly costs, $	118.1	98	76.6	80.3
Maintained, utilized lumens	2835	2934	1800	2416
Maintained, utilized lumens per unit cost, lumens/$1 yr	23.4	30.0	23.4	30.1

Table 5B

COST SENSITIVITY TO A CHANGE IN BALLAST LOSS FOR 70 W HPS

Item	Hg CLEAR	HPS	(LUCALOX/D)	LPS
Nominal watts	175	100	70	55
Actual watts (avg.)	215	130	94[a]	84
Yearly energy cost, $	107.5	65.0	47.0	42.0
Yearly capital charge, $	0	20.1	20.0	21.8
Total yearly costs, $	118.1	98.0	79.6	80.3

[a]GE Reactor Ballast (catalog).

Table 5C

COST SENSITIVITY TO A CHANGE IN REBULBING LABOR COST
(LABOR COST TAKEN AS 1/2 THAT IN TABLE 5A)

Item	Hg CLEAR	HPS	(LUCALOX/D)	LPS
Nominal watts	175	100	70	55
Yearly energy cost, $	107.5	65.0	44.0	42.0
Yearly maintenance cost, $	5.5	8.2	7.9	10.2
Yearly capital charge, $	0	20.1	20.2	21.8
Total yearly costs, $	113	93.3	71.9	74.0

Table 5D

COST SENSITIVITY TO A CHANGE IN LAMP LIFE
(LIFE FOR ALL LAMPS INCREASED 25 PERCENT)

Item	Hg CLEAR	HPS	(LUCALOX/D)	LPS
Nominal watts	175	100	70	55
Yearly energy cost, $	107.5	65.0	44.0	42.0
Yearly maintenance cost, $	8.5	10.3	10.1	13.2
Yearly capital charge, $	0	20.1	20.0	21.8
Total yearly costs, $	116.0	95.4	74.1	77.0

Residential Street Lighting

The first case considered is a residential street lighting installation of a 175 watt mercury vapor light, installed on a side-street pole at a height of 25 feet, with a davit that extends the light fixture 6 feet from the edge of the 30-foot-wide street. (The installation dimensions are important. The light distribution, treated below, is substantially different for HPS and LPS fixtures. If a longer davit or a center-street suspension were possible, the LPS distribution efficiency could be substantially improved.) The spacing of poles is 150 feet.

By far the greatest number of street lights are of this type. (Later we consider a major street in a commercial area.) The alternatives to be considered are:

- 100 w high-pressure sodium, which has a slightly higher lumen output than the original mercury vapor lamp,
- 70 w high-pressure sodium, which has substantially less lumen output, and
- 55 w low-pressure sodium, which also has less lumen output than the original mercury vapor lamp.

All are to be installed on the same pole and davit as the original mercury vapor fixture.

The nominal life (to 50 percent survivors) of the mercury vapor and HPS lamps is 24,000 hr, and of LPS lamps, 18,000 hr (catalog and specification sheet values from manufacturers, Table 6 and Table 7). We assume a group relamping policy of replacing all lamps after a fixed period (4 years for HPS and 3 years for LPS) when the number of survivors should be somewhat over 80 percent for either lamp type. Lamp life is a subject of contention, as is relamping policy. On the basis of an admittedly small sample, SDG&E has suggested that LPS lamp life is less than catalog values. Barry and Garty (and others) have shown that lamp life can depend on the type of pole and suggest more complicated wear-out models. The type of ballast and the quality of electrical line regulation also affect lamp life.

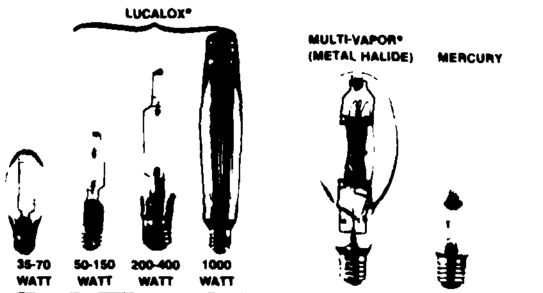
The present relamping policy in San Diego is to replace on failure. They estimate an equivalent lamp useful life of 5 years for HPS, and 4 years for LPS. Practice varies widely; many municipalities use group relamping at prespecified times to improve manpower resources. Others do group relamping based on observed failure rate. To replace only on failure, if LPS is adopted, may result in energy waste because of the rise in wattage for long-life lamps. Clearly, such a policy is easily changed, if experience shows that to be desirable. Sensitivity calculations show that 25 percent variations in the replacement interval do not make significant changes in overall costs if uniformly applied to all lamp types.

For HPS lamps there is a lumen depreciation during life, which we take from specification sheets at the mean value over (used) lamp life. LPS lamps maintain their lumen output but increase their wattage during life. We take the average lamp power over the used life (3 years at 4,165 hr/yr = 12,495 hr). (4,165 hr/yr is SDG&E's standard assumption for the usage of street lights.)

We assume a lumen depreciation from dirt accumulation of 0.95 for all lamp types. The LPS light is claimed to have an advantage because it attracts fewer insects, but we did not find quantitative data and it cannot be a large factor in any case.

Table 6

CATALOG LAMP DATA FOR HIGH-PRESSURE SODIUM LAMPS



HIGH INTENSITY DISCHARGE LAMPS

High Intensity Discharge (HID) lamps are those which have a gaseous discharge arc tube, operating at pressures and current densities sufficient to generate desired quantities of visible radiation within their arcs alone. These lamp types have become popular primarily for three reasons:

1. High efficacy — more lumens per watt of power consumed
2. Long lamp life and good lumen maintenance — reduces operating expenses
3. Compact source — permits good light control by use of reflectors and refractors, resulting in high system efficiency

The three principal HID lamps now in common use are mercury, *metal halide* (General Electric Multi-Vapor), and high pressure sodium (General Electric Lucalox).

HID WARMUP CHARACTERISTICS
(TIME TO REACH 80% LIGHT OUTPUT)

Mercury	5-7 minutes
Metal Halide	2-4 minutes
Lucalox	3-4 minutes

HID RESTRIKE CHARACTERISTICS

All HID lamps will deionize when there is a power interruption or if the lamp socket voltage drops below the amount required to sustain the arc for more than a few cycles. Because it takes greater voltage to ionize the arc tube vapors while they are hot and under higher *pressure, the lamp will not re-start immediately.*

TIME TO RESTRIKE

Mercury	3-6 minutes	
Metal Halide	10-15 minutes	(MXR175 5-10 minutes)
Lucalox	1 minute	

STROBOSCOPIC EFFECT

HID lamp output tends to follow the alternating current waveform. This can cause small moving objects to flicker. To avoid this annoyance three phase power is suggested for mercury and Lucalox lamps. Split phase ballasting can also be used with mercury lamps. Single phase power can be used with metal halide lamps.

LIGHTING SYSTEM MAINTENANCE FACTOR

The lighting system maintenance factor (MF) is the product of the lamp lumen depreciation (LLD) and the luminaire dirt depreciation (LDD). The lamp lumen depreciation is given in the lamp tables for both the "mean" and "end of relamping period." The mean value is taken at approximately 40% life for Multi-Vapor and 50% life for Lucalox lamps. For mercury lamps the value is taken at 8,000 hours. This is due to the extreme long life of the mercury lamp. A 16,000-hour economic life is *suggested for this lamp. The values for "end of relamping period" are taken at the end of the lamp's life.* The user may also use a more convenient group relamping period and should adjust the value accordingly.

Luminaire dirt depreciation (LDD) is a function of the *in service conditions* and the type of luminaire. Enclosed and filtered luminaires have built in maintenance characteristics which reduce the amount and effect of dirt accumulation. While it is not possible to select one number to describe all conditions, the following LDD values are suggested.

OUTDOOR APPLICATIONS

Luminaire Type	Luminaire Dirt Depreciation (LDD)
Enclosed and filtered	0.95
Unfiltered	0.80

INDOOR APPLICATIONS

Luminaire Type	Luminaire Dirt Depreciation (LDD)		
	Light	Medium	Heavy
Enclosed and filtered	0.97	0.93	0.88
Enclosed	0.94	0.86	0.77
Open and ventilated	0.94	0.84	0.74

LUCALOX LAMP DATA

GE Ordering Abbreviation	Ballast ANSI Code	Finish	Light Center Length Inches	Vertical or Horizontal: Initial Lumens	Lamp Lumen Depreciation: Mean	Lamp Lumen Depreciation: End of Relamping Period
35-WATT Life 16,000 hours 10 hours/start - Medium Base Only						
LU35/med	S76	Clear	3 1/16	2,250	0.90	0.73
LU35/D/med	S76	Diffuse	3 1/16	2,150	0.90	0.73
50-WATT Life 24,000+ hours 10 hours/start - Mogul Base▲						
LU50	S68	Clear	5	4,000	0.90	0.73
LU50/D	S68	Diffuse	5	3,800	0.90	0.73
70-WATT Life 24,000+ hours 10 hours/start - Mogul Base▲						
LU70	S62	Clear	5	5,800	0.90	0.73
LU70/D	S62	Diffuse	5	5,400	0.90	0.73
100-WATT Life 24,000+ hours 10 hours/start - Mogul Base ▲						
LU100	S54	Clear	5	9,500	0.90	0.73
LU100/D	S54	Diffuse	5	8,800	0.90	0.73
150-WATT Life 24,000+ hours 10 hours/start - Mogul Base ▲						
LU150/55	S55	Clear	5	16,000	0.90	0.73
LU150/55/D	S55	Diffuse	5	15,000	0.90	0.73
LU150/100	S56	Clear	5	15,000	0.70	0.73
200-WATT Life 24,000+ hours 10 hours/start - Mogul Base						
LU200	S66	Clear	5¾	22,000	0.90	0.73
250-WATT Life 24,000+ hours 10 hours/start - Mogul Base						
LU250	S50	Clear	5¾	27,500	0.90	0.73
LU250/D	S50	Diffuse	5	26,000	0.90	0.73
LU250/S	S50	Clear	5¾	30,000	0.90	0.73
LU250/DX*	S50	Clear	5¾	22,500	0.92	0.75
310-WATT Life 24,000+ hours 10 hours/start - Mogul Base						
LU310	S67	Clear	5¾	37,000	0.90	0.73
400-WATT Life 24,000+ hours 10 hours/start - Mogul Base						
LU400	S51	Clear	5¾	50,000	0.90	0.73
LU400/D	S51	Diffuse	7	47,500	0.90	0.73
1000-WATT Life 24,00 hours 10 hours/start - Mogul Base						
LU1000	S52	Clear	8¾	140,000	0.90	0.73

* Life 10,000 hours at 10 hours/start CRI 65, color temp 2200°

NOTES

Similar wattage clear and diffuse Lucalox lamps may not have the same bulb size or light center length. If lamps are interchanged the socket position may need to be changed to obtain the desired photometric distribution.

▲ Most Lighting Systems Department products will be furnished with Mogul Base Sockets. Any exceptions will be noted on product pages.

LU50/Med	LU70/Med	LCL 3-7/16 (Medium socket must
LU50/D/Med	LU70/D/Med }	be rated for 4KV)
LU100/Med	LU150/Med	
LU100/D/Med	LU150/D/Med	

LUCALOX AVG. LIFE VS. HOURS/START

HRS/START	ESTIMATED AVG. LIFE▼
Cont	24,000+
10	24,000+
5	18,000
2.5	13,500
1.2	10,000

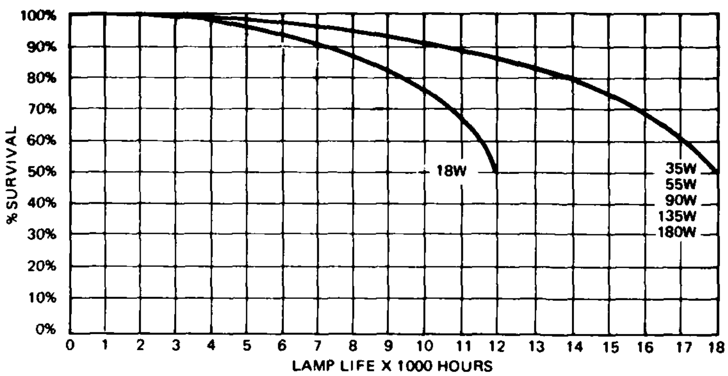
▼ Does not apply to 35W Lucalox nor E-Z Lux® lamps

Data subject to change without notice
®Registered Trademark of General Electric Company

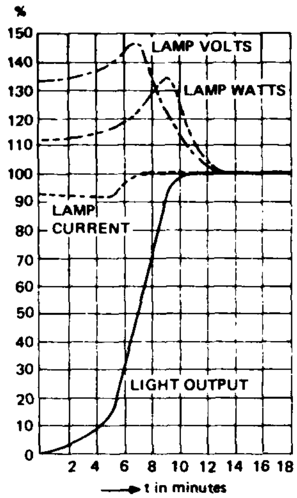
Table 7A

CATALOG LAMP DATA FOR LOW-PRESSURE SODIUM LAMPS (LAMP LIFE)

Lamp Type: LOW PRESSURE SODIUM (SOX)



LAMP SURVIVAL (At 10 hours per start)



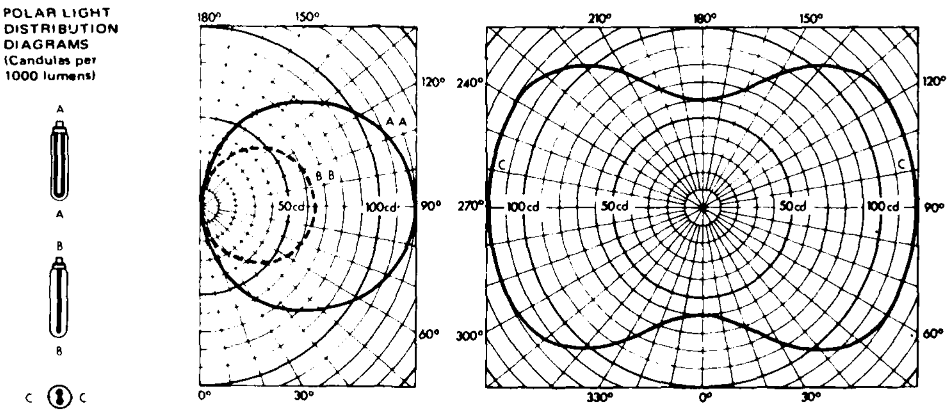
LAMP PERFORMANCE DURING STARTING PERIOD.

SOX WATTS RISE OVER LIFE HOURS

	100	2000	5000	10000	18000	Average Watts over life
SOX 18*	17	18	20	18	—	18.6
SOX 35	35	36	37	38	39	37.5
SOX 55	55	56	58	60	61	58.9
SOX 90	90	93	100	116	122	109.1
SOX 135	130	140	149	173	178	161.8
SOX 180	176	182	190	191	192	188.9

*Lamp power at 12,000 hours is 18 watts

POLAR LIGHT DISTRIBUTION DIAGRAMS (Candulas per 1000 lumens)



Ordering Information			
Product Code	**Lamp Description**	**ANSI Code**	**St. Pack Quantity**
09299	SOX 18	L69RA-18	20
09300	SOX 35	L70RB-35	12
09301	SOX 55	L71RC-55	9
09302	SOX 90	L72RD-90	9
09303	SOX 135	L73RE-135	9
09304	SOX 180	L74RF-180	9

NORTH AMERICAN PHILIPS LIGHTING CORPORATION
Bank Street ■ Hightstown, N.J. 08520 ■ 609-448-4000

Printed in U.S.A. 1/83 SS-264

Table 7B

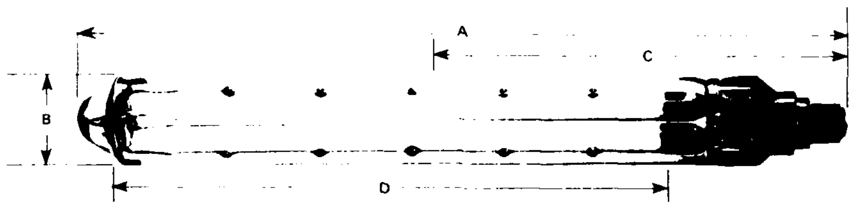
CATALOG LAMP DATA FOR LOW-PRESSURE SODIUM LAMPS
(LAMP ELECTRICAL CHARACTERISTICS)

Norelco®

SPECIFICATION SHEET

NORTH AMERICAN PHILIPS LIGHTING CORPORATION

Lamp Type: LOW PRESSURE SODIUM [SOX]



PHYSICAL DIMENSIONS – SOX LAMPS

Lamp Designation	Product Code	ANSI Code	Max. Overall length – A		Max. Diameter B		Light Center length – C		Light Length D	
			in.	mm	in.	mm	in.	mm	in.	mm
SOX 18	09299	L69RA-18	8.50	216	2.13	54	5.55	141	3.62	92
SOX 35	09300	L70RB-35	12.19	310	2.13	54	7.25	184	7.57	192
SOX 55	09301	L71RC-55	16.75	425	2.13	54	9.56	243	12.00	305
SOX 90	09302	L72RD-90	20.79	528	2.68	68	11.50	292	15.88	403
SOX 135	09303	L73RE-135	30.50	775	2.68	68	16.38	416	25.44	646
SOX 180	09304	L74RF-180	44.13	1120	2.68	68	23.00	584	38.00	965

BASE: Double Contact Bayonet-Medium (BY-22d)

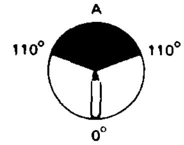
ELECTRICAL CHARACTERISTICS

Lamp Designation	Nominal Watts	Nominal Lamp Volts	Nominal Lamp Current	Max. Current Crest Factor	Max. Starting Current	Min Ballast open circuit volts	
						RMS	Peak
SOX 18	18	57	0.35	1.6	0.42	300	424
SOX 35	35	70	0.60	1.6	0.60	390	551
SOX 55	55	109	0.59	1.6	0.59	410	580
SOX 90	90	112	0.94	1.6	0.94	420	594
SOX 135	135	164	0.95	1.6	0.95	540	764
SOX 180	180	240	0.91	1.6	0.91	600	848

PERFORMANCE DATA

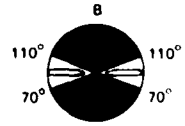
Lamp Designation	Lumens	Rated Life	Warm Up Time	Operating Position
SOX 18	1,800	12,000	7 min.	A–Base up ± 110°
SOX 35	4,800	18,000	7 min.	A–Base up ± 110°
SOX 55	8,000	18,000	7 min.	A–Base up ± 110°
SOX 90	13,500	18,000	9 min.	B–Horizontal ± 20°
SOX 135	22,500	18,000	9 min.	B–Horizontal ± 20°
SOX 180	33,000	18,000	9 min.	B–Horizontal ± 20°

A



18W, 35W 55W

B



90W, 135W, 180W

Light Output Over Life – 100%
Base Temperature Limit – 150° C
Bulb Temperature Limit – 150° C
Restart Time – 1 minute
Lamp Brightness – 10cd/cm²

The lamp power is constant[8] for HPS lamps, using the most efficient ballast types, but it rises slowly during life for LPS. We take an average power over the used lamp life (from specification sheets), since we are computing energy consumption.

The ballast power consumption is a major issue that greatly affects the comparison, especially at small sizes. We use a compilation of ballast power consumption made by the Advance Transformer Co. (Freegard, 1978), and plotted on Fig. 8. The figure shows the ballast losses (as a fraction of lamp nominal power) for ballasts designed for HPS and LPS lamps over the entire range of lamp rating that is produced. The general trend of higher losses in small sizes is as expected, but there clearly are other factors at play as well. Without researching the whole subject of ballast design (evidently substantially more

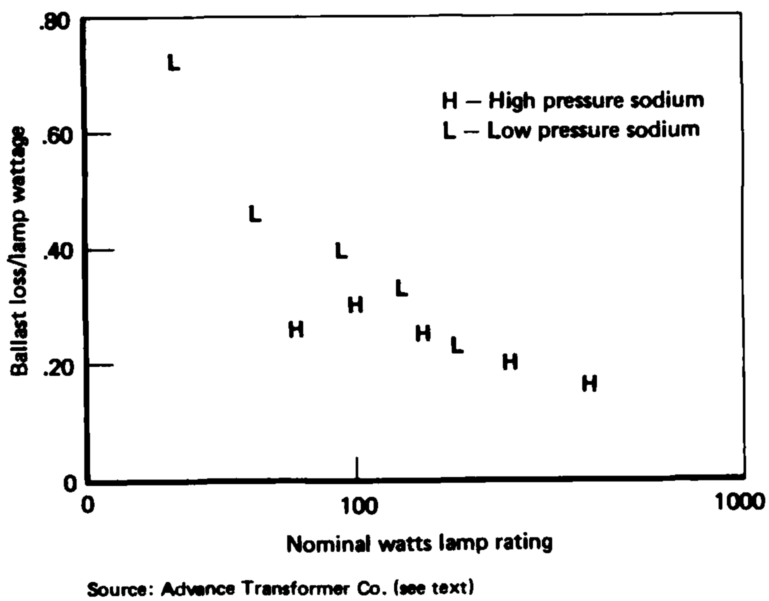


Fig. 8 -- Ballast losses

[8]Alternative ballasts are available for HPS lamps that approximate a constant lumen output. We expect their power consumption to be substantially higher.

complicated than one might expect) we can point out that the ballast for 70 w HPS is an outlier, i.e., it has substantially smaller losses than the main trend, and smaller (fractional) losses than the 100 w HPS ballast. The data shown in Fig. 8 have been used in our cost estimates because they represent data on commercially available ballasts assembled in a consistent way. But there are many more commercially available ballasts, and we expect that there are still other possibilities for low-loss ballast that remain to be exploited in an era of high energy costs. As it is, the high lumens/watt efficiency of LPS lamps in small sizes (as must be used in a retrofit process) is substantially compromised by the high ballast losses. The ballast losses for a 70 w HPS lamp are 18 w less than the 25 w for a 55 w LPS lamp. This is an area where a modest investment in development could substantially improve the economic position of LPS. If developed, improved LPS ballasts could in the future be retrofitted into LPS light fixtures.

Table 4 shows the per fixture power consumption (averaged over the used life) for the candidate retrofits. All the retrofits offer substantial power reductions, but the difference in consumed power for the 70 w HPS and the 55 w LPS fixtures is small because of the higher loss ballast that is available for LPS.

To estimate the useful light produced by the retrofits, the fraction of the light produced by the lamp that reaches the street must be found. This is a somewhat narrow interpretation of the useful light. Some of the "spill" light falls on the sidewalk and is useful there. We calculated that light and found that for all the retrofits considered, the sidewalks are illuminated to values higher than the IES recommended standards for residential area sidewalks. And police would point out that the spill light in some areas is most useful for discouraging and controlling crime. In no circumstances would a narrowly illuminated "tunnel" of light be desirable for street lighting and driving. Lighting of surroundings as well as streets is important. On the other hand, utility and city street lighting departments are sensitive to complaints by residents of excessive spill light "into the bedroom window." We expect that this other form of light pollution would be particularly troublesome for LPS lighting not only because of its monochromatic nature, but also because the fixtures that are available for LPS lighting have a relatively high fraction of this light emitted at high angles. The Norelco SRX 114 (Fig. 9) luminaire that is used in our estimates emits 9 percent of the lamp lumens into the upper hemisphere, whereas luminaires for HPS lamps commonly keep upward emission to less than 2 percent. These "spill light" issues are not further analyzed here.

The fraction of light that is deposited at the street is found from a "utilization" curve that is based on photometric measurements of a lamp and luminaire combination. The use of these curves is fully explained in the *IES Handbook* (1981). Figures 9 and 10 give utilization curves for the Norelco SRX 114 55 w LPS luminaire and the General Electric M 250 A luminaire, suitable for 70 and 100 w HPS lamps. The utilization coefficient for HPS is 0.39, for LPS, 0.318. (These values are sensitive to details of street width and mounting location. A mounting nearer the center of the street improves the relative LPS utilization. A wider street improves the relative HPS utilization. A center street suspension, or a mounting in the median strip of a divided road, results in a utilization factor for LPS as high as or higher than for HPS. These arrangements are common in Europe, but are precluded in the retrofits considered here, which use existing street side poles.)

Cutoff luminaires for HPS, having a flat lower lens (so that the lens is not visible from side aspect, and no light is directly emitted into the upper hemisphere) can be used to minimize horizontal emission and glare to drivers or spill light in residential areas. (That effect can also be approached by changing the bulb position in a conventional luminaire.) Generally the luminaires are expected to have a less uniform distribution on the street, and somewhat poorer light utilization. In the present instance, we found that there was a slight improvement in utilization from the noncutoff HPS luminaire used in our calculation. (That is not the case for the commercial street installation to be considered later.) Only relatively crude cutoff luminaires seem to be available for small LPS bulbs. The Norelco 55 w luminaire, Cat. No. 34798-501, appears to be a noncutoff luminaire with an added aluminum baffle inside extending to below the bulb level. Its light utilization is very poor, as taken from a

CERTIFIED TEST REPORT NO. ERL2182C

NORELCO CAT. NO. S.R.X. 114-55 LUMINAIRE
CLEAR POLYCARBONATE PRISMATIC WRAPAROUND LENS, HORIZONTAL ARC TUBES
ONE 55 WATT LOW PRESSURE SODIUM LAMP, RATED 8,000 LUMENS

ISOLUX

MOUNTING HEIGHT FOR ISOLUX 25.0 FEET

Mounting height	Mult. factor
10	6.25
15	2.78
20	1.56
25	1.00
30	0.69
35	0.51
40	0.39
45	0.31
50	0.25

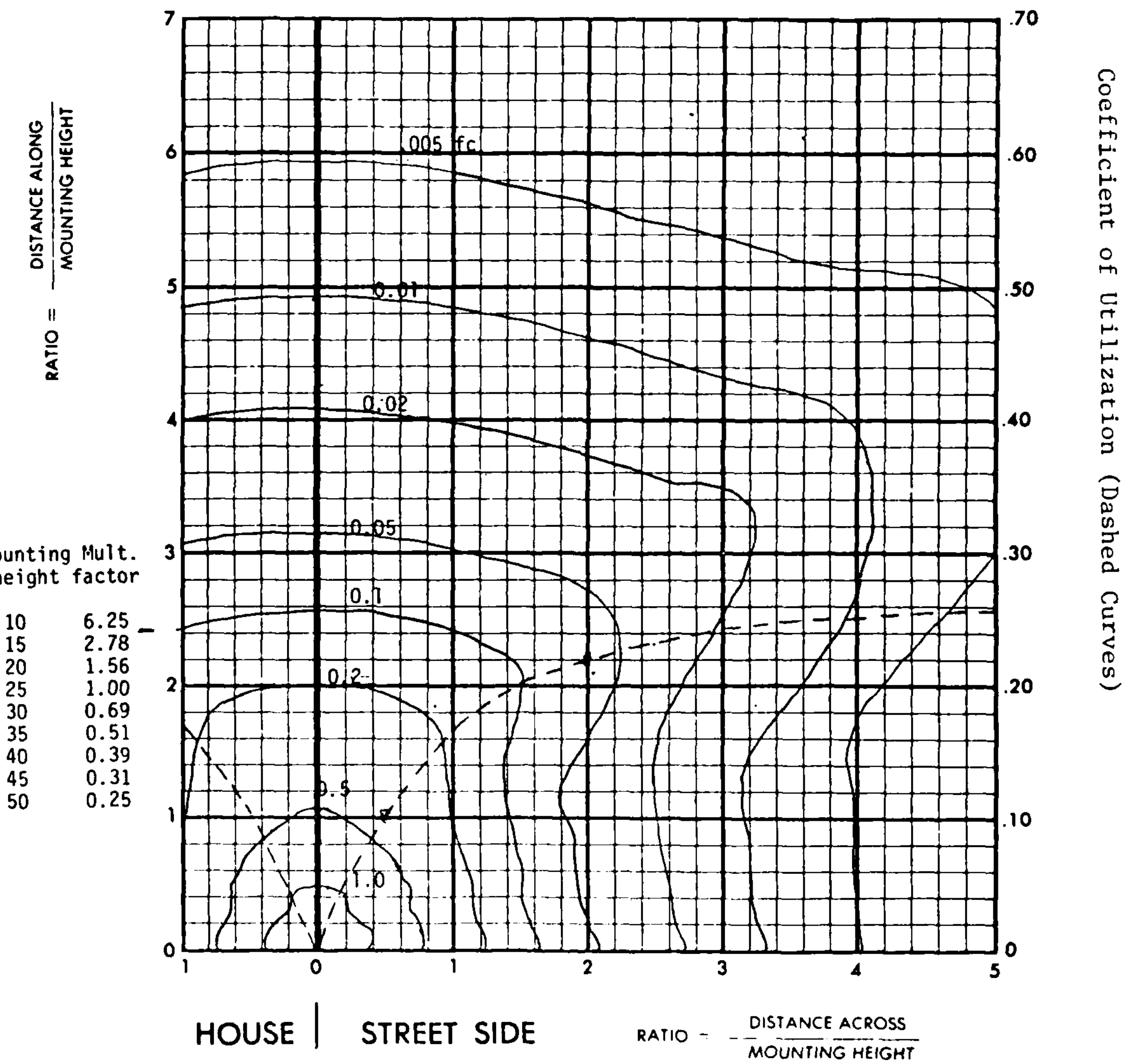


Fig. 9--Photometric data for Norelco SRX 114 Luminaire

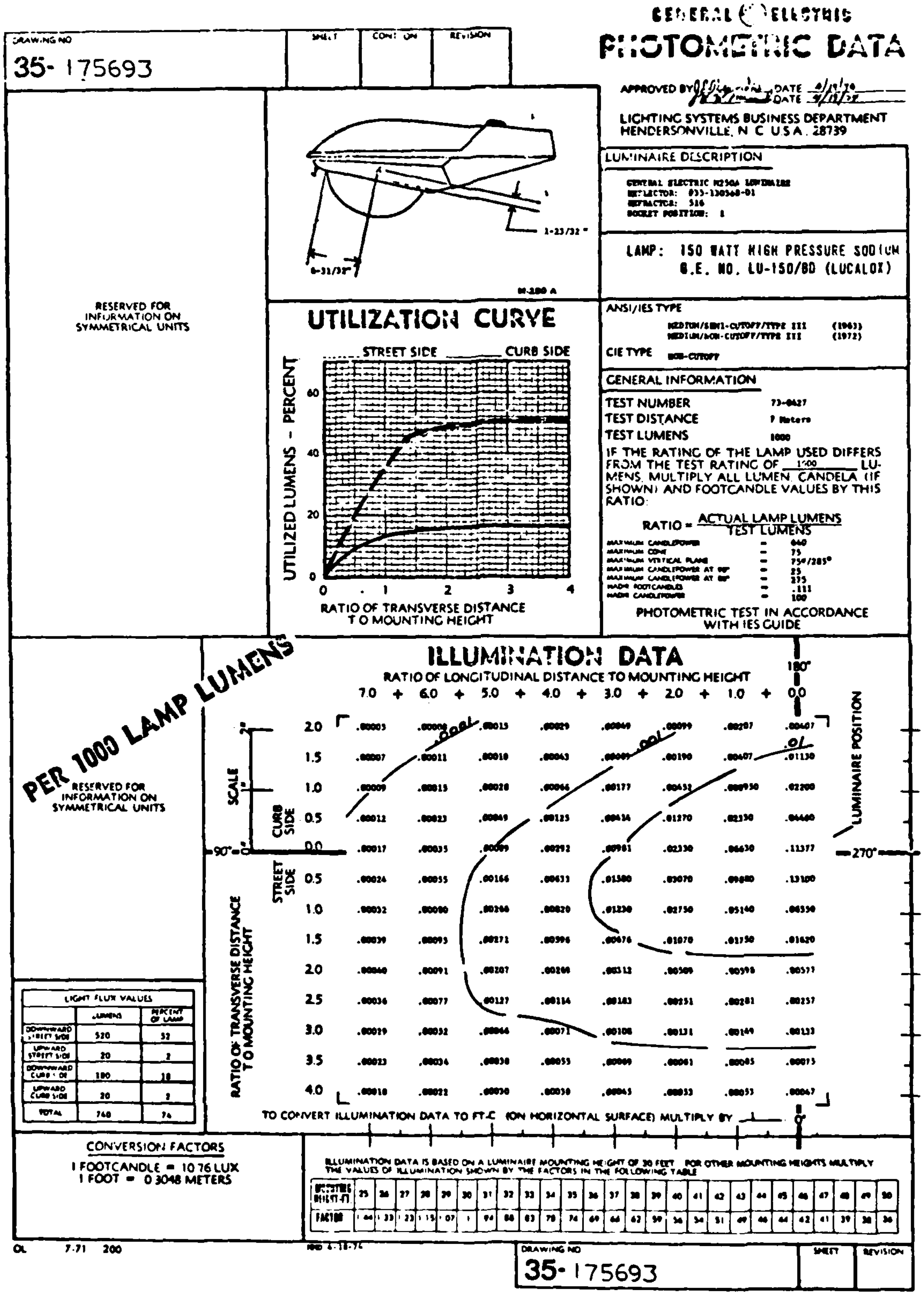


Fig. 10--Photometric data for General Electric M 250 Luminaire

photometric test report of Lighting Sciences, Inc. (1983). These effects are shown in the bottom part of Table 4. Table 4 also gives the utilization coefficient for the fixture identified just below the coefficient. No cutoff luminaires are shown for mercury vapor lamps, as that retrofit is not an interesting case.

Cutoff luminaires are proposed principally to reduce glare to drivers, and in part to reduce spill light. It can be argued that the glare produced by LPS (noncutoff) fixtures would be less (other things being equal) than that produced by HPS purely because the fixture has a larger area, and the surface brightness therefore is lower. Present methods for calculating glare, however, do not take that into account.

It clearly has been possible to function acceptably well with noncutoff fixtures in the past. Introduction of LPS lighting may, because of the lower utilization, effectively rule out cutoff fixtures. The quality of light distribution as measured by glare and spill as well as color rendition will therefore be poorer with LPS lighting. In the rest of this study, we do not assume cutoff luminaires for LPS.

The product *of initial* lumens, *lamp lumen depreciation*, dirt depreciation, and utilization coefficient gives the maintained, utilized lumens in Table 4. The maintained, utilized lumens/watt is a measure of the efficiency of the whole installation: fixture, ballast, lamp, and lamp support.

Finally, for a representative pole spacing of 150 ft, we give the average lumens per square foot *(foot candles) on the street*. Table 8 gives the IES recommended values for streets of all kinds. For the present example of a local street in a residential area, the recommended illumination is 0.4 lumens/ft^2. All the proposed retrofits meet this recommendation, except the LPS with a cutoff fixture.

The following elements of cost are considered:

Capital Cost. New lamps and luminaires, installation, removal and disposal of old lamps and luminaires. No rewiring is assumed, since the new lamps typically require much less power than the old. No cost of poles or davits is assumed to be incurred. The salvage value of old equipment is assumed negligible. The cost for lamps and luminaires is based on quotations made to the City of San Diego. We are indebted to

Table 8

IES RECOMMENDED ILLUMINATION LEVELS

Roadway and Walkway Classification	Area Classification					
	Commercial		Intermediate		Residential	
	Foot-candle	Lux	Foot-candle	Lux	Foot-candle	Lux
Vehicular Roadways						
Freeway	0.6	6	0.6	6	0.6	6
Major and Ex-way	2.0	22	1.4	15	1.0	11
Collector	1.2	13	0.9	10	0.6	6
Local	0.9	10	0.6	6	0.4	4
Alleys	0.6	6	0.4	4	0.2	2
Pedestrian Walkways						
Sidewalks	0.9	10	0.6	6	0.2	2
Pedestrian Ways	2.0	22	1.0	11	0.5	5

the City Engineer's office for these data. The installation cost for both types was based on a crew of two earning $120/day each (a rough average of rates for electricians and apprentices), installing eight fixtures and lamps/day. An overhead rate of 150 percent was used as a rough estimate of cost elements other than direct labor (truck, tools, equipment supply and procurement, fringe benefits, and supervision). This overhead rate is substantially higher than that used by San Diego because it is intended to cover, roughly, items not included in the city's definition, but commonly so considered in industry. There it is intended to cover tools and equipment, payroll and management, and equipment supply and procurement, not just fringe benefits. The productivity assumption of eight installations per day per crew of two is a rough estimate taking into account many of the delays discussed below. Discussion with the City Engineer's office generally suggested higher productivity, but on examination could not be documented. It was assumed that the capital cost would be defrayed by the city over 20 years at a capital charge rate of 0.14 per year.

Maintenance Cost. Rebulbing and cleaning of fixtures on the third or fourth year schedule indicated earlier. A productivity of eight rebulbs/day for a one-man operation with operator controlled hoist-truck was assumed, with the same labor rate and overhead as above.

This maintenance productivity is an estimate based on a listing of the things that must be done in a rebulbing operation. The productivity estimate amounts to a man-hour spent for each rebulbing. Clearly it does not require an hour to change a light bulb. But of course this is not an ordinary bulb in a household fixture, either. The operator must get his assignment, collect his truck and equipment, get the required sizes of bulbs, and drive to the area. For each installation, he must park in a spot from which the fixture will be accessible to his hoist. If in a heavily traveled area, he may have to put out traffic warning devices (cones, etc.). If parking is unavailable, he may have to come back later. Once parked he can turn off the power to the fixture, inspect it visually for condition (broken lines, etc.), get the required parts into the hoist cab, and hoist himself into position. There he will open the fixture, remove the old bulb, clean the fixture reflector and lens, insert the new bulb, if necessary replace the lens, and do other miscellaneous maintenance (check operability/cleanness of photoelectric switching, replace gaskets, etc.). After making notations on the fixture of the rebulbing date, and entering the required data in a log, he can lower and secure the hoist, switch power back on, and proceed to the next fixture on his schedule. At the end of the day after returning to a depot, he must dispose of the old bulbs according to prescribed procedure. Our productivity estimate clearly is susceptible to many changes depending on local circumstances (travel distances required, parking congestion, etc.). We are wary of underestimates. Much of this discussion also applies to the estimate of capital cost.

Energy Cost. Energy consumed is based on the previously calculated power consumption, a use of 4165 hr/yr, and 0.12 $/kw-hr. This number is approximately that given in Table 9, a national survey showing San Diego's power costs to be second only to New York's (U.S. DOE). This agrees roughly with per kw-hr energy costs deduced from the LS-2 Rate Schedule of SDG&E for street lighting.

Table 9

RETAIL PRICES FOR THE SPECIFIED ENERGY CONSUMPTION AND DEMAND OF ELECTRICITY IN SELECTED CITIES, FEBRUARY 1982, 1981 (CENTS PER KILOWATT HOUR)

City and State	Residential 500 kWh February 1982	Residential February 1981	Residential Percent Difference	Commercial 10,000 kWh, 40 kW demand[1] February 1982	Commercial February 1981	Commercial Percent Difference	Industrial 200,000 kWh, 500 kW demand[1] February 1982	Industrial February 1981	Industrial Percent Difference
Atlanta, Ga.	5.93	4.89	21.3	7.98	6.41	24.5	4.94	4.02	22.9
Baltimore, Md.	7.63	6.51	17.1	NR	NR	—	NR	NR	—
Boston, Mass.	10.76	10.04	7.2	11.01	10.21	7.8	7.96	7.76	2.6
Buffalo, N.Y.	6.25	5.54	12.8	7.20	6.53	10.3	5.21	4.76	9.5
Chicago, Ill.	7.98	7.16	11.5	8.55	7.93	7.9	6.36	5.62	13.0
Cincinnati, Ohio	6.51	4.85	34.1	NR	NR	—	NR	NR	—
Cleveland, Ohio[2]	7.77	6.32	22.9	7.79	6.37	22.3	5.53	4.58	21.0
Columbus, Ohio[2]	6.22	6.09	2.2	NR	NR	—	NR	NR	—
Dallas, Tex.	7.15	6.52	9.6	NR	NR	—	NR	NR	—
Denver, Colo.	7.17	5.59	28.4	6.93	5.71	21.3	4.64	3.56	30.6
Detroit, Mich.	6.33	6.87	-7.9	7.22	6.73	7.2	5.72	5.21	9.8
Fort Worth, Tex.	6.91	6.23	10.9	6.45	5.77	11.8	4.37	3.71	17.9
Houston, Tex.	6.49	5.55	17.0	6.37	5.56	14.7	5.11	4.41	15.9
Indianapolis, Ind.	5.37	5.03	6.6	NR	NR	—	NR	NR	—
Kansas City, Mo.[2]	7.32	7.02	4.4	7.69	7.27	5.8	5.06	4.79	5.7
Long Beach, Calif.	9.16	7.21	27.1	8.79	6.91	27.2	8.16	6.25	30.6
Los Angeles, Calif.	7.50	7.05	6.4	6.99	6.56	6.5	6.56	6.14	6.9
Louisville, Ky.	5.57	4.91	13.6	5.19	4.55	13.9	3.83	3.32	15.6
Miami, Fla.	7.84	5.80	35.2	6.76	6.52	3.6	6.11	4.64	31.6
Milwaukee, Wis.	6.95	5.26	32.2	7.19	5.65	27.2	4.85	3.90	24.2
Minneapolis, Minn.	6.37	5.59	14.0	5.12	4.58	11.8	4.11	3.65	12.8
Nashville, Tenn.	4.30	3.60	19.4	5.22	4.49	16.3	4.38	3.72	17.7
Newark, N.J.	8.78	8.77	0.0	8.70	8.71	-0.1	6.28	6.28	0.1
New Orleans, La.[2]	6.38	5.92	7.9	NR	NR	—	NR	NR	—
New York, N.Y.[2]	13.47	13.20	2.0	12.86	12.70	1.2	10.26	10.70	-4.1
Philadelphia, Pa.	8.68	7.74	12.2	9.30	8.24	13.0	6.63	5.88	12.7
Pittsburgh, Pa.	8.61	7.13	20.8	NR	NR	—	NR	NR	—
Portland, Oreg.[2]	3.30	4.32	-23.6	NR	NR	—	NR	NR	—
Richmond, Va.	8.27	7.57	9.2	6.45	5.95	8.5	4.93	4.56	8.2
Rochester, N.Y.	6.71	6.05	10.9	NR	NR	—	NR	NR	—
San Antonio, Tex.	5.50	4.69	17.3	5.67	4.95	14.7	4.23	3.55	19.2
San Diego, Calif.	11.56	10.47	10.4	NR	NR	—	NR	NR	—
San Francisco, Calif.	8.38	5.45	53.7	9.43	5.95	58.3	9.00	5.53	62.8
St. Louis, Mo.	5.08	4.59	10.8	5.73	5.18	10.5	3.54	3.28	7.8
St. Paul, Minn.	6.45	5.74	12.3	NR	NR	—	NR	NR	—
Seattle, Wash.	0.92	0.92	0.0	2.04	2.04	0.0	1.61	1.61	0.0
Tampa, Fla.	7.59	7.21	5.3	NR	NR	—	NR	NR	—
Toledo, Ohio	8.14	7.34	11.0	NR	NR	—	NR	NR	—
Tucson, Ariz.	7.50	6.87	9.3	NR	NR	—	NR	NR	—
Washington, D.C.	5.97	5.62	6.3	NR	NR	—	NR	NR	—
Low	**0.92**	**0.92**	**0.0**	**2.04**	**2.04**	**0.0**	**1.61**	**1.61**	**0.0**
Median	**7.05**	**6.07**	**16.1**	**7.19**	**6.37**	**12.9**	**5.11**	**4.58**	**11.6**
High	**13.47**	**13.20**	**2.0**	**12.86**	**12.70**	**1.2**	**10.26**	**10.70**	**-4.1**

[1]Price is based both on an energy consumption charge and a demand charge. The demand charge is a charge based on the highest average measured demand in the month during a specified period of time, usually 60 minutes.
[2]Majority of customers served at this rate.
NR Not reported.
Note: Retail prices for electricity (including State sales tax and all other applicable taxes) in major U.S. cities are shown for representative amounts of consumption for residential, commercial, and industrial service. Percent difference is calculated before rounding.
Source: •Energy Information Administration Form 101.

These cost elements are put on a yearly basis for a single installation. There are roughly 10,000 installations of this size in San Diego.

Table 5A summarizes the cost estimates. All of the candidate retrofits result in sizable reductions in energy cost. The energy costs for 70 w HPS and 55 w LPS are substantially the same, but the maintained, utilized lumens are significantly smaller for 70 w HPS. The yearly maintenance cost is higher for LPS because the frequency of relamping is higher. The energy cost is lowest for LPS, but much of the efficacy advantage of LPS is lost because of higher ballast losses. Capital costs are different only because of the small differences in quoted cost of hardware. No one element of the cost is dominant.

According to our estimates, the 70 w HPS bulb supplies just enough light to meet the IES suggested standards for residential street illumination, at 150 ft lamp spacing. But it produces only about two-thirds the light of the mercury vapor bulb being replaced. The next larger HPS bulb is substantially oversized. 55 w LPS produces a substantial margin over the IES standard[9] but also gives less light than the mercury vapor bulb being replaced.

In Tables 5B to 5D, we explore the sensitivity of the cost comparisons to changes in input data. Two areas are critical: the difference in ballast losses between HPS and LPS and the difference in rebulbing cost. Table 5B shows the effect of using a common GE ballast for the 70 w HPS bulb, instead of the statistical outlier that we used previously, shown in Fig. 8. The figures enclosed in the third column of Table 5B have been changed to reflect this adjustment. This change makes the overall costs almost identical for 70 w HPS and 55 w LPS. Because maintenance costs are an important area of difference, and because it is uncertain what their magnitude will be, Table 5C shows the effect of reducing the labor cost for rebulbing and cleaning. Here we reduce the labor costs for rebulbing all lamp types by a factor of one-half. This does not alter the ordering of the alternatives. Finally, Table 5D shows the effect of increasing the used lamp life by 25 percent

[9] Unless a cutoff luminaire is insisted on.

for all bulb types--in effect running them until there are 65 percent survivors instead of 82 percent survivors. This change also does not alter the ordering of alternatives.

There are still other factors affecting a cost comparison, which we cannot quantify, but which we discuss briefly below.

Vandalism of street lights in some areas is a costly item for the city. In these areas, it is especially important to replace lights as a crime control measure. The plastic transparency used for LPS light is much stronger and resistant to damage than is the glass transparency used in most HPS lights. Polycarbonates have also been used to a lesser degree on HPS lights but are less satisfactory. In either application, they are subject to yellowing after a few years exposure to sunlight. This may represent a significant additional cost, but we were not able to quantify it.

Further inflation of energy costs may well take place. At present, however, they have been going down, and we did not feel justified in making an estimate. (If fuel inflation were definite, the nuclear industry would be in much better condition.) Because better efficacy is the only *cost* advantage that LPS has, further increases in energy cost would tend to improve their cost position.

Ballasts are a substantial contributor to losses in small street lights and definitely effect the cost comparison. A full exploration of possibilities for improvement is beyond the scope of this study. Improvements in ballasts (and in luminaires) for LPS could substantially improve their cost position.

The capital charge rate used in our estimates was intended to reflect city financing, but it is not the result of significant study. Alternative financial arrangements are conceivable that grossly change the value. Utility financing would be much more expensive. On the other hand, federal financing would reduce the (immediate local) effective charge rate to 0. We did not consider either of these possibilities.

We conclude that the difference in the cost saving between installing 70 w HPS and 55 w LPS is too small to be a significant issue. Factors that are not predictable (such as future energy or lamp costs), or are not accessible to a study of this kind (such as major price concessions), could easily alter the cost comparisons.

Commercial Street Lighting Installation

We proceed to examine another street lighting situation for a larger lamp requirement. We consider retrofits for 400 w mercury vapor lights on a major street in a commercial area. The dimensions of the installation are:

Height	40 ft
Davit length	6 ft
Street width	60 ft
Light spacing	75 ft

Tables 10 and 11 summarize the light and energy and the cost comparisons, in parallel to the treatment of residential street lighting in Tables 4 and 5.

In this case, no good match to the original mercury vapor illumination is available when using LPS. 135 w LPS gives about 20 percent less light on the street than the original, and 180 w LPS gives about 15 percent more. If the lower illumination (and power consumption) is deemed acceptable (as it probably would be for the residential case), then a significant reduction in power is possible. In both the cases considered, ballast losses and poor utilization[10] (i.e., light distribution) partly cancel out the big advantage of LPS: the better efficacy of its bare bulb.

The HPS luminaire we used for this case has a very high utilization and was a noncutoff type. A brief investigation of a flat lens cutoff variation of that luminaire shows that roughly 20 percent poorer utilization would result, making the illumination produced substantially equal for 200 w HPS and 135 w LPS. But, of course, the LPS light would not have the same cutoff characteristic.

Cutoff HPS luminaires may be offered as a concession to astronomical interests, because they provide complete shielding from direct upper-hemisphere emissions. But, of course, they do not affect the reflected light that we earlier indicated to be the principal source of difficulty.

---

[10]Utilization curves are given in Figs. 11 and 12.

Table 10

LIGHT OUTPUT AND ENERGY CALCULATIONS
(COMMERCIAL STREET)

Item	Mercury Vapor (Hg Deluxe)	HP Sodium (Lucalox D)	LP Sodium (SOX)	LP Sodium (SOX)
Nominal watts	400	200	135	180
Nominal life	24,000 hr	24,000 hr	18,000 hr	18,000 hr
Lamp lumen depreciation	.85	.90	1	1
Initial lumens	22,500	22,000	22,500	33,000
Replacement interval, yr	4	4	3	3
Dirt depreciation	.95 ----→			
Lamp power (avg), w	400	200	174	191
Ballast power, w	64	50	43	40
Power to fixture, w	464	250	217	231
Utilization coefficient	.51	.51	.34	.34
Fixture	←-----GEM400---→		←--NORELCO-----→ SRP 252	
Maintained, utilized lumens	9,270	9,590	7,270	10,700
M, U lumens/w	20.0	38.4	33.5	46.1
Average illumination[a], lumens/ft^2 (=footcandles)	2.06	2.13	1.62	2.37

[a]IES recommended illumination for a major street in a commercial area is 2.0 footcandles (lumens/ft^2).

Table 11

COST CHANGES PER FIXTURE
(COMMERCIAL STREET)

Item	Mercury Vapor (Hg Deluxe)	HP Sodium (Lucalox D)	LP Sodium (SOX)	LP Sodium (SOX)
Nominal watts	400	200	135	180
Installation labor & overhead, $	0	188	188	188
Hardware cost, $	0	223	181	198
Capital increment, $	0	411	369	386
Actual watts (avg)	464	250	217	231
Yearly energy cost, $ (4165 hr, 0.12 $/kw-hr)	231.91	124.95	108.46	115.45
Yearly maintenance cost, $	17.72	17.72	22.29	23.62
Yearly capital charge, $ (charge rate = 0.14)	0	57.54	51.66	54.04
Total yearly costs, $	250	200	182	193
Yearly savings/ fixture	--	49.40	67.20	56.50
Maintained, utilized lumens	9270	9590	7270	10,700

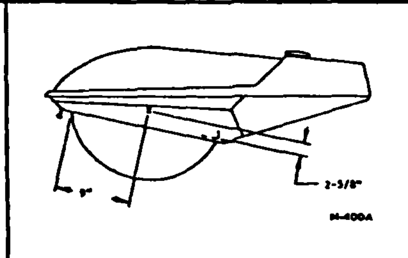
DRAWING NO	SHEET	CONT ON	REVISION
35-175819			

GENERAL ELECTRIC

PHOTOMETRIC DATA

APPROVED BY ... DATE Aug 21, 74
DATE ...

LIGHTING SYSTEMS BUSINESS DEPARTMENT
HENDERSONVILLE, N. C. U.S.A., 28739



RESERVED FOR INFORMATION ON SYMMETRICAL UNITS

PER 1000 LAMP LUMENS

LUMINAIRE DESCRIPTION

GENERAL ELECTRIC M400 OR M400A LUMINAIRE
REFLECTOR: 35-231865-04 OR 35-231865-05
REFRACTOR: 510
SOCKET POSITION: 6

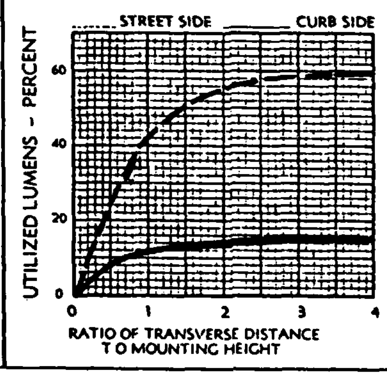
LAMP:
250 or 400 WATT HIGH PRESSURE SODIUM
G.E. NO. LU250/BD or LU400/BD (LUCALOX)
ANSI: S50BD or S51BD

ANSI/IES TYPE

MEDIUM/SEMI-CUTOFF/TYPE III (1972)

CIE TYPE NON-CUTOFF

UTILIZATION CURVE



GENERAL INFORMATION

TEST NUMBER 74-0525
TEST DISTANCE (METERS) 7
TEST LUMENS 1000

IF THE RATING OF THE LAMP USED DIFFERS FROM THE TEST RATING OF 1000 LUMENS, MULTIPLY ALL LUMEN, CANDELA (IF SHOWN) AND FOOTCANDLE VALUES BY THIS RATIO:

$$\text{RATIO} = \frac{\text{ACTUAL LAMP LUMENS}}{\text{TEST LUMENS}}$$

MAXIMUM CANDLEPOWER	=	750
MAXIMUM CONE	=	70°
MAXIMUM VERTICAL PLANE	=	72.5°/287.5°
MAXIMUM CANDLEPOWER AT 90°	=	22
MAXIMUM CANDLEPOWER AT 82°	=	174
NADIR FOOTCANDLES	=	.113
NADIR CANDLEPOWER	=	102

PHOTOMETRIC TEST IN ACCORDANCE WITH IES GUIDE

ILLUMINATION DATA

RATIO OF LONGITUDINAL DISTANCE TO MOUNTING HEIGHT

RATIO OF TRANSVERSE DISTANCE TO MOUNTING HEIGHT

		7.0	6.0	5.0	4.0	3.0	2.0	1.0	0.0
CURB SIDE	2.0	.00008	.00007	.00008	.00016	.00035	.00074	.00168	.00356
	1.5	.00009	.00009	.00010	.00021	.00050	.00127	.00431	.00885
	1.0	.00012	.00012	.00016	.00036	.00096	.00247	.01330	.01890
	0.5	.00014	.00016	.00028	.00079	.00297	.00755	.02490	.04240
	0.0	.00011	.00020	.00048	.00167	.00646	.03210	.08200	.11333
STREET SIDE	0.5	.00009	.00026	.00075	.00284	.01590	.06030	.14400	.14400
	1.0	.00011	.00034	.00102	.00383	.01800	.04170	.03940	.03280
	1.5	.00013	.00040	.00119	.00403	.01280	.01650	.01670	.01810
	2.0	.00015	.00044	.00122	.00327	.00688	.00594	.00536	.00489
	2.5	.00018	.00048	.00107	.00226	.00327	.00254	.00261	.00196
	3.0	.00021	.00040	.00083	.00137	.00132	.00095	.00122	.00104
	3.5	.00016	.00031	.00059	.00083	.00070	.00054	.00061	.00060
	4.0	.00014	.00025	.00045	.00043	.00035	.00034	.00037	.00037

.0001 .001 .01

SCALE 2" 1" 0" -90° 180° 270° LUMINAIRE POSITION

TO CONVERT ILLUMINATION DATA TO FT-C (ON HORIZONTAL SURFACE) MULTIPLY BY 1

RESERVED FOR INFORMATION ON SYMMETRICAL UNITS

LIGHT FLUX VALUES		
	LUMENS	PERCENT OF LAMP
DOWNWARD STREET SIDE	600	60
UPWARD STREET SIDE	10	1
DOWNWARD CURB SIDE	150	15
UPWARD CURB SIDE	10	1
TOTAL	770	77

CONVERSION FACTORS

1 FOOTCANDLE = 10.76 LUX
1 FOOT = 0.3048 METERS

ILLUMINATION DATA IS BASED ON A LUMINAIRE MOUNTING HEIGHT OF 30 FEET. FOR OTHER MOUNTING [illegible] MULTIPLY THE VALUES OF ILLUMINATION SHOWN BY THE FACTORS IN THE FOLLOWING TABLE

MOUNTING HEIGHT-FT.	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	[illegible]	47	48	49	50
FACTOR	1 44	1 33	1 23	1 15	1 07	1	94	88	83	78	74	69	66	62	59	56	54	51	49	46	[illegible]	[illegible]	41	39	38	36

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DRAWING NO	SHEET	REVISION
35-175819		

Fig. 11--Photometric data for General Electric M 400 Luminaire

North American Philips Lighting Corporation

Hightstown
New Jersey 08520

Telephone 609-448-4000

Norelco®

Photometric Data
Test No. 2634

Luminaire type **SRP 252**

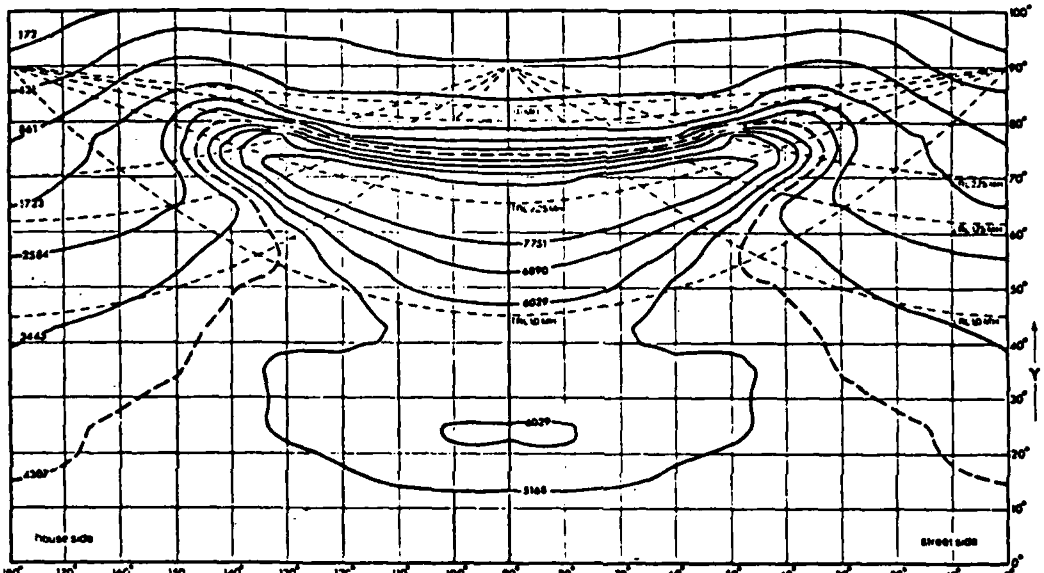
LUMINAIRE SRP 252
refractor type: fixed
reflector position: fixed
socket setting: f
angle of tilt: 0°

LAMP
type: 1 SON 400 W
luminous flux: 33000 lm

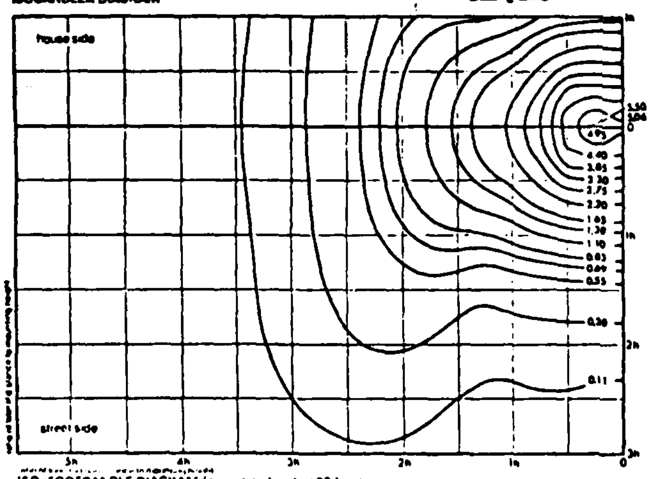
LIGHT FLUX VALUES

	lumens	% of lamp flux
downward street side	13672	38.4 %
downward house side	13672	38.4 %
upward	504	1.0 %
total luminaire	25636	78.8 %

CANDLE POWER VALUES
maximum intensity: 6613 cd
intensity at nadir: 4586 cd



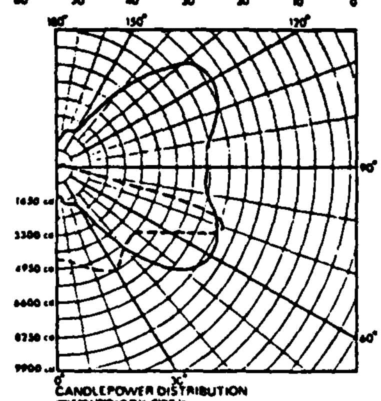
ISOCANDELA DIAGRAM



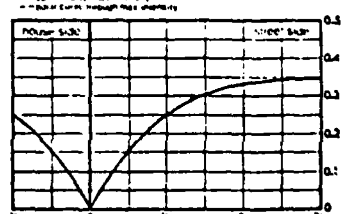
ISO-FOOTCANDLE DIAGRAM (mounting height = 30 feet)

factor	2.23	1.86	1.56	1.33	1.15	1	0.88	0.78	0.69	0.62	0.56
mounting height in feet	20	22	24	26	28	30	32	34	36	38	40

IES-SPECIFICATION
type 4 distribution medium classification cut off



CANDLEPOWER DISTRIBUTION



COEFFICIENT OF UTILIZATION CURVE

Fig. 12--Photometric data for Norelco SRP 252 Luminaire

The cost comparison in Table 11 is made using the same labor cost, productivity, and overhead as for the previous case. All the retrofits considered for 400 w mercury vapor lights are cost effective, and the savings produced by them are of the same order. The largest saving occurs with 135 w LPS, which produces about 20 percent less light. The robustness of this cost comparison, like the previous one for residential street lighting, is poor. Because the cost estimates are fairly close, changes in unpredictable factors or data by nature inaccessible to a study of this kind could result in a different ordering of the alternatives.

OTHER ISSUES

Three issues, other than cost, that are commonly considered when comparing LPS and HPS lighting are public acceptance, visual effectiveness of light, and disposal problems. Below, we consider each of these briefly in turn; we have made no attempt to treat them exhaustively.

Public Acceptance

Opponents of LPS lighting claim that they find such lights disorienting, and that under them colors cannot be identified. Sodium lamps, in general, do not have good color rendition characteristics, and in sales areas for fruit, vegetables, flowers, cars, and other commodities, they will be a drawback. Street lighting, however, is not intended to illuminate such areas, and, in any case, they commonly have their own illumination. The spectral quality of HPS lights (where color is important) is preferable to that of LPS lighting, since HPS lamps span a wider range of the visible spectrum. Alternatively, where insect control is a goal, the repellent properties of monochromatic yellow LPS light is the best choice.

Formal surveys to gauge public opinion of LPS and HPS lights were commissioned in San Jose and San Diego. The results of these polls are given in the Table 12. Data are taken from (Turturici, 1980) and (Baade, 1981). The values show a good public acceptance of both types of light, particularly when the respondents are informed of the

Table 12

PUBLIC ACCEPTANCE OF HPS AND LPS LIGHTING (PERCENT)

Lighting Type	San Diego[a]		San Jose	
	No Knowledge of Energy Savings	Knowledge of Energy Savings	No Knowledge of Energy Savings	Knowledge of Energy Savings
Commercial HPS	--	--	50	87
Residential HPS	--	--	57	75
Commercial LPS	83	93	61	83
Residential LPS	67	83	55	68

[a] The respondents were asked their opinion before and after being informed that both types of lights would result in energy savings.

potential energy savings. The data also show that there is no clear preference for one type or the other.

Visual Effectiveness

Much research has been done on the physiological effects of spectral light on the human eye. Although there are some situations where special spectra would be preferred, there are no data that unequivocally prove the superiority of heterochromatic (HPS) or monochromatic (LPS) light.

The photopic response occurs when the eye is adapted to relatively high luminances; the scotopic response occurs when the eye is adapted to low luminances. Time is required to adapt from one lighting level to another. In a comparative study by the San Jose Police Department, the findings were that both HPS and LPS aid law enforcement because they increase or disperse light. While some officers stated that LPS lighting would create some difficulties, it was concluded that it would not create a hazard (Turturici, 1981).

Disposal

Both LPS and HPS lamps contain sodium. When sodium comes in contact with moisture, sodium hydroxide is formed spontaneously, and care must be exercised to insure its safe disposal. The City of Long Beach, which employs LPS lighting, disposes of the sodium in the same manner that they dispose of other discharged lamps. Opponents of LPS lighting claim that because such lamps contain slightly more sodium than HPS lamps, they pose an undue safety hazard. There is no evidence that special handling of LPS lamps would be required.

IV. CONCLUSIONS AND FUTURE WORK

There are two basic conclusions that can be drawn from our research. First, if HPS lighting is uniformly adopted in San Diego, it will pose a problem for astronomers at Palomar and Mt. Laguna Observatories. Although we cannot gauge the extent of the problem without detailed spectra of the sky glow over the city, we can conclude qualitatively that implementing LPS street lighting would mitigate the light pollution significantly. Other methods like turning off unnecessary lights and shielding, though less promising, might also be somewhat effective.

Second, our initial results indicate that the costs of adopting LPS or HPS lighting are comparable in the San Diego area. The decision by the city council concerning the choice in lighting should be made on factors other than cost. These factors are the unnatural appearance and poor color rendition of LPS lighting on the one hand, and the disadvantages to research astronomers because of HPS lighting on the other hand. The cost of electric power in San Diego is relatively high compared with that in other U.S. cities, a fact that makes efficient use of electricity important. Future work should resolve the contentious issues in the San Diego/Palomar Observatory case and address the relative costs for locations surrounding other observatories.

Some potential future developments that would improve LPS lighting have been identified. One is the reduction of losses in LPS ballasts, especially in small sizes. Another is an improvement in LPS light distribution either through luminaire redesign or fixture mounting changes. The bulb for LPS fundamentally must be large. That makes it difficult to control light distribution with a luminaire of reasonable size and weight, but the low temperature characteristics of the bulb may permit the use of modern light-weight materials and an improved design overall. Whether the market would support such a development is uncertain. The light utilization from present luminaires could be substantially improved if they were placed over the center of the street. In many cases, this would require replacement of poles, and at least replacement of davits (extension arms). The probable costs and effectiveness of such measures are also subjects for future research.

An issue on which better data are badly needed is the fraction of the artificial astronomical interference that is due to street lighting (and hence relatively easily controlled by municipal action) and how much is due to advertising, private exterior and interior lighting, street sign lighting, and light from other sources. In addition to the "source term" for these types of lighting, the detailed paths by which the light reaches the telescope needs study. Analytical approaches to the latter problem can be visualized, but it is not presently clear how best to approach determination of the source distribution.

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