Design of an Energy Efficient Outdoor Nighttime Urban Lighting System

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Vitae

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Prior to coming to Brookhaven National Laboratory, Mr. Harrington was employed as a mechanical engineer at Unisys Corporation, Great Neck, New York. He performed numerous duties during his nine-year tenure there, including authoring administrative procedures, calculating proper size and construction of hydraulic and pneumatic components used in a variety of projects, and coordinating design reviews for the North Warning System program.

After hours, Mr. Harrington pursues an active concern in light conservation and energy-efficient lighting design thanks to his interest in amateur astronomy and memberships in the International Dark-Sky Association and New England Light Pollution Advisory Group. He has written four books on the subject of astronomy, including Touring the Universe Through Binoculars and Star Ware (John Wiley and Sons, Inc.; 1990 and 1994, respectively), Astronomy For All Ages (Globe Pequot Press; 1994), and Sky &

Telescope Observer's Guide: The Deep Sky (Sky Publishing Corporation; 1995), as well as a book on bicycling, Short Bike Rides In and Around New York City (Globe Pequot Press; 1992). His next book, detailing solar and lunar eclipses, is expected to be released in 1997. In addition, Mr. Harrington has written numerous articles for leading astronomical journals around the world, including *Astronomy* and *Sky & Telescope* magazines.

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Dedication

To my wife, Wendy, and daughter, Helen.

For their love and support through yet another night-school degree.

Abstract

Since the oil crisis of the 1970's, the world has become painfully aware that our planet has a finite and exhaustible amount of natural resources. As a result, we now see more energy-efficient automobiles, electrical appliances, and over conservation-oriented devices aimed to curb our energy-thirsty society. Yet, each year throughout the civilized world, untold megawatts of electrical energy is needlessly wasted by poorly designed, over-powered, and ill-placed lighting fixtures. While the aim of a lighting fixture should be to aim its light down toward the ground, many fixtures lose as much as half of their light skyward.

The first part of this project investigates the current status of outdoor lighting in the United States by examining present-day exterior illumination systems, discussing the pros and cons of each both from an operational point of view as well as from an energy-efficient perspective. In here, the reader shall see that high-pressure sodium lamps, the most common streetlight in use today, are not the most energy efficient. In addition, the most familiar streetlight fixtures are not designed to aim their light down, but instead cast much of it wastefully to the sides and upwards. By simply replacing these with full-cutoff fixtures of proper design, which direct all of their light downward, lower-wattage lamps could be used without loss of useful illumination.

The second portion of this project applies some of what was discussed in the first half to a specific case: Brookhaven National Laboratory. During this research project, it was found that this world-class research facility suffers from poorly designed, wasteful lighting fixtures; indeed, these fixtures prove more wasteful than many found along state, county, and local roadways throughout the Laboratory's home county of Suffolk in the state of New York.

In an effort to stem the tide of wasting electrical energy at the Laboratory, this thesis offers three proposals. All go a long way to save electricity by diminishing or curtailing the use of unabated nighttime lighting. This, in turn, will offer the Laboratory an opportunity to both save money (as much as $15,000 per year) as well as to set an example for other institutions throughout the country and the world.

Chapter 1: Introduction

Have you ever noticed, as you are driving toward a large metropolitan area, how lights from the city seem to illuminate the sky even while you are still many miles away? This effect, called *light pollution*, is the cumulative result of hundreds, thousands, even tens of thousands of poorly designed and improperly placed streetlights, billboard and roadside lights, commercial and industrial building lights, and residential lights. The International Dark-Sky Association (IDA) estimates that as much as fifty percent (50%) of the light generated by nighttime lighting fixtures is wasted as it shines skyward, rather than down toward the ground where the illumination is desired[1]. Figure 1 offers dramatic testimony to the wastefulness of outdoor lighting as all major and several minor cities in the United States and Canada are easily identifiable. It is difficult to prove from this photo that outdoor nighttime lighting is primarily designed to shine downward!

Since the energy crisis of the 1970s, exterior lighting has gained increasing importance as a key component of environmental design. In the past, poor lighting design could be compensated for by increased lighting levels, but the present day awareness of energy conservation has created a need to use nighttime light wisely and efficiently. While it was once acceptable to use three to four watts per square foot (approximately 35 watts per square meter) to illuminate a building exterior, current guidelines in some parts of the United States are considering mandatory limits of less than one watt per square foot (10 watts per square meter). With such constraints in the offing, lighting must be designed and placed discerningly, or the ability to perform visually demanding tasks will be severely impaired.

The efficient and effective use of outdoor lighting can offer major energy and cost savings. New, much improved light fixtures, or *luminaires*, are now available which provide considerably more light per

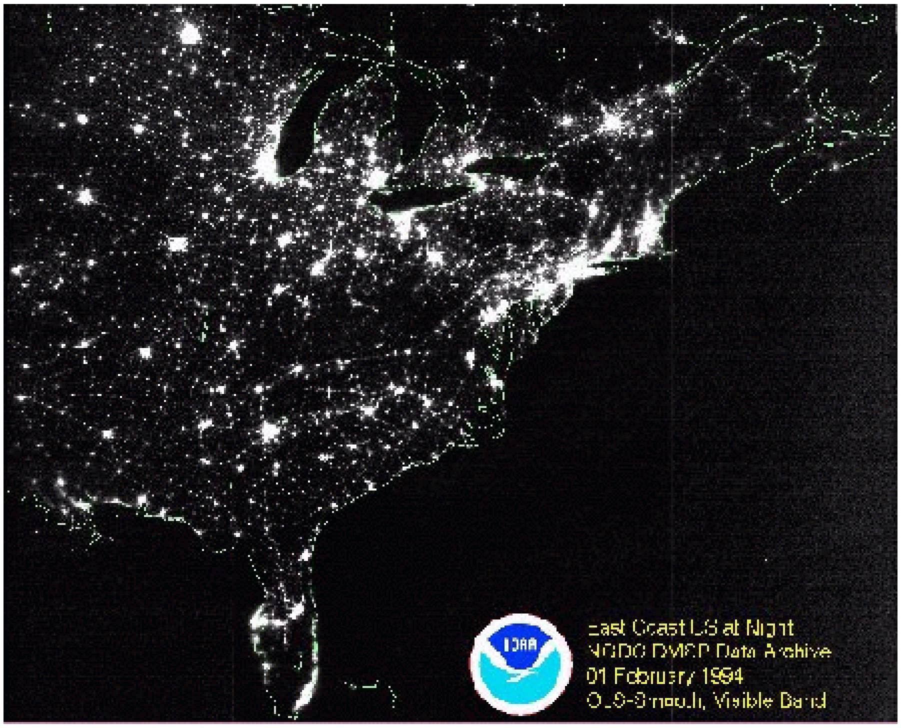

Figure 1. The East Coast of the United States and Canada at night. Courtesy National Oceanographic and Atmospheric Administration.

unit of energy consumed. Most newer fixtures offer better light control, aiming the light downward toward the ground where it is needed rather than wasting it by letting it scatter upward and skyward. Replacement of older fixtures with new luminaires can greatly improve efficiency. The city of Tucson, Arizona, exemplifies the success of changing to more efficient luminaires. After converting from older fixtures to newer street lights encased in downward- facing housings, the Page (Arizona) Electric Utility calculates that the city realizes an estimated $2 million savings in annual power costs[2].

The purpose of this design project is two-fold. The first half is an audit and cost study to demonstrate the wastefulness of commercial, industrial, residential, and community lighting by exploring current lighting technology and contrasting it to luminaires used in the past. The second part of this project proposes a design for a more energy-efficient lightning system that might be applicable to a small city. For the purposes of this study, I selected the redesign of the exterior lighting system of Brookhaven National Laboratory. The investigation will balance the projected cost of the fixtures against the estimated savings in energy to the community.

Chapter 2: The Science of Lighting

Lighting design has two major components: (1) *quantity*, or the amount of light, specified in terms of luminance and intensity; and (2) *quality*, referred to in terms of the color-rendering properties of a lighting system, the absence or presence of veiling reflections, the effectiveness of a luminaire lighting its intended target, and the amount of glare caused by a lighting system within its sphere of influence.

While quantity (e.g., intensity and luminance) is rather simple to measure photometrically, trying to ascertain the quality of a lighting system is much more difficult to evaluate. Yet, the quality of a lighting system is an important factor in evaluating the effectiveness of a design, as it will directly affect the requirements for quantity.

Proper lighting design requires that attention be paid to both quantity and quality; one without the other often yields a visual environment that is both uncomfortable for its inhabitants and inefficient in its energy utilization.

Measurement of Light Levels

The visual portion of the electromagnetic spectrum is generally considered to include the wavelengths between 380 and 760 nm (nanometers), ranging from violet at the short end to red at the long. This is called the *visible spectrum*. Any energy within this narrow range will stimulate the human eye's sense of vision. Different wavelengths of energy are perceived as different colors, as summarized in Table 1.

Photometry is the measurement of light across the visible spectrum. Although lighting engineers and designers make many assumptions about the way in which the human visual system functions, photometry serves as the means to specify and measure light, providing the basis for all current lighting units and measurement techniques.

Table 1. Color versus Energy Wavelength

Color	Wavelength (nm)
Red	760 - 630
Orange	630 - 590
Yellow	590 - 560
Green	560 - 490
Blue	490 - 440
Indigo	440 - 420
Violet	420 - 380

To understand the relationship between lighting units, Pitts and Kleinstein[3] recommends starting with a point source; that is, an infinitesimally small source of light that has no area and radiates light equally in all directions. This radiation pattern creates a perfect sphere, as shown in Figure 2.

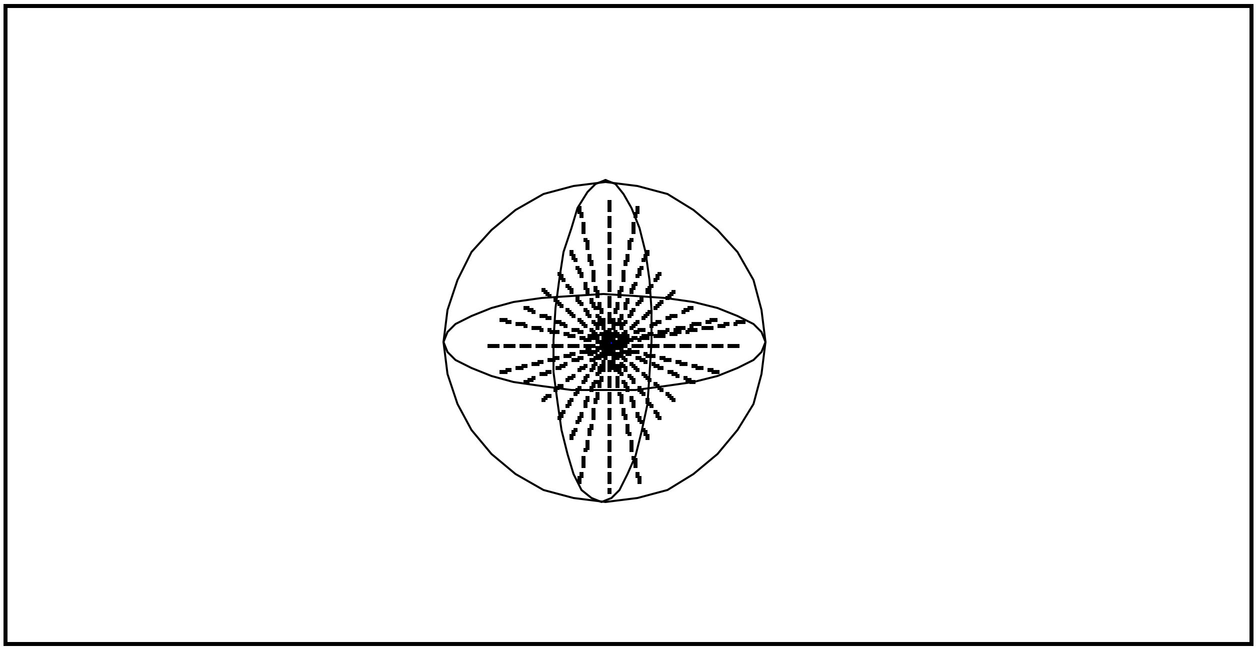

Figure 2. A theoretical point source of light.

The amount of total light output from a luminaire in a given time is expressed in *lumens*, which in turn is a measure of *flux* (F). Since actual sources of light are not omnidirectional, their radiance pattern is always specified by how many lumens are being emitted at a given angle in a specified direction. This quantity is called *intensity* (I) and is measured in lumens per steradian. The relationship between flux and intensity is demonstrated in the following equation:

$$I = \frac{F}{4\pi} \qquad \textbf{(1)}$$

Intensity does not speak of the amount of light that strikes a surface or an area. This second quantity is called *illuminance* (E) and is measured in footcandles. This is the quantity that is typically specified in lighting plans and proposals. The relationship between intensity and illuminance is given by the equation:

$$E = \frac{I \cos\theta}{r^2} \qquad \textbf{(2)}$$

with r symbolizing the distance between the light source and surface and θ denoting the angle between the normal of the surface and the line connecting between the source and the point where the illuminance is being specified. If this angle were zero (and, therefore, cosine $\theta = 1$), then the illuminance equation corresponds directly to the inverse-square law, which simply states that the amount of illuminance reduces by the square of increasing distance from the light source.

While illuminance is a measure of how much light falls *onto* a surface, the real measure of a lighting system's effectiveness is how much light shines in a given direction, or more correctly, how many lumens will be fall on the surface being considered. This final term is defined as *luminance* (L) and is calculated form the formula:

$$L = E\frac{\rho}{\pi} \qquad \textbf{(3)}$$

where ρ is the *albedo*, or reflectance of the surface.

Of these, only illuminance and luminance are measured with photometers. Most measurement instruments utilize either photodiodes, charge-coupled devices (CCDs) or photomultiplier tubes (PMTs), with the latter preferred for low-light situations.

Finally, *efficacy* (K) is an important consideration when judging the usefulness of one lamp style over another. Efficacy is the ratio of the total luminous flux emitted by a source to the total power input to the source. The following equation demonstrates this relationship:

$$K = \frac{Flux\ emitted}{input\ power} = \frac{light\ output}{power\ input} \qquad \textbf{(4)}$$

Helms and Belcher[4] liken efficacy to miles per gallon. The larger a lamp's efficacy, the higher the light output with less power consumption.

Color, Vision, Contrast, and Nonvisual Effects of Light and Radiant Energy

To appreciate our ability to perceive objects under varying lighting conditions, it is first important to have a basic understanding of how the human eye works. The human eye (Figure 3) measures about an inch in diameter and is surrounded by a two-part protective layer: the transparent, colorless cornea and the white, opaque sclera. The cornea acts as a window to the eye and lies in front of a pocket of clear fluid called the aqueous humor and the eye's iris. Besides giving the eye its characteristic color, the iris regulates the amount of light entering the eye and, more importantly, varies its focal ratio. Under low-light conditions, the iris relaxes, dilating the pupil (the circular opening in the center of the iris), while bright light will tense the iris, constricting the pupil, increasing the focal ratio, and masking lens aberrations to produce sharper views.

From the pupil, light passes through the eye's lens and across the eyeball's interior, the latter being filled with fluid called the vitreous humor. Both the lens and cornea act to focus the image onto the retina. The retina is composed of ten layers of nerve cells, including photo-sensitive receptors called rods and cones. Cones are concerned with brightly-lit scenes, color vision, and resolution. Rods are low-level light receptors but cannot distinguish color. There are more cones towards the fovea centralis (the center of the retina and our perceived view), while rods are more numerous toward the edges. There are neither rods nor cones at the junction with the optic nerve (the eye's blind spot).

Figure 3. Cross section of the human eye. From Star Ware by Philip S. Harrington, John Wiley & Sons, 1994.

In order to perceive images under dim lighting, the eye experiences a two-step adaptation process in order to adapt to the changing conditions. First, after being plunged into darkness, the eye's pupil quickly dilates to between 5 and 7 mm in diameter, doubling the pupil's normal, daytime aperture of 2.5mm. A shift in the eye's chemical balance also occurs, but much more slowly. The build-up of a chemical substance called rhodopsin (also known as visual purple) increases the sensitivity of the rods. Most people's eyes become adjusted to the dark in 20 to 30 minutes, though some require as little as 10 minutes or as long as one hour.

Our ability to perceive color involves the complex interaction of the wavelengths across the visual spectrum and the human visual system. If our visible window were restricted to only one precise wavelength, then our perception would be restricted to that one color. For example, if the human eye was only sensitive to energy at 550 nm, then our world would appear only as varying intensities of yellow. If it were stimulated at only 485 nm, then our world would appear blue, and so on. Our eyes' ability to perceive the wavelength composition of light is critical to the sensation of color perception.

While the eye's sensitivity to dim lighting increases dramatically during the dark adaptation process, it loses most of its sensitivity to color. As a result, most people at night only sense varying shades of light and dark, rather than accurate color perception.

Besides lighting intensity, contrast is critical for image perception. Contrast is a measure of an observer's ability to distinguish between two areas. This value, termed contrast threshold (C), can be expressed as:

$$C = \left| \frac{L_o - L_b}{L_b} \right| \qquad \textbf{(5)}$$

where L_o = luminance of test object

L_b = luminance of background

The ability to see an object is greatly affected by physical contrast and the surrounding luminance. If the luminance of the background is much greater than the object, the target will be perceived only in silhouette. If, on the other hand, the luminance of an object is much greater than the surroundings, the eye will experience discomfort, resulting in reduced perception.

Lighting Engineering

There are several different types and designs of luminaires from which to choose. Some are clearly more energy efficient than others. Below are brief capsule summaries of the most popular types of light sources in use today.

The Standard Incandescent Lamp is the most common interior light source in use today. The incandescent lamp produces light by passing an electrical current through a wire or filament. The filament's resistance to the flow of electrical current raises the filament to a high temperature, causing it to incandesce, or glow. Tungsten is used as a filament material, as no other substance is as efficient in converting electrical energy into light on the basis of life and cost.

Despite its popularity, the operating efficiency of a standard incandescent lamp makes it a poor choice for illumination. A 100 watt lamp, which is rated at 1,750 lumens, has an efficacy of

$$K = \frac{1750}{100} = 17.5\frac{lm}{W}$$

Tests measuring the life-cycle of such a lamp show that the average life expectancy is approximately 750 hours. Therefore, in an application that requires illumination 11.23 hours/day, the number of years a 100 watt standard incandescent lamp will operate will be:

$$no.\ years = \frac{life}{hours/year} = \frac{750}{4100} = 0.18\ year\ (2\ months)$$

The low initial cost of incandescent lamps is more than offset by their short life and low efficacy. As a result, incandescent bulbs are not commonly used for roadway lighting. Instead, other, more efficient (and initially more costly) light sources are preferred.

Fluorescent Lamps were first shown at the 1938 World's Fair in New York. They operate by passing electrical current through a low-pressure atmosphere of argon to a small quantity of mercury droplets. The mercury vaporizes and, in the process, radiates ultraviolet energy. A thin chemical coating of phosphor on the inside of the bulb wall is excited into fluorescence by the ultraviolet radiation, producing visible light.

Fluorescent lamps are very efficient at producing light. Recall from the example above, a 100-watt incandescent lamp is rated at 1,750 lumens. By comparison, a 40-watt fluorescent lamp is rated at 3,150 lumens. To calculate the efficacy of this lamp, we must also take the lamp's ballast into consideration. Assuming a single-lamp ballast that consumes 14 watts, the overall efficacy is:

$$K = \frac{3150}{40+14} = 58.3 \ \frac{lumens}{watt}$$

The system's efficacy can be improved by using a two-lamp or three-lamp ballast. A two-lamp ballast (requiring 92 watts) increases efficacy to 68.5 lumens/watt, while a three-lamp ballast (consuming 140 watts) produces a system efficacy of 67.5 lumens/watt.

Further, the life expectancy of fluorescent lamps is much longer than incandescent lamps. Typically, the 40-watt fluorescent lamp cited above has a life rating of 20,000 hours. Assuming an 11.23-hour/day operating period (equal to the previous incandescent example), the 40-watt fluorescent lamp will last:

$$no.\ years\ '\ \frac{life}{hours/year}\ '\ \frac{20000}{4100}\ '\ 4.9\ years$$

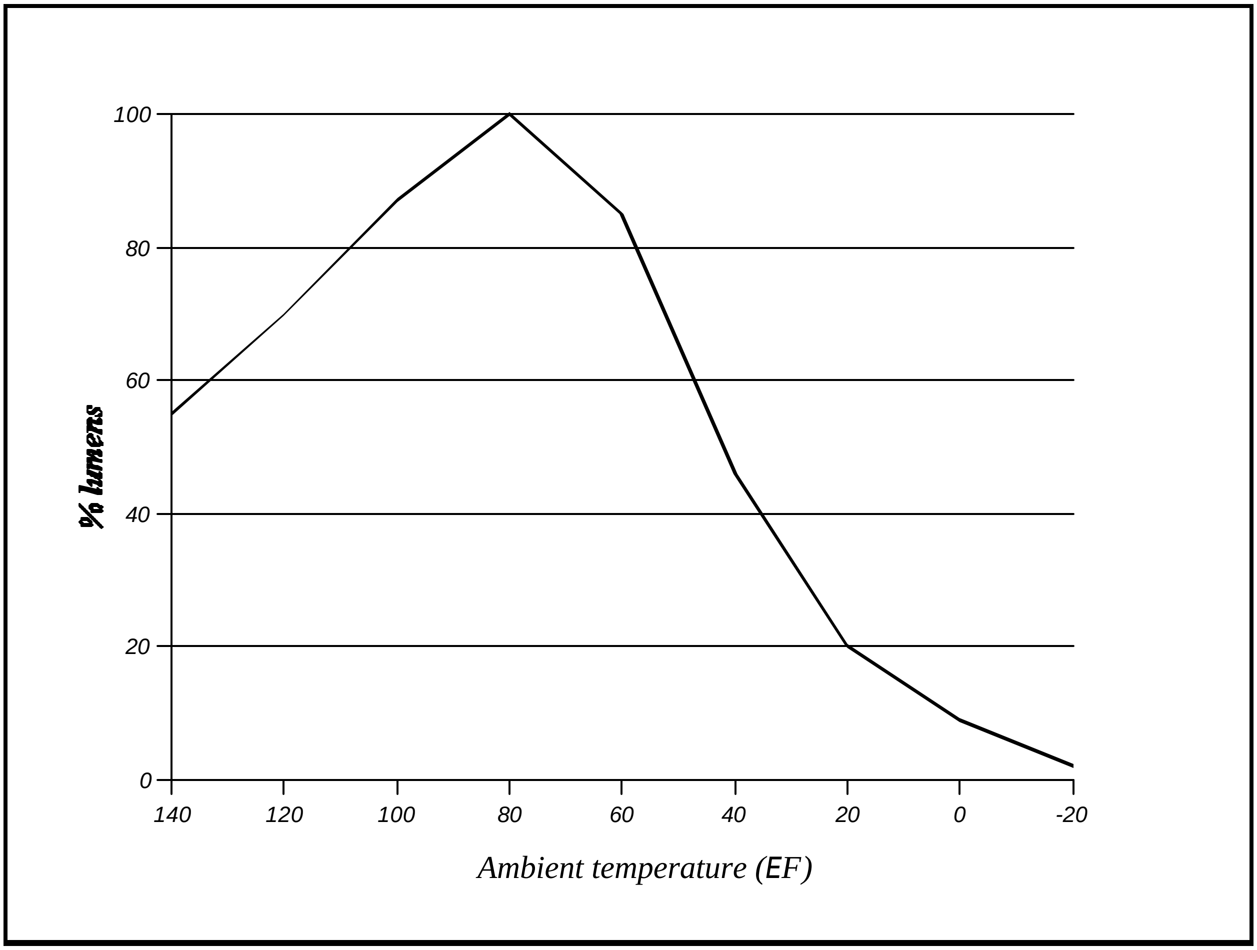

Figure 4. Ambient Temperature Effects on Fluorescent Lamps. (Based on data supplied by General Electric Lighting.)

Despite their attractive efficacy and life-cycle cost, fluorescent lamps are not generally used for exterior lighting. As Figure 4 demonstrates, fluorescent lamps are greatly affected by ambient temperature. The most efficient lamp operation is achieved when the air surrounding the lamp is approximately 80EF.

Far from this narrow temperature range and the lamps lumen output drops off rapidly, caused by a reduction in mercury pressure and subsequently, less ultraviolet radiation. While low-temperature ballasts are available for starting and operating fluorescent lamps as low as G20EF (by using a higher starting voltage), they do nothing to overpower the dramatic loss in light output.

Low-Pressure Sodium Lamps. No other lamp has as high an efficacy as the low-pressure sodium (LPS) lamp. LPS lamps have been used extensively as exterior light sources in Europe for the past half-century as well as in the United States, though on a much more limited basis.

Light is produced in an LPS lamp by a c-shaped arc tube constructed of glass and filled with sodium gas as well as small amounts of neon and argon. Visible light is produced by electrons bombarding the sodium, resulting in monochromatic yellow light (primary wavelength = 589 nm).

As noted previously, efficacy of LPS lamps is second to none. Table 2 below itemizes the efficacy and lumens for several of the more popular LPS lamp in use today.

Table 2. Low-Pressure Sodium Lamp Efficacy[5]

Lamp Wattage	Lumens	Efficacy (Lamp + Ballast)	Annual KWH Consumption	Annual Operating Cost[a]
35	4,800	80.0	246	$15.99
55	8,000	100.0	328	$21.32
90	13,500	108.0	513	$33.35
135	22,500	126.4	738	$47.97
180	33,000	150.0	902	$58.63

Note: a. Assuming a cost per Kilowatt-Hour (KWH) of 6.5¢ (the power rate paid by Brookhaven National Laboratory, the case study).

Except for low-wattage (e.g., <35 watts) LPS lamps, all have a projected life cycle of 18,000 hours. Therefore, using the life-cycle equation from above, any of the LPS lamps specified in Table 2 have a projected operational life of:

$$no.\ years \; ' \; \frac{life}{hours/year} \; ' \; \frac{18000}{4100} \; ' \; 4.4\ years$$

LPS lamps are not as effected by temperature extremes as fluorescent lamps. Manufacturers state that lumen output is constant over a temperature range of +14EF (S10EC) to +104EF (+40EC)[6] (the effect on lumen output beyond this range is undocumented).

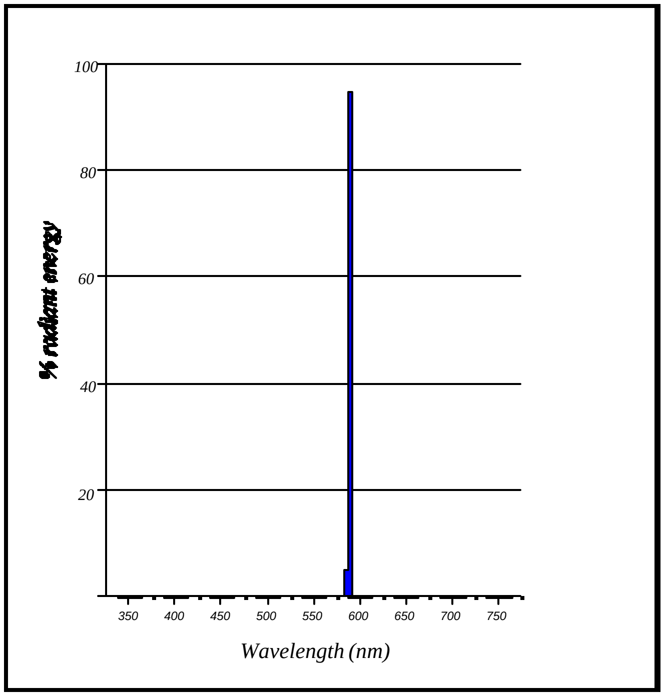

Figure 5. Spectral distribution curve for a low-pressure sodium lamp.

Perhaps the biggest drawback to LPS lamps is their monochromatic yellow color. As shown in Figure 5, most of the light output is at a single wavelength of 589 nm. As a result, all nonyellow objects take on varying shades of gray or brown, greatly impairing the lamp's color-rendering potential. Depending on the application, this may make an LPS lamp less attractive than other sources with broader emission spectra.

Mercury Vapor Lamps, one of three high-density discharge (HID) sources (the others being metal halide and high-pressure sodium **S** see below), utilizes an arc tube somewhat akin to that used in LPS lamps. The arc tube, constructed of quartz, contains mercury as well as small quantities of krypton, neon, and argon. Upon energizing, an arc is struck between the lamp's main and starting electrode. This, in turn, ionizes the mercury to produce light at 405, 436, 546, and 578 nm, lending a bluish-green cast, as well as in the ultraviolet range. Frequently, a thin layer of phosphor is coated on the inside of the fixture, reacting with the UV radiation to offer a better balance in color.

Unlike that of LPS lamps, the efficacy of mercury-vapor lights vary widely with lamp wattage. In general, the greater the lamp wattage, the higher the efficacy, as shown in the examples cited in Table 3. From this, it can be seen that mercury-vapor lamps increase in efficacy as their wattage increases, but overall, they are less energy efficient than other LPS lamps as well as both metal halide and high-pressure sodium lamps (discussed below).

Table 3. Efficacy of Mercury-Vapor Lamps[7]

Lamp Wattage	Mean Lumens	Efficacy (Lamp + Ballast)	Annual KWH Consumption	Annual Operating Cost[a]
175	7,140	35	841	$54.67
250	10,540	37	1,169	$75.99
400	18,570	41	1,866	$121.29
700	29,850	39	3,137	$203.91
1000	46,200	42	4,469	$290.49

Note: a. Assuming a cost per Kilowatt-Hour (KWH) of 6.5¢ (the power rate paid by Brookhaven National Laboratory, the case study).

Life testing of all HID lamps is based on a burning cycle of 10 hours per start, although in this application, calculations are based on an 11.23-hour per day operational cycle. All lamps listed in the table above have rated lives of between 16,000 and 24,000 hours. Using an average of 20,000 hours, the life expectancy of the above mercury-vapor lamps is shown below:

$$no.\ of\ years = \frac{20000}{4100} = 4.9\ yr$$

From this, it is clear that life expectancy of mercury-vapor lamps is slightly better than LPS lamps and similar to other HID alternatives.

Metal Halide Lamps work on the same principle as mercury-vapor lamps. Gases inside an arc tube, including mercury, argon, neon, krypton, as well as metal iodides, are ionized to produce light. Because of the mix of elements involved, color of the light produced is much broader than either mercury-vapor, low-pressure sodium, and high-pressure sodium lamps.

Efficacy of metal halide lamps can vary widely between manufacturers and lamp wattage. In general, the higher the wattage, the higher the lamp's efficacy.

Table 4. Metal Halide Lamp Efficacy[8]

Lamp Wattage	Lumens	Efficacy (Lamp + Ballast)	Annual KWH Consumption	Annual Operating Cost[a]
175	10,800	49	902	$58.63
250	17,000	58	1,210	$78.65
400	25,600	55	1,907	$123.96
1,000	88,000	77	4,674	$303.81

Note: a. Assuming a cost per Kilowatt-Hour (KWH) of 6.5¢ (the power rate paid by Brookhaven National Laboratory, the case study).

Like efficacy, the anticipated lifetime of a metal halide lamp also varies between manufacturers and lamp wattage. Figures frequently quoted in the lamp industry range from as low as 7,500 hours to over 20,000 hours. The 400-watt lamp noted above has an average rated life of 20,000 hours, resulting in a projected life of:

$$\textit{no. of years} = \frac{20000}{4100} = 4.9\ \textit{yr}$$

In sum, the primary advantages of metal halide lamps are their excellent color rendition, high efficacy, and long life. Yet, they remain less popular alternatives for outdoor nighttime lighting than high-pressure sodium lamps, described below.

<u>High-Pressure Sodium Lamps</u>. As with metal halide and mercury-vapor lamps, high-pressure sodium (HPS) lamps produce light when gas contained in an arc tube (in this case, sodium) is excited into fluorescence. As can be seen from Figure 6, HPS lamps emit light across the visible spectrum. The majority of light generated falls between 550 nm and 650 nm, resulting in the lamp's characteristic orange cast.

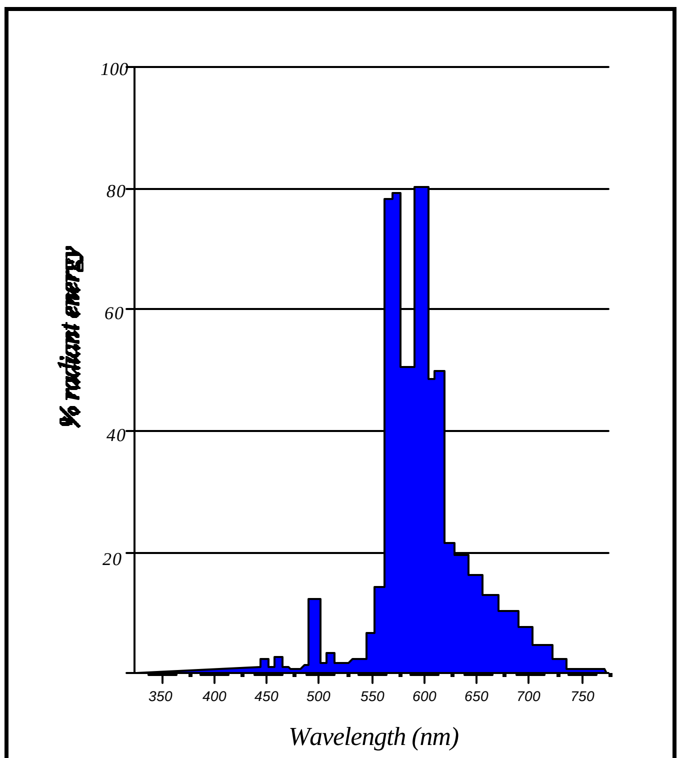

Figure 6. Spectral distribution curve for a high-pressure sodium lamp.

In general HPS lamps enjoy both a high efficacy and long operating life. Table 5 itemizes efficacy as a function of lamp wattage.

Table 5. Efficacy of High-Pressure Sodium Lamps[9]

Lamp Wattage	Mean Lumens	Efficacy (Lamp + Ballast)	Annual KWH Consumption	Annual Operating Cost[a]
100	8,550	66	533	$34.65
150	14,400	75	791	$51.42
200	19,800	80	1,009	$65.59
250	24,750	84	1,205	$78.33
400	45,000	97	1,907	$123.96

Note: a. Assuming a cost per Kilowatt-Hour (KWH) of 6.5¢ (the power rate paid by Brookhaven National Laboratory, the case study).

The life-span of most HPS lamps between 50W and 1000W is rated at 24,000 hours. As a result, a HPS lamp can be expected to last:

$$no.\ of\ years = \frac{24000}{4100} = 5.8\ yr$$

This makes HPS lamps the longest lasting of any of the common types of lamps. This, combined with its high efficacy and low cost, has led to HPS lamps becoming the most popular type of exterior luminaire in use today.

Chapter 3: Design Considerations

In the past, designing exterior lighting was simple. The most common philosophy was to flood an area with as much light as practical, while giving little or no consideration to the system's efficiency or effectiveness. But in these energy-conscience times, this approach is both irresponsible and unnecessary. Today, luminaires are designed to yield sufficient illumination across a target area while minimizing scatter, glare, and excessive power consumption. Unfortunately, it is not always easy to find these from among a market that continues to be dominated by poorly designed fixtures that are throwbacks to a more thoughtless age.

First, to design a efficient lighting system, it is necessary to understand why outdoor nighttime lighting is necessary in the first place. The purpose of outdoor lighting systems can be summed up in three basic goals:

- Lighting of roadways and sidewalks for way-finding and object avoidance;
- Safety of users; and
- Security against vandalism, thievery, and other crimes.

To address all three of these diverse purposes, the Illuminating Engineering Society of North America (IESNA) has established recommended lighting levels for outdoor lighting. Table 6 below summarizes their advice.

Table 6a. IESNA Recommended Lighting Levels: Roadway Lighting[10]

	Average Illuminance (footcandles)	Uniformity Ratio
Expressway/major divided highway	9	3:1
Major road	13	3:1
Secondary road	9	4:1
Local/residential road	4	6:1

Table 6b. IESNA Recommended Lighting Levels: Parking Lots[11]

	Average Illuminance (footcandles)	Minimum Illuminance (footcandles)	Uniformity Ratio
High level of activity (Athletic centers/shopping centers)	2	0.7	3:1
Medium level of activity (Hotel/hospital/office/condominium)	1	0.3	3:1
Low level of activity (Industrial/educational facilities/churches)	0.5	0.1	4:1

Table 6c. IESNA Recommended Lighting Levels: Other Areas[12]

	Average Illuminance (footcandles)
Building entrance (active)	5
Building entrance (inactive)	1
Vital Buildings (Power plants, sensitive areas)	5
Loading Platforms	20
Storage Yards (active)	20
Storage Yards (inactive)	1
Floodlit buildings and monuments (dark surroundings)	5

Many urban and suburban areas ignore this advice by assuming that if a little light is good, then more light is better. Studies by the International Dark-Sky Association and other agencies prove this to be a false assumption; indeed, too much light can be counterproductive. Many designers consider only quantity of light while ignoring quality.

A poor-quality lighting system will be plagued with overwhelming glare, wasted spill light (light trespass), and eclipsing shadows, all of which lead to poor transient adaptation. Direct glare is the major problem with most exterior lighting. Glare can cause annoyance, discomfort, and a loss of visibility. This results when a light source's luminance is much higher than the surroundings to which the eye has become accustomed, such as a brightly lit building set amongst dark surroundings.

Perhaps the most poignant example of these is seen while driving at night along a country road, when from around a bend, another car approaches. The overwhelming brightness of the car's headlights can temporarily blind the driver. This same effect can be witnessed when driving along poorly illuminated roads, alternately passing from under overly bright, ill-designed lights to areas of comparative darkness. In cases such as this, the eye will never becomes adjusted to the changing conditions. While glare and light spill can never be completely eliminated, well-designed fixtures with full cut-off shielding will go a long way to minimize the effect.

Another misconception is that an overabundance of exterior lighting will deter crime. A study conducted in 1977 by the National Institute of Law Enforcement and Criminal Justice for the United States Department of Justice (Appendix 2) concluded:

> *There is no statistically significant evidence that street lighting impacts the level of crime, [although] there is strong indication that increased lighting decreases the fear of crime.*[13]

Further, the International Dark-Sky Association indicates that poorly designed and executed lighting, resulting in glare and light misdirection, may actually compromise the very goals that the lighting system was supposed to achieve (Appendices 3 and 4)!

According to the IES Lighting Handbook[14], glare as it affects human vision may be divided into two categories: Disability Glare and Discomfort Glare. The former, also termed "blinding glare," refers to our reduced ability to perceive an object because of overlighting or poorly designed, misdirected lighting. Discomfort Glare results in annoyance and eye strain but does not affect an observer's ability to perceive an object. Factors affecting the amount of glare perceived by the eye include size and displacement angle of a light source, surround luminance, exposure time, and motion.

While it is not possible to eliminate disability and discomfort glare, it is possible to reduce their impact by proper distribution of the light flux from luminaires. The light radiating from luminaires must be directionally placed and apportioned according to the application, taking into account luminaire mounting height, overhang of the luminaires, longitudinal spacing of the luminaires, the amount of light directed toward the target area, and size of the target area.

To understand how glare and stray light pollution can waste energy, it is imperative to look at the characteristic distribution of luminous flux from a luminaire. These distribution values, usually expressed as a percentage of a luminaire's overall light output, represent the lumens distributed within a given zone, as illustrated in Figure 7.

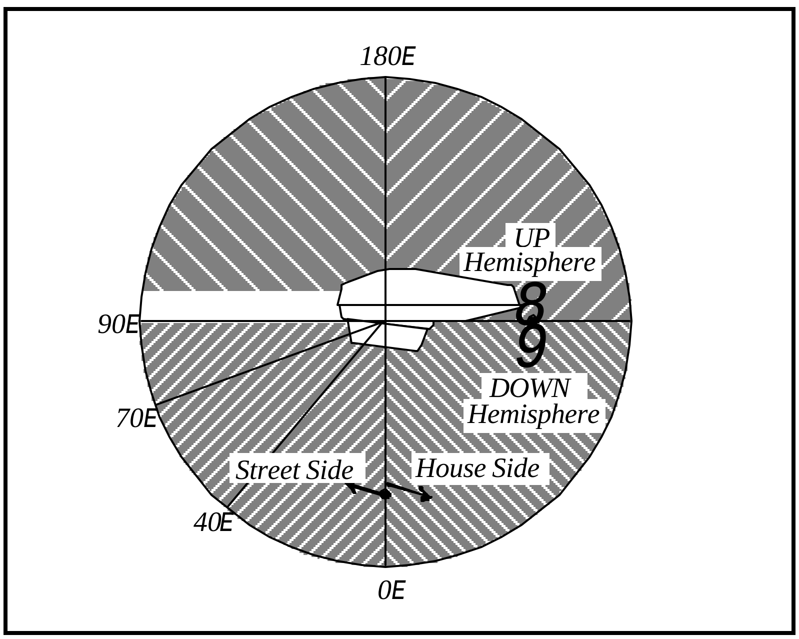

Figure 7. Distribution Terminology.

By reducing glare and light trespass, streets and walkways can be more efficiently illuminated at night while also lowering energy consumption.

Chapter 4: Case Study: Brookhaven National Laboratory

Brookhaven National Laboratory is located in the town of Brookhaven, approximately 60 miles east of New York City. The Laboratory's site was formerly used by the Army as a military camp during World Wars I and II, and as a Civilian Conservation Corps Camp in between. The land was transferred to the Atomic Energy Commission in 1947 for the establishment of BNL. Today, hundreds of individual buildings cover the site's 5,300 acres.

BNL is funded by the Department of Energy (DOE) and managed by Associated Universities Inc. (AUI), which is comprised of representatives from the Massachusetts Institute of Technology, University of Pennsylvania, University of Rochester, as well as Columbia, Cornell, Harvard, Johns Hopkins, Princeton, and Yale Universities.

The research conducted in the Laboratory's eight major research departments cover a broad spectrum of the physical, biomedical, and environmental sciences, as well as in energy technologies. The Laboratory was established to provide facilities for scientific research which, because of size, complexity, and mode of operation, were beyond the means of most single universities. These include two research-grade nuclear reactors, particle accelerators, and various engineering facilities. Throughout the Laboratory complex, emphasis is placed on interdisciplinary and interinstitutional cooperation and collaboration.

Present Outdoor Lighting System

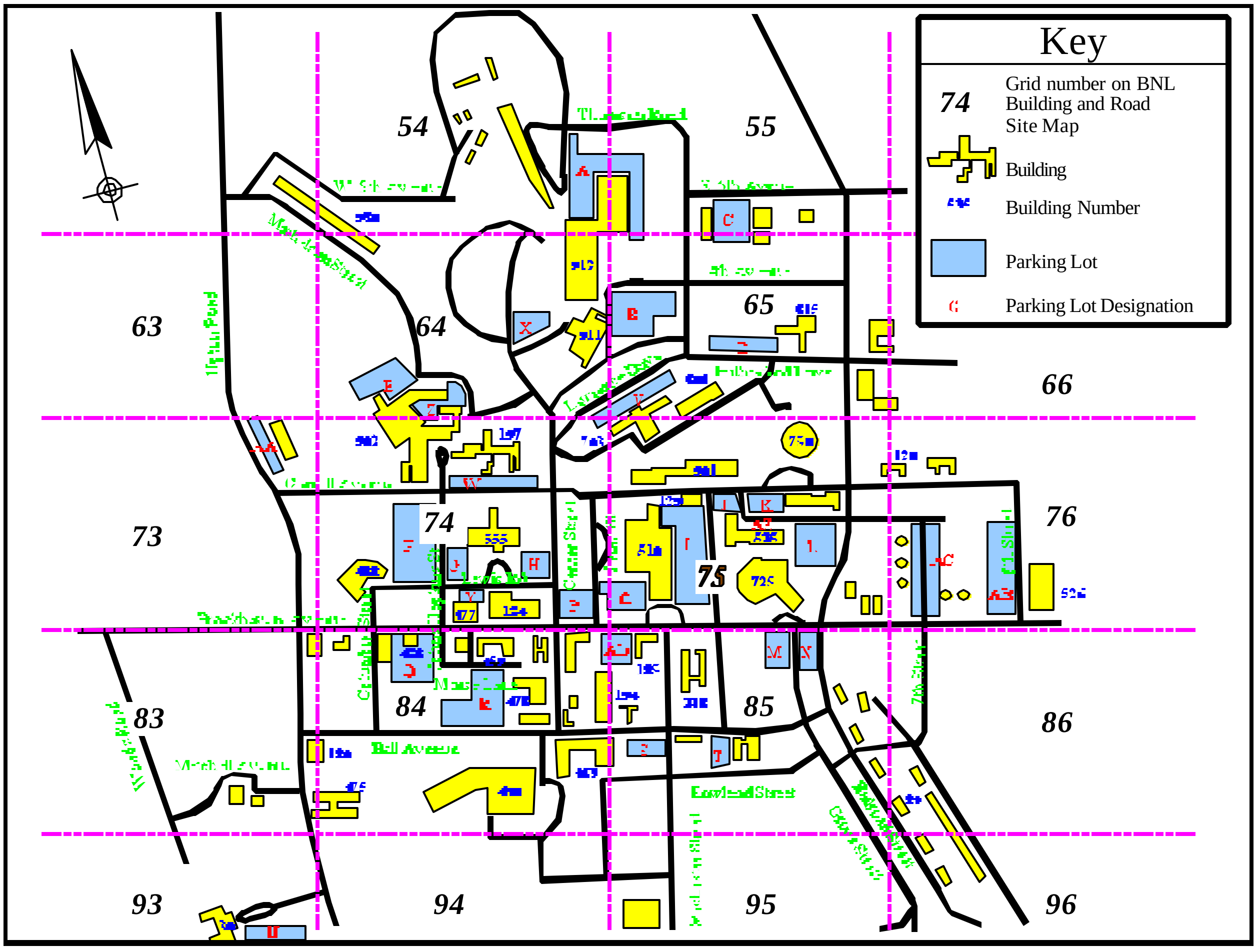

Figure 8. Site map of Brookhaven National Laboratory.

The Laboratory's major facilities, roads and parking facilities are lit at night by streetlights that are maintained by the Plant Engineering Division. In all, 373 luminaires light the roads and parking areas. Figure 8 is a general map showing the central portion of the Laboratory site. This map is overlaid with a grid system that corresponds to the grid layout used on Plant Engineering's site maps (see Appendix 5). Specific locations of all exterior lighting is highlighted on these latter site maps. This thesis restricts its measurement and evaluation to this portion of the Laboratory, for it is there that most of the nighttime lighting is located.

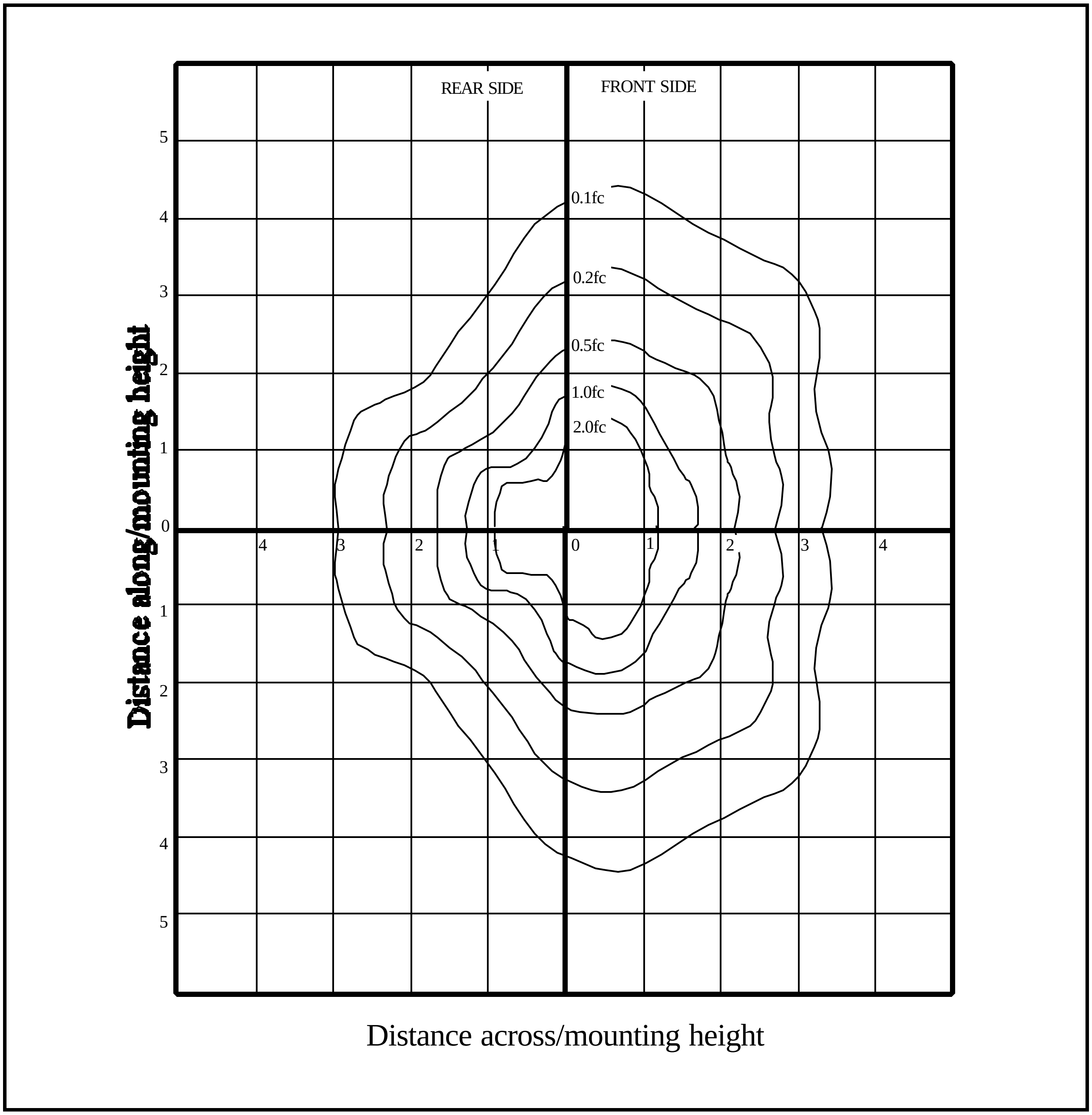

Figure 9. Horizontal isofootcandle diagram for 250-watt HPS Refractopack® luminaire. Based on data supplied by Holophane Company, Inc.

The most common luminaire used throughout the Laboratory is the 250-watt Refractopack® by Holophane Company, Inc., of Montvale, New Jersey. Figure 9 below is a horizontal isofootcandle chart of the 250-watt HPS Refractopack, based on information supplied by the manufacturer. The luminaire itself is located at the "0" point centered in the diagram. The numbers to either side of the 0 point (e.g., 1, 2, 3, etc.), as well as along the left y-axis, represent the horizontal distance away from the luminaire expressed in terms of a luminaire mounting height of 30 feet (therefore, 1 = 30 feet, 2 = 60 feet, and so on). The curved lines within the chart are the footcandle values found at those distances away from the luminaire. Therefore, at a distance of 40 feet, an illumination of approximately one footcandle can be expected. Holophane's sales literature for the Refractopack is include herewith as Appendix 6. The Refractopack is a vertical-burning HPS lamp that distributes more than ninety percent (90%) of its lumens to the side. As Figure 10 shows, the lamp's housing offers little cut-off and redirection of the light downward. Figure 11, based on manufacturer-supplied measurements recounted in Appendix 7, is a vertical isofootcandle diagram that further illustrates this characteristic by demonstrating that most of the light from the Refractopack radiates between 50E and 100E from the lamp's nadir. This latter graph plots vertical illuminance measured at several discrete horizontal angles as shown in the insert figure at upper right. Environmentally conscience full-cut-off luminaires have cut-off angles of 90E and below. The Refractopack, with its limited cut-off shielding, peaks at 70E, with as much as 35% of the light spilling wastefully above this accepted cut-off angle[15]. The

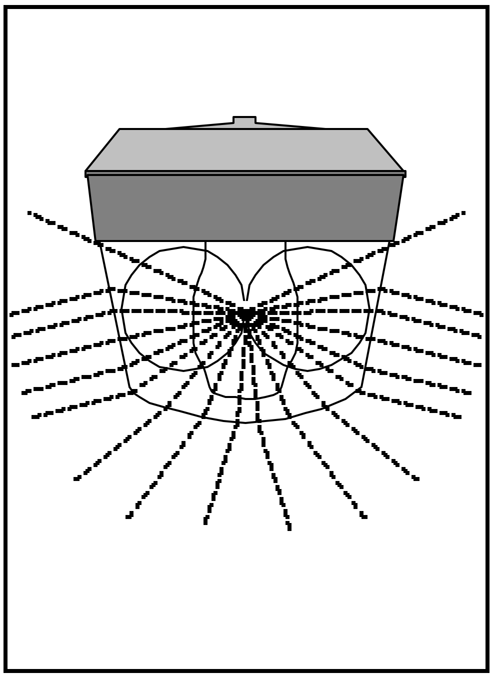

Figure 10. Distribution of illumination from Refractopack® luminaire. Note how most of the light is directed nearly parallel to the horizon.

high angular dispersement of the light from the Refractopack can also result in inordinately high amounts of debilitating glare, leading the

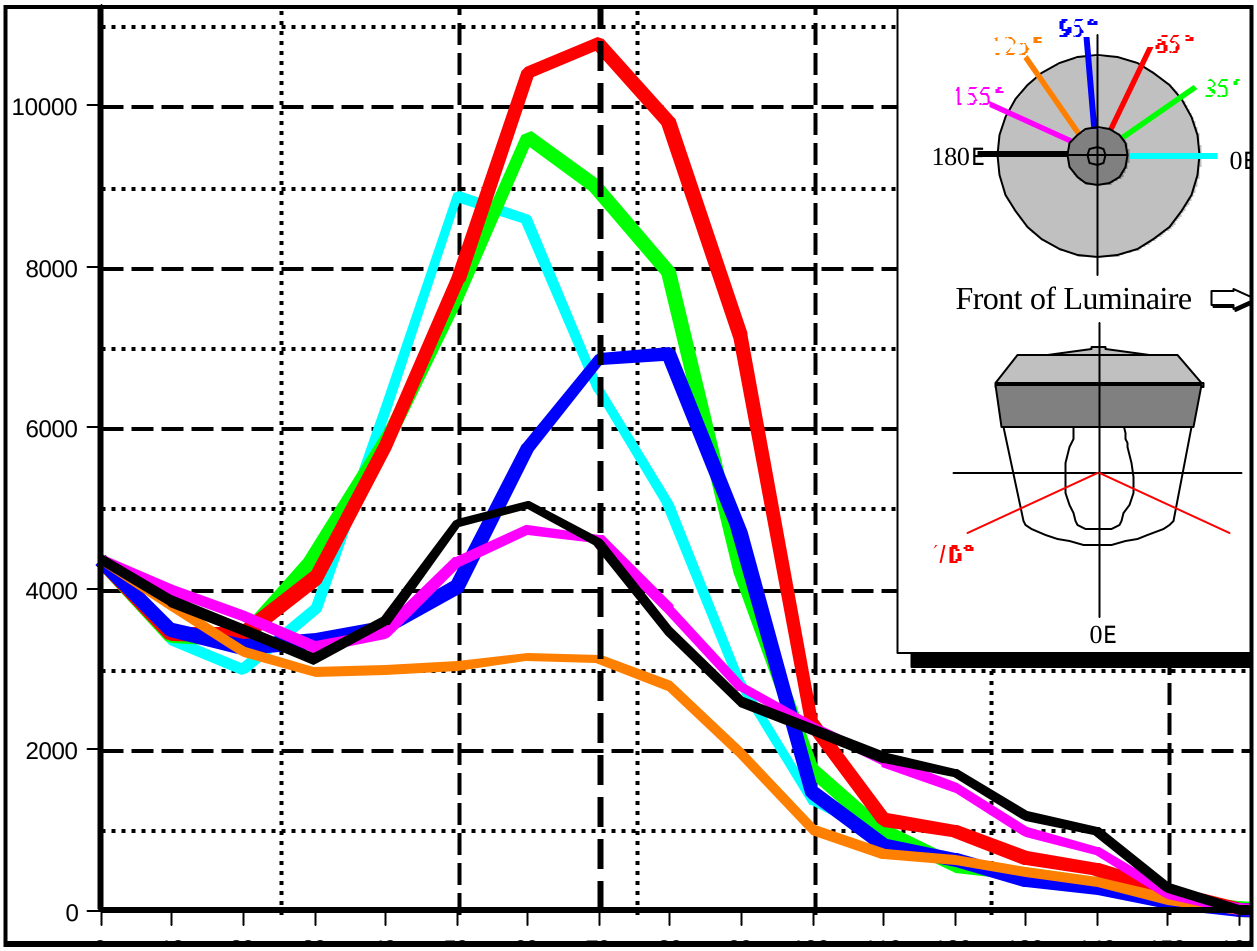

Figure 11. Vertical isofootcandle chart for the 250-watt Refractopack HPS luminaire.

International Dark-Sky Association to brand luminaires of this design as "very bad[16]" (Appendix 8).

Many of the buildings within the Laboratory complex are also illuminated with wall-mounted luminaires from Holophane's Wallpack® series. Like the pole-mounted luminaires, Wallpacks feature HPS lamps in lensed housings and are designed for perimeter and security lighting, task lighting, accent lighting as well as illumination of walkways. While Wallpacks come in versions that range from 35W LPS to 400W HPS, the Laboratory primarily uses the 250W HPS model (see Figure 12). The Wallpack housings are semi-cut-off in design, creating minimal light scatter above 90E. They do, however, project much of their light to the sides, compromising their ability to illuminate doorways, leading to a "bad" rating by the International Dark-Sky Association[17]. Holophane's sales literature for the Wallpack is include herewith as Appendix 9.

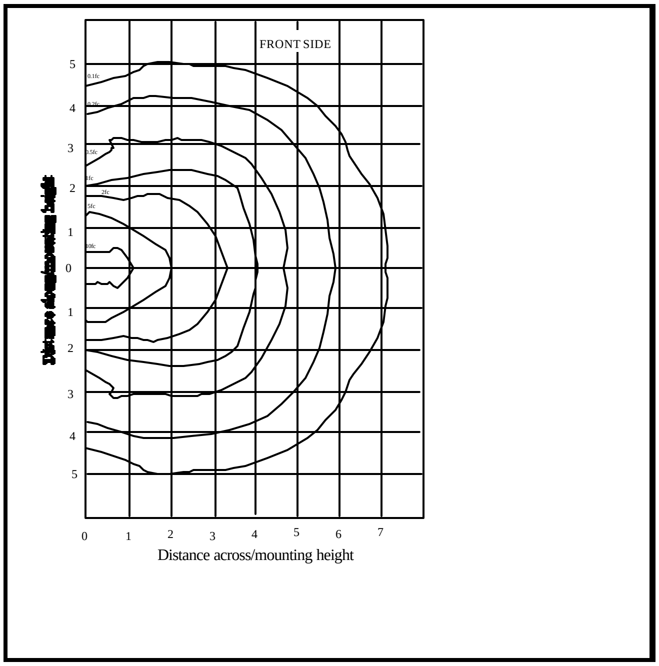

Figure 12. Isofootcandle chart for 250-watt HPS Wallpack luminaire

At the Laboratory's rate of 6.5¢ per kilowatt-hour, each 250-watt HPS Refractopack lamp on-site costs approximately $78 per year to operate, for a total of $17,784, while the 145 250-watt Wallpacks total $11,310 per year.

For this study, I surveyed each of the Laboratory's major parking lots and other lighted areas using a recently calibrated photometer. The instrument chosen was a Model IL1400A photometer and Model SCL110 photopic detector, both by International Light, Inc. of Newburyport, Massachusetts. As detailed in Appendix 10, these instruments are designed to respond to artificial illumination in much the same way as the human eye; that is, they are sensitive across the visible spectrum, with peak sensitivity around 580 nanometers. The IL1400A will read directly in footcandles, with an automatically adjusting dynamic range from 5×10^{-4} footcandles (fc; roughly equal to starlight on a moonless night) to $1\times10^{+5}$fc (direct sunlight).

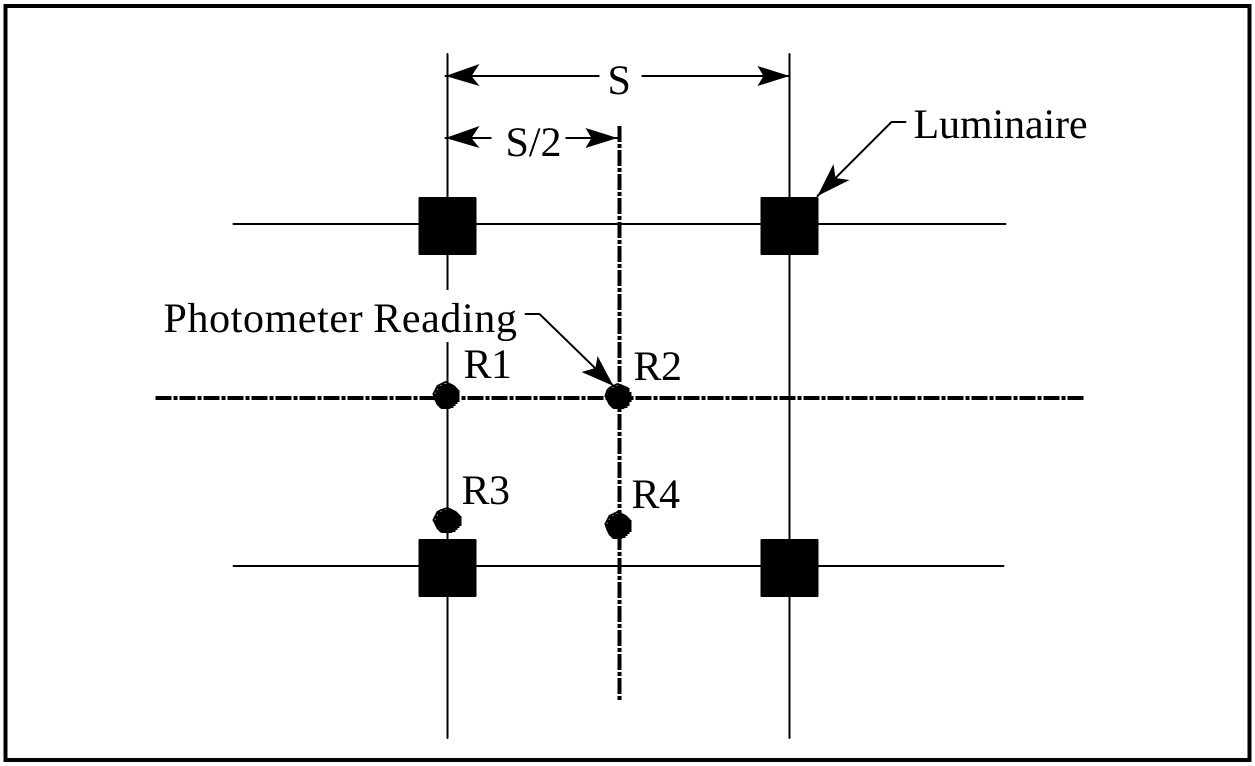

Figure 13. Typical locations of photometer reading points in parking lots

Following recommendations in Helms and Belcher[18], photometer readings were taken in each of the specified parking lots approximately following the pattern in Figure 13. All readings were made at least one hour after sunset to ensure that all luminaires were had reached normal operating conditions and that all ambient light measured came from the installed luminaires, not from remaining sunlight. Prior to each measurement, the photometer was zeroed to ensure accuracy and repeatability. Several readings were taken in each area, both immediately adjacent to luminaires as well as in central locations where there was the least amount of light. These readings were then collected, sorted, and averaged to arrive at the results shown in Table 7.

Table 7. Survey Results

Observation Point	Location	Maximum Illuminance (footcandles)	Minimum Illuminance (footcandles)	Uniformity Ratio
A	Bldg. 912 parking lot	2.0	1.0	2:1
B	Bldg. 911 parking lot	2.7	0.6	5:1
C	Bldg. 924 parking lot	2.5	0.6	4:1
D	Bldg 815 parking lot	2.3	1.0	2:1
E	Bldg. 902 parking lot (rear)	2.6	1.1	2:1
F	Bldg. 488 parking lot	2.8	0.8	4:1
G	Bldg. 555 parking lot	4.3	1.0	4:1
H	Bldg. 555 parking lot	3.2	1.1	3:1
I	Bldg. 129/510 parking lot	3.3	1.0	3:1
J	Bldg. 535 parking lot	2.4	0.2	12:1
K	Bldg. 535 parking lot	0.6	0.1	6:1
L	Bldg. 535/725 parking lot	4.8	1.5	3:1
M	Bldg. 725 parking lot	1.6	0.4	4:1
N	Bldg. 725 parking lot	4.2	0.7	6:1
O	Bldg. 510 parking lot	3.0	1.0	3:1
P	Bldg. 134 parking lot	3.1	1.0	3:1
Q	Bldg. 438 parking lot	4.2	0.7	6:1
R	Bldg. 478 parking lot	3.2	0.3	11:1
S	Bldg. 463 parking lot	3.2	0.5	6:1
T	Bldg. 452 parking lot	2.8	1.0	3:1
U	Bldg. 30 parking lot	5.3	0.8	7:1
V	Bldg. 703 parking lot	3.7	1.7	2:1
W	Bldg. 197 parking lot	2.7	0.4	7:1
X	Bldg. 911 parking lot	3.0	1.2	3:1

Y	Bldg. 477 parking lot	3.7	0.4	9:1
Z	Bldg. 902 parking lot (front)	2.4	0.9	3:1
AA	Bldg. 624 parking lot	2.9	0.9	3:1
AB	Bldg. 526 parking lot	3.9	1.1	4:1
AC	Tank area	3.6	0.2	18:1
AD	Bldg. 185 parking lot	2.6	0.7	4:1
AE	Bldg 535 loading dock	12.2	3.4	4:1

From these, it is clear that few of the Laboratory's parking areas meet the criteria recommended by the IESNA listed earlier in this paper. Most are dramatically over-illuminated, seemingly without regard to their purpose or level of activity. At the same time, the survey also demonstrates the severe lack of illumination uniformity, with ratio limits exceeding IESNA recommendations by more than 300%. The figures here point to the fact that a great deal of energy is being wasted by the ineffective and inefficient use of outdoor lighting.

Chapter 5: Recommendations

From the definitions provided in the IES Lighting Handbook, the level of nighttime activity in Laboratory's parking lots qualifies them as "industrial" in nature, requiring an average illuminance of 0.5 footcandles, a minimum of 0.1 footcandles of illuminance (4:1 uniformity ratio). Table 7 clearly demonstrates that neither standard is being adhered to in any of the Laboratory's parking lots.

Brookhaven National Laboratory needs a strategic lighting plan to illuminate the institution's grounds at night effectively and efficiently, but before that plan can be designed, it must first be determined where lighting is required, how much is necessary, and during which hours. The vast majority of Laboratory departments and divisions operate Monday through Friday with a work day that begins at 8:30 a.m. and ends at 5:00 p.m. On any given weekday, most of the employees have left the site by 5:30 p.m., leaving behind a minimal numbers of cars and traffic. The lighting in the parking lots and around buildings, however, stays on throughout the night, even though few employees are around to benefit from it.

According to the United States Naval Observatory's Astronomical Almanac[19], the earliest sunset at Brookhaven National Laboratory occurs at 4:18 p.m. on December 20. Further, the sun sets at or before 5:00 p.m. from approximately October 25 to January 28, a total of 96 days; on the remaining days of the year, the sun sets after 5:00 p.m. local time. Most outdoor lighting in parking lots and along sidewalks is designed to turn on within ten minutes of sunset, to help the eye's slow transition between day and night vision.

From this, it is clear that for most of the year, outdoor lighting at the Laboratory is not necessary for the safe passage of employees from building to building and off-site after work. Indeed, the unbridled use of most of the Laboratory's 228 HPS Refractopack streetlights and 145 building-mounted Wallpacks serves little purpose. Therefore, the first recommendation of this report is to determine which luminaires are necessary and which are not, and to eliminate as many as practicable. It should be emphasized up front that, although not all the recommended substitutions may be possible in all locations due to security concerns and other overriding factors, some consideration should be given to more energy-efficient, environmentally friendly lighting options. Three viable options are discussed below.

<u>Proposition One</u>

An initial savings in energy could be realized by simply downsizing the lamps in each luminaire from 250 watts to 150 watts. Given the parameters cited earlier, a 150-watt HPS luminaire consumers energy at a rate of 791 kilowatt-hours per annum. This is a savings of 34.4% over the energy consumed by an equivalent 250-watt luminaire. To better illustrate and comprehend the importance of this impact, these figures need to be expanded to a site-wide scale. If each of the 228 HPS Refractopack streetlights currently in use around the site were replaced with 150-watt HPS luminaires, the Laboratory would realize an energy savings of 94,392 kilowatt-hours per annum. Converting this to dollars and cents, this change would realize the Laboratory an annual electric-bill savings of $6,100. An additional savings of 60,030 kilowatt-hours, or $3,900, could be enjoyed by replacing the 250-watt HPS lamps in the 145 WallPack luminaires with 150-watt lamps. Together, the Laboratory would save 154,422 kilowatt-hours, or $10,000, each year while still meeting, or exceeding, IESNA recommendations.

This substitution does not, however, address the issue of glare. Lacking cut-offs, the Holophane luminaires are fraught with excess glare that can potentially blind oncoming motorists. To reduce this danger as well as to illuminate target areas more effectively, a full cut-off fixture should be substituted for the Holophane Refractopack streetlights. A full cut-off luminaire permit lowering the overall wattage of the luminaire while still providing nighttime illumination within IESNA criteria. Two possible substitutes are the RM series from Hubbell Lighting, Inc. and the RML luminaires by Stonco Lighting, Inc. Each features an HPS lamp set in a full-cut-off fixture that eliminates spill light from shining wastefully toward the horizon and upper hemisphere. Both are available in wattages ranging from 70 to 250 watts.

Figure 14 compares the horizontal isofootcandle diagrams of the 150-watt Refractopack to Hubbell's RM-150, 150-watt HPS luminaire (Appendix 11). Note the amount of ground illumination directly under each luminaire is approximately equal, but that the Hubbell is between 28% and 50% greater than the Refractopack toward the fringes because of its more efficient design. Figure 15, based on

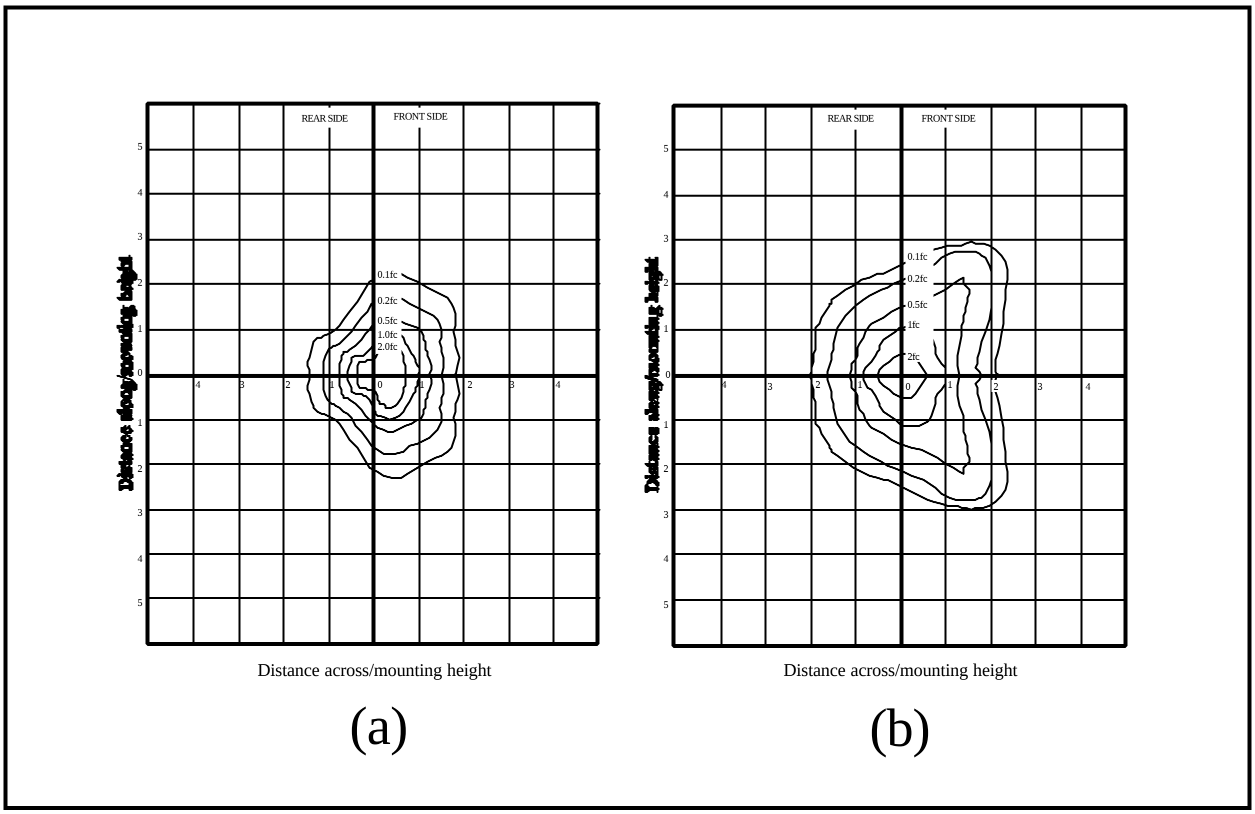

Figure 14. Isofootcandle diagrams for (a) 150-watt Holophane Refractopack and (b) Hubbell RM-150 HPS luminaires.

manufacturer-supplied measurements recounted in Appendix 12, shows the Hubbell's vertical distribution, which clearly shows that all of the light is directed downward, eliminating any spill light at or above 90E. This is in sharp contrast to the Holophane Refractopack luminaires currently installed at the Laboratory, where each casts as much as 35% of its available light above 90E.

Another potential substitute for the Laboratory's pole-mounted streetlights is the RML series of

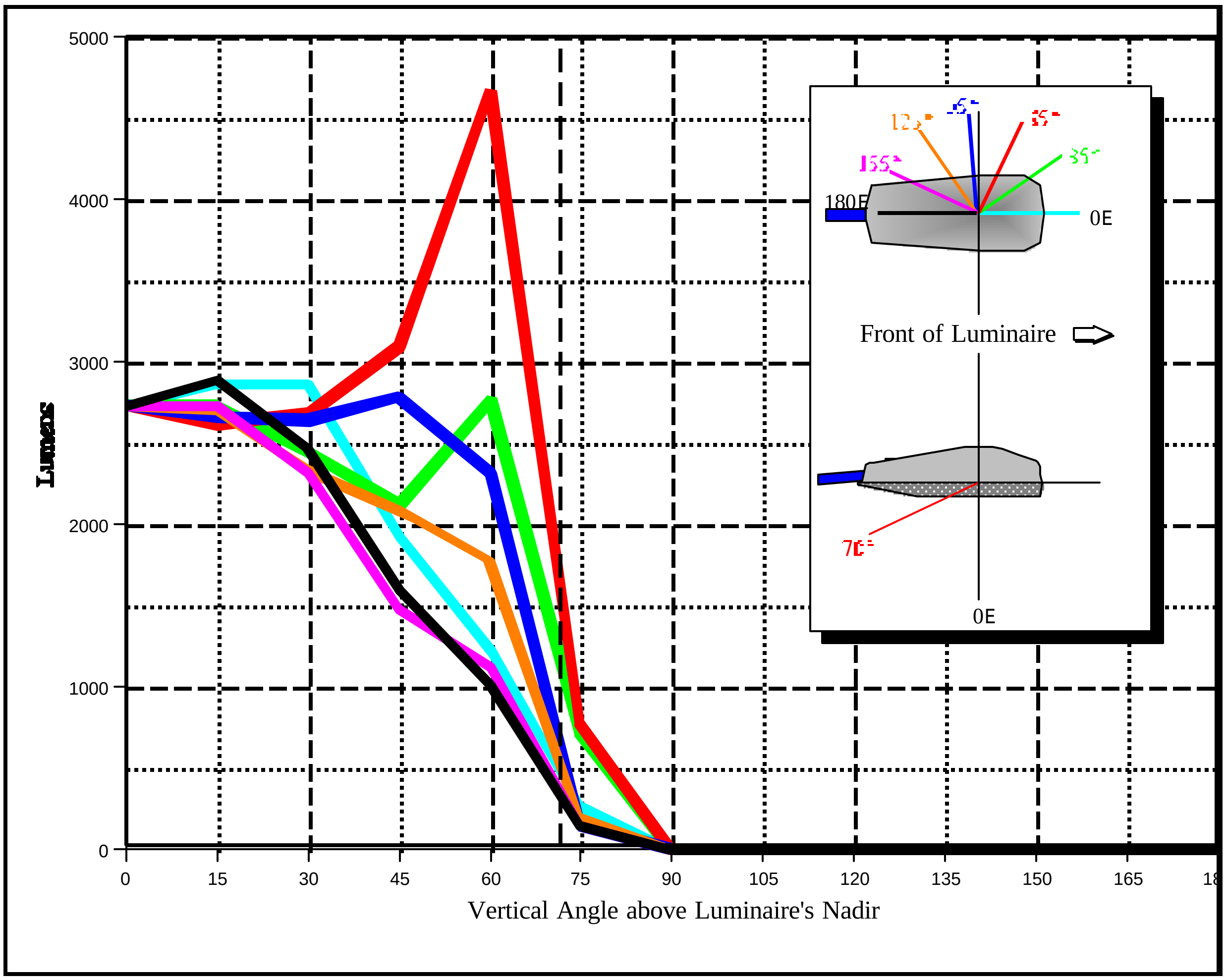

Figure 15. Vertical distribution of light from the Hubbell RM-150 full-cutoff luminaire.

roadway luminaires manufactured by Stonco, Inc. of Union, New Jersey. Like the RM-150 by Hubbell, Stonco's RML series feature full cut-off housings and are available from 150 to 400 watts (Appendix 13). Figure 16 shows the horizontal isofootcandle diagram of the RML4150LX, 150-watt HPS luminaire, while Figure 17 shows a characteristic slice of its vertical light distribution.

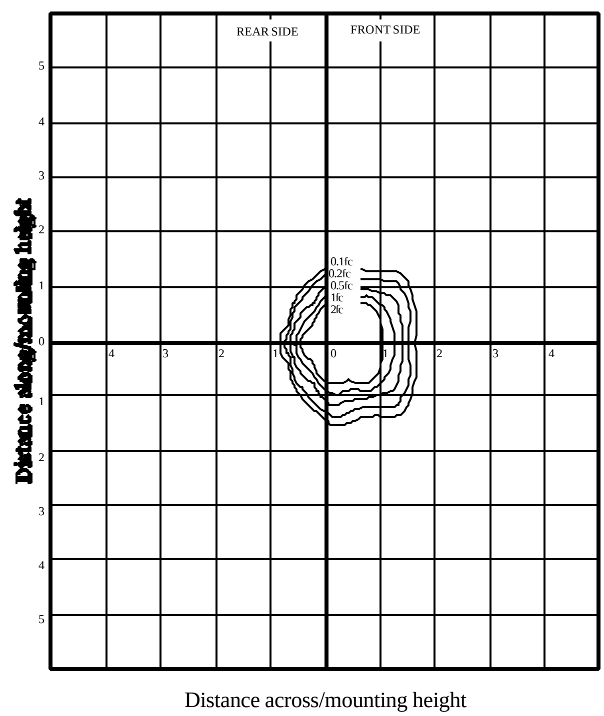

Figure 16. Isofootcandle diagram of the Stonco RML4150LX luminaire.

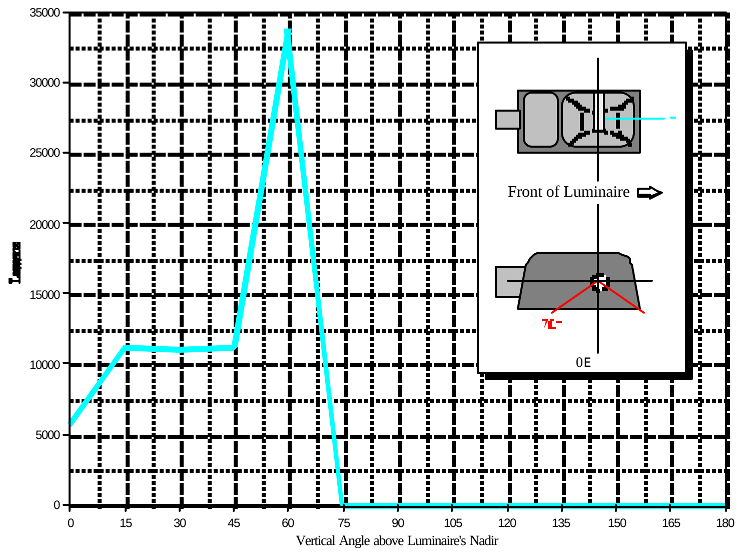

Figure 17. Vertical isofootcandle diagram of the Stonco RML4150LX luminaire.

Light cut-off from the Stonco luminaire is even more restricted than with the Hubbell. As Figure 17 shows, no light is projected at angles greater than 75E above the lamp's nadir. This restriction permits the light to be focused more precisely, though the narrower throw may restrict its usefulness in areas where broader coverage is required. This narrow cast of light, however, would lead to insufficient lighting in many of the parking areas due to the broad gaps between the light poles, making total conversion to the Stonco fixture impractical. It may, however, be a better choice where light poles are closely set, such as Parking Lots I, L, M, N, O, P, and AB (see Figure 8, previous).

Consideration of replacing luminaires currently installed through Brookhaven National Laboratory cannot be adequately accessed without taking into account the cost of a new luminaire. At the time of this writing, each 150-watt luminaire, complete with ballast and all necessary accessories, retails for approximately $150, with discounts available for quantity orders. If all 228 roadway luminaires were to be replaced at the same time, and without possible discounts into consideration, the cost to the Laboratory would be $34,200. As a result of this initial investment, cost savings would not realized until the third year after conversion, although energy savings as well as increased motorist safety would be effective immediately.

Similarly, the wall-mounted Wallpacks could be replaced with full-cutoff fixtures, such as the PR series of area cutoff floodlights from Ruud Lighting of Racine, Wisconsin (Appendix 14). As Figure 18 shows, these luminaires are designed to direct all of their light downward, below 80E, thereby eliminating unwanted glare. At present, these wall-mounted 150 HPS luminaires (catalog number MPRW515-M) retails for $149 per luminaire, with a lab-wide replacement program costing $21,605. Again, because of the initial investment, cost savings would not be realized until the third year after conversion.

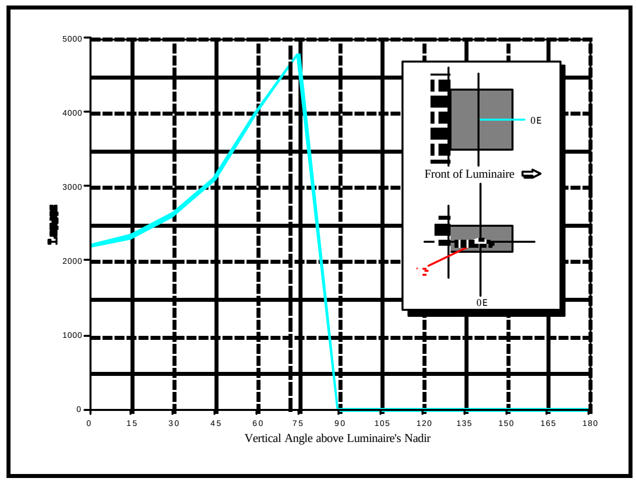

Figure 18. Vertical isofootcandle diagram of the Ruud MPRW515-M luminaire

This report is not meant to suggest that immediate replacement of all 373 HPS luminaires should be effected. Instead, a program of replacement-by-attrition should be implemented. As a luminaire's housing becomes damaged, it should be replaced by a more energy-efficient, full cut-off fixture like those described herein. Though this replacement program might take several years to effectuate, it would seem a more sensible, cost-effective alternative to replacing all luminaires in a short period.

Proposition Two

In areas where security concerns exist or where total elimination of lighting is not possible, the luminaires should be outfitted with industrial-quality motion sensors. The long restrike times of HPS luminaires make it impractical to turn the lamps off completely when not in use, as popular incandescent home units do. Instead, HPS lamps are outfitted with sensors that automatically increase and decrease the luminaires' output. When motion is detected, turn on a luminaire for a prescribed length of time whenever an object moves within the sensor's area of influence. Once the motion ceases, the sensor turns the light off until motion is once again detected. These could serve the needs of security and after-hours building personnel, while still contributing to the Laboratory's overall energy-conservation program.

Ruud Lighting manufactures roadway luminaires equipped with integrated bi-level motion sensors. According to the manufacturer-supplied information in Appendix 15, a 250-watt HPS lamp requires 305 watts to operate at its nominal light output, but only 134 watts in its "powered-down" mode, a savings of 171 watts. Assume that each lamp operates an average of 11.23 hours per day, but because of the limited nighttime activity level, only requires peak power 25% of that time. Given the cost of electricity cited earlier in this paper, the Laboratory would save 301 kWh, or $19.57, per year per luminaire ($47.10 versus $66.61). If each of the Laboratory's 373 building and roadway luminaires were outfitted with a bi-level motion sensor, the total savings enjoyed would be 111,956 kWh or $7,277 per year.

WideLite, a subsidiary of Genlyte Corporation offers a similar bi-level system that, unlike the Ruud system, can be retrofit onto existing luminaires (Appendix 16). The bi-level sensor can be attached to luminaires either by direct wiring or by fiber optics, thereby greatly increasing installation flexibility. Both the Ruud and WideLite systems are designed not to shorten the life expectancy of the effected lamps.

Substantial savings would be realized by downgrading each luminaire to 150 watts and installing bi-level motion sensors. Again, if each of the 373 luminaires currently in use at Brookhaven National Laboratory was converted to a 150-watt, bi-level lighting unit (maximum power consumption: 190 watts, minimum power consumption: 70 watts), the electricity used to power each luminaire would be 410 kWh per year, a 60% savings in electricity over the current lighting system. At the current rate of 6.5¢/kWh, the total annual cost of power consumption used for outdoor lighting would be reduced by $14,908.

Proposition Three

Additional savings may be expected by eliminating some roadway and parking lot luminaires altogether. Table 8 itemizes these potential savings by percentage of eliminated *roadway* luminaires only (e.g., leaving all building-mounted luminaires in place).

Table 8. Energy Savings versus Luminaire Elimination

Percentage of Roadway Luminaires Eliminated (Actual Number of Eliminated Luminaires)	Annual Energy Savings	Annual Cost Savings
5% (19)	22,895 KWH	$1,500
10% (37)	44,585 KWH	$2,900
20% (75)	90,375 KWH	$5,900

30% (112)	134,960 KWH	$8,800
40% (149)	179,545 KWH	$11,700

Conclusion

From the evidence presented in this paper, it is clear that a large percentage of nighttime lighting, and therefore energy, is being needlessly wasted by today's society. With comparatively simple planning and investigation, improvements in roadway lighting systems, whether they be for lighting rural farm roads, mall and shopping-center parking lots, or industrial spaces, will yield a substantial savings of energy and, therefore, public and private dollars.

Specifically, Brookhaven National Laboratory must assess the need for nighttime lighting throughout the facility's parking areas and buildings. From this investigation, it is evident that many of the Laboratory's buildings and parking areas are over-illuminated for the amount of after-dark activity that they see. Through a phased-in program of reduced and eliminated lighting, the Laboratory may expect to save between 154 megawatt-hours ($10,000) and 230 megawatt-hours ($15,000), or even more each year, an important cost-cutting measure in these times of reduced operational budgets. Moreover, with more efficiently designed luminaires, the disabling glare associated with the existing lights along the Laboratory's streets and byways would be eliminated, thereby promoting safer driving conditions.

Appendices

Appendix 1. Definitions

- Accent lighting: lighting used to emphasize or draw attention to a special object or building.
- Ambient light: the general overall level of lighting in an area.
- Bulb: source of electric light from within a lamp or luminaire.
- Burning cycle: the length of time that a lamp will be turned on during an average day of operation.
- Coefficient of Utilization (CU): ratio of lumens from a luminaire received on the work plane to the total lumens emitted by the luminaire in all directions.
- Cosine Law: illuminance on a surface varies as the cosine of the angle of incidence of the light.
- Cut-off angle (of a luminaire): the angle, measured from a luminaire's nadir (straight down) up to the first point at which the light source is not visible.
- Cut-off fixture: a fixture designed to prevent light from shining above a specified cut-off angle.
- Efficacy: the energy efficiency of a lighting system, rated in lumens per watt.
- Energy (radiant energy): power expressed in ergs, joules, or kilowatt-hours (KWH).
- Fixture: the assembly for a lighting system, composed of the bulb, shield, ballast, housing, and the attachment parts.
- Floodlight: a fixture designed to "flood" a well-defined area with light.
- Footcandle: illuminance produced on a surface one foot from a uniform point source, and expressed as lumens per square foot.
- Full-cut-off fixture: A fixture designed to emit zero light emission above the horizontal plane through its bulb.

- Glare: intense and/or blinding light, resulting in reduced visual performance and visibility, often accompanied by discomfort.
- High-Intensity Discharge (HID) lamp: any of several types of lamps that produce light by the passage of an electrical current through a gas. Examples include mercury, metal-halide, and high-pressure sodium lamps.
- High-Pressure Sodium (HPS) lamp: HID lamp where radiation is produced from sodium vapor at relatively high partial pressure. Characterized by orange-gray color.
- Incandescent lamp: lamp that produces light from a metal filament heated to a high temperature by an electric current.
- Intensity: degree or amount of energy or light.
- Inverse-Square Law: illuminance at a point varies directly with the intensity of a point source and inversely as the square of the distance from the source.
- Light Pollution: light shining from a luminaire up into the sky (see also light trespass).
- Light Trespass: light falling where it is neither wanted nor needed (see also light pollution).
- Low-Pressure Sodium (LPS) lamp: HID lamp where radiation is produced from sodium vapor at relatively low partial pressure. Characterized by yellow color.
- Lumen: unit of luminous flux, the flux emitted by a point source with a uniform luminous intensity of one candela.
- Luminaire: a complete lighting unit, including the bulb, fixture, and other parts.
- Mercury-Vapor lamp: HID lamp where light is produced by radiation from mercury vapor. Characterized by blue color.

- Metal-Halide lamp: HID lamp where light is produced by radiation from metal-halide vapors. Characterized by white color.
- Mounting height: height of a luminaire above the ground.
- Nanometer: unit of measure frequently used to express the wavelength of light. One nanometer (nm) equals 10^{-9} meter.
- Operating life: The anticipated length of time that a lamp will emit light, based on laboratory testing.
- Operating hours per year: The length of time that a lamp will be energized during a 52-week period. Studies conducted by the International Dark-Sky Association indicate that, on average, a streetlight is on for 4,100 hours per year (11.23 hours per day).
- Photometry: the quantitative measurement of light distribution and level.
- Semi-cut-off fixture: a fixture that provides some cut-off of stray lighting, but less than a full-cut-off fixture.
- Stray light: radiated light from a fixture that falls away from the desired area. See also light trespass.
- Task lighting: lighting designed for a specific purpose or task.
- Transient adaptation: the eye's attempt to adjust to rapidly changing levels of light.
- Uniformity ratio: the ratio of the most brightly lit portion of an area (typically a parking lot) to the dimmest.

Appendix 2. US Department of Justice Study of Street Lighting and Crime

Appendix 3. Control of Outdoor Lighting at Wesleyan University

Appendix 4. Dark Campus Programs Reduces Vandalism and Save

Appendix 5. Brookhaven National Laboratory Building and Road Site Map

Appendix 6. Holophane Refractopack Technical Information Bulletin

Appendix 7. Holophane Refractopack Photometric Report

Appendix 8. Good Lights S Bad Lights

Appendix 9. Holophane Wallpack Technical Information Bulletin

Appendix 10. International Light Photometer IL1400A Technical Information Bulletin and Operating Instructions

Appendix 11. Hubbell RM-150 Technical Information Bulletin

Appendix 12. Hubbell RM-150 Photometric Report

Appendix 13. Stonco RML Series Technical Information Bulletin

Appendix 14. Ruud Lighting PR Series Technical Information Bulletin

Appendix 15. Ruud Lighting Two-Level Lighting System Technical Information Bulletin

Appendix 16. WideLite Lighting Two-Level Lighting System Technical Information Bulletin

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