NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Electrical and Electronic Engineering

ILLUMINATION AND LIGHTING DESIGN

Graduation Project
EE - 400

Student: Mohammad Abu Zahrah (971232)

Supervisor: Prof. Dr. Haldun GÜRMEN

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I would like to thank all people who helped me in doing this project specially my supervisor Prof. Dr. Haldun GÜRMEN.

Dedication

To both my parents...
Subhi & Heyam

ABSTRACT

This project contains general information about about illumination and lighting design. Lighting design is the main subject in the project and it include outdoor lighting design, sport light design, design guide for specific sport.

For football field lighting, C, γ angels are used to determine the illuminance at each point on the field.

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CHAPTER ONE

LIGHT

1.1 Introduction

electromagnetic radiation that can be detected by the human eye. In terms of wavelength, electromagnetic radiation occurs over an extremely wide range, from gamma rays with a wavelength of 3 10^{-14} centimetre to long radio waves measured in millions of kilometres. In that spectrum the wavelengths visible to humans occupy a very narrow band, from about 7 10^{-5} centimetre (red light) down to about 4 10^{-5} centimetre (violet). The spectral regions adjacent to the visible band are often referred to as light also, infrared at the one end and ultraviolet at the other. The speed of light in a vacuum is a fundamental physical constant, the currently accepted value of which is exactly 299,792,458 metres per second, or about 186,282 miles per second (299,792 kilometres per second).

Light, a basic aspect of the human environment, cannot be defined in terms of anything simpler or more directly appreciated by the senses than itself. Light, certainly, is responsible for the sensation of sight. It is propagated with a speed that is high but not infinitely high. Physicists are acquainted with two methods of propagation from one place to another, as (1) particles and as (2) waves, and for a long time they have sought to define light in terms of either particles or waves. In the early 19th century a wave description was favoured, though it was difficult to understand what kind of wave could possibly be propagated across the near.vacuum of interstellar space and with the extremely high speed of almost 300,000 kilometres per second. In the latter half of the 19th century a British physicist, James Clerk Maxwell, showed that certain electromagnetic effects could be propagated through a vacuum with a speed equal to the measured speed of light. Thus, in the second half of the 19th century, light was described as electromagnetic waves. Such waves were visualized as analogous to those on the surface of water (transverse waves) but with an extremely short wavelength of about 500 nanometres (one nanometre is 10^{-9} metre). The analogy is valid up to a certain point but the experimental results obtained at the end of the 19th century and in the early years of the 20th century revealed properties of light that could not have been predicted from knowledge that was obtainable about other waves. These results led to the quantum theory of light, which in its primitive form asserted that, at least in regard to its emission and absorption by matter, light behaves like particles rather than waves. The results of certain important experiments on the spreading of light into shadows and other experiments (on the interaction of beams of light) that supported the wave theory found no place in a particle theory. For a time it was believed that light could not be adequately described by analogy with either waves or particles..that it could be defined only by a description of its properties. A reconciliation of wave and particle concepts did not emerge until after 1924.

Two properties of light are, perhaps, more basic and fundamental than any others. The first of these is that light is a form of energy conveyed through empty space at high velocity (in contrast, many forms of energy, such as the chemical energy stored in coal or oil, can be transferred from one place to another only by transporting the matter in which the energy is stored). The unique property of light is, thus, that energy in the form of light is always moving, and its movement is only in an indirect way affected by motion of the matter through which it is moving. (When light energy ceases to move, because it has been absorbed by matter, it is no longer light.)

The second fundamental property is that a beam of light can convey information from one place to another. This information concerns both the source of light and also any objects that have partly absorbed or reflected or refracted the light before it reaches the observer. More information reaches the human brain through the eyes than through any other sense organ. Even so, the visual system extracts only a minute fraction of the information that is imprinted on the light that enters the eye. Optical instruments extract much more information from the visual scene; spectroscopic instruments, for example, reveal far more about a source of light than the eye can discover by noting its colour, and telescopes and microscopes extract scientific information from the environment. Modern optical instruments produce, indeed, so much information that automatic methods of recording and analysis are needed to enable the brain to comprehend it.

From the standpoint of wave motion, blue light has a somewhat higher frequency and shorter wavelength than red. In the quantum theory, blue light consists of higher energy quanta than the red.

The subject of light is so wide and its associations are so numerous that it cannot be accommodated within one article of reasonable length. There are three main divisions of the subject of light: physical optics, physiological optics, and optical instrumentation. This article deals primarily with physical optics, treating the nature and behaviour of light. It also discusses the interaction of light with matter. Although electromagnetic theory is considered here, further elucidation may be obtained in the article electromagnetic radiation. The article photoreception includes the physiological and psychological aspects of light, while the article optics treats the practical application of light. The experimental evidence that led to the quantum theory of radiation is included in the present article along with a brief statement of some of the basic ideas. The quantum theory of radiation, however, is so closely associated with the quantum theory of matter that the two must be considered together, as is done in the article quantum mechanics.

1.2 Historical survey

From 500 BC to AD 1650

In this period, there were innumerable confusions and false starts toward an understanding of light. Sometimes an idea was stated, though not clearly, and then almost forgotten for centuries before it reappeared and was generally accepted. The uses of plane and curved mirrors and of convex and concave lenses were discovered independently in China and in Greece. References to burning mirrors go back almost to the start of history, and it is possible that Chinese and Greek knowledge were both derived from a common source in Mesopotamia, India, or Egypt. The formulation of general empirical laws and of speculation about the theory of light derives mainly from Mediterranean (Greek and Arab) sources. Pythagoras, Greek philosopher and mathematician (6th century BC), suggested that light consists of rays that, acting like feelers, travel in straight lines from the eye to the object and that the sensation of sight is obtained when these rays touch the object. In this way, the more mysterious sense of sight is explained in terms of the intuitively accepted sense of touch. It is only necessary to reverse the direction of these rays to obtain the basic scheme of modern geometrical optics. The Greek mathematician Euclid (300 BC), who accepted the Pythagorean idea, knew that the angle of reflected light rays from a mirror equals the angle of incident light rays from the object to the mirror. The idea that light is emitted by a source and reflected by an object and then enters the eye to produce the sensation of sight was known to Epicurus, another Greek philosopher of Samos (300 BC). The Pythagorean hypothesis was eventually abandoned and the concept of rays travelling from the object to the eye was finally accepted about AD 1000 under the influence of an Arabian mathematician and physicist named Alhazen.

Angles of incidence and of refraction..*i.e.*, the change in direction of a light ray going from one transparent medium to another..were measured by an astronomer, Ptolemy, in the 1st century in Alexandria. He correctly deduced that the ray is bent toward the normal (*i.e.*, the direction perpendicular to a boundary plane, such as the plane separating air and water) on entering the denser medium. A Dutchman, Willebrord van Roijen Snell, discovered the so.called sine law that gives the index of refraction (a measure of the change in direction) for light in a transparent medium. The laws of reflection and refraction were brought together by a 17th.century French mathematician, Pierre de Fermat, who postulated that the rays of light take paths that require a minimum time. He assumed that the velocity of light in a more dense medium is less than that in a less dense one in the inverse ratio of the indices of refraction.

The idea of rectilinear propagation of light..that is, that it travels in a straight line..was applied in a practical sense to drawing and painting long ago. Euclid was familiar with the basic idea, but the main theory was developed by Leonardo da Vinci, and a complete description of shadows was given by the Danish astronomer Johannes Kepler in 1604. Kepler also was the first to apply the laws of rectilinear propagation to photometry (the measurement of light intensities).

From 1650 to 1895

At the beginning of this period, the result of the conflict between the corpuscular theory and the wave theory was in doubt. At the end of the period, the wave theory was generally accepted and seemed capable of explaining all known optical phenomena though, with hindsight, it can now be seen that there were some important difficulties.

Diffraction..*i.e.*, the spreading of light into shadows..was first observed in Italy in the 17th century. In England, a worker, who independently noticed diffraction, also observed the interference colours of thin films, which are commonly seen today in an oil film on a wet road surface or in the iridescent colours of a butterfly's wing. He believed that light consists of vibrations propagated at great speed. Christiaan Huygens, of Holland, greatly improved the wave theory. In England, Sir Isaac Newton did not attach much importance to the small amount of spreading of light, and he knew that strictly rectilinear propagation could not be reconciled with the wave theory. Polarization phenomena (which can be accounted for by transverse wave motion in a single plane) discovered in the 17th century by a Danish physicist, Erasmus Bartholin, and by Huygens were not consistent with the theory of longitudinal waves (waves vibrating in the direction of propagation, like compression waves in a coiled spring), which was the only wave theory then considered. Newton therefore supported the corpuscular theory, although he did not reject the wave theory completely. He accepted a concept of a luminiferous ether, and he postulated that the particles had "fits of easy reflection" and "fits of easy transmission"; *i.e.,* he assumed that they changed regularly between (1) a state in which they were reflected at a glass surface and (2) a state in which they were transmitted. He thus introduced periodicity..one of the basic ideas of wave theory..in a form that anticipates the quantum mechanics. Newton, using a glass wedge, or prism, discovered that white light can be separated into light of different colours and took the first steps toward a theory of colour vision.

In the century following his death the great authority of Newton was quoted to uphold the corpuscular theory and to oppose the wave theory in a way that he probably would not have approved. It was not until the 19th century that the work of Thomas Young of England; Augustin.Jean Fresnel, François Arago, and Armand.Hippolyte.Louis Fizeau, all of France; Irish scientist Humphrey Lloyd; and German physicist Gustav Kirchhoff established the transverse.wave concept of light; *i.e.,* light is a wave vibration at right angles to the direction of travel. A universal medium pervading all space and called the ether was supposed to be some kind of elastic solid. This made it possible to accept the transmission of light through a vacuum, but there was no completely satisfactory theory of the ether or of the way in which light is modified by transparent materials like glass. The necessity for an elastic solid disappeared when Maxwell proposed an electromagnetic theory of light. He stated the laws of electromagnetism in a clear mathematical form and generalized the concept of an electric current. From his equations he predicted the existence of transverse electromagnetic waves having a constant speed *c in vacuo*. The constant *c* had a value of 300,000 kilometres per second and was derived from measurements on electrical circuits. It was known from the work of Ole Rømer, a Danish astronomer; Jean.Bernard.Leon Foucault of France; and others that the velocity of light was not much different from the velocity constant *c*. A.A. Michelson, a physicist in the United States, measured the velocity of light and showed that it is equal to *c* within a small margin of experimental error. This result, together with the work of a German physicist (Heinrich Rudolf Hertz) on electromagnetic waves of larger wavelength, confirmed Maxwell's predictions. The existence of a connection between electromagnetism and light had, indeed, been demonstrated in England much earlier in the century by Michael Faraday, who observed the rotation of the plane of polarization of a beam of light by a magnetic field (Faraday effect).

From 1900 to the present

Maxwell's theory is a theory of waves in a continuous (*i.e.,* infinitely divisible) medium. The energy of the waves is also infinitely divisible so that an indefinitely small amount can be emitted or absorbed by matter. Classical physical theories of the 19th century had predicted that in such a system the energy in equilibrium would be distributed so as to give an equal amount to each mode (frequency) of vibration. Because a continuous medium has an infinite number of modes of vibration, and the atoms (which constitute matter) have only a finite number, all the energy of the universe would be transformed into waves of high frequency. Maxwell understood this difficulty, which was later most clearly stated in the Rayleigh.Jeans law (after two English physicists, Lord Rayleigh and Sir James Hopwood Jeans) of the radiation of a blackbody (a body in which the intake and output of energy are in equilibrium). The German physicist Max Planck demonstrated that it is necessary to postulate that radiant.heat energy is emitted only in finite amounts, which are now called quanta. At first, it was hoped to retain, without modification, the theory of light as electromagnetic waves in free space and to use the quantum concept only in relation to the interaction between radiation and matter. In 1905, however, Einstein showed that, in the photoelectric effect, light behaves as if all the energy were concentrated in quanta..*i.e.,* particles of energy now called photons. In the same year, Einstein published the theory of relativity, which modified the whole of physics and gave a special role to the velocity constant *c*. Because light, in some situations, behaves like waves and, in others, like particles, it is necessary to have a theory that predicts when and to what extent each kind of behaviour is manifested. The main development of the quantum mechanics, which does precisely this, took place between 1925 and 1935.

Light from ordinary sources is emitted by atoms the phases of which are not correlated with one another, so that there is a random irregularity or incoherence between the waves emitted from different atoms. This places severe restrictions on the conditions under which the periodicity associated with wave theory can be observed. In England, Lord Rayleigh appreciated this effect and knew that, by the use of pinholes or slits and light of a narrow range of wavelength, effectively coherent light could be produced. For a long time, interest in this topic lapsed. About 1935 Frits Zernike, a Dutch physicist, and others extended the theory of coherence to include the concept of partial coherence. This appeared to be of practical importance only in a few rather special applications (*e.g.,* in the Michelson stellar interferometer; see below Interference). A theory of stimulated emission, attributable to the work of Einstein and an English physicist, Paul A.M. Dirac, postulated that under certain conditions atoms could be made to radiate in phase so that highly coherent radiation could be maintained indefinitely. The practical realization of these conditions, previously thought to be impossible, was achieved in 1960.

A second major development in the theory of light in this century is the application of so.called Fourier transform methods (a mathematical treatment of light waves) to a wide range of optical problems and, especially, to the transfer of information in optical systems (see optics).

Today, the theory of light has again reached a point at which all known terrestrial phenomena are included in one logical theory. The known unsolved problems concern the transmission of light over the vast distances of intergalactic space. Here the theory of light impinges on the science of cosmology.

1.3 General characteristics of waves

1.3.1 Basic concepts of wave theory

In this section on the wave theory of light, those properties of light that are consistent with a wave theory are described using a minimum of mathematical formulation. It is convenient to introduce the basic concepts of wave theory in relation to mechanical systems. Below, in the section on Interference, and beyond, it will be necessary to consider results obtained by more sophisticated mathematical methods, such as Fourier analysis.

1.3.2 Periodicity in time and space

If one end of a stretched rope is vibrated, a wave will run along the rope. Figure 1 (top) represents a profile of the wave..*i.e.*, a "snapshot" of the displacement of the rope from its normal position. It gives the variation of this displacement (indicated by ξ) at different points (z) along the axis of propagation for one specific instant of time. Similarly, Figure 1 (bottom) shows the variation with time of the displacement at one arbitrary point on the axis. In Figure 1 (top) the distance between successive crests is constant and is called the wavelength (λ). Similarly, the constant time between crests in Figure 1 (bottom) is called the period (τ). The temporal frequency ($\nu_t = 1/\tau$) is the number of vibrations per unit time and the spatial frequency or wave number ($\nu_s = 1/\lambda$) is the number of waves per unit length. The wave shown in Figure 1 (top) may be represented by the cosine of an angle (φ) to give the displacement for a particular point on the axis at any instant of time:

$$\xi = A\cos\Phi = A\cos 2\pi(\nu_t t - \nu_s z), \qquad (1)$$

in which $\xi$is the displacement at any point z on the axis at a time t, A is the amplitude (the maximum displacement); the angle φ(phi) in this case is equal to $2\pi(\nu_t t \,.\, \nu_s z)$ and is called the phase angle, or simply, the phase.

1.3.3 Energy

The energy per unit volume (W) stored in a wave motion is proportional to the square of the amplitude (A) so that, with a suitable choice of units, $W = A^2$.

1.3.4 Phase velocity

Any one crest moves forward a distance λin a time τ; *i.e.*, with a velocity b of the wavelength divided by the period or the temporal frequency divided by the spatial frequency,

$$b = \frac{\lambda}{\tau} = \frac{\nu_t}{\nu_s} = \lambda\nu_t. \qquad (2)$$

(2)The velocity b is called the phase velocity because the phase angle φwill remain constant when the time t changes by an incremental amount t_0 and z changes by $z_0 = bt_0$. (This may be seen by substituting $t = t_0$ and $z = z_0$ in the expression for this phase and using $b = v_t/v_s$.)

The velocity of light in vacuum (denoted by c) is the same for all frequencies; all colours travel through space with the same speed. The phase velocity (denoted by b) in a material medium, on the other hand, depends on the medium and on the temporal frequency and, hence from equation (2), on the wavelength.

1.3.5 Wave surfaces

Two.dimensional waves are formed by vibrating (dipping) the end of a rod up and down in the surface of a liquid. Waves spread from the point of origin (where the rod contacts the surface) and, at any moment, the phase at any point on a circle is the same; *i.e.*, if, at a given moment, the wave is at a maximum at one point on a circle then it is at a maximum everywhere on this circle, and the circle as a whole is a wave crest. Similarly, a trough is found at all points on another circle (the radius of which is $\lambda/2$ greater than that of the first circle). As the waves progress farther and farther from the origin, they become less strongly curved about the origin so that, at great distances, they are approximately plane waves.

Light waves are propagated in three dimensions and, for waves from a point source in an isotropic medium (*i.e.*, one in which the speed is the same along any radius), the phase is constant over spherical surfaces drawn about the point source as a centre. The surfaces of constant phase are called wave surfaces, and waves are called plane, spherical, ellipsoidal, and so on according to the shapes of the wave surfaces.

1.3.6 Reflection and refraction

The similarity between the behaviour of light waves and the surface waves of a liquid may be demonstrated with the so.called ripple tank. For reflection of a train of surface waves incident on a flat object, it may be readily observed that the angle of reflection is equal to the angle of incidence. For waves that are refracted in passing from one medium of the ripple tank in which the phase velocity is b_1, to another in which the phase velocity is b_2, measurements of angles of incidence (θ_i) and refraction (θ_r) of the surface waves verify Snell's sine law of refraction; *i.e.*, that the ratio of the sines of the angle of incidence and refraction is a constant, or

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{b_1}{b_2} = n_{12}, \qquad (3)$$

in which the constant n_{12} is called the index of refraction from medium 1 to medium 2. The index of refraction (n) from vacuum to a material medium is called the index of the medium and, for transparent mediums is always greater than unity (one). When n_{12} is less than unity, as happens when light is refracted as it passes from glass into air, the refracted ray grazes the surface if sin $\theta_i = n_{12}$, θ_i being the angle of incidence in the glass. At angles of incidence greater than this critical angle there is total reflection; *i.e.*, light, instead of penetrating into the air, is reflected back into the glass.

1.3.7 Dispersion

Newton found that, when a beam of white light is refracted by a glass prism, it is dispersed, or split, into beams of different colours. This phenomenon is now interpreted in the following way: the velocity of light in glass varies fairly rapidly with its wavelength, whereas its velocity in air varies little; thus the index of refraction and hence the angle of refraction depend on wavelength. A beam of white light, containing as it does a wide range of wavelengths, is thus dispersed by a glass prism so that light of one wavelength emerges from it in a different direction from light of another wavelength. Because colour depends on wavelength, the emergent light forms a spectrum. All material mediums are, to some extent, dispersive (*i.e.*, phase velocity varies with the temporal or spatial frequency).

1.3.8 Wave groups

When a stone is dropped into a quiescent pond, a few waves may be seen travelling out from the point of impact. This group of waves maintains its identity as it is propagated over a considerable distance, although it finally dies away. The velocity of the group as a whole is called the group velocity. Careful observation shows that the group velocity is less than the phase velocity. Individual waves may be seen to appear at the back of the group, advance through it, and die out as they reach the front of the group. In a nondispersive medium the group velocity is equal to the phase velocity, while in a dispersive medium it may be greater than, less than, or equal. For light waves, the group velocity is almost always less than the phase velocity.

1.3.9 Interference

When two or more wave motions are present at the same place and time, the simplest assumption is that the resultant displacement (ξ_R) is the algebraic sum of the individual displacements (ξ_1, ξ_2, ξ_3, etc.), *i.e.*,

$$\xi R = \xi_1 + \xi_2 + \xi_3 + \cdots + \xi N. \qquad (4)$$

Nearly all observations on light are in accord with this equation, which is a statement of the principle of superposition. These phenomena constitute the subject of what is known as linear optics. The possibility that additional phenomena might be observed at high intensities of light has long been accepted, and the use of lasers in the attainment of the necessary high intensities has led to the discovery of frequency doubling and other effects that cannot be predicted from equation (4). These new observations constitute the material of nonlinear optics. Equation (4) is valid for all the phenomena of interference, diffraction, etc., which will be described in this article.

Two waves are said to be coherent if their phase difference remains constant during a period of observation. Figure 2 shows two equal coherent plane waves travelling across the same space, with the wave fronts inclined at a small angle α, AB representing a surface corresponding to a crest of one wave. (The surface must be assumed to be perpendicular to the page.) C_1 D_1, C_2 D_2, etc., represent surfaces that correspond to crests of the other wave. The intermediate dotted lines represent troughs. At points such as P_1 (and P_2, P_3, . . .), a crest of one wave coincides with a crest of the other and according to the principle of superposition the displacement is twice that of either wave alone. At points Q_1, Q_2, etc., a crest of one wave meets a trough of another; so the displacements being equal and opposite, the resultant is zero. Thus, an observer looking at a plane that is perpendicular to the page and passes through AB sees a series of straight lines through P_1, P_2, P_3, etc., representing large displacement and a series of lines through Q_1, Q_2, Q_3, etc., representing zero displacement.

There are many ways in which coherent beams of light can be made to cross at an angle of about one part in a thousand. The eye (or a low.power magnifier) can be focussed on a plane such as that through AB. The resulting parallel light and dark lines are called interference fringes. From Figure 2 it may be seen that the separation (d) of two bright fringes is λ/α or 1,000 λif α= 0.001. When αhas this value, d = 0.5 millimetre for blue.green light and this would imply that $\lambda$is about 0.5 ×0.001 or 1/2,000 part of a millimetre (this is usually written 500 nanometres).

In this experiment the spatial periodicity of the light waves (about 2,000 waves per millimetre) has been made to produce fringes with periodicity of about two per millimetre. The spatial periodicity of a light wave is too high for the human eye, and it cannot be magnified directly. Interference methods effectively magnify it so that the resultant fringes can be seen by eye or with a convenient magnification. The following method of producing interference fringes, developed by Thomas Young, is now called Young's experiment.

In the arrangement shown in Figure 3, light of one wavelength passes through a slit S producing semicylindrical waves that are intercepted by two other slits P_1 and P_2. The two slits P_1 and P_2 act as secondary sources of coherent, semicylindrical waves the combined effect of which is observed on the plane perpendicular to the page and designated AB. In a typical case the separation (a) of P_1 and P_2 is a millimetre and the distances l_1 and l_2 are each about a metre. The slits are a centimetre or so long but are much less than a millimetre wide. They are accurately parallel to one another and, as represented in the drawing, are at right angles to the page. Because the waves from P_1 and P_2 are indirectly derived from the same small source, they are coherent. When they cross plane AB they are nearly plane because of the large radius, and they intersect at an angle αequal to 0.001. It may be shown that the intensity (I) for these fringes varies from point to point along the line AB in the way shown in Figure 4 (curve A), which is in accord with the equation

$$I = 2A^2(1 + \cos \varepsilon) = 2I_0(1 + \cos \varepsilon), \qquad (5)$$

in which A is the amplitude of either wave, I_0 is the intensity of one wave acting alone and the phase difference $\varepsilon = 2\pi ya/\lambda l_2$. Bright fringes are seen in positions for which $\varepsilon = 2\pi p$ or $y = p\lambda/l_2a$ (in this case p is a whole number, which may be positive, zero or negative..0, +/.1, +/.2, +/.3, etc.). Because cos εvaries from .1 to +1, I varies from $4I_0$ to zero. The average, in accordance with the law of conservation of energy, is $2I$.

1.3.10 Diffraction

Plane waves that pass through a restricted opening emerge as divergent waves. When the opening is less than one wavelength in diameter the emergent wave is nearly spherical. Whenever a beam of light is restricted by holes or slits or by opaque obstacles that block out part of the wave front, some spreading occurs at the edges of geometrical shadows. This effect, called diffraction, is also obtained with transparent obstacles that cause an irregularity in the wave front. Diffraction can be demonstrated by allowing a parallel beam of light to fall on a grating consisting of an array of equally spaced narrow slits. If the extent of physical separation of two adjacent slits is e, then the path difference between any two adjacent rays emitted in a direction symbolized by $\theta$is e sin θ, and if this path difference is an integral number (p) of wavelengths,

$$e \sin \theta = p\lambda, \text{ or } \nu_s \sin \theta = pg, \qquad (6)$$

in which ν_s is the spatial frequency ($1/\lambda$) and g is the number of lines per unit width of the grating, then the waves from different slits have phases that differ by angles of $2p\pi$, and they reinforce one another. Thus, when lenses are employed with a grating, sharp lines are obtained for each wavelength at values of θcorresponding to integral values of p. If white light is used, each line is drawn out into a spectrum of wavelengths because the direction of reinforcement depends on the wavelength.

1.3.11 Polarization

In the propagation of waves on a rope or across the surface of a liquid the displacement (as shown in Figure 1) is in a direction perpendicular to the direction of propagation and the waves are said to be transverse. Sound waves in a gas consist of alternate dilation and compression and the displacement is in the direction of propagation. The waves are longitudinal. If a beam of longitudinal waves is propagated in a vertical direction, there is nothing to distinguish one azimuthal plane from another..everything that is true for an east.west plane is equally true for a north.south plane. With transverse waves the displacement may be in the east.west plane; in that case, there is no component in the north.south plane, and this should manifest itself in the form of a property that depends on the azimuth. Such an effect is called an azimuthal property. An ordinary beam of light from a thermal source does not exhibit any azimuthal property, but experiments show that light can have an azimuthal property and must be represented by transverse waves.

If an unsilvered glass plate has an index of refraction equal to 1.5 and the angle of incidence of a beam of light is 57°, about 15 percent of the light will be reflected from the two glass surfaces of the plate (Figure 5); this percentage will not be altered when the glass plate is rotated about an axis parallel to the beam of light so as to change the azimuth of the plane of reflection. If a second mirror (G_2), parallel to the first (G_1), is used to reflect the beam in the same plane as that of the original reflection, about 30 percent of the light incident on the second plate of glass will be reflected; but if the second plate is turned so as to reflect the light in a plane perpendicular to that of the first reflection..*i.e.*, out of the plane of the page..hardly any light will be reflected. Thus, after the first reflection, the beam of light will have acquired an azimuthal property..it will be reflected more strongly when the transverse displacement is in one azimuthal plane than when in another. Further tests will show that the transmitted light has a complementary azimuthal property; it is more strongly reflected in the perpendicular plane..though the difference is less marked.

These results may be understood if ordinary light consists of a mixture of transverse waves with displacements in all azimuthal planes but only one component is reflected from a glass surface when the angle of incidence is 57°. The reflected light is said to be plane.polarized because all of the displacement of the wave is in one azimuthal plane. The transmitted light (about 85 percent of the whole) contains about 50 parts of a component that is polarized in a perpendicular plane and about 35 parts of light that is polarized in the same way as the reflected light. It is more strongly reflected in the plane of the page, but because it is only partially polarized, the azimuthal effect is less.

The above experiments do not show whether or not the reflected light has its displacement in the plane of reflection or perpendicular to it. It is a matter of choice whether the reflected light is said to be polarized in or perpendicular to the plane of reflection. Some controversy (and some difference of nomenclature) that formerly led to confusion was removed by the electromagnetic theory (see below). In this theory light is represented by two vectors (quantities that can be represented graphically by arrows that point in the field directions), a magnetic vector in the plane of reflection and an electric vector perpendicular to it. Confusion is avoided by specifying the plane of the electric vector instead of speaking of the plane of polarization.

The azimuthal property of reflected light at the surface of any medium..glass, plastic, a liquid..is most strongly manifested when the angle of incidence is so chosen that its tangent is equal to the index of refraction; that is, it satisfies Brewster's law (after Sir David Brewster, a British physicist), which states that, at the polarizing angle, the incident and refracted beams make an angle of 90° with one another: $\tan \theta_i = n$, in which θ_i is the angle of incidence, called the polarizing angle, and n is the index of refraction of the medium. Nevertheless, there is some azimuthal difference after reflection at any angle except $\theta_i = 0$ or $\theta_i = 90°$. Other ways of producing polarized light are described in a later section.

It is found that the plane of polarization of a beam of polarized light is rotated when the beam is passed through certain mediums (especially sugar solutions). These mediums are said to be optically active. Most mediums do not normally rotate the plane of polarization, but do so when there is a magnetic field in the direction of propagation (the Faraday effect).

1.3.12 The wave equation

The expression for a plane wave, given in equation (1) and showing the relationship between displacement (ξ), the time span (t), and distance (z) along the wave, may be differentiated twice with respect to t and z; that is, to find out how the displacement changes with position and time. This operation yields the partial differential equation:

$$\frac{\partial^2 \xi}{\partial z^2} = \frac{1}{b^2} \cdot \frac{\partial^2 \xi}{\partial t^2}, \qquad (7a)$$

in which b is the phase velocity. For a three.dimensional wave the analogous expression is

$$\frac{\partial^2 \xi}{\partial z^2} + \frac{\partial^2 \xi}{\partial y^2} + \frac{\partial^2 \xi}{\partial x^2} = \frac{1}{b^2} \cdot \frac{\partial^2 \xi}{\partial t^2}. \qquad (7b)$$

There are many solutions of this basic equation. Some correspond to the sinusoidal plane waves, which have already been considered. Others correspond to groups of plane waves that differ slightly either in direction, or wavelength, or both. Yet another solution of the general wave equation is:

$$\xi = \frac{A}{r} \cos 2\pi(v_t t - v_3 r), \qquad (8)$$

in which r is the magnitude of a radius vector drawn from the origin and A is a constant. This represents spherical waves.

1.3.13 Energy of a beam of light

The energy in a small volume (dV), through which plane waves are passing, is proportional to the product of the square of the amplitude (A), or its energy per unit volume (W), and the small volume; that is, $A^2 dV = WdV$. The rate of transport of energy across a surface normal to the direction of propagation is proportional to the product of the energy per unit volume, the phase velocity, and a small area (dS) normal to the direction of propagation, or $WbdS$. For spherical waves, the rate of transport is inversely proportional to r^2, *i.e.*, $(A/r^2)dS$. Because the area of a sphere is $4\pi r^2$ in which r is its radius, this equation implies that the total energy crossing any sphere surrounding a point source is independent of the radius. Thus, inverse.square law for the intensity of radiation at a distance r from a point source is in accord with the law of conservation of energy..the total energy of a wave remains the same even though the wave is spread over a greater area

1.3.14 Doppler.Fizeau effect

The length of a wave train emitted in one second by a stationary light source is equal to the velocity of light (c) times one second, which in itself is equal to the product of its frequency (ν_t) times its wavelength (λ)..*i.e.*, $c = \nu_t\lambda$. If the source moves away from the observer with a velocity (υ) that is small compared with the velocity of light, then the length of the wave train increases so as to be numerically equal to the sum of the two velocities ($c + \upsilon$) and the number of waves remains the same. The wavelength λ increases to λ' by a factor $(c + \upsilon)/c$; that is $\lambda' = (1 + \upsilon/c)\lambda$. This change was discovered by an Austrian physicist, Christian Doppler, in the 19th century in relation to sound waves and subsequently applied to light waves by Fizeau. It is called the Doppler.Fizeau effect. The Doppler.Fizeau effect is easily observed when part of the light from a gas laser is allowed to be scattered by a moving body and mixed with a little unscattered light. It is known from the study of sound waves that the beat frequency is equal to the difference between the frequencies of the two waves that are mixed. Although the frequency of light waves is extremely high (more than 10^{14} per second), the beat frequency may be a megahertz (10^6 cycles per second), which is easily detected by radio amplifiers, or even a few hundred cycles per second, which the human ear can detect. Thus, just as interference fringes provide a periodic phenomenon in which two light waves combine to produce fringes of low spatial frequency, so the Doppler.Fizeau effect produces beats the temporal frequency of which is a known, but very small, fraction of the temporal frequency of the light waves. In this way the periodicity of light in both space and time is exhibited and measured.

1.3.15 Light spectrum

It was seen, in the preceding section, that white light can be dispersed into a spectrum by refraction, by diffraction, or by interference. Newton showed that if a suitably oriented slit is used to select a small region of the spectrum, the light that passes through the slit is much more homogeneous than the original white light, and he was unable to observe any further dispersion when passing this light through a second prism. Delicate methods of interferometry nevertheless show that this light is never entirely of one wavelength, however fine the slit, but covers a range ($\Delta\lambda$) of wavelengths. The ratio of the wavelength divided by this range, which measures the purity of the spectrum, may be a few thousand for a spectrum formed by a prism and up to a million for a spectrum formed by a large diffraction grating. It is never infinite, as it would be if $\Delta\lambda$ were zero.

The spectrum of a hot body such as the solar photosphere is continuous (every wavelength is represented); but a German physicist, Joseph von Fraunhofer, early in the 19th century observed that the solar spectrum contains numerous dark lines appearing at certain wavelengths, which are attributed to wavelengths originally emitted by inner layers of the Sun but then absorbed by various elements (in gaseous form) in the cooler outer layers. Emission spectra produced by electric sparks and arcs contain sharp bright lines which are characteristic of the elements in the electrodes.

In monochromatic light, colour and wavelength are associated. Nevertheless, as Newton said, "the rays, to speak properly, are not coloured." Colour is a sensation in the human mind. Light of one wavelength can stimulate the visual system so that a certain colour sensation (*e.g.*, red) is produced. The way in which the visual system analyzes colour is entirely different from the way in which physical instruments form a spectrum.

There are a number of ways in which spectra are produced in nature. The rainbow is the most striking of these. The primary rainbow is formed by reflection and refraction of light in raindrops. The rays emerging from the drops are spread out, but for any given wavelength there is a minimum angle of deviation and there is a concentration of energy at this angle. For green light the minimum angle of deviation is about 138° and an observer with his back to the Sun sees the bow at an angle of 42° to the direction of the Sun's rays. Because of the dispersion of water, the angles for different wavelengths are not exactly the same, and the red is seen on the outside and blue on the inside of the bow. A weaker rainbow is formed by rays that have been twice reflected. In this the colours are reversed. Still weaker supernumerary bows are caused by diffraction in droplets. A rainbow may be regarded as a spectrum of the Sun, but the purity is low.

1.3.16 Velocity of light

The accepted value of the velocity of light (c) in vacuum is 299,792.458 kilometres per second (see Table 1). The velocity is the same for all wavelengths over the whole range of the electromagnetic spectrum from radio waves to gamma rays. Methods of measurement are of three types: (1) measurement of the time (T) in which a group of waves covers a known distance (l), (2) measurement of the frequency (ν_t) and wavelength (λ) of monochromatic waves, and (3) indirect methods, such as measurement of the change of frequency or wavelength (Doppler.Fizeau effect) when a beam of light is reflected from a mirror moving with a known velocity.

Methods of type (3) have, so far, given an accuracy of only a few percent. Methods of type (2) cannot be used for light waves because the frequency is about 1.5×10^{14} hertz and is too high to be measured directly. The following sections will review measurements of the velocity of light by methods of type (1) and compare the results of the best measurements with the results obtained for radio waves by methods (1) and (2).

Table 1.1 The Constant of the Velocity of Light
(in kilometers per second)

Derived from measurements
of the velocity of light

By	Year	Value
Michelson	1927	299,796 + or . 4
Michelson, Pearson and Pease	1935	299,774 + or . 11
Value accepted in 1941	1941	299,773 + or . 3
Bergstrand	1951	299,793.1 + or . 0.2
Bergstrand (mean value)	1957	299,792.9 + or . 0.2
Value adopted by 17th General Congress on Weights and Measures	1983	299,792.458

Derived from measurements
on radio waves

Essen (10,000 MHz)	1950	299,792.5 + or . 1
Froome (24,000 and 75,000 MHz)	1951.58	299,792.5 + or . 0.1
Value adopted by 12th General Assembly of the Radio Scientific Union	1957	299,792.5 + or . 0.4

Derived from electrical
measurements

Rosa and Dorsey (ratio of units)	1907	299,788 + or . 30
Mercier (Lecher wires)	1923	299,795 + or . 30

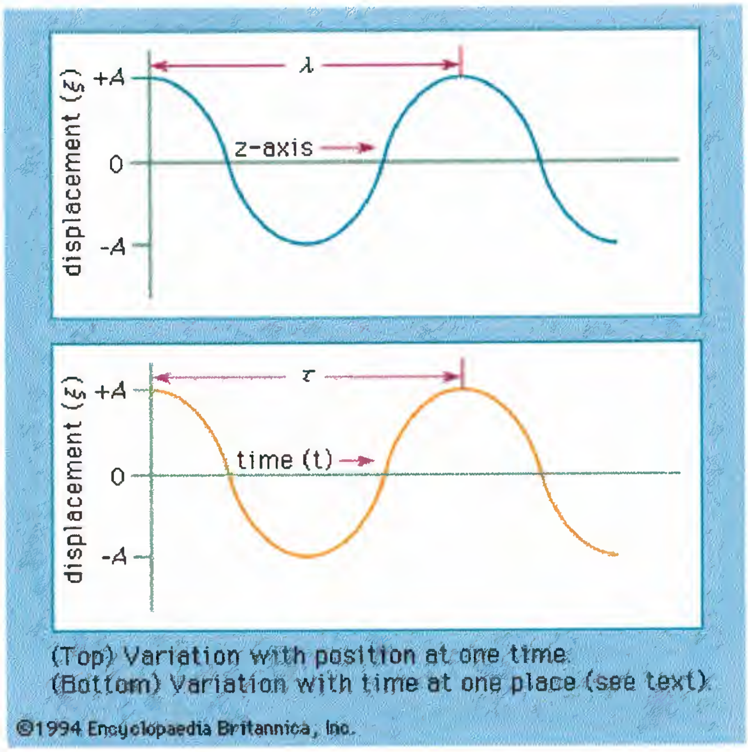


Figure 1.1 . wave profiles

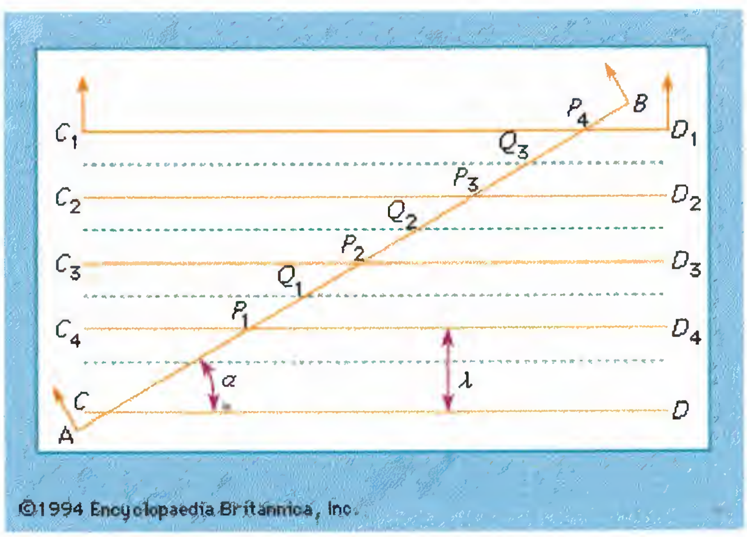


Figure 1.2: Interference of two plane waves AB and CD with directions inclined at an angle α. The crests of CD are represented as C_1D_1, C_2D_2, etc., and the troughs are shown as broken lines .

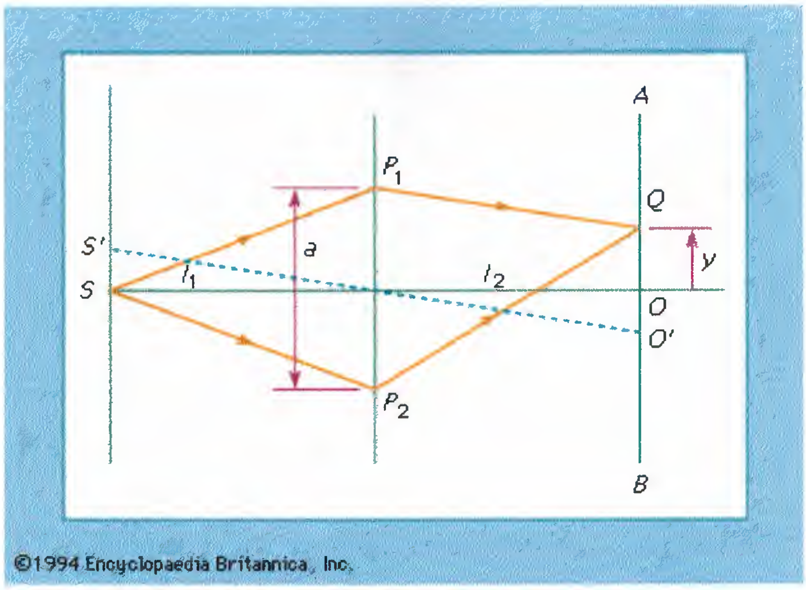


Figure 1.3: Young's experiment .

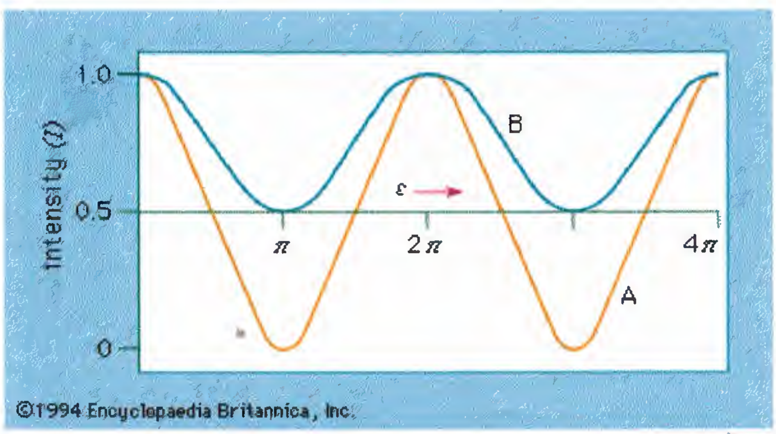


Figure1. 4: Interference fringes obtained in Young's experiment.

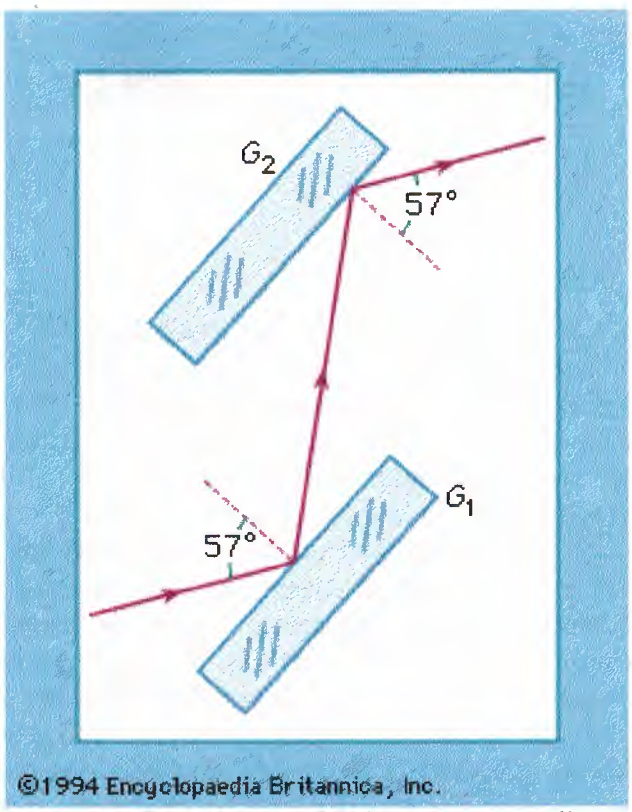


Figure1.5: Malus' experiment. Successive reflections at two unsilvered mirror surfaces, G_1 and G_2 .

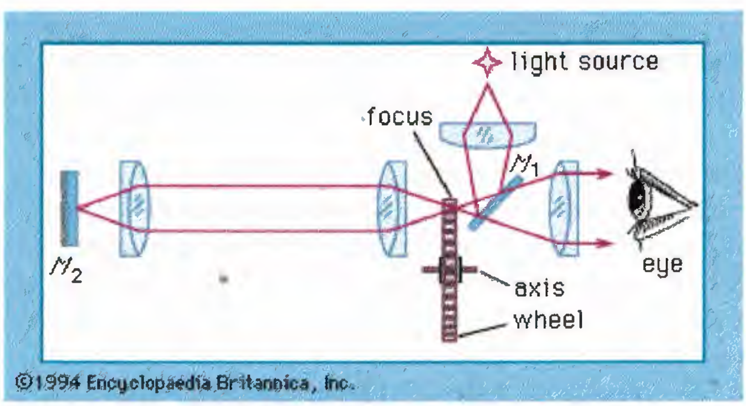


Figure1.6: Fizeau's method for measuring the velocity of light.

CHAPTER TWO

ILLUMINATION SOURCES

2.1 Introduction

The refinement of the coiled filament made possible the development of the tubular lamp, which in turn made possible a second type of spotlight, the ellipsoidal reflector spotlight. This type of spotlight uses an ellipsoidal reflector to gather the light at the focal point of the reflector. In front of the reflector, the beam of light is shaped by means of adaptable shutters, an iris, or a predetermined pattern. One or two lenses are used as an objective to project the image. The field of the beam is of even intensity, and a hard or soft edge can be obtained by focus adjustment. The focal lengths of the lenses can be changed if necessary to compensate for the length of throw or to widen or narrow the field. Special wide.angle lenses are useful in projecting patterns, such as leaves, at close distance. Available in a range from 250 to 3,000 watts, the ellipsoidal spotlight is a highly efficient and versatile light source. The larger ellipsoidal spotlight can also be fitted with coloured quartz patterns of any design, from realistic clouds to abstract rotating patterns. Used in combinations at different intensities, a cyclorama can be flooded with light in either bold or subtle patterns.

Borderlights and striplights are available with wiring for control in three circuits. Older types had reflectors that produced a soft, even blend; later versions use a range of highly efficient sealed.beam lamps, such as the quartz halogen sealed.beam lamps, which are available in a variety of wattages and reflectors..from flood to narrow spot. Mounted in striplights, the sealed.beam lamps have become a versatile and effective source, either for lighting large surfaces or as a strong backlight wash. Television and motion.picture lighting has rapidly developed such sources, which were initiated in the theatre.

A floodlight is a refined version of the old bunchlight..a half dozen old filament lamps grouped into a square housing, usually painted white on the inside to serve as a reflector. Later, a single large.wattage lamp replaced such multiple lamps. Floodlights today are usually ellipsoidal reflectors in a wide or narrow beam. The reflectors are mat.finished, accommodate a variety of lamp sizes, and do not require a lens. The quality of light is soft and diffused; it is ideal for a wash of light over a drop or a cyclorama. Usually, more than one circuit is used to achieve a variety of colour changes. Large banks of fluorescent lamps with colour filters are effective in lighting a large and very high cyclorama, but the difficulty in dimming fluorescent sources has limited their use.

The parabolic "beam" projector was developed for outdoor lighting and slightly modified for stage lighting. The familiar carbon arc searchlight, which throws an intense narrow beam of light several miles into the night sky, is a simple parabolic unit without a lens. Such a searchlight consists of a strong pinpoint source (the arc) and a large parabolic reflector of silvered glass. The same simple optical principles were adapted to incandescent lamps for floodlighting the exteriors of buildings. The output is highly efficient, but to reinforce it and control it a lens can be added in front of the source. Used in a phalanx as far offstage as possible, beam projectors can serve as a strong source to give the effect of long rays of sunlight streaking across the stage. A most significant advance was made by hanging beam projectors so that they provided backlighting; this resulted, for the first time, in the actors' being strongly separated from the background, creating an illusion of depth and a haze.

2.2 Projections and special effects

A significant amount of lighting equipment has been developed for "special effects." Standard effects include moving clouds, water ripple, fire effects, rain or snow, painted rainbows, and fireworks. For practicality, most special effects are built around a standard spotlight housing. The effect head, containing a painted or photographic transparent disk and the mechanism for revolving it, is placed in front of the spotlight housing. An additional objective lens is used to magnify and focus the image.

The oldest effect projector, dating from the World War I era, is the Linnebach lantern, often called a "scene" projector. It is simple both in principle and in construction. A concentrated light source is placed in a deep black box, and a painted slide is placed on the side of the box left open; since light travels in straight lines, the design painted on the glass is thus projected against a drop onstage, greatly enlarged, at a relatively short distance. Since no lens is used in a Linnebach lantern, the light source must be powerful and concentrated. The design must be simple and bold, for any line narrower than the point source itself will be lost. The overall effect is stylized and borders on the abstract. Rear projection with at least two projectors is required for any ambitious production. Large incandescent lights replaced the original carbon arcs in the Linnebach lantern.

About mid.20th century there was renewed interest in the use of projections. Fortunately, the development of new projection equipment provided a powerful instrument to produce effects not possible before. In the post.World War II years at the music festivals at Bayreuth, Ger., Richard Wagner's grandson Wieland reduced three.dimensional scenic elements to the barest essentials and then flooded the stage with multiple, overlapping projected patterns. In later years more scenic elements were added to give variety of texture and depth to the flow of light and pattern. Still later at the Festspielhaus in Salzburg, Austria, the productions of Wagner's music dramas designed by Gunther Schneider.Siemssen elaborated this concept to achieve even more dramatic and sumptuous productions; he filled the vast, extra.wide stage with patterns of light in depth, softened with scrims (loosely woven meshes that diffuse the light) and translucent drops (backdrops with sections dyed to transmit some light). The Czechoslovakian designer Josef Svoboda did more than any other contemporary designer with "visions in space." For some productions, Svoboda used a direct, journalistic approach, massing three.dimensional screens to create a montage effect with slides and film. Polyvision, a production conceived and executed by Svoboda for the Czech pavilion at the 1967 international exhibition at Montreal, was a brilliant multimedia experience. In his other productions, which were equally stylized but more indirect and abstract, he used alternating surfaces of scrim and scenic elements to catch the patterned light, cast complex shadows, and float in depth before a seemingly infinite background.

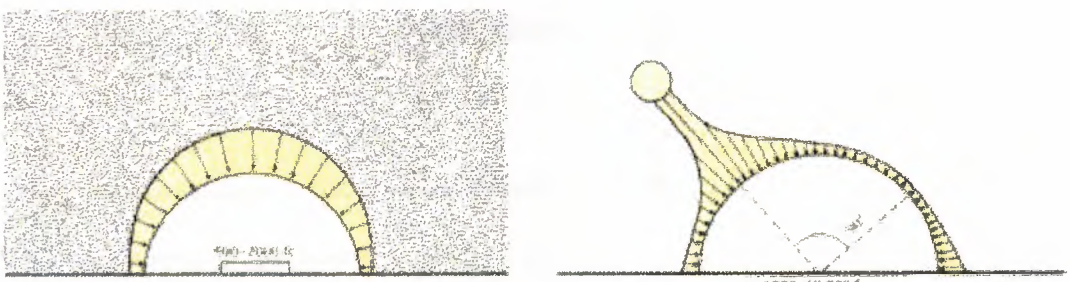
Innovative contributions to lighting and the use of projections were also made in dance. The American Alwin Nikolais made very original use of dancers, costumes, light, and projections to form moving geometric and abstract designs. At times, the moving bodies of the dancers become the screen for the projections. The Robert Joffrey Ballet, which was also based in New York City, in its production *Astarte*, created a unique combination of film and slides on a moving, pulsating screen.

2.3 Daylighting

Daylight that enters a window can come from several sources: direct sunlight, clear (blue) sky, clouds, and reflections from the ground and nearby buildings. The light from each source varies not only in quantity but also in such qualities as color, diffuseness, and efficacy.

Although sky conditions can be infinitely variable, it is useful to understand the daylight from two specific conditions, overcast sky and clear sky with sunlight. A daylighting design that works under both of those conditions will also work under most other sky conditions.

The brightness of an overcast sky is typically three times greater at the zenith than at the horizon. Although the illumination from an overcast day is quite low .. 500 to 2000 foot.candles .. it is still 10 to 50 times greater than is needed indoors.



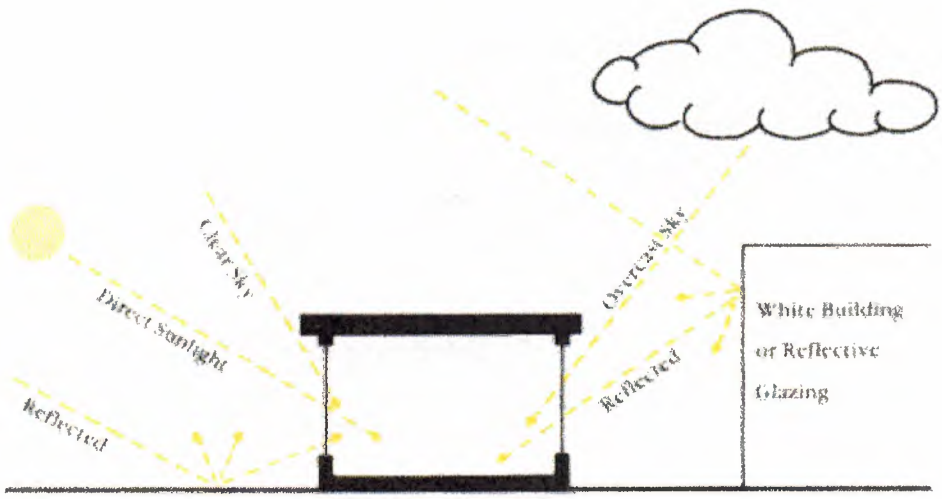
The brightness distribution on an overcast day (left) and on a clear day (right).

On a clear day, the brightest part of the sky is around the sun and is about 10 times brighter than the darkest part of the sky, which is at 90 degrees to the sun. Under such a sky the illumination is quite high .. 6000 to 10,000 footcandies, a level more than 100 times that required for good indoor illumination. Under such conditions, windows and skylights can be quite small. The main difficulty with the clear sky is the challenge of the direct sunlight; it is not only extremely bright but also is constantly changing direction. Consequently, to understand clear day illumination, it is also necessary to understand the daily and seasonal movements of the sun.

2.3.1 Light quantity and quality

Most climates have enough overcast and clear days to make it necessary to design for both conditions. The main exceptions are parts of the Northeast and the Pacific Northwest, where overcast skies predominate, and the Southwest, where clear skies predominate. In these areas, designers should focus upon the predominant condition. Under overcast skies, the designer's main challenge is quantity; for clear sky conditions, the challenge is quality.

The daylight from clear skies consists of two components, skylight and direct sunlight. Light from blue sky is diffuse and of low brightness; direct sunlight is directional and extremely bright. Because of direct sunlight's potential for glare, excessive brightness ratios, and overheating, designers sometimes assume it should be excluded from a building.



Various sources of daylight. Sometimes, reflected light is the major source of daylight.

Often, in fact, people erroneously believe that direct sunshine is appropriate only for solar heating. Although direct beam sunlight has a lower efficacy (lumens per watt) than skylight, its efficacy is comparable to and its color rendering quality is superior to the best electric sources. Therefore, it is not a good policy to exclude direct sunlight because, with the proper design, it can supply both high quality and high quantity daylight.

The light from clear skies, especially the light from the northern sky, is rich in the blue end of the spectrum. The color rendering quality of such light is excellent, but it is slightly on the cool side.

Reflected light from the ground and neighboring structures can be a significant source of daylight. Reflected light may even be the major source of daylight; the reflectance factor of the reflecting surface is critical in this regard. A white painted building frequently reflects about 80 percent of the incident light; lush green grass reflects only about 10 percent, and mostly green light at that. The reflectances for some common surfaces are shown on the accompanying table.

TYPICAL REFLECTANCES

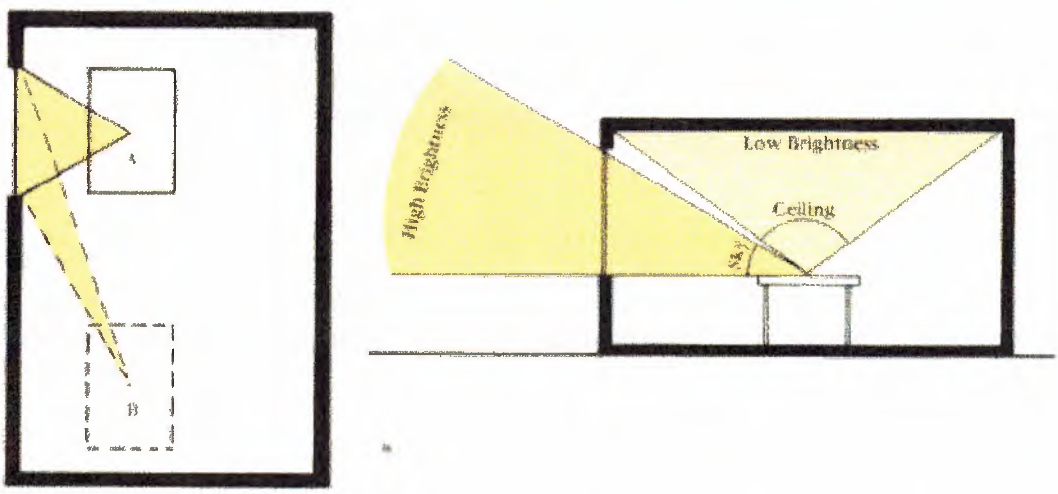
Material	Reflectances (in percentages)
Aluminum, polished	70.85
Asphalt	10
Brick, red	25.45
Concrete	30.50
Glass, clear or tinted	7
reflective	20.40
Grass, dark green	10
dry	35
Mirror (glass)	80.90
Paint, white	70.90
Paint, black	4
Porcelain enamel, white	60.90
Snow	60.75
Stone	5.50
Vegetation, average	25
Wood	5.40

2.3.2 Conceptual model

Direct beam light can be nicely modeled with arrows, but a diffuse source cannot. To understand and to predict the effect of a diffuse light source requires a different kind of

visual model. The illuminating effect of a diffuse source on a point is a function of both the brightness and the apparent size of the source. Apparent size is a consequence of actual size, proximity, and tilt. For example, the apparent size of a source decreases if the actual size of that source decreases or if the source is moved further away or if the source is tilted. If a flat source is tilted 90 degrees, its apparent size is zero.

This model can be used to visualize the way a table in a room will be illuminated by a window. Moving the table from a position near a window to one farther away decreases the illumination for two reasons: it changes the proximity and tilt of the window in relation to a point on the table. Everything else remains constant.



The relative contributions of two sources of daylight, sky and ceiling, are demonstrated in this model.

A section of that room with the table shows the relative contributions of two main sources of daylight .. the sky and the ceiling .. for a point on the table. Some of the daylight entering the window is reflected off the ceiling, which then becomes a low brightness light source for the table. Even though its brightness is low, the illumination from the ceiling is significant because of its large apparent size. The combination of brightness and apparent size determines the contribution. The sky is the major source of light despite its smaller apparent size, because it is much brighter than the ceiling. If the walls are a light color, they will also reflect some light on the table; but for simplicity, the walls' contribution is omitted from the accompanying drawing.

2.3.3 The daylight factor

One of the best ways for an architect to determine the quantity and the quality of daylighting is to use physical models. Although most daylighting model tests are conducted under the real sky, the usefulness of actual measured illumination data is limited. Unless a model can be tested under the worst daylight conditions, illumination measured inside it cannot indicate the lowest expected illumination level.

Typical minimum daylight factors

Type of space	Daylight Factor
Art Studio	4.0.6.0%
Factory, laboratory	3.0%
Office, classroom, gymnasium	2.0%
Lobby, lounge, living room	1.0%
Corridor, bedroom	0.5%

This general guide for checking the adequacy of illumination supplied by windows is adapted from M. David Egan's Concepts in Architectural Lighting with permission from McGraw Hill.

Fortunately, there is a solution to this problem .. the daylight factor, which is the ratio of the illumination indoors to that outdoors. The daylight factor describes how effectively a design takes daylight indoors. It is not necessary, then, to test the model under the worst conditions to determine the daylight factor. Although winter overcast skies are usually the worst design condition, the model can be tested under an overcast sky at any time of year or day.

If the measured daylight factor is greater than the typical minimum for that kind of space shown on the accompanying table, then there will be more than enough daylight for most of the year. Multiplying the daylight factor by the average minimum daylight shown in the average illumination table lets a designer determine the average minimum indoor illumination.

Average illumination from overcast skies

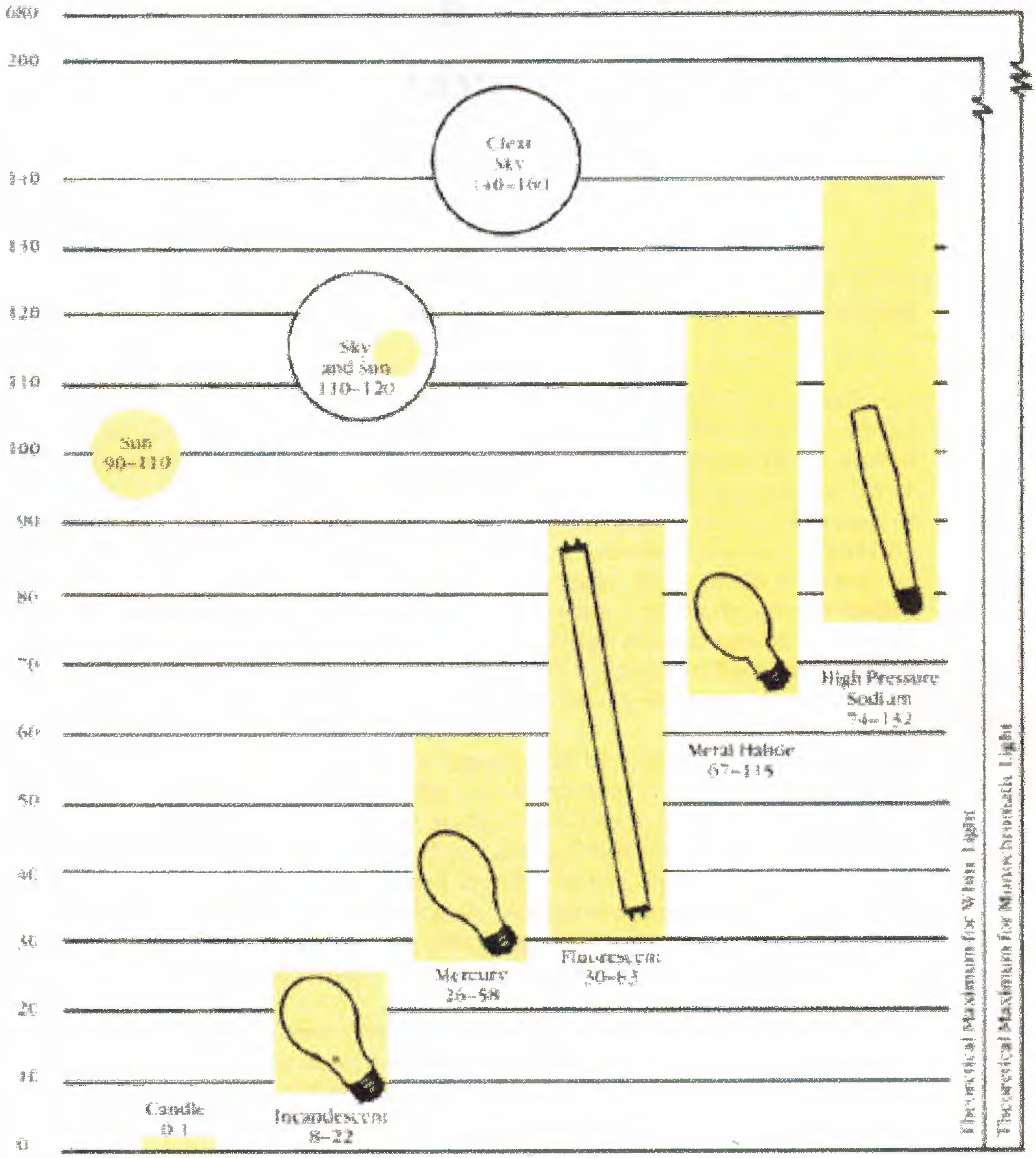
North Latitude	Illumination
46°	700 fc
42°	750 fc
38°	800 fc
34°	850 fc
30°	900 fc

Values above are typical for overcase sky conditions from 8 a.m. to 4 p.m. Adapted from Egan's Concepts in Architectural Lighting, McGraw Hill.

The absolute illumination is a poor indicator of visibility because the human eye has a great ability to adapt. Relative brightness between the interior and the window, however, is a critical consideration in daylight design, and the daylight factor is a good indicator of this relationship. The higher the factor the less extreme are the brightness differences.

If a design excludes direct sunlight, then clear days behave similarly to the overcast conditions explained above. If direct sunlight is included, as it generally should be, then the model has to be tested with a sun machine to simulate the various sun angles throughout the year. Model testing will be explained in a later column.

During the design process, several alternative schemes usually must be compared. Because actual outdoor lighting varies greatly from hour to hour and day to day, footcandle measurements cannot be compared; but the daylight factor can. As the outdoor illumination changes, the indoor illumination changes proportionately and the daylight factor remains constant for any particular design.


200
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Clear Sky
Sky and Sun
110–120
Sun
90–110
High Pressure Sodium
74–132
Metal Halide
67–115
Mercury
26–58
Fluorescent
30–63
Candle
Incandescent
8–22
Theoretical Maximum for White Light
Theoretical Maximum for Monochromatic Light

CHAPTER THREE

LAMP

3.1 Introduction

a device for producing illumination, consisting originally of a vessel containing a wick soaked in combustible material, and subsequently such other light.producing instruments as gas and electric lamps.

The lamp was invented at least as early as 70,000 BC. Originally it consisted of a hollowed.out rock filled with moss or some other absorbent material that was soaked with animal fat and ignited. In the Mediterranean area and the Middle East, the earliest lamp had a shell shape. Originally, actual shells were used, with sections cut out to provide space for the lighting area; later these were replaced by pottery, alabaster, or metal lamps shaped to resemble their natural prototypes. Another basic type of primitive lamp, found in ancient Egypt and China, was the saucer lamp. Made of pottery or bronze, it was sometimes provided with a spike in the centre of the declivity to support the wick, which was used to control the rate of burning. Another version had a wick channel, which allowed the burning surface of the wick to hang over the edge. The latter type became common in Africa and spread into East Asia as well.

In ancient Greece lamps did not begin to appear until the 7th century BC, when they replaced torches and braziers. Indeed, the very word lamp is derived from the Greek *lampas,* meaning a torch. The pottery version of a Greek lamp was shaped like a shallow cup, with one or more spouts or nozzles in which the wick burned; it had a circular hole in the top for filling and a carrying handle. Such lamps usually were covered with a heat.resisting red or black glaze. A more expensive type was produced in bronze. The standard form had a handle with a ring for the finger and a crescent above for the thumb. Hanging lamps made of bronze also became popular.

The Romans introduced a new system of manufacturing terra.cotta lamps, using two molds and then joining the parts together. In metal, shapes became more complex, sometimes assuming animal or vegetable forms; very large versions for use in circuses and other public places appeared during the 1st century AD.

Very little information is available about medieval lamps, but it would appear that such as existed were of the open, saucer type, and considerably inferior in performance to the closed lamps of the Romans. The great step forward in the evolution of the lamp occurred in Europe in the 18th century with the introduction of a central burner, emerging from a closed container through a metal tube and controllable by means of a ratchet. This advance coincided with the discovery that the flame produced could be intensified by aeration and a glass chimney. Until the late 18th century, the primary fuels burned in lamps included vegetable oils such as olive oil and tallow, beeswax, fish oil, and whale oil. With the drilling of the first well for petroleum oil in 1859, the kerosene lamp (paraffin in British usage) grew popular. In the meantime, however, coal gas and then natural gas for illumination were coming into wide use. Coal gas had been used as a lamp fuel as early as 1784, and a "thermolampe" using gas distilled from wood was patented in 1799. Although coal gas was denounced as unsafe, it won increasing favour for street lighting, and by early in the 19th century most cities in the United States and Europe had gaslighted streets and increasing numbers of homes converted to the new fuel.

The early gas lamps made use of a simple burner in which the yellow light of the flame itself was the source of the illumination. But during the 1820s a new form of burner was introduced in which a controlled amount of air was admitted to the gas current, producing a high.temperature but nonluminous flame that heated a refractive, noncombustible material to a very high temperature. This became the source of light; the higher the temperature of the material, the whiter the colour of the light and the greater the output. By the 1880s, a woven network of cotton threads impregnated with thorium and cerium salts was the standard light.emitting material used in gas lamps.

The development of the electric lamp at the turn of the 19th century stemmed the trend toward gas lamps, and by 1911 the conversion of gas fixtures for use with electricity had begun. Soon electricity was rapidly replacing gas for general illuminating purposes. In England and Europe, however, gas enjoyed wide use for a number of years longer.

3.2 Electric lamps.

Modern lamps and lighting began with the invention of the incandescent electric lamp about 1870. An incandescent lamp is one in which a filament gives off light when heated to incandescence by an electric current. The incandescent lamp was not the first lamp to use electricity, however; lighting devices employing an electric arc struck between electrodes of carbon had been developed early in the 19th century. These arc lamps, as they were called, were reliable but cumbersome devices that were best used for street lighting. In 1876 Pavel Yablochkov, a Russian electrical engineer, introduced the Yablochkov candle. This was an arc lamp having parallel carbon rods separated by porcelain clay, which vaporized during burning of the arc. Alternating current was used to ensure equal rates of consumption of the two points of the rods. This lamp was widely used in street lighting for a time.

In the decades before the Edison incandescent carbon.filament lamp was patented in 1880, numerous scientists had directed their efforts toward producing a satisfactory incandescent lighting system. Outstanding among them was Sir Joseph Wilson Swan of England. In 1850 Swan had devised carbon filaments of paper; later he used cotton thread treated with sulfuric acid and mounted in glass vacuum bulbs (only possible after 1875).

The final development of the incandescent lamp was the result of concurrent work by Swan and Thomas A. Edison of the United States, using the vacuum pump of Hermann Sprengel and Sir William Crookes. These lamps by Swan and Edison consisted of a filament of carbon wire in an evacuated glass bulb, two ends of the wire being brought out through a sealed cap and thence to the electric supply. When the supply was connected, the filament glowed and, by virtue of the vacuum, did not oxidize away quickly as it would have done in air. The invention of a completely practical lamp ordinarily is credited to Edison, who began studying the problem in 1877 and within a year and a half had made more than 1,200 experiments. On Oct. 21, 1879, Edison lighted a lamp containing a carbonized thread for the filament. The lamp burned steadily for two days. Later he learned that filaments of carbonized visiting card paper (bristol board) would give several hundred hours' life. Soon carbonized bamboo was found acceptable and was used as the filament material. Extruded cellulose filaments were introduced by Swan in 1883.

Concurrently, recognizing that the series wiring systems then used for arc lights would not be satisfactory for incandescent lamps, Edison directed much effort toward the development of dynamos and other necessary equipment for multiple circuits.

The first commercial installation of Edison's lamp was made in May 1880 on the steamship *Columbia*. In 1881 a New York City factory was lighted with Edison's system, and the commercial success of the incandescent lamp was quickly established.

The most important subsequent improvement in the incandescent lamp was the development of metallic filaments, particularly of tungsten. Tungsten filaments quickly replaced ones made of carbon, tantalum, and metalized carbon in the early 1900s, and they are still used in most filament lamps today. Tungsten is highly suitable for such lamps because of all the materials suitable for drawing into filament wires, it has the highest melting point. This means that lamps can operate at higher temperatures and therefore emit both whiter light and more light for the same electrical input than was possible with less durable and less refractory carbon filaments. The first tungsten.filament lamps, introduced in the United States in 1907, made use of pressed tungsten. By 1910 a process (patented in 1913) for producing drawn tungsten filaments had been discovered.

The early tungsten lamps, like carbon lamps, suffered from the migration of filament molecules to the glass bulb, causing a blackening of the bulb, a loss in light output, and progressive thinning of the filament until it broke. About 1913 it was found that the introduction of a small amount of inert gas (argon or nitrogen) reduced migration and enabled the filament to be run at a higher temperature, giving a whiter light, higher efficiency, and longer life. Further improvements followed, including the development of the coiled filament.

3.2.1 Electric discharge lamps.

During the late 19th century, Sir William Crookes and other physicists experimented with methods of generating radiation by striking an arc between electrodes in an evacuated tube to which small amounts of an elemental gas had been admitted. In about 1910 the French physicist Georges Claude developed such a tube with neon gas as the filling; when a high voltage was applied to the two electrodes at either end of the tube, it emitted a deep red light. Neon signs soon decorated the exteriors of commercial buildings in the world's cities, and experiments with other vapour fillings..such as mercury, argon, helium, krypton, and xenon..enabled a variety of colours to be produced.

Using the same basic principle, Peter Cooper Hewitt marketed the mercury.arc lamp in 1901, the energy efficiency of which proved to be two or three times that of the contemporary incandescent lamp. Creating a nearly shadow.free light and less glare, the lamp immediately found wide use for industrial and street lighting in the United States.

A promising electric discharge lamp developed in Europe by 1931 was the high.intensity sodium.vapour lamp, and although it was not satisfactory for commercial or domestic use because of its characteristic yellow colour, by the mid.20th century sodium.vapour lamps were being used for street and highway lighting and for the illumination of bridges and vehicular tunnels all over the world.

Despite these inventions, electric discharge lamps were little used in interior lighting until the development in the 1930s of the fluorescent tube. This is a long tube with a mercury.vapour filling, and inner walls coated with a material which fluoresces white or near white when subjected to the radiation of the mercury discharge. This fluorescence multiplies the lamp's light emission by a hundredfold. Fluorescent lamps gradually became a mainstay of interior lighting, particularly in offices, factories, and other work environments.

3.2.2 Modern electrical light sources

By the mid.20th century the atmospheric arc lamp was used chiefly in large.wattage units for searchlights, for projectors calling for a high intensity and concentrated source, and for other special applications requiring small but powerful sources of blue and ultraviolet energy.

Incandescent electric lamps remain the most common source of home illumination and are used for most portable lamps. They are inexpensive, reliable, and readily available, but they are inefficient in their use of energy.

Luminescent lamps, which produce less heat than incandescent lamps, include electric discharge lamps, semiconductor lamps, and chemical lamps. Of the electric discharge lamps, the fluorescent lamp gives off a neutral white light, the sodium.vapour lamp emits a yellow.orange light, and the mercury.vapour lamp gives off a whitish blue.green light.

Glow lamps are very low.power electric discharge lamps, with large metal electrodes in an atmosphere of neon. The neon glows orange near the negative electrode, producing a dim light suitable for pilot or indicator lamps. Neon lamps for signs are also electric discharge lamps. The light.emitting diode (LED) is a form of luminescent lamp. The device is a crystalline semiconductor diode; when current flows through the diode, electrons combine with "holes" (localized positive charges) and drop to a state of lower energy. Part of the released energy is emitted as a photon. The colour of light given off depends on the crystal material used. Green LED's, for example, are made of gallium phosphide treated with nitrogen. LED's do not produce enough light for illumination, but are used for indicators. Segmented LED's provide the digital displays on many electronic devices.

The electroluminescent lamp, another semiconductor lamp, consists of a flat.plate capacitor with a phosphor (similar to those used with fluorescent lamps) in the dielectric; it is used with alternating current. These lamps are used for night.lights and engineering applications such as luminous instrument panels

3.2.3 Fluorescent lamp

electric discharge lamp, cooler and more efficient than incandescent lamps, that produces light by the fluorescence of a phosphor coating. A fluorescent lamp consists of a glass tube filled with a mixture of argon and mercury vapour. Metal electrodes at each end are coated with an alkaline.earth oxide that gives off electrons easily. When current flows through the ionized gas between the electrodes, it emits ultraviolet radiation. The inside of the tube is coated with phosphors, substances that absorb ultraviolet radiation and fluoresce (reradiate the energy as visible light). Two common phosphors are zinc silicate and magnesium tungstate. A starter and ballast provide the extra voltage, up to four times of the operating voltage, needed to ionize the gas when starting.

3.3 Luminescence

3.3.1 Electroluminescence

Like thermoluminescence, the term electroluminescence includes several distinct phenomena, a common feature of which is that light is emitted by an electrical discharge in gases, liquids, and solid materials. Benjamin Franklin, in the United States, for example, in 1752 identified the luminescence of lightning as caused by electric discharge through the atmosphere. An electric.discharge lamp was first demonstrated in 1860 to the Royal Society of London. It produced a brilliant white light by the discharge of high voltage through carbon dioxide at low pressure. Modern fluorescent lamps are based on a combination of electroluminescence and photoluminescence: mercury atoms in the lamp are excited by electric discharge, and the ultraviolet light emitted by the mercury atoms is transformed into visible light by a phosphor.

The electroluminescence sometimes observed at the electrodes during electrolysis is caused by the recombination of ions (therefore, this is a sort of chemiluminescence). The application of an electric field to thin layers of luminescing zinc sulfide can produce light emission, which is also called electroluminescence.

A great number of materials luminesce under the impact of accelerated electrons (once called cathode rays)..*e.g.*, diamond, ruby, crystal phosphors, and certain complex salts of platinum. The first practical application of cathodoluminescence was in the viewing screen of an oscilloscope tube constructed in 1897; similar screens, employing improved crystal phosphors, are used in television, radar, oscilloscopes, and electron microscopes. The impact of accelerated electrons on molecules can produce molecular ions, ions of molecule fragments, and atomic ions. In gas.discharge tubes these particles were first detected as "canal rays" or anode rays. They are able to excite phosphors but not as efficiently as electrons can.

3.3.2 Radioluminescence

Radioactive elements can emit alpha particles (helium nuclei), electrons, and gamma rays (high.energy electromagnetic radiation). The term radioluminescence, therefore, means that an appropriate material is excited to luminescence by a radioactive substance. When alpha particles bombard a crystal phosphor, tiny scintillations are visible to microscopic observation. This is the principle of the device used by an English physicist, Ernest Rutherford, to prove that an atom has a central nucleus. Self.luminous paints, such as are used for dial markings for watches and other instruments, owe their behaviour to radioluminescence. These paints consist of a phosphor and a radioactive substance, *e.g.*, tritium or radium. An impressive natural radioluminescence is the aurora borealis: by the radioactive processes of the sun, enormous masses of electrons and ions are emitted into space in the solar wind. When they approach the Earth, they are concentrated by its geomagnetic field near the poles. Discharge processes of the particles in the upper atmosphere yield the famous luminance of the auroras.

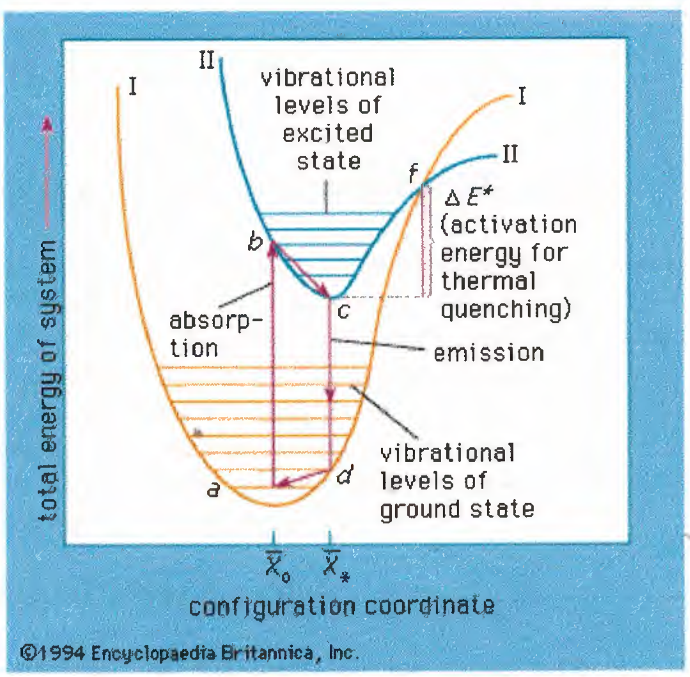


Figure3.1: Energy levels of a luminescent centre.

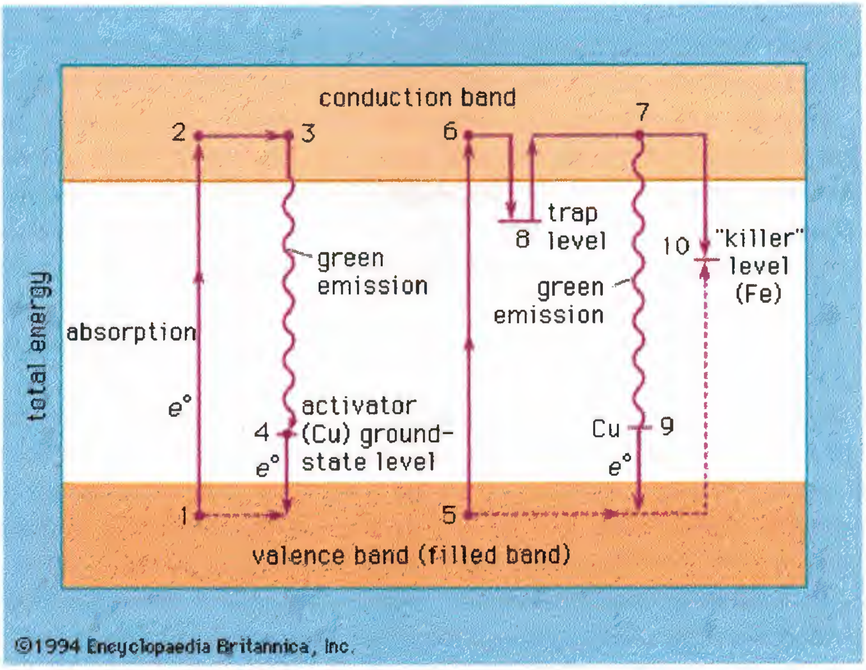


Figure 3.2: Transition of an electron from the valence band to the conduction band by light absorption .

3.3.3 Luminescent materials and phosphor chemistry

The first phosphor synthesized was probably an impure barium sulfide preparation with very low luminance efficiency and with the serious shortcoming that it was rather quickly decomposed in moist air, yielding hydrogen sulfide. A more stable sulfide.type phosphor was produced in 1866 by heating zinc oxide in a stream of hydrogen sulfide. In 1887 it became known that these sulfides do not luminesce in a chemically pure state but only when they contain small quantities of a so.called activator metal. Later, other materials, such as certain metal oxides, silicates, and phosphates, were found to luminesce if they were prepared by special procedures.

Sulfide.type phosphors, activators, fluxes

The sulfides of zinc and of cadmium are the most important basic materials of sulfide.type phosphors. An important condition of getting highly efficient phosphors is that these sulfides must first be prepared to the highest possible chemical purity before the necessary amount of activator can be added precisely. The emission of zinc sulfide can be shifted to longer wavelengths by increasing substitution of the zinc ions by cadmium ions. Zinc sulfide and cadmium sulfide phosphors are especially efficient in electroluminescence.

Sulfide.type phosphors are produced from pure zinc or cadmium sulfide or their mixtures by heating them together with small quantities (0.1.0.001 percent) of copper, silver, gallium, or other salts (activators) and with about 2 percent of sodium or another alkali chloride at about 1,000° C (1,832° F). The role of the alkali halides is to facilitate the melting process and, above all, to serve as coactivators (fluxes). Only small quantities of the alkali halide are integrated into the phosphor, but this small quantity is highly important for its luminescence efficiency. Copper.activated zinc and cadmium sulfides exhibit a rather long afterglow when their irradiation has ceased, and this is favourable for application in radar screens and self.luminous phosphors.

Oxide.type phosphors

Certain oxide.type minerals have been found to luminesce when irradiated. In some of them, activators must first be introduced into the crystal. Examples are ruby (aluminum oxide with chromium activator..bright.red emission) and willemite (zinc orthosilicate with manganese activator..green emission). On the other hand, scheelite (calcium tungstate) emits a blue luminescence without activator. All of these minerals have been made synthetically, with remarkably higher efficiencies than those that occur naturally. Silicates, borates, and phosphates of the second group of the periodic table of elements, such as zinc silicate, zinc beryllium silicate, zinc and cadmium borates, and cadmium phosphates, become efficient phosphors when activated with manganese ions, emitting in the red to green region of the spectrum. They have been incorporated into colour television screens to emit the colours blue (silver.activated zinc sulfide), green (manganese.activated zinc orthosilicate), and red (europium.activated yttrium vanadate).

Centres, activators, coactivators, poisons

The study of phosphor chemistry has yielded a detailed picture of the role of the above.mentioned activators and fluxes. Philipp Anton Lenard, a physicist in Germany, was the first (1890) to describe activator ions as being distributed in zinc sulfide and other crystalline materials that serve as the host crystal. The activator ions are surrounded by host.crystal ions and form luminescing centres where the excitation.emission process of the phosphor takes place. These centres must not be too close together within the host crystal lest they inactivate each other. For high efficiency, only a trace of the activator may be inserted into the host crystal, and its distribution must be as regular as possible. In high concentration, activators act as "poisons" or "killers" and thus inhibit luminescence. The term killer is used especially for iron, cobalt, and nickel ions, whose presence, even in small quantities, can inhibit the emission of light from phosphors.

Phosphors, such as calcium tungstate or zinc sulfide, that need no activator appear to have their luminescing centres in special groups of atoms different from the symmetry of their own crystal lattice, such as the group WO_4 in the compound calcium tungstate ($CaWO_4$), or, similarly, the SiO_4 group in zinc orthosilicate, (Zn_2SiO_4). That luminescing properties of a centre are strongly dependent on the symmetry of neighbouring ion groups with respect to the whole phosphor molecule is clearly proved by the spectral shifts of certain phosphors activated with lanthanide ions, which emit in narrow spectral regions. Because of this altering effect on the symmetry of luminescing centres, small quantities (about 0.2 percent) of titania incorporated in zinc orthosilicate give a remarkable increase in luminescence. Titania is called an intensifier activator because it increases the host.crystal luminescence, whereas a substance that produces luminescence not exhibited by the chemically pure host crystal is called an originative activator.

The fluxes (*e.g.*, sodium chloride) act as coactivators by facilitating the incorporation of activator ions. Copper ions, for instance, are used as activators of zinc chloride phosphors and are usually introduced in the copper(II), or cupric, form (the Roman numeral indicates the oxidation state; that is, I means that the element has one electron involved in a chemical bond and II that it has two electrons involved; the larger oxidation state is indicated by the *.ic* ending and the smaller by the *.ous* ending). If a copper(II) compound is incorporated into the zinc sulfide by heating, copper(I) sulfide (or cuprous sulfide, formula Cu_2S) will be produced with crystals that will not fit into the host.crystal zinc chloride because their form is so different, and only a relatively few luminescent centres will be possible. On the other hand, if a coactivator such as sodium chloride is introduced along with the copper(II) salt, the copper(II) ions are reduced to form copper(I) chloride (or cuprous chloride, formula CuCl) crystals with the same structure as the host crystal. Thus, many luminescent centres will be produced, and strong activation will result.

In describing a luminescent phosphor, the following information is pertinent: crystal class and chemical composition of the host crystal, activator (type and percentage), coactivator (intensifier activator), temperature and time of crystallization process, emission spectrum (or at least visual colour), and persistence. A few phosphors and their activators are listed in the Table.

3.3.4 Organic luminescent materials

Although the inorganic phosphors are industrially produced in far higher quantities (several hundred tons per year) than the organic luminescent materials, some types of the latter are becoming more and more important in special fields of practical application. Paints and dyes for outdoor advertising contain strongly fluorescing organic molecules such as fluorescein, eosin, rhodamine, and stilbene derivatives. Their main shortcoming is their relatively poor stability in light, because of which they are used mostly when durability is not required. Organic phosphors are used as optical brighteners for invisible markers of laundry, banknotes, identity cards, and stamps and for fluorescence microscopy of tissues in biology and medicine. Their "invisibility" is due to the fact that they absorb practically no visible light. The fluorescence is excited by invisible ultraviolet radiation (black light

Photoradiation in gases, liquids, and crystals

When describing chemical principles associated with luminescence, it is useful, at first, to neglect interactions between the luminescing atoms, molecules, or centres with their environment. In the gas phase these interactions are smaller than they are in the condensed phase of a liquid or a solid material. The efficiency of luminescence in the gas phase will be far greater than in the condensed phases because in the latter the energy of the electrons excited by photons or by chemical.reaction energy can be dissipated as thermal, nonradiative energy by collision of the atoms or by the rotational and vibrational energy of the molecules. This effect has to be taken into account even more when the radiation of single atoms is compared with that of multi.atomic molecules. For molecules, radiative (electronic.excitation) energy is internally converted to vibrational energy; that is, there are radiationless transitions of electrons in atoms. This is the explanation for the fact that only a relatively small number of compounds are able to exhibit efficient luminescence. In crystals, on the other hand, the binding forces between the ions or atoms of the lattice are strong compared with the forces acting between the particles of a liquid, and electron.excitation energy, therefore, is not as easily transformed into vibrational energy, thus leading to a good efficiency for radiative processes.

3.4 Luminescence physics

3.4.1 Mechanism of luminescence

The emission of visible light (that is, light of wavelengths between about 690 nanometres and 400 nanometres, corresponding to the region between deep red and deep violet) requires excitation energies the minimum of which is given by Einstein's law stating that the energy (E) is equal to Planck's constant (h) times the frequency of light (ν), or Planck's constant times the velocity of light (c) in a vacuum divided by its wavelength (λ); that is,

$$E = h\nu = \frac{hc}{\lambda}.$$

The energy required for excitation therefore ranges between 40 kilocalories (for red light), about 60 kilocalories (for yellow light), and about 80 kilocalories (for violet light) per mole of substance. Instead of expressing these energies in kilocalories, electron volt units (one electron volt = 1.6×10^{-12} erg; the erg is an extremely small unit of energy) may be used, and the photon energy thus required in the visible region ranges from 1.8 to 3.1 electron volts.

The excitation energy is transferred to the electrons responsible for luminescence, which jump from their ground.state energy level to a level of higher energy. The energy levels that electrons can assume are specified by quantum mechanical laws. The different excitation mechanisms considered below depend on whether or not the excitation of electrons occurs in single atoms, in single molecules, in combinations of molecules, or in a crystal. They are initiated by the means of excitation described above: impact of accelerated particles such as electrons, positive ions, or photons. Often, the excitation energies are considerably higher than those necessary to lift electrons to a radiative level; for example, the luminescence produced by the phosphor crystals in television screens is excited by cathode.ray electrons with average energies of 25,000 electron volts. Nevertheless, the colour of the luminescent light is nearly independent of the energy of the exciting particles, depending chiefly on the excited.state energy level of the crystal centres.

Electrons taking part in the luminescence process are the outermost electrons of atoms or molecules. In fluorescent lamps, for example, a mercury atom is excited by the impact of an electron having an energy of 6.7 electron volts or more, raising one of the two outermost electrons of the mercury atom in the ground state to a higher level. Upon the electron's return to the ground state, an energy difference is emitted as ultraviolet light of a wavelength of 185 nanometres. A radiative transition between another excited state and the ground.state level of the mercury atom produces the important ultraviolet emission of 254.nanometre wavelength, which, in turn, can excite other phosphors to emit visible light. (One such phosphor frequently used is a calcium halophosphate incorporating a heavy.metal activator.)

This 254.nanometre mercury radiation is particularly intensive at low mercury vapour pressures (around 10^{-5} atmosphere) used in low.pressure discharge lamps. About 60 percent of the input electron energy may thus be transformed into near.monochromatic ultraviolet light; *i.e.*, ultraviolet light of practically one single wavelength.

Whereas at low pressure there are relatively few collisions of mercury atoms with each other, the collision frequency increases enormously if mercury gas is excited under high pressure (*e.g.*, eight atmospheres or more). Such excitation leads not only to collisional de.excitation of excited atoms but also to additional excitation of excited atoms. As a consequence, the spectrum of the emitted radiation no longer consists of practically one single, sharp spectral line at 254 nanometres, but the radiation energy is distributed over various broadened spectral lines corresponding to different electronic energy levels of the mercury atom, the strongest emissions lying at 303, 313, 334, 366, 405, 436, 546, and 578 nanometres. High.pressure mercury lamps can be used for illumination purposes because the emissions from 405 to 546 nanometres are visible light of bluish.green colour; by transforming a part of the mercury line emission to red light by means of a phosphor, white light is obtained.

When gaseous molecules are excited, their luminescence spectra show broad bands; not only are electrons lifted to levels of higher energy but vibrational and rotational motions of the atoms as a whole are excited simultaneously. This is because vibrational and rotational energies of molecules are only about 10^{-2} and 10^{-4}, respectively, those of the electronic transition energies, and these many energies can be added to the energy of a single electronic transition, which is represented by a multitude of slightly different wavelengths making up one band. In larger molecules, several overlapping bands, one for each kind of electronic transition, can be emitted. Emission from molecules in solution is predominantly bandlike caused by interactions of a relatively great number of excited molecules with molecules of the solvent. In molecules, as in atoms, the excited electrons generally are outermost electrons of the molecular orbitals.

The terms fluorescence and phosphorescence can be used here, on the basis not only of the persistence of luminescence but also of the way in which the luminescence is produced. When an electron is excited to what is called, in spectroscopy, an excited singlet state, the state will have a lifetime of about 10^{-8} second, from which the excited electron can easily return to its ground state (which normally is a singlet state, too), emitting its excitation energy as fluorescence. During this electronic transition the spin of the electron is not altered; the singlet ground state and the excited singlet state have like multiplicity (number of subdivisions into which a level can be split). An electron, however, may also be lifted, under reversal of its spin, to a higher energy level, called an excited triplet state. Singlet ground states and excited triplet states are levels of different multiplicity. For quantum mechanical reasons, transitions from triplet states to singlet states are "forbidden," and, therefore, the lifetime of triplet states is considerably longer than that of singlet states. This means that luminescence originating in triplet states has a far longer duration than that originating in singlet states: phosphorescence is observed.

The interactions of a large number of atoms, ions, or molecules are greater still in solution and in solids; to obtain a narrowing of the spectral band, subzero temperatures (down to that of liquid helium) are applied in order to reduce vibrational motions. The electronic energy levels of crystals such as zinc sulfide and other host crystals used in phosphors form bands: in the ground state practically all electrons are to be found on the valence band, whereas they reach the conduction band after sufficient excitation. The energy difference between the valence band and the conduction band corresponds to photons in the ultraviolet or still shorter wavelength region. Additional energy levels are introduced by activator ions or centres bridging the energy gap between valence band and conduction band, and, when an electron is transferred from the valence band to such an additional energy level by excitation energy, it can produce visible light on return to the ground state. A rather close analogy exists between the forbidden transitions of certain excited molecular electronic states (triplet.singlet, leading to phosphorescence) and the transition of an electron of an inorganic phosphor kept in a trap: traps (certain distortions in the crystal lattice) are places in the crystal lattice where the energy level is lower than that of the conduction band, and from which the direct return of an electron to the ground state is also forbidden.

When a solid is bombarded by photons or particles, the excitation of the centres can occur directly or by energy transfer. In the latter case, excited but nonluminescing states are produced at some distance from the centre, with the energy moving through the crystal in the form of excitons (ion.electron pairs) until it approaches a centre where the excitation process can occur. This energy transfer can also be realized by radiation in inorganic phosphors containing two activators, as well as in solutions of organic molecules

3.4.2 Spontaneous and stimulated emission

The radiative return of excited electrons to their ground state occurs spontaneously, and when there exists an assembly of excited electrons their individual spontaneous radiative transitions are independent of each other. Therefore, the luminescence light is incoherent (the emitted waves are not in phase with each other) in this case. Sometimes the emission of luminescence can be stimulated by irradiation with photons of the same frequency as that of the emitted light; such stimulated transitions are used in lasers, which produce very intensive beams of coherent monochromatic light.

The spontaneous luminescent emission follows an exponential law that expresses the rate of intensity decay and is similar to the equation for the decay of radioactivity and some chemical reactions. It states that the intensity of luminescent emission is equal to an exponential value of minus the time of decay divided by the decay time, or $L = L_0$ exp $(.t/\tau)$, in which L is the intensity of emission at a time t after an initial intensity L_0, and τ is the decay time of the luminescence; that is, the time in which the assembly of the excited atoms would decrease in luminescence intensity to a value of 0.368 L_0.

When excited atoms of the centres are in contact with other atoms, as is the case in condensed phases (liquids, solids, in gases of not.too.low pressure), part of the excitation energy will be transformed into heat by collisional deactivation (thermal quenching). The decay time, therefore, has to be replaced by an effective excited.state lifetime, resulting in a more complicated exponential decay law that depends on the collision frequency, the energy imparted to the excited atoms of the centre that causes the transfer of excitation energy into heat (activation energy), a constant, and the temperature of the luminescent material. This law describes the actual luminescence decay of a great number of luminescent materials; *e.g.*, calcium tungstate.

Increase of activation energy for nonradiative deactivation of excited.centres luminescence decay can be achieved by changing the host crystal or by electron traps. The traps are imperfections in the crystal lattice where electrons are captured after they have been ejected from a luminescent centre by excitation energy. That the luminescent properties of phosphor centres are strongly dependent on the chemical nature of the host crystal may be seen in the Table, showing that the same activator ions (manganese ions with two positive charges, indicated as Mn^{2+}, or Mn[II]), in different host crystals yield remarkably different.coloured emissions and decay times (measured in fractions of a second).

Prolonging the emission time of phosphors up to days or even longer (production of phosphorescence of the phosphors) is possible by inserting traps into the host crystal. Trapped electrons cannot return directly to the centre. In order to be released from the traps they must first obtain additional thermal energy..in this case, thermal energy stimulates luminescence..after which they recombine with a centre and undergo radiative transition. Trapping in crystals has its analogy to forbidden transitions in molecules (triplet.singlet transitions) or in radiation processes from metastable atomic.energy levels.

An example of a practical application of stimulated emission of a phosphor with trapped electrons is cubic strontium sulfide/selenide activated with samarium and europium ions, the coactivators being strontium sulfate and calcium fluoride. This phosphor has been used in devices for viewing scenes at night by reflected infrared light emitted by infrared lamps. The traps in this phosphor have been identified as samarium ions, whereas europium ions are the active ions in the centres. The phosphor is first excited by photons of about three electron volts (blue light), which results in an ejection of an electron from a europium ion (Eu^{2+}) centre. This excited electron is trapped by a triply charged samarium ion (Sm^{3+}), which is transferred to a doubly charged samarium ion (Sm^{2+}). Heat or irradiation by infrared photons releases one electron from the doubly charged samarium ion (Sm^{2+}). The electron is then recaptured from a triply charged europium ion (Eu^{3+}), yielding an excited doubly charged europium ion (Eu^{2+}), which returns to its ground state by emitting a photon of 2.2 electron volts energy (yellow light). The trap depth of this phosphor (*i.e.*, the energy required for release of an electron from it) is large compared to the thermal energy of the lattice of the host crystal, and, therefore, the lifetime of the traps at room temperature is many months long. Bombarding this phosphor with photons of energy higher than that of infrared photons but not sufficient for excitation can lead to photoquenching: the traps are emptied far more rapidly, and thermal deactivation of the centres is enhanced.

When iron, cobalt, or nickel ions are present in a phosphor, an excited electron can be captured by these ions. The excitation energy is then emitted as infrared photons, not as visible light, so that luminescence is quenched. These ions, therefore, are called killers..the killing process being opposite to stimulation.

In chemiluminescence, such as the oxidation of luminol, light emission depends not only on radiative and quenching or intramolecular deactivation processes but also on the efficiency of the chemical reaction leading to molecules in an electronically excited state.

In bioluminescence reactions, the production of electronically excited molecules, as well as their radiative transitions back to their ground state, is efficiently catalyzed by the enzymes acting here, and bioluminescence light output is therefore high.

The luminescence photons emitted by one kind of excited atom, molecule, or phosphor can excite another to emit its specific luminescence: this type of energy transfer is observed with inorganic as well as organic substances. Thus, excited benzene molecules can excite naphthalene molecules by radiative.energy transfer. The radiation produced by the luminol chemiluminescence can produce fluorescence when fluorescein is added to the reaction mixture. In most of these cases the acceptor molecules have luminescent electrons with energy levels lower than those of the primary excited molecules, and emitted secondary luminescence is therefore of longer wavelength than the primary. Practical application of this phenomenon, called cascading, is used in radar kinescopes, which have composite fluorescent screens consisting of a layer of blue.emitting zinc sulfide/silver (chloride) phosphor..the hexagonal crystal, ZnS/Ag(Cl) deposited on a layer of yellow.emitting zinc or cadmium sulfide/copper [chloride] phosphor [the hexagonal crystal, (Zn,Cd)S/Cu (Cl)].

The cathode.ray electrons excite the blue.emitting phosphor, whose photons, in turn, excite the yellow.emitting phosphor, which has traps with a decay time of about 10 seconds. Excitation of the blue.emitting phosphor alone would be unfavourable, as the sharply focussed cathode rays are absorbed by the blue phosphor to a small extent only, and its decay time is too short; also, direct excitation of the yellow.emitting phosphor alone would yield poor efficiency because the traps are emptied too rapidly by the heat produced by the relatively high.energetic electron impact.

Another energy.transfer mechanism is referred to as sensitization: a calcium carbonate phosphor (rhombohedral $CaCO_3$/Mn), for example, emits orange light under cathode.ray irradiation but is not excited by the 254.nanometre emission of mercury atoms, whereas this emission produces the same orange light with calcium carbonate (rhombohedral $CaCO_3$) activated by manganese and lead ions. This is not cascade luminescence: a mechanical mixture of a manganese and a lead.activated calcium carbonate exhibits no emission under ultraviolet radiation. In a phosphor containing both activators, the lead ions act as sensitizers in introducing an additional excitation band into the system from which the manganese ions get their excitation energy in a nonradiative energy transfer. Similar sensitization is observed in gases and in liquids.

3.4.3 Solid state energy states

The complicated problems concerning the energy states in solids of a luminescence centre are commonly visualized by adapting the energy.level diagram used in describing energy transitions in an isolated diatomic molecule (Figure 1).

In this diagram, the potential energy of a centre is plotted as a function of the average distance ($\bar{x}$) between the atoms: $\bar{x}^*$ represents the ground state and $\bar{x}_o$ represents the lowest excited state of the centre. In a tetrahedral permanganate.ion centre (MnO_4), for example $\bar{x}$would be the average distance between the central manganese ion and an oxygen ion in any of the corners of the tetrahedron.

At a temperature of absolute zero the ground.state energy level is near the bottom of curve I at the minimum amplitude of atomic vibration. At room temperature (300 K [81° F]) the ground state lies higher, at *a*, where the centre has considerable vibrational energy. When an electron of the centre is excited, it is lifted to the higher energy level at *b* in curve II. This electronic transition occurs far more rapidly than the readjustment of the atoms of the centre, which then occurs within a time of about 10^{-12} second to reach the minimum vibrational level at *c*. The energy difference (*b* . *c*) is dissipated as heat in the host.crystal lattice. From the excited.state level *c*, the electron can return to the ground.state level *d* shown in Curve I, the liberated energy being emitted as a photon.

The last step is a readjustment of the centre to *a*, the energy difference (*d* . *a*) again being dissipated as heat. Nonradiative transition of the excited electron back to its ground state occurs when the electron is excited to an energy level above the intersection point *f* of the ground.state and the excited.state energy curve. This is caused mainly by increasing the vibrations of the lattice by application of higher temperatures. The energy difference (*f* . *c*) is equal to the activation energy already mentioned, and therefore most centres become increasingly nonradiative at higher temperatures. In trap.type phosphors the temperature must be sufficiently high, of course, to eject the electron from the traps.

In some phosphors..calcium tungstate ($CaWO_4$), for example..absorption and emission of the exciting energy appear to take place mainly in the same centre; the excited electron remains near the centre. Such phosphors do not exhibit photoconductivity because only a few excited electrons succeed in reaching the conduction band where they are freely mobile. The luminescence decay is exponential.

Zinc sulfide phosphors, however, are photoconducting, which means that many excited electrons are lifted to the conduction band of the host crystal. The energy levels of different centres and of the host.crystal lattice have to be taken into account simultaneously.

The relative levels of the zinc sulfide valence band (ground state of the host.crystal lattice) and the conduction band (excited state of the host.crystal lattice), of activator levels and of trap levels are shown in Figure 2. Points 1, 2, 3, and 4 represent one situation in a host crystal, and points 5, 6, 7, 8, 9, and 10 represent another situation.

The activator ions introduce additional ground.state levels and excited.state levels of energies between those of the valence and the conduction band of the zinc sulfide.

When the excitation energy is sufficiently high, an electron is raised to the conduction band (1 →2, 5 →6, corresponding to the ionization continuum in a gas). It moves away from the centre (2 →3, 6 →8) and may either be trapped by an imperfection of the lattice (8) or return to an ionized centre (activator), in which it first occupies an excited level (3 →4) and then drops to the ground state of the activator centre by emitting a photon. An activator centre that captures such an excited electron has already lost one of its own electrons to a positive hole (electron vacancy) in the host.crystal lattice.

The energetic level of the traps is about 0.25 electron volt beneath the conduction.band level. A trapped electron (8) must be raised to the conduction band by thermal energy before a recombination with an ionized activator centre can occur. The green emission (530 nanometres) of the zinc sulfide phosphor (ZnS/Cu) is explained by the recombination of an electron from the conduction band and a copper ion in an activator centre (7 →9); the blue emission (463 nanometres) is due to recombination of the excited electron and a copper ion in an interstitial place.

Direct excitation of the activator centres is also possible. When an electron recombines with a killer ion (10), no visible emission occurs.

In solid.state electroluminescence, the radiative processes occurring in a phosphor under irradiation are produced by applying external electric fields of several hundred volts, alternating at several thousand cycles per second. Special preparations of zinc sulfide (hexagonal ZnS), with an iodine coactivator and high concentrations of a copper activator, are embedded in a thin layer of about 0.01 centimetre (0.004 inch) of insulating organic material or glass, which is mounted between the electrodes.

High luminescence efficiencies result. Application of a direct.current field yields luminescence in crystals of gallium arsenide (GaAs), silicon carbide (SiC), cadmium sulfide (CdS), and zinc monocrystals of sulfide with copper activator (ZnS/Cu); the cathode injects electrons into the conduction band, whereas the anode removes electrons.

3.5 Efficiency of luminescence; luminance

The efficiency of luminescence emission must be regarded on an energy and a quantum basis. When every exciting photon yields an emitted photon of the same energy (as is the case for resonance excitation..*i.e.*, excitation of fluorescence by a monochromatic light of exactly the same wavelengths as the resulting fluorescence..and radiation of isolated atoms in dilute gases), the luminescence efficiency is 100 percent with respect to input energy as well as to the number of quanta. When the number of secondary photons is equal to that of the primary but their energy is less because some energy is dissipated as heat, the quantum efficiency is 100 percent but the luminescence efficiency is less than 100 percent. The quantum efficiency of most luminescences is far lower than 100 percent; zinc sulfide phosphors have about 20 percent efficiency, and solid.state electroluminescence is less than 10 percent efficient.

In chemiluminescence the quantum efficiency is about 1 percent in "brilliant" reactions, such as the oxidation of luminol, and up to 23 percent in the oxalate chemiluminescence. Solid.state electroluminescence, or electroluminescence of gases excited by high.frequency electric fields, is usually less than 10 percent.

The light intensity of luminescent processes depends chiefly on the excitation intensity, the density, and the lifetime of the radiative atoms, molecules, or centres. For practical purposes this luminous intensity per unit area is called photometric brightness or luminance of a material and is measured in lambert or millilambert (0.001 lambert) units (one lambert is equal to one candle per square centimetre divided by π).

3.6 luminescence (summary)

a process by which some materials emit light when they are relatively cool. Familiar examples of luminescence are the light emissions from: electronically excited gases in neon lamps and lightning; tiny inorganic crystals used as coatings in luminescent watch dials, television and radar kinescopes, fluorescent lamps, and X.ray fluoroscope screens; and certain organic materials undergoing oxidation in fireflies and glowworms. Because they luminesce at room temperature such materials emit what is sometimes loosely called cold light, to distinguish it from the temperature.dependent light emitted by incandescent sources.

The process of luminescence is started by exciting some material, usually with ultraviolet radiation, X.rays, electrons, alpha particles, electric fields, or energy liberated during some chemical reactions. Suitable materials convert one or more of these invisible input energies to light. Few luminescent materials are efficient enough for practical use. The efficient ones are custom.made to convert a particular input energy to light of a particular colour and intensity. The colour is determined by the material, while the intensity depends on the material and the input energy. Every kind of atom, when alone, will luminesce; and each kind of atom exhibits characteristic spectral lines, which have been interpreted in terms of quantum theory.

According to quantum theory an isolated atom or ion can exist indefinitely in an unexcited state (called the ground state) or it can be excited and exist for short periods in one or another of various discrete excited states. In other words, a given kind of atom can exist briefly in one of several separate and distinct states of higher energy, but not in intermediate states. Each state has an energy level that corresponds to a different configuration of the electrons in the atom. When the excited atom drops from a higher to a lower energy level, the difference in energy between the two sharply defined levels is radiated as a discrete bit (quantum) of light that is called a photon.

A lone excited atom loses its excess energy by radiation, in the absence of collisions with other atoms. An excited atom in a molecule, however, can dissipate excess energy by converting it to increased agitation of all the atoms that are bound together in the molecule. Spectroscopic analysis of light from luminescing molecules shows that the energy levels of the constituent atoms are altered and proliferated into many additional closely spaced levels as a result of vibrations and rotations of the atomic ensemble. A multiatom ensemble generally has lower efficiency of luminescence than an isolated atom because the assemblage can convert excitation energy into atomic motion, which in condensed matter is thermal agitation (heat).

The probability of dissipating input energy as heat is enormously increased on going from an isolated atom to one bound to myriads of others in an elemental liquid or solid. Most elemental liquids and solids, therefore, are nonluminescent. Mercury is an efficient luminescent gas but is a nonluminescent liquid. There are some nonelemental liquids, however, that have relatively high luminescence efficiencies. In benzene C_6H_6 (which luminesces as a gas, a liquid, and a solid) the hexagonal benzene molecule emits ultraviolet radiation in all three physical states. Crystals are generally the most efficient sources of luminescence, because their ordered structures provide stable arrangements of atoms and permit relatively efficient ingress and internal transport of input energy, and emission of photons.

The terms phosphorescence and fluorescence are often used instead of luminescence. While the distinction does not hold absolutely, the two terms are commonly used to designate luminescence that persists after the activating radiation has ceased (phosphorescence) versus luminescence that ceases within about 10^{-8} seconds after the activating radiation does so (fluorescence).

Instances of luminescence may also be distinguished by the manner in which it is produced. Thus, chemiluminescence proceeds from chemical reactions, as the oxidation of luminol by hydrogen peroxide; bioluminescence, a subcategory of chemiluminescence, occurs in living creatures such as fireflies or glowworms; triboluminescence occurs when crystals of certain substances, such as sugar, are crushed. Similarly, thermoluminescence, photoluminescence, electroluminescence, and radioluminescence are stimulated by heat, light, electric discharge, and radiation, respectively.

candela

SI unit of measurement, defined as the luminous intensity in a given direction of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and has a radiant intensity in that same direction of 1/683 watt per steradian (unit solid angle). The candela, abbreviated as cd, has replaced the standard candle or lamp as a unit of luminous intensity in calculations involving artificial lighting and is sometimes called the "new candle."

CHAPTER FOUR

LIGHTING DESIGN

4.1 Introduction

In the era of painted wings and drops, the standard illumination was an even, flat wash from footlights and borderlights. Architecture and furniture, including tables and chairs, were painted into the background with heavy shadows and exaggerated perspective. The actors had to resort to grotesquely heavy makeup to convey any facial expression, while their very presence (and every movement) was visually in conflict with the forced perspective of the painted scenery. By contrast, the impressive effects of modern lighting made it seem almost limitless in its possibilities. Borrowing effects from Rembrandt and other painters, the theatre designer began to "paint with light"..putting light where he wanted it and taking it away from where he did not want it. Thus, romantic effects were born, such as that of the lone figure in a shaft of searing light, isolated by darkness. The first requisite of stage lighting, however, is visibility. Good illumination provides plasticity and modeling of the actors and of the inanimate objects. Superior lighting is orchestrated to underline the development of the drama.

Many plays permit no approach other than realism, which must be achieved by suggestion. Nature provides the model. On a cloudy day, the overcast sky diffuses the direct sunlight and produces a soft, shadowless light of low intensity and cool colour. Intense "sunlight" on stage and the attendant light of the bright sky together produce reflected light that diffuses or fills in shadows, while the ambient light of the stage "Moon" reflected from sky, trees, and buildings is too weak to wash out the shadows. So, by means of the direction, diffusion, and intensity of light, as well as its colour, it is possible to suggest time, place, and season.

The means of suggesting natural lighting indoors are more arbitrary. The simulated sky or sunlight seen through a door or window..a scenic element provided by the dramatist and the designer..is essential to indicate the time of day or night. To render the feeling of bright daylight flooding a room, the strong motivating light (*i.e.,* light that suggests the direction of its source) must be supplemented with additional light from other directions for adequate illumination. If only a sliver of sunlight creeps through a parted curtain in a dark room as the scene begins, the mood may be retained as the scene progresses as the illumination of important areas is slowly increased. Artificial light indoors is easier to suggest because it more closely approaches the normal quality of stage lighting. Actual light fixtures are used on stage to suggest the sources of the light, and opaque shades can be used on some of these fixtures so that they cast actual patches of light against walls and furniture. The exteriors seen through doors and windows are darkened and different in colour from their appearance in a brightly sunlit scene. The walls fall off in shadow even though the general illumination is more diffused and even than in daylight. Light serves as a unifying medium for the stage composition. It is a mobile and changing accent that reinforces the action, sustains the mood, and focuses the attention of the audience. Light and shade, brightness and contrast, define the size and shape of objects, but it is colour that creates emotional response, mood, and atmosphere.

The dynamic potential of lighting is best realized when the changes of light underscore and propel the development of the drama. The first real attempt at creating space and a real haze on stage (in a depth of 30 feet) came into being with the use of backlighting..light emanating from the rear of the stage rather than the front..which made the actors appear to be pulled away from the background. At first, parabolic beam projectors were used to achieve this effect, then ellipsoidal spotlights, and later, in some instances, sealed.beam parabolic reflector lamps. The ellipsoidal reflector spotlights afford the best control and the least spill. The beam projector may be deployed in a battery offstage to create the illusion of paths of sunlight or moonlight or a strong sidelight or crosslight. For strong crosslight, clusters of low.wattage units were supplanted by powerful ellipsoidal spotlights, hung low. With the addition of lamps attached to the auditorium's boxes, or box booms, besides the lamps already on the balcony rail or ceiling coves, modern lighting began to take shape. The open stage of the musical and dance furthered the development of effective lighting.

In bold outline, modern lighting can be described in terms of a square consisting of a lucid pattern of strong backlight, paths of strong crosslight, and the necessary fill light from the front from the boxes and first pipe (*i.e.*, lights hanging from a horizontal pipe just inside the proscenium) on stage, plus special lights as needed. Richer colours are used in the backlighting and crosslighting. Lights creating warm and cool effects are wired to circuits that allow them to be controlled right, centre, and left stage. The crosslighting coming from offstage and from the box booms is usually less saturated in colour. The lights on the balcony rail give a pale wash..passive illumination to produce visibility without destroying the sharp modeling of the backlighting and sidelighting. Special lights, in colour or clear, cut through particular areas from the box booms and the pipes on stage.

When box sets began to go out of style, and suggestive sets, skeletal fragments without ceiling and walls, were introduced, the necessary lighting technique was already within reach in the layouts for musicals. There was need for more special lights, different circuiting, softer colours, more pattern projections, and more intricate, overlapping changes of light. The pattern of back, sides, and front, however, still holds; it is a clear.cut, three.dimensional approach, with distinct functions meshing into a controlled pattern.

For the most part, ellipsoidal reflector spotlights are used to cover acting areas from all locations. Fresnel spotlights are used for area washes or to accent plastic scenery elements. The appearance of scenery as it is illuminated by the lighting intended for the acting areas is totally unpredictable; it is necessary to provide separate blending or accent lighting for most plastic scenery. Patterned projections, such as leaves or abstract patterns, may be used in wide.angle, ellipsoidal spotlights to project on scenery that is solid or even made of gauze.

The three.dimensional approach to lighting developed within the confines of the proscenium stage; it is also valid for the thrust stage or arena theatre. For theatre in the round, the predominant angles for lighting tend to be sharper and also to be steeper, to avoid spill into the audience area that would disturb the spectators. The ellipsoidal reflector spotlight is used for all acting areas, and an added high hat (a hollow tube that extends six to 12 inches) will confine unwanted spill as well as hide the lens and colour frame.

In simple language, lighting is a matter of hanging the right instrument in the right place and focusing on the right target. Stage lighting cannot be mastered except through the observation and experience that are necessary to learn the practical and aesthetic functions of light. It is essential to know the physical characteristics of different light sources and how and when to use them to best advantage. It is also mandatory to learn the complexities of control and how to build lighting changes. Stage lighting must be more than good illumination. Light must be used as a subtle flux, exerting a subconscious influence that unifies all the media of the theatre.

The creative concept formed for lighting a production requires that the essential qualities of the play be understood and absorbed. The theme or main line of the script may suggest an overriding motif: enervating heat, damp clamminess, dappled sunlight, cold penetrating north light, a feeling of being in limbo or underwater. The final choice must satisfy the particular qualities of the production and the concepts of the playwright, director, and actors, as well as the designer. Attending run.throughs in the final period of rehearsals reinforces previous impressions and suggests refinements in the rhythmic changes of light required. The actors' performances suggest lighting changes that can enhance the emotional range of the total performance.

4.2 Lighting controls

The dream of a practical system of remote control of lighting has always tantalized designers. Relays for remote switching have been commonplace for years. Motor.driven dimmers have proved practical for controlling auditorium lighting but for stage lighting are too cumbersome, expensive, and limited in speed control and are unpredictable in responding to changes. Banks of resistance and transformer switchboards were too bulky to be installed in a light booth at the rear of the auditorium with a clear view of the stage.

The first primitive but successful remote.controlled dimmer was used in 1890 but not perfected until later; it used a reactor coil operating on a relatively small amount of direct current to control a huge amount of alternating current.

Remote control became a reality largely as the result of the development by George Izenour of Yale University in 1948 of a dimmer using the thyratron, a type of electron tube. His concept brought continuous and instantaneous control to remote systems for the first time. In addition to its simplicity of operation, the development gave the lighting designer the facility for an "infinite" combination of preset cues. It also became practicable to install the control console at a vantage point in the auditorium from which the lighting designer (or operator) could see every nuance of lighting on stage.

Meanwhile, transformer manufacturers achieved a major breakthrough in design with the development of new magnetic alloys. The result was a reactor with great efficiency and speed. This new reactor, combined with the silicon rectifier, another post.World War II development, resulted in a device called a magnetic amplifier, which has no moving parts or tubes and can control large amounts of alternating current with no time lag.

Tube manufacturers, meanwhile, were furthering the development of the transistor, namely, the silicon.controlled rectifier, or SCR, a transistor.like device that can handle heavy currents and perform in the same manner as the thyratron tube but with the advantage that it is compact, lightweight, inexpensive, efficient, and long.lasting. Control consoles using all three types of dimmers are in current use.

The design of lighting control boards is no longer a matter only of electrical engineering, in which the only concerns are engineering requirements or code specifications. Previously, the lighting designer had to make the most of whatever the engineers had given him. Now the remote lighting.control console gives the lighting designer a flexible, artistic tool. Freed from the limitations of the mechanical controls and of the personnel who would operate them, the lighting artist can concentrate on the execution of his concept. No longer is there any reason for the mechanical limitations to interfere with the lighting.

The biggest advance in stage lighting control in recent years has been the ability to record instantly and recall on cue the entire contents of a stage picture. A video display unit can present the information on the lighting state for any cue in an easily readable form. The present systems work on a principle of one dimmer for each light in order to eliminate cross patching of circuits. In the previous generation of preset boards, each lantern was equipped with a number of dimmers and several cues could be preset. On cue the board cut from one set of dimmers to another to effect the change. The memory system board is much more flexible and is probably capable of even further development and sophistication. The development of memory system boards and new lighter weight dimmer packs are a material help to touring.

4.2 Lumınaires

1. Luminaire Efficiency
2. Directing Light

A luminaire, or light fixture, is a unit consisting of the following components:

1. lamps
2. lamp sockets
3. ballasts
4. reflective material
5. lenses, refractors, or louvers
6. housing

4.2.1 Luminaire

The main function of the luminaire is to direct light using reflective and shielding materials. Many lighting upgrade projects consist of replacing one or more of these components to improve fixture efficiency. Alternatively, users may consider replacing the entire luminaire with one that is designed to efficiently provide the appropriate quantity and quality of illumination.

There are several different types of luminaires. The following is a listing of some of the common luminaire types:

1. General illumination fixtures such as 2x4, 2x2, & 1x4 fluorescent troffers
2. down lights
3. Indirect lighting (light reflected off the ceiling/walls)
4. Spot or accent lighting
5. Task lighting
6. Outdoor area and flood lighting

4.2.2 Luminaire Efficiency

The efficiency of a luminaire is the percentage of lamp lumens produced that actually exit the fixture. The use of louvers can improve visual comfort, but because they reduce the lumen output of the fixture, efficiency is reduced. Generally, the most efficient fixtures have the poorest visual comfort (e.g. bare strip industrial fixtures). Conversely, the fixture that provides the highest visual comfort level is the least efficient. Thus, a lighting designer must determine the best compromise between efficiency and VCP when specifying luminaires. Recently, some manufacturers have started offering fixtures with excellent VCP and efficiency. These so.called "super fixtures" combine state.of.the.art lens or louver designs to provide the best of both worlds.

Surface deterioration and accumulated dirt in older, poorly maintained fixtures can also cause reductions in luminaire efficiency. Refer to Lighting Maintenance for more information.

4.2.3 Directing Light

Each of the above luminaire types consist of a number of components that are designed to work together to produce and direct light. Because the subject of light production has been covered by the previous section, the text below focuses on the components used to direct the light produced by the lamps.

4.2.4 Reflectors

Reflectors are designed to redirect the light emitted from a lamp in order to achieve a desired distribution of light intensity outside of the luminaire.

In most incandescent spot and flood lights, highly specular (mirror.like) reflectors are usually built into the lamps.

One energy.efficient upgrade option is to install a custom.designed reflector to enhance the light control and efficiency of the fixture, which may allow partial delamping.

Retrofit reflectors are useful for upgrading the efficiency of older, deteriorated luminaire surfaces. A variety of reflector materials are available: highly reflective white paint, silver film laminate, and two grades of anodized aluminum sheet (standard or enhanced reflectivity). Silver film laminate is generally considered to have the highest reflectance, but is considered less durable.

Proper design and installation of reflectors can have more effect on performance than the reflector materials. In combination with delamping, however, the use of reflectors may result in reduced light output and may redistribute the light, which may or may not be acceptable for a specific space or application. To ensure acceptable performance from reflectors, arrange for a trial installation and measure "before" and "after" light levels using the procedures outlined in Lighting Evaluations. For specific name.brand performance data, refer to Specifier Reports, "Specular Reflectors," Volume 1, Issue 3, National Lighting Product Information Program.

4.2.5 Lenses and Louvers

Most indoor commercial fluorescent fixtures use either a lens or a louver to prevent direct viewing of the lamps. Light that is emitted in the so.called "glare zone" (angles above 45 degrees from the fixture's vertical axis) can cause visual discomfort and reflections, which reduce contrast on work surfaces or computer screens. Lenses and louvers attempt to control these problems.

Lenses

Lenses made from clear ultraviolet.stabilized acrylic plastic deliver the most light output and uniformity of all shielding media. However, they provide less glare control than louvered fixtures. Clear lens types include prismatic, batwing, linear batwing, and polarized lenses. Lenses are usually much less expensive than louvers. White translucent diffusers are much less efficient than clear lenses, and they result in relatively low visual comfort probability. New low.glare lens materials are available for retrofit and provide high visual comfort (VCP>80) and high efficiency.

Louvers

Louvers provide superior glare control and high visual comfort compared with lens.diffuser systems. The most common application of louvers is to eliminate the fixture glare reflected on computer screens. So.called "deep.cell" parabolic louvers (with 5.7" cell apertures and depths of 2.4" (provide a good balance between visual comfort and luminaire efficiency. Although small.cell parabolic louvers provide the highest level of visual comfort, they reduce luminaire efficiency

4.2.6 Distribution

One of the primary functions of a luminaire is to direct the light to where it is needed. The light distribution produced by luminaires is characterized by the Illuminating Engineering Society as follows:

1. Direct (90 to 100 percent of the light is directed downward for maximum use.
2. Indirect (90 to 100 percent of the light is directed to the ceilings and upper walls and is reflected to all parts of a room.
3. Semi.Direct (60 to 90 percent of the light is directed downward with the remainder directed upward.
4. General Diffuse or Direct.Indirect (equal portions of the light are directed upward and downward.
5. Highlighting (the beam projection distance and focusing ability characterize this luminaire.

The lighting distribution that is characteristic of a given luminaire is described using the candela distribution provided by the luminaire manufacturer (see diagram on next page). The candela distribution is represented by a curve on a polar graph showing the relative luminous intensity 360 around the fixture (looking at a cross.section of the fixture. This information is useful because it shows how much light is emitted in each direction and the relative proportions of downlighting and uplighting. The cut.off angle is the angle, measured from straight down, where the fixture begins to shield the light source and no direct light from the source is visible. The shielding angle is the angle, measured from horizontal, through which the fixture provides shielding to prevent direct viewing of the light source. The shielding and cut.off angles add up to 90 degrees. The lighting upgrade products mentioned in this document are described in more detail in Lighting Upgrade Technologies.

CHAPTER FIVE

OUTDOOR LIGHTING

5.1 Introduction

After the sun sets, life goes on. Shipping, maintenance and materials handling operations often continue in outdoor locations long into the night, and effective outdoor lighting can enhance the productivity of these activities. As daylight vanishes, the potential for accidents and crime increases. Therefore, conservation efforts directed toward outdoor lighting systems should not sacrifice productivity or safety.

5.2 Outdoor lighting upgrade goals

Every outdoor lighting upgrade should satisfy each of these goals:

• Deliver the light level needed to provide adequate security, safety and productivity.

• Minimize visual fatigue by maintaining relatively uniform light levels and controlling glare, particularly in applications involving vehicle use. The human eye is easily fatigued when it must continually adapt to differing degrees of brightness. In some cases, direct glare can severely reduce visibility, increasing the risk of accidents.

• Select light sources that provide the appropriate color rendering performance. In activities such as materials handling and out.door retail activities, color identification can be critical. How.ever, a high CRI rating is not important for routine surveillance where the visual task is detecting potential security problems.

• Use the light sources and luminaires that will most economically deliver lumens to the outdoor area. This may involve upgrading to a more efficient outdoor lighting source and/or installing efficient luminaries with improved lighting distribution performance.

• Install automatic controls to eliminate daytime operation and minimize unnecessary nighttime operation.

5.3 Recommended light levels and uniformity ratios

The IESNA recommends specific maintained illuminance values for outdoor lighting applications. Table 17.1 lists these recommendations for some of the more common applications. Note that where vehicle operation is assumed, the lighting system should maintain a uniformity ratio that does not exceed the maximum value shown.
For example, assume that the average maintained light level in a covered parking area is 5 fc. To maintain an average.to.minimum uniformity ratio of no more than 4:1, the minimum light level (typically between luminaire locations) should be no less than 1.25 fc. The IESNA *Lighting Handbook* lists illuminance recommendations for many other outdoor lighting applications not shown in the table.

5.4 Light source selection factors

To maximize energy savings, use the lowest.wattage outdoor lighting systems that deliver the appropriate light levels and desired color quality. The variables of color rendering requirements and mounting height will significantly affect the choice of upgrade solutions.
Other factors that affect light source selection are the mini.mum starting temperature and the physical layout of the outdoor area to be illuminated.

5.4.1 Color Rendering

Under sources with a low CRI, colors will appear unnatural or less bright than under high CRI sources. Therefore, avoid using HPS and LPS sources in outdoor lighting applications where high quality color rendering is important (such as car sales, billboards and sports facilities). For example, metal halide lamps may be used to illuminate a softball field (where color rendering is important),

Table 5.1. Target light levels and uniformity ratios. Source: Illuminating Engineering Society of North America.

Outdoor Lighting Applications	**Recommended Maintained Illuminance (And Maximum Uniformity Ratios)**
Building Exteriors	5 fc entrances 1 fc surroundings
Billboards/Signs	100 fc dark surfaces; bright surroundings 50 fc light surfaces; bright surroundings 50 fc dark surfaces; dark surroundings 20 fc light surfaces; dark surroundings
Gardens	0.5 fc general lighting 1 fc path and steps
Loading Platforms	20 fc
Recreational Sports	10 fc basketball 10 fc tennis 10 fc softball (infield) 7 fc softball (outfield)
Local Commercial Roadways	8 fc (6:1 average.to.minimum uniformity ratio)
Covered Parking Facilities	5 fc (4:1 average.to.minimum uniformity ratio)
Open Parking Facilities: General Parking & Pedestrian Area	3.6 fc high activity (4:1 avg/min uniformity) 2.4 fc medium activity (4:1 avg/min uniformity) 0.8 fc low activity (4:1 avg/min uniformity)
Open Parking Facilities: Vehicle Use Area (only)	2.0 fc high activity (3:1 avg/min uniformity) 1.0 fc medium activity (3:1 avg/min uniformity) 0.5 fc low activity (4:1 avg/min uniformity)

High.pressure sodium lamps may be used to illuminate the roadway and parking areas. Refer to the Table 17.2 for typical CRI and efficacy values of light sources used for outdoor applications. As Table .2 shows, the most efficacious outdoor lighting sources generally deliver the lowest color rendering performance. However, in many outdoor applications, lighting system selections are driven by color rendering and mounting height factors, leaving relatively few decisions to make regarding efficacy. To the extent possible, avoid using low.efficacy sources such as incandescent, mercury vapor, VHO fluorescent and other magnetic.ballast fluorescent systems.

5.4.2 Mounting Height

To illuminate large outdoor areas with high.mounted luminaries, use either HPS or metal halide lamps. These are energy.efficient, high.output "point" sources. Point source luminaries are inherently the most effective for long.distance light projection. For lighting smaller areas and/or where luminaries are mounted at lower heights, the more diffuse sources may be used. Fluorescent and LPS lamps are "low.pressure discharge" sources which, unlike point sources, provide relatively diffuse (scattered) light and are more effective at lower mounting heights (below 20.25 ft.). HID sources may also be used at these lower mounting heights, provided that adequate glare shielding is provided. The mounting height of low.wattage (<18W) compact fluorescent sources should generally be limited to 10 ft. or less.

Table 5.2. Typical performance of outdoor light sources. Source: Manufacturer literature

Fluorescent

Light Source	CRI Rating	Maintained Efficacy (lm/W)
T4 Compact Fluorescent	82 . 86	25 . 65
T5 Twin.Tube Fluorescent	82 . 85	35 . 74
T8 Standard	75 . 85	70 . 90
T12 Standard	62 . 85	50 . 90
T8 High Output	80	81
T12 Very High Output	62 . 85	42 . 44

High.intensity discharge

Light Source	CRI Rating	Maintained Efficacy (lm/W)
Metal Halide	65 . 85	38.86
High.Pressure Sodium Standard HPS	22	45 . 115
High.Pressure Sodium Deluxe HPS	65	42 . 73
Mercury Vapor	22 . 50	19 . 43
Low.Pressure Sodium	0	50 . 150

5.4.3 Cold.Weather Performance

Note that the light output and efficacy of fluorescent systems can drop dramatically in temperatures under 50°F, depending on the lamp type and chemistry. Some compact fluorescent lamps utilize a mercury amalgam (mercury alloy) that allows for cold.weather starting and near.peak operating performance at temperature extremes. With low.temperature fluorescent electronic ballasts available for most standard and high.output full.size fluorescent lamps, low.temperature starting and high efficacy can be achieved
with outdoor fluorescent lighting systems. Where low temperatures are expected to prevail, clear tubular insulating jackets can help increase lumen output from linear fluorescent systems. Both low.pressure and high.pressure sodium sources will start reliably at temperatures as low as .40°F. Most metal halide systems require a minimum starting temperature of .20°F. And unlike fluorescent systems, HID system wattage and lumen output are essentially independent of ambient temperature.

5.5 Outdoor luminaires

To maximize effectiveness and minimize waste and light tres.pass, outdoor luminaires should confine the lighting to the target area. The choice of outdoor luminaires is driven by the size of the outdoor area, the need to control spill light, and aesthetics.

5.5.1 High Mounting Luminaires

High mounting luminaires generally use HID sources and are mounted on poles at least 15 ft. high. These luminaires are described below and illustrated in Figure .1. High Mast . With mounting heights of 60.100 ft., high mast luminaires are used to illuminate large areas. These systems are Outdoor Lighting usually equipped with a lowering device for convenient maintenance at ground level. High mast lighting is typically used for highway interchange lighting and off.street areas such as industrial yards
and large parking lots. Refractor luminaires provide wide beam distribution and are generally used where spill light control is not important. The wide beam distribution allows for wider spacing of luminaires.
Typical applications include highway, street and general area lighting. The refractor luminaires that use fluorescent or LPS lamps need to be mounted at lower heights because of their reduced optical control. Cut.Off . Primarily used for lighting medium to large areas, this
luminaire is very effective in minimizing direct glare. Where aesthetic appearance is a concern for low.glare street lighting and parking lot applications, a low.profile, horizontal lamp unit may be used.

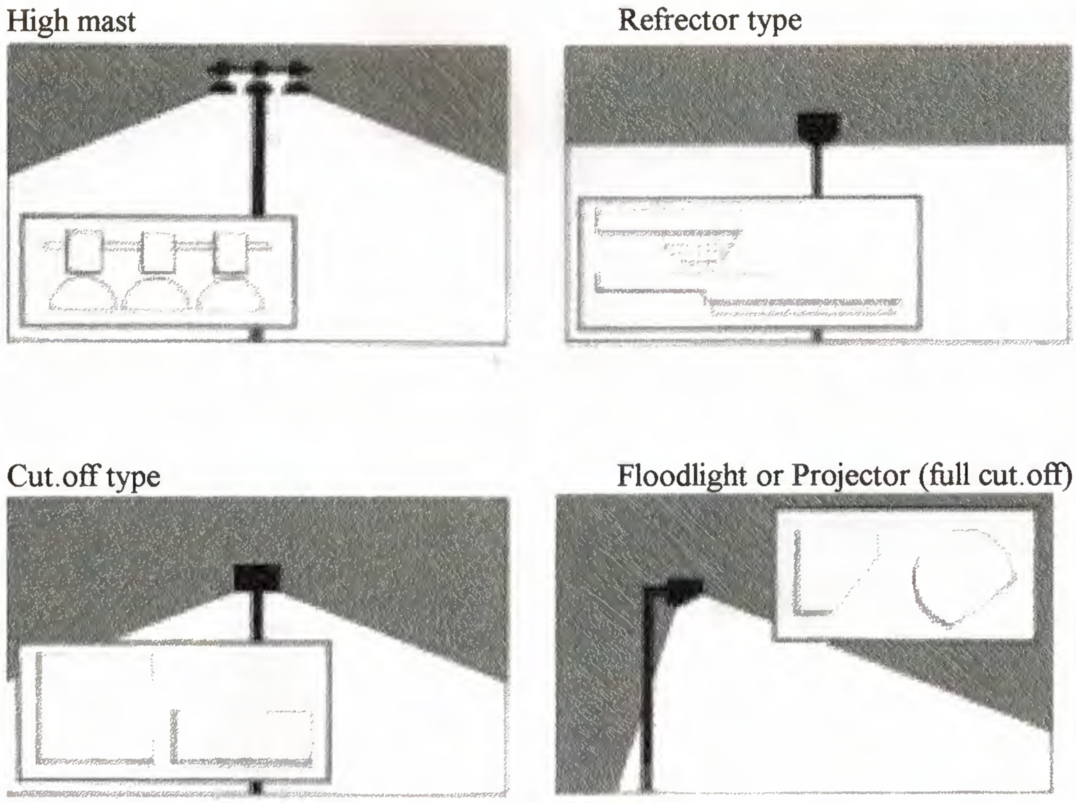


Figure 5.1. Common high.mount outdoor luminaires. Courtesy: National Lighting Bureau.

Floodlight . Using an efficient reflector for sharp cut.off control, these luminaires are typically used where control of glare and light trespass are critical. Typical examples include airport apron lighting or areas immediately adjacent to residential properties

5.5.2 Medium And Low Mounting Luminaires

Medium and low mounting luminaries may use compact fluorescent, LPS or HID sources. Mounting configurations for these luminaires include both building.mount and pole mount.

These luminaires are described below and illustrated.ed in Figure 17.2. Building.Mounted Refractor. Using lower wattage HID lamps, building.mounted refractor luminaries produce a wide beam distribution for general lighting around buildings. Without a sharp cut.off however, its glare may be objection.able in some applications. Building.Mounted Cut.Off Instead of using a refractor/lens, this luminaire uses a reflector to achieve tight beam control and low brightness. The upper part of the beam is cut off to prevent light trespass beyond the intended illumination area.

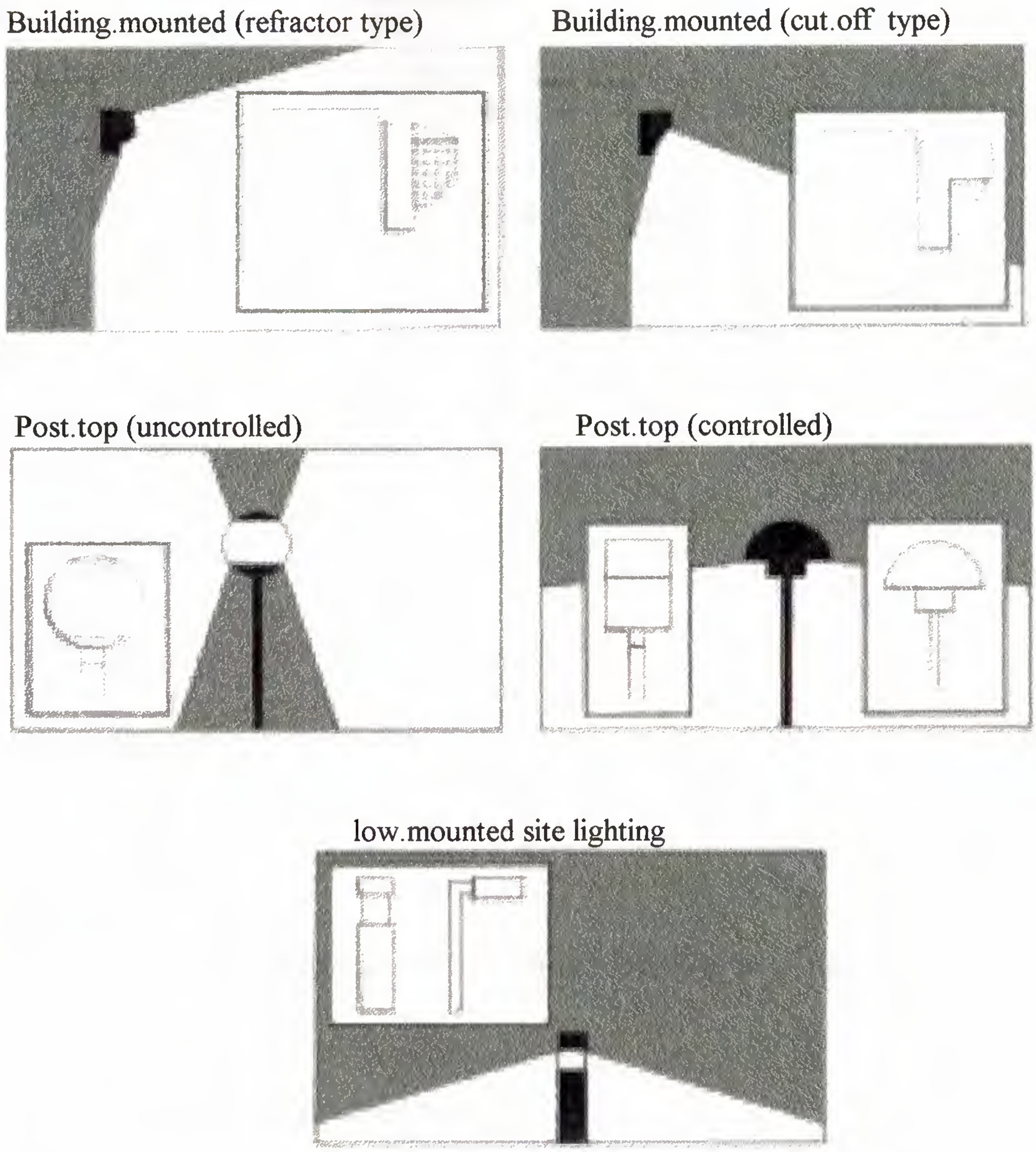


Figure 5.2. Common medium and low mounting outdoor luminaires. Courtesy: National Lighting Bureau.

Post.Top . Typically used for pedestrian walkways and small.area lighting, these decorative luminaires can utilize low.wattage compact fluorescent or HID sources. Some post.top luminaires feature diffusing globes that allow the light to be distributed in all directions, wasting most of the light that is emitted above horizontal. "Controlled" post.top luminaires are more efficient because they direct the majority of the lamp light onto the desired area.

Low.Mounted Site Lighting . Compact fluorescent and HID sources are generally used in low.mounted site lighting to provide illumination for walkways and small areas. Mounted below eye level, these decorative luminaires can efficiently deliver glare.free light.

5.6 Outdoor lighting applications

Table 5.3 provides guidance in choosing light sources for out.door lighting applications. The four applications shown in the table illustrate the diversity that exists in outdoor lighting applications.

Table 5.3. Light sources for outdoor lighting applications.

Lamp Area	High. pressure sodium (CRI>22)	Metal halide (CRI>65)	Linear fluorescent (CRI>62)	Compact fluorescent (CRI>80)	Low. pressure sodium (CRI=0)
Large Area; High Mounting (Parking Lot)	•	•			
Small Area; Low Mounting (Walkway)	•	•		•	(•)*
Sign/Billboard		•	•	•	
Covered (Parking Garage)	•	•	•		(•)*

*LPS lamp use is limited to applications where monochromatic sources are acceptable.

5.6.1 Parking Lots (Large Areas)

Effective outdoor parking lot illumination can attract customers to retail establishments, promote traffic and pedestrian safety, deter crime and vandalism, and create a sense of personal security. In addition to selecting efficient light sources, energy.efficient parking
lot lighting must provide proper light distribution. Parking lot luminaires should efficiently direct the light to the parking surface. Even if an extremely efficacious light source is used,
a narrow lighting distribution will cause uneven illumination (or will require more luminaires in new installations). Therefore, the selection of the luminaire's optical system is part of the lighting upgrade design. Some luminaires that use interchangeable or rotational optical systems allow users to change the lighting distribution after the luminaire is installed. By limiting the illumination to the parking surface, lighting energy is reduced and neighboring inhabitants won't have the annoyance of light trespass. In general, luminaires that limit light
output at high angles (above 75°) reduce the potential for light trespass.

5.6.2 Walkway/Architectural Lighting

Walkway and architectural lighting can be used for facilitating pedestrian safety and traffic while enhancing the outdoor appearance. Architectural luminaires that use HID sources include post.tops and bollards, many of which provide indirect light with reflective surfaces to reduce glare. Lower level illumination applications such as pathway or garden lighting may use low.wattage compact fluorescent or low.voltage halogen sources.

5.6.3 Signs

Effective sign lighting is essential for the sign's message to be communicated at night. Signs can be illuminated internally or externally. The goal of sign lighting is to provide high visibility through the proper selection of light sources. Internally illuminated signs are used widely in retail applications, typically utilizing linear fluorescent lamps. In these applications, color rendering is not as important as color temperature. Typically, cool.white (4100K) provides good results. EPACT has allowed full.wattage cool white lamps to be used in outdoor sign applications, because the energy.saver (reduced wattage) alternatives require a
much higher (60°F) minimum starting temperature.

Externally illuminated signs include most roadway signs and billboards. Light sources with cooler color temperatures (>4000K) are normally chosen for these applications, because they can improve nighttime visual acuity, which is needed for reading words and numbers at a distance. Compared with warmer sources (such as HPS), cooler sources (such as metal halide and fluorescent) cause the pupil to constrict to a smaller size, thereby creating a more distinct image on the eye's retina. The specific light source that is chosen depends on the size of the sign and the distance the light source is placed from the sign.

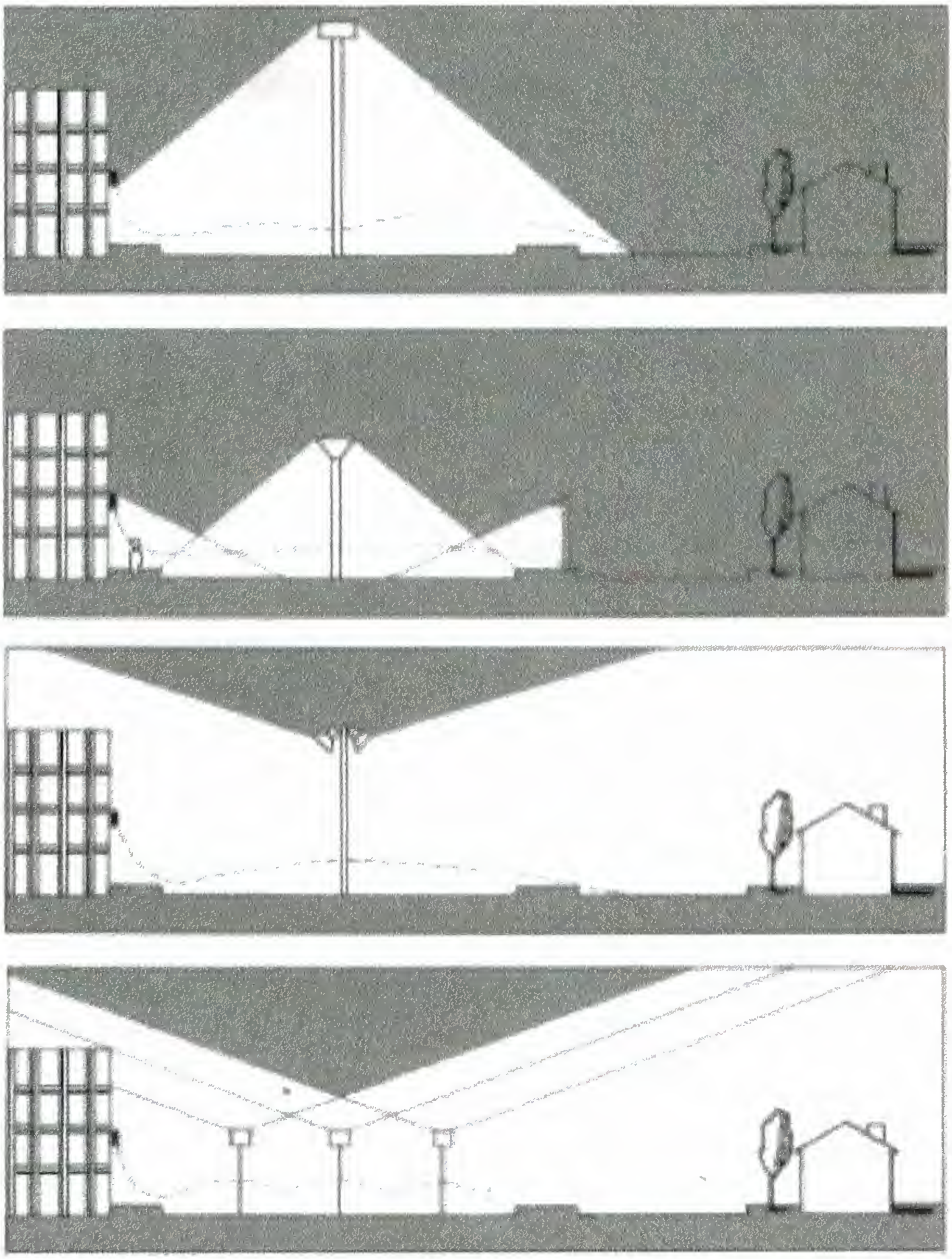


Figure 17.3. Energy can be saved by controlling the distribution of light from outdoor systems. The top two illustrations show how the lighting can be confined to the target area without wasting energy on spill light. However, the bottom two illustrations show that light trespass not only wastes energy, but can aggravate the neighbors.

CHAPTER 6

SPORT LIGHTING

6.1 Background

Sports and sports area should be lit so that those taking part and those watching, whether at the event or on television, can see clearly all that is going on. This calls for suitable brightness and colour contrasts over the playing area, sufficient light at all points, correct distribution of light and adequate control of glare.

Scope

The Guide is concerned chiefly with the lighting of sports arenas and other playing and recreational areas. References is also made to the lighting of associated ancillary areas and to the provision, where necessary, of emergency lighting.

6.2 Lapms choice consideration

6.2.1 Lamps

The following properties should be considered when choosing lamps for a sport lighting installation:

1. Luminus efficacy
2. Initial and running costs
3. Rated life
4. Colour renderingas judged visually and, when relevant, by colour television and film requirements
5. Size and shape of the source.

The type of lamp chosen should has the best balance of properties for the application. Manufacturer data can be very important and useful information in terms of choosing the right lamp for the job.

1. Types

Three types of lamps are commonly used in sport lighting:

1. Incandescent (tungsten, tungsten halogen);
2. Fluorescent (tubular);
3. High.pressure discharge (mercury vapour, metal halide, sodium vapour, some mercury lamps known as fluorescent mercury lamps.have a coating of fluorescent powder on the outer bulb to improve colour rendering.)

2. Luminous efficacy, Wattage, Life and Cost.

Efficacy, wattage rating, life and cost are to some extent interrelated. For example, high pressure discharge lamps and the associated control gear cost considerably more than the lower efficacy incandescent lamps, however they last longer and produce light more cheaply. the comparative importance of long lamp life depends on how difficult and costly it is to change them. The need to match lamps to the application is evident.

3. Colour rendering

Colour is important to most sport, and very noticeable colour distortion caused by using unsuitable lamps would properly be criticized. the light from all lamps alters to some extent the appearance of colours compared with their appearance under daylight. Although daylight is popularly taken as a standard of reference its colour varies continually, the colour rendering requirements of the sport should be considered when deciding the type of lamps to be used.

6.3 Classification of Floodlights

Two floodlights classification system are used in the Guide. the first simplifies reference to the type of floodlight which should be used for a given sport, and the second classifies floodlights in terms of beam divergence.

System 1

Floodlights are designated as Type A, Type B Type C, characterized as follows:

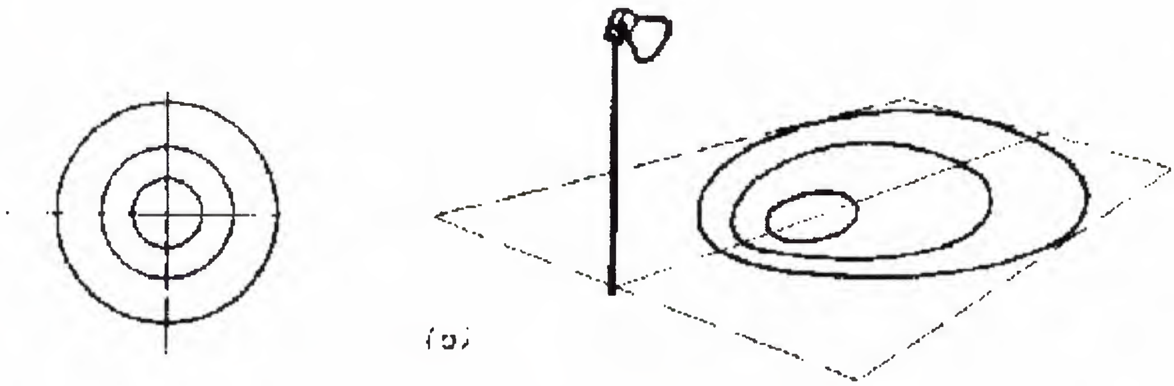
Type A: Floodlights giving symmetrical beams, usually by means of paraboloidal reflectors.

Type B: Floodlights giving fan.shaped beams, usually by using linear lamps in through reflectors

Type C: Floodlights giving fan.shaped beams with an asymmetric intensity distribution in the vertical plane and rapid run.back in intensity above the peak to control glare.

Type A floodlight

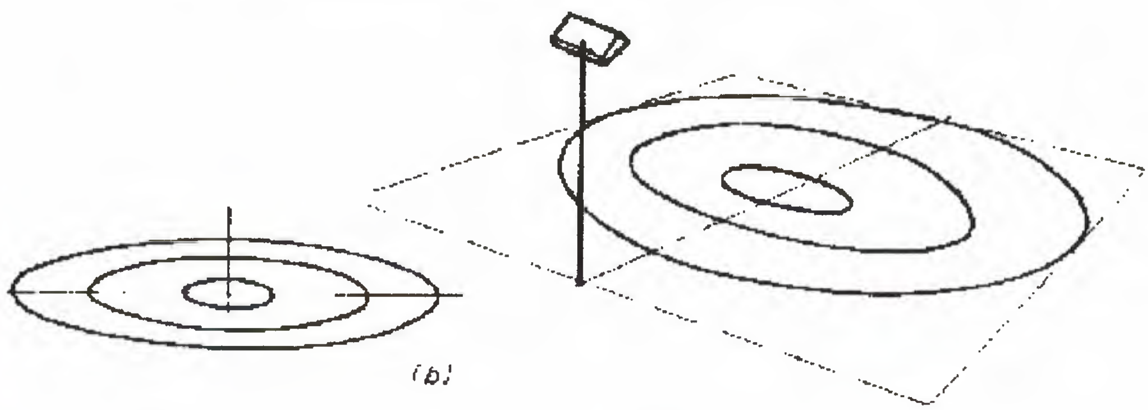
'Type A floodlight' gives out symmetrical beams.



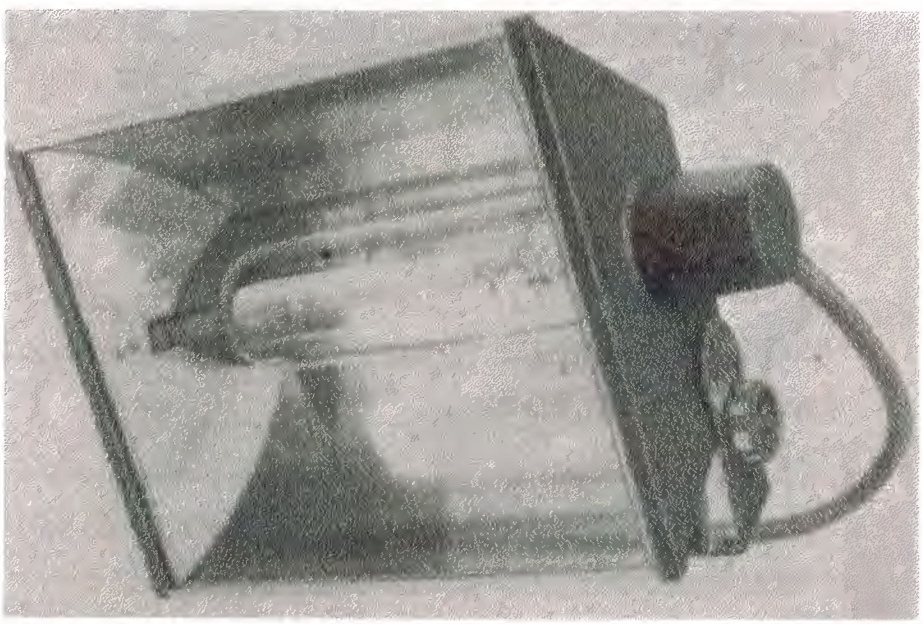
A typical 'Type A floodlight'

Type B floodlight

'Type B floodlight' gives out fan shaped beams.

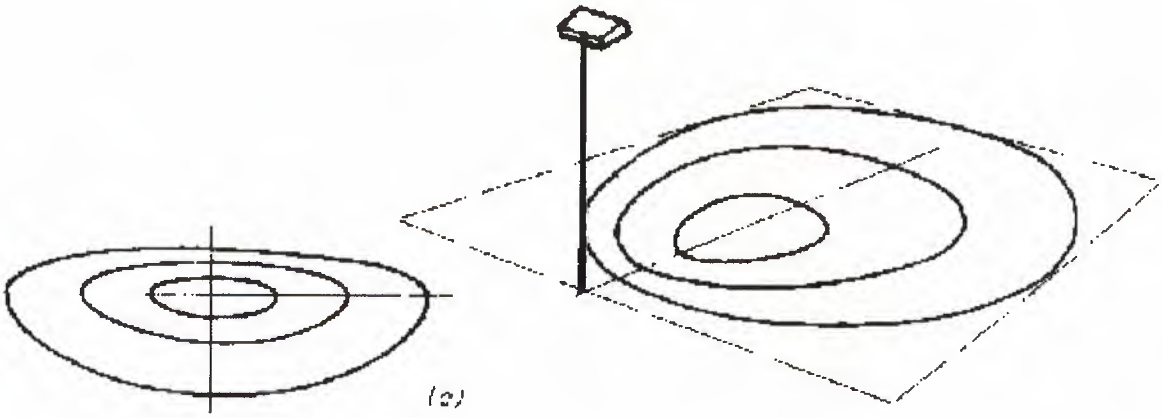


A typical 'Type B floodlight'



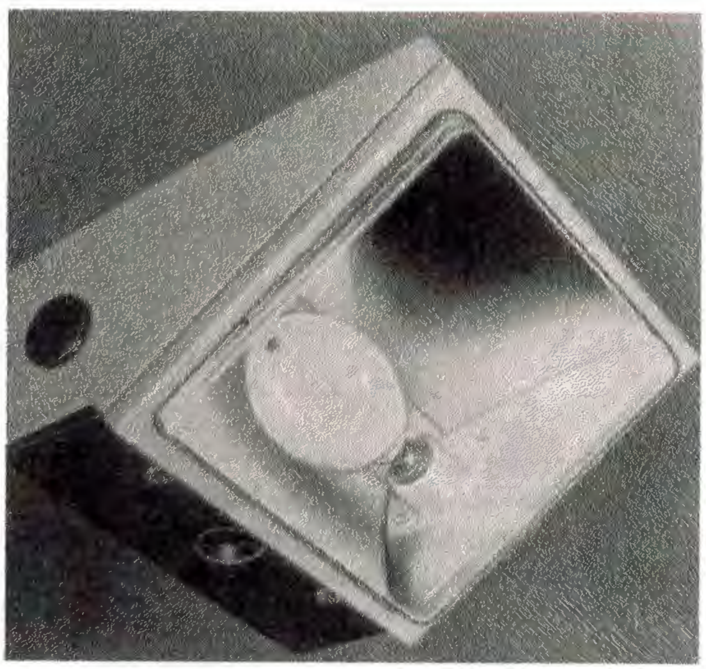
Type C floodlight

'Type C floodlight' gives out fan shaped beams with an asymmetric intensity.



(c)

A typical 'Type C floodlight'



SYSTEM 2
Floodlights are also cassified by its beam divergence:

Classification number	Beam Divergence
NN	Less than 5 degree
N	5 up to 10 degrees
1	11 up to 18 degrees
2	19 up to 29 degrees
3	30 up to 46 degrees
4	47 up to 70 degrees
5	71 up to 100 degrees
6	101 up to 130 degrees
7	131 and above

For fan.shaped beams the horizontal angle is indicated first and the vertical second. the letters H for horizontal and V for vertical precede the corresponding classification numbers.

CHAPTER 7

DESIGN GUİDE FOR SPECİFİC SPORT

7.1 Badminton court lighting

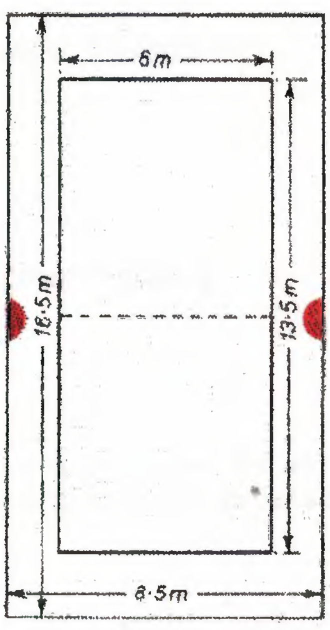
Requirements

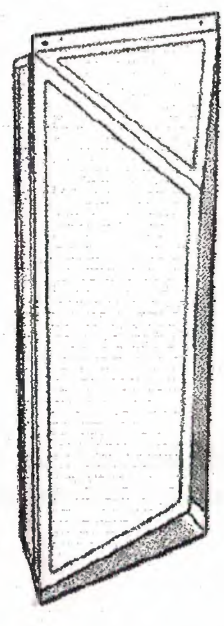
Players must be able to follow the flight of the shuttlecock against the background, and do so without being troubled by glare or having their attention distracted by bright sources near their sight lines. The shuttlecock is seen by light transmitted by and reflected from the transluscent feathers. Much of the play takes play near the net, and the lighting of this area.including the space above the court to a height of at least 7 m is important.

Recommendation

The most general favoured lighting system consist of a large low.brightness luminaire at each end of the net positioned as shown in fig.3a. Incandescent lamps are preferred. A typical luminaire is shown in fig.3b. Six 150 W tungsten filament lamps are housed in a diffusing enclosure designed to direct the light otwards to the court and upwards across the space above the net. With this system the illuminance falls off shrply towards the back of the court, however the values are adequate remmembering that the shuttlecock has transluscent feathers, and that much of the play is near the net. Some general lighting of the surrounding areas is normally needed and this can provibe useful 'back.up' lighting for the rear parts of the court. The general lighting luminaires should be mounted well outside the court area and away from the normal sight lines of the players. This applies also to the luminaires installed when badminton matches are televised. These luminaires should be mounted at least 10 m away, horizontally and vertically, from the outside court.

Fig.7.1a. (left) Recommended lighting layout for badminton court.
Fig.7.1b. (right) Luminaire for badminton court lighting.





Surface refectance values

The shuttlecock is seen more clearly if the walls and ceiling are not too bright. With the prefered lighting system the surface reflectances should be of the following order:

1. Back walls: 0.2(Munsell value 5)
2. Side walls: 0.4.0.6 (Munsell value 7.8)
3. Ceiling: 0.6.0.7 (Munsell value 8.9)

For National and International standard

1. Service illuminance lux: 300
2. Plane of measurements: Vertical above net facing luminaires
3. BZ classification: Special Units
4. Mounting height (m): 3 (above ends of net)

For Club and county standard

1. Service illuminance lux: 200
2. Plane of measurements: Vertical above net facing luminaires
3. BZ classification: Special Units
4. Mounting height: 3 (above ends of net)

For Recreational using fluorescent light

1. Service illuminance lux: 200
2. Plane of measurements: Horizontal on court
3. BZ classification: BZ 5.10
4. Mounting height: 5 (minimum)

7.2 Basketball court lighting

Requirements

A Player must be able to follow the movement of the ball and the other players. Although the ball is large the action is fast and high illuminanaces are needed.

Recommendation

Suitable lighting is provided by reflector luminaires mounted above the court and spaced to meet uniformity requirements. The reflectors should have sufficiently deep skirts (or be fitted with louvres) to shield the lamps from spectators sitting around the court. Glare to players cannot be overcome in this way as they miust look upwards from time to time but it can be reduced by lowering the brightness contrast between the luminaires and the ceiling against which they are seen. The ceiling reflectance should be not less than 0.6 (Munsell value 8) and preferably nearer 0.8 (Munsell value 9.5), and the reflectors should be slotted to give a good amount of upward light. If fluorescent lamps are used, the luminaires should preferably be arranged in continuous lines running from end to end of the court (fig.4).

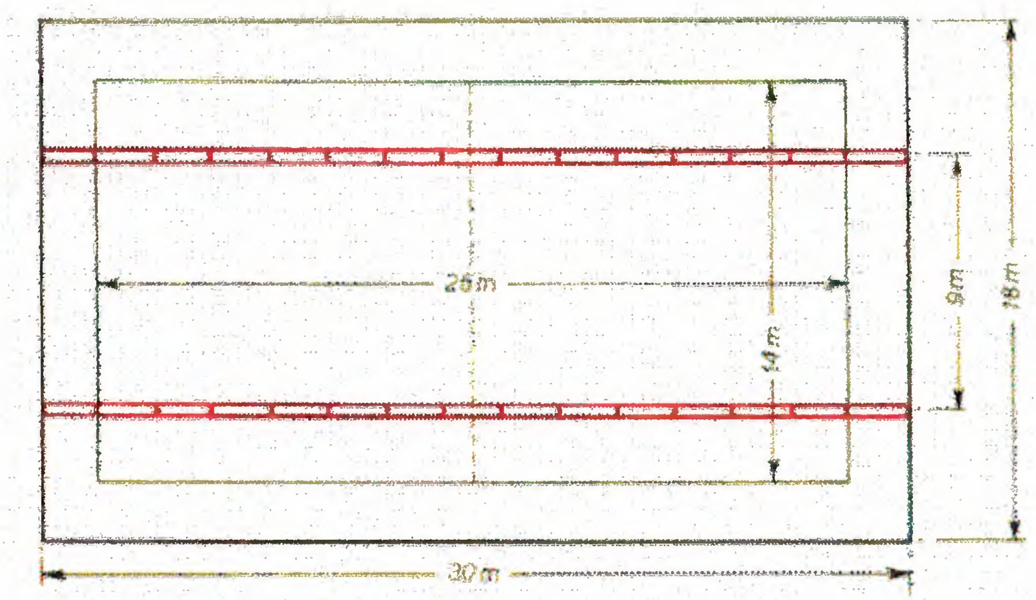
For National and International standard

1. Service illuminance lux: 300
2. Plane of measurements: Vertical above net facing luminaires
3. BZ classification: Special Units
4. Mounting height (m): 3 (above ends of net)

For Club, county standard and Recreational

The service illuminance lux is adequate with 500 and 300 respectively, all the other data are the same as the National and International standard.

Fig.7.2 Typical layout for basket ball court.



7.3 Indoor cycling lighting

Requirements

Spectators are a distance away from the far side of the track, and if they are to follow the races clearly the illuminace on horizontal and vertical surfaces over the track area should be high and glare adequately controlled. The recommended illuminance is fully adequate for the competitors, and as they normally look ahead and slightly downwards, they should not be troubled by glare from light sources mounted well above the track.

Recommendation

Lighting up to a level of at least 300 lux should be provided over the whole area by a suitable general lighting system. The illuminance over the track should be increased from the general lighting level to the recommended value by installing Type A or B floodlights over the track or beyond its outer perimeter. Alternatively, high.bay reflectors may be mounted over the track. Thw wattage of lamp required will depend on the light distribution of the luminaires, their mounting height, location and spacing. the luminaires are often attached to the roof structure and serviced from cat.walks.

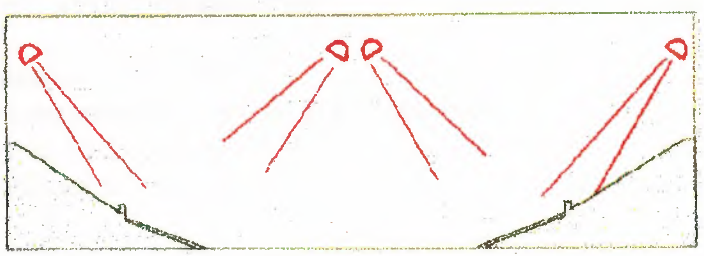
For National and International standard of competition

1. Service illuminance lux: 750
2. Plane of measurements: Horizontal on track
3. Uniformity ratio: 0.8
4. Beam classification: H3 or H5V3 (or BZ.2 if high bay reflectors are used)
5. Type: A or B
6. Mounting Height (m): 8 (minimum)

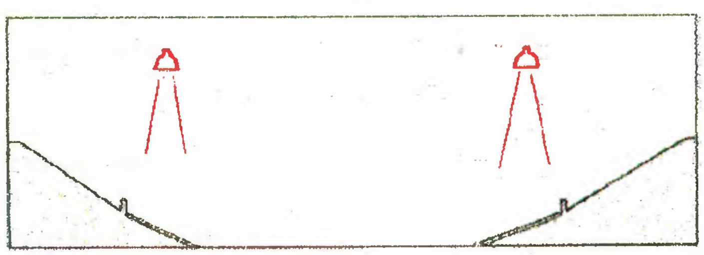
For Club, county standard

The service illuminance lux is adequate with 500. all other requirements are the same as the National and International standard.

Fig.7.3 Typical layout for indoor cycle track by:
(a) floodlights, (b) high.bay luminaires.



(a)



(b)

7.4 Golf driving range lighting

Requirements

The player must be able to follow the flight of his ball down the range. He will also need a reasonable amount of light over the tee area.

Recommendation

The flight path of the ball and the target area should be illuminated by a narrow beam Type A floodlight mounted behind the tee at a height of not less than 5m, and aimed at the far end of the range. If the spill light is insufficient for the tee area, a Type B or C floodlight should be mounted adjacent to the main floodlight and aimed at the tee (fig 6).

In some layouts a number of ranges converge towards a common target area. the ranges should be lit individually(or in pairs, depending on the layout) by the system described, at lower wattage lamps can be used as each floor light contributes to the illuminance at the end of the range. Covered tee areas may be lit by normal interior lighting systems, usually using fluorescent lamp luminaires.

For All standard of competition
*** With illuminance at the end of range**

1. Service illuminance lux: 50
2. Plane of measurements: Vertical at ground level
3. Aiming point: End of range
4. Beam classification: N or 1
5. Type: A
6. Mounting Height (m): 5 (minimum)

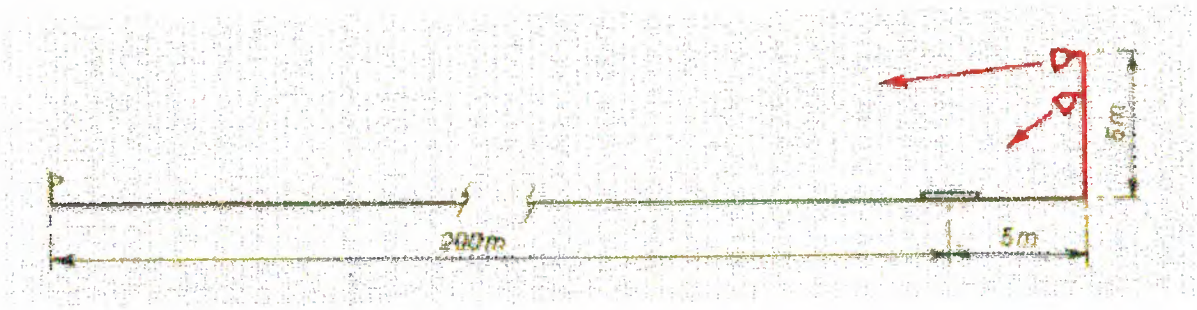
*** With illuminance at tee**

1. Service illuminance lux: 50
2. Plane of measurements: Horizontal on track
3. Uniformity ratio: Tee
4. Beam classification: H5 or V3.5
5. Type: B or C
6. Mounting Height (m): 5 (minimum)

Example

Consider a layout where six ranges converge towards a single target area 200 m from the tees. The recommended illuminance over the target area can be provided by norrow.beam Type A floodlights mounted behind the tees at a height of 5 m. The floodlights house 1500 W Class B2 tunsten filament projector lamps, and the beams are aimed at the end of the range. If additionallighting is needed for the tee areas, Type B or C floodlights may be used with 500 W tungsten filament lamps.

Fig.7.4 Recommended floodlighting scheme for golf driving range:



7.5 Ice hockey rinks lighting

Requirements

Players and spectators see the puck in silhouette against the ice and surrounding barriers, and must be able to follow its movement and also the movements of the players themselves. The illuminance on the rink and on vertical surfaces over it should reach all points from several directions to reduce shadow densities.Players look ahead or downwards for most of the time and should not be troubled by direct glare from luminaires mounted several metres above the rink. Reflections of the sources at the ice may, however, cause distraction and momentary disability glare.

7.5.1 Outdoor rinks

Recommendation

Outdoor rinks are usually lit by floodlights mounted on poles positioned along the sides, or by luminaires suspended overhead or catenary wires. Overhead systems have the disadvantage that in strong winds the luminaires may swing sufficiently to cause distracting reflections on the ice. The systems are similar in design to those for indoor rinks (see below).

Floodlighting systems are similar to the side lighting systems used in sports stadia and fig.5 shows a typical layout.

The floodlights should be aimed to give

1. High illuminance on vertical surfaces over the rink,
2. Acceptably low direct glare to spectators on the opposite side, and
3. Freedom from bright reflections in the ice which could cause the puck to 'disappear' momentarily at certain angles of view. The last requirement is often the most difficult to meet and some interference with vision must usually be accepted.

The rebound of the puck from the barriers is seen most clearly if these are light in colour and free from advertisements or other confusing patterns.

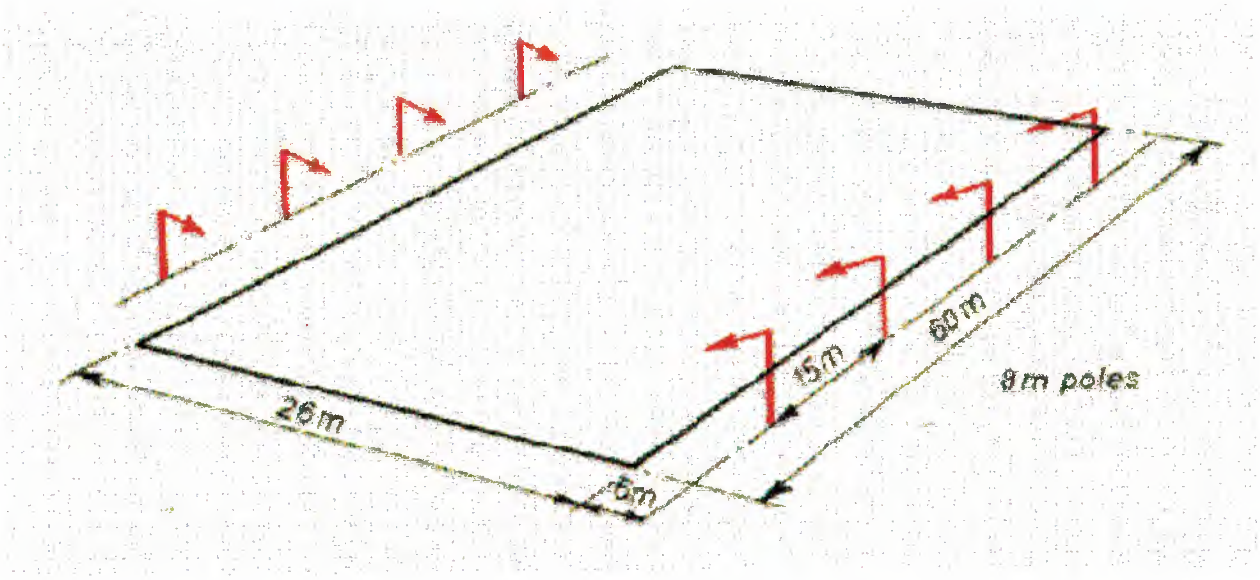
National and International standard

1. Service illuminance lux: 500
2. Plane of measurements: Horizontal on rink
3. Uniformity ratio: 0.5
4. Beam classification: H5 V3.4
5. Type: B or C
6. Mounting Height (m): 8 (minimum)

For Club and Recreational rinks;
The service illuminance lux can be reduced to 300 and 150 respectively.

Example
An illumination of about 500 lux is provided by continuous runs of slotted through reflectors, each with two 1500 mm (5 ft) 65 W high efficacy fluorescent lamps, mounted at 6 m and with 9 m between the runs (fig 6). About the same illuminance is provided by high.bay reflectors housing 400 W high pressure sodium or metal halide lamps or 700 W mercury fluorescent lamps mounted at 8m on 5m x 5m centres over the rink area.

Fig.7.5 Typical floodlighting scheme for outdoor ice hockey rink.



7.5.2 Indoor rinks

Recommendation

Most indoor rinksare lit from overhead, altough floodlighting similar to that described for outdoor rinks is sometimes used. The luminaires are normally attached to the roof structure.

Suitable overhead systems consist of fluorescent lamps in reflectors mounted in lines above the rink as shown in fig 6, or high pressure discharge or incandescent lamps in high.bay reflectors mounted in a regular pattern over the whole area. the light distribution should not be too concentrating otherwise vertical surfaces will be inadequately lit. On the other hand, the lamps should be sufficiently shielded to prevent spectators seeing them at normal angles of view. This is especially important when high pressure discharge or incandescent lamps are used.

National and International standard

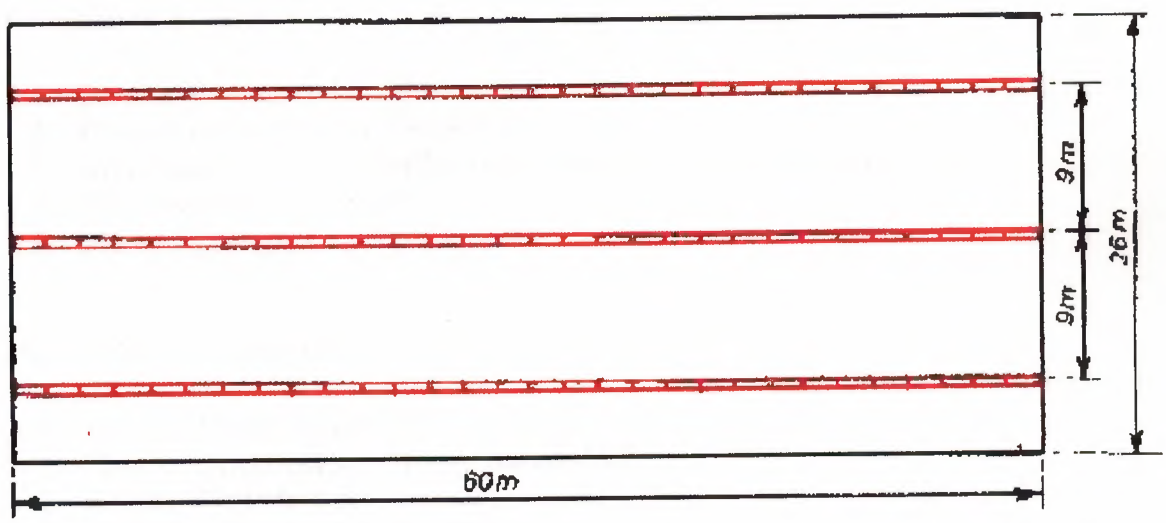
1. Service illuminance lux: 750
2. Plane of measurements: Horizontal on rink
3. Uniformity ratio: 0.8
4. Beam classification: BZ 2.3
5. Flux fraction ratio: 0.2.2
6. Mounting Height (m): 8 (minimum)

For Club and Recreational rinks;

The service illuminance lux can be reduced to 500 and 300 respectively.

Example
An illumination of about 500 lux is provided by continuous runs of slotted through reflectors, each with two 1500 mm (5 ft) 65 W high efficacy fluorescent lamps, mounted at 6 m and with 9 m between the runs (fig 6). About the same illuminance is provided by high.bay reflectors housing 400 W high pressure sodium or metal halide lamps or 700 W mercury fluorescent lamps mounted at 8m on 5m x 5m centres over the rink area.

Fig.7.6 Typical lighting layout for indoor ice hockey rink using fluorescent lamps.



7.6 Lighting for rifle and pistol shooting

Requirements

Ranges are usually about 20m long and 4m wide. The targets must stand out clearly against the background and good vision is needed in the firing zone and along the range.

The attention of marksmen must not be distracted by bright sources near to their lines of sight. Some prefer the lighting in the firing zone to be switched off when they are firing.

Recommendation

There are several ways of lighting a range satisfactorily. A typical scheme consists of a series of single fluorescent lamps mounted across the range and screened from the firing posotions by baffles or reflectors (fig.9). The higher illuminances needed on the targets and in the firing zone are provided by multiuple lamp units. The lamps in the firing zone should be individually switched.

Room surface reflectances should be of the following order:

1. Wall behind targets: 0.2.0.3 (Munsell value 5.6)
2. Other walls: 0.4.0.6 (Munsell value 7.8)
3. Ceiling: 0.6 (Munsell value 8)
4. Floor: 0.2 (Munsell value 5)

For all standard of competition
* Illumination at "target"

1. Service illuminance lux: 1000
2. Plane of measurements: Vertical at target
3. BZ classification: Angle reflectors or spotlights should be used B or C
4. Flux fraction ratio: 0.2.0.5
5. Mounting Height (m): 3 (minimum)

* Illumination at "Firing zone"

1. Service illuminance lux: 300
2. Plane of measurements: Horizontal on floor
3. BZ classification: 3.6
4. Flux fraction ratio: 0.2.0.5
5. Mounting Height (m): 3 (minimum)

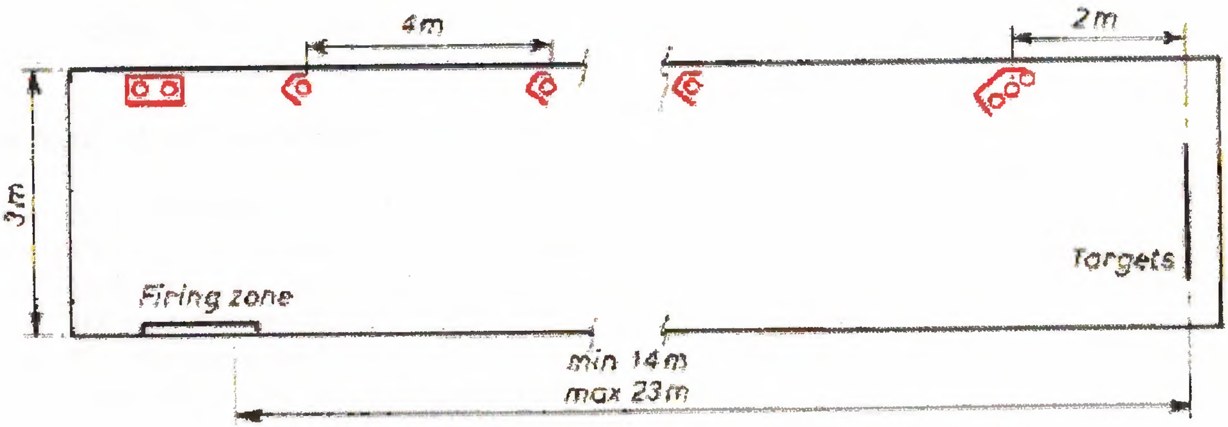
* Illumination at "Range"

1. Service illuminance lux: 150
2. Plane of measurements: Horizontal on floor
3. BZ classification: 3 (or angle reflectors)
4. Flux fraction ratio: 0.2.0.5
5. Mounting Height (m): 3 (minimum)

Example

For a 4m wide range, a luminaire housing two 1500mm (5ft) 65 W high efficacy fluorescent lamps gives about 300 lux over the firing zone. Angle reflectors, each with one 1500mm 65 W lamp spaced at 4m intervals down the firing range, give about 150 lux on the floor. Three 1500mm 65 W lamps in a large angle reflector mounted as shown in fig.9 provide the recommended illuminance of about 1000 lux on the targets.

Fig.7.7 Typical Lighting for rifle and pistol shooting



7.7 Lighting for squash court

Requirements

Visual demands are exacting chiefly because the speed of play is high and the ball is small in size. Being dark.coloured, the ball must be seen in silhouette against the court surfaces which should therefore be fairly brught. The court lines must be clearly seen by players, spectators and marker. Restriction of glare is important.

Recommendation

Squash courts are normally lit by ceiling.mounted fluorescent lamp luminaires positioned as shown in fig.10. Angle reflectors are used for the front units to emphasize the striking wall and to restrict glare when a player takes a high ball. Where there is sufficient ceiling height, the other luminaires should be mounted parallel to the side wals. Through reflectors or prismatic diffusers may be used and should direct some light on to the ceiling. This may not be necessary if the ceiling is more than 6m high. Lamps should be protecteed by wire guards or impact.resistant covers.

With this lighting system the court surfaces will be suitably gright if reflectances lie in the following ranges:

1. Walls: 0.6.0.8 (Munsell value 8.9.5)
2. Ceiling: 0.6.0.8 (Munsell value 8.9.5)
3. Floor: 0.3.0.4 (Munsell value 6.7)

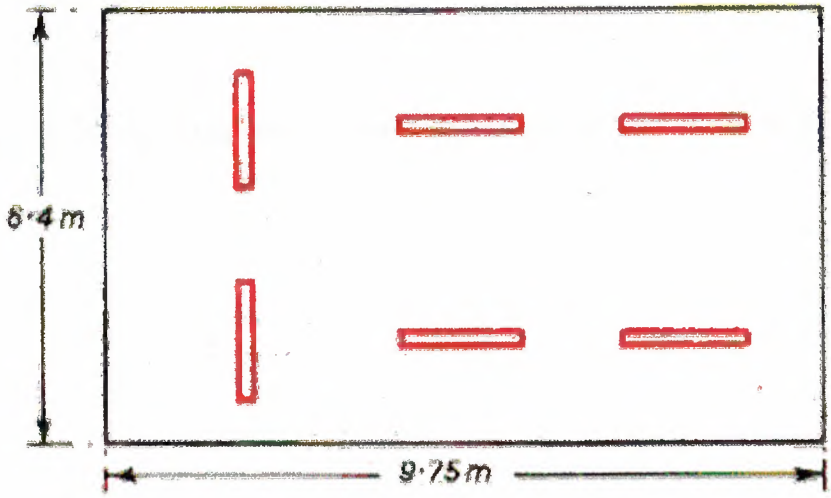
For National and International standard;

- Service illuminance lux: 500
- Plane of measurements: horizontal at floor
- Uniformity ratio: 0.8
- BZ classification: BZ 4.6
- Flux fraction ratio: 0.2.0.4
- Mounting Height (m): 5 (minimum)

For recreational standard;
The service illuminance luxes are adequate with 150 lux.

Example
An illuminance of about 300 lux on the floor is provided by an installation of six reflectors each housing wo 1800mm (6ft) 85 W high.efficacy fluorescent lamps.

Fig.7.8 Recommended lighting layout for squash court.



7.9 Lighting for volleyball (outdoors)

Requirements

The visual requirements are similar to those for lawn tennis. The sport is largely aerial and is played at high speed.

Recommendation

The lighting layout for club and county play should be similar to that for club and county lawn tennis, i.e; groups of Type B or C floodlights_of appropriate classification should be mounted on poles located parallel to and outside the sides of the court.

For recreational play, it will usally be sufficient to light the court by two floodlights mounted on poles at each end of the net.

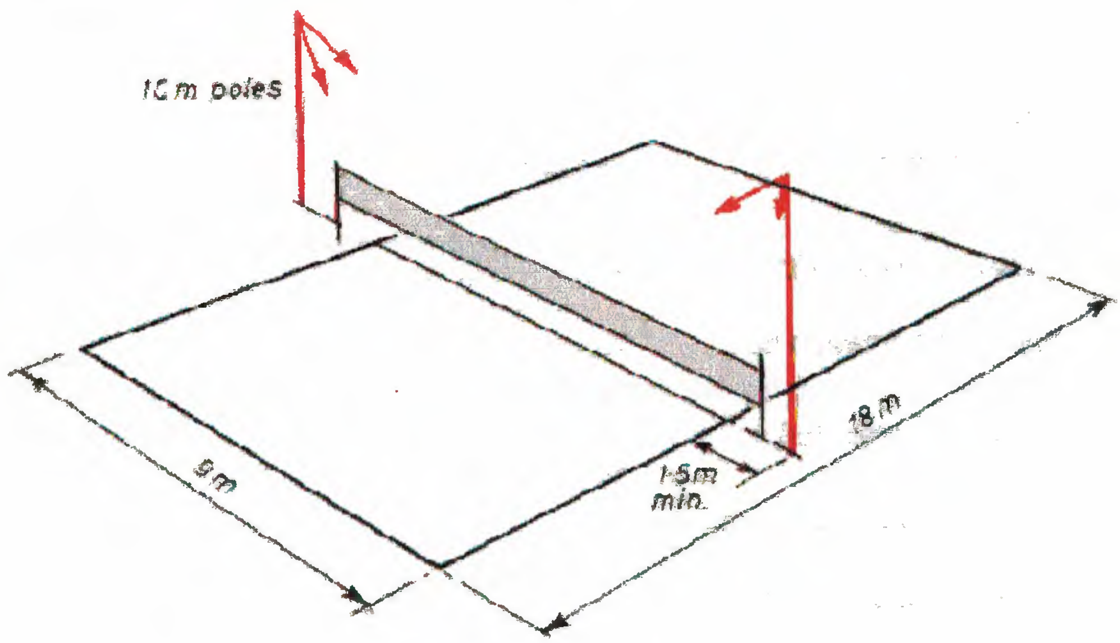
For Club and county standard of play

1. Service illuminance lux: 300
2. Plane of measurements: horizontal on court
3. Uniformity ratio: 0.5
4. BZ classification: H5 V3.4
5. Type: B or C
6. Mounting Height (m): 9 (minimum)

For recreational standard;

The service illuminance luxes are adequate with 150 lux.

Fig.7.9 Typical floodlighting scheme for outdoor volley ball court lit to recreational standard.



7.8 Football field lighting:

For football field lighting design the following procedure must be applied:

- Lampe choice:

The properties mentioned in (chapter 6) should be considered when choosing lamps for a sport lighting installation.

- Number of lamps:

To find the number of lamps, the following expressions are applied:

$$N = \phi A/\phi L$$

$$\phi A = E.A$$

Where,

N: Number of lamps.
A: Area of the field = length * width
E: Illuminance.
ΦA: flux needed for that area.
ΦL: lamp's flux.

- Number of masts and its positions:

The number of masts and its positions should be determined.

- Illuminance:

In order to determine the illuminance at any point on the plan the following expression is applied

$$E = I \cos^2\theta/h^2$$

Where,

Θ: The angel where the projector is directed.
I: Light intensity at the point where we want to find the illuminance.
h: The height of the mast.

Light intensity could be found by determining the values of (C) and (γ) angles, which could be found using the following expressions:

$$C = \tan^{-1} \quad [\tan B \sqrt{(1+ \tan^2 B)}] / \tan B$$

$$\gamma = \tan^{-1} \sqrt{[\tan^2 B + \tan^2 \beta \, (1+\tan^2 B)]}$$

Where,

$$B = \tan^{-1} [X`\sqrt{(1+y`^2)}/(1+y`Y`)] - \tan [x`/\sqrt{1+y`^2}]$$

$$\beta = \cos^{-1} \; [1+y`Y`+X`^2 ((1+y`^2)/(1+y`Y`))] / \sqrt{[(1+X`^2+Y`^2)(1+y`+(X`^2(1+y`)/ (1+y`Y`))}$$

$X` = X/h \qquad Y` = Y/h \qquad x` = x/h \qquad y` = y/h$

(X, Y): The point where we want to find the light intensity.
(x,y): The point where the projector is directed, h : The height of the mast.

Using the table of C and γ for each type of lamps, we can find the light intensity at each point.

The following example explains the way of designing a lighting system for a football field.

- Chosen lamp:

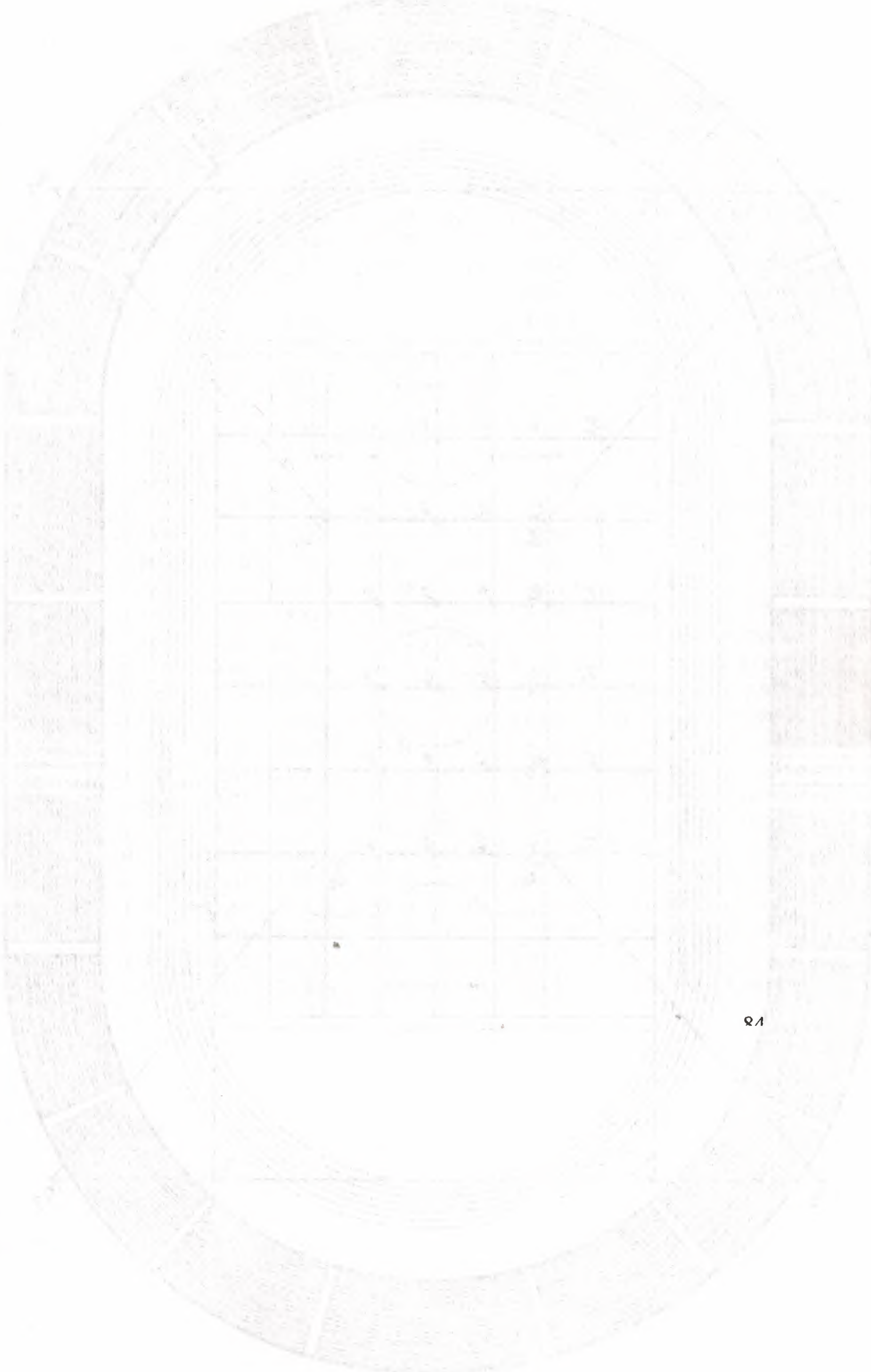
Luminaire: MVFO24/1000 NB
Lamp: 1x HPI-T1000W
Lamp flux: 1x 85000.00 lm

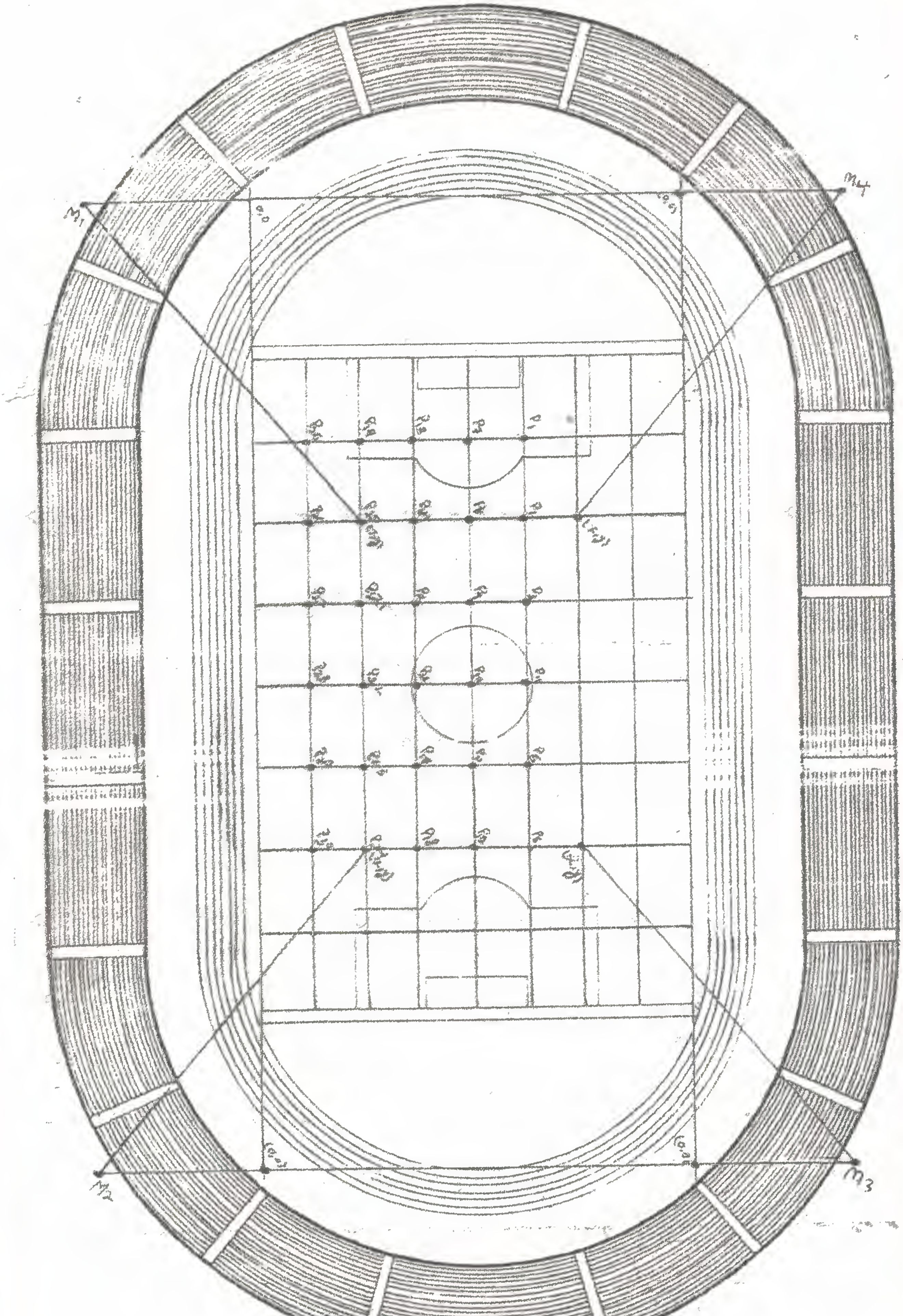
- Number of lamps determination:

Area to be illuminated = width x length = 70 x 105 = 7350
Needed flux = E x A = 7350 x 1000 = 7350000
Number of lamps = needed flux / lamp flux = 7350000 / 85000 = 86

- Number of masts = 4 masts positioned at corners

Number of lamps for each mast = 86 / 4 = 21.5 = 22




M1
M2
M3
M4

- Illuminance at each point of the points shown in figure above:

Values of B. β. C. γ. I. and illuminance. Where the projector is directed to the point P1* (0.85. -0.785)

P	X`	Y`	B	β	C	γ	$Cos^3\theta$	I	E
P01	0.85	-0.785	00.00	00.000	000.00	00.00	1.91629	143735.00	110.1750
P02	0.85	-1.050	-3.126	7.1240	293.57	7.776	1.86440	77621.680	49.25680
P03	0.85	-1.315	-5.766	12.967	293.57	14.17	1.98390	50722.840	26.34320
P04	0.85	-1.580	-8.016	17.725	293.57	19.40	1.06228	28713.000	12.20040
P05	0.85	-1.845	-9.952	21.608	293.57	23.69	0.87421	24815.056	8.677430
P06	0.85	-2.110	-11.63	24.798	293.57	27.23	0.72582	23521.020	6.828800
P07	0.68	-0.785	-5.625	00.000	00.000	5.625	2.15608	140665.70	121.3140
P08	0.68	-1.050	-8.411	7.4780	318.10	11.24	1.74731	77558.880	54.20776
P09	0.68	-1.315	-10.72	13.495	306.60	16.90	1.40420	43379.040	24.36514
P10	0.68	-1.580	-12.67	18.318	303.52	22.19	1.13208	26847.940	12.15761
P11	0.68	-1.845	-14.32	22.208	301.21	26.23	0.92094	24229.630	8.925610
P12	0.68	-2.110	-15.74	25.376	300.00	29.58	0.75774	22606.660	6.851990
P13	0.51	-0.785	-11.91	00.000	00.000	11.91	2.38845	132528.73	126.6153
P14	0.51	-1.050	-14.20	7.7940	330.85	16.16	1.89693	62148.334	46.15642
P15	0.51	-1.315	-16.07	13.953	318.09	21.16	1.49923	33393.512	20.02582
P16	0.51	-1.580	-17.63	18.823	311.63	25.57	1.19305	27395.082	13.07348
P17	0.51	-1.845	-18.93	22.711	307.78	29.24	0.96088	25940.291	9.970200
P18	0.51	-2.110	-20.05	25.854	305.30	32.29	0.78458	21901.105	6.873270
P19	0.34	-0.785	-18.79	00.000	0.0000	18.80	2.58784	123608.50	127.9516
P20	0.34	-1.050	-20.44	8.0460	337.96	21.90	2.02051	58753.926	47.48516
P21	0.34	-1.315	-21.76	14.310	325.36	25.77	1.57538	30955.772	19.50684
P22	0.34	-1.580	-22.85	19.210	318.10	29.52	1.24077	25409.905	12.61114
P23	0.34	-1.845	-23.75	23.091	313.37	32.65	0.99161	22153.685	8.787130
P24	0.34	-2.110	-24.52	26.210	310.14	35.27	0.80494	20118.139	6.477560
P25	0.17	-0.785	-26.15	0.0000	00.000	26.15	2.72422	109069.10	118.8513
P26	0.17	-1.050	-27.01	8.2100	342.38	28.14	2.10269	60347.544	50.75687
P27	0.17	-1.315	-27.69	14.538	330.84	31.00	1.62490	27334.854	17.76656
P28	0.17	-1.580	-28.26	19.454	323.28	33.85	1.27129	21370.059	10.86702
P29	0.17	-1.845	-28.72	23.329	318.10	36.36	1.01100	22076.967	8.927930
P30	0.17	-2.110	-29.12	26.430	314.40	38.53	0.81767	18226.996	5.961470

Values of C. γ. I. and illuminance where the projector is directed at the point P2*(0.85.-1.050)

P	X`	Y`	B	β	C	γ	cos θ	I	E
P01	0,85	-0,785	3,664	06,864	062,04	7,770	1,91629	63195,88	48,44065
P02	0,85	-1,050	0,000	00,000	000,00	00,00	1,86440	143735,0	107,1918
P03	0,85	-1,315	-3,010	05,645	298,00	6,390	1,98390	84544,42	67,09107
P04	0,85	-1,580	-5,512	10,251	298,00	11,63	1,06228	28367,98	12,05390
P05	0,85	-1,845	-7,612	14,014	298,00	15,90	0,87421	43853,69	15,33493
P06	0,85	-2,110	-9,410	17,110	298,00	19,46	0,72582	28621,41	8,309600
P07	0,68	-0,785	-1,988	07,283	285,20	7,550	2,15608	76667,26	66,12030
P08	0,68	-1,050	-5,254	00,000	000,00	5,250	1,74731	141151,2	98,65396
P09	0,68	-1,315	-7,882	05,872	323,15	9,820	1,40420	88523,91	49,72211
P10	0,68	-1,580	-10,03	10,586	313,00	14,54	1,13208	49125,67	22,24568
P11	0,68	-1,845	-11,83	14,391	308,62	18,55	0,92094	47514,78	17,50330
P12	0,68	-2,110	-13,33	17,493	306,20	21,86	0,75774	28063,97	8,506080
P13	0,51	-0,785	-8,312	07,667	317,05	11,29	2,38845	57723,42	55,14780
P14	0,51	-1,050	-11,00	00,000	000,00	11,00	1,89693	133706,9	101,4530
P15	0,51	-1,315	-13,13	6,0670	335,00	14,45	1,49923	79322,67	47,56917
P16	0,51	-1,580	-14,34	10,871	322,20	17,93	1,19305	46807,02	22,33725
P17	0,51	-1,845	-16,25	14,707	316,83	21,78	0,96088	32304,27	12,41621
P18	0,51	-2,110	-17,43	17,810	313,00	24,70	0,78458	28466,89	8,933820
P19	0,34	-0,785	-15,26	07,983	331,95	17,17	2,58784	59495,82	61,58627
P20	0,34	-1,050	-17,18	00,000	000,00	17,18	2,02051	125705,9	101,5960
P21	0,34	-1,315	-18,68	06,221	341,20	19,65	1,57538	71880,71	45,29577
P22	0,34	-1,580	-19,88	11,088	330,05	22,65	1,24077	36348,00	18,03980
P23	0,34	-1,845	-20,85	14,945	323,13	25,45	0,99161	30708,42	12,18031
P24	0,34	-2,110	-21,66	18,048	318,56	27,90	0,80494	27051,62	8,709970
P25	0,17	-0,785	-22,68	08,192	339,53	24,00	2,72422	59669,15	65,02076
P26	0,17	-1,050	-23,69	00,000	000,00	23,69	2,10269	114274,5	96,11354
P27	0,17	-1,315	-24,47	06,318	345,04	25,22	1,62490	72090,19	46,85574
P28	0,17	-1,580	-25,08	11,226	334,91	27,33	1,27129	42651,86	21,68915
P29	0,17	-1,845	-25,58	15,094	328,01	29,44	1,01100	27050,10	10,93906
P30	0,17	-2,110	-25,99	18,195	323,13	31,35	0,81767	24147,34	7,897820

Values of C. γ. I. and illuminance where the projector is directed at the point P3* (0.85.-1.315)

P	X`	Y`	B	β	C	γ	$Cos^3 \theta$	I	E
P01	0.85	-0.785	00.00	12.702	060.20	14.68	1.91629	32481.11	24.89729
P02	0.85	-1.050	-3.126	5.4760	058.97	06.40	1.58644	71094.87	45.11510
P03	0.85	-1.315	-5.766	00.000	000.00	00.00	1.29839	143735.0	74.64963
P04	0.85	-1.580	-8.016	04.479	301.03	05.23	1.06228	91009.04	38.67083
P05	0.85	-1.845	-9.952	08.146	301.03	09.52	0.87421	72366.89	25.30554
P06	0.85	-2.110	-11.63	11.166	301.03	13.06	0.72582	56983.86	16.54401
P07	0.68	-0.785	-5.625	12.857	082.57	12.97	2.15608	34886.43	30.08717
P08	0.68	-1.050	-8.411	05.748	288.82	06.07	1.74731	83603.94	58.43280
P09	0.68	-1.315	-10.72	00.000	000.00	4.853	1.40420	141541.3	79.50092
P10	0.68	-1.580	-12.67	04.624	327.07	8.530	1.13208	98163.65	44.45164
P11	0.68	-1.845	-14.32	08.362	317.02	12.32	0.92094	71488.27	26.33456
P12	0.68	-2.110	-15.74	11.413	312.41	15.56	0.75774	45944.93	13.92572
P13	0.51	-0.785	-11.91	13.545	288.82	14.33	2.38845	49490.06	47.28181
P14	0.51	-1.050	-14.20	05.990	286.07	9.770	1.89693	67795.70	51.44148
P15	0.51	-1.315	-16.07	00.000	00.00	10.07	1.49923	142971.1	85.73862
P16	0.51	-1.580	-17.63	04.747	338.10	12.82	1.19305	92402.29	44.09622
P17	0.51	-1.845	-18.93	08.543	327.07	15.86	0.96088	60126.71	23.10982
P18	0.51	-2.110	-20.05	11.616	320.88	18.60	0.78458	42767.08	13.42168
P19	0.34	-0.785	-18.79	14.109	309.10	18.30	2.58784	38301.67	39.64744
P20	0.34	-1.050	-20.44	06.183	335.80	15.24	2.02051	77337.50	62.50448
P21	0.34	-1.315	-21.76	00.000	00.000	15.59	1.57538	142139.1	89.56924
P22	0.34	-1.580	-22.85	04.842	343.74	17.54	1.24077	86046.17	42.70540
P23	0.34	-1.845	-23.75	08.679	333.62	19.85	0.99161	49652.85	19.69451
P24	0.34	-2.110	-24.52	11.763	327.10	22.00	0.80494	36083.94	11.61816
P25	0.17	-0.785	-26.15	14.485	322.07	24.00	2.72422	31975.96	34.84382
P26	0.17	-1.050	-27.01	06.308	342.47	21.40	2.10269	72523.23	60.99755
P27	0.17	-1.315	-27.69	00.000	000.00	21.35	1.62490	141271.0	91.82050
P28	0.17	-1.580	-28.26	04.900	347.12	22.52	1.27129	82841.64	42.12630
P29	0.17	-1.845	-28.72	08.765	338.10	24.10	1.01100	55747.18	22.54416
P30	0.17	-2.110	-29.12	11.862	331.70	25.70	0.81767	20556.88	06.72350

Values of C. γ. I. and illuminance where the projector is directed at the point P4* (0.85.-1.580)

P	X`	Y`	B	B	C	γ	$Cos^3\ \theta$	I	E
P01	0.85	-0.785	10.900	16.14	056.84	19.40	1.91629	11407.17	8.743780
P02	0.85	-1.050	06.420	09.70	056.80	11.62	1.58644	47924.84	30.41195
P03	0.85	-1.315	02.870	04.37	056.76	05.23	1.29839	77939.20	40.47819
P04	0.85	-1.580	00.000	00.00	000.00	00.00	1.06228	143735.0	61.07473
P05	0.85	-1.845	-2.350	03.59	303.17	04.29	0.87421	101098.1	35.35239
P06	0.85	-2.110	-4.300	06.55	303.15	07.83	0.72582	81524.84	23.66894
P07	0.68	-0.785	05.130	17.15	073.84	17.88	2.15608	15458.44	13.33185
P08	0.68	-1.050	01.110	10.19	083.85	10.25	1.74731	45879.52	32.06630
P09	0.68	-1.315	-1.990	04.55	293.57	04.96	1.40420	84052.36	47.21053
P10	0.68	-1.580	-4.460	00.00	000.00	04.46	1.13208	143062.9	64.78346
P11	0.68	-1.845	-6.455	03.68	330.23	07.43	0.92094	106868.4	39.36775
P12	0.68	-2.110	-8.050	06.70	320.00	10.46	0.75774	82851.26	25.11189
P13	0.51	-0.785	-1.387	18.08	274.24	18.13	2.38845	32976.17	31.50477
P14	0.51	-1.050	-4.710	10.63	293.60	11.62	1.89693	61455.49	46.63071
P15	0.51	-1.315	-7.230	04.70	326.85	08.62	1.49923	97691.98	58.58510
P16	0.51	-1.580	-9.190	00.00	000.00	09.19	1.19305	143103.6	68.29190
P17	0.51	-1.845	-10.75	03.76	304.60	11.40	0.96088	66827.24	25.68518
P18	0.51	-2.110	-12.03	06.81	330.20	13.80	0.78458	73173.51	22.96419
P19	0.34	-0.785	-8.600	18.85	293.66	20.65	2.58784	25954.90	26.86685
P20	0.34	-1.050	-10.99	10.97	314.53	15.48	2.02051	54576.14	44.10865
P21	0.34	-1.315	-12.77	04.89	338.84	13.66	1.57538	90250.99	56.87184
P22	0.34	-1.580	-14.14	00.00	000.00	14.14	1.24077	129641.6	64.34216
P23	0.34	-1.845	-15.22	03.80	345.81	15.68	0.99161	96977.69	38.46562
P24	0.34	-2.110	-16.10	06.89	336.46	17.48	0.80494	68765.02	22.14069
P25	0.17	-0.785	-16.37	19.36	308.74	25.15	2.72422	26874.08	29.28436
P26	0.17	-1.050	-17.63	11.19	326.85	20.78	2.10269	37484.89	31.52764
P27	0.17	-1.315	-18.55	04.90	344.92	19.16	1.62490	83522.19	54.28608
P28	0.17	-1.580	-19.25	00.00	000.00	19.25	1.27129	123142.4	62.61988
P29	0.17	-1.845	-19.80	03.86	348.73	20.16	1.01100	91455.31	36.98453
P30	0.17	-2.110	-20.25	06.95	340.60	21.36	0.81767	67621.60	22.11686

Values of C. γ. I. and illuminance where the projector is directed at the point P5* (0.85.-1.8450)

P	X`	Y`	B	β	C	γ	$Cos^3\ \theta$	I	E
P01	0.85	-0.785	14.03	19.27	055.28	23.69	1.91629	7672.840	5.881350
P02	0.85	-1.050	9.220	13.02	055.29	15.91	1.58644	28210.40	17.90164
P03	0.85	-1.315	4.450	07.80	055.30	09.50	1.29839	58627.97	30.44879
P04	0.85	-1.580	2.440	03.52	055.34	04.28	1.06228	89141.72	37.87739
P05	0.85	-1.845	00.00	00.00	000.00	00.00	0.87421	143735.0	50.26183
P06	0.85	-2.110	-2.01	02.91	055.30	3.540	0.72582	98599.23	28.62612
P07	0.68	-0.785	8.186	20.50	069.16	22.00	2.15608	6645.690	5.731460
P08	0.68	-1.050	3.860	13.68	074.54	14.20	1.74731	30837.05	21.55275
P09	0.68	-1.315	0.056	08.13	086.00	08.15	1.40420	54292.76	30.49507
P10	0.68	-1.580	-2.02	3.640	298.84	04.16	1.13208	129031.6	58.42964
P11	0.68	-1.845	-4.09	00.00	000.00	04.09	0.92094	141883.9	52.26662
P12	0.68	-2.110	-5.80	02.97	332.74	06.50	0.75774	114105.4	34.58489
P13	0.51	-0.785	1.560	21.64	086.00	21.70	2.38845	5725.044	5.469590
P14	0.51	-1.050	-2.03	14.26	277.93	14.40	1.89693	47930.29	36.36816
P15	0.51	-1.315	-4.70	08.40	299.03	09.62	1.49923	70924.68	42.53296
P16	0.51	-1.580	-6.76	03.74	331.00	07.72	1.19305	106180.6	50.67151
P17	0.51	-1.845	-8.40	00.00	000.00	08.40	0.96088	137072.9	52.68424
P18	0.51	-2.110	-9.70	03.01	342.59	10.17	0.78458	109995.8	34.52020
P19	0.34	-0.785	-5.80	22.60	283.67	23.26	2.58784	24836.06	25.70870
P20	0.34	-1.050	-8.40	14.74	299.04	16.10	2.02051	43090.86	34.82621
P21	0.34	-1.315	-10.3	08.60	319.70	13.38	1.57538	68114.21	42.92231
P22	0.34	-1.580	-11.7	03.80	341.85	12.32	1.24077	100933.9	50.09430
P23	0.34	-1.845	-12.80	00.00	000.00	12.85	0.99161	131311.8	52.08404
P24	0.34	-2.110	-13.80	03.10	347.30	14.08	0.80494	104990.3	33.80436
P25	0.17	-0.785	-13.76	23.19	299.04	26.77	2.72422	23670.22	25.79315
P26	0.17	-1.050	-15.13	15.04	314.16	21.20	2.10269	31733.86	26.69059
P27	0.17	-1.315	-16.75	08.75	331.90	18.83	1.62490	50983.10	33.13698
P28	0.17	-1.580	-16.84	03.86	346.91	17.27	1.27129	94510.00	48.05985
P29	0.17	-1.845	-17.42	00.00	000.00	17.42	1.01100	125395.4	50.70990
P30	0.17	-2.110	-17.88	03.09	350.02	18.14	0.81767	99605.13	32.57765

Values of C. γ. I. and illuminance where the projector is directed at the point P6* (0.85.-2.110)

P	X`	Y`	B	β	C	Γ	$Cos^3\theta$	I	E
P01	0.85	-0.785	16.76	21.78	54.18	27.23	1.91629	6682.060	5.12191
P02	0.85	-1.050	11.68	15.67	54.18	19.46	1.58644	11549.95	7.32932
P03	0.85	-1.315	7.30	10.56	54.19	13.06	1.29839	42263.87	21.9499
P04	0.85	-1.580	4.60	6.340	54.20	7.830	1.06228	67356.41	28.6205
P05	0.85	-1.845	2.07	2.87	54.26	3.540	0.87421	62822.53	21.9680
P06	0.85	-2.110	00.00	00.00	00.00	00.00	0.72582	143735.0	41.7303
P07	0.68	-0.785	10.87	23.18	66.23	25.47	2.15608	6265.840	5.40386
P08	0.68	-1.050	6.28	16.46	69.70	17.60	1.74731	17233.95	12.0452
P09	0.68	-1.315	2.810	10.98	75.83	11.34	1.40420	53447.73	30.0205
P10	0.68	-1.580	0.118	6.55	88.97	6.550	1.13208	66359.43	30.0496
P11	0.68	-1.845	-2.02	2.95	304.44	3.570	0.92094	73055.67	26.9119
P12	0.68	-2.110	-3.77	00.00	00.00	3.770	0.75774	142027.7	43.0480
P13	0.51	-0.785	4.14	24.47	80.97	24.80	2.38845	5602.350	5.35237
P14	0.51	-1.050	0.319	17.17	88.96	17.18	1.89693	17358.08	13.1708
P15	0.51	-1.315	-2.50	11.36	282.22	11.62	1.49923	59614.92	35.7505
P16	0.51	-1.580	-4.64	6.730	304.45	8.160	1.19305	81165.61	38.7338
P17	0.51	-1.845	-6.33	3.010	334.49	7.000	0.96088	113355.6	43.5684
P18	0.51	-2.110	-7.68	0.00	0.000	7.680	0.78458	138005.2	43.3104
P19	0.34	-0.785	-3.36	25.54	277.00	25.75	2.58784	23959.13	24.8009
P20	0.34	-1.050	-6.13	17.74	288.46	18.74	2.02051	31260.04	25.2644
P21	0.34	-1.315	-8.13	11.65	304.46	14.17	1.57538	54370.31	34.2615
P22	0.34	-1.580	-9.62	6.86	324.25	11.80	1.24077	79254.85	39.3348
P23	0.34	-1.845	-10.78	3.06	344.05	11.20	0.99161	108541.1	43.0521
P24	0.34	-2.110	-11.72	00.00	0.000	11.72	0.80494	132774.7	42.7502
P25	0.17	-0.785	-11.50	26.25	292.00	28.50	2.72422	23022.46	25.0873
P26	0.17	-1.050	-12.96	18.12	304.44	22.15	2.10269	27219.98	22.8940
P27	0.17	-1.315	-14.00	11.83	319.12	18.25	1.62490	43625.14	28.3546
P28	0.17	-1.580	-14.77	6.94	334.47	16.29	1.27129	69562.63	35.3737
P29	0.17	-1.845	-15.36	3.09	348.48	15.66	1.01100	102805.3	41.5744
P30	0.17	-2.110	-15.83	00.00	00.00	15.83	0.81767	127453.6	41.6859

Values of C. γ. I. and illuminance where the projector is directed at the point P12* (0.68.-2.11)

P	X`	Y`	B	β	C	γ	$\cos^3\theta$	I	E
P01	0.85	-0.785	20.53	21.78	48.73	29.58	1.91629	6560.275	5.028560
P02	0.85	-1.050	15.45	15.66	46.47	21.86	1.58644	10906.23	6.920830
P03	0.85	-1.315	11.50	10.56	43.07	15.56	1.29839	37441.38	19.44541
P04	0.85	-1.580	08.37	06.34	37.37	10.50	1.06228	70719.49	30.04956
P05	0.85	-1.845	05.84	02.87	26.25	06.50	0.87421	116713.4	40.81281
P06	0.85	-2.110	03.77	00.00	00.00	03.77	0.72582	142030.8	41.23552
P07	0.68	-0.785	-16.18	25.28	300.54	29.73	2.15608	22626.14	19.51351
P08	0.68	-1.050	10.04	16.47	59.46	19.21	1.74731	11876.56	8.300810
P09	0.68	-1.315	06.58	10.98	59.45	12.76	1.40420	41546.70	23.33595
P10	0.68	-1.580	03.88	06.55	59.50	7.610	1.13208	65207.06	29.52784
P11	0.68	-1.845	01.74	2.950	59.48	03.42	0.92094	95979.00	35.35636
P12	0.68	-2.110	00.00	00.00	00.00	00.00	0.75774	143735.0	43.56550
P13	0.51	-0.785	07.91	24.47	73.17	25.64	2.38845	5915.950	5.651980
P14	0.51	-1.050	04.08	17.17	77.04	17.64	1.89693	16142.67	12.24861
P15	0.51	-1.315	01.27	11.36	83.70	11.43	1.49923	41084.11	24.63781
P16	0.51	-1.580	-0.872	06.73	277.36	06.78	1.19305	77919.20	37.18460
P17	0.51	-1.845	-2.56	03.01	310.32	03.95	0.96088	109843.7	42.21865
P18	0.51	-2.110	-3.92	00.00	00.00	03.92	0.78458	141963.1	44.55256
P19	0.34	-0.785	0.403	25.54	89.16	25.55	2.58784	5330.163	5.517440
P20	0.34	-1.050	-2.37	17.75	277.36	17.90	2.02051	34058.80	27.52646
P21	0.34	-1.315	-4.350	11.65	290.20	12.42	1.57538	57583.68	36.28647
P22	0.34	-1.580	-5.87	06.86	310.37	09.02	1.24077	82161.29	40.77731
P23	0.34	-1.845	-7.02	03.06	336.37	07.65	0.99161	112376.2	44.57335
P24	0.34	-2.110	-7.95	00.00	00.00	07.95	0.80494	137655.6	44.32180
P25	0.17	-0.785	-7.73	26.25	285.25	27.30	2.72422	23467.99	25.57279
P26	0.17	-1.050	-9.20	18.12	296.04	20.25	2.10269	26164.29	22.00616
P27	0.17	-1.315	-10.23	11.83	310.30	15.60	1.62490	51476.45	33.45763
P28	0.17	-1.580	-11.00	6.940	327.45	12.98	1.27129	75402.29	38.34327
P29	0.17	-1.845	-11.60	3.090	344.98	12.00	1.01100	107348.8	43.41185
P30	0.17	-2.110	-12.07	00.00	00.00	12.07	0.81767	132321.6	43.27816

Values of C. γ. I. and illuminance where the projector is directed at the point P13* (0.51.-0.785)

P	X`	Y`	B	β	C	γ	$Cos^3\theta$	I	E
P01	0.85	-0.785	11.90	00.00	00.00	11.90	1.91629	132541.7	101.59
P02	0.85	-1.050	8.78	7.120	39.31	11.28	1.86440	62996.54	46.980
P03	0.85	-1.315	6.140	12.980	65.08	14.33	1.98390	32626.26	25.890
P04	0.85	-1.580	3.90	17.72	77.98	18.14	1.06228	13996.53	5.9479
P05	0.85	-1.845	1.96	21.61	85.06	21.69	0.87421	4472.700	1.5640
P06	0.85	-2.110	0.278	24.80	89.40	24.80	0.72582	5402.668	1.5685
P07	0.68	-0.785	6.280	00.00	00.00	6.820	2.15608	139118.6	119.98
P08	0.68	-1.050	3.50	7.470	65.07	8.250	1.74731	59595.41	41.653
P09	0.68	-1.315	1.185	13.50	85.09	13.54	1.40420	32330.79	18.159
P10	0.68	-1.580	-0.758	18.32	272.29	18.33	1.13208	32094.08	14.533
P11	0.68	-1.845	-2.411	22.20	275.88	22.33	0.92094	25016.99	9.2156
P12	0.68	-2.110	-3.830	25.37	278.02	25.64	0.75774	24007.54	7.2765
P13	0.51	-0.785	00.00	00.00	00.00	00.00	2.38845	143735.0	137.32
P14	0.51	-1.050	-2.30	7.800	286.30	8.120	1.89693	74586.46	56.594
P15	0.51	-1.315	-4.16	13.95	286.30	14.54	1.49923	48334.23	28.986
P16	0.51	-1.580	-5.72	18.82	286.30	19.64	1.19305	27479.66	13.113
P17	0.51	-1.845	-7.02	22.71	286.30	23.72	0.96088	24724.16	9.5027
P18	0.51	-2.110	-8.14	25.85	286.30	27.02	0.78458	23585.64	7.4019
P19	0.34	-0.785	-6.88	00.00	00.00	6.88	2.58784	139035.2	143.92
P20	0.34	-1.050	-8.53	8.040	316.74	11.70	2.02051	74309.58	60.057
P21	0.34	-1.315	-9.85	14.31	303.85	17.31	1.57538	40037.19	25.229
P22	0.34	-1.580	-10.93	19.21	298.56	21.99	1.24077	25555.03	12.683
P23	0.34	-1.845	-11.85	23.09	295.72	25.80	0.99161	24063.04	9.5444
P24	0.34	-2.110	-12.62	26.21	293.93	28.90	0.80494	22901.52	7.3737
P25	0.17	-0.785	-14.24	00.00	00.00	14.24	2.72422	129512.1	51.804
P26	0.17	-1.050	-15.10	8.210	331.03	17.14	2.10269	57124.72	48.044
P27	0.17	-1.315	-15.79	14.54	316.38	21.33	1.62490	32524.47	21.139
P28	0.17	-1.580	-16.35	19.45	308.56	25.20	1.27129	26763.60	13.609
P29	0.17	-1.845	-16.81	23.33	303.84	28.48	1.01100	23706.96	9.5880
P30	0.17	-2.110	-17.23	26.43	300.79	31.21	0.81767	21984.83	7.1905

Values of C. γ. I. and illuminance where the projector is directed at the point P14* (0.51.-1.05)

P	X`	Y`	B	β	C	γ	$Cos^3θ$	I	E
P01	0.85	-0.785	14.66	6.860	25.44	16.15	1.91629	54903.35	42.084
P02	0.85	-1.050	11.00	00.00	00.00	11.00	1.86440	133706.9	99.713
P03	0.85	-1.315	7.990	5.650	35.41	09.77	1.98390	74773.86	59.337
P04	0.85	-1.580	5.50	10.250	62.61	11.62	1.06228	45572.51	19.364
P05	0.85	-1.845	3.38	14.01	76.70	14.40	0.87421	29436.29	10.293
P06	0.85	-2.110	1.593	17.11	84.830	17.18	0.72582	17443.08	5.0642
P07	0.68	-0.785	9.01	7.28	39.20	11.56	2.15608	62557.34	53.950
P08	0.68	-1.050	5.75	00.00	00.00	05.75	1.74731	140503.9	98.202
P09	0.68	-1.315	3.12	5.870	62.11	06.65	1.40420	45529.97	25.573
P10	0.68	-1.580	0.967	10.58	84.84	10.63	1.13208	44232.78	20.030
P11	0.68	-1.845	-0.822	14.39	273.2	14.41	0.92094	47339.57	17.438
P12	0.68	-2.110	-2.33	17.50	277.35	17.64	0.75774	36227.41	10.980
P13	0.51	-0.785	2.690	7.660	70.780	08.12	2.38845	57770.65	55.193
P14	0.51	-1.050	00.00	00.000	00.000	00.00	1.89693	143735.0	109.06
P15	0.51	-1.315	-2.122	6.070	289.20	06.43	1.49923	82209.96	49.300
P16	0.51	-1.580	-3.840	10.870	289.20	11.52	1.19305	61157.09	29.185
P17	0.51	-1.845	-5.250	14.71	289.20	15.60	0.96088	44281.70	17.019
P18	0.51	-2.110	-6.430	17.810	298.20	18.90	0.78458	31026.24	9.7370
P19	0.34	-0.785	-4.260	7.980	297.90	09.04	2.58784	73185.35	75.756
P20	0.34	-1.050	-6.182	00.00	00.00	06.18	2.02051	139947.1	113.10
P21	0.34	-1.315	-7.690	6.220	320.84	09.88	1.57538	86395.74	54.442
P22	0.34	-1.580	-8.870	11.09	308.20	14.16	1.24077	56818.06	28.199
P23	0.34	-1.845	-9.850	14.94	302.66	17.84	0.99161	37052.23	14.696
P24	0.34	-2.110	-10.66	18.05	299.58	20.87	0.80494	26021.64	8.3783
P25	0.17	-0.785	-11.68	8.190	324.58	14.23	2.72422	67017.98	73.028
P26	0.17	-1.050	-12.70	00.00	00.000	12.70	2.10269	131505.9	110.60
P27	0.17	-1.315	-13.47	6.320	334.58	14.85	1.62490	73429.46	47.722
P28	0.17	-1.580	-14.08	11.23	320.80	17.93	1.27129	46069.52	23.427
P29	0.17	-1.845	-14.58	15.09	313.03	20.87	1.01100	31521.91	12.747
P30	0.17	-2.110	-14.99	18.20	308.20	23.41	0.81767	27824.15	9.1000

Values of C. γ. I. and illuminance where the projector is directed to the point P15* (0.51. -1.315)

P	X`	Y`	B	β	C	γ	$Cos^3θ$	I	E
P01	0.85	-0.785	17.49	12.11	35.52	21.164	1.91629	19283.82	14.78136
P02	0.85	-1.050	13.38	5.470	22.50	14.44	1.58644	69878.39	44.34315
P03	0.85	-1.315	10.07	00.00	00.00	10.07	1.29839	134910.9	70.06679
P04	0.85	-1.580	7.37	4.480	31.41	8.620	1.06228	88235.54	37.49234
P05	0.85	-1.845	5.13	8.15	58.00	9.62	0.87421	56712.71	19.83153
P06	0.85	-2.110	3.250	11.17	73.97	11.62	0.72582	41945.55	12.17797
P07	0.68	-0.785	11.78	12.85	48.19	17.37	2.15608	24109.52	20.79282
P08	0.68	-1.050	8.10	5.74	35.54	9.92	1.74731	76341.51	53.35691
P09	0.68	-1.315	5.22	00.00	00.00	5.22	1.40420	141190.0	79.30360
P10	0.68	-1.580	2.890	4.62	58.00	5.45	1.13208	76105.47	34.46299
P11	0.68	-1.845	0.997	8.36	83.25	8.42	0.92094	53497.66	19.70725
P12	0.68	-2.110	-0.582	11.41	272.89	11.43	0.75774	59830.46	18.13437
P13	0.51	-0.785	3.56	9.73	70.10	10.35	2.38845	48514.39	46.34968
P14	0.51	-1.050	2.33	5.990	68.82	6.43	1.89693	65960.25	50.04879
P15	0.51	-1.315	00.00	00.00	00.00	00.00	1.49923	143735.0	86.19673
P16	0.51	-1.580	-1.85	4.75	291.20	5.10	1.19305	88326.69	42.15126
P17	0.51	-1.845	-3.34	8.54	291.20	9.17	0.96088	71280.35	27.39675
P18	0.51	-2.110	-4.57	11.62	291.20	12.47	0.78458	57524.03	18.05288
P19	0.34	-0.785	-1.71	14.11	276.77	14.20	2.58784	48581.88	50.28885
P20	0.34	-1.050	-8.53	8.05	316.38	11.70	2.02051	74047.98	59.84587
P21	0.34	-1.315	-5.53	00.00	00.00	5.53	1.57538	140788.7	88.71828
P22	0.34	-1.580	-6.81	4.84	324.47	8.35	1.24077	97102.40	48.19270
P23	0.34	-1.845	-7.85	8.68	311.82	11.68	0.99161	70828.50	28.09370
P24	0.34	-2.110	-8.70	11.77	305.98	14.60	0.80494	53410.11	17.19677
P25	0.17	-0.785	-9.28	14.48	301.97	17.14	2.72422	39766.80	43.33340
P26	0.17	-1.050	-10.43	6.310	328.59	12.17	2.10269	80446.25	67.66141
P27	0.17	-1.315	-11.28	00.00	00.00	11.28	1.62490	133344.4	86.66853
P28	0.17	-1.580	-11.94	4.90	337.49	12.85	1.27129	91188.18	46.37065
P29	0.17	-1.845	-12.47	8.76	324.84	15.20	1.01100	62207.59	25.15675
P30	0.17	-2.110	-12.90	11.860	316.75	17.45	0.81767	46316.29	15.14858

Values of C. γ. I. and illuminance where the projector is directed to the point P16* (0.51. -1.58)

P	X`	Y`	B	β	C	γ	$Cos^3\theta$	I	E
P01	0.85	-0.785	20.09	16.14	40.11	25.56	1.91629	11823.44	9.0628
P02	0.85	-1.050	15.61	9.70	32.44	18.32	1.86440	33072.51	24.664
P03	0.85	-1.315	12.05	4.37	20.130	12.80	1.98390	82250.25	65.272
P04	0.85	-1.580	9.190	00.00	00.00	9.190	1.06228	136050.2	57.809
P05	0.85	-1.845	6.84	3.60	27.77	7.720	0.87421	99777.19	34.890
P06	0.85	-2.110	4.880	6.550	53.46	8.160	0.72582	66346.83	19.263
P07	0.68	-0.785	14.32	17.15	51.30	22.20	2.15608	8636.349	7.4482
P08	0.68	-1.050	10.30	10.19	45.162	14.45	1.74731	41539.69	29.033
P09	0.68	-1.315	7.190	4.54	32.44	8.50	1.40420	88485.95	49.700
P10	0.68	-1.580	4.720	00.00	00.00	4.720	1.13208	141601.4	64.121
P11	0.68	-1.845	2.74	3.680	53.40	4.60	0.92094	81521.80	32.031
P12	0.68	-2.110	1.095	6.70	80.74	6.780	0.75774	60559.99	18.355
P13	0.51	-0.785	7.80	18.08	67.43	19.64	2.38845	8768.639	8.3774
P14	0.51	-1.050	4.47	10.63	67.44	11.52	1.89693	44310.76	33.622
P15	0.51	-1.315	1.960	4.70	67.40	5.09	1.49923	72475.67	43.463
P16	0.51	-1.580	00.00	00.00	00.00	00.00	1.19305	143735.0	68.593
P17	0.51	-1.845	-1.570	3.760	292.57	4.08	0.96088	95804.22	36.823
P18	0.51	-2.110	-2.85	6.81	292.60	7.40	0.78458	78980.26	24.786
P19	0.34	-0.785	0.587	18.85	88.28	18.85	2.58784	10560.15	10.931
P20	0.34	-1.050	-1.810	10.97	279.26	11.12	2.02051	61123.53	49.400
P21	0.34	-1.315	-3.580	4.820	306.52	6.000	1.57538	92694.96	58.411
P22	0.34	-1.580	-4.95	00.00	00.00	4.95	1.24077	141497.4	70.226
P23	0.34	-1.845	-6.03	3.82	327.56	7.140	0.99161	106019.6	42.052
P24	0.34	-2.110	-6.91	6.89	314.84	9.75	0.80494	268.6166	26.497
P25	0.17	-0.785	-7.18	19.35	289.28	20.60	2.72422	25871.68	28.190
P26	0.17	-1.050	-8.44	11.19	306.56	13.98	2.10269	56576.38	47.585
P27	0.17	-1.315	-9.36	4.89	339.23	10.55	1.62490	100057.9	65.033
P28	0.17	-1.580	-10.06	00.00	00.00	10.06	1.27129	134923.8	68.611
P29	0.17	-1.845	-10.61	3.85	339.88	11.28	1.01100	97343.17	39.365
P30	0.17	-2.110	-11.06	6.95	327.56	13.04	0.81767	75156.89	24.581

Values of C. γ. I. and illuminance where the projector is directed to the point P17* (0.51.-1.845)

P	X`	Y`	B	β	C	γ	Cos^3 θ	I	E
P01	**0.85**	**-0.785**	**22.42**	**19.28**	**42.53**	**29.25**	**1.91629**	**8410.783**	**6.447000**
sP02	**0.85**	**-1.050**	**17.61**	**13.03**	**37.40**	**21.78**	**1.58644**	**16956.92**	**10.76045**
P03	**0.85**	**-1.315**	**13.84**	**7.81**	**29.84**	**15.85**	**1.29839**	**77233.05**	**40.11145**
P04	**0.85**	**-1.580**	**10.84**	**3.52**	**18.14**	**11.40**	**1.06228**	**94661.47**	**40.22279**
P05	**0.85**	**-1.845**	**8.40**	**00.00**	**00.00**	**8.40**	**0.87421**	**137072.9**	**47.93220**
P06	**0.85**	**-2.110**	**6.37**	**2.91**	**24.64**	**7.00**	**0.72582**	**108826.7**	**31.59544**
P07	**0.68**	**-0.785**	**16.57**	**20.50**	**52.68**	**26.14**	**2.15608**	**7169.260**	**6.183000**
P08	**0.68**	**-1.050**	**12.25**	**13.68**	**48.92**	**18.29**	**1.74731**	**18915.15**	**13.22025**
P09	**0.68**	**-1.315**	**8.95**	**8.13**	**42.55**	**12.07**	**1.40420**	**56383.60**	**31.66954**
P10	**0.68**	**-1.580**	**6.37**	**3.64**	**29.82**	**7.33**	**1.13208**	**99566.20**	**45.08676**
P11	**0.68**	**-1.845**	**4.29**	**00.00**	**00.00**	**4.29**	**0.92094**	**141795.8**	**52.23417**
P12	**0.68**	**-2.110**	**2.600**	**2.98**	**48.89**	**3.95**	**0.75774**	**98315.61**	**29.79907**
P13	**0.51**	**-0.785**	**9.95**	**21.63**	**66.46**	**23.72**	**2.38845**	**6590.590**	**6.296520**
P14	**0.51**	**-1.050**	**6.36**	**14.27**	**66.46**	**15.60**	**1.89693**	**26676.61**	**20.24146**
P15	**0.51**	**-1.315**	**3.690**	**8.40**	**66.45**	**9.168**	**1.49923**	**54989.27**	**32.97663**
P16	**0.51**	**-1.580**	**1.630**	**3.74**	**66.45**	**4.07**	**1.19305**	**86429.14**	**41.24571**
P17	**0.51**	**-1.845**	**00.00**	**00.00**	**00.00**	**00.00**	**0.96088**	**143735.0**	**55.24483**
P18	**0.51**	**-2.110**	**-1.321**	**3.030**	**293.54**	**03.30**	**0.78458**	**107802.7**	**33.83194**
P19	**0.34**	**-0.785**	**2.590**	**22.57**	**82.80**	**22.71**	**2.58784**	**5716.974**	**5.917850**
P20	**0.34**	**-1.050**	**-0.006**	**14.74**	**270.03**	**14.74**	**2.02051**	**45707.84**	**36.94126**
P21	**0.34**	**-1.315**	**-1.90**	**8.60**	**282.32**	**8.820**	**1.57538**	**70900.16**	**44.67788**
P22	**0.34**	**-1.580**	**-3.33**	**3.81**	**311.10**	**5.05**	**1.24077**	**101341.6**	**50.29665**
P23	**0.34**	**-1.845**	**-4.460**	**00.00**	**00.00**	**4.46**	**0.99161**	**141718.9**	**56.21195**
P24	**0.34**	**-2.110**	**-5.360**	**3.07**	**330.16**	**6.17**	**0.80494**	**113459.8**	**36.53133**
P25	**0.17**	**-0.785**	**-5.37**	**23.19**	**282.33**	**23.77**	**2.72422**	**24646.99**	**26.85753**
P26	**0.17**	**-1.050**	**-6.730**	**15.03**	**293.57**	**16.44**	**2.10269**	**41172.94**	**34.62957**
P27	**0.17**	**-1.315**	**-7.71**	**8.75**	**311.10**	**11.64**	**1.62490**	**70492.08**	**45.81703**
P28	**0.17**	**-1.580**	**-8.450**	**3.850**	**335.36**	**9.28**	**1.27129**	**103791.2**	**52.77949**
P29	**0.17**	**-1.845**	**-9.03**	**00.00**	**00.00**	**9.03**	**1.01100**	**136257.4**	**55.10249**
P30	**0.17**	**-2.110**	**-9.50**	**3.09**	**341.86**	**9.970**	**0.81767**	**109701.1**	**35.87972**

Values of C. γ. I. and illuminance where the projector is directed at the point P18* (0.51.-2.110)

P	X`	Y`	B	β	C	γ	Cos^3 θ	I	E
P01	0.85	-0.785	24.44	21.78	44.00	32.29	1.91629	6238.027	4.781550
sP02	0.85	-1.050	19.36	15.66	40.23	24.71	1.58644	12343.97	7.833190
P03	0.85	-1.315	15.41	10.56	35.05	18.60	1.29839	28724.56	14.91827
P04	0.85	-1.580	12.29	6.34	27.60	13.80	1.06228	67337.76	28.61262
P05	0.85	-1.845	9.76	2.870	16.50	10.17	0.87421	104793.5	36.64461
P06	0.85	-2.110	7.68	00.00	00.00	7.680	0.72582	138005.2	40.06677
P07	0.68	-0.785	18.54	23.17	53.40	29.36	2.15608	6065.595	5.231160
P08	0.68	-1.050	13.96	16.47	50.77	21.46	1.74731	8958.511	6.261320
P09	0.68	-1.315	10.50	10.99	46.81	15.15	1.40420	36543.47	20.52574
P10	0.68	-1.580	7.80	6.550	40.23	10.17	1.13208	69377.91	31.41654
P11	0.68	-1.845	5.65	2.950	27.62	6.37	0.92094	107971.1	39.77396
P12	0.68	-2.110	3.920	00.00	00.00	3.920	0.75774	141963.1	43.02845
P13	0.51	-0.785	11.83	24.47	65.75	27.03	2.38845	5981.133	5.714250
P14	0.51	-1.050	8.00	17.17	65.76	18.89	1.89693	12300.99	9.333650
P15	0.51	-1.315	5.180	11.360	67.97	12.47	1.49923	39989.71	23.98151
P16	0.51	-1.580	3.04	6.730	65.78	7.40	1.19305	63059.64	30.09332
P17	0.51	-1.845	1.36	3.012	65.72	3.30	0.96088	97506.59	37.47685
P18	0.51	-2.110	00.00	00.00	00.00	00.00	0.78458	143735.0	45.10864
P19	0.34	-0.785	4.32	25.54	81.04	25.88	2.58784	5490.660	5.683580
P20	0.34	-1.050	1.550	17.75	85.170	17.81	2.02051	14866.36	12.01505
P21	0.34	-1.315	-0.440	11.65	272.15	11.65	1.57538	57870.44	36.46717
P22	0.34	-1.580	-1.940	6.860	285.72	7.130	1.24077	78499.17	38.95977
P23	0.34	-1.845	-3.10	3.06	315.33	4.35	0.99161	110552.7	43.85007
P24	0.34	-2.110	-4.04	00.00	00.00	4.04	0.80494	141908.8	45.69123
P25	0.17	-0.785	-3.820	26.25	277.70	26.52	2.72422	23718.75	25.84604
P26	0.17	-1.050	-5.28	18.11	285.70	18.85	2.10269	30683.38	25.80705
P27	0.17	-1.315	-6.320	11.83	297.73	13.40	1.62490	54515.01	35.43258
P28	0.17	-1.580	-7.08	6.94	315.38	9.91	1.27129	81956.24	41.67606
P29	0.17	-1.845	-7.680	3.080	338.01	8.27	1.01100	111529.5	45.10253
P30	0.17	-2.110	-8.16	00.00	00.00	8.16	0.81767	137383.7	44.93381

Values of C. γ. I. and illuminance where the projector is directed at the point P21* (0.34.-1.315)

P	X`	Y`	B	β	C	γ	Cos^3 θ	I	E
P01	0.85	-0.785	23.02	12.11	28.750	25.85	1.91629	22258.35	17.06138
P02	0.85	-1.050	18.90	5.470	16.49	19.48	1.58644	57364.46	36.40211
P03	0.85	-1.315	15.60	00.00	00.00	15.60	1.29839	100304.6	52.09380
P04	0.85	-1.580	12.90	4.480	19.34	13.64	1.06228	79254.39	33.67614
P05	0.85	-1.845	10.66	8.150	37.730	13.38	0.87421	50145.97	17.53524
P06	0.85	-2.110	8.780	11.170	52.29	14.170	0.72582	37804.17	10.97561
P07	0.68	-0.785	17.30	12.860	37.51	21.44	2.15608	16955.39	14.62287
P08	0.68	-1.050	13.630	5.750	23.130	14.77	1.74731	67288.52	47.02956
P09	0.68	-1.315	10.74	00.00	00.00	10.74	1.40420	134043.5	75.28955
P10	0.68	-1.580	8.420	4.620	28.920	9.60	1.13208	88555.56	40.10079
P11	0.68	-1.845	6.520	8.360	52.31	10.60	0.92094	55284.99	20.36566
P12	0.68	-2.110	4.490	11.410	66.90	12.42	0.75774	40537.17	12.28665
P13	0.51	-0.785	10.88	13.54	51.92	17.30	2.38845	22573.97	21.56672
P14	0.51	-1.050	7.850	5.99	37.53	9.86	1.89693	74018.42	56.16310
P15	0.51	-1.315	5.52	00.00	00.00	5.52	1.49923	141385.1	84.78751
P16	0.51	-1.580	3.680	4.75	52.30	6.00	1.19305	77829.97	37.14202
P17	0.51	-1.845	2.19	8.54	75.73	8.810	0.96088	53272.42	20.47536
P18	0.51	-2.110	0.950	11.61	85.38	11.65	0.78458	40060.95	12.57241
P19	0.34	-0.785	2.540	10.13	76.06	10.44	2.58784	46441.43	48.07320
P20	0.34	-1.050	1.64	6.18	75.158	6.39	2.02051	63825.87	51.58432
P21	0.34	-1.315	00.00	00.00	00.00	00.00	1.57538	143735.0	90.57490
P22	0.34	-1.580	-1.28	4.84	284.85	5.010	1.24077	86974.36	43.16607
P23	0.34	-1.845	-2.320	8.68	284.85	8.98	0.99161	70773.65	28.07194
P24	0.34	-2.110	-3.17	11.760	284.87	12.18	0.80494	57766.57	18.59945
P25	0.17	-0.785	-3.76	14.48	284.25	14.95	2.72422	46436.95	50.60179
P26	0.17	-1.050	-4.90	6.30	307.70	7.98	2.10269	84733.11	71.26699
P27	0.17	-1.315	-5.75	00.00	00.00	5.75	1.62490	140503.9	91.32191
P28	0.17	-1.580	-6.42	4.9	322.52	8.10	1.27129	96733.10	49.19033
P29	0.17	-1.845	-6.90	8.76	307.90	11.13	1.01100	70493.38	28.50752
P30	0.17	-2.110	-7.37	11.86	301.42	13.93	0.81767	53457.66	17.48429

Values of C. γ. I. and illuminance where the projector is directed at the point P23* (0.34.-1.845)

P	X`	Y`	B	β	C	γ	Cos^3 θ	I	E
P01	0.85	-0.785	26.87	19.29	37.75	32.65	1.91629	7141.048	5.473730
sP02	0.85	-1.050	22.07	13.03	31.62	25.46	1.58644	17584.46	11.15868
P03	0.85	-1.315	18.30	7.80	23.60	19.85	1.29839	38238.03	19.85915
P04	0.85	-1.580	15.30	3.52	13.14	15.70	1.06228	87146.23	37.02948
P05	0.85	-1.845	12.85	00.00	00.00	12.85	0.87421	131311.7	45.91760
P06	0.85	-2.110	10.83	2.91	15.15	11.21	0.72582	102622.2	29.79410
P07	0.68	-0.785	21.03	20.5	46.18	29.04	2.15608	7503.080	06.47090
P08	0.68	-1.050	16.70	13.68	40.27	21.46	1.74731	14679.99	10.26020
P09	0.68	-1.315	13.40	8.13	31.64	15.63	1.40420	49174.16	27.62014
P10	0.68	-1.580	10.82	3.63	18.70	11.41	1.13208	107918.6	48.86900
P11	0.68	-1.845	8.75	00.00	00.00	8.75	0.92094	136619.8	50.32746
P12	0.68	-2.110	7.06	2.98	22.93	7.66	0.75774	107980.7	32.72852
P13	0.51	-0.785	14.41	21.64	57.90	25.8	2.38845	6813.895	06.50986
P14	0.51	-1.050	10.82	14.27	53.56	17.84	1.89693	19487.99	14.78694
P15	0.51	-1.315	8.15	8.39	46.16	11.68	1.49923	55013.44	32.99112
P16	0.51	-1.580	6.10	3.73	31.56	7.15	1.19305	97353.29	46.45894
P17	0.51	-1.845	4.45	00.00	00.00	4.45	0.96088	143064.5	54.98713
P18	0.51	-2.110	3.13	3.03	44.10	4.35	0.78458	90865.55	28.51652
P19	0.34	-0.785	7.04	22.57	73.57	23.58	2.58784	6074.372	06.28780
P20	0.34	-1.050	4.45	14.73	73.56	15.37	2.02051	26094.61	21.08977
P21	0.34	-1.315	2.56	8.61	73.56	8.98	1.57538	53111.98	33.46862
P22	0.34	-1.580	1.13	3.80	73.50	3.97	1.24077	85141.35	42.25633
P23	0.34	-1.845	00.00	00.00	00.00	00.00	0.99161	143735.0	57.01163
P24	0.34	-2.110	-0.910	3.07	286.50	3.20	0.80494	107679.8	34.67031
P25	0.17	-0.785	-0.91	23.19	272.13	23.20	2.72422	24690.77	26.90524
P26	0.17	-1.050	-2.28	15.04	278.43	15.20	2.10269	44819.33	37.69646
P27	0.17	-1.315	-3.26	8.75	290.28	9.33	1.62490	70430.43	45.77696
P28	0.17	-1.580	-3.99	3.85	315.96	5.55	1.27129	103529.2	52.64625
P29	0.17	-1.845	-4.57	00.00	00.00	4.57	1.01100	135558.2	54.81974
P30	0.17	-2.110	-5.03	3.09	328.37	5.90	0.81767	113251.9	37.04107

Values of C. γ. I. and illuminance where the projector is directed at the point P24* (0.34.-2.11)

P	X`	Y`	B	β	C	γ	Cos^3 θ	I	E
P01	0.85	-0.785	28.48	21.78	39.96	35.29	1.91629	4677.264	03.58520
sP02	0.85	-1.050	23.40	15.67	35.23	27.91	1.58644	12611.72	08.00309
P03	0.85	-1.315	19.45	10.56	29.24	22.03	1.29839	28330.43	14.71358
P04	0.85	-1.580	16.32	6.34	21.58	17.47	1.06228	53759.72	22.84315
P05	0.85	-1.845	13.79	2.87	11.89	14.08	0.87421	97966.40	34.25728
P06	0.85	-2.110	11.72	00.00	00.00	11.72	0.72582	131074.7	38.05466
P07	0.68	-0.785	22.58	23.17	48.11	31.92	2.15608	5736.052	04.94695
P08	0.68	-1.050	17.99	16.47	43.74	24.20	1.74731	11058.16	07.72881
P09	0.68	-1.315	14.52	10.98	37.75	18.14	1.40420	28381.09	15.94109
P10	0.68	-1.580	11.83	6.55	29.25	13.50	1.13208	67006.50	30.34269
P11	0.68	-1.845	9.69	2.95	17.02	10.12	0.92094	103945.7	38.29110
P12	0.68	-2.110	7.95	00.00	00.00	7.95	0.75774	137655.6	41.72286
P13	0.51	-0.785	15.86	24.47	59.02	28.89	2.38845	5880.829	05.61843
P14	0.51	-1.050	12.04	17.17	55.98	20.87	1.89693	8446.456	06.40893
P15	0.51	-1.315	9.22	11.35	51.42	14.60	1.49923	36074.65	21.63368
P16	0.51	-1.580	7.07	6.72	43.77	9.74	1.19305	67497.26	32.21104
P17	0.51	-1.845	5.39	3.01	29.25	6.17	0.96088	106669.5	40.99864
P18	0.51	-2.110	4.04	00.00	00.00	4.04	0.78458	136244.4	42.75785
P19	0.34	-0.785	8.35	25.54	73.01	26.78	2.58784	5666.576	05.86568
P20	0.34	-1.050	5.58	17.75	73.1	18.57	2.02051	12682.00	10.24964
P21	0.34	-1.315	3.59	11.64	73.1	12.17	1.57538	39873.87	25.12660
P22	0.34	-1.580	2.095	6.86	73.09	7.17	1.24077	61129.54	30.33908
P23	0.34	-1.845	0.930	3.06	73.11	3.19	0.99161	96923.66	38.44419
P24	0.34	-2.110	00.00	00.00	00.00	00.00	0.80494	143735.0	46.27922
P25	0.17	-0.785	0.214	26.25	89.56	26.25	2.72422	5274.604	05.74767
P26	0.17	-1.050	-1.25	18.11	273.81	18.15	2.10269	32874.26	27.64975
P27	0.17	-1.315	-2.28	11.83	79.24	12.04	1.62490	39087.60	25.40538
P28	0.17	-1.580	-3.05	6.94	293.60	7.58	1.27129	78453.69	39.89496
P29	0.17	-1.845	-3.65	3.08	319.71	4.78	1.01100	75446.92	30.51073
P30	0.17	-2.110	-4.12	00.00	00.00	4.12	0.81767	136140.8	44.52730

Values of C. γ. I. and illuminance where the projector is directed at the point P25* (0.17. -0.785)

P	X`	Y`	B	β	C	γ	$\cos^3\theta$	I	E
P01	0.85	-0.785	26.150	00.00	00.00	26.15	1.91629	128489.1	98.48895
sP02	0.85	-1.050	23.02	7.120	17.72	24.04	1.58644	41196.32	26.14220
P03	0.85	-1.315	20.380	12.960	33.470	24.00	1.29839	17990.99	09.34373
P04	0.85	-1.580	18.140	17.730	45.750	25.15	1.06228	9622.279	04.08862
P05	0.85	-1.845	16.198	21.61	54.84	26.77	0.87421	6735.207	02.35519
P06	0.85	-2.110	14.52	24.790	61.510	28.50	0.72582	5819.591	01.68959
P07	0.68	-0.785	20.52	00.00	00.00	20.52	2.15608	120956.9	104.3171
P08	0.68	-1.050	17.74	7.480	23.32	19.19	1.74731	42224.55	29.51175
P09	0.68	-1.315	15.420	13.50	42.07	20.38	1.40420	14551.21	08.17312
P10	0.68	-1.580	13.480	18.320	54.850	22.60	1.13208	8055.511	03.64779
P11	0.68	-1.845	11.830	22.22	63.33	25.02	0.92094	6521.90	02.40251
P12	0.68	-2.110	10.410	25.380	69.140	27.29	0.75774	5787.195	01.75408
P13	0.51	-0.785	14.24	00.00	00.00	14.24	2.38845	129512.2	123.7333
P14	0.51	-1.050	11.950	7.80	33.466	14.23	1.89693	54923.06	041.6740
P15	0.51	-1.315	10.08	13.950	54.83	17.15	1.49923	21848.12	013.1021
P16	0.51	-1.580	8.520	18.82	66.50	20.59	1.19305	7192.238	03.43228
P17	0.51	-1.845	7.230	22.710	73.26	23.77	0.96088	6096.143	02.34306
P18	0.51	-2.110	6.10	25.85	77.630	26.51	0.78458	5511.468	01.72968
P19	0.34	-0.785	7.360	00.00	00.00	7.360	2.58784	138419.4	143.2829
P20	0.34	-1.050	5.720	8.050	46.480	11.13	2.02051	57544.81	46.50795
P21	0.34	-1.315	4.390	14.310	73.290	14.95	1.57538	28007.50	17.64898
P22	0.34	-1.580	3.30	19.210	80.620	19.48	1.24077	9821.24	04.87436
P23	0.34	-1.845	2.390	23.09	84.410	23.20	0.99161	5598.100	02.22045
P24	0.34	-2.110	1.630	26.210	86.690	26.26	0.80494	5262.287	01.69433
P25	0.17	-0.785	00.00	00.00	00.00	00.00	2.72422	143735.0	156.6263
P26	0.17	-1.050	-0.860	8.200	275.94	8.250	2.10269	71813.89	60.40094
P27	0.17	-1.315	-1.550	14.53	275.96	14.61	1.62490	46876.89	30.46810
P28	0.17	-1.580	-2.110	19.45	275.96	19.56	1.27129	27465.02	13.96640
P29	0.17	-1.845	-2.570	23.32	275.94	23.46	1.01100	24664.71	09.97441
P30	0.17	-2.110	-2.960	26.43	275.93	26.59	0.81767	23693.49	07.74938

Values of C. γ. I. and illuminance where the projector is directed at the point P26* (0.17.-1.05)

P	X`	Y`	B	β	C	γ	$Cos^3\ \theta$	I	E
P01	0.85	-0.785	27.35	6.860	14.680	28.13	1.91629	1584.45	1.214510
sP02	0.85	-1.050	23.70	00.00	00.00	23.70	1.58644	114240.6	72.49434
P03	0.85	-1.315	20.68	5.645	15.63	21.40	1.29839	54752.44	28.43601
P04	0.85	-1.580	18.18	10.25	30.09	20.78	1.06228	51065.77	21.69846
P05	0.85	-1.845	16.07	14.01	42.03	21.20	0.87421	13834.56	4.837720
P06	0.85	-2.110	14.28	17.11	51.29	22.15	0.72582	8671.518	2.517580
P07	0.68	-0.785	21.70	7.280	19.07	22.83	2.15608	38925.04	33.57020
P08	0.68	-1.050	18.43	00.00	00.00	18.43	1.74731	125382.2	87.63263
P09	0.68	-1.315	15.81	5.870	20.670	16.84	1.40420	58336.49	32.76644
P10	0.68	-1.580	13.65	10.58	38.370	17.21	1.13208	32789.66	14.84821
P11	0.68	-1.845	11.86	14.39	51.29	18.57	0.92094	16466.23	6.065760
P12	0.68	-2.110	10.36	17.50	60.29	20.25	0.75774	8066.145	2.444820
P13	0.51	-0.785	15.38	7.670	26.910	17.14	2.38845	49849.93	47.62563
P14	0.51	-1.050	12.69	00.00	00.00	12.69	1.89693	131518.9	99.79286
P15	0.51	-1.315	10.570	6.070	30.090	12.17	1.49923	70742.23	42.42355
P16	0.51	-1.580	8.850	10.87	45.570	15.31	1.19305	36729.28	17.52795
P17	0.51	-1.845	7.444	14.706	63.730	16.44	0.96088	23587.07	9.065740
P18	0.51	-2.110	6.260	17.810	71.180	18.84	0.78458	11737.26	3.683530
P19	0.34	-0.785	8.44	7.980	43.690	11.59	2.58784	57841.02	59.87332
P20	0.34	-1.050	6.50	00.00	00.00	6.50	2.02051	139532.8	112.7709
P21	0.34	-1.315	5.012	6.220	51.290	7.98	1.57538	69367.53	43.71209
P22	0.34	-1.580	3.820	11.088	71.23	11.72	1.24077	42302.68	20.99516
P23	0.34	-1.845	2.840	14.94	79.48	15.21	0.99161	25985.23	10.30689
P24	0.34	-2.110	2.030	18.040	83.80	18.16	0.80494	13479.04	4.339930
P25	0.17	-0.785	1.0080	8.191	83.03	8.25	2.72422	54195.17	59.05583
P26	0.17	-1.050	00.00	00.00	00.00	0.00	2.10269	143735.0	120.8920
P27	0.17	-1.315	-0.775	6.318	276.97	6.36	1.62490	79479.48	51.65848
P28	0.17	-1.580	-1.390	11.230	276.97	11.31	1.27129	59986.57	30.50413
P29	0.17	-1.845	-1.889	15.09	276.97	15.21	1.01100	44628.53	18.04778
P30	0.17	-2.110	-2.30	18.195	276.97	18.33	0.81767	32342.09	10.57806

Values of C. γ. I. and illuminance where the projector is directed at the point P27* (0.17.-1.315)

P	X`	Y`	B	β	C	γ	$\cos^3\theta$	I	E
P01	0.85	-0.785	28.77	12.11	24.03	31.01	1.91629	16997.34	13.02873
sP02	0.85	-1.050	24.66	5.470	12.94	25.22	1.58644	54646.93	34.67763
P03	0.85	-1.315	21.350	00.00	00.00	21.35	1.29839	119204.4	61.90952
P04	0.85	-1.580	18.65	4.450	13.76	19.16	1.06228	69285.20	29.44011
P05	0.85	-1.845	16.410	8.145	26.87	18.27	0.87421	43683.95	15.27558
P06	0.85	-2.110	14.53	11.16	38.195	18.25	0.72582	27302.02	7.926540
P07	0.68	-0.785	23.06	12.86	30.23	26.23	2.15608	17497.02	15.08999
P08	0.68	-1.050	19.38	5.75	16.87	20.18	1.74731	52818.75	36.91629
P09	0.68	-1.315	16.50	00.00	00.00	16.50	1.40420	126586.2	71.10094
P10	0.68	-1.580	14.170	4.620	18.28	14.89	1.13208	75403.90	34.14530
P11	0.68	-1.845	12.28	8.360	34.64	14.82	0.92094	57129.12	21.04500
P12	0.68	-2.110	10.70	11.410	47.390	15.59	0.75774	33814.33	10.24899
P13	0.51	-0.785	16.640	13.540	40.073	21.33	2.38845	14888.88	14.22454
P14	0.51	-1.050	13.61	5.990	24.033	14.84	1.89693	65841.28	49.95852
P15	0.51	-1.315	11.28	00.00	00.00	11.28	1.49923	133344.4	79.96557
P16	0.51	-1.580	9.430	4.750	26.88	10.55	1.19305	86029.51	41.05500
P17	0.51	-1.845	7.94	8.54	47.40	11.64	0.96088	54036.64	20.76909
P18	0.51	-2.110	6.70	11.62	60.420	13.38	0.78458	38356.43	12.03748
P19	0.34	-0.785	9.570	14.11	56.510	16.99	2.58784	22792.81	23.59366
P20	0.34	-1.050	7.399	6.183	40.07	9.630	2.02051	71893.07	58.10427
P21	0.34	-1.315	5.750	00.00	00.00	5.750	1.57538	140503.9	88.53881
P22	0.34	-1.580	4.470	4.840	47.38	6.580	1.24077	79974.92	39.69219
P23	0.34	-1.845	3.44	8.70	68.54	9.330	0.99161	51558.05	20.45019
P24	0.34	-2.110	2.588	11.770	77.77	12.04	0.80494	39367.82	12.67549
P25	0.17	-0.785	1.990	14.48	82.340	14.61	2.72422	28204.16	30.73373
P26	0.17	-1.050	0.853	6.300	82.32	6.360	2.10269	62109.46	52.23878
P27	0.17	-1.315	00.00	00.00	00.00	00.00	1.62490	143735.0	93.42200
P28	0.17	-1.580	-0.661	4.90	277.67	4.940	1.27129	83885.75	42.65725
P29	0.17	-1.845	-1.189	8.760	277.67	8.844	1.01100	69842.29	28.24422
P30	0.17	-2.110	-1.620	11.861	277.67	11.97	0.81767	57496.76	18.80535

Values of C. γ. I. and illuminance where the projector is directed at the point P28* (0.17.-1.580)

P	X`	Y`	B	β	C	γ	$\cos^3\theta$	I	E
P01	0.85	-0.785	30.160	16.140	29.950	33.83	1.91629	7780.073	5.963550
sP02	0.85	-1.050	25.67	9.70	21.55	27.32	1.58644	25750.79	16.34083
P03	0.85	-1.315	22.120	4.370	11.48	22.52	1.29839	67208.55	34.90516
P04	0.85	-1.580	19.250	00.00	00.00	19.25	1.06228	123025.9	52.27518
P05	0.85	-1.845	16.900	3.588	12.170	17.26	0.87421	83470.70	29.18837
P06	0.85	-2.110	14.940	6.550	24.006	16.28	0.72582	57814.37	16.78513
P07	0.68	-0.785	24.380	17.150	36.780	29.50	2.15608	10309.75	8.891460
P08	0.68	-1.050	20.360	10.190	27.330	22.67	1.74731	29026.22	20.28712
P09	0.68	-1.315	17.250	4.550	15.022	17.82	1.40420	71001.46	39.88010
P10	0.68	-1.580	14.790	00.00	00.00	14.79	1.13208	128800.1	58.32481
P11	0.68	-1.845	12.790	3.680	16.210	13.30	0.92094	89618.37	33.01326
P12	0.68	-2.110	11.160	6.700	31.237	12.98	0.75774	64693.02	19.60820
P13	0.51	-0.785	17.86	18.08	46.790	25.20	2.38845	9146.011	8.737920
P14	0.51	-1.050	14.53	10.620	36.790	17.93	1.89693	30569.11	23.19498
P15	0.51	-1.315	12.020	4.70	21.55	12.89	1.49923	79819.14	47.86690
P16	0.51	-1.580	10.06	00.00	00.00	10.06	1.19305	134923.8	64.38834
P17	0.51	-1.845	8.490	3.760	24.01	9.28	0.96088	96981.76	37.27513
P18	0.51	-2.110	7.220	6.810	43.54	9.913	0.78458	66821.89	20.97085
P19	0.34	-0.785	10.64	18.840	61.590	21.54	2.58784	7566.455	7.832310
P20	0.34	-1.050	8.25	10.970	53.50	13.70	2.02051	39524.58	31.94392
P21	0.34	-1.315	6.47	4.81	36.80	8.06	1.57538	84903.68	53.50222
P22	0.34	-1.580	5.11	00.00	00.00	5.11	1.24077	141332.4	70.14440
P23	0.34	-1.845	4.02	3.80	43.62	5.54	0.99161	89771.52	35.60733
P24	0.34	-2.110	3.15	6.89	56.57	7.58	0.80494	67015.69	21.57744
P25	0.17	-0.785	2.88	19.35	81.86	19.56	2.72422	7857.551	8.562280
P26	0.17	-1.050	1.62	11.19	81.87	11.31	2.10269	41779.44	35.13968
P27	0.17	-1.315	0.701	4.89	81.85	4.94	1.62490	68612.37	44.59530
P28	0.17	-1.580	00.00	00.00	00.00	00.00	1.27129	143735.0	73.09155
P29	0.17	-1.845	-0.55	3.85	278.10	3.89	1.01100	96615.42	39.07128
P30	0.17	-2.110	-0.999	6.95	278.14	7.02	0.81767	77156.88	25.23555

Values of C. γ. I. and illuminance where the projector is directed at the point P29* (0.17.-1.845)

P	X`	Y`	B	β	C	γ	$\cos^3\theta$	I	E
P01	0.85	-0.785	32.6	21.78	36.56	38.52	1.91629	1858.45	1.424530
sP02	0.85	-1.050	27.52	15.66	31.26	31.36	1.58644	10305.84	6.539840
P03	0.85	-1.315	23.57	10.55	24.99	25.70	1.29839	25784.17	13.39116
P04	0.85	-1.580	20.44	6.34	17.66	21.36	1.06228	74187.89	31.52332
P05	0.85	-1.845	17.91	2.87	9.26	18.13	0.87421	121051.7	42.32984
P06	0.85	-2.110	15.83	00.00	00.00	15.83	0.72582	127453.6	37.00335
P07	0.68	-0.785	26.70	23.178	43.62	34.78	2.15608	4816.613	4.154000
P08	0.68	-1.050	22.11	16.47	38.14	27.32	1.74731	11578.80	8.092700
P09	0.68	-1.315	18.64	10.98	31.27	21.53	1.40420	22830.62	12.82350
P10	0.68	-1.580	15.95	6.55	22.67	17.21	1.13208	54113.09	24.50414
P11	0.68	-1.845	13.81	2.94	12.17	14.12	0.92094	96997.92	35.73171
P12	0.68	-2.110	12.07	00.00	00.00	12.07	0.75774	132321.6	40.10615
P13	0.51	-0.785	19.98	24.47	53.10	31.19	2.38845	5493.889	5.248750
P14	0.51	-1.050	16.157	17.17	48.0	23.42	1.89693	9381.031	7.118060
P15	0.51	-1.315	13.34	11.35	41.04	17.45	1.49923	28932.29	17.35046
P16	0.51	-1.580	11.20	6.73	31.26	13.04	1.19305	64323.77	30.69659
P17	0.51	-1.845	9.51	3.01	17.66	9.97	0.96088	103385.2	39.73631
P18	0.51	-2.110	8.156	00.00	00.00	8.158	0.78458	137386.3	43.11622
P19	0.34	-0.785	12.47	25.54	65.68	28.24	2.58784	5707.227	5.907760
P20	0.34	-1.050	9.70	17.74	62.23	20.15	2.02051	7829.940	6.328190
P21	0.34	-1.315	7.71	11.64	56.94	13.93	1.57538	37035.47	23.33798
P22	0.34	-1.580	6.22	6.85	47.99	9.25	1.24077	65659.98	32.58757
P23	0.34	-1.845	5.05	3.06	31.26	5.90	0.99161	104879.2	41.59971
P24	0.34	-2.110	4.12	00.00	00.00	4.12	0.80494	141872.6	45.67957
P25	0.17	-0.785	4.33	26.25	81.29	26.58	2.72422	5406.125	5.890990
P26	0.17	-1.050	2.87	18.11	81.29	18.33	2.10269	12957.15	10.89795
P27	0.17	-1.315	1.84	11.83	81.28	11.97	1.62490	39142.66	25.44116
P28	0.17	-1.580	1.069	6.94	81.29	7.02	1.27129	59520.57	30.26716
P29	0.17	-1.845	0.474	3.90	81.28	3.13	1.01100	96257.84	38.92667
P30	0.17	-2.110	00.00	00.00	00.00	00.00	0.81767	143735.0	47.01112

Values of C. γ. I. and illuminance where the projector is directed at the point P30* (0.17.-2.11)

P	X`	Y`	B	β	C	γ	$\cos^3\theta$	I	E
P01	0.85	-0.785	30.160	16.140	29.950	33.83	1.91629	7780.073	5.963550
P02	0.85	-1.050	25.67	9.70	21.55	27.32	1.58644	25750.79	16.34083
P03	0.85	-1.315	22.120	4.370	11.48	22.52	1.29839	67208.55	34.90516
P04	0.85	-1.580	19.250	00.00	00.00	19.25	1.06228	123025.9	52.27518
P05	0.85	-1.845	16.900	3.588	12.170	17.26	0.87421	83470.70	29.18837
P06	0.85	-2.110	14.940	6.550	24.006	16.28	0.72582	57814.37	16.78513
P07	0.68	-0.785	24.380	17.150	36.780	29.50	2.15608	10309.75	8.891460
P08	0.68	-1.050	20.360	10.190	27.330	22.67	1.74731	29026.22	20.28712
P09	0.68	-1.315	17.250	4.550	15.022	17.82	1.40420	71001.46	39.88010
P10	0.68	-1.580	14.790	00.00	00.00	14.79	1.13208	128800.1	58.32481
P11	0.68	-1.845	12.790	3.680	16.210	13.30	0.92094	89618.37	33.01326
P12	0.68	-2.110	11.160	6.700	31.237	12.98	0.75774	64693.02	19.60820
P13	0.51	-0.785	17.86	18.08	46.790	25.20	2.38845	9146.011	8.737920
P14	0.51	-1.050	14.53	10.620	36.790	17.93	1.89693	30569.11	23.19498
P15	0.51	-1.315	12.020	4.70	21.55	12.89	1.49923	79819.14	47.86690
P16	0.51	-1.580	10.06	00.00	00.00	10.06	1.19305	134923.8	64.38834
P17	0.51	-1.845	8.490	3.760	24.01	9.28	0.96088	96981.76	37.27513
P18	0.51	-2.110	7.220	6.810	43.54	9.913	0.78458	66821.89	20.97085
P19	0.34	-0.785	10.64	18.840	61.590	21.54	2.58784	7566.455	7.832310
P20	0.34	-1.050	8.25	10.970	53.50	13.70	2.02051	39524.58	31.94392
P21	0.34	-1.315	6.47	4.81	36.80	8.06	1.57538	84903.68	53.50222
P22	0.34	-1.580	5.11	00.00	00.00	5.11	1.24077	141332.4	70.14440
P23	0.34	-1.845	4.02	3.80	43.62	5.54	0.99161	89771.52	35.60733
P24	0.34	-2.110	3.15	6.89	56.57	7.58	0.80494	67015.69	21.57744
P25	0.17	-0.785	2.88	19.35	81.86	19.56	2.72422	7857.551	8.562280
P26	0.17	-1.050	1.62	11.19	81.87	11.31	2.10269	41779.44	35.13968
P27	0.17	-1.315	0.701	4.89	81.85	4.94	1.62490	68612.37	44.59530
P28	0.17	-1.580	00.00	00.00	00.00	00.00	1.27129	143735.0	73.09155
P29	0.17	-1.845	-0.55	3.85	278.10	3.89	1.01100	96615.42	39.07128
P30	0.17	-2.110	-0.999	6.95	278.14	7.02	0.81767	77156.88	25.23555

Illuminance values by all projectors

P \ P*	P1*	P2*	P3*	P4*	P5*	P6*
P01	**110.1750**	**48,44065**	**24.89729**	**8.743780**	**5.881350**	**5.12191**
P02	**49.25680**	**107,1918**	**45.11510**	**30.41195**	**17.90164**	**7.32932**
P03	**26.34320**	**67,09107**	**74.64963**	**40.47819**	**30.44879**	**21.9499**
P04	**12.20040**	**12,05390**	**38.67083**	**61.07473**	**37.87739**	**28.6205**
P05	**8.677430**	**15,33493**	**25.30554**	**35.35239**	**50.26183**	**21.9680**
P06	**6.828800**	**8,309600**	**16.54401**	**23.66894**	**28.62612**	**41.7303**
P07	**121.3140**	**66,12030**	**30.08717**	**13.33185**	**5.731460**	**5.40386**
P08	**54.20776**	**98,65396**	**58.43280**	**32.06630**	**21.55275**	**12.0452**
P09	**24.36514**	**49,72211**	**79.50092**	**47.21053**	**30.49507**	**30.0205**
P10	**12.15761**	**22,24568**	**44.45164**	**64.78346**	**58.42964**	**30.0496**
P11	**8.925610**	**17,50330**	**26.33456**	**39.36775**	**52.26662**	**26.9119**
P12	**6.851990**	**8,506080**	**13.92572**	**25.11189**	**34.58489**	**43.0480**
P13	**126.6153**	**55,14780**	**47.28181**	**31.50477**	**5.469590**	**5.35237**
P14	**46.15642**	**101,4530**	**51.44148**	**46.63071**	**36.36816**	**13.1708**
P15	**20.02582**	**47,56917**	**85.73862**	**58.58510**	**42.53296**	**35.7505**
P16	**13.07348**	**22,33725**	**44.09622**	**68.29190**	**50.67151**	**38.7338**
P17	**9.970200**	**12,41621**	**23.10982**	**25.68518**	**52.68424**	**43.5684**
P18	**6.873270**	**8,933820**	**13.42168**	**22.96419**	**34.52020**	**43.3104**
P19	**127.9516**	**61,58627**	**39.64744**	**26.86685**	**25.70870**	**24.8009**
P20	**47.48516**	**101,5960**	**62.50448**	**44.10865**	**34.82621**	**25.2644**
P21	**19.50684**	**45,29577**	**89.56924**	**56.87184**	**42.92231**	**34.2615**
P22	**12.61114**	**18,03980**	**42.70540**	**64.34216**	**50.09430**	**39.3348**
P23	**8.787130**	**12,18031**	**19.69451**	**38.46562**	**52.08404**	**43.0521**
P24	**6.477560**	**8,709970**	**11.61816**	**22.14069**	**33.80436**	**42.7502**
P25	**118.8513**	**65,02076**	**34.84382**	**29.28436**	**25.79315**	**25.0873**
P26	**50.75687**	**96,11354**	**60.99755**	**31.52764**	**26.69059**	**22.8940**
P27	**17.76656**	**46,85574**	**91.82050**	**54.28608**	**33.13698**	**28.3546**
P28	**10.86702**	**21,68915**	**42.12630**	**62.61988**	**48.05985**	**35.3737**
P29	**8.927930**	**10,93906**	**22.54416**	**36.98453**	**50.70990**	**41.5744**
P30	**5.961470**	**7,897820**	**06.72350**	**22.11686**	**32.57765**	**41.6859**

P \ P*	P12*	P13*	P14*	P15*	P16*	P17*	P18*	P21*
P01	**5.028560**	**101.59**	**42.084**	**14.78136**	**9.0628**	**6.447000**	**4.781550**	**17.06138**
P02	**6.920830**	**46.980**	**99.713**	**44.34315**	**24.664**	**10.76045**	**7.833190**	**36.40211**
P03	**19.44541**	**25.890**	**59.337**	**70.06679**	**65.272**	**40.11145**	**14.91827**	**52.09380**
P04	**30.04956**	**5.9479**	**19.364**	**37.49234**	**57.809**	**40.22279**	**28.61262**	**33.67614**
P05	**40.81281**	**1.5640**	**10.293**	**19.83153**	**34.890**	**47.93220**	**36.64461**	**17.53524**
P06	**41.23552**	**1.5685**	**5.0642**	**12.17797**	**19.263**	**31.59544**	**40.06677**	**10.97561**
P07	**19.51351**	**119.98**	**53.950**	**20.79282**	**7.4482**	**6.183000**	**5.231160**	**14.62287**
P08	**8.300810**	**41.653**	**98.202**	**53.35691**	**29.033**	**13.22025**	**6.261320**	**47.02956**
P09	**23.33595**	**18.159**	**25.573**	**79.30360**	**49.700**	**31.66954**	**20.52574**	**75.28955**
P10	**29.52784**	**14.533**	**20.030**	**34.46299**	**64.121**	**45.08676**	**31.41654**	**40.10079**
P11	**35.35636**	**9.2156**	**17.438**	**19.70725**	**32.031**	**52.23417**	**39.77396**	**20.36566**
P12	**43.56550**	**7.2765**	**10.980**	**18.13437**	**18.355**	**29.79907**	**43.02845**	**12.28665**
P13	**5.651980**	**137.32**	**55.193**	**46.34968**	**8.3774**	**6.296520**	**5.714250**	**21.56672**
P14	**12.24861**	**56.594**	**109.06**	**50.04879**	**33.622**	**20.24146**	**9.333650**	**56.16310**
P15	**24.63781**	**28.986**	**49.300**	**86.19673**	**43.463**	**32.97663**	**23.98151**	**84.78751**
P16	**37.18460**	**13.113**	**29.185**	**42.15126**	**68.593**	**41.24571**	**30.09332**	**37.14202**
P17	**42.21865**	**9.5027**	**17.019**	**27.39675**	**36.823**	**55.24483**	**37.47685**	**20.47536**
P18	**44.55256**	**7.4019**	**9.7370**	**18.05288**	**24.786**	**33.83194**	**45.10864**	**12.57241**
P19	**5.517440**	**143.92**	**75.756**	**50.28885**	**10.931**	**5.917850**	**5.683580**	**48.07320**
P20	**27.52646**	**60.057**	**113.10**	**59.84587**	**49.400**	**36.94126**	**12.01505**	**51.58432**
P21	**36.28647**	**25.229**	**54.442**	**88.71828**	**58.411**	**44.67788**	**36.46717**	**90.57490**
P22	**40.77731**	**12.683**	**28.199**	**48.19270**	**70.226**	**50.29665**	**38.95977**	**43.16607**
P23	**44.57335**	**9.5444**	**14.696**	**28.09370**	**42.052**	**56.21195**	**43.85007**	**28.07194**
P24	**44.32180**	**7.3737**	**8.3783**	**17.19677**	**26.497**	**36.53133**	**45.69123**	**18.59945**
P25	**25.57279**	**51.804**	**73.028**	**43.33340**	**28.190**	**26.85753**	**25.84604**	**50.60179**
P26	**22.00616**	**48.044**	**110.60**	**67.66141**	**47.585**	**34.62957**	**25.80705**	**71.26699**
P27	**33.45763**	**21.139**	**47.722**	**86.66853**	**65.033**	**45.81703**	**35.43258**	**91.32191**
P28	**38.34327**	**13.609**	**23.427**	**46.37065**	**68.611**	**52.77949**	**41.67606**	**49.19033**
P29	**43.41185**	**9.5880**	**12.747**	**25.15675**	**39.365**	**55.10249**	**45.10253**	**28.50752**
P30	**43.27816**	**7.1905**	**9.1000**	**15.14858**	**24.581**	**35.87972**	**44.93381**	**17.48429**

P \ P*	P23*	P24*	P25*	P26*	P27*	P28*	P29*	P30*
P01	**5.473730**	**03.58520**	**98.48895**	**1.214510**	**13.02873**	**5.963550**	**1.424530**	**5.963550**
P02	**11.15868**	**08.00309**	**26.14220**	**72.49434**	**34.67763**	**16.34083**	**6.539840**	**16.34083**
P03	**19.85915**	**14.71358**	**09.34373**	**28.43601**	**61.90952**	**34.90516**	**13.39116**	**34.90516**
P04	**37.02948**	**22.84315**	**04.08862**	**21.69846**	**29.44011**	**52.27518**	**31.52332**	**52.27518**
P05	**45.91760**	**34.25728**	**02.35519**	**4.837720**	**15.27558**	**29.18837**	**42.32984**	**29.18837**
P06	**29.79410**	**38.05466**	**01.68959**	**2.517580**	**7.926540**	**16.78513**	**37.00335**	**16.78513**
P07	**06.47090**	**04.94695**	**104.3171**	**33.57020**	**15.08999**	**8.891460**	**4.154000**	**8.891460**
P08	**10.26020**	**07.72881**	**29.51175**	**87.63263**	**36.91629**	**20.28712**	**8.092700**	**20.28712**
P09	**27.62014**	**15.94109**	**08.17312**	**32.76644**	**71.10094**	**39.88010**	**12.82350**	**39.88010**
P10	**48.86900**	**30.34269**	**03.64779**	**14.84821**	**34.14530**	**58.32481**	**24.50414**	**58.32481**
P11	**50.32746**	**38.29110**	**02.40251**	**6.065760**	**21.04500**	**33.01326**	**35.73171**	**33.01326**
P12	**32.72852**	**41.72286**	**01.75408**	**2.444820**	**10.24899**	**19.60820**	**40.10615**	**19.60820**
P13	**06.50986**	**05.61843**	**123.7333**	**47.62563**	**14.22454**	**8.737920**	**5.248750**	**8.737920**
P14	**14.78694**	**06.40893**	**041.6740**	**99.79286**	**49.95852**	**23.19498**	**7.118060**	**23.19498**
P15	**32.99112**	**21.63368**	**013.1021**	**42.42355**	**79.96557**	**47.86690**	**17.35046**	**47.86690**
P16	**46.45894**	**32.21104**	**03.43228**	**17.52795**	**41.05500**	**64.38834**	**30.69659**	**64.38834**
P17	**54.98713**	**40.99864**	**02.34306**	**9.065740**	**20.76909**	**37.27513**	**39.73631**	**37.27513**
P18	**28.51652**	**42.75785**	**01.72968**	**3.683530**	**12.03748**	**20.97085**	**43.11622**	**20.97085**
P19	**06.28780**	**05.86568**	**143.2829**	**59.87332**	**23.59366**	**7.832310**	**5.907760**	**7.832310**
P20	**21.08977**	**10.24964**	**46.50795**	**112.7709**	**58.10427**	**31.94392**	**6.328190**	**31.94392**
P21	**33.46862**	**25.12660**	**17.64898**	**43.71209**	**88.53881**	**53.50222**	**23.33798**	**53.50222**
P22	**42.25633**	**30.33908**	**04.87436**	**20.99516**	**39.69219**	**70.14440**	**32.58757**	**70.14440**
P23	**57.01163**	**38.44419**	**02.22045**	**10.30689**	**20.45019**	**35.60733**	**41.59971**	**35.60733**
P24	**34.67031**	**46.27922**	**01.69433**	**4.339930**	**12.67549**	**21.57744**	**45.67957**	**21.57744**
P25	**26.90524**	**05.74767**	**156.6263**	**59.05583**	**30.73373**	**8.562280**	**5.890990**	**8.562280**
P26	**37.69646**	**27.64975**	**60.40094**	**120.8920**	**52.23878**	**35.13968**	**10.89795**	**35.13968**
P27	**45.77696**	**25.40538**	**30.46810**	**51.65848**	**93.42200**	**44.59530**	**25.44116**	**44.59530**
P28	**52.64625**	**39.89496**	**13.96640**	**30.50413**	**42.65725**	**73.09155**	**30.26716**	**73.09155**
P29	**54.81974**	**30.51073**	**09.97441**	**18.04778**	**28.24422**	**39.07128**	**38.92667**	**39.07128**
P30	**37.04107**	**44.52730**	**07.74938**	**10.57806**	**18.80535**	**25.23555**	**47.01112**	**25.23555**

P*: The point where the projector is directed.
P: The point where the illuminance is calculated.

Total illuminance by all masts

Point	Total illuminance by mast 1	Total illuminance by mast 2	Total illuminance by mast 3	Total illuminance by mast 4	Total illuminance by all
P01	539,239380	000.000000	000.000000	778,277540	1317,51692
P02	726,520780	438,210860	499,849870	908,661450	2573,24296
P03	825,558970	569,753460	656,041420	967,731640	3019,08549
P04	694,845600	694,845600	836,070550	836,070550	3061,83230
P05	569,753460	825,558970	967,731640	656,041420	3019,08549
P06	438,210860	726,520780	908,661450	499,849870	2573,24296
P07	676,042260	000.000000	000.000000	676,042260	1352,08452
P08	794,732240	483,675930	483,675930	794,732240	2556,81634
P09	833,056080	617,321800	617,321800	833,056080	2900,75576
P10	784,403300	784,403300	784,403300	784,403300	3137,61320
P11	617,321800	833,056080	833,056080	617,321800	2900,75576
P12	483,675930	794,732240	794,732240	483,675930	2556,81634
P13	778,277540	000.000000	000.000000	539,239380	1317,51692
P14	908,661450	499,849870	438,210860	726,520780	2573,24296
P15	967,731640	483,675930	967,731640	825,558970	3244,69818
P16	836,070550	836,070550	694,845600	694,845600	3061,83230
P17	656,041420	967,731640	825,558970	569,753460	3019,08549
P18	499,849870	908,661450	726,520780	438,210860	2573,24296
P19	913,125420	000.000000	000.000000	000.000000	913,125420
P20	1045,19342	518,584250	000.000000	000.000000	1563,77767
P21	1062,07172	682,604840	000.000000	000.000000	1744,67656
P22	870,661590	870,661590	000.000000	000.000000	1741,32318
P23	682,604840	1062,07172	000.000000	000.000000	1744,67656
P24	518,584250	1045,19342	000.000000	000.000000	1563,77767
P25	926,198560	000.000000	000.000000	000.000000	926,198560
P26	1096,63561	530,74264	000.000000	000.000000	1627,37825
P27	1060,17482	689,32723	000.000000	000.000000	1749,50205
P28	910,86195	910,86195	000.000000	000.000000	1821,72390
P29	689,32723	1060,17482	000.000000	000.000000	1749,50205
P30	530,74264	1096,63561	000.000000	000.000000	1627,37825
				Average=	2113,91958

As we see we got an average illuminance of 2113,91958 lux , and this value is more that the value that we have chosen .

To solve this problem, the power of the lamp could be reduced to 500 W, so that illuminance is going to be reduced to half.

The following values show the illuminance at each point after reducing the power of the lamp:

Point	Illuminance
P01	658,758460
P02	1286,62148
P03	1509,54275
P04	1530,91615
P05	1509,54275
P06	1286,62148
P07	676,042260
P08	1278,40817
P09	1450,37788
P10	1568,80660
P11	1450,37788
P12	1278,40817
P13	658,758460
P14	1286,62148
P15	1622,34909
P16	1530,91615
P17	1509,54275
P18	1286,62148
P19	456,562710
P20	781,888840
P21	872,338280
P22	870,661590
P23	872,338280
P24	781,888840
P25	463,099280
P26	813,689130
P27	874,751030
P28	910,861950
P29	874,751030
P30	813,689130
Average	1056,959791

As shown above, by using lamp of 500 W , we got an average value near to the needed illuminance .

Conclusion

For lighting design we should take some considerations into account, such as the amount of illuminance that we need, lamp's kind…ect.

Using C Y formulas the amount of illuminance could be found, the average of the calculated illuminance must be approximately equal to the chosen illuminance.

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