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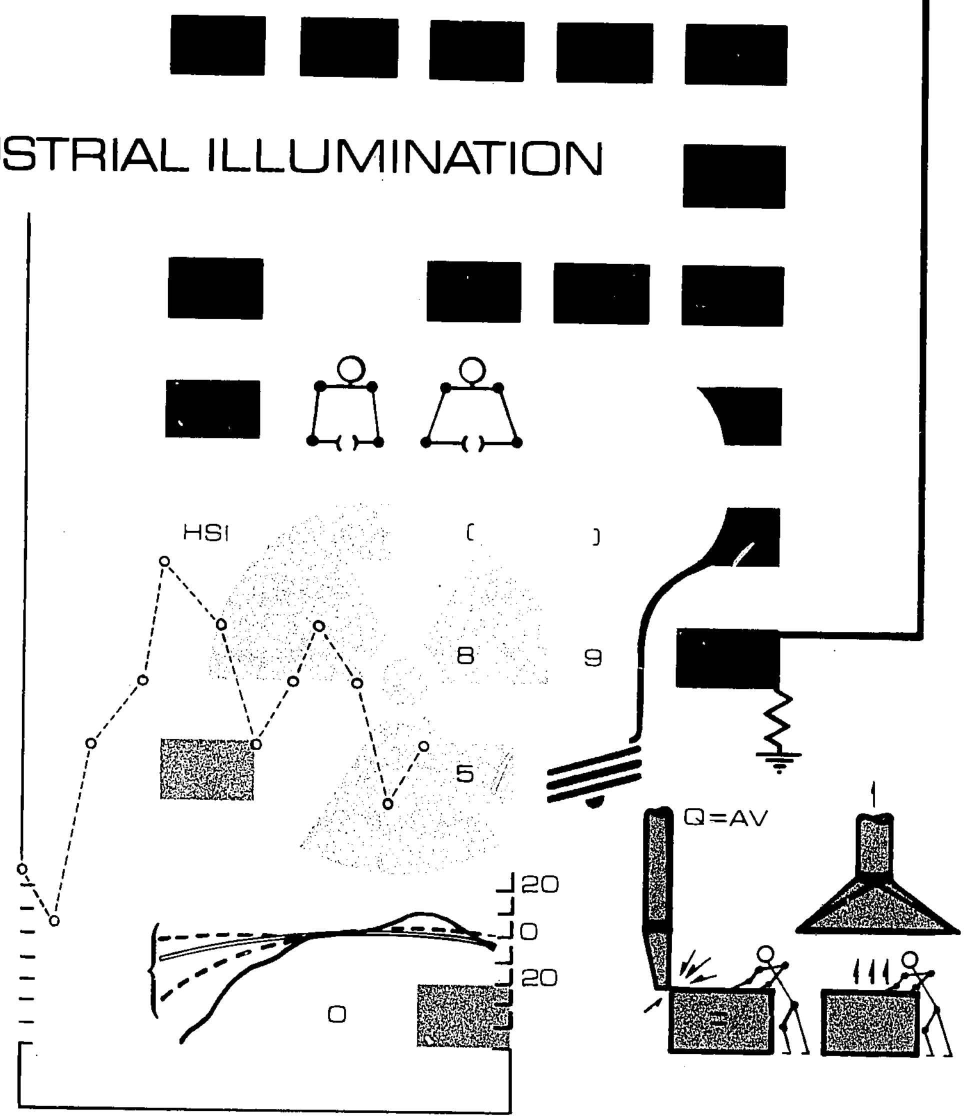
INDUSTRIAL HYGIENE ENGINEERING & CONTROL

INDUSTRIAL ILLUMINATION



Student Manual

U.S. DEPARTMENT OF HEALTH, EDUCATION AND WELFARE
Public Health Service
Center for Disease Control
National Institute for Occupational Safety and Health

Division of Training and Manpower Development

INTRODUCTION TO INDUSTRIAL HYGIENE ENGINEERING AND CONTROL (552)

This is a modularized course designed for use as a one, two, or three week short course or as a one or two semester academic course at either the undergraduate or graduate level. It examines the fundamentals for design of controls to eliminate or satisfactorily deal with occupational health hazards. Lectures, augmented by problem solving sessions, are intended to assist the trainee in selecting, designing, and applying control methods in the work environment. Primary attention is given to industrial ventilation, noise and vibration control, heat stress, and industrial illumination as well as new engineering topics.

The training course manual has been specially prepared for the trainees attending the course and should not be included in reading lists of periodicals as generally available.

Section 5 — Student Manual

INDUSTRIAL ILLUMINATION

Division of Training and Manpower Development
National Institute for Occupational Safety and Health

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
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Center for Disease Control

Cincinnati, Ohio

November 1978

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FOREWORD

This text is designed for use by individuals at an advanced level of study in industrial hygiene. The emphasis is on the control of exposures to occupational health hazards. A series of lesson plans has been developed around the material presented in the text that can be utilized in a formal classroom setting for presentation as a course or a series of courses.

The text was developed under the sponsorship of the National Institute for Occupational Safety and Health, Division of Training and Manpower Development, Cincinnati, Ohio (Contract CDC—210—75—0076). Serving as Project Officer for the development of the text and lesson plans was Robert B. Weidner, J.D., Branch Chief, Division of Training and Manpower Development.

Authors of the text and lesson plans are:

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Also assisting as consultants to the development of the material were Ralph J. Vernon, Ph.D., and Richard B. Konzen, Ph.D., of the Department of Industrial Engineering, Texas A&M University. Art work for the text was prepared by Carole D. Byers. Preparation of the manuscript was the responsibility of Elaine S. Holmes.

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INTRODUCTION

The creation of this text came out of an attempt to design a course to teach the fundamentals of industrial hygiene engineering as related to the design of controls for exposure to health hazards in the workplace. During the design of the course, it was necessary to research the existing literature in the field of industrial hygiene. As this research was being conducted, it became evident that no single source provided sufficient coverage of the subject to be adequate for use as a text for the course. In fact, to the dismay of the authors, the subject of control received very little attention in many of the existing texts on industrial hygiene. For the most part, existing texts emphasize the recognition, measurement and evaluation of occupational health hazards. Though this is an important concern of the industrial hygienist, the sparse coverage of control topics indicated a need for an additional text.

The objective of this text is to fill this gap that was discovered; to provide a text that can act as a single reference source on the subject of industrial hygiene engineering and control. In the preparation of this text, the authors soon discovered a reason for the prior omission of such a single source. The control of occupational health hazard exposures requires a broad knowledge of a number of subject areas. To provide a text that includes the necessary theoretical foundation as well as the practical application of the theory is a significant undertaking. It is the hope of the authors that in some way the objective has been reached and that this text will prove to be a valuable and needed addition to the literature of industrial hygiene.

A second objective, or perhaps a hidden agenda, during the preparation of this text was to provide the reader with a systematic approach to problem solving in the field of industrial hygiene. Throughout the text, the systems approach to problem solving is emphasized. In fact, at one point consideration was given to titling the text "A Systems Approach to Industrial Hygiene Control." The systems approach has been utilized effectively in the area of occupational safety: witness the many texts on the topic of systems safety. However, the same emphasis has not been found in industrial hygiene. Systems analysis techniques are not limited in their application and thus should be equally applicable and useful to the field of industrial hygiene as they are to the field of occupational safety.

The text has been divided into eight (8) sections, each of which covers a subject area. This structure allows for reference to a single topic area without the need to consult other sections of the book, thus allowing for the use of the text as a basis for classroom instruction in a number of separate courses. For example, Section 2—Industrial Ventilation can serve as the basis for a one- or two-semester course.

The authors are indebted to the many who labored in the past to develop the field to the level at which it now exists. Much of that which is presented herein does not represent new knowledge but rather a reorganization of existing bodies of knowledge into a single document. Many of those responsible for the original work in the field are referenced within this text.

Bruce B. Byers
Ronald J. Hritz
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1978

Section 5

Industrial Illumination

CHAPTER 1

LIGHT

Introduction

The purpose of industrial lighting is to provide an efficient and comfortable seeing of industrial tasks and to help provide a safe working environment. Adequate lighting is not for safety alone. Lighting adequate for seeing production and inspection tasks will be more than needed for safety. Light is more for comfort and convenience than for safety.

It has been shown that adequate industrial lighting results in many benefits; for example:

1. Promotes few production and inspection mistakes.
2. Increases production.
3. Reduces accidents.
4. Improves morale.
5. Improves housekeeping.

What Is Light?

The nature of light is not easy to understand. The question, "What is light?" has been extremely illusive throughout the history of science.

Near the end of the seventeenth century, there were two theories to explain the nature of light; the particle or corpuscular theory and the wave theory. In the nineteenth century, the discovery of interference and diffraction--the bending of light as it passes through different media--made the wave theory of light the predominant theory; i.e., interference and diffraction could not be explained adequately by the particle or corpuscular theory.

In the late 1800's, light was thought be be electromagnetic waves, which at certain frequencies could be seen by the human eye. This conceptualization of light was primarily used to explain the propagation of light. To conceputalize the propagation of light, an understanding of electrical forces and fields and magnetic forces and fields is needed.

To illustrate electrical forces, the simple case of an electrical charge at rest will be discussed. Each atom has a positively charged core, the nucleus, which is surrounded by negatively charged electrons. The nucleus consists of a number of protons, each with a single unit of positive charge and one or more neutrons (except for hydrogen). A neutron is a neutral particle. Normally, an atom is in a neutral or uncharged state because it contains the same number of protons as electrons. If, for some reason, a neutral atom loses one or more of its electrons, the atom will have a net positive charge and is referred to as an "ion." A negative ion is an atom which has gained one or more additional electrons. That is, an object which has an excess of electrons is negatively charged; and an object which has a deficiency of electrons is positively charged. Objects can be electrically charged in many different ways.

It is known that objects with the same charge repel each other while objects with opposite charges attract each other. That is, some force exists between charged objects. In 1784 Charles Augustine de Coulomb found that the force of attraction or repulsion between two charged objects is inversely proportional to the square of the distance separating them. Coulomb's law can be stated as:

> The force of attraction or repulsion between two point charges is directly proportional to the product of the two charges and inversely proportional to the square of the distance between them.

From Coulomb's law, the following may be written:

$$F \propto \frac{qq'}{r^2}$$

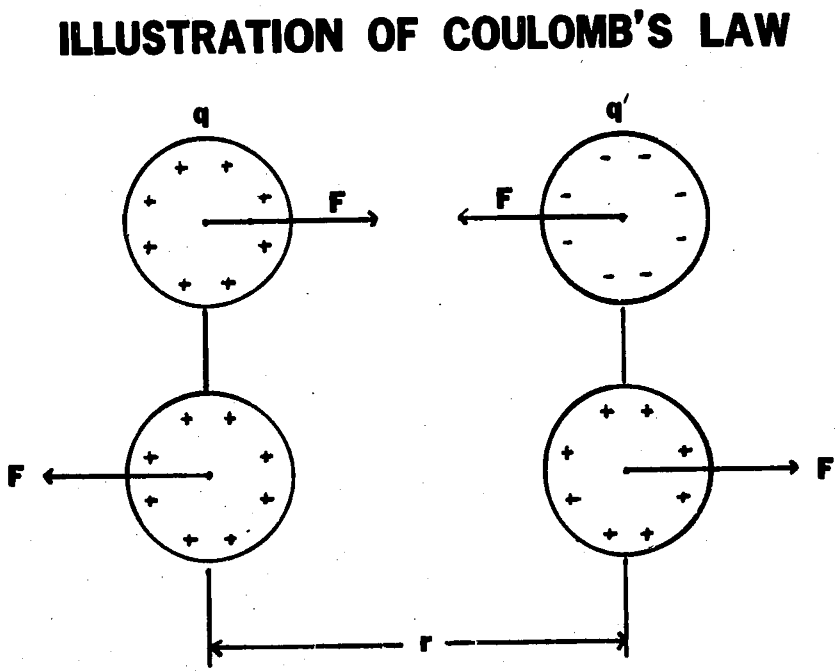
or

$$F = \frac{kqq'}{r^2}$$

where F denotes the magnitude of force; q and q', the magnitude of two charges; r represents the distance between the charges; and k represents Coulomb's constant, a proportionality constant that takes into account the property of the medium separating the charged bodies.

The units attached to q, q', and k are of no concern for conceptual development. This relationship can be graphically illustrated by Figure 5.1.1.

Figure 5.1.1



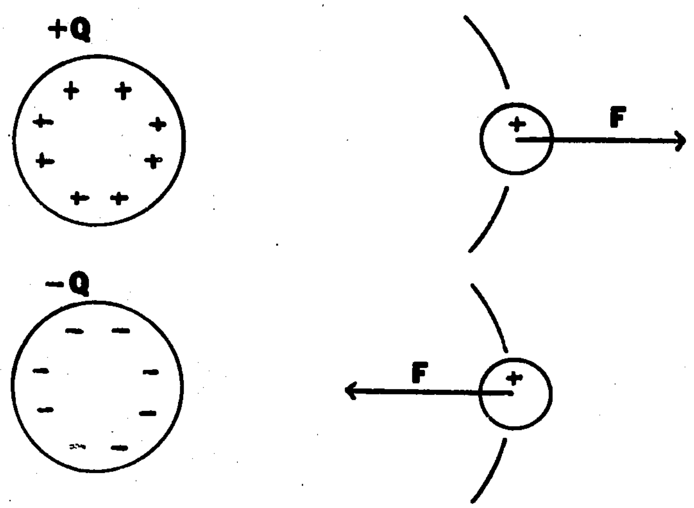
Electrically charged bodies then exhibit a force. The presence of an electrically charged object alters the space around it. This alteration in the surrounding space can be described by introducing the concept of fields. An electrical field is said to exist in a region of space in which an electric charge will experience an electrical force. The strength of the electrical field at any point will be proportional to the force a given charge experiences at any point; i.e., the strength of an electrical field can be represented by the force per unit charge. The electrical field intensity, E, is then defined at a point in terms of the force, F, experienced by an arbitrary positive charge, +q, when it is placed at that point. Thus

$$E = \frac{F}{+q}$$

Since the electrical field intensity is defined in terms of a positive charge, its direction at any point would be the same as the electrostatic (at rest) force on a positive charge at that point. (See Figure 5.1.2.)

Figure 5.1.2

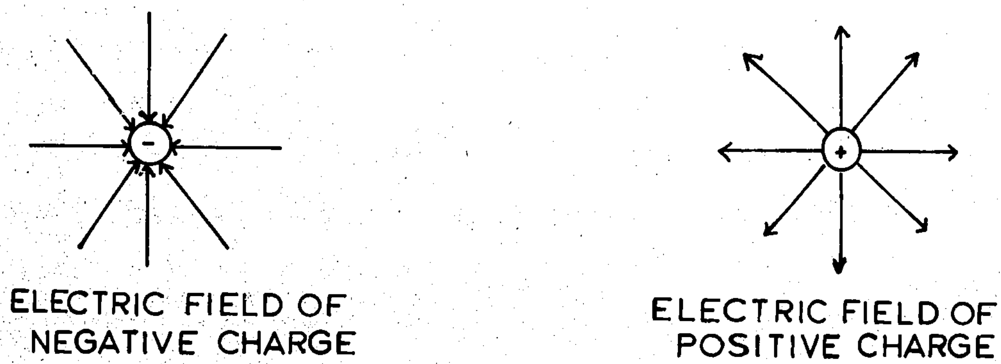
DIRECTION OF ELECTRICAL FIELDS



On this basis, the electrical field in the vicinity of a positive charge would be outward or away from the charge, while in the vicinity of a negative charge the direction of the field would be inward or toward the charge. (See Figure 5.1.3)

Figure 5.1.3

DIRECTION OF ELECTRICAL FIELDS



If an electrically charged particle is brought into the field created by another electrically charged particle, then

$$E = \frac{F}{q'} = \frac{kqq'/r^2}{q'} = \frac{kq}{r^2}$$

where E denotes the electrical field intensity, F denotes force, r denotes the distance between the two emitted charges, q and q' denote the magnitude of the charges, and k denotes Coulomb's constant.

Magnetic forces and fields are similar to electrical forces and fields. The magnetic law of forces states: Like magnetic poles repel each other while unlike magnetic poles attract each other. In the eighteenth century, deCoulomb discovered that (1) the force of attraction or repulsion between the poles of two magnets is inversely proportional to the square of the distance, r, between the poles; and (2) the force of attraction or repulsion between two poles is along a line joining the two poles and directly proportional to the product of the pole strengths, p_1 and p_2. These two statements may be combined to form a mathematical statement:

$$F = \frac{kp_1p_2}{r^2}$$

where F denotes the force between two poles of strength p_1 and p_2 which are separated by a distance, r. The value of the proportional constant, k, depends upon the units chosen and the medium surrounding the magnets.

Every magnet is surrounded by a space in which the magnetic effects are present. These regions are called "magnetic fields." The strength of the magnetic field at any point is referred to as the magnetic field intensity, H, and is defined in terms of the force exerted on a unit north pole; i.e., the magnetic field intensity, H, at any point is the magnetic force per unit north pole placed at that point;

$$H = \frac{F}{p}$$

where H denotes the magnetic field intensity, F denotes force, and p denotes the the magnitude of the unit north pole.

A more useful expression for computing the magnetic field intensity is given by

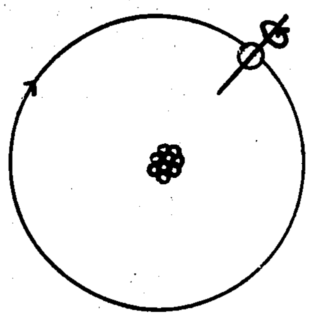
$$H = \frac{F}{p'} = \frac{kpp'/r^2}{p'} = \frac{kp}{r^2}$$

where p' denotes a test pole placed distance r from the pole p, and the remaining symbols are defined as before.

Magnetism is believed to result from movements of electrons within the atoms of substances. That is, magnetism results from a change in motion. The magnetic polarity of two atoms stems primarily from the spin of electrons about their own axis and is due also to their orbital motions around the nucleus. (See Figure 5.1.4.)

Figure 5.1.4

A CHARGE IN MOTION



As can be seen, magnetism is closely related to electrical phenemona.

If compass needles were placed around an electrical current, a magnetic field would be produced. (Figure 5.1.5.) If a moving charged particle creates a magnetic field, will a moving magnetic field create an electrical field? The answer is "yes." (Figure 5.1.6.) This figure consists of a wire with some loops in it and a regular bar magnet. If the magnet is moved up and down, the meter to the right will register an electrical current or electrical field. A magnetic field is created by the movement of a charged particle, and the movement of a magnetic field creates an electrical field.

Figure 5.1.5

A MOVING CHARGE CREATES A MAGNETIC FIELD

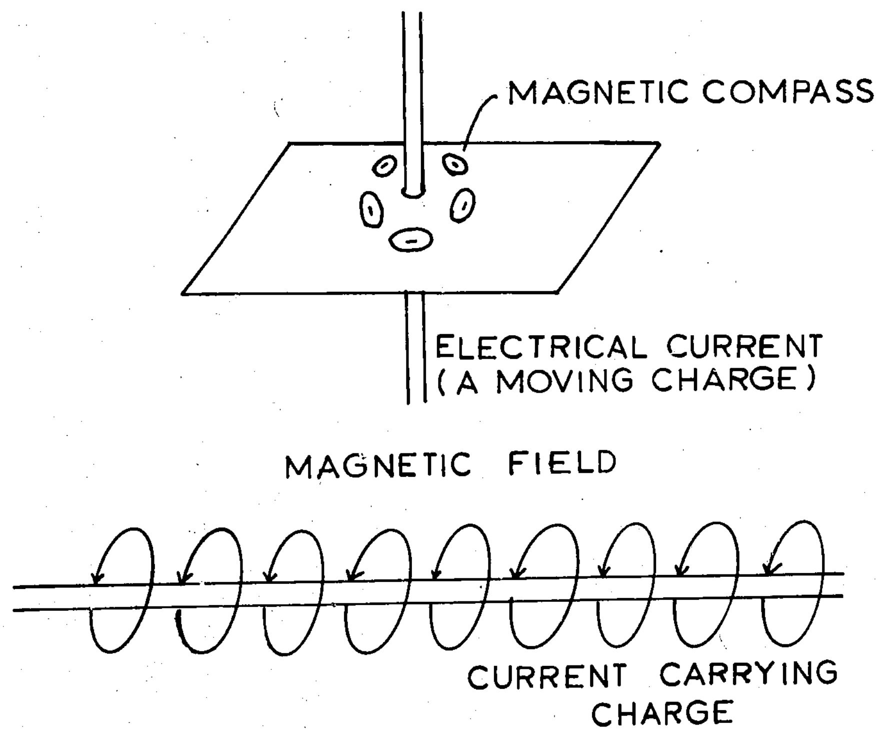
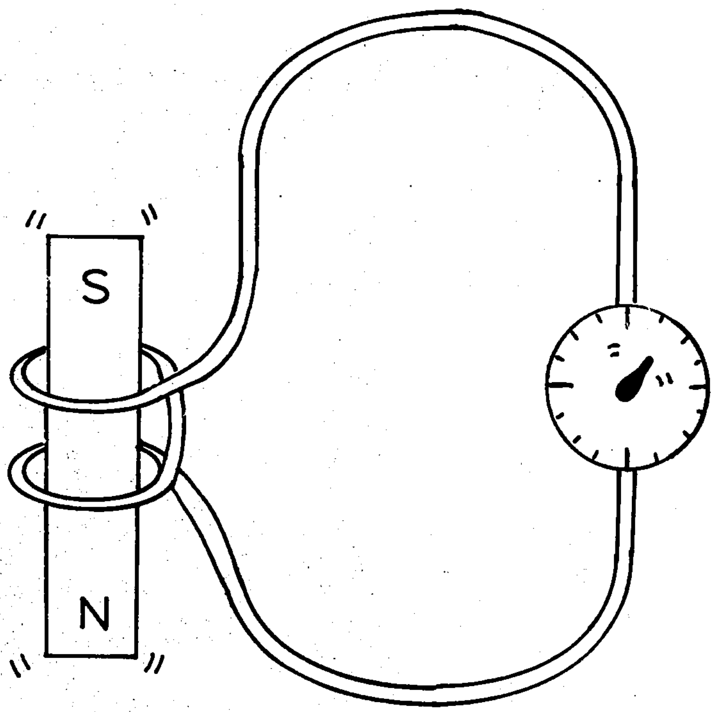


Figure 5.1.6

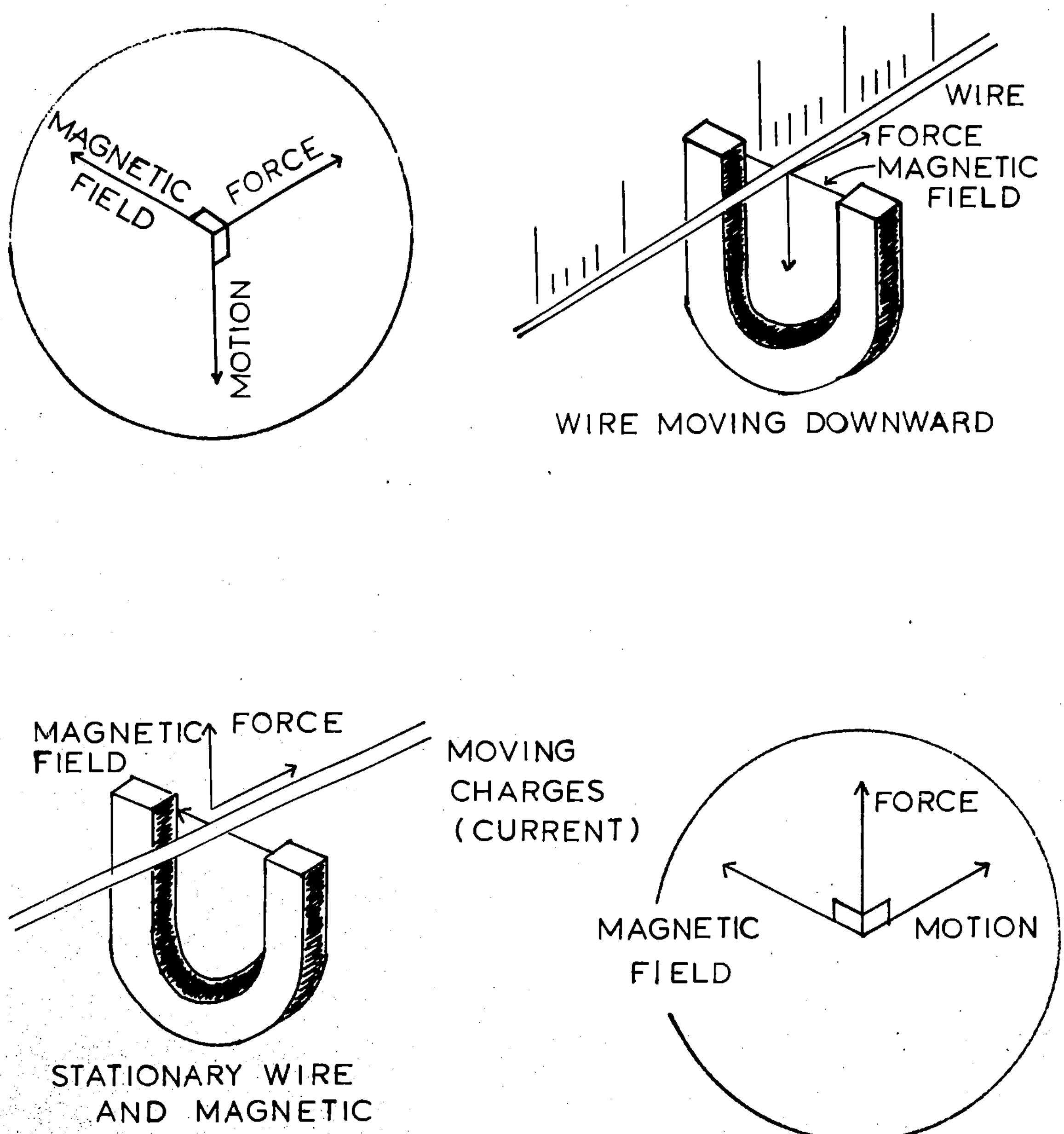
A MOVING MAGNETIC FIELD CREATES AN ELECTRICAL FIELD



The upper part of Figure 5.1.7 indicates that when a wire with no initial current is moved downward the charges in the wire experience deflecting force perpendicular to their motion. Since there is a conducting path made by the wire in this direction, the electrons follow it, thereby constituting a current. In the lower half of the diagram where the magnet is stationary and the wire is stationary, when a current moves through the wire to the right, there is a perpendicular upward force on the electron. Since there is no conducting path upward, the wire is tugged upward along with the electrons of the charged particles. The relationship between magnetic fields and electrical fields can by summarized by saying that moving charges experience a force that is perpendicular to the magnetic field lines that they traverse.

Figure 5.1.7

MOVING CHARGES EXPERIENCE A FORCE THAT IS PERPENDICULAR TO THE MAGNETIC FIELD LINES THEY TRAVERSE

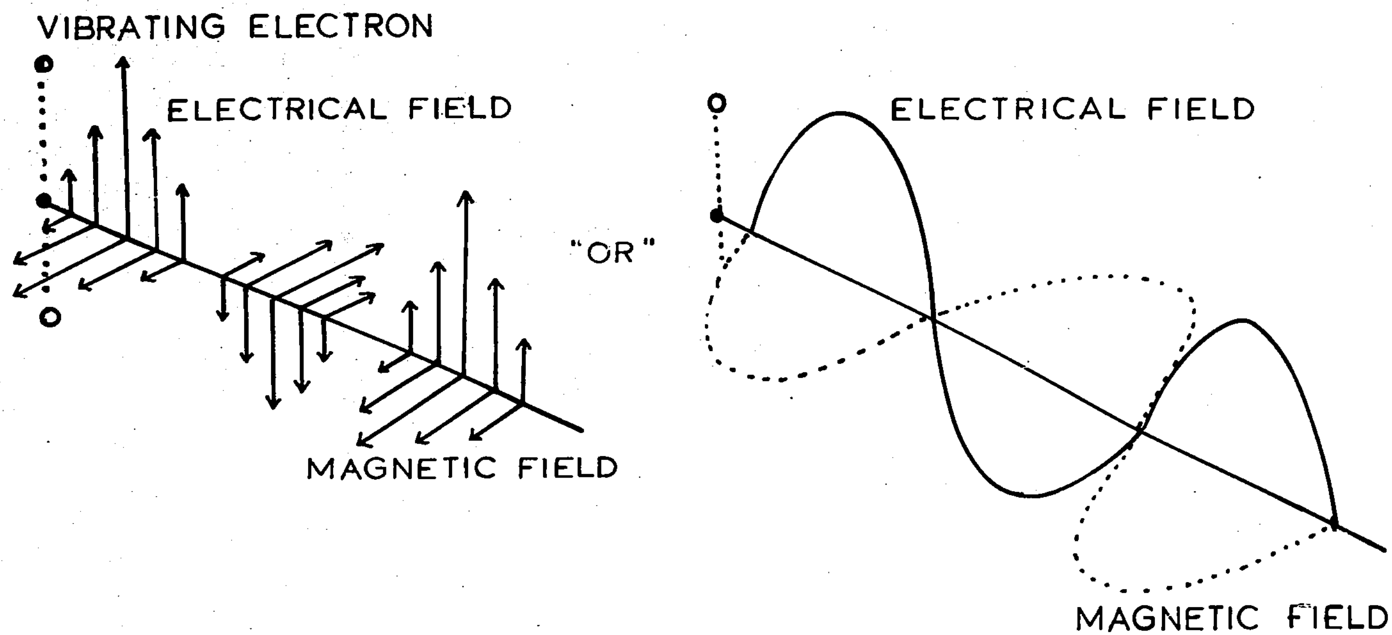


The fact that a magnetic field induces an electrical field and a moving electrical field produces a magnetic field is how an electromagnetic wave is produced. Consider an electrical charge vibrating back and forth at a certain frequency. The charge, because it is a moving charged particle, will produce an electrical field around it. The moving charge, if it vibrates back and forth, creates a magnetic field. However, the magnetic field is also changing or moving; and the moving magnetic field produces an electrical field. Thus, the two fields are mutually induced. The changing magnetic field induces an electrical field which induces a magnetic field, etc., and electromagnetic waves are produced.

Consider first the initial magnetic field induced by the moving charge. This changing magnetic field induces a changing electrical field, which in turn induces a magnetic field. The magnitude of this further induced magnetic field depends not only on the vibrational rate of the electrical field but also on the motion of the electrical field or the speed at which the induced field emanates from the vibrating charge. The higher the speed, the greater the magnetic field it induces. At low speeds, electromagnetic regeneration would be short lived because the slow-moving electrical field would induce a weak magnetic field which in turn would induce a weaker electrical field. The induced fields become successively weaker, causing the mutual induction to die out. But what about the energy in such a case? The fields contain energy given to them by the vibrating charge. If the fields disappear with no means of transferring energy to some other form, energy would be destroyed. Low speed emanation of electrical and magnetic fields is incompatible with the law of energy and conservation. At emanating speeds too high, on the other hand, the fields would be induced to ever-increasing magnitudes with a crescendo of ever-increasing energies--again clearly in contradiction with the conservation of energy. At some critical speed, however, mutual induction would continue indefinitely with neither a loss nor a gain in energy. This critical speed without loss or gain of energy is 186,000 miles per second--the speed of light. Thus, energy in an electromagnetic wave is equally divided between electrical and magnetic fields that are perpendicular. Both fields oscillate perpendicular to the direction of the wave propagation. (Figure 5.1.8.)

Figure 5.1.8

REPRESENTATION OF ELECTROMAGNETIC WAVE



Electromagnetic Spectrum

In 1885 H. R. Hertz showed that radiation of electromagnetic energy can occur at any frequency. All electromagnetic waves travel at the same speed in a vacuum. The waves are different from one another in their frequency and wavelength. The relationship between velocity, frequency, and wavelength is as follows:

$$C = f\lambda$$

where C denotes velocity, f denotes frequency, and λ denotes wavelength.

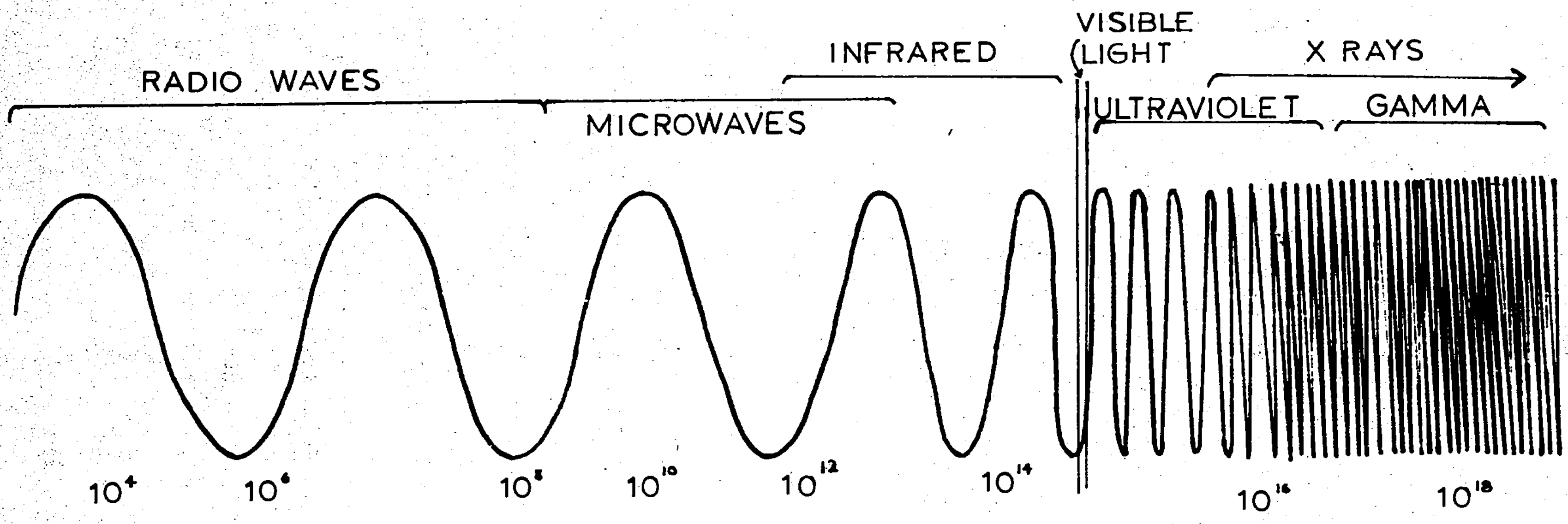
If the speed or velocity of electromagnetic waves is constant, then when the frequency changes, the wavelength must change. The higher the frequency of the vibrating charge, the shorter the wavelength.

Figure 5.1.9 shows the electromagnetic spectrum. It goes from radio waves to gamma waves. In all sections of the electromagnetic spectrum, the waves are the same in nature; they differ only in frequency and wavelength.

Electromagnetic waves in principle can have any frequency from zero to infinity. The classification of electromagnetic waves according to frequency is called the "electromagnetic spectrum." Electromagnetic waves with frequencies of the order of several thousand hertz (kilocycles/sec) are classified as radio waves. The VHF (very high frequency) television band starts at about 15 million hertz (megacycles/sec). Still higher frequencies are called "microwaves" followed by infrared waves often called "heat waves." Further still is visible light which makes up only one percent of the measured electromagnetic spectrum. Beyond light, the higher frequencies extend into the ultraviolet, X-ray, and gamma ray regions. There is no sharp distinction between these regions which actually overlap each other. The spectrum is simply broken up into these arbitrary regions for classification.

Figure 5.1.9

ELECTROMAGNETIC SPECTRUM

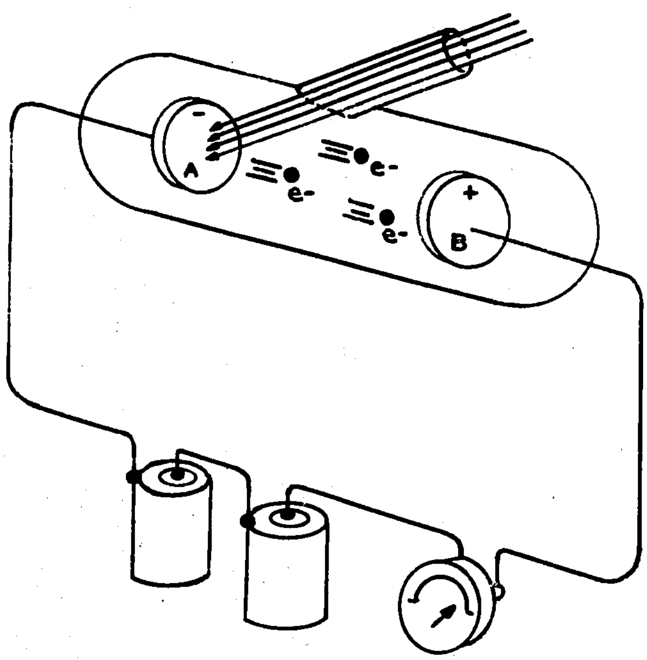


The Quantum Theory

Around 1885 light was thought to be wave like and not particle like. However, in 1887 Hertz noticed that an electrical spark would jump more readily between charged fields when their surfaces were illuminated by the light from another spark. This observation is commonly known as the "photoelectric effect." The arrangement for the photoelectric effect can be seen in Figure 5.1.10.

Figure 5.1.10

PHOTOELECTRIC EFFECT

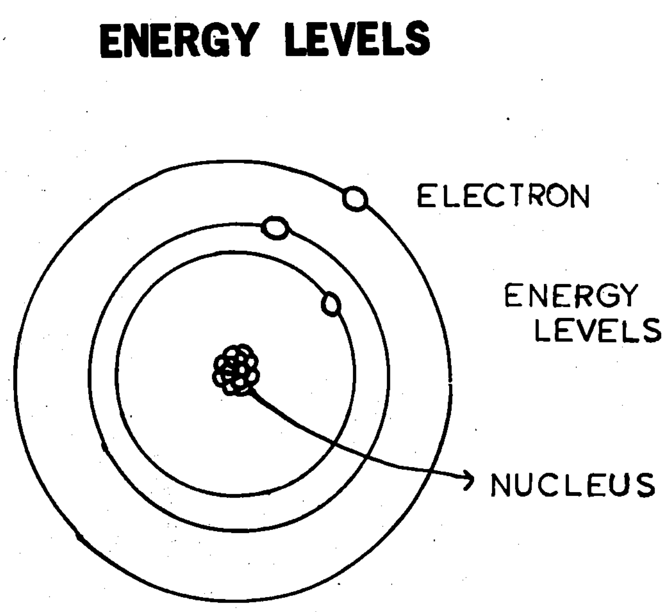


Light shining on the negatively charged photosensitive metal plate liberates electrons, which are attracted to the positive plate, producing a measurable current. This photoelectric effect could not be explained by the electromagnetic wave theory of light. The brightness of light in no way affected the energies of the ejected electrons. If light was accepted to be electromagnetic radiation, then the stronger electric fields of bright light would surely interact with electrons, causing them to eject at greater speeds and, thus, greater energies.

Yet, this was not the case. No increase in electron kinetic energy was detected. A weak beam of ultraviolet light produced a given number of electrons but much higher kinetic energies. This was most puzzling; the wave theory of light could not explain this phenomenon.

In an attempt to bring experimental observations into agreement with theory, Max Planck published his quantum hypothesis. He found that the problem with the electromagnetic theory of light lay with the assumption that energy is radiated continuously. He postulated that electromagnetic energy is absorbed or emitted in discrete packets or quanta, referred to as photons. Planck postulated that the energy states of electrons in atoms are quantized; i.e., electrons can only vibrate with certain discrete amounts of energy. An electron farther away from the nucleus has a greater potential energy with respect to the nucleus than the electron nearer the nucleus; the furthermost electron is at a higher energy level. When an electron in an atom is raised to a higher energy level, the atom is said to be excited. The higher level of the electron is only momentary. The electron loses its temporarily acquired energy when returning to a lower energy level. (Figure 5.1.11.)

Figure 5.1.11



Radiation occurs when an electron makes the transition from a higher energy state to a lower energy state; i.e., when the atom becomes de-excited. This energy is in quanta. The electron moves in discrete steps from higher levels to lower levels. Each element has its own number of electrons; each element also has its own characteristics of energy levels. An electron's dropping from a higher energy level to a lower energy level in an excited atom emits energy in photons or quanta with each jump. So for each element, the amount of energy will be different.

Planck postulated that the energy of the resulting quanta of radiation would be equal to the difference in the energy state of the atom. Further, he postulated that the frequency of the emitted radiation is proportional to this energy difference. Planck's equation can be written as

$$E = hf$$

where E denotes the energy of the photon, f denotes the frequency of radiation, and h is the proportionality factor called Planck's constant.

Thus, a photon or quantum of infrared radiation has a tiny energy; a quantum of green light, a small energy; and a quantum of ultraviolet light, a larger energy. The greater the radiation frequency of the quantum, the greater the energy.

With Planck's theory, the nature of light was seen to be dualistic--it had wave-like properties and particle properties (quanta or photons being released upon de-excitation). It is customary to discuss the wave-like properties of light when the propagation of light is discussed, and it is customary to use the particle theory when the interaction of light with matter is discussed. Light may be thought of as radiant energy transported in photons which are carried along by a wave field.

The Emission Spectra

Every element has its own characteristic pattern of electron levels. An electron dropping from higher to lower energy levels in an excited atom emits a photon with each jump. Many frequency characteristics of an atom are emitted corresponding to the many paths the electron may take when jumping from level to level. These frequencies combine to give light from each excited atom its own characteristic color. This unique pattern can be seen when the light is sent through a prism.

Each component color is focused at a definite position according to its frequency and form. If the light given off by a sodium vapor lamp is analyzed, a single yellow line is produced. If the width of the ray of yellow light could be narrowed, it would be found that the line is really composed of two very close lines. These lines correspond the the two predominant frequencies of light emitted by the excited sodium atoms. The rest of the spectrum is dark. (Actually, there are many other lines too dim to be seen with the naked eye.)

This situation is not unique in sodium. Examining the light from a mercury vapor lamp reveals two strong yellow lines close together (but in different positions than those of sodium), a very intense green line, and several blue and violet lines. Similar but more complicated patterns of lines are found in light emitted by a neon tube. The light emitted by every element in a vapor state produces its own characteristic pattern of lines. These lines correspond to the electron transitions between atomic energy levels and are characteristic of each element as are the fingerprints of people.

Incandescence

Light emitted from a neon tube is red because the average difference in neon energy level is proportional to the frequency of red light. Light emitted by a common incandescent lamp, however, is white. All frequencies of visible radiation are emitted. Does this mean that tungsten atoms making up the lamp filament are characteristic by an infinite number of energy levels? The answer is a definite "no." If the filament were vaporized and then excited, the tungsten gas would emit a finite number of frequencies, producing an overall bluish color. The frequency of light emitted by atoms depends not only upon the energy levels within the atom but also on the spacings between neighboring atoms themselves. In a gas, the atoms are far apart. Electrons undergo transition between energy levels within the atom quite unaffected by the presence of neighboring atoms. But when the atoms are closely packed, as in a solid, the electrons of the outer orbits make transitions not only within the energy levels of the parent atoms but also between the levels of neighboring atoms. These energy level transitions are no longer well defined but are altered by interactions between neighboring atoms, resulting in an infinite variety of energy level differences, thence, an infinite number of radiation frequencies. And this is why tungsten filament light produces white light.

Mercury vapor light is bright and less expensive than incandescent lamps. Most of the energy in incandescent lamps is converted to heat, while most of the energy put into mercury vapor lamps is converted to light. As the filament in a tungsten filament lamp becomes heated, wider energy level transitions take place, and higher frequencies of radiation are emitted. A hotter filament produces a whiter light.

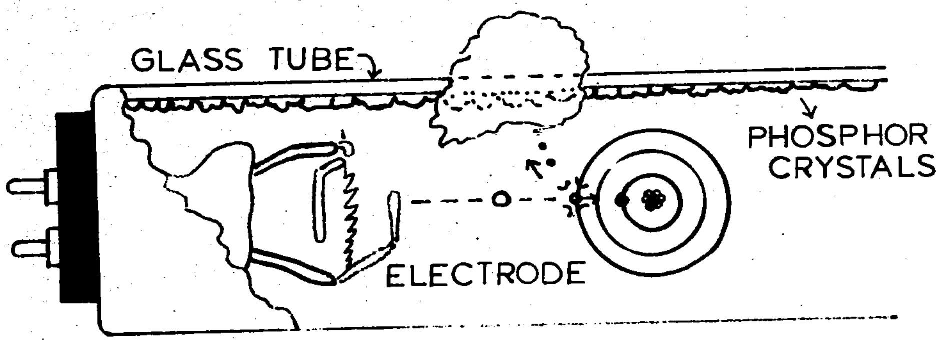
Fluorescence and Fluorescent Lamps

Atoms absorb light as well as emit light. An atom will most strongly absorb light having the same frequency or frequencies to which it is tuned, the same frequency it emits. For example, when a beam of white light passes through a gas, the atoms of the gas absorb selected frequencies. This absorbed energy is reradiated in all directions instead of the directions of the incident light.

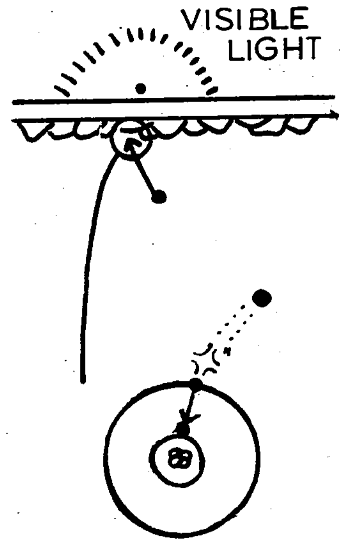
Some atoms become excited when absorbing a photon of light. Ultraviolet light has more energy per photon than lower frequency light. Many substances undergo excitation when illuminated by ultraviolet light. When a substance excited by ultraviolet light emits visible light upon de-excitation, this action is called fluorescence. What happens in some of these materials is that a photon of ultraviolet light collides with an atom of the material and gives up its energy in two parts. Part of the energy goes into heat, increasing the kinetic energy of the entire atom. The other part of the energy goes into excitation, boosting the electron to a higher orbit. Upon de-excitation, this part of the energy is released as a photon of light. Since some of the energy of the ultraviolet photon is converted to heat, the photon emitted has less energy and, therefore, lower frequency than the ultraviolet photon. That is, the secondary photon of light that is released is of less energy than the primary photon since some energy goes to heat; thus, it is of a lower frequency. Light emitted from fluorescent lamps is produced by primary and secondary excitation processes. The primary process is excitation of a gas by electron bombardment; and the secondary process is excitation by ultraviolet photons, fluorescence. The common fluorescent lamp consists of a cylindrical gas tube with electrodes at each end. (See Figure 5.1.12.) Like the neon sign tube, electrons are boiled off from the electrodes and forced to vibrate back and forth at high speeds within the tube by an A.C. voltage; and the tube is filled with very low pressure mercury vapor which is excited by the

Figure 5.1.12

FLUORESCENT LAMP



1. Electrode emits electron at high speed.
2. Collides with atom (usually mercury atom).
3. Collision causes excitation. Upon de-excitation, a photon is released (ultraviolet light).
4. Ultraviolet photon hits phosphor crystals where excitation takes place.



5. Upon de-excitation, a photon is released, producing visible light.

impact of high speed electrons. As the energy levels in the mercury are relatively far apart, the resulting emission of light is of very high frequency, mainly ultraviolet light. This is the primary excitation process. The secondary process occurs when the ultraviolet light impinges upon a thin coating of powdery material made up of phosphors on the inner surface of the glass tube. The phosphors are excited by the absorption of the ultraviolet photon and give off a multitude of lower frequencies in all directions that combine to produce white light. Different phosphors can be used to produce different colored lights.

Comparing Different Light Sources

The process of excitation and de-excitation (and the release of photons) explains how light is emitted. Mercury vapor lamps, fluorescent lamps, and incandescent lamps all work on the same principle.

Incandescent lamps produce extremely white light. The hotter the filament, the whiter the light. However, the hotter they burn, the weaker they get and the more wear and tear on the filament, thus decreasing the life of the lamp.

High pressure mercury lamps are more efficient than filament lamps. They are more efficient because less energy is converted into heat. They are about twice as efficient as filament lamps. One of the disadvantages of high pressure mercury lamps is that there is a delay in starting and restarting them. Several minutes are required for the lamps to reach full brightness. In cases of power interruption, the lamps will not restart until the arc tube has cooled sufficiently for the mercury vapor to condense (about five minutes). This disadvantage can be overcome by installing a filament lamp along with a mercury lamp.

Fluorescent lamps (low pressure mercury lamps) are about three times as efficient as filament lamps. A coating on the glass filters out the radiation that would be harmful to the eyes or to the skin. In the past, fluorescent lamps were started with a starter that heated the electrodes at the end of the tube. Modern lamps are started with a ballast; they have sufficient voltage to start the lamp immediately. Fluorescent lamps--fluorescent bulbs--give long life, about 7500 hours. The lamp is affected by the number of starts. Lamps will last longer if started less frequently.

When deciding what type of lamp to use, one has to look at both efficiency and cost. Where costs are low, a shorter lamp life would be sufficient. Where lamps are costly or the labor costs of replacing them are high, a longer-life lamp is more economical.

Incandescent filament lamps came in various shapes and sizes. The lamp bulbs are designated by a letter code followed by a numeral. The letter indicates the shape (straight, S; flame, F; globe, G; general service, A; tubular, T; pear shape, PS; parabolic, PAR; and reflector, R). The number indicates the size--the diameter of the bulb in eights of an inch. Thus, a T-12 lamp is a tubular lamp that is 12/8 inches or 1 1/2 inches in diameter. Incandescent lamps also come with different kinds of bases: disc, candelabra, intermediate, mogul, bayonet, bipost, etc.

Mercury vapor lamps are designated by ASA nomenclature; e.g., a lamp marked H33-1-CL/C. H denotes mercury; 33-1, ballast number; CL, arbitrary letters designating physical characteristics of the lamp such as bulb size, shape, material, and finish; and C indicates the color of the light.

CHAPTER 2

LIGHT AND SEEING/DESIGN OF A LIGHTING SYSTEM

The last chapter discussed the nature of light. Light was seen as radiant energy transported in photons that are carried by a wave field. In this chapter, the eye is discussed. Also discussed are some objective factors in the seeing process. The chapter ends by introducing some terms used by illumination engineers.

Behavior of Light

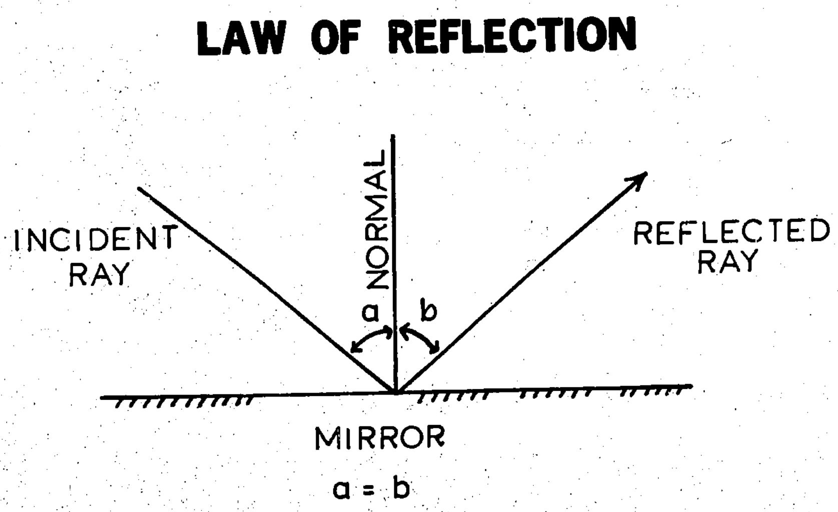
In the last chapter, how light originates was discussed. This chapter discusses briefly the behavior of light after it leaves the source. Three basic characteristics of light will be discussed. The first characteristic is:

> Light travels in a straight line unless it is modified or redirected by means of a reflecting, refracting, or diffusing medium.

When light travels, it travels in a straight line. When it is incident upon a surface, part of the light is reflected. On a metallic surface, almost 100 percent of the light is reflected; while on a clear glass surface, only a small portion is reflected. The ratio of light reflected from a surface to that incident upon it is called reflectance.

The law of reflectance is simply stated as: The angle of incidence is equal to the angle of reflection. (See Figure 5.2.1.)

Figure 5.2.1



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Reflections may be of several types; the most common are specular (see Figure 5.2.2), diffuse (see Figure 5.2.3),

Figure 5.2.2

SPECULAR REFLECTION

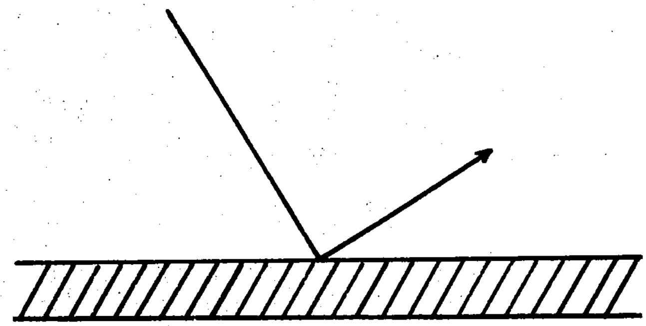
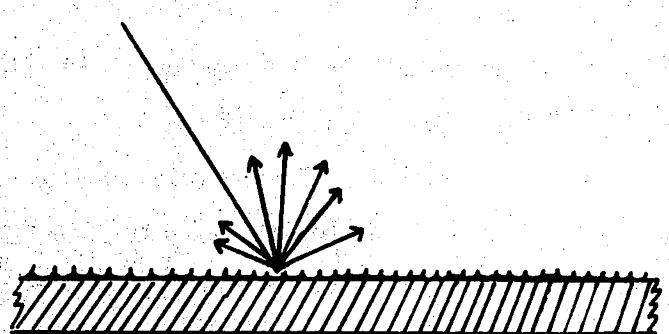


Figure 5.2.3

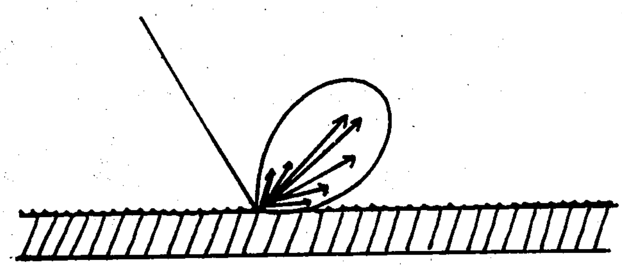
DIFFUSE REFLECTION



spread reflection (see Figure 5.2.4),

Figure 5.2.4

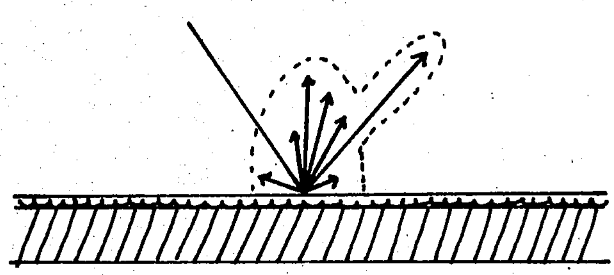
SPREAD REFLECTION



and mixed reflection (see Figure 5.2.5), which is a combination of diffuse and spread reflection.

Figure 5.2.5

MIXED REFLECTION

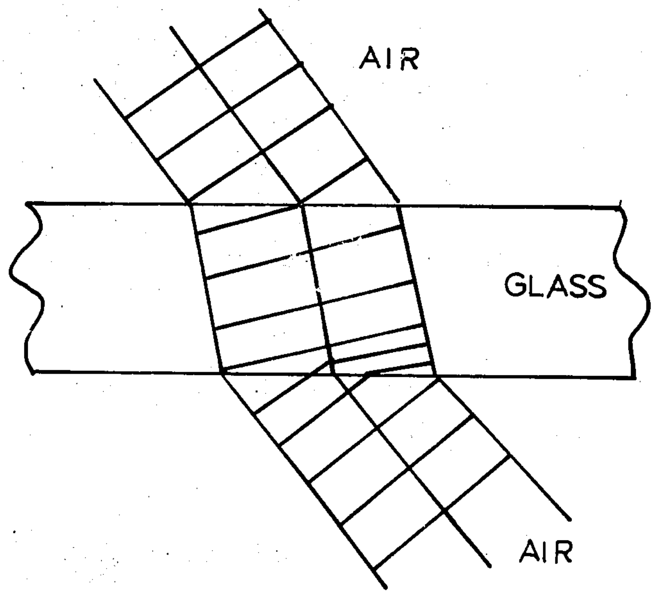


Rarefraction is the "bending" of light as it passes from one transparent medium to another. The speed at which light travels through these materials is what makes light bend. The speed of light is consistent in space. However, light has a lesser speed in a transparent medium. In water, light travels 75 percent of its speed in a vacuum; in glass, about 67 percent, depending upon the type of glass; in a diamond; about 41 percent. When light emerges from these media, it again travels at its original speed. This concept may be troublesome because from what is known about energy, this may seem like strange behavior. If a bullet is fired through a board, the bullet slows when passing through the board and emerges at a speed less than its incident speed. It loses some of its kinetic energy while interacting with the fibers and splinters in the board. But things are different with light. To understand the strange behavior of light, the individual photons of light that make up a beam and the interaction between the photons and the molecules they encounter must be considered. Incident photons interact with the electrons of molecules. Orbiting electrons can be though of as attached to little springs. These electrons will resonate at certain frequencies and can be forced into vibration over the range of frequencies. This range varies for different molecules. In clear glass, for example, the range extends over the entire visible region. When a photon is incident upon a transparent medium such as glass, it is absorbed by a molecule at the surface. An electron in the absorbing molecule is set in vibration at a frequency equal to that of the incident photon. This vibration then causes the emission of the second photon of identical frequency. It is a different but indistinguishable photon. The second photon travels at 186,000 miles per second until it quickly is absorbed by another molecule in the glass, whereupon an electron is set in vibration re-emitting a different but indistinguishable photon of its own. This absorption/re-emission process is not an instantaneous event. Some time is required for the process; and, as a result, the average speed of light through the material is less than 186,000 miles per second. That is, the photon that enters the glass is not the same photon that leaves the glass.

Light bends when it passes obliquely from one medium to another. This is called refraction. It is the slowing of light upon entering the transparent medium that causes the refraction. (See Figure 5.2.6.)

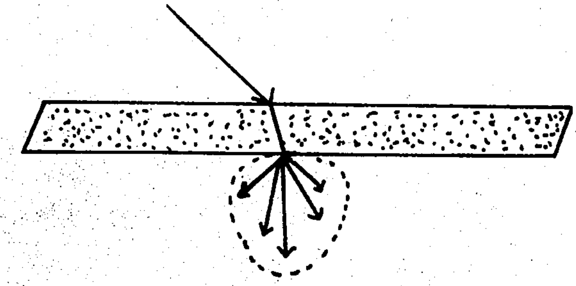
Figure 5.2.6

REFRACTION OF LIGHT



The straight line travel of light can also be altered by a diffusing material. Light traveling through a transparent or translucent material is said to be transmitted, such as light traveling through a clear glass plate. When light leaves the material, it may become diffuse. (See Figure 5.2.7.) The degree of diffusion depends upon the type and density of the material. Most luminaires are made so that the light leaving the luminaire becomes diffuse.

Figure 5.2.7



DIFFUSING GLASS

The second characteristic of light is:

Light waves pass through one another without alteration of either.

That is, a beam of red light will pass directly through a beam of blue light unchanged in direction and color.

The third characteristic of light is:

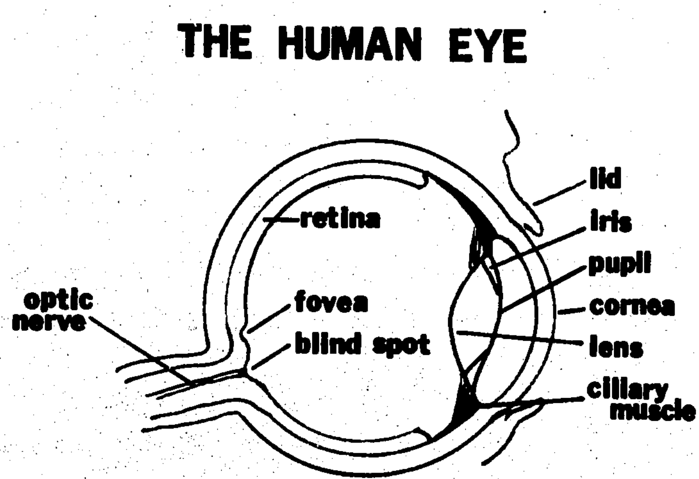
Light is invisible in passing through space unless some medium, such as dirt or dust or water, scatters it in the direction of the eye.

The scattering of light is similar to the phenomenon of resonance in sound and forced vibration. Atoms and molecules behave like tuning forks and selectively scatter waves of the appropriate frequency. A beam of light falls upon an atom and causes the electrons to vibrate. The vibrating electron in turn radiates light in different directions. An example of scattering is a searchlight beam sweeping across the sky at night. Such beams are seen by light being scattered by particles (dust or water droplets) in the atmosphere.

The Human Eye

Figure 5.2.8 shows the structure of the eye. Light passes through the cornea (a protective coating over the front of the eye). Light next passes through the pupil, an opening in the iris that can be widened or narrowed to let more or less

Figure 5.2.8



light in by contractions in the muscles of the iris, the colored portion of the eye. Light passes through the pupil into the lens, a transparent capsule behind the iris whose shape can be changed in order to focus objects at various distances. The lens is controlled by the ciliary muscle, which is ring shaped and changes the curvature of the lens. The light is then focused through the lens into the inner lining of the back of the eyeball, the retina. There the light stimulates receptor cells that transmit the information to the brain via the optic nerve.

More than six million cones and 100 million rods are distributed in the retina. Rods are slim nerve cells--receptors--which are sensitive to low levels of illumination. Rods have no color response. They are found only on the outside of the foveal region, increasing in number with the distance from the fovea. The outer portion of the retina is composed chiefly of rods which do not afford distinct vision but are highly sensitive to movement and flicker. When light strikes a rod, it causes the breakdown of a chemical, rhodopsin (visual purple). This photosensitive chemical triggers activity in the optic nerve and, subsequently, in the brain.

Cones are the receptors that make possible the discrimination of fine detail and the perception of color. Cones are insensitive at low levels of illumination. The cones are found mainly near the center of the retina, with the greatest concentration at the fovea. A few cones are mixed with rods all the way to the outer edges of the retina, but the center of the eye is the most color-sensitive portion. The cones also contain a photosensitive chemical that breaks down when struck by light waves.

The eye has the ability to adapt to a wide variety of illumination levels. Adaptation involves a change in the size of the pupils along with photochemical changes in the rods and cones. In dim light--low levels of illumination--the chemicals in the rods and cones are built up faster than they are broken down by light stimulation. The greater the concentration of these chemicals, the lower the visual threshold. Thus, the adaptation to darkness is a matter of building up a surplus of rhodopsin in the rods and other chemicals in the cones.

The cones adapt quickly in the dark (10 minutes or so), but the rods adapt slowly and continue to adapt even after 30 minutes or more of darkness. These are only rough estimates since the length of time of adaptation depends upon the previous state of adaptation and the magnitude of the change. When completely adapted, the rods are much more sensitive to light than the cones. Thus, to see a dim light in pitch darkness, one should not look directly at it since the center of the eye contains only the less sensitive cones. By looking away from the object, the image will fall on the edge of the retina where the rods are. This manner of viewing affords a higher likelihood of seeing the dim light. Since the rods work in dim light and the cones do not, vision in very dim light is entirely colorless. Although vision is colorless in dim light, the eye becomes relatively sensitive to energy at the blue end of the spectrum and almost blind to red.

Visual acuity is the ability to discriminate the details in the field of vision. The normal field of vision extends approximately 180° in the horizontal plane and 170° in the vertical plane (60° above the horizontal and 70° below). One way the ability to discriminate detail in the field of vision can be measured is by using the familiar eye chart. Standard perfect vision is often called "20/20 vision." If a person stands 20 feet away from the eye chart and sees the material on the chart clearly, he is seeing normally. He is said to have 20/20 vision. If he does not see normally, some of the material will be blurred. If a person standing 20 feet away from the chart sees what a person with normal vision sees at 50 feet, he has 20/50 vision. If a person has 20/10 vision, he sees things 20 feet away as sharply as a person with normal vision sees them at 10 feet.

Part of the retina, the "blind spot," has no visual acuity. This spot is the point at which the nerves of the eye converge to form the optic nerve. The optic nerve extends through the back wall of the eyeball and connects the eye to the brain. People are usually unaware of the blind spot; they compensate for this blind spot in their vision primarily by moving their heads and making use of their other eye.

The four most common causes of defective vision are astigmatism, the inability to bring horizontal lines and vertical lines into focus at the same time; myopia, where objects focus in front of the retina--nearsightedness; hypermetropia, where objects focus behind the retina--farsightedness; and presbyopia, loss of elasticity of the lens with age. All of these visual defects can usually be corrected by properly fitted corrective glasses or lenses.

Variables in the Seeing Process

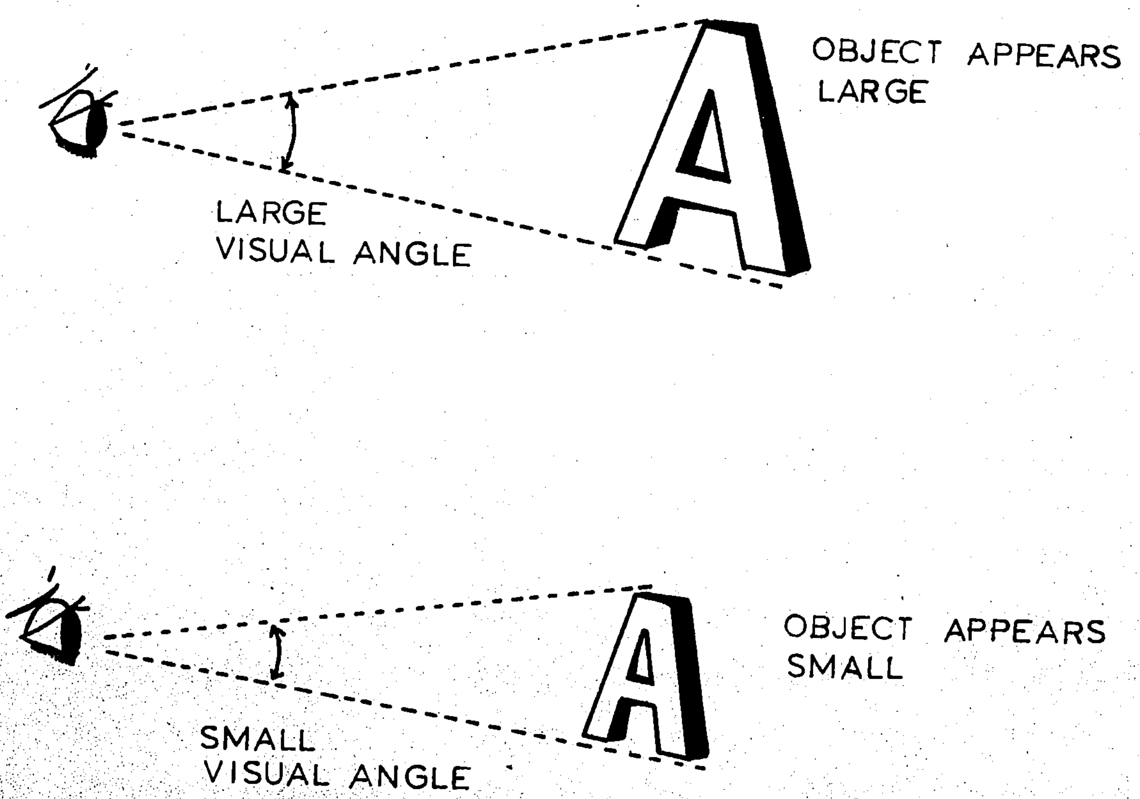
What makes an object easy to see? Investigations have shown that adequate seeing depends upon at least four variables. These are the size of the object, the contrast of the object with its background, the brightness of the object, and the time available to see the light.

The obvious factor in seeing an object is its size. The size of the object depends upon the visual angle. The larger an object in terms of its visual angle--the angle subtended by the object at the eye--the more readily it can be seen. The familiar eye test chart illustrates this principle. The person who brings a small object closer to his eyes in order to see it more clearly is unconsciously making use of the size factor by increasing the visual angle. (See Figure 5.2.9.)

Figure 5.2.9

SIZE OF OBJECT

VISUAL ANGLE OF OBJECT

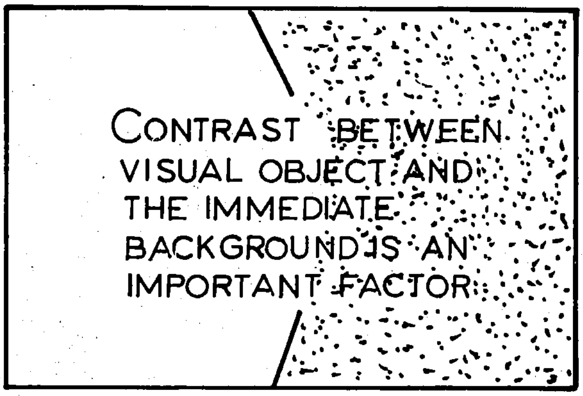


Along with the size of the object is visual acuity. Visual acuity, expressed as the reciprocal of the visual angle in minutes, is a measure of the smallest detail that can be seen. Since visual acuity increases markedly with increase in illumination, light is sometimes said to act as a magnifier, making visible small details that could not be seen with less light.

The second factor involved in seeing objects is contrast. Contrast primarily refers to two factors--color contrast and brightness contrast. Color contrast refers to the color between the object to be seen and its immediate background. For a given set of conditions, visibility is at its highest when the contrast is at a maximum. Black print on white paper is much more visible than the same print on grey paper. (See Figure 5.2.10.) Brightness contrast is the brightness between the object and its immediate background.

Figure 5.2.10

CONTRAST



The third factor in seeing is brightness. The luminance or brightness of an object depends upon the intensity of the light striking it and the proportion of that light reflected in the direction of the eye. A white surface will have a much higher luminance than a black surface receiving the same illumination. However, by adding enough light to a dark surface, it is possible to make it as "bright as the white one." The darker an object or visual task, the greater the illumination necessary for greater illuminance and, under like circumstances, for equal visibility. In addition, the brightness between the object and its immediate background should be approximately the same. Different ratios in brightness between the object and the background can cause problems for the viewer.

The fourth factor in seeing is time. Seeing is not an instantaneous process--it requires time. The eye can see very small detail under very low levels of illumination if sufficient time is allotted and eyestrain is ignored. However, more lighting is required for quick seeing. The time factor is particularly important when the visual object is in motion. High lighting levels actually make moving objects appear to move more slowly and greatly increase their visibility.

Size, luminance, contrast, and time are mutually interrelated and interdependent. Within limits, deficiency in one can be made up by an adjustment in one or more of the others. In most cases, size is a fixed factor of the visual task, with luminance, contrast, and time subject to some degree of modification. Of these, luminance and contrast are usually most directly under the control of the illuminating engineer. Properly employed, they can be of tremendous aid in overcoming unfavorable conditions, a small size, and limited time for seeing.

To see the interrrelation among the four factors, consider the following:

A. Small objects must have a high contrast to be seen.
B. Low contrast objects must be large in size.
C. As brightness increases, contrast and size can be decreased.
D. When more time is available for seeing objects, the smaller the size can be and the lower the contrast.
E. In most situations, the object is fixed, contrast is usually fixed, and the time for seeing is fixed; thus, brightness is most often the variable under the control of the engineer.

Terminology Used in the Science of Light

There are some terms related to the science of light with which everyone working with light should be familiar.

Luminous Flux (F). Luminous flux in the total radiant power emitted from a light source that is capable of affecting the sense of sight. Actually, it is more precisely defined as the time rate of flow of light (of luminous energy). In ordinary practice, the time element can be neglected, and luminous flux is commonly considered a definite quantity. Luminous flux is measured in units of a lumen where one lumen is defined as the luminous flux emitted from a 1/60 cm^2 opening in a standard source and included within a solid angle of 1 steradian. The standard source consists of a hollow enclosure maintained at a temperature of solidification of platinum, about 1773°C. A solid angle in steradians is given by

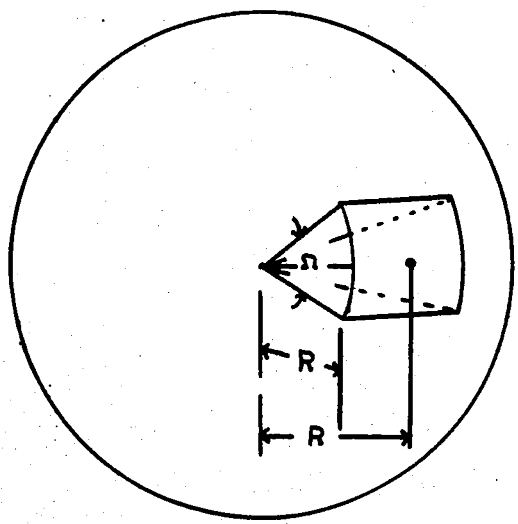
$$\Omega = \frac{A}{R^2}$$

where Ω denotes a solid angle, A denotes surface area, and R denotes distance (or radius of a sphere) and where R is perpendicular to the surface, A.

A solid angle can be graphically illustrated as in Figure 5.2.11.

Figure 5.2.11

DEFINITION OF A SOLID ANGLE IN STERADIANS



In the definition of a lumen, then, one steradian can be defined as the solid angle subtended at the center of a sphere by an area A on its surface that is equal to the square of its radius R. It can be shown that there are 4 steradians in a complete sphere.

$$\Omega = \frac{A}{R^2}$$

$$= \frac{4\pi R^2}{R^2}$$

$$= 4\pi \text{ steradians}$$

A <u>lumen</u> is often defined as the flux falling on a surface one square foot in area, every part of which is one foot from a point source having a luminous intensity of one candela (candlepower) in all directions. Luminous intensity is a term not yet defined.

<u>Luminous Intensity</u>. Luminous intensity of a light source is the luminous flux emitted per solid angle:

$$\text{Intensity} = \frac{\text{Flux}}{\Omega}$$

The unit for intensity is the lumen per steradian called a <u>candela</u> or <u>candlepower</u>, as it was called when the international standard was defined in terms of the quantity of light emitted by the flame of a certain candle. (This initial standard was replaced by the platinum standard.) This standard candle had a luminous intensity in a horizontal direction of approximately one candela. If a light from a candle with a candlepower of 1 fell on a surface of one square foot, where every part of the surface was one foot from the candle, the amount of flux would be one lumen. Note from the above equation that

$$\text{Flux} = \text{Intensity} \bullet \Omega$$

If the light source is an isotropic source (one which emits light uniformly in all directions), then the total flux emitted would be

$$\text{Flux} = 4\pi \text{ Intensity}$$

since the total solid angle for an isotropic source is 4π steradians.

Example

If a spotlight one foot away from a wall had a bulb with a candlepower of 1 candela and the beam covered an area of 1 square foot of the wall, what would the luminous intensity of the spotlight be?

Solution

Total flux emitted by the 1 candela bulb is

$$\text{Flux} = 4\pi \text{ intensity}$$
$$= 4\pi \text{ 1 candela}$$
$$= 12.56 \text{ lumens} \quad \text{(flux is measured in lumens)}$$

The light is concentrated into a solid angle given by

$$\Omega = \frac{A}{R^2}$$
$$= \frac{1 \text{ ft}^2}{1 \text{ ft}^2}$$
$$= 1 \text{ steradian}$$

And the intensity of the beam is given by

$$\text{Intensity} = \frac{\text{Flux}}{\Omega}$$
$$= \frac{12.56 \text{ lumens}}{1 \text{ steradian}}$$
$$= 12.56 \text{ candela} \quad \text{(intensity is measured in candela)}$$

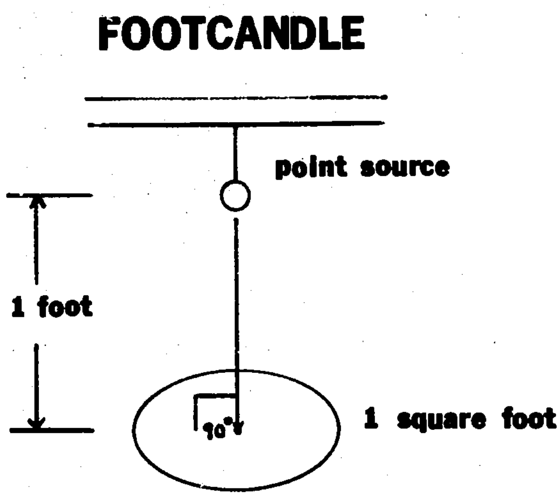
Note that the units of intensity, candela (lumens/steradian) and the units of flux (lumen) are the same dimensionally because the solid angle in steradian is dimensionless. Also note that flux and intensity will be equal when $\Omega = 1$ steradian (i.e., when $A = R^2$).

Illumination. Illumination is the density of luminous flux on a surface area; i.e.,

$$\text{Illumination} = \frac{\text{Flux}}{\text{Area}}$$

When flux is measured in lumens and area is measured in square feet, then illumination is expressed in lumens per square feet. The lumens per square feet is sometimes called the footcandle. If a lumen is defined as the flux falling on a surface area of one square foot, where every part of the surface is one foot from a point source having a luminous intensity of 1 candela (candlepower), then it is obvious that one lumen uniformly distributed over one square foot of surface provides the illumination of one footcandle. Visually, a footcandle is the illumination at a point, X, on a surface which is one foot from and perpendicular to a uniform point source of one candela. (See Figure 5.2.12.)

Figure 5.2.12



In this special case where the incident light is perpendicular to the surface, it can be shown that

$$\text{Illumination} = \frac{\text{Intensity}}{\text{Square distance}}$$

The relationship

$$\text{Illumination} = \frac{\text{Lumens (Flux)}}{\text{Area}}$$

is important and will be used during the discussion of the lumen method of designing a lighting system.

Luminance. Luminance (sometimes called photometric brightness) is a measure of the brightness of a surface, when viewed from a particular direction, emitting or reflecting one lumen per square foot. Luminance is direction specific and is often measured in footlambert units.

Reflectance. Reflectance is a measure of how much light is reflected from a surface. It is the ratio of luminance to illumination.

$$\text{Reflectance} = \frac{\text{Luminance}}{\text{Illumination}}$$

The Measurement of Light

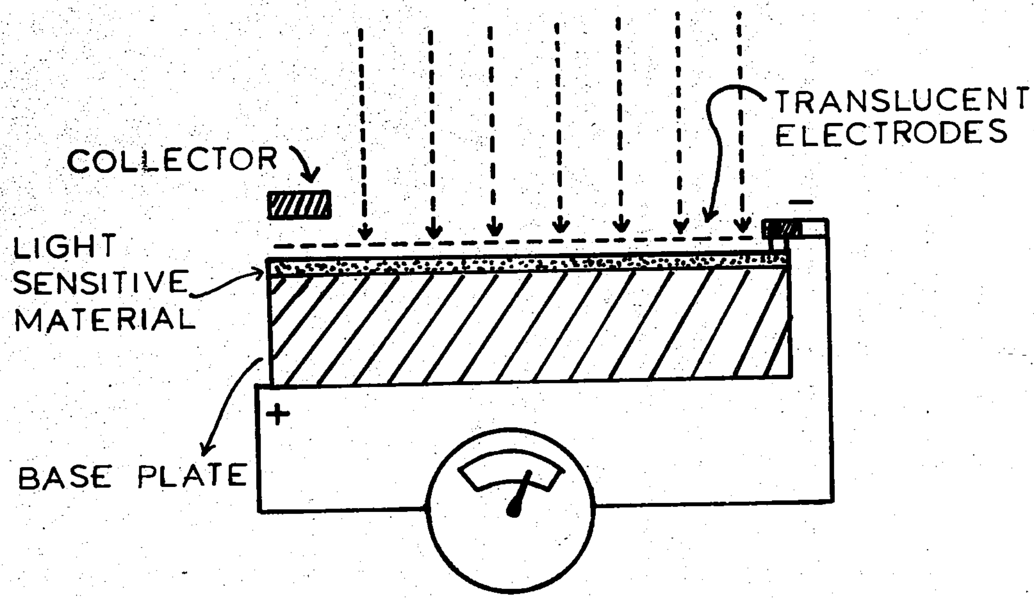
Footcandle Measurements. Illumination measurements are most commonly made with one of several types of footcandle meters embodying a light-sensitive, barrier-layer cell. (See Figure 5.2.13.) This type of cell consists essentially of a film of light-sensitive material mounted on a metal-based plate and covered by a very thin translucent layer of metal spattered on its outer surface. Light striking the cell surface causes the semiconducting, light-sensitive material to emit electrons that are picked up by the metal collector in contact with the translucent front electrode. A potential difference is thus set up between the collector and the base plate; and, when a microammeter is connected between them, it measures the current generated by the cell. Since the current is proportional to the intensity of the incident light, the meter can be calibrated to read directly in footcandles. Portable meters are made in a number of types and with a wide range of sensitivity for various applications. Although portable, light-sensitive cell meters are simple and highly convenient to use, most of them are not designed to be precision instruments. Careful handling and frequent calibration will help to maintain reliability. Ordinary measurements made in the field should not be expected to have an accuracy greater than ±5% under the most favorable conditions. In addition, all light-sensitive cells have certain inherent characteristics that the user must understand if he is to obtain the best possible results:

A. There is a need to have the instrument color corrected. The instrument needs to be color corrected because the response of the light-sensitive cells to the various wavelengths of the visible spectrum is quite different from that of the human eye.

B. They must be cosine corrected; that is, adjusted for the angle of the reflected light.

Figure 5.2.13

ILLUMINATION METER



INSTRUMENTS NEEDED TO BE

(a) COLOR CORRECTED

(b) COSINE CORRECTED TO COMPENSATE FOR LIGHT REFLECTED FROM THE LIGHT DETECTING CELL SURFACE

C. All light-sensitive cells exhibit a certain amount of fatigue; that is, a tendency for the meter indication to drop off slowly over a period of minutes until a constant reading is reached. This effect is most noticeable at high footcandle values, particularly if the cell has just been previously in the dark for some time or exposed to a much lower level of illumination. Before any measurements are recorded, therefore, the meter should be given as long an adaptation period as may be necessary at the footcandle level to be measured.

In addition, there is a constant need to have the instrument calibrated.

Brightness or luminance is measured using a photoelectric tube. The instrument is aimed at the surface to be measured, and a lens focuses the image on a small area on the tube which produces a current proportional to luminance. The current is read on a microammeter calibrated in footlamberts.

Brightness is also measured by a visual luminance meter. This uses an optical system to bring the eyes of the observer side by side to the surface to be measured and a comparison field inside the meter.

Luminance can be measured with a footcandle meter providing the reflectance of the surface is known. This is because illuminance equals luminance divided by reflectance.

Reflectance can be measured by a cell-type footcandle meter. There are two procedures that can be used. The more accurate procedure requires a piece of matte material at least one foot square, the reflectance of which is known. White blotting paper, at about 80 percent reflectance, is suitable. The blotting paper is placed against the surface to be measured, and the meter is held two to four inches away with the cell facing the paper, reading A. The blotting paper is then removed without moving the meter, and the reading B is noted. The reflectance of the surface is reading B divided by reading A times 0.80. In all measurements of this sort, special care must be taken to maintain all conditions, especially the position of the meter, constant for both readings of a pair.

Light Survey Procedures

"How to Make a Lighting Survey," developed by the Illuminating Engineering Society, provides detailed information on taking a lighting survey. A set of instructions and a form are included with this information.

The survey includes reporting on the following information:

1. Description of the illuminated area:
   a. room dimensions
   b. color
   c. reflectance
   d. conditions of room surface
   e. temperature surrounding the lights
2. Description of the general lighting system:
   a. quantities
   b. conditions
   c. wattages
   d. lamps
   e. distribution
   f. spacings
   g. mountings
3. Description of any supplementary lighting that might be used.
4. Description of instruments to be used.
5. Illumination measurement:
   a. operator must be aware not to cast shadows
   b. operator must be careful not to reflect additional light with his clothing
   c. test surfaces should be as close as possible to the working plane. If there is not definite working plane, take measurements on a horizontal plane 30 inches above the floor.
6. Luminance measurements.

Evaluation of Results. Data resulting from a light survey can be used to compare the illumination levels for compliance with the recommended levels; to compare the luminance with compliance luminance levels; to determine luminance ratios for visibility and safety; to determine indications of comfort and pleasantness in the area; to determine deficiencies in the area; and to determine a maintenance schedule--that is, a good housekeeping schedule.

CHAPTER 3
LIGHTING DESIGN

Introduction

In the last chapter the four factors of seeing industrial tasks--size, contrast, brightness, and time--were discussed. Also discussed were common lighting terminology and the behavior of light when it leaves the source.

This chapter discusses the design of a lighting system. The design of any lighting system involves the consideration of many variables: What is the purpose of the lighting--is it lighting for critical seeing, lighting for selling, or lighting for decoration? How severe is the seeing task, and for what length of time is it to be performed? What are the architectural and decorative requirements, together with the constructional limitations, of the area? What economic considerations are involved? The answers to such questions as these determine the amount of light that should be provided and the best means for providing it. Since individual tastes and opinions vary, especially in matters of appearance, no one solution of a lighting problem will be the most desirable under all circumstances. However, there are certain basic rules governing adequate lighting and the quality of that lighting. Two factors that must be considered in designing a lighting system are the quantity of light and the quality of light reaching the seeing task.

Quantity of Light

The most obvious consideration in designing a lighting system is the adequacy of the light on the seeing task. Research has shown that illumination of thousands of footcandles is required to see dark, low contrast tasks as easily as light-colored tasks of high contrast under low levels. However, the are other factors involved. These factors suggest that for any task the minimum number of footcandles is 30.

The Illuminating Engineering Society published a document entitled "Recommended Levels of Illumination" (RP-15), 1966, which contains a complete table of minimum footcandle levels recommended for certain kinds of tasks. A page from this document can be found in Table 5.3.1.

RECOMMENDED FOOTCANDLES

While for convenience of use this table sometimes lists locations rather than tasks, the recommended footcandle values have been arrived at for specific visual tasks. The tasks selected for this purpose have been the more difficult ones which commonly occur in the various areas.

In order to assure these values at all times, higher initial levels should be provided as required by the maintenance conditions (see page 9-15).

Where tasks are located near the perimeter of a room special consideration should be given to the arrangement of the luminaires in order to provide the recommended level of illumination on the task (see page 9-16).

The illumination levels shown in the table are intended to be minimum on the task irrespective of the plane in which it is located. The commonly used lumen method of illumination calculation (see page 9-1) gives results only for a horizontal work plane. The ratio of vertical to horizontal illumination will generally vary from 1/3 for luminaires having narrow distribution to 1/2 for luminaires of wide distribution. Where the levels thus achieved are inadequate, special luminaire arrangements should be used or supplemental lighting equipment employed.

Supplementary luminaires may be used in combination with general lighting to achieve these levels. The general lighting should be not less than 20 footcandles and should contribute at least one-tenth the total illumination level.

Many of the following values have appeared, or in the future will appear, in other reports of the Society, some of which are jointly sponsored with other agencies and organizations.

Interior Lighting

Area	Footcandles on Tasks*
Aircraft manufacturing	
Stock parts	
Production	100
Inspection	200
Parts manufacturing	
Drilling, riveting, screw fastening	70
Spray booths	100
Sheet aluminum layout and template work, shaping, and smoothing of small parts for fuselage, wing sections, cowling, etc.	100[j]
Welding	
General illumination	50
Precision manual arc welding	1000[a]
Subassembly	
Landing gear, fuselage, wing sections, cowling, and other large units	100
Final assembly	
Placing of motors, propellers, wing sections, landing gear	100
Inspection of assembled ship and its equipment	100
Machine tool repairs	100
Aircraft hangars	
Repair service only	100
Armories	
Drill	20
Exhibitions	30
Art galleries	
General	30
On paintings (supplementary)	30[b]
On statuary and other displays	100[c]
Assembly	
Rough easy seeing	30
Rough difficult seeing	50
Medium	100
Fine	500[a]
Extra fine	1000[a]
Auditoriums	
Assembly only	15
Exhibitions	30
Social activities	5
Automobile showrooms (see Stores)	
Automobile manufacturing	
Frame assembly	50
Chassis assembly line	100
Final assembly, inspection line	200
Body manufacturing	
Parts	70
Assembly	100
Finishing and inspecting	200
Bakeries	
Mixing room	50
Face of shelves (vertical illumination)	30
Inside of mixing bowl (vertical mixers)	50
Fermentation room	30
Make-up room	
Bread	30
Sweet yeast-raised products	50
Proofing room	30
Oven room	30
Fillings and other ingredients	50
Decorating and icing	
Mechanical	50
Hand	100
Scales and thermometers	50
Wrapping room	30
Banks	
Lobby	
General	50
Writing areas	70
Tellers' stations	150
Posting and keypunch	150
Barber shops and beauty parlors	100

* Minimum on the task at any time. For general notes see beginning of tabulation. For other notes see end of tabulation.

Source: "Recommended Levels of Illumination," The Illuminating Engineering Society

Evidence providing a sound basis for definite footcandle recommendations is not easy to obtain. Much work in this field has been carried on over a period of many years, using various methods and various criteria of visual performance. On the basis of such research, the Illuminating Engineering Society has made footcandle recommendations for a wide variety of representative industrial operations and other visual activities.

The "Recommended Levels of Illumination" document is divided into two parts--general interior lighting and lighting of industrial interiors. The illumination specified is to be provided on the work surface, whether it is horizontal, vertical, or oblique. Where there is no definite area, it is assumed that the illumination is measured on a horizontal plane 30 inches above the floor. The values given are not to be construed as initial footcandles provided by a new installation; they are recommended <u>minimum footcandles at any point on a task at any time</u>. This means that the installation must be so designed that the collection of dirt on luminaires, lamps, walls, and ceilings, and the normal depreciation of light output of the lamps themselves will not at any time lower the illumination below the recommended levels. In order to insure the minimum levels, one should design a lighting system with higher levels than those indicated in the tables. One can look at the minimum levels specified in the document as being the levels on the task when the lighting systems on the room surfaces have depreciated to their lowest level before maintenance procedures are effected (cleaning, relamping, painting, etc.). In addition, the recommended levels do not take into account the wearing of goggles. If goggles are worn, the levels of illumination should be increased in accordance with the absorption of the goggles. The levels specified in the document again should be viewed as minimum levels. They are not to be construed as standards. They are only suggested levels. However, one can use the tables to identify what level--what quantity of illumination--is needed for any specified task that he might have.

The quantity of light also depends upon the distribution of the luminaires. In light for seeing or light for production and inspection, it is usually desirable to position the luminaire to provide reasonably uniform general illumination over the entire area. The ratio of maximum footcandles under the luminaires to the minimum between then should never be greater than 2:1; and for best results, it it should be nearer to unity. Units with wide distribution characteristics can be spaced farther apart for the same mounting height than those with more concentrated distributions. Maximum spacing-to-mounting-height or ceiling-height ratios for various types of equipment are supplied by the manufacturers.

Quality of Light

In addition to the quantity of light, one must consider the quality of light when designing a lighting system. Quality of light refers to glare, brightness ratio, diffusion, and color.

Glare is the effect of brightness differences within a visual field sufficiently high to cause annoyance, discomfort, or loss of visual perception; while brightness is the intensity of light emitted, transmitted, or reflected from a given surface. Basically, there are two kinds of glare: glare caused by a bright light source which is sometimes called direct glare; and glare by bright reflections, sometimes called reflected glare. There are generally considered to be two forms of glare--discomfort glare and disability glare--each of which may be caused by a bright light source or by bright reflections on room surfaces. Discomfort glare, as its name implies, produces discomfort and may affect human performance but does not necessarily interfere with visual performance or visibility. In some cases, extremely bright sources (the sun) can even cause pain. Disability glare does not cause pain but reduces the visibility of objects to be seen. An example is the reduced visibility of objects on a roadway at night caused by glare of bright oncoming headlights.

Direct glare results from high brightness light sources or luminaires in the field of view that are not sufficiently shielded or cover too great an area. It is also possible that direct glare can result from improperly shaded windows.

An industrial environment, then, will be relatively comfortable if there is no direct glare; and seeing will be unimpaired if there is no disability glare. The effects of direct glare can be avoided or minimized by mounting the luminaires as far above or away from the normal lines of sight as possible. In general, this can be done by shielding luminaires to at least 25 degrees down from the horizontal and preferably down to 45 degrees. In other words, brightness of bare lamps preferably should not be seen when looking in the range of sight straight ahead to 45 degrees above the horizontal.

Direct glare from windows can be minimized by properly shielding the sources of daylight with adjustable shades, blinds, or louvers.

Reflected glare is bright areas on shiny surfaces that become annoying. Light sources between the vertical and 45 degrees from the vertical contribute to reflected glare. Luminaires with lens that polarize light (lens that transmit light waves which vibrate in only one direction) tend to reduce reflected glare in many cases. Reflected glare can also be reduced by adjusting the position of the seeing task and by controlling the distribution pattern of lighting fixtures.

In addition to the above information about glare, the following should be considered:

1. Glare is influenced by characteristics of the room and the use of the luminaires. This is particularly true when considering reflected glare.
2. Luminaire brightness that is comfortable in a small office where the lighting units are out of range of vision may be excessive in larger rooms where the luminaires farthest away may approach the line of vision.
3. Luminaires that do not have objectionable high brightness may, if mounted in large groups, present a total picture that is uncomfortable. This usually results when some type of fluorescent luminaires are mounted across the line of sight in an area with relatively low ceilings.
4. The color of walls and ceilings is extremely important. This is particularly true with reflected glare. Since specular reflection is directional, it is frequently possible to prevent reflected glare by positioning the light source, the work surface, or the worker so that the reflected light will be directed away from the eyes. Reflected glare may also be controlled by means of large-area, low-brightness sources, and by using light colors with dull, nonglossy reflected finishes on furniture and working surfaces.

The next concept to consider when dealing with quality of light is the brightness ratio or brightness contrast. Brightness is sometimes called luminance or photometric brightness. The brightness ratio refers to the different brightnesses in an area of the task and the immediate background surrounding the area. Even though the differences in brightness between a surrounding area and the task may not be severe enough to cause glare, the differences in the brightnesses may be detrimental to the lighting quality. If there is a difference in brightness between the task area and the surrounding background, the eyes will continuously have to adapt between the task and the surrounding area. It takes some time for the eyes to do this kind of adaptation; and, therefore, the visibility of the task will be affected. In addition, brighter surroundings tend to attract the eyes away from the task. The eyes function more efficiently and comfortably when the luminance within the visual environment is not too different than that of the seeing task. To reduce the effect, maximum luminance ratios are recommended as shown in Table 5.3.2. A ratio of the brightness of the task to that of the immediate surroundings of 3 to 1 is generally acceptable. Ratios no greater than 10 to 1 anywhere in the field of vision are desirable, and 30 to 1 or 40 to 1 is the maximum permissible.

Table 5.3.2

RECOMMENDED MAXIMUM LUMINANCE RATIOS

	Environmental Classification		
	A	B	C
1. Between tasks and adjacent darker surroundings	3 to 1	3 to 1	5 to 1
2. Between tasks and adjacent lighter surroundings	1 to 3	1 to 3	1 to 5
3. Between tasks and more remote darker surfaces	10 to 1	20 to 1	*
4. Between tasks and more remote lighter surfaces	1 to 10	1 to 20	*
5. Between luminaires (or windows, skylights, etc.) and surfaces adjacent to them	20 to 1	*	*
6. Anywhere within the normal field of view	40 to 1	*	*

*Luminance control not practical

A. Interior areas where reflectances of entire space can be controlled in line with recommendations for optimum seeing conditions.

B. Areas where reflectances of immediate work area can be controlled, but control of remote surroundings is limited.

C. Areas (indoor or outdoor) where it is completely impractical to control reflectances and difficult to alter environmental conditions.

Source: *the Industrial Environment--its Evaluation and Control*

As an aid in achieving these reduced luminance ratios, the reflectance upon room surfaces and equipment should be as listed in Table 5.3.3.

Table 5.3.3

RECOMMENDED REFLECTANCE VALUES
APPLYING TO ENVIRONMENTAL CLASSIFICATIONS
A AND B

	Reflectance* (percent)
Ceiling	80 to 90
Walls	40 to 60
Desk and bench tops, machines and equipment	25 to 40
Floors	Not less than 20

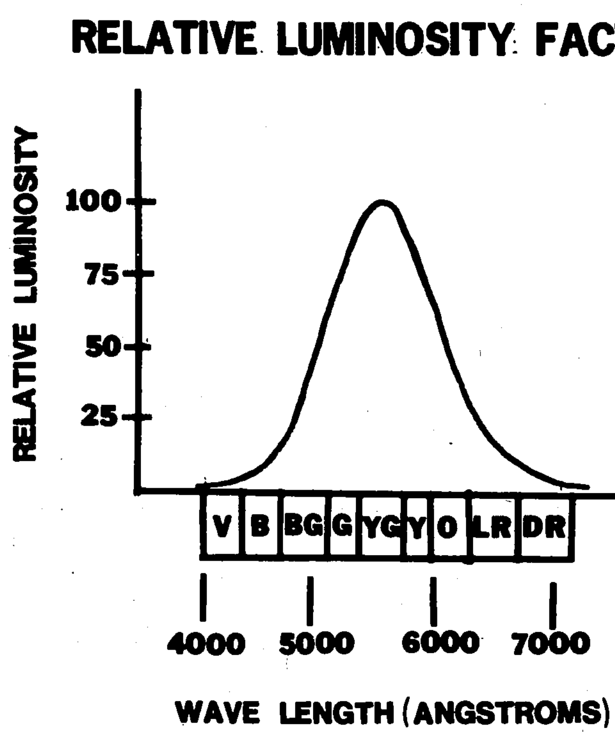
*Reflectance should be maintained as near as practical to recommended values

Source: *the Industrial Environment--its Evaluation and Control*

The third factor influencing the quality of light is diffusion. Diffusion is light coming from many directions as opposed to light coming from one direction. Diffusion is measured in terms of the absence of sharp shadows. The degree or absence of diffusion depends upon the type of work being performed. Perfectly diffuse light is ideal illumination for many critical seeing tasks; for example, in schools and offices. Where polished metal surfaces must be viewed, a highly diffused light is essential to prevent annoying specular reflections. In other cases, direct lighting may be more important or desirable than diffuse lighting; for example, surface irregularities that are almost invisible under diffuse light may be clearly revealed in light directed at a glazing angle. Diffusion is achieved by multiple lighting sources, by having a large number of low brightness luminaires, by indirect or partially indirect lighting in which the ceilings and walls become secondary sources, and by light-colored, matte finishes on ceilings, walls, furniture, and even on the floors. A quality lighting system will have luminaires spaced so that the ratio of the intensity below the luminaires to the intensity between the luminaires is 1 to 1. Ratios of 1.5 to 1 are acceptable, and the maximum is 2 to 1.

The fourth factor to consider when discussing the quality of light is <u>color</u>. Color is the sensation produced in the eye in response to light in certain portions of the dichromatic spectrum (wavelengths of 3,800 to 7,200 angstroms, where to convert angstroms to inches multiply by 3.937×10^{-9}). The eye is more sensitive to energy emitted at certain wavelengths than at others. The effectiveness of energy emitted at a given wavelength in producing a response in the eye is indicated by the relative luminosity factor. (See Figure 5.3.1.)

Figure 5.3.1



Source: *Westinghouse Lighting Handbook*

A source of light might be emitted in (1) a narrow band of one or two frequencies (line spectrum), (2) a continuous spectrum containing various quantities of all frequencies in the visibility spectrum (such as tungsten lamps), or (3) an equal energy spectrum containing equal amounts of energy at each wavelength in the visible spectrum.

Color is often described by a temperature, where the temperature compares the color of a light source with the color of a black box heated to various temperatures (usually measured in degrees Kelvin). Designation of color by temperature is usually limited to colors with continuous spectrum characteristics because black bodies do not emit colors comparable to those with line-band radiation.

Objects appear to be a certain color because they have the ability to absorb light energy of particular wavelengths. The characteristic of the reflected light determines the color of the object.

For performance of ordinary visual tasks, no one color light source has any advantage over any other. However, color must be considered a key factor in specialized applications. For example, minor color differences are best distinguished when an object is viewed under a light with low energy in the spectral region of the object's maximum reflectivity.

Color may also be important for psychological reasons. Certain colors convey a feeling of warmth, and others appear cool. The design of a lighting system must recognize psychological and traditional factors in achievement of quality for a particular seeing task.

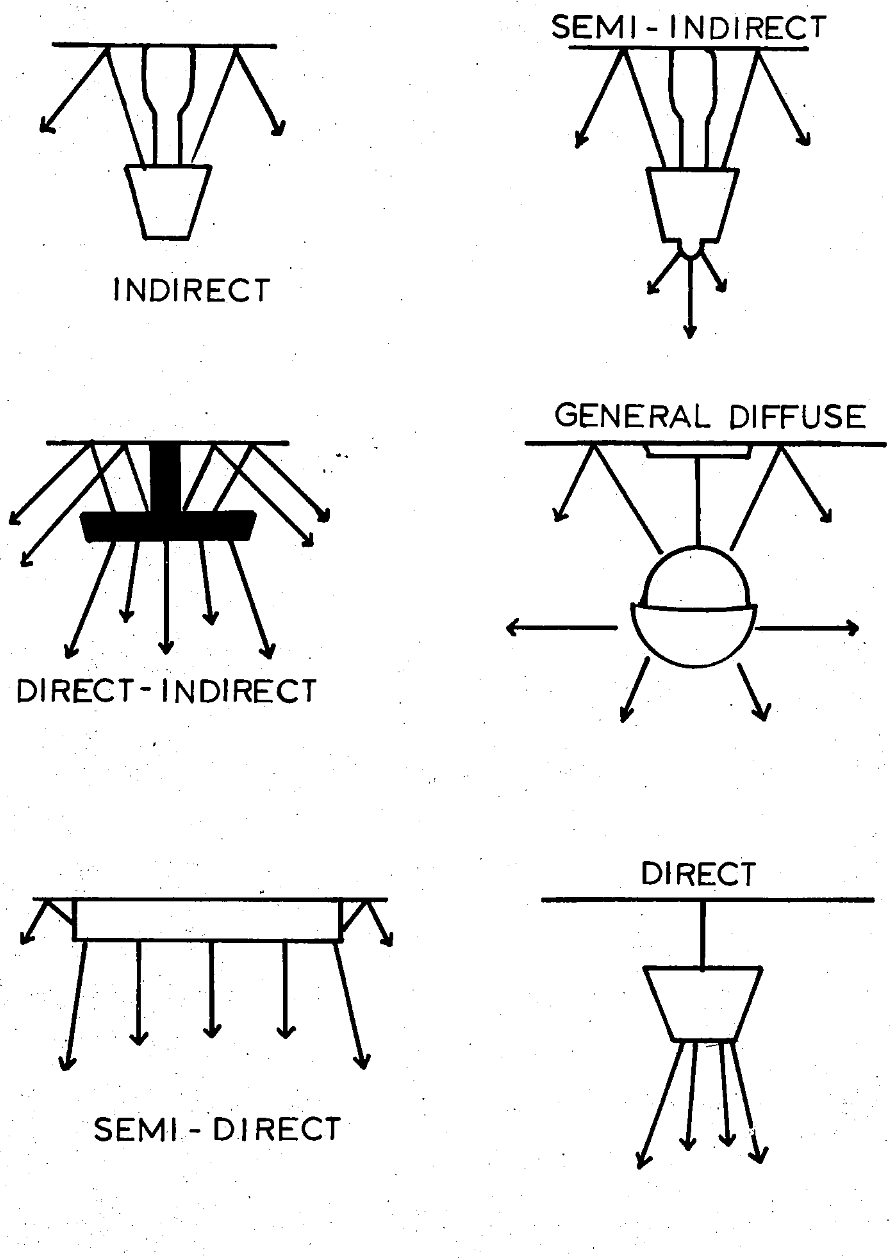
Luminaire Classification

Luminaires are designed to control the source of light so that it can be better used for a given seeing task. The materials used in luminaires are designed to reflect, refract, diffuse, or obscure light. Luminaires are classified into two general types, general and supplemental. General lighting luminaires are subdivided as shown in Figure 5.3.2.

Indirect Lighting. Ninety to 100 percent of the light output of the luminaire is director toward the ceiling at an angle above the horizontal. Practically all the light effective at the work plane is redirected downward by the ceiling and, to a lesser extent, by the side walls. Since the ceiling is in effect a secondary lighting source, the illumination produced is quite diffuse in character. Because room finishes play such an important part in redirecting the light, it is particularly important they they be as light in color as possible and be

Figure 5.3.2

CLASSIFICATION OF LUMINAIRES



carefully watched and maintained in good condition. The ceiling should always have a matte finish if reflected images of light sources are to be avoided. For comfort, the ceiling luminance must be within the prescribed limits. Diffuse lighting is usually desirable because it gives even distribution and minimum shadows and minimum reflected glare.

Semi-Indirect Lighting. Sixty to 90 percent of the light output of the luminaire is directed toward the ceiling at angles above the horizontal while the balance is directed downward. Semi-indirect lighting has most of the advantages of the indirect system but is slightly more efficient and is sometimes preferred to achieve a desirable luminance ratio between the ceiling and the luminaire at high-level installations. The diffuse medium employed in these luminaires is glass or plastic of lower density than that employed in indirect equipment.

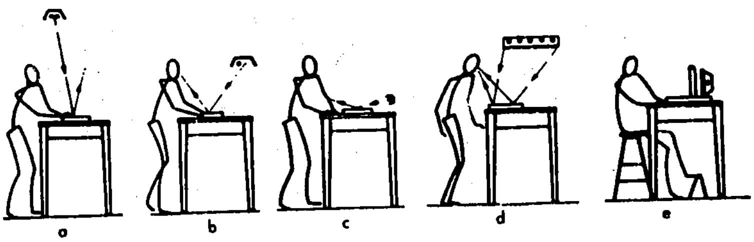
General Diffuse or Indirect Lighting and Direct-Indirect Lighting. Forty to 60 percent of the light is directed downward at angles below the horizontal. The major portion of the illumination produced on ordinary working planes is a result of light coming directly from the luminaire. There is, however, a substantial portion of the light directed to the ceiling and the side walls. The difference the general diffuse and direct-indirect lighting classification is the amount of light produced in a horizontal direction. The general diffuse type is exemplified by the enclosing globe (lamp) which distributes light nearly uniformly in all directions, while the direct-indirect luminaire produces very little light in a horizontal direction due to the density of its side panels.

Semi-Direct Lighting. Sixty to 90 percent of the light is directed downward at angles below the horizontal. The light reaching the normal working plane is primarily the result of the light coming directly from the luminaire, not from the ceiling or from the walls. There is a relatively small indirect component, the greatest value of which is that it brightens the ceiling around the luminaire, with the resultant lowering of the brightness contrasts.

Supplementary Lighting. The supplementary lighting category of luminaire is also subdivided. These luminaires are used along with the general lighting system but are localized near the seeing tasks to provide the higher levels or quality of light not readily obtainable from the general lighting system. They are divided into five major subtypes, from S-I to S-V, based upon their light distribution and luminance characteristic. Each has a specific group of applications, as shown in Figure 5.3.3.

Figure 5.3.3

SUPPLEMENTARY LUMINAIRES



Examples of Placement of Supplementary Luminaires: (a) Luminaire located to prevent reflected glare--reflected light does not coincide with angle of view. (b) Reflected light coincides with angle of view. (c) Low angle lighting to emphasize surface irregularities. (d) Large-area surface source and pattern are reflected toward the eye. (e) Transillumination from diffuse sources.

Source: the Industrial Environment--its Evaluation and Control

Lighting Systems or Illumination Methods

The illumination produced by any one of the five types of luminaire systems may be further classified according to the distribution of light throughout the area. Whether the lighting is general, localized general, or supplementary depends upon the location of equipment and its distribution characteristics.

General Lighting. General lighting is the arrangement of lighting equipment so that a uniform level of illumination is produced. Factors affecting uniform distribution of light are:

a. the physical characteristics of the room

b. the level of illumination desired

c. the appearance of the finished installation

Uniform lighting can be obtained using the lumen method (described later) which gives the number of luminaires needed to provide a certain quantity of light. After the number of luminaires is computed, the approximate location can be made so that the total number of luminaires can be adjusted to be evenly divisible by the number of rows. The exact distance between fixtures is determined by dividing the length of the room by the number of luminaires in a row, allowing for about one-third of this distance between the wall and the first unit. In a similar manner, the distance between the rows is the width of the room, divided by the number of rows, with about one-third of the distance left between the side of the wall and the first row. In high ceiling industrial areas, these recommended distances may be up to one-half of the luminaire spacing.

Localized General Lighting. Localized general lighting is the positioning of general lighting equipment with reference to particular work areas where high intensities are necessary, with the spill light from the same luminaires usually providing sufficient illumination for adjacent areas. Luminaires of a direct, semi-direct, or direct-indirect type are usually employed for this purpose since a substantial direct component is essential where it is desirable to concentrate most of the light on the restricted area beneath the luminaire; that is, the work plane.

Supplementary Lighting. Supplementary lighting is the provision of relatively high intensity at specific work points by means of direct lighting equipment used in conjunction with general localized illumination. It is frequently necessary where specialty seeing critical tasks are involved and where it is not feasible to provided the desired intensity by either general lighting or localized general lighting. It is also used where the light of directional quality is required for certain inspection tasks. Equipment used for this purpose varies in distribution characteristics depending upon the area to be covered, by the distance from the equipment location to the work point, and the footcandles required. When using supplementary lighting, care must always be exercised to keep a reasonable relationship between the intensities of the general illumination and the supplementary lighting, since an excessive luminance ratio between the work point and its surroundings creates an uncomfortable seeing condition.

Other Factors to Consider When Designing a Lighting System

When designing a lighting system, one must consider the quantity of light, the quality of light, the type of light (that is, direct or indirect), and the type of lighting system (e.g., supplementary, general localized, or general). In addition, other factors should be considered. Such factors are:

1. The choice of light source
   - --filament
   - --mercury vapor
   - --fluorescent
2. Heat produced from the source
3. Efficiency of the lamp or light source
4. Electrical features
   - --use equipment that conforms to the industrial specifications
   - --use adequate type of wiring and circuits
5. Mechanical structure of the support of the fixtures
6. Appearance/decoration

One of the other characteristics to consider when designing a lighting system is the maintenance of the luminaires. There are three things to look at in maintenance of luminaires.

1. The light source
2. The luminaire
3. The room surface

The life of the light source is a maintenance problem. Length of life is different for filament, mercury vapor, and fluorescent lamps. Filament lamps have the least length of life. Mercury vapor and fluorescent last longer; however, near the end of their life, they are only about 75 percent of the output of the beginning of their life. It is frequently found to be economical to establish a replacement program in which new lamps are installed before the old ones have reached the end of their life; that is, the 75 percent of their original output. Such a program can be best carried out by systematically replacing the lamps in a specific area after they have burned a predetermined number of hours. This procedure is commonly termed "group relamping." This method has an advantage in that it results in less variation in the illumination level effectiveness in the area.

The second factor to consider in maintenance of the system is the luminaires. Luminaires do not function efficiently when they are covered with dirt. The amount of dirt depends upon the characteristics of the environment, the room area, and the type of activity being conducted in the room. The reason dirt interferes with the luminaire is that the light must travel through the layer of dirt; and because dirt changes the distribution characteristics of the equipment, it is necessary to take this into consideration when the lamp is to provide a direct beam of light--the dirt makes the resulting light diffuse. Because maintenance of the luminaires and the dust accumulating on them is a problem, one must consider these problems beforehand before selecting the type of luminaire. One should look for such things as how difficult the unit is to handle, its weight, its size, its accessibility or inaccessibility. One must also look to see if the luminaire is hinged or otherwise secured to the main body of the fixture. For purposes of cleaning, it is of an advantage to be able to remove the lamps and reflecting equipment readily. The normal cleaning heights of the luminaires must also be considered. They can be cleaned at regular heights usually from stepladders. However, where ceilings are high or the floor area beneath the luminaires is inaccessible, telescoping ladders with extension platforms may be required. These are frequently necessary for use in machine shops and large auditoriums. In these conditions, the possibility of catwalks or messenger cables should be considered. The cleaning schedule depends upon how dirty the environment is. If the cleaning coincides with the replacement schedule, the labor costs will be reduced.

The third factor to consider in maintenance is the room surface. If the lighting system is indirect lighting, the dirt on the room surfaces may affect the quality of light. A reduction in the reflection factor due to dirt has less effect in a direct system than in an indirect or partly indirect system. The necessity for cleaning or refinishing room surfaces varies with conditions. In areas where the dirt sticks to the surface, walls and ceilings should be reconditioned once or twice a year. Where the dirt condition is less severe or where air-cleaing systems are employed, room surfaces may be permitted to go several years between servicings.

Lumen Method of Lighting Design

Introduction

The following characteristics of designing a good lighting system have been discussed: the quality of light; the quantity of light; luminaire classification; illumination systems; and the maintenance of luminaires, room surfaces, and light sources.

There are two types of calculations that can be used in designing a lighting system. One is the lumen method; the other is the point-by-point method. The lumen method is appropriate when talking about generalized lighting only. It is a way for computing the average illumination throughout the entire room. The procedure is not very good when general localized or supplementary lighting is used. In these cases, one must compute the illumination at the point where the actual seeing task is located. The average illumination throughout the room is meaningless in this case. In the case of generalized localized lighting or supplementary lighting, the point-by-point method is used to calculate the quantity of illumination. The point-by-point method will not be discussed in this text.

The first step in the lumen method is to analyze the seeing task and the working environment. One should ask himself the following questions:

1. How should the task be portrayed by the light?
2. Should the lighting be diffuse or directional or some combination of both?
3. Are shadows important?
4. Is color important?
5. What is the area atmosphere and, therefore, the type of maintenance characteristics that will be needed?
6. What are the economics of the lighting system?

From the answers to the above questions, one can determine the following two things:

1. What level of illumination is needed for the task. (This can be determined by looking at the recommended standards.)
2. The type of luminaires that are needed (that is, direct, indirect, and the required maintenance considerations).

Once the type of luminaires that are going to be used and the amount of illumination needed have been determined, then it is possible to calculate the number of luminaires needed to produce that illumination using the technique that follows.

The Formula

The lumen method is based on the definition of a footcandle equaling one lumen per square foot; thus

$$\text{Footcandles} = \frac{\text{Lumens striking area}}{\text{Square feet of area}}$$

By knowing the initial lumen output of each lamp (published by the lamp manufacturer), the number of lamps installed in the area, and the square feet of area, one can calculate the lumens per square foot generated initially in an area. However, this value differs from the footcandles in the area. This difference occurs because some lumens are absorbed in the luminaire and also because of such factors as dirt on the luminaire and the gradual depreciation in lumen output of the lamp. (Recall that fluorescent lamps operate at only about 75 percent of their original output at the end of their life.) These factors plus others are taken into consideration in the lumen method formula which is as follows:

$$\text{Footcandles} = \frac{\text{Lamps per Luminaire x Lumens per Lamp x Coefficient of Utilization x Light Loss Factor}}{\text{Area per Luminaire}}$$

By manipulating this equation, one can determine the number of luminaires needed. This is as follows:

$$\text{Number of Luminaires} = \frac{\text{Footcandles x Area}}{\text{Lamps per Luminaire x Lumens per lamp x Coefficient of Utilization x Light Loss Factor}}$$

Or one can calculate the number of lamps needed:

$$\text{Number of Lamps} = \frac{\text{Footcandles x Area}}{\text{Lumens per lamp x Coefficient of Utilization x Light Loss Factor}}$$

And the number of luminaires can be computed as follows:

$$\text{Number of Luminaires} = \frac{\text{Number of Lamps}}{\text{Lamps per Luminaire}}$$

Knowing the type of luminaires and the number or quantity of light needed, the next step is to use the formula; that is, to apply the formula to the problem to determine the number of luminaires that are needed to cover the area. To use the formula, it is necessary for the user to understand conceptually some of the quantities in it; for example, the coefficient of utilization and the light loss factor.

Coefficient of Utilization

The coefficient of utilization is the ratio of the lumens reaching the work area (assume a horizontal plane 30 inches above the floor) to the total lumens generated by the lamps. It is a factor that takes into account the efficiency and distribution of the luminaires, luminaire mounting height, room proportions, and reflectance of walls, ceilings, and floors. (NOTE: Because of multiple reflections within a room, some light passes downward through the imaginary work plane more than once. Under some circumstances, this may cause the coefficient of utilization to be larger than 1.)

In general, the higher and narrower the room, the larger the percentage of light absorbed by the walls and the lower the coefficient of utilization. Rooms are classified according to shape by ten room cavity ratio numbers. The room cavity ratio is computed using the following formula:

$$\text{Room cavity ratio} = \frac{5h(\text{room length} + \text{room width})}{\text{room length} \times \text{room width}}$$

where h is the height of the cavity.

A more conveniently used formula is the following:

$$\text{Room cavity ratio} = \frac{10h}{\text{room width}} \times \text{Gaysunas Ratio}$$

The gaysunas ratio comprehends the influence of room length and varies with the ratio of the room length to the room width. The gaysunas number is picked up from Table 5.3.4.

Table 5.3.4

GAYSUNAS RATIO

Room Length / Room Width	Gaysunas Ratio
1.00	1.0
1.25	9/10
1.50	5/6
2.00	3/4
2.50	7/10
3.00	2/3
4.00	5/8
5.00	6/10
Infinity	1/2

Source: Westinghouse Lighting Handbook

One must compute the room cavity ratio before looking up the coefficient of utilization. A room can be broken up into three cavity areas: the ceiling cavity area, the distance between the ceiling and the luminaire plane; the room cavity area, the distance between the luminaire plane and the work plane; and the floor cavity area, the distance between the floor and the work plane.

In effect, then there can be a ceiling cavity ratio, a room cavity ratio, and a floor cavity ratio. All these cavity ratios are computed using the formula given previously.

Assume a room 20 feet by 40 feet by 12 feet high with the luminaires installed 2 feet from the ceiling and the work plane 2 1/2 feet from the floor. The ceiling cavity ratio would be equal to

$$\text{Ceiling cavity ratio} = \frac{10h}{\text{room width}} \times \text{Gaysunas ratio}$$

where h is the distance between the ceiling and the luminaire plane; in this case, 2 feet.

From the table of gaysunas ratios, the gaysunas ratio for room length/room width is 3/4. Substituting 2 feet for h and 3/4 for the gaysunas ratio in the formula above, the ceiling cavity ratio would be equal to

$$\text{Ceiling cavity ratio} = \frac{10 \times 2\text{ ft}}{20\text{ ft}}(3/4)$$

$$= 0.75$$

The floor cavity ratio would be equal to

$$\text{Floor cavity ratio} = \frac{10h}{\text{room width}} \times \text{Gaysunas ratio}$$

where h is the distance of the work plane from the floor; in this case, 2 1/2 feet. The gaysunas ratio remains the same.

Substituting in the formula, the floor cavity ratio would be equal to

$$\text{Floor cavity ratio} = \frac{10 \times 2\ 1/2\ \text{ft}}{20\ \text{ft}}(3/4)$$

$$= 0.94$$

The room cavity ratio also can be computed using the same formula:

$$\text{Room cavity ratio} = \frac{10h}{\text{room width}} \times \text{Gaysunas ratio}$$

where h equals the distance of the room cavity, the distance between the work plane and the luminaire plane. In this case, h would be 7.5 feet, and the gaysunas ratio would remain the same.

Substituting these values in the formula gives

$$\text{Room cavity ratio} = \frac{10 \times 7.5\ \text{ft}}{20\ \text{ft}}(3/4)$$

$$= 2.81$$

It should be pointed out that tables are available to compute the cavity ratios. One of these tables is shown in Table 5.3.5. The calculations just completed can be determined using this table. For example, from the table for room width 20 feet, room length 40 feet and ceiling cavity 2 feet, the ceiling cavity ratio is equal to about 0.75.

Table 5.3.5

ROOM CAVITY RATIOS

Room Dimensions		Cavity Depth																			
Width	Length	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0	6.0	7.0	8	9	10	11	12	14	16	20	25	30
8	8	1.2	1.9	2.5	3.1	3.7	4.4	5.0	6.2	7.5	8.8	10.0	11.2	12.5	....	....	....	....	....	....	....
	10	1.1	1.7	2.2	2.8	3.4	3.9	4.5	5.6	6.7	7.9	9.0	10.1	11.3	12.4	....	....	....	....	....	....
	14	1.0	1.5	2.0	2.5	3.0	3.4	3.9	4.9	5.9	6.9	7.8	8.8	9.7	10.7	11.7	....	....	....	....	....
	20	0.9	1.3	1.7	2.2	2.6	3.1	3.5	4.4	5.2	6.1	7.0	7.9	8.8	9.6	10.5	12.2	....	....	....	....
	30	0.8	1.2	1.6	2.0	2.4	2.8	3.2	4.0	4.7	5.5	6.3	7.1	7.9	8.7	9.5	11.0	....	....	....	....
	40	0.7	1.1	1.5	1.9	2.3	2.6	3.0	3.7	4.5	5.3	5.9	6.5	7.4	8.1	8.8	10.3	11.8	....	....	....
10	10	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	....	....	....	....	....
	14	0.9	1.3	1.7	2.1	2.6	3.0	3.4	4.3	5.1	6.0	6.9	7.8	8.6	9.5	10.4	12.0	....	....	....	....
	20	0.7	1.1	1.5	1.9	2.3	2.6	3.0	3.7	4.5	5.3	6.0	6.8	7.5	8.3	9.0	10.5	12.0	....	....	....
	30	0.7	1.0	1.3	1.7	2.0	2.3	2.7	3.3	4.0	4.7	5.3	6.0	6.6	7.3	8.0	9.4	10.6	....	....	....
	40	0.6	0.9	1.2	1.6	1.9	2.2	2.5	3.1	3.7	4.4	5.0	5.6	6.2	6.9	7.5	8.7	10.0	12.5	....	....
	60	0.6	0.9	1.2	1.5	1.7	2.0	2.3	2.9	3.5	4.1	4.7	5.3	5.9	6.5	7.1	8.2	9.4	11.7	....	....
12	12	0.8	1.2	1.7	2.1	2.5	2.9	3.3	4.2	5.0	5.8	6.7	7.5	8.4	9.2	10.0	11.7	....	....	....	....
	16	0.7	1.1	1.5	1.8	2.2	2.5	2.9	3.6	4.4	5.1	5.8	6.5	7.2	8.0	8.7	10.2	11.6	....	....	....
	24	0.6	0.9	1.2	1.6	1.9	2.2	2.5	3.1	3.7	4.4	5.0	5.6	6.2	6.9	7.5	8.7	10.0	12.5	....	....
	36	0.6	0.8	1.1	1.4	1.7	1.9	2.2	2.8	3.3	3.9	4.4	5.0	5.5	6.0	6.6	7.8	8.8	11.0	....	....
	50	0.5	0.8	1.0	1.3	1.5	1.8	2.1	2.6	3.1	3.6	4.1	4.6	5.1	5.6	6.2	7.2	8.2	10.2	....	....
	70	0.5	0.7	1.0	1.2	1.5	1.7	2.0	2.4	2.9	3.4	3.9	4.4	4.0	5.4	5.8	6.8	7.8	9.7	12.2	....
14	14	0.7	1.1	1.4	1.8	2.1	2.5	2.9	3.6	4.3	5.0	5.7	6.4	7.1	7.8	8.5	[illegible]	11.4	....	....	....
	20	0.6	0.9	1.2	1.5	1.8	2.1	2.4	3.0	3.6	4.2	4.9	5.5	6.1	6.7	7.3	8.6	9.8	12.3	....	....
	30	0.5	0.8	1.0	1.3	1.6	1.8	2.1	2.6	3.1	3.7	4.2	4.7	5.2	5.8	6.3	7.3	8.4	10.5	....	....
	42	0.5	0.7	1.0	1.2	1.4	1.7	1.9	2.4	2.9	3.3	3.8	4.3	4.7	5.2	5.7	6.7	7.6	9.5	11.9	....
	60	0.4	0.7	0.9	1.1	1.3	1.5	1.8	2.2	2.6	3.1	3.5	3.9	4.4	4.8	5.2	6.1	7.0	8.8	10.9	....
	90	0.4	0.6	0.8	1.0	1.2	1.4	1.6	2.0	2.5	2.9	3.3	3.7	4.1	4.5	5.0	5.8	6.6	8.3	10.3	12.4
17	17	0.6	0.9	1.2	1.5	1.8	2.1	2.3	2.9	3.5	4.1	4.7	5.3	5.9	6.5	7.0	8.2	9.4	11.7	....	....
	25	0.5	0.7	1.0	1.2	1.5	1.7	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	7.0	8.0	10.0	12.5	....
	35	0.4	0.7	0.9	1.1	1.3	1.5	1.7	2.2	2.6	3.1	3.5	3.9	4.4	4.8	5.2	6.1	7.0	8.7	10.9	....
	50	0.4	0.6	0.8	1.0	1.2	1.4	1.6	2.0	2.4	2.8	3.1	3.5	3.9	4.3	4.5	5.4	6.2	7.7	9.7	11.6
	80	0.4	0.5	0.7	0.9	1.1	1.2	1.4	1.8	2.1	2.5	2.9	3.3	3.6	4.0	4.3	5.1	5.8	7.2	9.0	10.9
	120	0.3	0.5	0.7	0.8	1.0	1.2	1.3	1.7	2.0	2.3	2.7	3.0	3.4	3.7	4.0	4.7	5.4	6.7	8.4	10.1
20	20	0.5	0.7	1.0	1.2	1.5	1.7	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	7.0	8.0	10.0	12.5	....
	30	0.4	0.6	0.8	1.0	1.2	1.5	1.7	2.1	2.5	2.9	3.3	3.7	4.1	4.5	4.9	5.8	6.6	8.2	10.3	12.4
	45	0.4	0.5	0.7	0.9	1.1	1.3	1.4	1.8	2.2	2.5	2.9	3.3	3.6	4.0	4.3	5.1	5.8	7.2	9.1	10.9
	60	0.3	0.5	0.7	0.8	1.0	1.2	1.3	1.7	2.0	2.3	2.7	3.0	3.4	3.7	4.0	4.7	5.4	6.7	8.4	10.1
	90	0.3	0.5	0.6	0.8	0.9	1.1	1.2	1.5	1.8	2.1	2.4	2.7	3.0	3.3	3.6	4.2	4.8	6.0	7.5	9.0
	150	0.3	0.4	0.6	0.7	0.8	1.0	1.1	1.4	1.7	2.0	2.3	2.6	2.9	3.2	3.4	4.0	4.6	5.7	7.2	8.6
24	24	0.4	0.6	0.8	1.0	1.2	1.5	1.7	2.1	2.5	2.9	3.3	3.7	4.1	4.5	5.0	5.8	6.7	8.2	10.3	12.4
	32	0.4	0.5	0.7	0.9	1.1	1.3	1.5	1.8	2.2	2.6	2.9	3.3	3.6	4.0	4.3	5.1	5.8	7.2	9.0	11.0
	50	0.3	0.5	0.6	0.8	0.9	1.1	1.2	1.5	1.8	2.2	2.5	2.8	3.1	3.4	3.7	4.4	5.0	6.2	7.8	9.4
	70	0.3	0.4	0.6	0.7	0.8	1.0	1.1	1.4	1.7	2.0	2.2	2.5	2.8	3.0	3.3	3.8	4.4	5.5	6.9	8.2
	100	0.3	0.4	0.5	0.6	0.8	0.9	1.0	1.3	1.6	1.8	2.1	2.4	2.6	2.9	3.1	3.7	4.2	5.2	6.5	7.9
	160	0.2	0.4	0.5	0.6	0.7	0.8	1.0	1.2	1.4	1.7	1.9	2.1	2.4	2.6	2.8	3.3	3.8	4.7	5.9	7.1

Source: Westinghouse Lighting Handbook

The ceiling cavity ratio is used to look up the coefficient of utilization. However, before the room cavity ratio can be used for this purpose, the reflectance of the ceiling and of the walls must be known. There are two ceiling reflecting values that are importance. The actual reflectance of the ceiling and the effective ceiling reflectance. The effective ceiling reflectance is actually an adjustment of the actual ceiling reflectance, using the ceiling cavity ratio. For example, a room is 20 feet by 40 feet by 12 feet high, the actual ceiling reflectance is 80 percent, and the reflectance of the walls is 50 percent. Although the actual ceiling reflectance is 80 percent, this must be adjusted for the fact that the lights will be installed 2 feet from the ceiling. This will change the reflectance. To compute the effective ceiling reflectance, a table such as the one provided in Table 5.3.6 must be used. For the example where the ceiling cavity ratio is 0.75 and the actual ceiling reflectance is 80%--which on the table is called the base reflectance--and the wall reflectance is 50%, the effective ceiling reflectance would be between 69% and 71%, or about 69.68%.

Table 5.3.6

EFFECTIVE CAVITY REFLECTANCE

EFFECTIVE CAVITY REFLECTANCES

Base Refl. % 90

Cavity Ratio \ Wall Refl. %	90	80	70	50	30	10	0
0.2	89	88	88	86	85	84	82
0.4	88	87	86	84	81	79	76
0.6	87	86	84	80	77	74	73
0.8	87	85	82	77	73	69	67
1.0	86	83	80	75	69	64	62
1.5	85	80	76	68	51	55	51
2.0	83	77	72	62	53	47	43
2.5	82	75	68	57	47	40	36
3.0	80	72	64	52	42	34	30
3.5	79	70	61	48	37	31	26
4.0	77	69	58	44	33	25	22
5.0	75	59	53	38	28	20	16
6.0	73	61	49	34	24	16	11
8.0	68	55	42	27	18	12	06
10.0	65	51	36	22	15	09	04

Base Refl. % 80

Cavity Ratio \ Wall Refl. %	90	80	70	50	30	10	0
0.2	79	78	78	77	76	74	72
0.4	79	77	76	74	72	70	68
0.6	78	76	75	71	68	65	63
0.8	78	75	73	69	65	61	57
1.0	77	74	72	67	62	57	55
1.5	75	72	68	61	54	49	46
2.0	74	69	64	56	48	41	38
2.5	73	67	61	51	42	35	32
3.0	72	65	58	47	37	30	27
3.5	71	63	55	43	33	26	24
4.0	70	61	53	40	30	22	20
5.0	68	58	48	35	25	18	14
6.0	66	55	44	31	22	15	10
8.0	62	50	38	25	17	11	05
10.0	59	46	33	21	14	08	03

Base Refl. % 70

Cavity Ratio \ Wall Refl. %	90	80	70	50	30	10	0
0.2	70	69	68	67	66	65	64
0.4	69	68	67	65	63	61	58
0.6	69	67	65	63	59	57	54
0.8	68	66	64	60	56	53	50
1.0	68	65	62	58	53	50	47
1.5	67	62	59	54	46	42	40
2.0	66	60	56	49	40	36	33
2.5	65	60	54	45	36	31	29
3.0	64	58	52	42	32	27	24
3.5	63	57	50	38	29	23	21
4.0	63	55	48	36	26	20	17
5.0	61	52	44	31	22	16	12
6.0	60	51	41	28	19	13	09
8.0	57	46	35	23	15	10	05
10.0	55	43	31	19	12	08	03

Base Refl. % 60

Cavity Ratio \ Wall Refl. %	90	80	70	50	30	10	0
0.2	60	59	59	58	56	55	53
0.4	60	59	59	57	54	52	50
0.6	60	58	57	55	51	50	46
0.8	59	57	56	54	48	46	43
1.0	59	57	55	51	45	43	41
1.5	59	55	52	46	40	37	34
2.0	58	54	50	43	35	31	29
2.5	58	53	47	39	30	25	23
3.0	57	52	46	37	28	23	20
3.5	57	50	44	35	25	20	17
4.0	57	49	42	32	23	18	14
5.0	56	48	40	28	20	14	11
6.0	55	45	37	25	17	11	07
8.0	53	42	33	22	14	08	04
10.0	51	39	29	18	11	07	02

Base Refl. % 50

Cavity Ratio \ Wall Refl. %	90	80	70	50	30	10	0
0.2	50	50	49	48	47	46	44
0.4	50	49	48	47	45	44	42
0.6	50	48	47	45	43	41	38
0.8	50	48	47	44	40	38	36
1.0	50	48	46	43	38	36	34
1.5	50	47	45	40	34	31	26
2.0	50	46	43	37	30	26	24
2.5	50	46	41	35	27	22	21
3.0	50	45	40	32	24	19	17
3.5	50	44	39	30	22	17	15
4.0	50	44	38	28	20	15	12
5.0	50	42	35	25	17	12	09
6.0	50	42	34	23	15	10	06
8.0	49	40	30	19	12	07	03
10.0	47	37	27	17	10	06	02

Base Refl. % 40

Cavity Ratio \ Wall Refl. %	90	80	70	50	30	10	0
0.2	40	40	39	39	38	36	36
0.4	41	40	39	38	36	34	34
0.6	41	40	39	37	34	32	31
0.8	41	40	38	36	33	31	29
1.0	42	30	38	34	32	29	27
1.5	42	39	37	32	28	24	22
2.0	42	39	36	31	25	21	19
2.5	43	39	35	29	23	18	15
3.0	43	39	35	27	21	16	13
3.5	44	39	34	26	20	14	12
4.0	44	38	33	25	18	12	10
5.0	45	38	31	22	15	10	07
6.0	44	37	30	20	13	08	05
8.0	44	35	28	18	11	06	03
10.0	43	34	25	15	08	05	02

Base Refl. % 30

Cavity Ratio \ Wall Refl. %	90	80	70	50	30	10	0
0.2	31	31	30	29	29	28	27
0.4	31	31	30	29	28	26	25
0.6	32	31	30	28	26	25	23
0.8	32	31	30	28	25	23	22
1.0	33	32	30	27	24	22	20
1.5	34	33	30	25	22	18	17
2.0	35	33	29	24	20	16	14
2.5	36	32	29	24	18	14	12
3.0	37	33	29	22	17	12	10
3.5	38	33	29	21	15	10	09
4.0	38	33	28	21	14	09	07
5.0	39	33	28	19	13	08	05
6.0	39	33	27	18	11	06	04
8.0	40	33	26	16	09	04	02
10.0	40	32	24	14	08	03	01

Base Refl. % 20

Cavity Ratio \ Wall Refl. %	90	80	70	50	30	10	0
0.2	21	20	20	20	19	19	17
0.4	22	21	20	20	19	18	16
0.6	23	21	21	19	18	17	15
0.8	24	22	21	19	18	16	14
1.0	25	23	22	19	17	15	13
1.5	26	24	22	18	16	13	11
2.0	28	25	23	18	15	11	09
2.5	29	26	23	18	14	10	08
3.0	30	27	23	17	13	09	07
3.5	32	27	23	17	12	08	05
4.0	33	28	23	17	11	07	07
5.0	35	29	24	16	10	06	04
6.0	36	30	24	16	10	05	02
8.0	37	30	23	15	08	03	01
10.0	37	29	22	13	07	03	01

Base Refl. % 10

Cavity Ratio \ Wall Refl. %	90	80	70	50	30	10	0
0.2	11	11	11	10	10	09	09
0.4	12	11	11	11	10	09	08
0.6	13	13	12	11	10	08	08
0.8	15	14	13	11	10	08	07
1.0	16	14	13	12	10	08	07
1.5	18	16	15	12	10	07	06
2.0	20	18	16	13	09	06	05
2.5	22	20	17	13	09	05	04
3.0	24	21	18	13	09	05	03
3.5	26	22	19	13	09	05	03
4.0	27	23	20	14	09	04	02
5.0	30	25	20	14	08	04	02
6.0	31	26	21	14	08	03	01
8.0	33	27	21	13	07	03	01
10.0	34	28	21	12	07	02	01

Base Refl. % 0

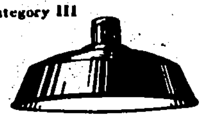
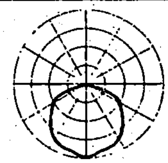
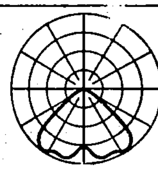
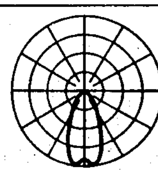
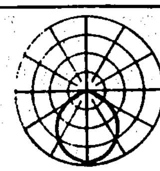
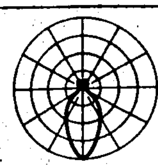
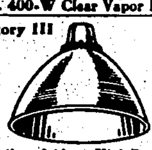
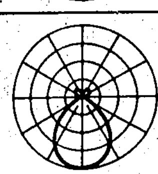
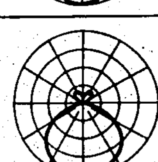
Cavity Ratio \ Wall Refl. %	90	80	70	50	30	10	0
0.2	02	02	02	01	01	00	0
0.4	04	03	03	02	01	00	0
0.6	05	05	04	03	02	01	0
0.8	07	06	05	04	02	01	0
1.0	08	07	06	04	02	01	0
1.5	11	10	08	06	03	01	0
2.0	14	12	10	07	04	01	0
2.5	16	14	12	08	05	02	0
3.0	18	16	13	09	05	02	0
3.5	20	17	15	10	05	02	0
4.0	22	18	15	10	05	02	0
5.0	25	21	17	11	06	02	0
6.0	27	23	18	12	06	02	0
8.0	30	25	20	12	06	02	0
10.0	31	25	20	12	06	02	0

Source: Westinghouse Lighting Handbook

Once the effective ceiling cavity reflectance is known, the coefficient of utilization can be determined from a table, such as is shown in Table 5.3.7. Notice that to look up the coefficient of utilization the following information must be known: the type of luminaire, the type of distribution of that luminaire, the <u>effective</u> ceiling cavity reflectance, the wall reflectance, and the room cavity ratio. For example, using the first luminaire on the table, the coefficient of utilization can be found for an effective ceiling cavity reflectance of 80%, wall reflectance of 50%, and a room cavity ratio (RCR) equal to 5. The coefficient of utilization is 0.50. (Note: The ceiling cavity reflectance in the table refers to the effective ceiling cavity reflectance.) The categories of luminaires as they are indicated on the table will be discussed later.

Table 5.3.7

COEFFICIENTS OF UTILIZATION

LUMINAIRE	DISTRIBUTION	Spacing Not to Exceed	Ceiling Cavity:	80%			50%			10%			0%
			Walls:	50%	30%	10%	50%	30%	10%	50%	30%	10%	0%
			RCR	Coefficients of Utilization									
Category III  Ventilated Dome Reflector	0 ↑ ↓ 79 	1.3 x Mounting Height	1	.85	.82	.79	.79	.77	.75	.73	.72	.71	.69
			2	.74	.69	.65	.70	.66	.62	.65	.62	.59	.58
			3	.65	.60	.54	.62	.57	.53	.57	.54	.51	.49
			4	.58	.51	.46	.55	.49	.45	.51	.47	.44	.42
			5	.50	.44	.38	.47	.42	.37	.45	.40	.36	.35
			6	.44	.38	.33	.43	.36	.32	.40	.35	.32	.30
			7	.40	.33	.28	.38	.33	.28	.36	.32	.27	.26
			8	.36	.29	.24	.34	.28	.24	.32	.27	.23	.22
			9	.33	.25	.20	.31	.25	.20	.29	.24	.20	.18
			10	.29	.22	.18	.28	.22	.18	.26	.21	.18	.17
Category I  R-52 Filament Reflector Lamp Wide Dist.—500- and 750-Watt	0 ↑ ↓ 100 	1.5 x Mounting Height	1	1.08	1.05	1.02	1.01	.99	.97	.94	.93	.91	.89
			2	.98	.93	.89	.93	.89	.86	.88	.85	.82	.80
			3	.89	.83	.78	.85	.80	.76	.80	.76	.73	.71
			4	.81	.74	.68	.77	.72	.67	.73	.69	.65	.64
			5	.73	.66	.60	.70	.64	.59	.56	.62	.58	.56
			6	.67	.59	.53	.64	.58	.52	.61	.56	.52	.50
			7	.60	.52	.47	.58	.51	.46	.55	.50	.46	.45
			8	.54	.46	.40	.52	.45	.40	.49	.44	.40	.38
			9	.48	.40	.35	.46	.39	.35	.44	.38	.34	.33
			10	.43	.36	.30	.42	.35	.30	.40	.34	.30	.28
Category I  R-57 Filament Reflector Lamp Narrow Dist.—500- and 750-Watt	0 ↑ ↓ 100 	.6 x Mounting Height	1	1.10	1.08	1.05	1.04	1.02	1.00	.97	.96	.95	.93
			2	1.02	.98	.94	.97	.94	.91	.91	.89	.88	.86
			3	.95	.90	.85	.91	.87	.83	.86	.83	.81	.79
			4	.88	.82	.78	.85	.80	.76	.81	.77	.75	.73
			5	.82	.76	.71	.79	.74	.70	.76	.72	.69	.67
			6	.77	.70	.66	.74	.69	.65	.72	.68	.64	.63
			7	.71	.65	.61	.69	.64	.60	.67	.63	.60	.58
			8	.66	.60	.56	.65	.59	.55	.63	.58	.55	.54
			9	.62	.55	.51	.60	.55	.51	.59	.54	.50	.49
			10	.58	.51	.47	.56	.51	.47	.55	.50	.46	.45
Category III  Ventilated Porcelain Enamel Low Bay 400-W Phos. Coated Vapor Lamp	0 ↑ ↓ 76 	1.2 x Mounting Height	1	.81	.78	.76	.76	.74	.72	.71	.69	.68	.67
			2	.73	.69	.65	.69	.66	.63	.64	.62	.60	.59
			3	.65	.60	.56	.62	.58	.55	.58	.55	.53	.51
			4	.59	.53	.49	.56	.52	.48	.53	.50	.47	.45
			5	.53	.47	.43	.51	.46	.42	.48	.44	.41	.40
			6	.48	.42	.38	.46	.41	.37	.44	.40	.37	.35
			7	.43	.37	.33	.41	.36	.32	.39	.36	.32	.31
			8	.39	.33	.29	.38	.32	.28	.36	.32	.28	.27
			9	.36	.30	.26	.34	.29	.25	.33	.28	.25	.24
			10	.32	.27	.23	.31	.26	.23	.30	.25	.22	.21
Category III  18" Ventilated Alum. High Bay Conc. Dist. 400-W Clear Vapor Lamp	8 ↑ ↓ 77 	.7 x Mounting Height	1	.93	.90	.88	.85	.83	.82	.76	.75	.74	.72
			2	.86	.82	.79	.79	.77	.74	.72	.70	.69	.67
			3	.79	.75	.71	.74	.70	.68	.68	.65	.64	.62
			4	.74	.69	.65	.69	.65	.62	.64	.61	.59	.57
			5	.68	.63	.59	.64	.60	.57	.60	.57	.54	.53
			6	.63	.58	.54	.60	.56	.52	.56	.53	.50	.49
			7	.59	.53	.49	.56	.51	.48	.52	.49	.46	.45
			8	.55	.49	.45	.52	.47	.44	.49	.45	.43	.41
			9	.50	.45	.41	.48	.43	.40	.45	.42	.39	.38
			10	.47	.41	.38	.45	.40	.37	.42	.38	.36	.35
Category III  18" Ventilated Alum. High Bay Spread Dist. 400-W Coated Vapor Lamp	10 ↑ ↓ 74 	1.2 x Mounting Height	1	.88	.86	.84	.80	.79	.77	.71	.70	.69	.67
			2	.81	.77	.74	.75	.72	.70	.67	.65	.64	.62
			3	.74	.70	.66	.69	.65	.62	.62	.60	.58	.56
			4	.68	.63	.59	.64	.60	.57	.58	.55	.53	.51
			5	.63	.57	.53	.59	.55	.51	.54	.51	.49	.47
			6	.58	.52	.48	.54	.50	.46	.50	.47	.44	.43
			7	.53	.47	.43	.50	.45	.42	.46	.43	.40	.39
			8	.48	.43	.39	.46	.41	.38	.42	.39	.36	.35
			9	.44	.39	.35	.42	.37	.34	.39	.35	.33	.31
			10	.41	.35	.31	.39	.34	.30	.36	.32	.39	.28
Category III  24" Ventilated Porcelain Enamel 1000-W Phosphor Coated Vapor Lamp	11 ↑ ↓ 73 	1.3 x Mounting Height	1	.86	.83	.80	.78	.76	.73	.68	.67	.65	.63
			2	.77	.72	.68	.70	.66	.63	.61	.59	.57	.55
			3	.68	.62	.57	.62	.58	.54	.55	.52	.49	.47
			4	.61	.55	.49	.56	.51	.47	.50	.46	.43	.41
			5	.55	.48	.42	.50	.45	.41	.45	.41	.38	.36
			6	.49	.42	.37	.45	.39	.35	.40	.36	.33	.31
			7	.43	.36	.31	.40	.34	.30	.36	.31	.28	.26
			8	.39	.32	.28	.36	.30	.26	.32	.28	.25	.23
			9	.35	.28	.24	.33	.27	.23	.29	.25	.22	.20
			10	.32	.25	.21	.29	.24	.20	.26	.22	.19	.17

COEFFICIENTS OF UTILIZATION

COEFFICIENTS OF UTILIZATION

Source: Westinghouse Lighting Handbook

Table 5.3.7 (Continued)

COEFFICIENTS OF UTILIZATION

COEFFICIENTS OF UTILIZATION

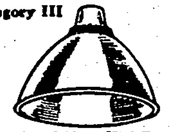
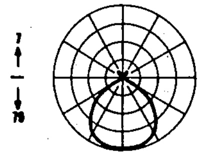
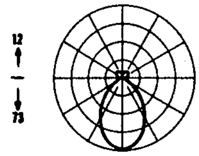
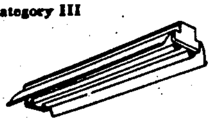
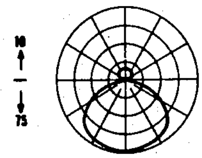
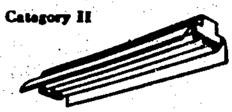
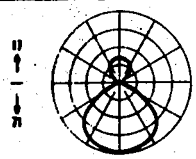
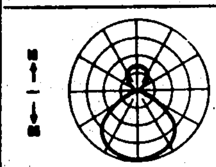
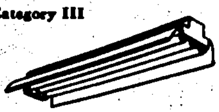
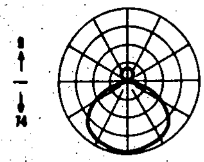
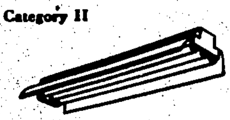
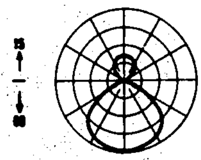
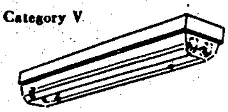
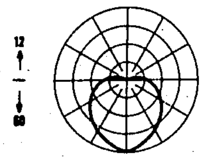
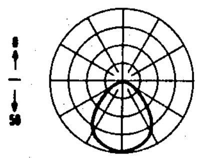
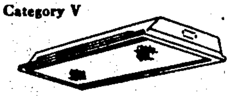
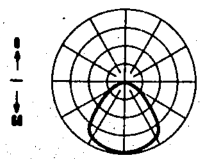
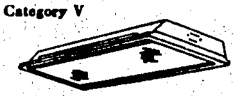
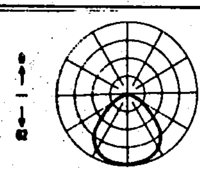
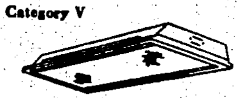
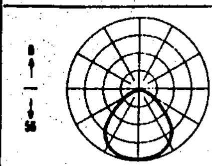
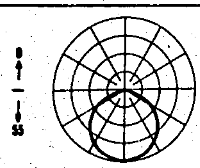
LUMINAIRE	DISTRIBUTION	Spacing Not to Exceed	Reflectances: Ceiling Cavity	80%			50%			10%			0%
			Walls	50%	30%	10%	50%	30%	10%	50%	30%	10%	0%
			RCR	Coefficients of Utilization									
Category III  24" Ventilated Alum. High Bay Spread Dist. 1000-W Phos. Ctd. Vapor Lamp		1.0 x Mounting Height	1	.91	.88	.86	.84	.82	.80	.75	.74	.73	.71
			2	.83	.78	.75	.77	.73	.71	.70	.67	.66	.64
			3	.75	.69	.65	.70	.65	.62	.64	.61	.58	.56
			4	.68	.62	.57	.63	.58	.55	.58	.55	.52	.50
			5	.61	.55	.50	.57	.52	.48	.53	.49	.46	.44
			6	.55	.49	.44	.52	.47	.43	.48	.44	.41	.39
			7	.50	.43	.38	.47	.41	.37	.43	.39	.36	.34
			8	.45	.39	.34	.43	.37	.33	.39	.35	.32	.30
			9	.41	.34	.30	.39	.33	.29	.36	.32	.28	.27
			10	.37	.31	.27	.35	.30	.26	.33	.28	.25	.24
Category III  24" Ventilated Alum. High Bay 1000-W Phos. Coated Vapor Lamp		1.3 x Mounting Height	1	.90	.88	.86	.81	.80	.78	.71	.70	.70	.67
			2	.83	.79	.76	.76	.73	.71	.67	.66	.64	.62
			3	.77	.72	.68	.70	.67	.64	.63	.61	.59	.57
			4	.71	.66	.62	.66	.62	.59	.59	.57	.55	.53
			5	.65	.60	.56	.61	.57	.53	.55	.52	.50	.48
			6	.60	.55	.50	.56	.52	.48	.52	.48	.46	.44
			7	.55	.50	.46	.52	.47	.44	.48	.44	.42	.40
			8	.51	.45	.41	.48	.43	.40	.44	.41	.38	.37
			9	.47	.41	.38	.44	.40	.37	.41	.38	.35	.34
			10	.44	.38	.34	.41	.37	.33	.38	.35	.32	.31
Category III  2 T-12 Lamps—Any Loading For T-10 Lamps—C.U. x 1.02		1.3 x Mounting Height	1	.88	.84	.81	.79	.77	.74	.69	.68	.66	.64
			2	.77	.71	.66	.70	.65	.62	.61	.59	.56	.54
			3	.68	.61	.56	.61	.56	.52	.54	.51	.48	.46
			4	.60	.52	.47	.54	.49	.44	.48	.44	.41	.39
			5	.52	.45	.39	.48	.42	.37	.43	.38	.35	.33
			6	.47	.39	.34	.43	.37	.32	.38	.34	.30	.28
			7	.42	.34	.29	.38	.32	.28	.34	.30	.26	.24
			8	.37	.30	.25	.34	.28	.24	.31	.26	.22	.21
			9	.33	.26	.21	.31	.25	.21	.28	.23	.19	.18
			10	.30	.23	.19	.28	.22	.18	.25	.20	.17	.15
Category II  2 T-12 Lamps—Any Loading For T-10 Lamps—C.U. x 1.02		1.3 x Mounting Height	1	.88	.85	.81	.77	.75	.73	.65	.64	.62	.59
			2	.77	.71	.67	.68	.64	.60	.57	.55	.53	.50
			3	.68	.61	.56	.60	.55	.51	.51	.48	.45	.42
			4	.60	.53	.47	.53	.48	.43	.45	.42	.38	.36
			5	.53	.45	.40	.47	.41	.36	.40	.36	.33	.30
			6	.47	.39	.34	.42	.36	.31	.36	.31	.28	.26
			7	.42	.34	.29	.38	.31	.27	.32	.28	.24	.22
			8	.38	.30	.25	.34	.28	.23	.29	.24	.21	.19
			9	.34	.26	.22	.30	.24	.20	.26	.21	.18	.16
			10	.31	.24	.19	.26	.22	.18	.24	.19	.16	.14
Category II  2 T-12 Lamps—Any Loading Center Shield For T-10 Lamps—C.U. x 1.02		1.3 x Mounting Height	1	.84	.81	.78	.74	.72	.70	.61	.60	.59	.56
			2	.75	.70	.65	.66	.62	.59	.55	.53	.51	.48
			3	.66	.60	.56	.59	.54	.51	.49	.47	.44	.42
			4	.59	.52	.47	.52	.47	.43	.44	.41	.38	.36
			5	.52	.45	.40	.46	.41	.37	.39	.36	.33	.31
			6	.47	.40	.35	.42	.36	.32	.36	.32	.29	.27
			7	.42	.35	.30	.37	.32	.28	.32	.28	.25	.23
			8	.38	.31	.26	.34	.28	.24	.29	.25	.22	.20
			9	.34	.27	.22	.30	.25	.21	.26	.22	.19	.17
			10	.31	.24	.20	.27	.22	.18	.23	.19	.17	.15
Category III  3 T-12 Lamps—430 or 800 MA For T-10 Lamps—C.U. x 1.02		1.3 x Mounting Height	1	.86	.83	.80	.78	.76	.73	.69	.67	.66	.64
			2	.75	.70	.66	.69	.65	.61	.61	.58	.56	.54
			3	.67	.60	.55	.61	.56	.52	.54	.51	.48	.46
			4	.59	.52	.47	.54	.49	.44	.48	.45	.41	.39
			5	.52	.45	.39	.48	.42	.38	.43	.39	.35	.33
			6	.46	.39	.34	.43	.37	.32	.38	.34	.30	.28
			7	.41	.34	.29	.38	.32	.28	.34	.30	.26	.25
			8	.37	.30	.25	.34	.28	.24	.31	.26	.23	.21
			9	.33	.26	.22	.31	.25	.21	.28	.23	.20	.18
			10	.30	.23	.19	.28	.22	.18	.25	.21	.17	.16
Category II  3 T-12 Lamps—430 or 800 MA For T-10 Lamps—C.U. x 1.02		1.3 x Mounting Height	1	.85	.82	.79	.76	.73	.71	.64	.63	.62	.59
			2	.75	.70	.65	.67	.63	.59	.57	.55	.52	.50
			3	.66	.60	.55	.59	.54	.50	.51	.48	.45	.42
			4	.59	.52	.46	.52	.47	.43	.45	.41	.38	.36
			5	.51	.44	.39	.46	.40	.36	.40	.36	.33	.30
			6	.46	.39	.33	.41	.35	.31	.36	.31	.28	.26
			7	.41	.34	.29	.37	.32	.27	.32	.28	.24	.23
			8	.37	.30	.25	.33	.27	.23	.29	.24	.21	.19
			9	.33	.26	.21	.30	.24	.20	.26	.21	.18	.16
			10	.30	.23	.19	.27	.21	.18	.23	.19	.16	.14

Table 5.3.7 (Continued)

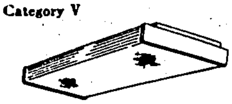
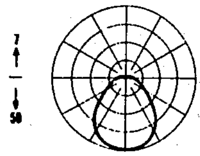
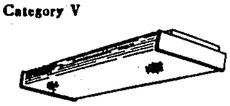
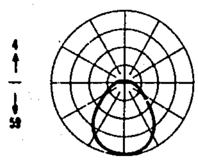
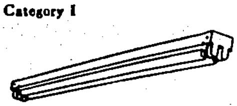
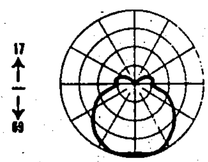
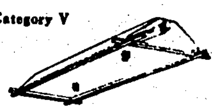
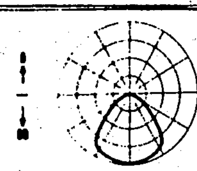
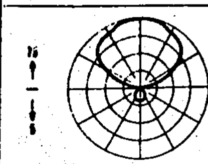
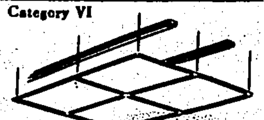
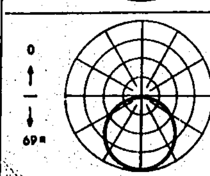
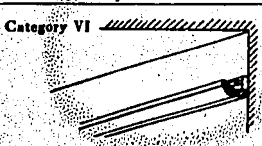
COEFFICIENTS OF UTILIZATION

COEFFICIENTS OF UTILIZATION													
LUMINAIRE	DISTRIBUTION	Spacing Not to Exceed	Reflectances										
			Ceiling Cavity	80%			50%			10%			0%
			Walls	50%	30%	10%	50%	30%	10%	50%	30%	10%	0%
			RCR	Coefficients of Utilization									
Category V  2 T-12 Lamps—430 MA For 800 MA—C.U. x .96		1.5 x Mounting Height	1	.70	.66	.63	.62	.59	.57	.52	.51	.49	.47
			2	.60	.54	.50	.53	.49	.46	.45	.42	.40	.37
			3	.52	.46	.41	.46	.41	.38	.39	.36	.33	.31
			4	.46	.39	.34	.41	.36	.32	.35	.31	.28	.26
			5	.40	.33	.28	.36	.30	.26	.31	.27	.24	.22
			6	.36	.29	.24	.32	.26	.22	.27	.23	.20	.18
			7	.32	.25	.21	.29	.23	.19	.25	.21	.17	.16
			8	.29	.22	.18	.26	.20	.17	.22	.18	.15	.13
			9	.26	.19	.15	.23	.18	.14	.20	.16	.13	.11
			10	.23	.17	.13	.21	.16	.12	.18	.14	.11	.10
Category V  2 T-12 Lamps—430 MA Prismatic Lens 1' Wide—For T-10 Lamps—C.U. x 1.02		1.2 x Mounting Height	1	.63	.61	.59	.59	.58	.56	.55	.54	.53	.52
			2	.57	.54	.51	.54	.51	.49	.50	.49	.47	.46
			3	.51	.48	.44	.49	.46	.43	.46	.44	.42	.41
			4	.46	.42	.39	.44	.41	.38	.42	.39	.37	.36
			5	.42	.37	.34	.40	.36	.34	.38	.35	.33	.32
			6	.38	.34	.30	.37	.33	.30	.35	.32	.29	.28
			7	.35	.30	.27	.33	.29	.27	.32	.29	.26	.25
			8	.31	.27	.24	.30	.26	.23	.29	.26	.23	.22
			9	.28	.24	.21	.27	.23	.20	.26	.23	.20	.19
			10	.26	.21	.18	.25	.21	.18	.24	.20	.18	.17
Category V  2 T-12 Lamps—430 MA Prismatic Lens 2' Wide—For T-10 Lamps—C.U. x 1.01		1.2 x Mounting Height	1	.73	.71	.68	.69	.67	.66	.64	.62	.61	.60
			2	.66	.62	.59	.62	.59	.57	.58	.56	.55	.53
			3	.59	.55	.51	.56	.53	.50	.53	.50	.48	.47
			4	.53	.48	.45	.51	.47	.44	.48	.45	.43	.41
			5	.48	.43	.39	.46	.42	.39	.44	.40	.38	.36
			6	.44	.38	.34	.42	.37	.34	.40	.36	.33	.32
			7	.39	.34	.30	.38	.33	.30	.36	.32	.30	.28
			8	.36	.30	.26	.34	.30	.26	.33	.29	.26	.25
			9	.32	.27	.23	.31	.26	.23	.29	.25	.23	.21
			10	.29	.24	.20	.28	.23	.20	.27	.23	.20	.19
Category V  4 T-12 Lamps—430 MA Prismatic Lens 2' Wide—For T-10 Lamps—C.U. x 1.02		1.2 x Mounting Height	1	.66	.64	.62	.62	.61	.59	.58	.57	.56	.55
			2	.60	.56	.53	.56	.54	.52	.53	.51	.49	.48
			3	.54	.50	.46	.51	.48	.45	.48	.46	.44	.43
			4	.49	.44	.41	.46	.43	.40	.44	.41	.39	.38
			5	.44	.39	.35	.42	.38	.35	.40	.37	.34	.33
			6	.40	.35	.31	.38	.34	.31	.36	.33	.31	.29
			7	.36	.31	.28	.35	.30	.27	.33	.30	.27	.26
			8	.32	.28	.24	.31	.27	.24	.30	.26	.24	.23
			9	.29	.24	.21	.28	.24	.21	.27	.23	.21	.20
			10	.27	.22	.19	.26	.23	.19	.25	.21	.18	.17
Category V  6 T-12 Lamps—430 MA Prismatic Lens 2' Wide—For T-10 Lamps—C.U. x 1.03		1.2 x Mounting Height	1	.60	.58	.56	.56	.55	.54	.52	.51	.50	.49
			2	.54	.51	.48	.51	.49	.47	.48	.46	.45	.44
			3	.49	.45	.42	.46	.43	.41	.44	.41	.40	.39
			4	.44	.40	.37	.42	.39	.36	.40	.37	.35	.34
			5	.40	.35	.32	.38	.35	.32	.36	.33	.31	.30
			6	.36	.32	.29	.35	.31	.28	.33	.30	.28	.27
			7	.33	.28	.25	.32	.28	.25	.30	.27	.25	.24
			8	.30	.25	.22	.28	.25	.22	.27	.24	.22	.21
			9	.27	.22	.19	.26	.22	.19	.25	.21	.19	.18
			10	.24	.20	.17	.23	.20	.17	.22	.19	.17	.16
Category V  8 T-12 Lamps—430 MA Prismatic Lens 4' x 4'—For T-10 Lamps—C.U. x 1.02		1.3 x Mounting Height	1	.59	.57	.55	.55	.54	.52	.51	.50	.49	.48
			2	.53	.50	.47	.50	.48	.46	.47	.45	.44	.43
			3	.48	.44	.41	.45	.42	.40	.43	.40	.39	.38
			4	.43	.39	.36	.41	.38	.35	.39	.36	.34	.33
			5	.39	.35	.31	.37	.34	.31	.35	.32	.30	.29
			6	.35	.31	.28	.34	.30	.28	.32	.29	.27	.26
			7	.32	.28	.25	.31	.27	.25	.29	.26	.24	.23
			8	.29	.25	.22	.28	.24	.22	.27	.24	.21	.20
			9	.26	.22	.19	.25	.21	.19	.24	.21	.19	.18
			10	.24	.20	.17	.23	.19	.17	.22	.19	.17	.16
Category V  4 T-12 Lamps—430 MA Prismatic Lens 2' Wide—For T-10 Lamps—C.U. x 1.02		1.2 x Mounting Height	1	.56	.54	.52	.52	.50	.49	.47	.46	.45	.44
			2	.50	.47	.45	.47	.44	.42	.43	.41	.40	.39
			3	.45	.41	.38	.42	.39	.37	.39	.37	.35	.34
			4	.41	.37	.34	.38	.35	.32	.35	.33	.31	.30
			5	.37	.32	.29	.34	.31	.28	.32	.29	.27	.26
			6	.33	.29	.26	.31	.28	.25	.29	.27	.24	.23
			7	.30	.26	.23	.29	.25	.22	.27	.24	.22	.20
			8	.27	.23	.20	.26	.22	.20	.24	.21	.19	.18
			9	.25	.20	.18	.23	.20	.17	.22	.19	.17	.16
			10	.22	.18	.16	.21	.18	.15	.20	.17	.15	.14

COEFFICIENTS OF UTILIZATION

Table 5.3.7 (Continued)

COEFFICIENTS OF UTILIZATION

COEFFICIENTS OF UTILIZATION												
LUMINAIRE	DISTRIBUTION	Spacing Not to Exceed	Ceiling Cavity (Reflectances)	80%			70%			50%		
			Walls	50%	30%	10%	50%	30%	10%	50%	30%	10%
			RCR	Coefficients of Utilization								
Category V  2 T-12 Lamps—430 MA 1' Wide Prismatic Wrap-Around		1.2 x Mounting Height	1	.68	.65	.63	.65	.63	.61	.61	.60	.58
			2	.60	.56	.53	.58	.55	.52	.55	.52	.49
			3	.54	.49	.45	.52	.48	.45	.50	.46	.43
			4	.49	.43	.40	.47	.43	.39	.45	.41	.38
			5	.44	.38	.34	.43	.38	.34	.40	.36	.33
			6	.40	.34	.30	.39	.34	.30	.37	.32	.29
			7	.36	.31	.27	.35	.30	.26	.33	.29	.26
			8	.32	.27	.24	.32	.27	.23	.30	.26	.23
			9	.29	.24	.21	.29	.24	.20	.27	.23	.20
			10	.27	.22	.18	.26	.21	.18	.25	.21	.18
Category V  4 T-12 Lamps—430 MA 2' Wide Prismatic Wrap-Around		1.3 x Mounting Height	1	.66	.64	.61	.64	.62	.60	.61	.59	.57
			2	.59	.55	.52	.57	.54	.51	.55	.52	.49
			3	.53	.48	.45	.52	.48	.44	.49	.46	.43
			4	.48	.43	.39	.47	.42	.39	.45	.41	.38
			5	.43	.38	.34	.42	.37	.34	.40	.36	.33
			6	.39	.34	.30	.38	.34	.30	.36	.32	.29
			7	.35	.30	.26	.34	.30	.26	.33	.29	.26
			8	.32	.27	.23	.31	.26	.23	.30	.26	.23
			9	.28	.24	.20	.28	.23	.20	.27	.23	.20
			10	.26	.21	.18	.25	.21	.18	.25	.20	.17
Category I  2 Lamp Strip—Any Loading		1.6 x Mounting Height	1	.83	.79	.75	.79	.76	.72	.73	.70	.67
			2	.71	.65	.60	.68	.62	.57	.62	.58	.54
			3	.62	.55	.49	.59	.53	.47	.55	.49	.44
			4	.55	.47	.41	.52	45	.39	.48	.42	.37
			5	.48	.40	.34	.46	.38	.33	.42	.36	.31
			6	.43	.35	.29	.41	.33	.28	.38	.31	.26
			7	.38	.30	.25	.36	.29	.24	.34	.27	.23
			8	.34	.26	.21	.33	.25	.21	.30	.24	.19
			9	.30	.23	.18	.30	.23	.18	.27	.21	.17
			10	.28	.21	.16	.27	.20	.15	.25	.19	.15
Category V  1 Lamp—Any Loading 2' Wide, 1' Deep Prismatic Lens		1.2 x Mounting Height	1	.64	.62	.60	.63	.61	.59	.60	.59	.57
			2	.58	.55	.52	.57	.54	.51	.55	.52	.50
			3	.52	.48	.45	.51	.47	.44	.49	.46	.44
			4	.47	.42	.39	.46	.42	.39	.45	.41	.38
			5	.42	.37	.34	.42	.37	.34	.40	.36	.34
			6	.38	.33	.30	.38	.33	.30	.37	.32	.30
			7	.35	.30	.26	.34	.30	.26	.33	.29	.26
			8	.31	.26	.23	.31	.26	.23	.30	.26	.23
			9	.28	.23	.20	.28	.23	.20	.27	.23	.20
			10	.26	.21	.18	.25	.21	.18	.25	.21	.18
Category VI  2 Lamp—Any Loading Opaque Sides		1.5 x Mounting Height	1	.68	.65	.62	.59	.56	.54	.42	.41	.39
			2	.59	.54	.51	.51	.48	.44	.37	.35	.32
			3	.52	.46	.42	.45	.40	.37	.32	.29	.27
			4	.46	.40	.35	.40	.35	.31	.28	.25	.23
			5	.40	.34	.30	.35	.30	.26	.25	.22	.20
			6	.36	.30	.26	.31	.27	.23	.22	.20	.17
			7	.32	.26	.22	.28	.23	.19	.20	.17	.14
			8	.29	.23	.19	.25	.20	.17	.18	.15	.13
			9	.26	.20	.17	.23	.18	.15	.17	.13	.11
			10	.24	.18	.15	.21	.16	.13	.15	.12	.10
Category VI  Luminous Ceiling—50% Transmission 80% Cavity Reflectance		1.5 to 2.0 x Mounting Height above Diffuser	1	①For cavities that are painted white use 70% effective ceiling cavity reflectance. ②For cavities that are obstructed or have lower reflectances use 50% effective ceiling cavity reflectance.			.60	.58	.56	.58	.56	.54
			2				.53	.49	.45	.51	.47	.43
			3				.47	.42	.37	.45	.41	.36
			4				.41	.36	.32	.39	.35	.31
			5				.37	.31	.27	.35	.30	.26
			6				.33	.27	.23	.31	.26	.23
			7				.29	.24	.20	.28	.23	.20
			8				.26	.21	.18	.25	.20	.17
			9				.23	.19	.15	.23	.18	.15
			10				.21	.17	.13	.21	.16	.13
Category VI  Cove Without Reflector	Cove 12 to 18 inches below ceiling. Reflectors with fluorescent lamps increase coefficients of utilization 5 to 10%.		1	.42	.40	.39	.36	.35	.33	.25	.24	.23
			2	.37	.34	.32	.32	.29	.27	.22	.20	.19
			3	.32	.29	.26	.28	.25	.23	.19	.17	.16
			4	.29	.25	.22	.25	.22	.19	.17	.15	.13
			5	.25	.21	.18	.22	.19	.16	.15	.13	.11
			6	.23	.19	.16	.20	.16	.14	.14	.12	.10
			7	.20	.17	.14	.17	.14	.12	.12	.10	.09
			8	.18	.15	.12	.16	.13	.10	.11	.09	.08
			9	.17	.13	.10	.15	.11	.09	.10	.08	.07
			10	.15	.12	.09	.13	.10	.08	.09	.07	.06

COEFFICIENTS OF UTILIZATION

COEFFICIENTS OF UTILIZATION

For ceiling mounted luminaires or recessed luminaires, the ceiling cavity reflectance is the same as the actual ceiling reflectance; that is, one does not need to compute the ceiling cavity ratio and adjust the ceiling reflectance by the ceiling cavity ratio. But for suspended luminaires, it is necessary to determine the effective ceiling cavity reflectance as has been done in the example.

NOTE: The coefficients of utilization determined in the examples presented will be applicable for areas having 20 percent floor cavity reflectance. If the actual floor cavity reflectance differs substantially from 20 percent, a correction may be necessary depending upon the accuracy desired. Correction factors for floor cavity reflectance of 10 percent and 30 percent are given in Table 5.3.8. The effective floor cavity reflectance is determined in the same manner and using the same tables as were used in determining effective ceiling cavity reflectance. For 30 percent effective floor cavity reflectance, multiply by the appropriate factor found in the table. For 10 percent effective floor cavity reflectance, divide by the appropriate factor found in the table.

In the calculations included in this chapter, correction will not be made for floor cavity reflectance. The floor cavity reflectance will be assumed to be 20 percent. However, you should be aware that such adjustments can and should be made, depending upon the accuracy that you desire.

Table 5.3.8

FACTOR FOR EFFECTIVE FLOOR CAVITY REFLECTANCES
OTHER THAN 20 PERCENT

Percent Effective Ceiling Cavity Reflectance	80			70			50			10		
Percent Wall Reflectance	50	30	10	50	30	10	50	30	10	50	30	10
Room Cavity Ratio												
1	1.08	1.08	1.07	1.07	1.06	1.06	1.05	1.04	1.04	1.01	1.01	1.01
2	1.07	1.06	1.05	1.06	1.05	1.04	1.04	1.03	1.03	1.01	1.01	1.01
3	1.05	1.04	1.03	1.05	1.04	1.03	1.03	1.03	1.02	1.01	1.01	1.01
4	1.05	1.03	1.02	1.04	1.03	1.02	1.03	1.02	1.02	1.01	1.01	1.00
5	1.04	1.03	1.02	1.03	1.02	1.02	1.02	1.02	1.01	1.01	1.01	1.00
6	1.03	1.02	1.01	1.03	1.02	1.01	1.02	1.02	1.01	1.01	1.01	1.00
7	1.03	1.02	1.01	1.03	1.02	1.01	1.02	1.01	1.01	1.01	1.01	1.00
8	1.03	1.02	1.01	1.02	1.02	1.01	1.02	1.01	1.01	1.01	1.01	1.00
9	1.02	1.01	1.01	1.02	1.01	1.01	1.02	1.01	1.01	1.01	1.01	1.00
10	1.02	1.01	1.01	1.02	1.01	1.01	1.02	1.01	1.01	1.01	1.01	1.00

Source: Westinghouse Lighting Handbook

The Light Loss Factor

The other factor in the formula that needs to be explained is the light loss factor.

From the day the new lighting is energized, the illumination is in the process of continually changing as the lamp ages, as the luminaire accumulates dirt and dust, and as the effect of other contributing factors is felt. Some contributing loss factors may, in some instances, tend to increase the illumination; but their net effect is nearly always to cause a decrease in illumination. The final light loss factor is the product of all contributing loss factors; it is the ratio of the illumination when it reaches its lowest level at the task just before corrective action is taken to the initial level if none of the contributing loss factors were considered. In this context, the initial illumination is that which would be produced by lamps producing initially rated lumens. (NOTE: Lamp manufacturers rate filament lamps in accordance with lumen output when the lamp is new. Vapor discharge lamps, including fluorescent, mercury, and other common types, are rated in accordance with their output after 100 hours of burning.)

There are eight contributing loss factors that must be considered. Some of these must be estimated; others can be evaluated on the basis of extensive test data or published information. Of the eight factors, only four factors can be obtained from published information. The remaining four factors have to be estimated. Only the four common factors that can be located in test data or by manufacturers' published data will be discussed here. These four factors will be considered the only four factors contributing to the light loss factor.

1. Ballast Performance. Fluorescent lamps as well as some other lamps contain electrical circuits for starting. All circuits of these types of lamps include a ballast which serves as (1) autotransformers to step up supply voltage (e.g., 120, 208, 240, 277, volts, etc.) to the necessary starting value (e.g., 255 or 500 volts) and (2) a choke to limit the current through the lamp. Ballast consists of a core and coil which stabilize the operation of the lamps; a power capacitor which corrects the power factor and reduces the load on the electrical distribution system; a radio interference-suppressing capacitor which reduces feedback of radio frequency energy to the power line; and a compound which fills all voids inside the ballast case, improving heat dissipation and reducing sound.

The Certified Ballast Manufacturers (CMB) Association specification for fluorescent lamps requires the ballast to operate a fluorescent lamp at 95 percent of the output of the lamp when operated on a reference ballast. A reference ballast is the laboratory standard used by lamp manufacturers in establishing lamp ratings. For ballast bearing the CBM label, use a factor of 0.95. For ballast not bearing the CBM label, lumen output is usually lower. Lamp life is also usually shortened. Consult with the ballast manufacturer for this light loss factor.

2. Luminaire reflectance and transmission changes. This effect is usually small but may be significant over a long period of time for luminaires with inferior finishes or plastic. Comprehensive data are usually not available.

3. Lamp lumen depreciation. The gradual reduction in lumen output of a lamp as it burns through life is more rapid for some lamps than for other lamps. The contributing light loss factor for fluorescent lamps is usually expressed as a ratio of the lumen output of the lamp at 70 percent of rated life to the initial (100) hour value. Since the life is influenced by burning hours per start, the contributing loss factor is usually expressed as a function of burning hours per start, even though it is actually a function of lamp burning hours. The lamp lumen depreciation for fluorescent filament and mercury lamps can usually be found in manufacturers' data. As an example, Table 5.3.9 is a listing of fluorescent lamps.

Table 5.3.9

FLUORESCENT LAMP DATA

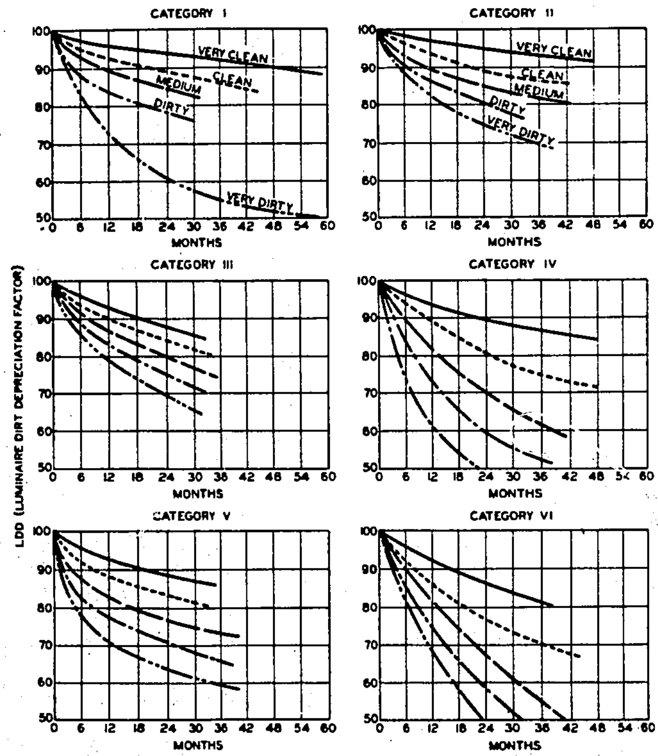
Lamp Ordering Abbreviation (1)	Approx. Watts	Base	Lamp Lumen Depreciation (LLD) (2) Hours per Start 6	12	18	(3) Rated Initial Lumens
Pre-Heat-Rap. St.						
F40CW	40	Med. Bipin	.88	.87	.86	3150
F40T10/CW/99	40	Med. Bipin	.86	.84	.83	3150
FB40CW/6	40	Med. Bipin	.85	.83	.81	2950
Slimline						
F48T12/CW	38.5	Single Pin	.88	.87	.86	2900
F72T12/CW	56	Single Pin	.88	.87	.86	4400
F96T12/CW	73.5	Single Pin	.88	.87	.86	6300
High Output						
F48T12/CW/HO	60	Rec. D.C.	.85	.84	.83	4000
F72T12/CW/HO	85	Rec. D.C.	.85	.84	.83	6450
F96T12/CW/HO	110	Rec. D.C.	.85	.84	.83	9000
***SUPER-Hi**						
F48T12/CW/SHO	110	Rec. D.C.	.80	.79	.78	6900
F72T12/CW/SHO	160	Rec. D.C.	.80	.79	.78	10,900
F96T12/CW/SHO	215	Rec. D.C.	.80	.79	.78	15,500
F96T12/CW/SHOH	215	Rec. D.C.	.80	.79	.78	15,500

(1) For Standard Cool White lamp. Other colors must have proper designations.
(2) Lamp Lumen Depreciation values apply to Standard Cool White, Standard Warm White and White lamps at 70% of rated life.
(3) Values apply to Standard Cool White. For other colors multiply by the following factors: White and Standard Warm White, 1.04; Daylight, .86; Cool Green, .92; Warm White Deluxe and Cool White Deluxe, .75.

Source: Westinghouse Lighting Handbook

Using Table 5.3.9, it is found that a fluorescent lamp--a high output lamp F96T12/CW/HO--would have a lamp lumen depreciation of 0.85 if it burns six hours per start; 0.84 if it burns 12 hours per start; and 0.83 if it burns 18 hours per start.

4. Luminaire dirt depreciation. This factor varies with the type of luminaire and the atmosphere in which it is operating. Luminaires are divided into six categories. The category for each luminaire has its own set of dirt depreciation curves. The dirt depreciation curves are as follows:



Source: Westinghouse Lighting Handbook

After determining the category, the luminaire dirt depreciation factor can be read from one of the five curves for each category. The point on the curve should be selected on the basis of the number of months between cleaning the luminaires. The particular curve selected should be based on dirt content and atmosphere. For example, in category II If cleaning were every 24 months and the conditions were very dirty, the luminaire dirt depreciation factor would be about 0.70.

The total light loss factor is determined by multiplying the separate four factors together. For example, if a lamp had a ballast performance of 0.95, luminaire reflectance of 0.98, lamp lumen depreciation of 0.85, and luminaire dirt depreciation of 0.70, the combined light loss factor would be 0.55.

Using the Formula. Recall that the formula for the number of lamps is as follows:

$$\text{Number of lamps} = \frac{\text{footcandles x area}}{\text{lumens per lamp x coefficient of utilization x light loss factor}}$$

where the number of luminaires is as follows:

$$\text{Number of luminaires} = \frac{\text{number of lamps}}{\text{lamps per luminaire}}$$

Problem. Assume a small office 20 feet by 40 feet with 2 1/2 foot ceilings is to be illuminated for regular office work. The reflectance of the ceiling is 80% (actual reflectance, not effective reflectance), and reflectance of the walls is 50%. The luminaires will be installed 2 feet from the ceiling, and the work plane is 2 1/2 feet from the floor. The luminaires will have opaque sides and are category VI lamps with 75% direct and 5% direct light. Assume that the environment will be considered clean and that the luminaires will be cleaned every 12 months. The ballast will meet the requirements of the Certified Ballast Manufacturers. From this information, compute the number of lamps and the number of luminaires that will be needed to provide a sufficient quantity of light.

Solution. The first task is to determine the number of footcandles that are recommended for regular office work. Using "Recommended Levels of Illumination," published by the Illuminating Engineering Society, regular office work requires a minimum of 100 footcandles.

The second step is to determine the coefficient of utilization. To do this, the room cavity ratio and the ceiling cavity ratio must be computed. The room cavity ratio would be

$$\text{Room cavity ratio} = \frac{10h}{\text{room width}} \text{ x Gaysunas ratio}$$

Using 8 feet for h and a gaysunas ratio of 3/4, the room cavity ratio is 3.0. (If the table is used to compute the room cavity ratio, the room cavity ratio from the table is 2.9 with an 8-foot cavity depth.)

The ceiling cavity ratio is computed as follows:

$$\text{Ceiling cavity ratio} = \frac{10 \times 2 \text{ ft}}{20}(3/4)$$

$$= 0.75$$

Using the room cavity ratio and the ceiling cavity ratio, the effective cavity reflectance of the ceiling can be found using the Effective Cavity Reflectance Table, Table 5.3.5. The table shows that for an 80% base (actual ceiling) and a 50% wall reflectance, the cavity reflectance is between 69% for 0.8 cavity ratio and 71% for 0.6 cavity ratio; so for this room, the ceiling cavity reflectance is approximately 70%. Using the effective ceiling reflectance as 70% and the wall reflectance of 50%, use the Coefficient of Utilization Tables (Table 5.3.7) to look up the coefficient of utilization. This is done by finding the luminaire that is in category VI with a 75% distribution of light hitting the ceiling for a room cavity ratio of 3.0, a ceiling effective cavity reflectance of 70%, and a wall reflectance of 50%. The coefficient of utilization is then 0.45.

The next step is to determine the light loss factor. The first consideration in determining the light loss factor is the ballast performance. Although the ballast performance is not indicated in the data given, it has a CBM label so assume the ballast performance is 0.95. The second factor to consider in computing the light loss factor is the luminance reflectance and transmission changes which was not give. Assume that to be about 0.98. Next, condsider the lamp lumen depreciation. Assume that the luminaire takes a F96T12/CW/HO lamp that will burn 12 hours per start. Using the lamp data for fluorescent lamps, Table 5.3.9, the lamp lumen depreciation factor would be 0.84. The next factor to consider is the dirt depreciation factor. This can be computed from the appropriate dirt depreciation curves. For a category VI lamp for a 12-month replacement, it would be around 0.86 under the clean condition. This means that the total light loss factor would be

$$0.95 \times 0.98 \times 0.84 \times 0.86 = 0.67$$

The next thing needed in order to use the formula is the lumens per lamp. This can be found using the lamp data provided in the lamp data table (Table 5.3.9).

For F96T12/CW/HO lamp, the rated initial lumens is 9,000. Substituting these values in the basic formula gives

$$\text{Number of lamps} = \frac{\text{footcandles x area}}{\text{lumens per lamp x coefficient of utilization x light loss factor}}$$

$$\text{Number of lamps} = \frac{\text{100 footcandles x 20 ft x 40 ft}}{\text{9,000 lumens x 0.45 x 0.67}}$$

$$= \text{29.48 lamps or 30 lamps}$$

The number of luminaires can be computed using the following formula:

$$\text{Number of luminaires} = \frac{\text{number of lamps}}{\text{number of lamps per luminaire}}$$

Substituting in the equation gives approximately 15 luminaires (use 14). Fourteen 2-lamp luminaires can be installed in seven rows of two luminaires mounted crosswise in the room. Ordinarily, it is perferable for the luminaires to be mounted so that the lowest candlepower is projected in the direction of most of the workers in the area. This may require that some luminaires be mounted parallel to the line of sight of most workers. Other luminaires should be mounted perpendicular to the line of sight. This particular luminaire has low candlepower from all viewing directions, but it does tend to create a high ceiling brightness. However, the bright ceiling is shielded from view by the luminaires if they are mounted perpendicular to the line of sight. Since in this room the predominant line of sight is most likely to be parallel to the length of the room, it is suggested that the luminaires be mounted perpendicular to the room length.

Summary of Steps Involved in Computing Lumen Method

Step 1. Determine the required level of illumination using "Recommended Levels of Illumination," Illuminating Engineering Society.

Step 2. Determine type of luminaire.

a. distribution
b. category
c. lumens
d. lamp lumen depreciation
e. when replaced
f. environmental conditions

Step 3. Determine coefficient of utilization.

a. compute room cavity ratio

b. compute ceiling cavity ratio

c. compute floor cavity ratio

NOTE: Use either

$$\frac{5h(\text{room length} + \text{room width})}{\text{room length} \times \text{room width}}$$

or

$$\frac{10h}{\text{room width}} \times \text{Gaysunas ratio}$$

d. determine effective cavity reflectances using Effective Cavity Reflectances Table

Compute ceiling cavity reflectance
(If floor cavity reflectance other than 20%, use correction table)

NOTE: Compute floor cavity reflectance same as room cavity reflectance to determine if less than 20%.

e. Use effective ceiling cavity reflectance, room cavity reflectance, wall reflectance, and look up coefficient of utilization in table for selected luminaire.

Step 4. Determine light loss factor (LLF).

a. Ballast performance (0.95 if certified ballast) = ______

b. Luminaire reflectance and transmission changes = ______

c. Lamp lumen depreciation = ______

d. Luminaire dirt depreciation (determined from LLD curves) = ______

e. LLF = a x b x c x d = ______

Step 5. Use formula.

$$\text{Number of lamps} = \frac{\text{footcandles} \times \text{area}}{\text{lumens per lamp} \times \text{coefficient of utilization} \times \text{light loss factor}}$$

NOTE: Coefficient of utilization was computed in Step 3. Light loss factor computed in Step 4.

Step 6. Determine number of luminaires.

Step 7. Determine layout.

a. Spacing not to exceed (see Coefficient of Utilization Table)

b. Draw layout

Self-Test	
Industrial Illumination	Section 5

1. Write a brief description of light.

2. Which radiates more energy, infrared light or green light? Explain.

3. When light travels through one transparent medium to another, why does it appear to bend?

4. Explain how the human eye perceives color.

Self-Test

Industrial Illumination | Section 5

5. List four objective factors in seeing objects.

   a. ______________________________

   b. ______________________________

   c. ______________________________

   d. ______________________________

6. A tungsten filament lamp has an intensity of 800 candela and is located 2 feet from a surface whose area is 0.25 feet. The luminous flux makes an angle of 30^{o} with the normal of the surface. What is the illumination?

Self-Test	
Industrial Illumination	Section 5

7. How many luminaires should go into this warehouse where there are active fine conditions? What is the best arrangement of the luminaires?

Room Dimensions:

144' long x 48' wide x 13' high

Luminaires:

-distribution pattern 17% up, 69% down, Category I
-lamps will be FT2T12/CW/HO
-lamps will work 18 hours/start
-ballast is certified by Ballast Manufacturers Association
-conditions in the warehouse are considered dirty
-luminaires will be cleaned every 24 months
-luminaire reflectance about 80%

Mounting and Reflectance Information:

-assume floor reflectance of 20%
-assume mounting is 2 1/2' from ceiling
-assume work plane is 2 1/2' from floor
-wall reflectance is 30%
-base ceiling reflectance is 80%
-assume <u>no</u> adjustment for floor cavity ratio is required

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