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Underground Coal Mine Lighting Handbook

(In Two Parts) 1. Background

Compiled by W. H. Lewis

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
Robert C. Horton, Director

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS—Continued

TABLES

UNDERGROUND COAL MINE LIGHTING HANDBOOK

(In Two Parts)

1. Background

Compiled by W.H. Lewis[1]

ABSTRACT

This Bureau of Mines report and its companion report (Information Circular 9074) have been prepared as a complete reference on underground coal mine lighting. This report discusses the fundamentals of light and its interrelationship with the visual process. The purpose of the report is to insure an understanding of the numerous complex and interrelated factors that must be considered to design and implement a mine lighting system that will satisfy human needs for good vision and comfort. Topics include history, objectives, and technical considerations of coal mine lighting; light physics; light and vision relationships; and disability and discomfort glare.

[1]Electrical engineer, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA.

INTRODUCTION

This Bureau of Mines report and its companion report, Information Circular 9074, have been prepared as a complete reference on underground coal mine lighting. The reports are intended to assist those persons who design, install, and/or maintain mine lighting systems in making appropriate decisions. The reports include system design criteria and procedures, data and specifications to aid in selection of suitable mine lighting hardware, and guidelines for system installation and maintenance.

This report discusses the fundamentals of light and its interrelationship with the visual process; necessary background information for anyone involved with mine lighting. The report provides information to insure an understanding of the numerous, complex, and interrelated factors that must be considered to design and implement a mine lighting system that will satisfy human needs for good vision and comfort.

The design of good lighting systems for underground coal mines is no easy task because of the unique environment and work procedures encountered in coal mines. The primary objective of these reports is, therefore, to identify the major problems encountered in this lighting application and to provide guidance in the solution of these problems. If they are carefully designed and implemented, lighting systems provide mine workers improved visibility and contribute to improved safety, productivity, and morale. Properly designed lighting systems can prove to be a very cost-effective investment for the mine operator.

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CHAPTER 1.—COAL MINE LIGHTING

HISTORY

The theory that better lighting results in safer, more productive operations has motivated the development and application of artificial light sources for the industrial environment. After Edison patented the first practical incandescent lamp in 1879, industrial lighting systems evolved rapidly to the modern lighting systems that employ several types of light sources including incandescent, fluorescent, mercury vapor, sodium, and metal halide lamps. Research and observation, both qualitative and quantitative, indicate that improved lighting has in fact resulted in greater safety, increased production, and improved worker comfort.

Underground coal mining is one industrial activity that has not kept pace with the application of improved lighting technology in the working environment. There are several reasons for this, including the following:

1. Initially, mining lagged behind other industries because (1) early lamps had short service life in this application because of lack of mechanical strength, and (2) their light output was low, which provided little improvement over the open flame lamps then in use.
2. New electrical equipment had to be introduced into coal mines with particular care because of the potential that it could entail for explosions and mine fires.
3. Systems could not be permanently installed but had to be moved as the mine expanded and advanced.
4. The abusive and hazardous mine environment required the development of special and expensive hardware and circuitry; the limited market did not provide the incentive to develop this special equipment until mine lighting was required by law.

Artificial lighting has always been a necessity in the otherwise totally dark underground mine environment. The types of light sources that have been used in underground coal mine lighting, summarized in table 1, range from oil soaked wood chips, reeds, and bulrushes to the present day incandescent and arc-discharge lamps. Developments such as the Spedding flint mill, the flame safety lamp, and the carbide lamp were aimed at providing a light source that would not ignite a gassy environment. Prior to perfection of devices that could accomplish this, hundreds of lives were lost to explosions initiated by light sources. Initial efforts to use incandescent electric lamps in the mines occurred in Europe as early as 1902, but

Table 1.—Light sources used in underground mining

Type	Source	Time period
Saucer-type open flame lamps	Wood chips, reeds, and bulrushes soaked in oil	10,000 B.C.-16th century.
Hanging open flame lamps	Wick immersed in grease or oil	1500-1900.
Candleholders	Wick candles	1800-1900.
Carlisle Spedding flint mill	Sparks from flint held against rotating steel wheel.	1750-1813.
Spout lamps	Wick immersed in oil	1850-1920.
Flame safety lamps	Wick immersed in oil, naphtha, or gasoline	1796-present.[1]
Carbide lamps	Calcium carbide and water	1910-20.[2]
Arc lamps	Carbon electrodes and electric current	1878-
Personal lamps	Incandescent lamp	1920-55.
Cap lamps	..do	1925-present.
Face lighting	Incandescent, fluorescent high-pressure sodium lamps.	1975-present.

[1] Currently used to check for methane at the working face.
[2] Still used in some developing countries and some 1- or 2-person mines.

electric lighting was not successfully used at the working face for another 25 yr.

The battery powered personal lamp was developed in the 1920's and required the miner to carry a heavy, cumbersome battery that tended to leak acid. After smaller and lighter weight batteries were developed, the lamp's were mounted on miners' caps instead of being handheld as originally used. By 1935, the cap lamp was in common use and is still a primary source of light in coal mines.

In 1969, Congress passed the Federal Coal Mine Health and Safety Act, which included a mandate that "directs and authorizes the secretary to propose and promulgate standards under which all working places in a mine shall be illuminated by permissible lighting while persons are working in such places." As a result of this mandate the Bureau initiated a research and development program to develop (1) information to be used in establishing lighting regulations, and (2) lighting hardware that could be safely used to gain compliance with these regulations. Major results of this research included—

1. Establishment of 0.06 fL as the minimum reflected light level on all surfaces required by the regulations to be lighted:
2. Development and successful demonstration of permissible lighting hardware for underground application.

The Federal lighting regulations, 30 CFR 75.1719 through 75.1719-4, were proposed in 1976 and, following public hearings and comments, were amended and published in 1978. These regulations prescribe the requirements for illumination of working places, in underground coal mines, while persons are working in such places, and while self-propelled mining equipment is operated in such places. A discussion of these requirements and the Mine Safety and Health Administration (MSHA) policies in enforcement are presented in Information Circular (IC) 9074.

OBJECTIVES

The general goal of industrial lighting is to improve safety and increase production. Statistics show that underground mining is one of the most hazardous industries and mining personnel should, therefore, benefit most significantly from the use of lighting that is consistent with the capabilities of modern technology. To realize these benefits, mine lighting must achieve specific goals as follows:

1. *Increase the visibility of hazards.*—Because of the low luminance levels and poor contrast in coal mines, hazards have always been difficult to visually identify. A few examples of such hazards include frayed or cut cables, misplaced tools and timbers that may prevent a tripping hazard, and slips in roof rock. A primary goal of mine lighting is to increase the visibility of these objects which are visibly manifested by subtle details, and, hence, reduce injuries that may result if the hazards go undetected.
2. *Increase visual response of the peripheral field to enable early detection of hazards.*—With the narrow-beamed cap lamp alone, movement of personnel, machines, and roof or rib material is difficult to detect when it occurs in a miner's peripheral field of vision, outside the localized main beam of the cap lamp. Another major goal of mine lighting is to allow miners to quickly detect even subtle movement anywhere in their normal field of vision. This will provide additional time for personnel to react and thereby avoid injuries.
3. *Improved vision for performance of tasks.*—If miners can clearly see the details of tasks, they can perform them faster and with fewer mistakes. Studies in many other industries have conclusively shown that improved lighting increases productivity and work quality. Cost-effective investments in lighting systems capable of producing very high luminance level have been made at many industrial plants. Hence, an important goal of mine lighting is to illuminate work areas consistent with the needs for optimum performance of underground tasks.
4. *Increase general comfort and reduce fatigue.*—Working in poorly lighted environments causes worker fatigue, reduces comfort, and adversely affects morale. Improved lighting offers considerable potential for improving the psychological aspects of working in a mine environment and should produce corresponding improvements in related areas such as productivity, absenteeism, etc.

STUDIES

How close have modern mine lighting systems come to achieving these goals? This question can only be answered conclusively through controlled studies of mining operations. Unfortunately, there are many interrelated factors, such as geologic conditions, seam height, and gas emissions, which can affect safety and production in the mine environment. Because these conditions change continually and are virtually impossible to precisely control or to isolate, determining the effect of a single factor, such as light levels, is very difficult. Unlike other safety technology such as cabs and canopies, "saves" (i.e., prevented injuries or fatalities) attributable to lighting systems are difficult to document or count.

Although the studies described show wide variation in the magnitude of results and cannot be considered conclusive, the analyses consistently indicate improved safety and/or production in the lighted mine sections.

A more reliable evaluation of mine lighting will require detailed studies similar to those conducted for lighting of roadways, offices, schools, and manufacturing facilities. It should be noted that at many mines there is a deficiency in accident reporting—the lack of operators' comments or descriptions of lighting conditions associated with mining operations or accidents. Lighting data should be included as part of accident reports to provide an additional basis for assessing the benefits of face lighting and in identifying shortcomings.

SAFETY

Halmos[2] reported that in a Hungarian mine a 60 pct decrease in the accident rate was recorded for a lighted section compared with the rate in a section where only cap lamps were used. In the same study, another test showed that increasing the lighting level by a factor of 12.5 (20 to 250 lx) decreased the number of accidents by 42 pct.

A 24-month study conducted in a West Virginia coal mine compared the major accident records for one lighted conventional section with records from five unlighted

[2] Influence of Lighting on Productivity and Safety in Mining.

sections. Results showed no accidents in the lighted section and a total of 10 accidents (five in one section) in the five unlighted sections.

Mishra and Dixit[3] reported that 35 pct of all minor accidents in India's coal mines can be attributed to poor lighting.

Productivity

Halmos describes two studies on productivity. In one 2-month study, the part of the working areas illuminated with general lighting showed a 5 pct increase per worker in production compared with production in those sections using only cap lamps. In a second mine, a similar study showed a 26 pct increase in production per worker.

In a 1-yr study at a U.S. mine,[4] a test section equipped with general stope lighting showed a 17 pct increase in tons per worker-shift over the next highest producing section.

Opinion Surveys

A joint committee with representatives from the United Mine Workers of America (UMWA), Bituminous Coal Operators Association (BCOA), and MSHA conducted an extensive opinion survey of room-and-pillar face personnel in 1979, shortly after implementation of the lighting standards. The survey indicated an overall favorable response to systems implemented in seam heights greater than 42 in and an unfavorable response to systems in lower seam height mines, primarily from glare problems. Several changes in official enforcement of the lighting standards resulted from the particular personnel acceptance problems identified in the survey.

Bituminous Coal Research, Inc., conducted a similar study in 1980, interviewing management and face personnel at longwall and room-and-pillar mines. Both management and face personnel unanimously approved of longwall lighting, citing many benefits and no major problems. Acceptance of room-and-pillar systems increased from the 1979 survey markedly so for low seam height applications. Many equipment operators, despite an overall favorable opinion of the room-and-pillar systems, cited problem areas, indicating that careful implementation is required and general improvement is possible.

MAJOR TECHNICAL CONSIDERATIONS

The underground coal mine is one of the most difficult lighting applications encountered by industrial lighting designers. There are several unique technical considerations that must be carefully addressed in designing and implementing mine lighting systems. These considerations are reviewed briefly in the following and are discussed in more detail in other sections of this report and IC 9074.

1. *Mine lighting is a nonstationary application.*—For most lighting applications, the object or area to be lighted is confined to a specific location and lighting hardware can be permanently installed. In coal mining the working face not only continually advances (or retreats), but several faces are being mined at the same time by the same equipment. The designer, therefore, has two choices. One is to mount the hardware on the machines so the area around the machine is lighted regardless of where it is operating. The second choice is to mount a system semipermanently at each active face and move the system as the face is advanced. Both systems pose unique problems with respect to electrical design and logistics. At the present time, mine lighting systems are almost exclusively machine mounted.

2. *Lighting in a low-reflectivity, low-contrast environment.* —Under equal illumination, the brightness of surfaces within a person's field of vision is dependent on the reflectivity of these surfaces. Reflectivity, or reflectance, is a measure of the ability of a surface to reflect incident light supplied by a light source (see chapter 2). In most lighting applications, exposed surfaces reflect a relatively high percentage of light, which helps in providing good visibility of objects and/or surface details. In the coal mine, nearly all surfaces have low reflectivity, especially the ribs and face which have an average reflectivity of only 4 pct. Therefore, to provide a given general level of surface brightness, the output of light sources used in mine lighting systems would have to be much higher (15 to 20 times) than would be required in applications with high reflectivity surfaces.

Another important lighting design consideration is the relationship between the light level required for good visibility of detail, and the contrast between the detail and the background against which it is viewed. For example, if critical details such as roof slips or cracks were white against the dark coal or rock surfaces, very low light levels would be required to see them. However, there is very little contrast between a slip and its background (often distinguishing between shades of gray), so higher light levels are required to make them acceptably visible. This applies to many other signs of serious mine hazards.

Both low coal-surface reflectivity and low contrast require that light sources with relatively high output be utilized to achieve acceptable visibility. As discussed in item 6 of this section, this can lead to glare problems. Compromises between visibility levels and reducing the system's glare level must frequently be made in mine lighting system designs.

3. *Abusiveness of the environment.*—Few environments expose lighting hardware to the abuse found in the underground coal mine. The major hazards include impacts from striking rib or roof, roof rock falling on the hardware, mechanical shock produced by machine vibration and motion, and corrosion potential from moisture, salts, and other corrosive agents found in mines. These conditions require special consideration in the design and installation of hardware if adequate service life and acceptable maintenance costs are to be realized.

4. *Poor power regulation.*—Light sources and associated power control devices are sensitive to fluctuations in supply voltage, especially large and fast fluctuations, and to extended operation above or below design voltage. The effects of poorly regulated power include variation in light output, extinguishment of arc discharge lamps, destruction of lamps, and a general reduction in service life of power-conditioning components because of heat buildup. These problems have been particularly prevalent with dc power systems, which frequently experience extreme high-voltage transients and very poor voltage regulation. A system designer must, therefore, be familiar with the character of a mine's electrical system and take steps to protect against poor regulation and/or transients.

[3] A New Psychoengineering Strategy for Safety in Mines.

[4] Permissible Mine Lighting Systems Cut Down on Accidents and Increase Coal Output.

5. *Increased electrical hazards.*—Any time additional electrical equipment is added to a mining machine, the potential for an electrical fault and an associated shock hazard is increased. This makes it imperative that the system designer comply with all Federal electrical design requirements, that all electrical devices be of adequate capacity, and that cables be adequately protected from mechanical damage. Additionally, lighting systems add another potential source of heat and electrical arcing which, in a gassy mine, could trigger a disastrous methane explosion. Federal and State regulations provide specific requirements for design of electrical equipment to prevent such occurrences. A system designer must comply with these standards, discussed in IC 9074 (chapter 2), assure that a total system or its individual components will not ignite an explosive gas-air mixture.

6. *Glare potential.*—A lighting system is effective only if it improves a person's ability to ascertain visual information from his or her surroundings. Experience with mine lighting has shown that in this regard the effectiveness of many systems is impaired by glare. Factors such as the high light-source output (as required by low coal-surface reflectivity), the extreme contrast between light sources and their low-reflectivity surroundings, the frequent necessity of locating light sources near the line of sight to meet prescribed light levels, and job procedures that place the light sources in or near the line of sight of workers at various times in the work cycle, result in glare problems that are difficult to resolve. The system designer must be familiar with the factors that determine the nature, level, and impact of glare and must also be familiar with design techniques that can minimize glare potential. These considerations are discussed in Chapter 4, "Disability and Discomfort Glare" and in IC 9074 (chapter 5).

In addition to these major technical considerations, each type of machine, lighting hardware, and mine may have unique requirements that should be considered in design. It is important that each application be considered individually to assure the design for that application is optimum.

Even though problems still exist, the attitude toward mine lighting has become more positive as miners gain experience with working in lighted sections. Significantly, the results of the survey completed in 1980 showed that, overall, 74 pct of the miners liked mine lighting compared with 60 pct that expressed favorable opinions during the survey conducted in 1979. Improved lighting system design should result in greater acceptance of mine lighting. The information in this report and IC 9074 is presented to assist the coal industry personnel in achieving better lighting of their workplaces and its attendant benefits.

CHAPTER 2.—LIGHT PHYSICS

Light is a form of energy that enables us to see; it is known as *visible energy*. It is the tool most readily at the disposal of the lighting system designer to improve the seeing environment. To use it most effectively; one must understand light's physical properties and behavior.

The following topics and associated key concepts will be addressed in this chapter.

Nature of light	Radiant energy, wavelength and frequency, and electromagnetic spectrum.
Interpretation of visible light .	Color, brightness, and the spectral luminous efficiency curve.
Physical behavior of light .	Absorption, reflection, and transmission.
Lighting energy quantification, lighting units . .	Luminous flux, illumination, intensity, luminance, cosine law, and inverse square law.

The section on lighting units presents example problems to illustrate the use of each major concept in design applications.

Light is a form of radiant energy; one of several known energy forms, which include electrical, chemical, atomic, thermal, and mechanical energy. Light is called *radiant energy* because it travels through space from its point of origin, or source, in all directions as a repeating, or cyclical, wave pattern, much as the mechanical wave that results when a pebble is dropped in a pond. Light waves are made up of both electric and magnetic energy components, and therefore are called electromagnetic waves.

Electromagnetic radiation is a byproduct of any process where an electrical charge is accelerated. Many processes, both natural and artificial, accelerate charges and hence produce electromagnetic radiation. Those processes that produce visible light generally occur on an atomic or molecular scale and involve acceleration of electrons. Some of these are (1) heated bodies (e.g., the common incandescent light bulb), (2) arc discharge (e.g., mercury lamp), (3) fluorescence (e.g., a glow-in-the-dark watch face), and (4) chemical process (e.g., the firefly).

Because it consists of waves, radiant energy is characterized by two special properties: wavelength and frequency. Wavelength is the distance covered as an energy cycle repeats itself. Frequency is the number of times the cycle repeats itself during a unit of time, for instance, in 1 s. When wavelength is multiplied by frequency, the product is the speed at which the wave is carried forward from its source. For radiant energy, this speed is a constant in a given transmission medium. The speed equals 186,000 mi/s when the medium is a vacuum, and is slightly less in air.

Visible light is only a narrow part of a broad spectrum of radiant (electromagnetic) energy. At one end of this *electromagnetic spectrum* are cosmic rays; electric power transmission waves are at the opposite end. Even though the effect of, uses of, and the generating processes for the different groups of radiant energy may differ, all are electromagnetic energy differing only in wavelength and frequency. The various categories of energy are arranged on the electromagnetic spectrum on the basis of wavelength and frequency, as shown in figure 1.

Visually evaluated radiant energy, or visible light, is that portion of the electromagnetic spectrum with wavelengths between 380 and 780 nm. Longer or shorter wavelengths stimulate very little or no response in the eye.

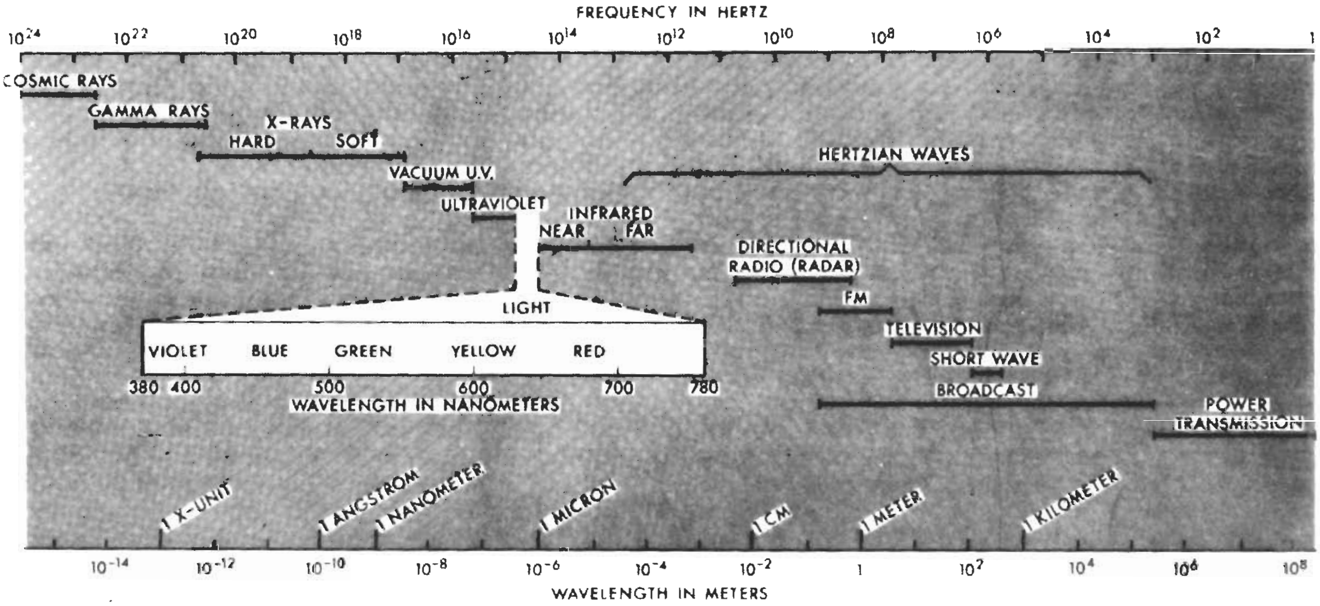


Figure 1.—Radiant energy (electromagnetic) spectrum.

PERCEPTION

The two fundamental interpretations of the light that enters our eyes is made on the basis of that light's physical characterisics. Wavelength composition is interpreted as color and the combination of energy level and wavelength composition is interpreted as brightness.

Colors are, simply, the names assigned to various wavelengths, or mixtures of wavelengths, of visible light. For example, light wavelengths between 380 to 400 nm appear violet in color, while light wavelengths of approximately 600 nm appear yellow (see figure 1).

When seen separately, individual visible wavelengths of light appear as distinct colors. When light consists of a blend of the wavelengths across the entire visible portion of the electromagnetic spectrum, it appears white. (Black is not a color, just the absence of light.) Certain sources, such as incandescent light bulbs and the Sun, give off relatively balanced amounts of all visible wavelengths and hence appear white. When light sources or reflectors give off higher or lower amounts of one or more visible wavelengths, our eyes distinguish such wavelength imbalances as colors. Because of the way our eyes interpret wavelength characteristics of light, mixtures of several wavelengths may appear the same as a certain individual wavelength. For example, blue and yellow when mixed appear green.

Perception of brightness is affected by two physical characteristics of light—energy content of the light striking the eye and the wavelength composition of that light. The more energy at a given wavelength of light striking the eye, the greater the sensation of brightness produced. However, the eye does not respond to all wavelengths in the 380- to 780-nm range equally. It does not take nearly as much energy in a beam of 555-nm light for it to appear as bright as 650-nm light. Figure 2 shows the brightness response of the eye to different wavelengths of light in terms of a percentage of the response at the wavelength to which the eye is most sensitive (555 nm). This is an average curve; a particular individual's response might vary somewhat. This curve is called the spectral luminous efficiency curve because it depicts the efficiency of light in producing a brightness sensation at various wavelengths. As can be seen from the curve, a meter measuring the *total energy* of a 650-nm beam of light would have to read nine times as high as one measuring a 555-nm beam of light for the beams to produce an equivalent brightness response.

The spectral luminous efficiency curve represents a weighting function that must be taken into account when assessing light energy for illumination design. Light measuring instruments incorporate filtering systems and/or employ special sensing devices that discriminate against light wavelengths in accordance with this function. Moreover, the function is assumed in the definition of all standard systems of lighting units as will be discussed later.

PHYSICAL BEHAVIOR

As a light travels from a light source to a person's eyes and encounters objects in between, it can be altered in many ways. This section examines these alteration processes which are important to understanding both the basis of what is seen and the light control methods that may be employed in illumination design.

When light or any other form of electromagnetic radiation encounters an object, it is transmitted, reflected, and/or absorbed. Transmitted light is the light that passes through an object. That is, it goes in one side and comes out another. Reflected light is light that does not penetrate an object; rather it bounces off the object's surface. Absorbed light is all the light that is neither transmitted nor reflected; rather it is "soaked up" by the material. The energy of absorbed light is changed to some other form such as heat.

Three ratios—absorptance, reflectance, and transmittance—can be used to quantify how light energy striking a given material is distributed. These ratios define the proportion of absorbed, reflected, or transmitted light relative to the total amount of light striking an object.

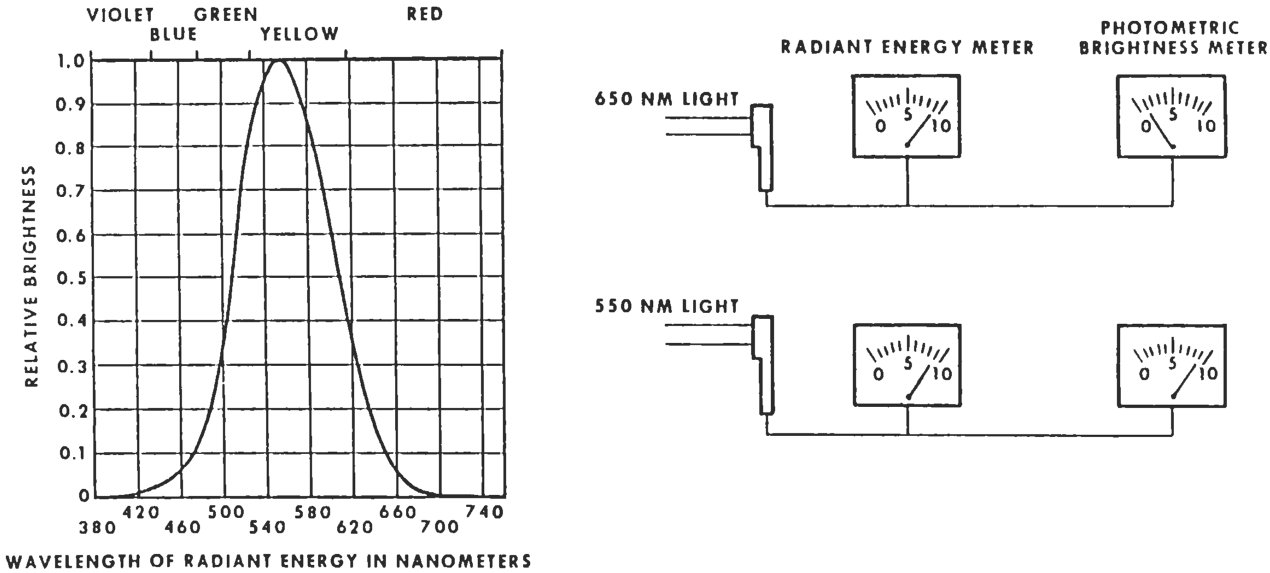


Figure 2.—Brightness sensitivity of the eye as a function of light wavelength.

The sum of the three ratios always equals 1, but for any material none of the individual ratios will equal 1. For example, a material that transmits light never has a transmittance equal to 1. Rather, its transmittance is reduced by positive reflectance and absorptance values. Many objects exhibit zero transmittance, but their reflectance will be less than 1, reduced by a positive absorptance value. It is evident that an object's absorptance acts to reduce the amount of light energy leaving the object's surface.

Absorption

If an object selectively absorbs light at certain wavelengths, while allowing other wavelengths to be transmitted or reflected, the object is said to have discriminant absorption properties. The discriminant absorption properties create wavelength imbalances in the reflected or transmitted light. As noted earlier, these imbalances are disguished by the eye as various colors. Objects that appear red under a white light contain molecules, given the special name pigments, which absorb wavelengths in the blue-green portion of the spectrum and reflect red light. Blue objects have pigments that absorb wavelengths in the green-red portion of the spectrum. Other colors, such as brown, purple, or pink, can be obtained through the proportionate mixing of pigments with different discriminant absorption properties.

It is important to recognize that color rendering through the discriminant absorption of various wavelengths of light is a subtractive process. That is, the wavelength mixture in the reflected or transmitted light can only be a subset of the wavelength mixture in the light that struck the object. The total energy of reflected-transmitted light in a given wavelength region cannot exceed the energy of light in the wavelength region that composed the incident beam. However, the relative proportion of one wavelength region to other wavelength regions in the reflected or transmitted beam may be changed, which will change the beam's color. If an object that reflects only wavelengths from the red portion of the spectrum and absorbs all others is illuminated by a light consisting of blue and green wavelengths only, the object cannot reflect any red wavelengths and would appear much darker and essentially colorless. Hence, regardless of the discriminant absorptive properties of an object, the eye cannot see colors that are not present in the source light that illuminates the object. This has impact on the selection of artificial light sources in cases where color discrimination is important, as with color coding of wire, pipes, etc.

Reflection

Special Importance of Reflected Light

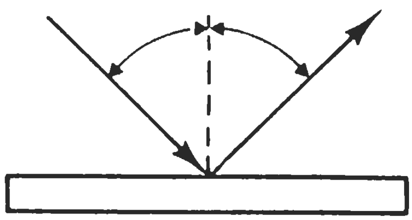
The eye does not see light that is traveling through air (space). Only the source of the light and the objects reflecting light from that source can be seen. For example, the sunlight striking the Moon at night cannot be seen. The space from the Sun to the Moon is completely dark. Only the light being reflected by the Moon's surface is seen. The reflected light, in turn, allows details of the Moon's surface to be discerned.

Eyes sense the light that enters them, process the character of this light, and interpret this character back to the object that reflected it. This is accomplished by "focusing an image" on the light-sensitive surface of the eye (the retina). Focusing an image is process by which the light reflected from points on an object in the direction of the eye are, through optical mechanisms within the eye, directed or focused to form an image of the object on the retina. (See chapter 3 for more details.) In this respect, light acts as a coded signal carrying information about an object that reflects it to the eye where the signal is subsequently decoded and translated. Spatial relationships, brightness, and color can be discerned. Hence, it is reflected light that has greatest bearing on what is seen. Because of this, lighting designers must evaluate the environment to find out (1) the proportion of light the environment reflects and (2) how the reflected light is distributed. As noted previously, the proportion or ratio of light specific surfaces in the environment reflect compared to incident light on these surfaces is measurable and is called reflectance. The other variable important to designers is distribution of reflected light.

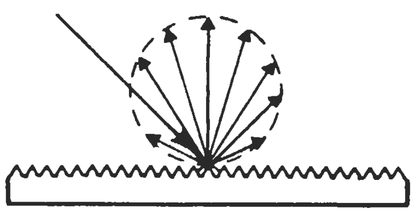
How Objects Distribute Reflected Light

Objects distribute reflected light in different ways, depending upon texture of the surface or near-surface layers of the object. The simplest case of reflection is shown by a perfectly smooth reflector, such as a mirror. For such reflectors, the direction of the reflected light is determined by the direction of the source of light, as shown in figure 3. The beam angle of the light source and the beam angle of the reflected light are equal in size, but on opposite sides of a line perpendicular to the surface. Objects that reflect light in this manner are called *specular reflectors.*

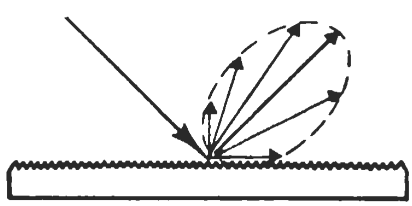
> *The Use of Specular Reflectors in Controlling Light.* —The principle of specular reflectance is used in the design of reflectors for control of light emission from lamps and luminaires. In brief, the curvature of the reflector can be adjusted to control the spread of the beam from a point source of light. The three reflectors shown in figure 4 indicate distribution that can be obtained with three different shapes—parabolic, circular, and elliptical.



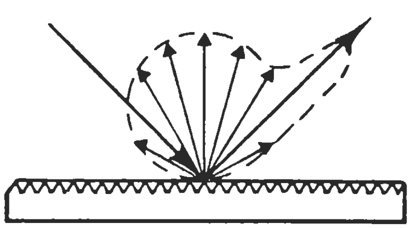
SPECULAR REFLECTION



DIFFUSE REFLECTION



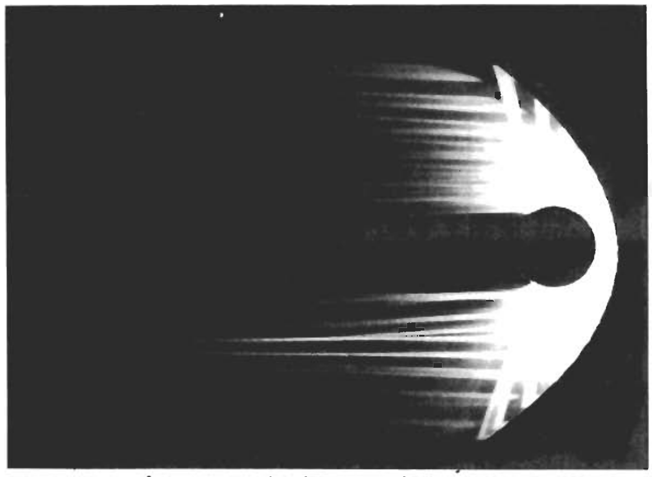
SPREAD REFLECTION



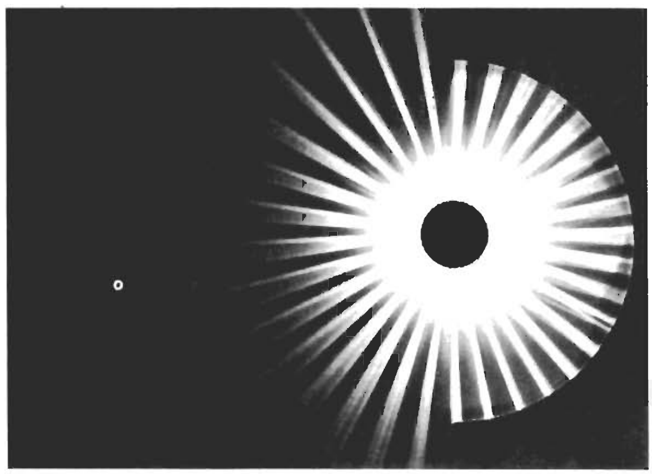
MIXED REFLECTION

Figure 3.— Classification of reflectors.

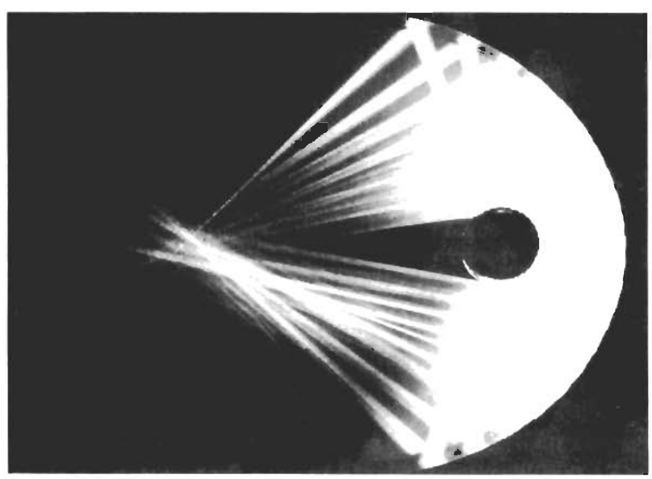
Diffuse reflectors represent the opposite extreme. Here, the texture of the reflecting surface is rough. Light is scattered in all directions. Such a surface would tend to appear equally bright from any direction of observation. A wall painted with flat paint is an example of a diffuse reflector.



A. Parabolic reflector



B. Circular reflector



C. Elliptical reflector

Figure 4.—Curved reflectors used to control light distribution.

Surfaces may reflect in combinations of diffuse and specular manners. A polished coal surface, for example, is primarily a diffuse reflector that reflects light uniformly over a wide range of directions but with an increase in light energy reflected at the specular angle of reflectance. Figure 3 illustrates various classifications of reflectors.

The type of reflector, in combination with the angle of observation and the incident angle of the source light striking the object, ultimately determine the perceived brightness of an object and the measured light energy reflected by an object. This leads to complications in reflectance measurement and in design procedures for reflectors, which are a combination of diffuse and specular.

Transmission

Transmission of light through a medium is affected by various properties of the medium. *Transparent* materials (e.g., clear glass) transmit light without scatter. Objects on the other side or within the transparent object can be seen in sharp detail. *Translucent* objects (e.g., frosted glass) also transmit light, but with some degree of scatter. Objects on the other side or within appear blurred in form.

Light can be controlled by using a material with certain transmission capabilities to cause scatter. This is known as *diffusion* (see figure 5). Diffusion is extremely important in the design of lighting systems for visual comfort (i.e. normal glare reduction). It is achieved through various means of treating the transmitting object, including surface etching, incorporation of light-scattering particles within the medium, and application of surface coatings.

The effect of diffusion is to make the light source appear larger and less bright. Consider clear, frosted, and soft-white household incandescent lamps. The two diffuse bulbs make the light source appear to be larger and, hence, reduce the perceived brightness per unit area. In fact, the clear bulb has a brightness per unit area over seven times greater than the frosted lamp. Diffusion always results in some reduction of light energy transmission and, thus, reduces efficiency of a light fixture. Through proper design of enclosed fixtures, the amount of energy loss can be reduced significantly by interreflection, shown in figure 6.

Many transmitting mediums may selectively transmit some wavelengths while absorbing or reflecting others. This property can be used for removing certain wavelengths to obtain a desired wavelength composition of the transmitted beam. Such a material can change the color of light with little alteration of light distribution. The dichroic reflector, an example of this type of medium, is used in some headlights to reflect a beam of visible light forward but transmit infrared wavelengths backwards; if reflected forward, the infrared energy would tend to heat objects and people.

The atmosphere is never a perfect transmitter of light (transmittance $|T| \neq 1$) even in what appears to be the clearest of conditions. This factor must be taken into account in some design problems, especially when fog or dust levels are significant and/or transmission distances are large. For such problems, transmittance is described by a transmissivity ratio, transmittance divided by unit distance.

For instance, light transmissivity is about 0.94 per mile in a very clear atmosphere. That is, 94 pct of the light reaches a receiver 1 mile away and 88 pct (0.94 X 0.94) reaches a receiver 2 miles away. But in even a very light fog, the transmissivity reduces sharply to only 0.05 per mile. Only 0.25 pct of the light energy would reach a receiver 2 miles away. The concept of transmissivity ratio is primarily used in signal design problems (e.g., in selection of a fan-on signal at a mine).

The direction of light backscatter is another very important factor to consider when working with atmospheric conditions such as dense fog or dust. Backscatter occurs when the particles in the air reflect the light back toward an observer looking through the medium. Backscatter in undesirable directions can impair visibility. For example, to prevent undesirable backscatter, it is necessary to use low-beam headlights while driving in a dense fog.

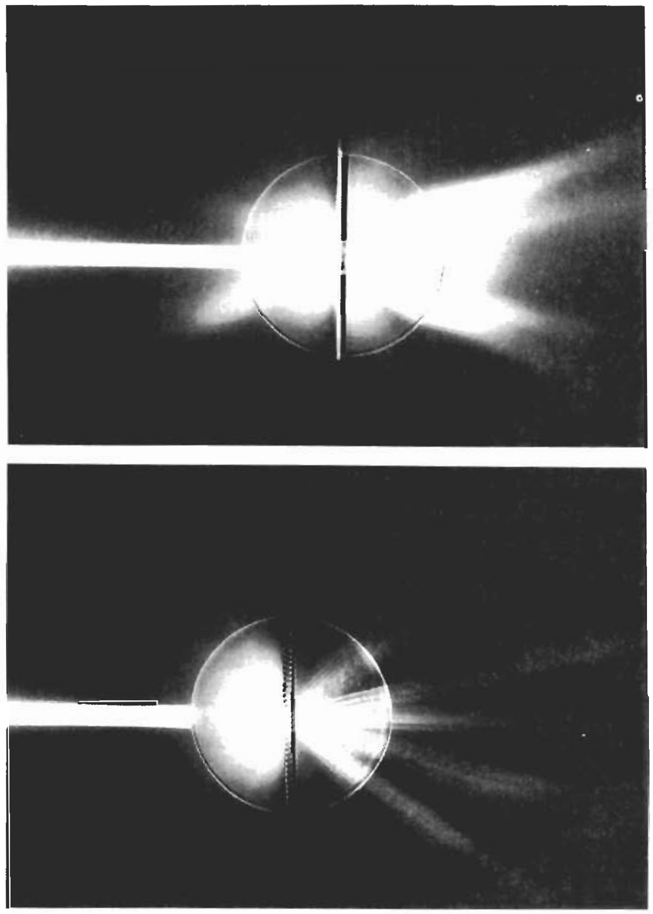


Figure 5.—Use of surface patterns to control light distribution.

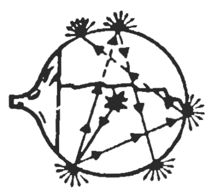


Figure 6.—Effect of interreflection on net light transmission for enclosed light fixtures.

When light passes from one transmitting medium (such as air) to another (such as glass), its speed will change. Figure 7 shows the progression of the light-wave fronts traveling through air into glass. Each line represents the position of the wave front after equal time intervals. As the light leaves the less dense medium (air) and enters the denser medium (glass), it slows down and the distance traveled in a given amount of time is reduced. The net effect is a bending, or deflecting, of the light waves, which is called *refraction*. This principle is illustrated by a straw in a glass of water; the straw appears to be bent at the point where it enters the water. The degree of bending is determined by the ratio of the speed of light in the two mediums.

The principle of refraction impacts upon lighting in two primary ways.

1. Lenses may be designed utilizing the refraction principle to control the distribution of light from a light source. This is accomplished by adjusting the lens curvature (see figure 8). These lenses may be used alone or in conjunction with specular reflectors to control light.
2. The eye utilizes the principle of refraction to obtain a focused image on the retina. (This is discussed in detail in chapter 3.)

QUANTIFYING LIGHT ENERGY

This section discusses the fundamental concepts that are employed by illumination engineers in the quantification of light energy for design purposes and explains their interrelationships. These concepts enable the designer to evaluate, and thus devise means to control, light energy levels and their distribution.

Two major systems of units are currently used for the quantification of light: Illumination Engineering Society (IES) and International System of Units (SI). The primary difference between IES and SI systems is that the IES system uses U.S. standard measures for linear dimensions in the unit definitions, while the SI system uses metric measures. Current U.S. coal mine lighting regulations customarily use IES units; therefore, these will be used primarily in this report.

Systems of lighting units are unique in that they explicitly apply a human weighting function to the physical energy quantity they measure. That is, all unit systems take into account how the eye exhibits different sensitivities to various light wavelengths in terms of perceived brightness and weight the energy measurements according to the spectral luminous efficiency curve (fig. 2). Radiometric units are used to quantify other types of electromagnetic radiation. They are similar to light energy units, but do not include a weighting function.

All standard systems of light units employ certain basic concepts which are based on convenient and meaningful approaches to light energy measurement and quantification. These basic concepts are luminous flux, illumination (illuminance), luminous intensity, and luminance. Each of these are discussed in detail. Examples are provided to illustrate each and show how the concepts are utilized for design purposes.

Luminous Flux	Symbol—ϕ	IES and SI unit—lumen (lm)

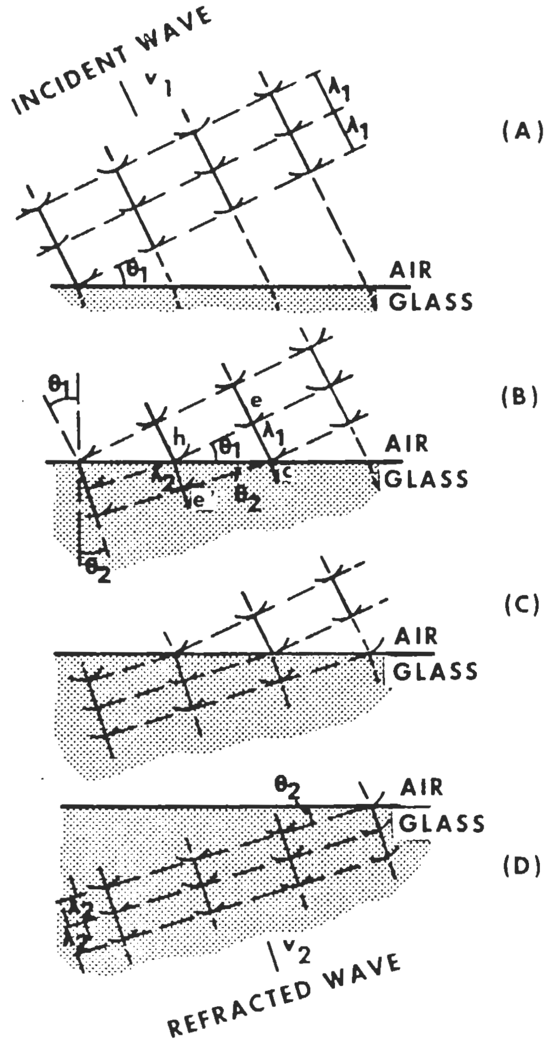


Figure 7.—Effect of changing transmission mediums on direction of light travel.

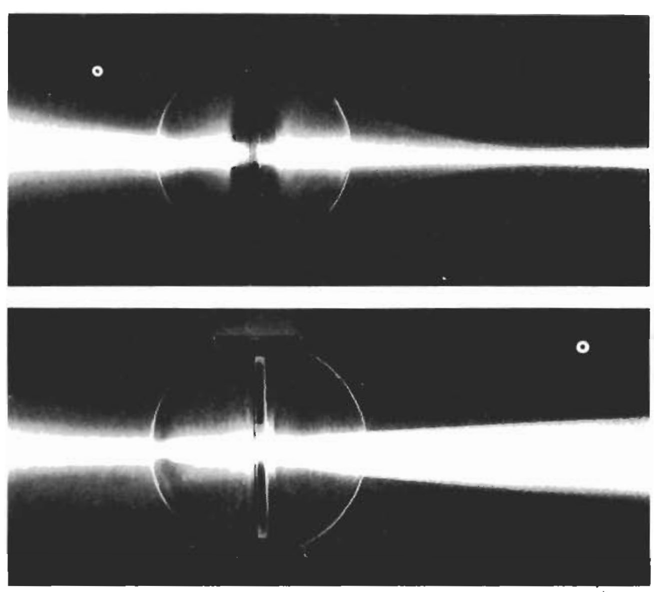


Figure 8.—Use of curved lens to control light distribution.

Luminous flux is the time rate flow of light energy. Flux is a *power* quantity in the same manner as horsepower or Btu per hour. The unit of luminous flux, the lumen, is most frequently used to describe the total lighting power of light sources. Other light energy concepts (e.g., illumination, luminous intensity, and luminance) use the lumen in conjunction with various geometric quantities to describe the distribution of light energy flow to the surroundings. Light sources are often evaluated for their total lumen output. For example, a 100-W incandescent lamp produces about 1,740 lm. Two or more light sources can be compared on the basis of their total luminous flux, or lumen, ratings. This is analagous to comparing two or more motors on the basis of their horsepower rating.

Total lumen ratings of light sources are extremely valuable for use in making preliminary approximations in lighting design problems. The number of lumens needed in a given situation will help determine the size and/or number of lighting fixtures necessary. These ratings are usually available from hardware manufacturers.

Illumination	Symbol—E	IES unit—footcandle (fc) SI unit—lux (lx)

Illumination (illuminance) is a measure of the density of luminous flux striking a surface. Mathematically, illumination may be defined as:

$$E = \phi / A_R, \quad (1)$$

where E is the illumination produced by the luminous flux, ϕ, falling on a *light-receiving* surface of area A_R (see figure 9).

The IES and SI systems have different units for illumination. The lux, used by SI, is the average illumination produced by 1 lm of light distributed over a 1-m^2 receiving area. The footcandle, used by IES, is the average illumination produced by 1 lm of light distributed over a 1-ft^2 receiving area.

As an example of the illumination concept, if light energy flowing at the rate of 9 lm is distributed over area A, which is equal to 1-ft^2, the illumination of area A is 9 fc. If the same energy is subsequently distributed over larger area B, which is equal to 3-ft^2, then the average illumination of area B is 3 fc, one-third as great as area A.

It should be noted that the *total* illumination levels from two or more light sources shining on a surface are obtained by adding the illumination level produced by each source separately. If light A illuminates the surface to 5 fc and light B illuminates the surface to 3 fc, the surface illumination will be 8 fc if both lights operate simultaneously.

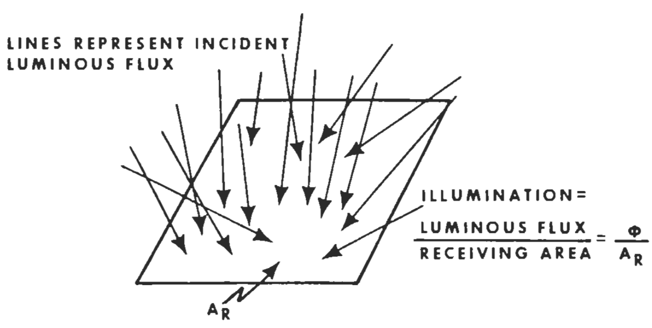


Figure 9.—Illumination.

When determining illumination, ϕ in equation 1 concerns the total lumens striking the receiving surface area, regardless of the originating direction of the luminous flux.

Until now, only *average* illumination over the entire receiving surface has been discussed. The illumination at any point on the receiving surface may also be determined simply by considering a very small area around the point as the receiving area. Point illumination for all points on a surface equals average illumination if the luminous flux is uniformly distributed over a surface. If the illumination is nonuniformly distributed, point illumination, Ep, would vary for each point on the surface.

Average illumination is an easy quantity to measure. Instruments are available that contain light-sensitive materials that convert total light energy striking them to proportional electrical energy levels. The resultant electrical energy levels can then be measured and read on standard (although sensitive) electrical meters. Since the area of exposed, light-sensitive material is known, the electrical energy values can readily be equated to illumination (energy per unit area) values (footcandle or lux). The significance of the fact that illumination is an easy quantity to measure is that illumination measurements can be converted to other light quantities (e.g., luminous intensity), which are meaningful but more difficult to measure directly. Such conversions are illustrated in this report.

Lighting design specifications are often presented in terms of illumination (footcandle or lux) levels. Specifications given in such terms (1) enable a good description to be made of light levels and how light should be distributed in a given environment, (2) make design calculations simpler than if the specifications are made in other terms (e.g., luminance), and (3) enable easy on-site verification that specifications are being met because of the relative simplicity of taking illumination measurements.

Specifications presented in terms of illumination levels do not consider how a receiving surface reflects light, however. This is a definite shortcoming because, as noted previously, reflected light determines what is seen. Various properties of the light-receiving surfaces in the surrounding environment can affect reflectivity.

Illumination and the Cosine Law

The cosine law is one of two very useful lighting laws. (The other—the inverse square law—is discussed later.) Based on geometric principles, the cosine law states that the illumination of a surface varies as the cosine of the angle between an imaginary perpendicular line to the surface (i.e., the normal) and the actual direction of the incident light (i.e., angle of incidence, θ, see figure 10). To illustrate the cosine law, imagine a light beam consisting of uniformly distributed parallel rays traveling in a particular direction. Assume that 10 lm is incident upon surface A, with a surface area of 1-ft^2, in figure 11. Note that surface A is perpendicular (normal) to the direction in which the light is traveling. The average illumination of this surface could be calculated according to the discussion in the previous section as follows: $E_1 = \phi/A$ of 10 lm divided by 1 ft^2 equals 10 fc.

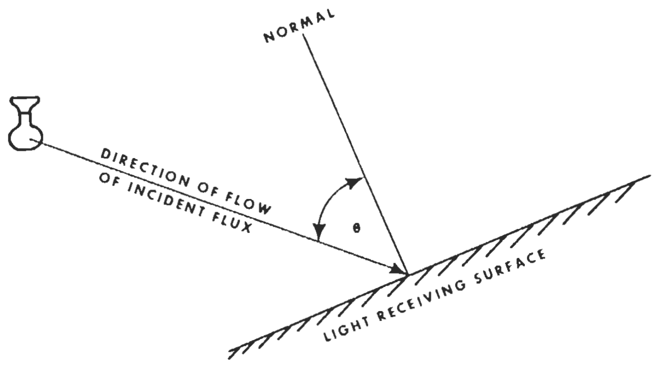


Figure 10.—Determining angle of incidence (θ) when applying the cosine law.

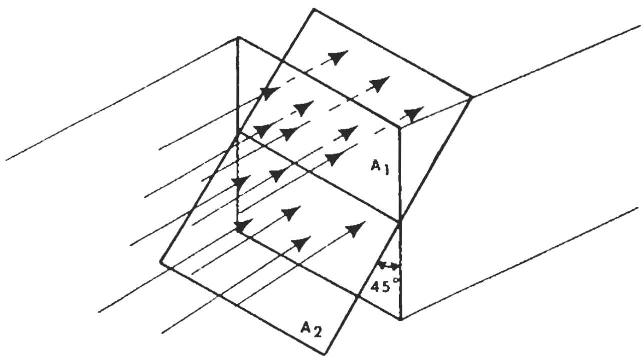


Figure 11.—Basis of the cosine law.

Now, imagine that instead of intersecting a surface perpendicular to the light's direction of travel, this same 10-lm beam intersects a surface rotated θ degrees, as surface A^2 is in figure 11. The illumination is now uniformly distributed over a larger area (A^2) which is equal to A^1, divided by the cosine of θ.

Therefore $E_2 = \phi/A_2$ which equals $\phi/A_1 \times \cos\theta$ or $E_1 \times \cos\theta$.

If θ is 45°, $E_2 = E_1 \cos 45 = 10\ (0.5) = 5$ fc.

Although the cosine law derived was for average illumination, the law also applies equally to point illumination.

Luminous Intensity	Symbol—I	IES and SI unit—candle (c)

Luminous intensity is a concept used to describe how a light source (e.g., a lamp or luminaire) distributes the total luminous flux, or lumens, it emits into various portions of the space surrounding the source. The geometric concept of the *solid angle* is used to define the particular portion of surrounding space in question. Before luminous intensity is discussed, the geometric concept of solid angle must be explained.

A solid angle is simply a three-dimensional angle. It is formed by a point at the center of a sphere and a surface, of any shape, which comprises a part of the surface of the sphere. Figure 12 illustrates various forms of solid angles.

The dimension of a solid angle, w, is determinated by finding the area, A, of the sphere subtended, or enclosed,

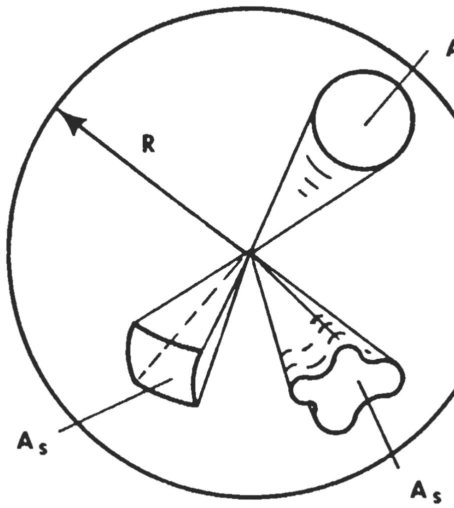


Figure 12.—Solid angle forms.

by the angle divided by the radius, R, of the sphere squared. Hence,

$$w = A_s/R^2. \quad (2)$$

The unit of the solid angle is the steradian (sr). A subtended surface area of 1 ft^2 on a sphere of 1-ft radius forms a solid angle of 1 sr.

Note that the spherical area subtended by a solid angle varies with the radius squared. For example, a 1-sr solid angle would subtend a 1-ft^2 area on a 1-ft radius sphere. The same solid angle would subtend 4 ft^2 on a 2-ft radius sphere, or 9 ft^2 on a 3-ft radius sphere. The following sample problem shows one use of the solid angle concept in a lighting design problem.

> *Problem.*—A mining vehicle incandescent headlight with a spot beam has an effective beam angle of 30°, as shown in figure 13. What spherical surface area will the beam subtend at 10 and 20 ft? (Note, beam angle can be converted to solid angle by using the formula $w = \pi\ (1 - \cos\theta)$ where θ is the beam angle.)
>
> *Solution.*—Equation 2 ($w = A_s/R^2$) defines the steradian. Therefore, any spherical subtended area, A_s, at any distance, R, is $A_s = wR^2$. Substituting the equation given for converting plane angles to solid angles, $A_s = 2\pi\ (1 - \cos\theta)R^2$.
>
> For 30° beam angle, θ, and radius of 10 ft, $A_s = 2\pi\ (1 - \cos 30°)(10^2)$ or $A_s = (0.84)(100)$ which equals 84 ft^2. When R equals 20 ft, $A_s = (0.84)\ (400)$, which equals 336 ft^2.

This problem shows how the light distributed from a luminaire might be described using the solid angle concept and how this concept conveniently describes beam spread with distance.

Luminous intensity is defined mathematically as follows:

$$I = \phi/w, \quad (3)$$

where I is equal to the luminous intensity of a point source of light in a direction defined by a particular solid angle, φ is the total luminous flux (lumens) emanating from the point source within the specified solid angle, and w is the dimension of that solid angle in steradians. The candle is the luminous intensity unit (both the SI and IES systems) and equals 1 lm/sr.

Figure 14 illustrates the concept of luminous intensity. The lines in the figure may be thought of as representing equal amounts of lumens, or light energy flow. As shown, solid angle A and solid angle B are the same size, but the density of luminous flux in solid angle B is greater than in solid angle A. Therefore, the luminous intensity is higher in B than it is in A.

Luminous intensity can be compared to the spray intensity of a garden hose with an adjustable nozzle. If a constant water flow is assumed, the nozzle can be adjusted to spray over a wide angle in a low-intensity spray or over a narrow angle in a high intensity spray. Luminous intensity differs from spray intensity in that the density of light energy flow (lumens) in a particular solid angle is considered rather than the density of water droplets in the solid angle.

As noted, intensity is a directional quantity, with the direction in question being defined by the line that forms the axis of the solid angle. The intensity of the light source may, indeed, vary with direction. Intensity, as calculated from equation 3, is an average intensity over the entire solid angle, w. As w is subdivided into smaller and smaller solid angles, the direction of the intensity is better defined and the distribution of light from the source is more accurately established. The following problems illustrate the concept of luminous intensity.

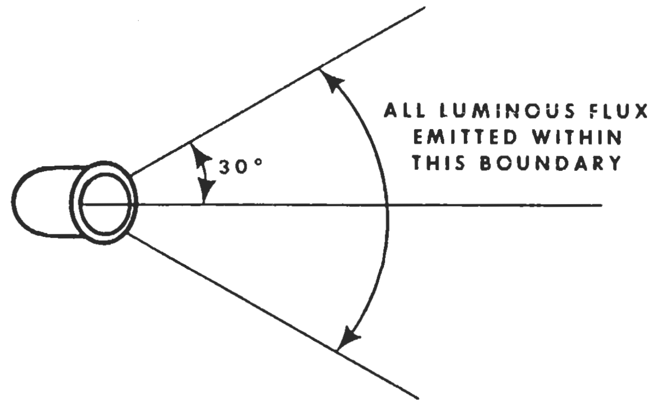


Figure 13.—Beam angle of mining vehicle headlight.

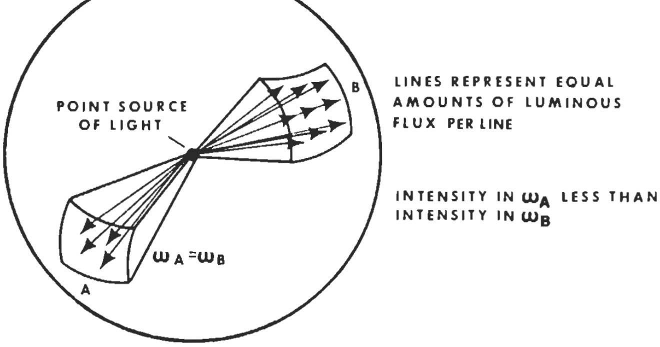


Figure 14.—Concept of luminous intensity.

Problem.—Assume that the manufacturer's specifications for a headlight show that it emits light at a rate of 1,800 lm. What is the *average* intensity of the headlight beam?

Equation 3 ($I = \phi/w$) is used to calculate an *average* intensity over the entire solid angle formed by the beam. If w equals 0.84 sr, the solution is I equals 1,800 lm divided by 0.84 sr or 2,143 c.

Problem.—Now assume that the light energy distribution varies within the beam of this headlight as follows:

Portion of beam angle	*Share of total lumens, pct*
0° to 10°	50
10° to 20°	35
20° to 30°	15

Using equation 3, calculate the *average* intensity within each portion of the beam. (Note.—Such a distribution might be found with typical "spot" 150-W incandescent headlight fixtures.)

Solution.—In order to use equation 3, w must be calculated for each portion of the beam. This may be done using the formula $w = A_s/R^2$ and subtracting the solid angle equivalent of the lower beam angle defining the range in question from the solid angle equivalent of the larger beam angle in this range. Using the formula for converting beam angle to solid angle ($w = 2\pi\ (1\text{-}\cos\theta)$) results in the following:

0° to 10° = 0.095 - 0, or 0.095 sr;
10° to 20° = 0.379 - 0.095, or 0.284 sr; and
20° to 30° = 0.824 - 0.379, or 0.463 sr.

To determine lumens within each portion, multiply the total lumens by the appropriate percentage, as follows:

0° to 10°—0.50 X 1,800 = 900 lm,
10° to 20°—0.35 X 1,800 = 630 lm, and
20° to 30°—0.15 X 1,800 = 270 lm, for a total of 1,800 lm.

The average intensity of each portion of the beam can be calculated using equation 3.

0° to 10°—I = 900/0.095, or 9,474 c;
10° to 20°—I = 630/0.284, or 2,218 c; and
20° to 30°—I = 270/0.463, or 583 c.

This is a more accurate and useful description or distribution of light from the headlight than the 2,143-c *average* intensity previously calculated. Nonetheless, the preceding example may have provided useful information if the light source was a more uniform emitter, as are some lamps.

Inverse Square Law

A common problem in lighting system design is determining the illumination on surfaces at various distances from a light source. This problem can be handled using the inverse square law.

Given the intensity of the light source depicted in figure 15 in the direction defined by the illustrated solid angle, the flow of luminous flux within that solid angle can be calculated:

$$I = \phi/w, \text{ therefore } \phi = Iw.$$

The illumination of the depicted surface subtended by the solid angle would be equal to this flux, ϕ divided by the area of the surface, A_s.

Thus $E = \phi/A_s = Iw/A_s$, since $\phi = Iw$.

The solid angle concept allows this area to be defined in terms of the distance from the source—$w = A_s/R^2$, therefore $A_s = wR^2$

Substituting $A_s = wR^2$ into the illumination equation, it is seen that

$$E = Iw/A_s,\ Iw/wR^2, \text{ and } I/R^2. \qquad (4)$$

This relationship among illumination, intensity, and distance between the source and light receiving surface is known as the inverse square law. It enables illumination of a surface to be calculated if the intensity of the light source and the distance between the light source and the surface are known.

In general practice, it is common to calculate the illumination at a point on a surface rather than an area on a sphere. The inverse square law can then be modified to use the distance, D, between the light source and the point rather than the radius, R, of the sphere. Equation 4 then becomes $E = I/D^2$.

The inverse square law assumes a point source of light. Most real light sources are not point sources, however. Nevertheless, the law can be applied, with negligible error, if the distance between the light source and the illuminated area is greater than five times the maximum dimension of the light source. Consequently, using the law is practical for most purposes encountered in lighting design, except where long, tubular light sources (e.g., fluorescent lamps) are used.

A second assumption inherent in the inverse square law is that the surface area is perpendicular to the direction of light flow. When this is *not* the case, the inverse square law can be combined with the cosine law as follows:

$$E_\theta = E_{normal} \times \cos\theta \text{ or } I/D^2 \times \cos\theta. \qquad (5)$$

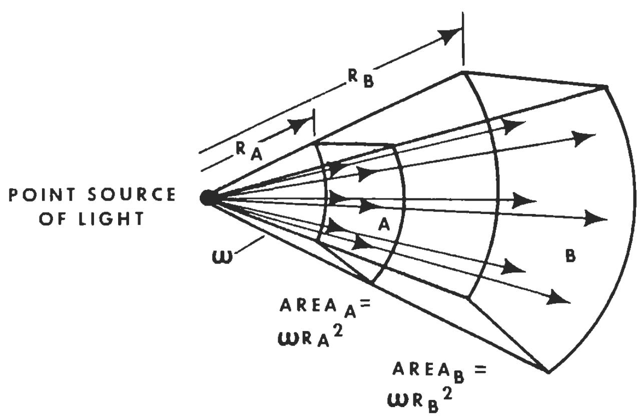


Figure 15.—Basis of the inverse square law.

The following problem illustrates uses of the inverse square law.

The average intensity for the central 10° of a headlight beam was calculated to be 9,474 c. Assume that this is the intensity at the beam axis.

Problem.—To what level of illumination would the headlight illuminate an area perpendicular to the lamp axis at a distance of 10 ft? At a distance of 15 ft?

Solution.—Using $E = I/D^2$, when D = 10 ft, E = 9,474 c/(10 ft)^2 or 94.7 fc. When D = 15 ft, E = 9,474 c/(15 ft)^2 or 42.1 fc.

Problem.—What would happen to the illumination of each surface in the first problem if their normals (with respect to the direction of the light) were tilted at an angle of 30° from the lamp axis?

Solution.—Equation 5 can be used to solve for E_θ of the surface titled θ° (in this case θ equals 30°).

At 10 ft, I/D^2 = 94.7 fc, therefore, E_θ = 94.7 cos 30° (0.866), or 82 fc.

At 15 ft, I/D^2 = 42.1 fc, therefore, E_θ = 42.1 cos 30° (0.866), or 36 fc.

Alternative solutions are available. If an illumination level measurement, $E\omega$, is taken at distance D_1, the illumination level, E_2, at distance D_2, can be calculated using a variation of the inverse square law show in the following.

At distance D_1 the illumination level is given by $E_1 = I/D^2{}_1$, and at distance D_2 by $E_2 = I/D^2{}_2$. Setting up the ratio of the two illumination values permits solving for E_2:

$$E_1/E_2 = \frac{I/D^2{}_1}{I/D^2{}_1}$$

Since I is constant, $E_1/E_2 = \dfrac{1/D^2{}_1}{1/D^2{}_2}$ and $D^2{}_2/D^2{}_1$

Solving for E_2

$$E_2 = E_1\, D^2{}_1/D^2{}_2 = E_1\, D^2{}_1/D_2.$$

For the first problem, the value of E at 10 ft was 94.7 fc. Using the alternative solution for E, at 15 ft E = 94.7 (10/15)^2, 94.7 (0.44), or 42.1 fc.

As shown previously, the illumination level on a surface oriented at angle θ to the centerline of the light source is adjusted by a factor equal to the cosine of θ. Therefore, the alternative equation for E_2 becomes $E_2 = E_1(D_1/D_1)^2 \cos\theta$. At θ = 30°, E_2 = 94.7(10/15)^2 cos 30°, which is 94.7 (0.44)(0.866) or 36 fc.

Candlepower Curves and Their Uses

The most common way of presenting lighting data on luminaires and lamps is by the candlepower curve or some variation of this curve. A candlepower curve is a plot of the intensities of a light source in a particular plane, at all angles around it. Figure 16 illustrates a candlepower curve for a household incandescent fixture. As shown, these curves are usually plotted using polar coordinates.

Candlepower curves are extremely valuable for various design calculations. They depict how a light fixture distributes its total luminous flux into the surrounding space. Also, because of the relationship between illumination and intensity—the inverse square law—these curves may be viewed as depicting a light fixture's ability to illuminate in various directions. The higher the intensity in a given direction, the greater the ability of that source to illuminate surfaces in that direction. The curves are obtained by making *illumination* measurements at various orientations with respect to the lighting fixture and utilizing the inverse square law to calculate the intensity at that orientation, as is illustrated in the following problem.

Problem.—Assume that the headlight is suspended in the center of a large room. (The room is painted black to minimize any secondary light reflections from the walls and ceiling.) An illumination meter is used to measure footcandle levels on the horizontal plane around the fixture. The measurements are taken at 3° intervals starting at the lamp central axis. A constant distance of 10 ft between the light and meter is maintained while the measurements are taken (fig. 17). The results of the measurements are as follows, in footcandles:

0°	96	12°	42	24°	3
3°	98	15°	17	27°	2
6°	89	18°	9	30°	0
9°	60	21°	4		

Because the beam is symmetrical about the beam axis, these data can be used to plot a candlepower curve (light intensity versus angle of observation).

Solution.—The inverse square law permits each illumination measurement to be converted to an intensity measurement by multiplying it by the square of the distance to the point of observation—$E = I/D^2$, therefore $I = E \times D^2$.

Since all measurements were made at 10 ft, the footcandle readings can be multiplied by 100 (10^2) to obtain the intensity in candles at that distance.

0°	96 fc	9,600 c	18°	9 fc	900 c
3°	98 fc	9,800 c	21°	4 fc	400 c
6°	89 fc	8,900 c	24°	3 fc	300 c
9°	60 fc	6,000 c	27°	2 fc	200 c
12°	42 fc	4,200 c	30°	0 fc	0 c
15°	17 fc	1,700 c			

Figure 18 shows these values plotted on polar coordinate paper to obtain the candlepower curve.

A candlepower curve applies only to the intensities in a single plane that passes through the light fixture. To fully describe a fixture's light distribution, several candlepower curves in different planes may be necessary, depending on the symmetry of the light distribution.

One of the primary uses of candlepower curves is to utilize these data to calculate the surface illumination that the fixture would provide, given the geometry and dimensions of a particular setting. The following sample problem illustrates an application of this technique, which involves the inverse square and cosine laws. Note that the technique is also applicable to determination of illumination levels obtained from more than one luminaire. In this case, the calculations would be performed for each luminaire separately and the obtained illumination values would be added at each point.

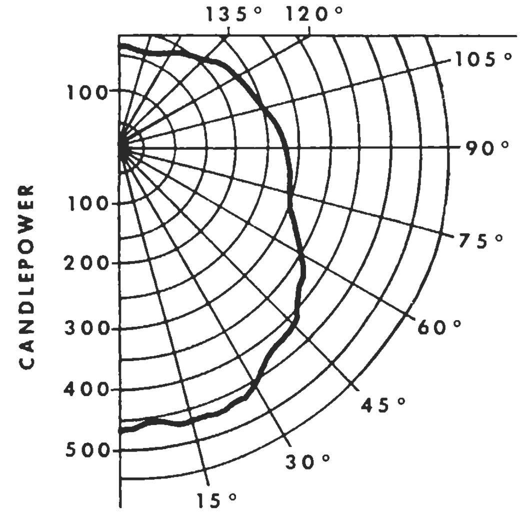


Figure 16.—Candlepower curve for a typical incandescent fixture.

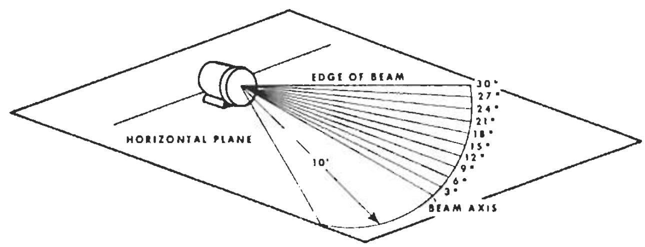


Figure 17.—Light measurement to establish candlepower curve for a mining vehicle headlight.

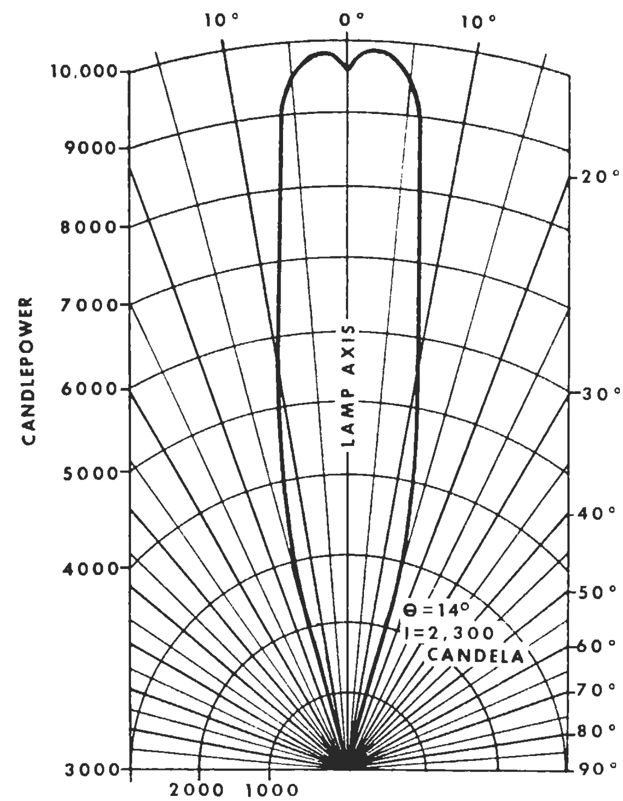


Figure 18.—Candlepower curve for a mining vehicle headlight.

Problem.—Using the candlepower curve established for the mining vehicle headlight in the previous problem, determine the illumination levels on the coal face if the headlight is mounted on the center of the inby end of the cutting machine and the machine is 8, 12, and 16 ft from the face.

Solution.—The inverse square law and the cosine law, coupled with the candlepower curve, enable calculation of illumination at any point on the coal face. Perform the calculations for 1-ft intervals from the beam axis, as shown in figure 19.

Illumination on a surface normal to the direction of light travel is defined by the inverse square law as $E_{normal} = I_\theta/D^2$. When the surface is not normal to D, as is the case in this problem, the actual illumination is reduced according to the cosine law— $E_{actual} = E_{normal} \times \cos\theta = I_\theta/D^2 \cos\theta$.

Both D and θ can be determined by using trigonometry. Referring to figure 19, it can be seen that $D^2 = X^2 + Y^2$. Also, $\tan\theta = X/Y$, therefore, $\theta = \arctan X/Y$.

Perform the calculations for Y = 8 ft and X = 2 ft from beam axis: $D^2 = X^2 + Y^2$, $2^2 + 8^2 = 68$; $D = \sqrt{68}$ or 8.25 ft; and $\theta = \arctan X/Y = \arctan 2/8$ or 14°.

To calculate E_{actual}, a value must be first obtained for I_θ, when θ equals 14°. This is done by consulting the candlepower curve, where the value shown for I_θ is 2,300 c. Hence, $E_{actual} = I_\theta/D^2 \cos\theta$, 2,300/68 cos 14°, or 33 fc.

The footcandle values obtained from the calculations in the preceding problem for different distances from the lamp axis and for the specified distances from the face are presented in table 2.

Table 2.—Footcandle values for different distances from lamp axis and specified distances from coal face

Distance from lamp axis, ft	Distance from headlight to face, ft— 8	12	16
0	150	67	38
1	121	64	38
2	33	38	34
3	6	15	18
4	2	5	8
5	0	2	5
6	0	1	2
7	0	0	1
8	0	0	1
9	0	0	0

Because the candle power curve for the headlight is symmetric about the lamp axis, lines of equal illumination will form concentric rings as shown in figure 20.

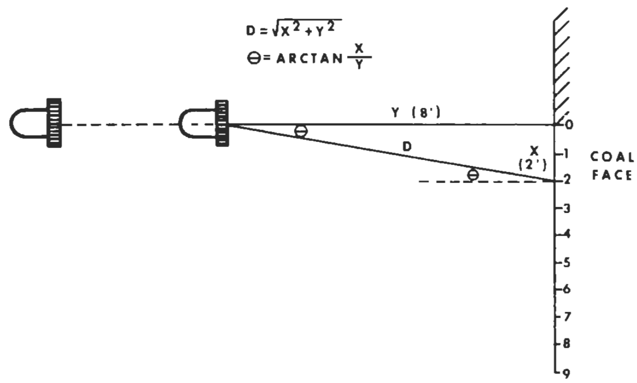


Figure 19.—Geometry for performing illumination calculations.

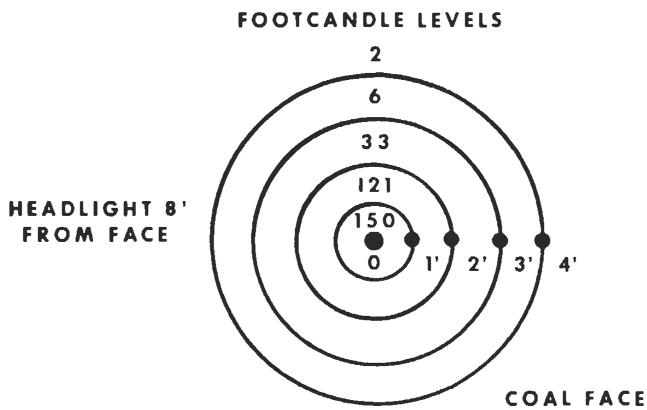


Figure 20.—Pattern of illumination with headlight 8 ft from mine face.

The preceding problem has illustrated how candlepower curves can be used to obtain illumination patterns on a surface for various luminaire locations. When curves are *not* symmetric, as for a fluorescent lamp, similar calculations can be performed using candlepower curves for different planes and then drawing lines to connect the points of equal candlepower levels.

Three conclusions can be drawn when comparing the values in table 2. As distance from the face is increased—

1. The luminaire distributes the light over a wider area;
2. Peak illumination levels are decreased; and
3. Differences in illumination between the various points tend to decrease; i.e., light distribution becomes more even.

Depending upon their intended use, candlepower curves can be converted to other forms for the sake of convenience. A commonly used alternative form is the isofootcandle curve. The following problem illustrates the conversion to and the application of isofootcandle curves.

An isofootcandle curve shows the distance a source will illuminate to a certain footcandle level in the various directions around the source. A typical drawing includes a family of curves at different footcandle levels.

Problem.—Using the inverse square law, convert the headlight candlepower curve to an isofootcandle curve. Use this curve to determine the illumination levels of a surface normal to the lamp axis and 35 ft away.

Solution.—To convert the candlepower curve to an isofootcandle curve, first read the candela values for a sampling of angles. For the purposes of this problem, the values will be read at 5° intervals. (To insure more accurate curves, one would read the values at smaller intervals, particularly where intensity values change rapidly.)

After the readings are taken, the inverse square law is used to calculate the distance the luminaire will light to the various footcandle values. The results of these calculations are summarized in table 3.

Assume the 2-, 4-, and 6-fc isolines are to be plotted. By taking the distance values for the various footcandle values of interest (2, 4, and 6 fc), the isofootcandle curves can be plotted on polar-coordinate graph paper as is shown in figure 21.

Illumination at a surface 35 ft along the lamp axis may be determined simply by drawing such a surface on the isofootcandle curve (fig. 21). Distances from the axis where the isolines intersect the surface may be scaled from the drawing. Because the headlight isofootcandle curve is symmetric about its axis, the isofootcandle lines would appear as shown in figure 22.

It is evident that use of an isofootcandle curve makes determination of footcandle levels much easier than the technique using candlepower curves applied in the preceding problem.

Table 3.—Illumination distances at various degrees from lamp axis and various levels of luminous intensity

Degrees from lamp axis	Luminous intensity, c	Distance of illumination of 2, 4, or 6 fc, ft		
		2 fc	4 fc	6 fc
0	9,600	69	49	40
5	9,400	68	48	39
10	5,300	51	36	29
15	1,700	29	21	17
20	500	16	11	9
25	300	12	9	7
30	0	NAp	NAp	NAp

NAp Not applicable.

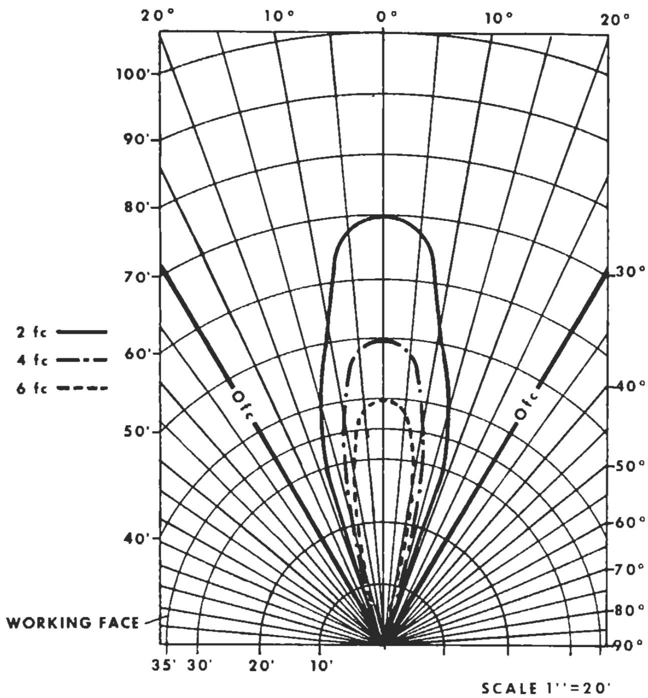


Figure 21.—Isofootcandle curve for a mining vehicle headlight.

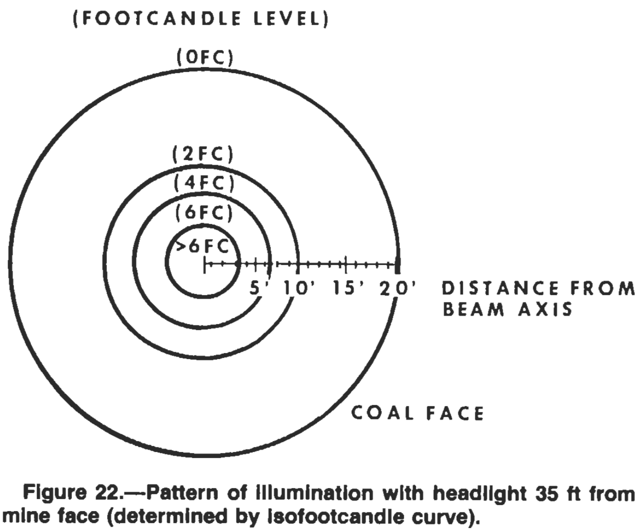


Figure 22.—Pattern of illumination with headlight 35 ft from mine face (determined by isofootcandle curve).

Luminance Symbol — L IES unit — Candle per square inch (c/in²)

SI unit — Candle per square meter (c/m²)

In physical terms, luminance is a concept used to quantify the density of luminous flux emitted by an *area* of a light source in a particular direction toward a light receiver such as an eye. The area of a light source, in practice, may be an area of a light reflecting surface, such as a wall or desk top; an area of a light emitter, such as a lamp; or an area of a light transmitter, such as a diffusing lens on a luminaire. The most common definition of luminance, L, is

$$L = \frac{I}{A_s \text{ projected}} = \frac{I}{A_s \cos \theta} \quad (6)$$

Referring to figure 23, I is the intensity of light produced by area A_s of the source in the direction of the receiver, P, and A_s projected is the projected area of the source when

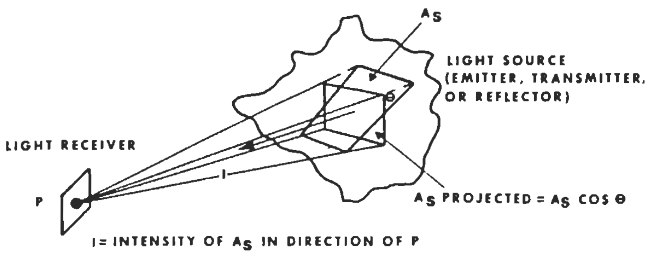


Figure 23.—Concept of luminance.

viewed from the receiver. A_s projected is equal to $A_s \cos \theta$ where θ is the angle between the normal to A_s and the angle of observation. Figure 23 illustrates the concept. When A_s is large, L is the *average* luminance of A_s; as A_s decreases, L approaches a value of point luminance.

The luminance concept is extremely important in illumination design because it is a physically measurable quantity that correlates with the subjective evaluation of "brightness" when viewing a surface or object. The mathematical definition of luminance (equation 6) does not, perhaps, appear meaningful at first. However, its significance becomes evident when one manipulates the variables involved and compares the effect on the magnitude of luminance with the effect on the subjective evaluation of brightness, if the same manipulation were to be observed in an actual lighting application.

First, vary the intensity, I, of the source while keeping the area, A_s, constant. For example, envision looking at an incandescent light bulb connected to a dimmer switch and the switch being manipulated to increase or decrease intensity. As the intensity of the bulb increases, so does the subjective evaluation of brightness of the area observed, and, in accordance with equation 6, so does the luminance.

Next, consider the effect of varying the area of the source while keeping the intensity of the source constant. In this case, envision 10 lighted wax candles first distributed over a 25-in^2 area and then over a 10-in^2 area. If the point of observation was distant from the two areas, the intensity in that direction would be approximately constant in both cases. However, the average luminance (see equation 6), as well as the subjective evaluation of brightness would be greater when the candles were distributed over the smaller area.

Finally, vary the distance of observation. In this case, consider observing the wall of a room from 8 and 12 ft. From equation 6 it can be seen that luminance is independent of distance. Likewise, the wall appears smaller, but not more or less bright as one moves away from it.

To summarize, luminance and, therefore, the perception of brightness—

Vary directly with the intensity of a light source of constant area;

Vary inversely with the area of a light source having a given intensity; and

Are independent of distance of observation.

A final variable of importance is the direction of observation. As noted previously, both light sources and light reflectors do not always distribute their flux uniformly; hence, their intensity varies with angle of observation. In addition, the projected area of the source also varies with angle of observation. Because of this, no generalizations can be made with respect to the effect of angle of observation except that angle of observation does have bearing. Candlepower curves (in the case of lamps and luminaires) and accurate reflectance measurements can be used to establish these effects.

Average Luminance and Candlepower Curves

A candlepower curve of a luminaire can be used in conjunction with the physical dimensions of the source and the definition of luminance to calculate the *average* luminance of the source when observed from a particular point. This calculation is useful in assessing the visual comfort (i.e., level of glare) of lighting designs. The following sample problem illustrates calculation of the average luminance observed at certain positions.

> *Problem.*—Assume that the lens of the mining vehicle headlight has a 4.5-in diameter. If an individual looks directly at the fixture from position P (fig. 24), determine the *average* observed luminance by using the candlepower curve derived previously. What is the *average* luminance observed at position Q?
>
> *Solution.*—Average luminance is equal to intensity divided by projected surface area. Projected surface area may be determined by multiplying the actual area by the cosine of the angle of incidence, θ: $Ap = Aa \cos \theta$. From geometry, actual area $= \pi(\text{diam}/2)^2$, $\pi(4.5/2)^2$ or 15.9 in^2; projected area in P direction $=$ 15.9 X cos 15° or 15.4 in^2, and projected area in Q direction $=$ 15.9 X cos 5° or 15.8 in^2.
>
> From the candlepower curve (fig. 18), it can be seen that the intensity at 15°, in the P direction, equals 1,700 c. Also, the intensity at 5°, in the Q direction, equals 9,400 c.
>
> It is known from equation 6 that $L_{average} = I/A_{projected}$. Therefore, $L_P = 1{,}700$ c/1.54 in^2, or 110 c/in^2, and $L_Q = 9{,}400$ c/15.8 in^2, or 594 c/in^2.
>
> Notice that the distance to P or Q did not enter the calculations since luminance is independent of distance.

As noted in a previous section, isointensity curves for luminaires are obtained by taking illumination (footcandle) measurements in a low-reflectance room and calculating intensity values using the inverse square law. Since coal mines and mine simulators are typically low reflectance, approximate luminance values of machine-mounted luminaires can be calculated directly from illumination measurements taken on-site without the necessity of having candlepower curves. The following problem explains this technique.

> *Problem.*—The measured illumination at an operator's station 6 ft from a single luminaire is 4 fc. For purposes of this measurement, the illumination meter was angled to the luminaire for maximum reading. The projected area of the luminous surface of the luminaire in the direction of the operator is 30 in^2. Solve for the average luminance of the light-emitting surface.
>
> *Solution.*—$I_\theta = ED^2$ and $L = I_\theta/Ap$; therefore, $L = ED^2/Ap$, $L = (4X6^2)/30$ or 4.8 c/in^2.

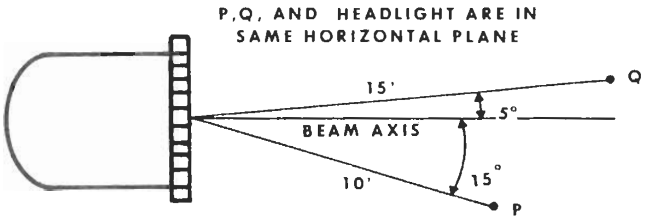


Figure 24.—Location of observation points P and Q for determining luminance of headlight.

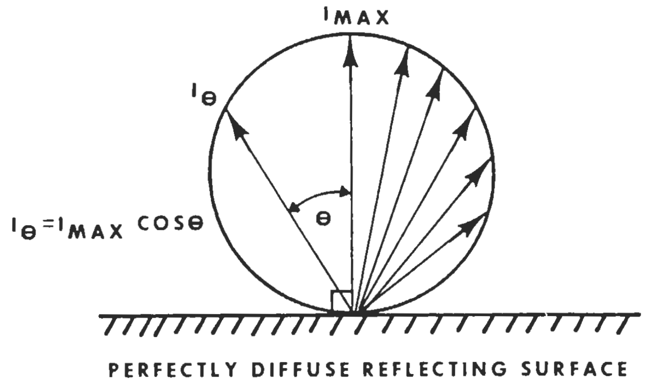


Figure 25.—Relationship between intensity and angle of observation for a perfectly diffuse reflector.

Perfectly Diffuse Reflectors and Emitters

Consider a small flat surface emitting or reflecting light such that the intensity varies with direction of observation as $I_\theta = I_{max} \times \cos\theta$ (see figure 25).

As mentioned earlier, the projected area of the surface at any angle θ is $A_\theta = A_{normal} \cos\theta$.

If the luminance at any angle θ is determined, then $L_\theta = I_\theta/A_\theta = I_{normal} \times \cos\theta / A_{normal} \times \cos\theta = I_{normal}/A_{normal}$ = constant.

For a small, flat surface, luminance is constant for any angle of observation. Such a surface is called a "perfectly diffuse" reflector or emitter. Many materials, such as a wall painted with a flat paint, approximate this distribution of emitted or reflected luminous flux.

For such a perfectly diffuse reflector or transmitter, the ratio of the luminance, L, of the surface to the total lumens per unit area emitted by the surface can be shown to equal a constant, π; luminance divided by lumens emitted per unit areas equals the constant, π.

Because of this relationship, illumination designers often consider lumens emitted per unit area to be the same as the luminance quantity. If the area is in square feet, the quantity lumens per square feet is given the special name of footlamberts. Luminance measured in footlamberts will be represented in this text by the symbol L'. Substituting into the constant equaling equation, $L' = L/\pi$.

The conversion between footlamberts (an L' quantity) and candles per square inch (an L quantity) is $144 \times \pi$ or 452 fL = 1 c/in^2. The value of the footlambert concept becomes evident in the next section.

Also note that since the luminance of a perfectly diffuse reflector has a constant relationship with the lumens emitted per unit area, this luminance could be easily measured directly with a photoelectric device similar to an illumination meter that converts light energy to electrical energy. The only requisite is that the field of acceptance of the device must be totally subtended by the area for which the luminance is being measured. Hence, such a device would be inadequate for small objects, but would work fine for large surfaces such as interior walls, coal ribs and roof, etc.

Relationship Among Reflectance, Illumination, and Luminance

Reflectance, p, is the ratio of reflected to incident light energy, which may be defined as lumens emitted per unit area divided by lumens incident per unit area.

For perfectly diffuse reflectors, lumens emitted per unit area is luminance, L', and lumens incident per unit area is illumination, E, therefore,

$$\rho = L'/E\ . \qquad (7)$$

This is an extremely important equation for illumination design because it can be used to determine the illumination that should be provided for an environment, given the desired luminance (i.e., brightness) level and the reflectance of the environment. The following sample problem utilizes equation 7.

The simple relationship among luminance, illumination, and reflectance represented by equation 7 applies only to perfectly diffuse reflectors. Although no surface exactly meets this criterion, such a relationship often applies over a wide range of viewing angles making the use of the formula a practical matter in many cases. Although coal has a specular component in its reflection, the cleaved surfaces are generally not well oriented. In the main, coal can be considered a diffusing surface, and for practical purposes of analysis, perfectly diffusing. In some design problems, detailed reflectance measurements from many angles of observation are often made to assess the limits to which this equation may be applied.

Problem.—Using the footcandle distribution derived for a surface 35 ft from a headlight, determine the luminance of the surface if it is coal with a reflectivity, ρ, of 4 pct or if it is rock-dusted coal with a reflectivity of 35 pct. In both cases, assume that the surface is a perfectly diffuse reflector.

Solution.—Because it is assumed that the surface is a perfectly diffuse reflector, luminance values in footlamberts can be determined by multiplying the footcandle values by the reflectivity—$L = \rho \times E$. Therefore $L' = 0.04 \times E$ for coal and $L' = 0.35 \times E$ for rock-dusted coal.

Figure 26 shows conversion of the following illumination levels to luminance levels.

Coal	*Rock-dusted coal*
$L' = 0.04 \times 2\ \text{fc} = 0.08\ \text{fL}$	$L' = 0.35 \times 2\ \text{fc} = 0.7\ \text{fL}$
$L' = 0.04 \times 4\ \text{fc} = 0.16\ \text{fL}$	$L' = 0.35 \times 4\ \text{fc} = 1.4\ \text{fL}$
$L' = 0.04 \times 6\ \text{fc} = 0.24\ \text{fL}$	$L' = 0.35 \times 6\ \text{fc} = 2.1\ \text{fL}$

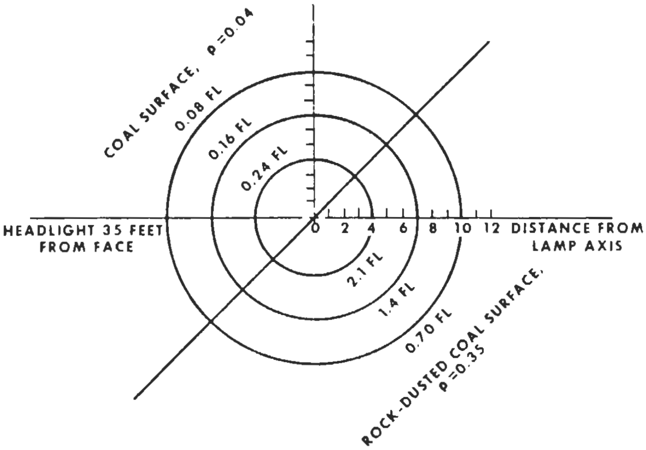


Figure 26.—Calculated luminance levels for coal and rock-dusted coal with headlight 35 ft from mine face.

Limits of Agreement Between Luminance and Perceived Brightness

As noted earlier, luminance is a physical concept that has been defined to correlate with the perceived brightness. It is important to recognize this correlation is not an absolute one, however. If a series of objects were observed under the same level of background illumination, they could easily be arranged in order of perceived brightness and this order would correspond to the ordering that would be obtained if the level of luminance from each object was measured with instruments.

In this case luminance and the subjective evaluation of brightness agree perfectly. Now imagine making a comparison of the subjective brightness of a miner's cap lamp if it was observed in the dark surroundings underground and outside on a sunny day. The cap lamp would not appear as bright when observed outside on a sunny day as it would underground. However, if the luminance of the cap lamp was measured, it would be the same regardless of where it was measured.

The purpose of this discussion is to illustrate the limits of the agreement of luminance and the subjective evaluation of brightness. In the case of the cap lamp, the eye adaptation state differed in the two instances and this affected the way brightness was evaluated. Luminance measurements and the subjective evaluation of brightnesses correlate only when the circumstances of seeing, primarily the eye adaptation state, remain constant.

CHAPTER 3.—LIGHT AND VISION RELATIONSHIPS

This chapter addresses the visual needs of the worker, which are the ultimate basis for illumination design. These needs are defined by (1) the requirements for optimal functioning of the visual sensory system, and (2) the light needed to establish an appropriate level of visibility necessary for safe, efficient work performance.

The lighting design process begins by carefully determining these needs. Then practical, technical, and economic factors are considered in establishing an appropriate system design.

This chapter explains how light and vision interact. It identifies the visual needs of coal miners and indicates, in general terms, what can be done to accommodate those needs. First, the functions of the eyes and the rest of the visual sensory system are examined. Then, various environmental factors that affect the visibility of surroundings are discussed.

THE EYE AND HOW IT WORKS

The eye (fig. 27) is the organ of sight. It senses the light that enters it and acts as the first processor of this light. It then provides this information to the brain information for determination of the form, size, shape, color, position, and motion of the objects in view.

To understand how light and vision interact, it is helpful to consider the eye as a mechanism made up of two subsystems: (1) the light control system and (2) the receiver-decoder system. The parts of each system are outlined in the following tabulation.

Light control system	*Receiver-decoder system*
Eyelid.	Retina and its photoreceptors, which are the rods and cones.
Cornea.	
Iris-pupil.	
Lens and its ciliary muscle.	

Parts of the Light Control System

The light control system focuses light on the light sensitive surface of the eye and controls the amount of light to which the receiver-decoder system is exposed. The parts of the light control system (see figure 27) are the—

Eyelid: A flap of skin that covers and protects the eye. Under extreme brightness, it closes to reduce the amount of light entering the eye.

Cornea: The clear, bulging, front portion of the sclera. It permits light to be transmitted into the eye and works in conjunction with the lens to focus light on the retina.

Iris-pupil: The iris is the colored portion of the eye consisting of muscle tissue that extends over the lens. The iris defines the circular opening called the pupil (the pupil itself is not an actual structure). Light passes through the pupil to the lens. The iris automatically controls the size of the pupil and, therefore, acts as a diaphragm controlling the amount of light entering the eye.

Lens-ciliary muscle: The lens is a flexible, transparent capsule surrounded by a ring of muscle tissue, called the ciliary muscle, directly behind the iris. The lens works in conjunction with the cornea to focus light on the retina.

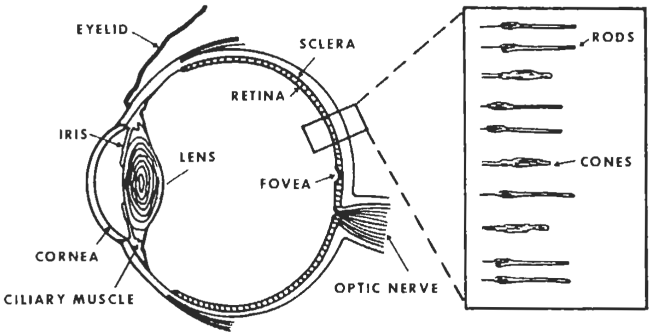


Figure 27.—Parts of the eye.

The ciliary muscle rounds or flattens the lens, thereby adjusting for objects at various distances from the eye.

Parts of the Receiver-Decoder System

The retina is a thin sheet of nerve tissue that lines the back of the eye. Photoreceptors are specialized cells of the retina. The retina contains two types of photoreceptors—rods and cones. The names are based on the shapes of these cells (see figure 27). The functions of the rods and cones differ in many ways, as will be discussed.

The receiver-decoder system uses the retina and its photoreceptors to (1) process characteristics of incoming light—brightness and color—and (2) pass this information on to the brain for final interpretation.

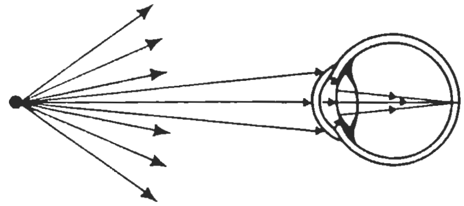
The functioning of the receiver-decoder system and the light control system are examined in detail in the following section. This basic knowledge is extremely important to illumination designers so that they are aware of factors under their control that could impair or enhance these various functions, and they can take appropriate measures in their designs.

LIGHT CONTROL SYSTEM OPERATION

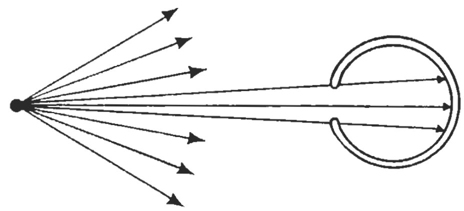
Light Focusing and Accommodation

The eye focuses an "image" of the surrounding environment on the retina by using two parts of the light-control system—the cornea and lens—to bend the incoming light. The light is bent in such a way that all the "rays" of light reflected in the direction of the eye from a particular point, P, on an object being viewed are projected onto a corresponding single spot on the retina (see figure 28*A*). Spatial relationships between the various points on the object are maintained in the image on the retina. The photoreceptors, in turn, respond to the focused image, and the response is integrated by the brain to perceive an object's form and shape. If the eye did not bend the light in such a manner, the light from a particular point on the object would spread over a relatively large area of the retina and only a blur would be perceived (fig. 28*B*).

The amount of light bending necessary to obtain a focused image varies with the distance between an object and the eye. The ciliary muscle adjusts the shape of the eye's lens, and this changes the degree of light bending. The process of changing the lens shape when focusing objects at various distances is called accommodation (see figure 29). When looking at distant objects, less bending is required, the ciliary muscle is relaxed, and the lens is flattened. When looking at nearby objects, more light bending is required, the ciliary muscle is tense, and the lens is rounded. This tension in the ciliary muscle is why some people get eye strain after looking at close objects after a period of time.



A-WITH THE CORNEA AND LENS, LIGHT REFLECTED FROM ANY POINT IN THE SURROUNDINGS IS FOCUSED ON A UNIQUE POINT ON THE RETINA. THIS CREATES A FOCUSED IMAGE ON THE RETINA. DETAILS CAN BE PERCEIVED.



B-WITHOUT THE CORNEA AND LENS, LIGHT REFLECTED FROM A POINT IN THE SURROUNDINGS WOULD SPREAD OVER A WIDE AREA OF THE RETINA. EVERYTHING WOULD APPEAR BLURRED.

Figure 28.—How the cornea and lens focus an image on the retina.

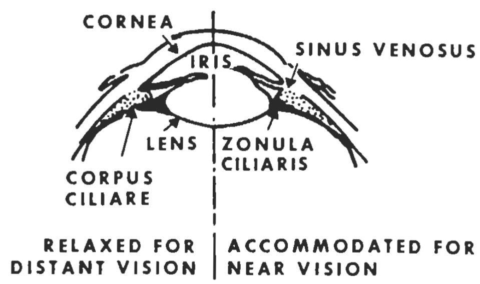


Figure 29.—Lens shape change when focusing (accommodation).

Pupil Size

Pupil size is another important light control function of the eye. As noted previously, pupil size is defined by the position of the iris on the lens. Pupil size serves the following two purposes:

1. It automatically regulates the amount of light permitted to enter the eye under different light levels. When the retina is exposed to low light levels, pupil size gets larger (dilation). When the retina is exposed to high light levels, pupil size narrows (constriction).
2. Pupil size prevents light that would pass through aberrations (i.e., deviations from appropriate curvature) on the outer edge of the cornea and lens from entering the eye. This is accomplished by opening only a limited central area of the lens for light passage. If not for the pupil, the aberrations would somewhat distort the image on the retina. This is why the pupil constricts for near vision.

Other Light Control Functions

Nature has provided the eye with other means for controlling light. The cornea, lens, and eye fluids act as filters. Virtually no light less than 300 nm and very little light above 1,400 nm in wavelength are transmitted by these mediums. Of the light between 300 and 1,400 nm, reduced amounts are transmitted, particularly between 300 and 380 nm. The major effect of this process is that ultraviolet radiation (wavelengths <380 nm) is "filtered," which helps prevent damage to the retina that might occur if the eye were exposed to high levels of ultraviolet radiation. However, it should be noted that these mediums permit considerable transmission of infrared wavelengths (780 to 100,000 nm) which might cause some damage to the retina if exposure is intense.

RECEIVER-DECODER SYSTEM OPERATION

Photoreceptor Function

As noted in chapter 2, the two physical characteristics of light that the eye interprets are its energy level and its wavelength composition. These characteristics ultimately yield perceptions of brightness and color, respectively. The process for making this interpretation begins in the photoreceptors (rods and cones), which contain light-sensitive chemicals (photochemicals). These chemicals react upon light exposure and produce electrical changes in the retina's nerve cells, which are connected to the rods and cones. The nerves subsequently send electrical impulses to the brain where they are processed at various levels to assess brightness and color. Both the rods and cones provide information that enable the brain to make a brightness interpretation of reflected light. However, only the signals from the cones allow the brain to make a color interpretation; rod signals are interpreted merely as various shades of grey. Figure 30 illustrates this interpretation process.

All the details of the process by which the photoreceptors interpret luminance and wavelength characteristics of the light are not precisely known. However, it is known that (1) the direct response of the photoreceptors to light relies on a photochemical reaction; and (2) there are various processes of neural interpretation of these photochemical reactions that enable brightness and color distinctions to be made by the brain.

Operation of the rods is the simplest. Rods contain a light-sensitive chemical called "rhodopsin" or "visual purple." Rhodopsin breaks down into different chemical compounds when exposed to light. This results in a change in electrical energy of the rod cell, one or more of which are connected to a ganglion cell (see figure 31). The change in electrical energy accumulates to a point where the ganglion cell sends a nerve impulse (electrical) to the brain. The frequency of impulses is proportional to the energy of light incident upon the rod. On this basis, the brain responds with an interpretation of what is called brightness.

Operation of the cones is more complex. The cones can be divided into three classes on the basis of the photochemical substances they contain. One class contains a chemical sensitive to short (blue) wavelengths, another to medium (green) wavelengths, and another sensitive to long (red) wavelengths. All three classes generate nerve impulses in a manner similar to the rods. The impulses from cones at a particular locale on the retina are passed to a portion of the brain where they are processed in the following two manners:

1. In an additive process, the signals whose frequency are proportional to the light energy striking the cone cells in question are combined to provide information that will then be used by the brain to make a brightness assessment.
2. In a differentiation process, the signals from all three classes of cones are *compared* to make an assessment of the wavelength mixture of light. This information is subsequently interpreted as color.

Following these two intermediate levels of processing, the brain integrates these neural assessments of brightness and color into the singular final perception "seen."

Light Levels Needed To Stimulate Photoreceptors

Typically, several rods are connected to one ganglion cell, whereas fewer, often only one, cones may be connected to a single ganglion cell. Because the photochemical response of all the photoreceptors combine to incite generation of a nerve impulse, the rods can operate under lower light levels than cones.

Rods begin to respond to luminances of 0.0001 to 0.001 fL. At approximately 0.001 fL some cones begin to function. All the photoreceptors begin to function when a general luminance level of 0.03 to 0.05 fL is reached.

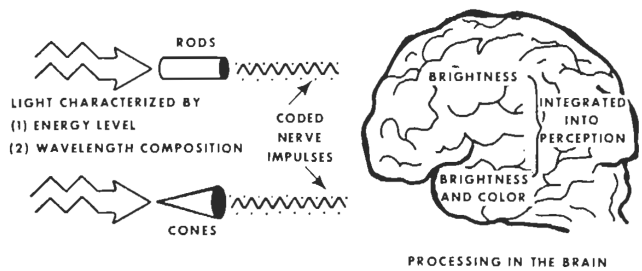


Figure 30.—Light interpretation process.

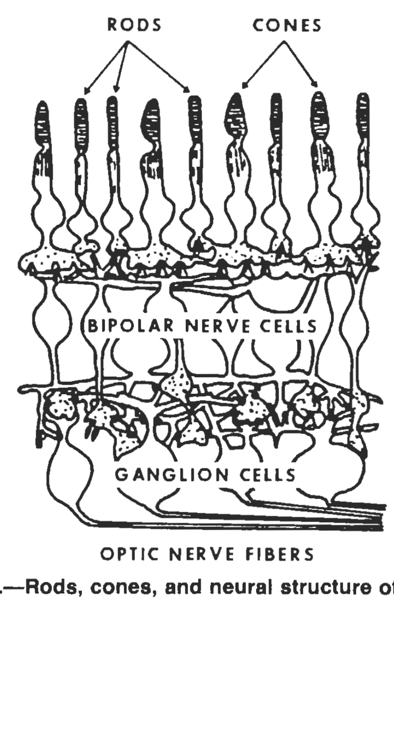


Figure 31.—Rods, cones, and neural structure of the retina.

Since only the cones respond to color, this explains why things seen in dim light are perceived as colorless. For example, think of being in a totally dark room, nothing can be seen (fig. 32*A*). Gradually, the room begins to get lighter and the outlines of the objects in the room can be seen. No colors can be seen, only various shades of gray (fig. 32*B*). This is because the rods alone are reacting to the small amount of light available. As the light gets brighter, things become clearer and colors become apparent (fig. 32*C*); now both rods and cones are responding.

Because of these phenomena, it is desirable that minimum luminance levels in a coal mine be at the level needed for the functioning of all photoreceptors; that is, at least 0.05 fL. This will permit colors and details to be seen. Unfortunately, cap lamp illumination by itself does not meet these minimum luminance levels for cone functioning at the periphery of the cap lamp beam (see figure 33). Consequently, general area lighting is desirable to supplement the cap lamp.

Time and Photoreceptor Response

The speed of photoreceptor response to a change in light stimuli is a function of light levels (photochemicals break down at a rate in proportion to the light energy striking them). This response is quicker at higher levels of illumination. The time delay is of particular importance under situations where reaction times are essential. Consider the next example.

Imagine an operator tramming a shuttle car down an entry and suddenly a person walks out of a crosscut in front of the car. Under low lighting levels, there is a delay between the time the individual steps into the entry and the time the photoreceptors signal the operator indicating the persons presence. This is true even if the operator's line of sight is directly upon the individual. This delay lengthens the total reaction time and can actually be significant enough to mean the difference between a safe stop and one that is too late. Hence, shortening of reaction times is another important benefit that can be realized by increasing general illumination levels in mines.

Photoreceptor Wavelength Sensitivity and the Purkinje Shift at Low Light Levels

The luminous efficiency curve was discussed previously (see figure 2). Also known as the eye sensitivity curve, this curve graphically illustrates how the eye exhibits different sensitivity to various wavelengths of light in terms of the brightness perceived. This sensitivity varies because of wavelength selective characteristics of the photochemicals in the photoreceptors and because some of the transparent media in the eye tend to absorb or filter out certain wavelengths. The former factor is the most significant. The luminous efficiency curve was derived for typical lighting conditions where cone functioning dominates; i.e., at luminance levels greater than 0.05 fL. Cone-dominant vision is called photopic vision.

What about low luminance levels, say of less than 0.01 fL, which may be found in some areas in underground mines? Remember that in such low luminance levels, primarily only the rods are functioning. Rod-dominant vision is called scotopic vision. These rods contain different photochemicals than the cones. The effect is that the eye becomes more sensitive to shorter wavelength light. This change in sensitivity is called the Purkinje shift (named after its discoverer). Figure 34 depicts the Purkinje shift by plotting the spectral luminous efficiency curve for scotopic and photopic vision.

In looking at the luminous efficiency curve for scotopic vision, notice that it has a shape similar to the luminous efficiency curve derived for photopic vision. The only difference in the two curves is that the point of greater sensitivity on the scotopic vision curve has been shifted to shorter wavelength light—from 550 to 502 nm.

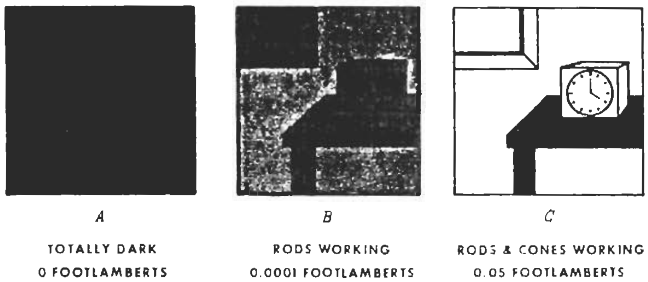


Figure 32.—Minimum general luminance levels for rod and cone functioning.

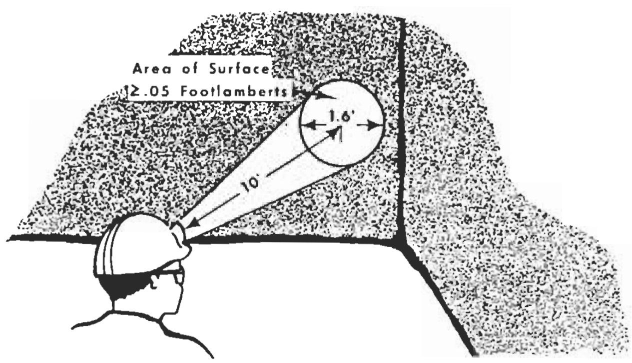


Figure 33.—Area of a coal surface 10 ft from observer (assumed reflectivity of 4 pct) that is illuminated above the minimum level for total cone function by a typical cap lamp beam.

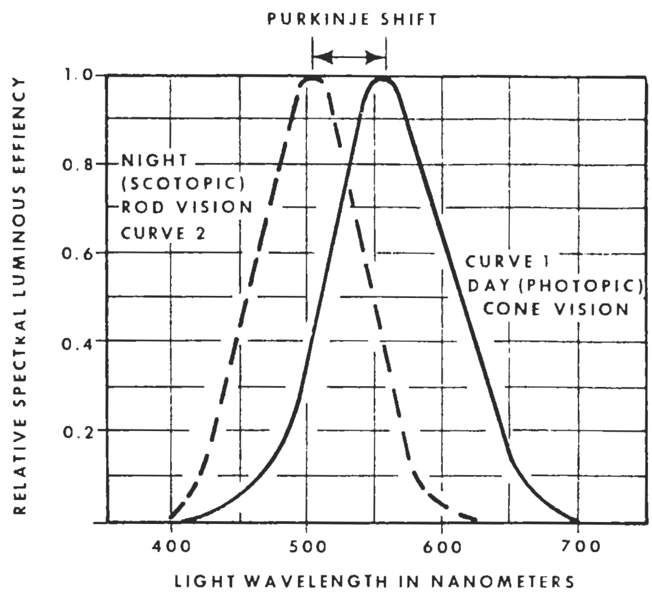


Figure 34.—Relative spectral luminous efficiency for scotopic and photopic vision depicting Purkinje shift.

The impact of the Purkinje shift in mine illumination design includes the following:

1. Typical light measuring devices are calibrated to the photopic curve. Consequently, serious errors in light measurement under scotopic conditions are possible.
2. As previously discussed, it is best to exceed the threshold for cone function. In areas of the mine where this is not feasible, paints that reflect the shorter wavelengths (e.g., green or blue),[5] or light sources that emit relatively more of their energy at shorter wavelengths, might be used to improve visibility. For instance, the British at one time used green fluorescent lamps to light some areas of their mines.

It should be noted that the mesopic range is between levels of 0.01 fL and 0.05 fL. The luminous efficiency curve that describes wavelength sensitivity at these levels lies between the scotopic and photopic curves.

Adaptation

Adaptation is an important function of the eye. When looking at an environment of uniform luminance, the level of light-sensitive chemicals present in the photoreceptors is optimal for performance and in a state of equilibrium. If the level of light is suddenly and significantly altered, even with changes in pupil size to regulate the amount of light permitted to enter the eye, the eye's photochemical balance is upset. As a result, the ability to see detail is temporarily suspended or reduced. Consider the following examples.

You have been working underground all day. At quitting time you get on the mantrip and go to the surface on a sunny day. At first, objects on the surface appear much brighter and detail is hard to see. The sunlight may hurt your eyes. The surface environment may appear "glaring," causing you discomfort. This occurs because adaptation to the dark underground environment has caused the level of photochemicals in your eye to become too great to accommodate the sudden increase in the amount of light. After a while, you become comfortable and seeing is easy.

On a sunny afternoon, you walk into a cinema. Initially, all you can see is the screen. Adaptation to the sunny outdoor environment has caused the concentration of photochemicals in your eyes to become so low that you cannot see details you normally would in the low level of light in the cinema. After a while, your eyes become adjusted and the surrounding details become visible.

These examples illustrate that (1) changing adaptation from light to dark or vice versa requires time, and (2) during that time, the ability to see details is below that which will be achieved once adaptation is complete.

Adaptation is reached at different rates by the cones and rods. The cones achieve adaptation much quicker. Thus, light adaptation (going from a dark environment to a light one) is relatively fast. Dark adaptation (going from light to dark) proceeds at a much slower pace. Figure 35 illustrates dark adaptation. The first part of the curve represents the dark adaptation of the cones. This usually takes 1 to 5 min. The curve levels off at the point where the rods come into play. Another 10- to 30-min period is required for the rods to be completely adapted, as can be seen in the second drop in the curve. It may be a total of 30 to 40 min until dark adaptation is complete.

[5]When comparing paints of equal total reflectance, paints that reflect the shorter wavelengths should be used.

The problem of adaptation when entering or leaving a mine is difficult to accommodate. A gradient in light levels, decreasing from the point of entry to the mine as one proceeds inby, will permit the adaptation process to take place gradually and simultaneously reduce the significance of the loss in visual performance. This can be achieved by two methods: (1) increased spacing intervals between light fixtures as one proceeds from the entrance to the mine; and/or (2) by using higher candlepowered fixtures near the entrance. Use of such systems are most desirable in situations where employees' jobs require them to frequently enter and exit the mine, such as track hauling of coal and supplies in a drift mine. Adaptation problems can also be serious on longwall lighting systems if operational status of the luminaires along the face is not maintained. Often a power distribution box will fail, leaving perhaps a 50-ft dark zone along the face that workers traverse, often quite quickly, while performing their jobs.

In addition to general light or dark adaptation, the following adaptation problems can be serious:

Local Adaptation.—When a visual field has a large, very bright area on a dark background, or, conversely, a large dark area in a bright background, local adaptation can occur. Local adaptation involves a change in photochemical concentrations in just a portion of the retina. If part of the eye is oriented to an area having significantly higher or lower levels of luminance, there will be significant time delay before that portion of the retina will properly perceive detail. This typically would occur when changing the point of eye fixation to another part of the visual setting.

Neural Sensitivity.—In addition to the shift in photochemical concentrations that occurs during any adaptation process, there is a neural component involved. When light levels are changed, there is a brief period when neural sensitivity is decreased. This causes a loss in ability to see detail, which can hinder task performance somewhat, especially if the eye must move from light to dark areas in the course of task performance. Lasting only a few milliseconds, it is not so noticeable as local adaptation.

To avoid visual loss from either of these two causes, the visual environment should be lighted with a reasonable degree of uniformity, avoiding excessively bright or dark areas, especially within the field of common visual tasks.

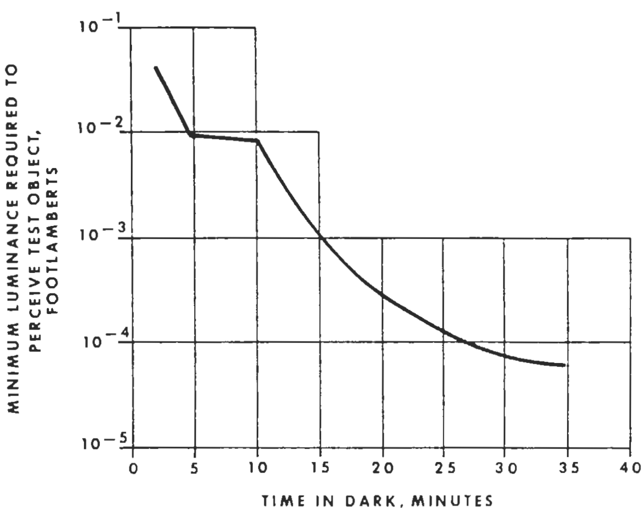


Figure 35.—Effect of dark adaptation on seeing.

VISUAL FIELD AND PERCEPTION WITHIN THE FIELD

Figure 36 summarizes the sight process, as discussed up to this point.

Image focused on retina

↓

Photoreceptors interpret brightness and color differences

↓

Brain integrates responses to form a perception

Figure 36.—Sight process.

This process alone does not fully explain the picture perceived through the eyes. Functions of the receiver-decoder system, the light control system, and other factors combine to determine this picture, including the following:

1. Photoreceptor distribution and neural connections to the brain.
2. Boundaries of the visual field.
3. Combined perception of both eyes.
4. Eye and head movements.

Impact of Photoreceptor Distribution

As implied earlier, there are many independent nerve passages between the photoreceptors and the brain. In some cases, there is a separate passage for each photoreceptor. In others, several receptors are connected to a single passage through a ganglion cell. This "receptor-to-nerve" ratio is quite important. When the ratio of photoreceptors to nerve passages is low, sensitivity to light is relatively low, but ability to resolve detail is high. When many photoreceptors share the same passage, sensitivity to light is high, but detail resolution is impaired. The general relationship between photoreceptor-nerve ratio, depending on type of photoreceptor is shown in table 4.

Table 4.—General relationship between photoreceptor-nerve ratio

	Cones	Rods
Photoreceptor-nerve ratio	Low[1]	High
Light sensitivity	Low	High
Ability to resolve detail	High	Low

[1] Generally.

Because of these differences in sensitivity and detail resolution, the distribution of rods and cones across the retina determines how we see in different parts of the visual field. Figure 37 shows this distribution. Overall, there are 20 times as many rods as there are cones in the retina. The rods generally outnumber the cones except in one area—the fovea—which is a tiny region in the center of the retina. At the fovea, the cones are packed exceedingly close together. The distribution of the rods is more

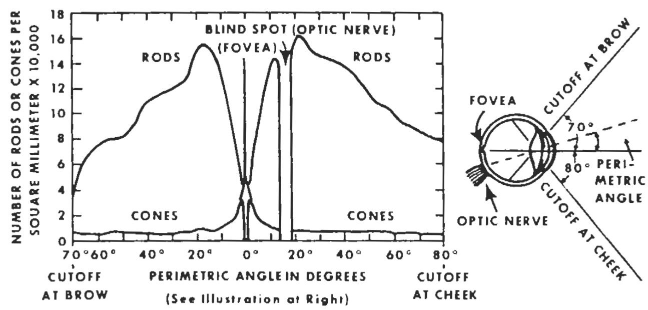


Figure 37.—Distribution of rods and cones across the retina.

spread out, from the fovea to the periphery of the retina. The blind spot, where no photoreceptors are located, is where the optic nerve enters the eyeball (see figure 37). The blind spot is not apparent because of a perceptual "filling-in" process. By both eyes working together, the blind spot in the right eye is filled in by the left eye, and vice versa.

The many, tightly packed cones in the fovea, each of which has its own nerve passage to the brain, allow for the best resolution of details. Therefore, if an object is to be seen with maximum clarity, it must be viewed directly. This causes the light to be focused on the fovea, which sends information concerning details to the brain. The foveal area is called the central field of vision and forms a 2° solid angle.

The area away from the fovea is known as the peripheral field of vision. As the distance from the fovea increases there is a steady increase in the number of rods, in the distance between the photoreceptors, and in the number of photoreceptors that share a nerve passage to the brain. These increases correspond to a decrease in the ability to see details.

The special importance of peripheral vision is that, even though forms are not sharp, spatial reference is good. This is especially important for the performance of tasks where overall perception is necessary, such as maneuvering a wide roof bolter to its proper position in an entry crowded with timbers.

The peripheral field of vision, because of its high sensitivity to light, is also sensitive to movement. Hunters know that their prey is often detected as movement seen "out of the corner of the eye," as opposed to detecting the details of the animal's appearance. When peripheral vision detects movement, a reflex is initiated which turns the eye to bring the object into central vision. Thus, the peripheral field of vision serves as an early warning device, which may alert a miner to on-the-job hazards. One instance where peripheral vision is often critical is in detecting rock dribble, which can precede a roof fall. Lighting systems that adequately illuminate areas in the peripheral field greatly enhance functioning of this hazard detection process.

Boundaries of the Visual Field

The boundaries of the human visual field are determined primarily by facial contours. Figure 38 shows these boundaries for a stationary head with eyes fixed at the center. The dark portions represent the cutoff by the eyebrows and cheeks. The gray portions, right and left, represent the regions seen by the respective eyes alone. The border between the gray and white areas represents the

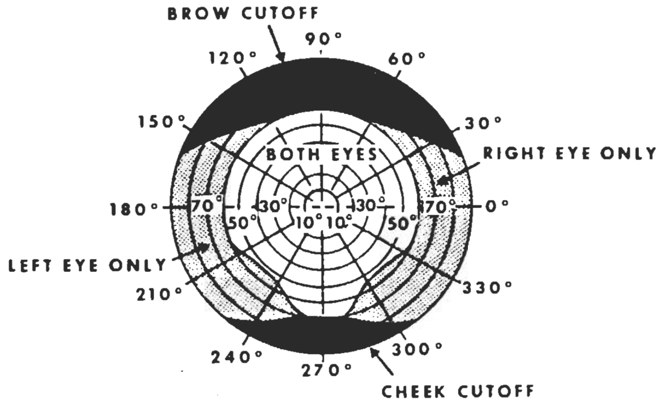


Figure 38.—Human visual field (head stationary and both eyes fixed at center (0° point)).

cutoff by the nose. The central 2° of this field represents central vision while the remainder represents peripheral vision.

Binocular and Stereoscopic Vision

When both eyes focus on the same object, vision is called binocular. Binocular vision is a component of normal human vision. It is achieved when both eyes work together to share and compare information. What is so special about the human visual system is how the brain takes the images from the two retinas and synthesizes them to form a single, three-dimensional picture.

The stereoscope, popular in the 19th century, presents two slightly different pictures separately to the eyes. The two, two-dimensional pictures appear as one, three-dimensional picture when viewed through the stereoscope. The eye works in much the same way. Stereoscopic vision is one means by which depth is perceived. Briefly, stereoscopic vision occurs because the eyes, being separated horizontally, receive somewhat different views. This small difference between the images is known as disparity. It is disparity that gives depth perception. In the eye, stereoscopic vision functions primarily for comparatively near objects (closer than approximately 110 yd).

Eye and Head Movements

The eyes do not get a detailed picture of an object just by focusing it upon the fovea. Eye movements are also essential to vision. When looking at a moving object, such as coal on a conveyor belt, the eyes follow along with smooth movements. When looking at a stationary object, the eyes scan the area of interest with a series of small rapid jerks. The function of eye movements is to keep sweeping the image over the retina so that the image does not fade away and thereby stop signaling the brain.

Both the eyes and the head may be moved to look at an object of interest. If an object lies in the central 40° of the visual field (see figure 39), normally only the eyes are moved to look at it. Eye movement alone can also be used to fixate on an object within the central 90° of the visual field, but for extended direct viewing of any object within either the 40° or the 90° field, the head position will be readjusted. Beyond the central 90° of the visual field, head movement is used for looking at an object.

In low-coal conditions, head movement is often restricted, as when drilling and installing roof bolts. Under such circumstances, a miner will prefer to move his or her eyes rather than his or her head to obtain focus over a wider visual field than the central 40°. However, if lighting is by cap lamp, which is dependent on head movement, this preference cannot be yielded to. This is an important human engineering problem that can be resolved by proper area lighting so that the illumination on the drill hole is independent of the miner's head position.

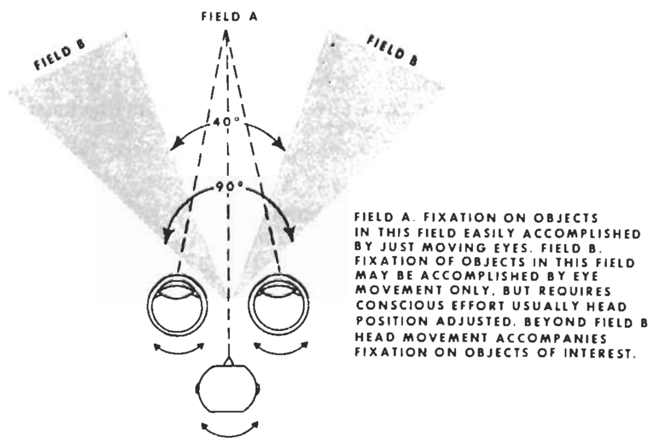


Figure 39.—General tendencies for eye or head movements to fixate at points of interest at various locations in the visual field.

The eye can be distracted from voluntary fixation by areas of high brightness, contrast, color, or by combinations of these. This is because of the involuntary tendency for the eye to move toward the light. The more intense the light, the more likely it is to attract and hold the eye's gaze. These types of distractions can hinder task performance, since it becomes more difficult to fixate on the darker area. Consequently, coal mine illumination systems should avoid exposed point sources of light and high contrast areas.

Miner Nystagmus

Under low light levels where the cones do not function, the point of focus shifts 20° to the side of the fovea where rod concentration is greatest (see figure 37). If the eyes work under such conditions for extended periods of time, they will not adjust to focusing on the fovea under normal light levels. This was a common problem for miners before the electric cap lamp was introduced. The condition is called miner's nystagmus. Spasmodic movement of the eyes, either rotary or from side, is a common symptom. The incidence of miner's nystagmus, once a very serious occupational health problem, has virtually disappeared since the introduction of the electric cap lamp.

COMMON VISUAL DEFECTS

This section discusses some common visual defects and the effects they may have on work performance. Some of these visual defects can be corrected through optical means. Others can be at least partially compensated for by proper illumination design. For others, no correction is available, and they may limit performance of certain tasks in mines.

Refractive errors are problems with the cornea-lens system such that the eyes do not focus a sharp image on the retina. The net effect is that the light reflected from a point on an object is focused over a small area of the retina instead of on a single point. This causes vision to blur. Refractive errors should not limit performance of mining tasks if they are corrected. Table 5 illustrates the common classes of refractive errors, all of which are correctable to some degree by optical means (i.e., wearing glasses or contact lenses).

There are several types of color blindness, which may result from genetic factors, eye disease, or heavy drinking and smoking. They include

- Total color blindness (gray vision only).
- Blue-green color blindness.
- Two types of red-green color blindness—Deutranopes (both red and green appear yellow) and Protanopes (both red and green appear yellow and some reds cannot be distinguished).

Total and blue-green color blindness are rare. Red-green color blindness is most common, especially in white males (8 pct of white males have red-green color blindness). Incidence of color blindness is much lower in black males and in women, regardless of race.

Color blindness can be a safety hazard. It may restrict performance of some tasks where color distinction is critical to safety. Such tasks may include electrical wiring, blast wiring, and handling gas cylinders—tasks in which color coding is used extensively. Traffic signals usually are not a problem for colorblind people since they can distinguish brightness differences between the red and the green. They also can remember the signals' positions relative to each other.

There is a gradual deterioration of the visual system's functions as a person grows older. Most of these problems can be reduced by optical means or by changes in environmental lighting conditions. Table 6 sets forth some of the effects of aging on the eye and some possible corrective measures.

Concerning safe and efficient task performance, it is often the case that the work experience of the older worker offsets the decline in visual performance. However, worker experience must not be relied upon when designing mine lighting systems; the visual needs of older employees should be considered.

ENVIRONMENTAL FACTORS AFFECTING VISION

So far, this chapter has discussed how the visual sensory system functions and how certain design parameters can enhance or hinder the functioning of the visual system. This discussion provides only part of the basis for determining the human visual needs that must be addressed in lighting design. The designer must also be concerned with the visibility of objects and details that make up a visual setting since this can directly affect job performance, efficiency, and safety. This section, therefore, defines and discusses the major factors that determine the relative visibility of objects.

Contrast and Seeing

Contrast is the term used to describe differences in luminance or color between an object and its background. An environment emitting or reflecting uniform levels of luminous flux having homogeneous wavelength composition (color) would create only a perception of uniform brightness and color when viewed. It is only through detection and discrimination of differences (i.e., contrasts) in luminance and wavelength composition that the visual system gains any useful information relative to the condition of the surroundings (color, size, shape, motion, etc.). Hence, contrast detection and discrimination is the most basic and important visual ability. Altering the environment to enhance this ability is a major objective for the lighting designer. A general relationship between environmental contrast and vision is that, under given lighting conditions, the greater the contrast the "easier" it is to see objects, details, and spatial relationships.

Table 5.—Common classes of refractive errors

Class	*Definition*
Myopia	Images from distant objects are focused in front of the retina. Also called nearsightedness.
Hyperobia	Images from distant objects are focused behind the retina. Also called farsightedness.
Astigmatism	Unequal curvature of the refractive surfaces of the eye. As a result, a ray of light is not sharply focused on the retina, but is spread over a more or less diffuse area.
Presbyopia	Farsightedness and impairment of vision due to advancing age. This occurs because of problems in bending the lens (accommodation). Causes problems for viewing near objects.

Table 6.—Age-related eye defects and possible corrective measures

Defect	*Possible corrective measure*[1]
Presbyopia	Bifocal lenses.
Cataract condition	Medical attention.
Increased glare sensitivity	Careful placement of lighting apparatus, etc.
Decrease in ability to detect movement in peripheral field.	Increase luminance levels.
Increased light scatter in eye (disability glare).	Careful placement of lighting apparatus, etc.
Decrease in ability to see detail	Increase luminance levels.
Increased adaptation time	Gradient spacing of luminaires from light to dark areas. Also, minimize extreme brightness differences in the visual field.

[1] The best corrective measures required in a given mining situation could be considerably more extensive than those noted here.

As indicated there are two types of contrast—color, (chromatic), contrast and luminous (brightness) contrast. Objects that have the same luminance as their background; i.e., zero luminance contrast, are often differentiated from the background by color or chromatic contrast. Even though color contrast can be significant, the maximum visibilities produced are generally less than 20 pct of the visibility produced by luminance contrast. In the underground coal mine there is, relative to other environments, little color contrast. Visibility is determined primarily by luminance contrast. Therefore, the discussion in this section will concentrate on luminance contrast.

It should be noted that the information and relationships subsequently presented in this section were derived from experiments involving only black, gray, and white (achromatic) objects and backgrounds illuminated by white light. At the present time, research is being conducted to determine the effect of color on these relationships, but results are not yet available.

Luminance contrast, C, a physically measurable quantity, is commonly defined by the relationship $C = L_b - L_o/L_b = \Delta L/L_b$, where L_b is luminance of the background, L_o is luminance of the object or detail, and ΔL is difference in object and background luminance.

Luminance and, hence, contrast, is a function of both the reflectivity, ρ, and illumination, E, of the object and background. When an object and its background (both assumed to be diffuse reflectors) are illuminated by uniform light (E = constant), contrast is dependent only on reflectivity; i.e., $C = L_b - L_o/L_b = E\rho_b - E\rho_o/E\rho_b = \rho_b - \rho_o/\rho_b$.

Hence, contrast might be controlled in certain situations by applying surface coatings (e.g., paint, reflective tape, etc.) to appropriately alter reflectivity.

Relationship Between Contrast Detection and Illumination Levels

If you were to reduce the illumination on the pages of this report, it is likely that you would have more difficulty reading the text. You would not have changed the contrast between the letters and paper. Contrast, as noted above, remains constant under uniform illumination, regardless of the particular illumination level. However, by reducing illumination levels, you would have reduced your *ability to detect* or distinguish contrasts.

Figure 40 shows "minimum perceptible contrast," the smallest contrast that can be distinguished, as a function of background luminance levels (which are directly proportional to level of illumination). This curve was derived from data collected under the following conditions:

1. The object being observed was a small circular spot or disk that subtended a solid angle of 4′ in the observer's field of vision.
2. The spot had a higher luminance than its background.
3. Observation time was 0.1 s.
4. Each point on the curve represents the level of luminance contrast necessary for detection of the disk by an observer 50 pct of the times they were presented.

The curve shows clearly that lower contrast can be detected as illumination levels are increased. At a background luminance of 0.1 fL, contrast of the spot has to be higher than 0.5; i.e., there had to be at least a 50 pct reflectivity difference between object and background to be perceptible. At a background luminance of 10 fL, contrast need only exceed 0.06 to be perceptible. Accordingly, increased illumination levels can be used to compensate for low contrast inherent in various tasks. Figure 41 illustrates this effect.

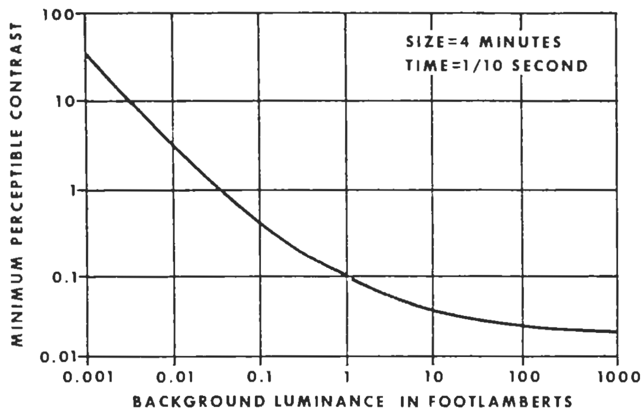


Figure 40.—Minimum perceptible contrast as a function of level of background luminance.

Notice that the curve is steep at lower levels of background luminance and levels off at higher levels of luminance. As background luminance is increased from 0.001 to 0.01 fL, minimum perceptible contrast decreases from 30 to 2.5. As background luminance increases from 10 to 100 fL, minimum perceptible contrast decreases from 0.05 to 0.03. The implication is that levels of illumination are reached beyond which increases do little to increase ability to detect contrasts. The point of most cost-effective illumination levels depends on the inherent level of contrast detection necessary for efficient performance of a task. Levels of illumination are reached beyond which increases produce only marginal or no increases in visual performance.

The use of this relationship between contrast detection and illumination to define appropriate illumination levels is discussed later. The following sections discuss the other major variables that affect the ability to detect contrasts.

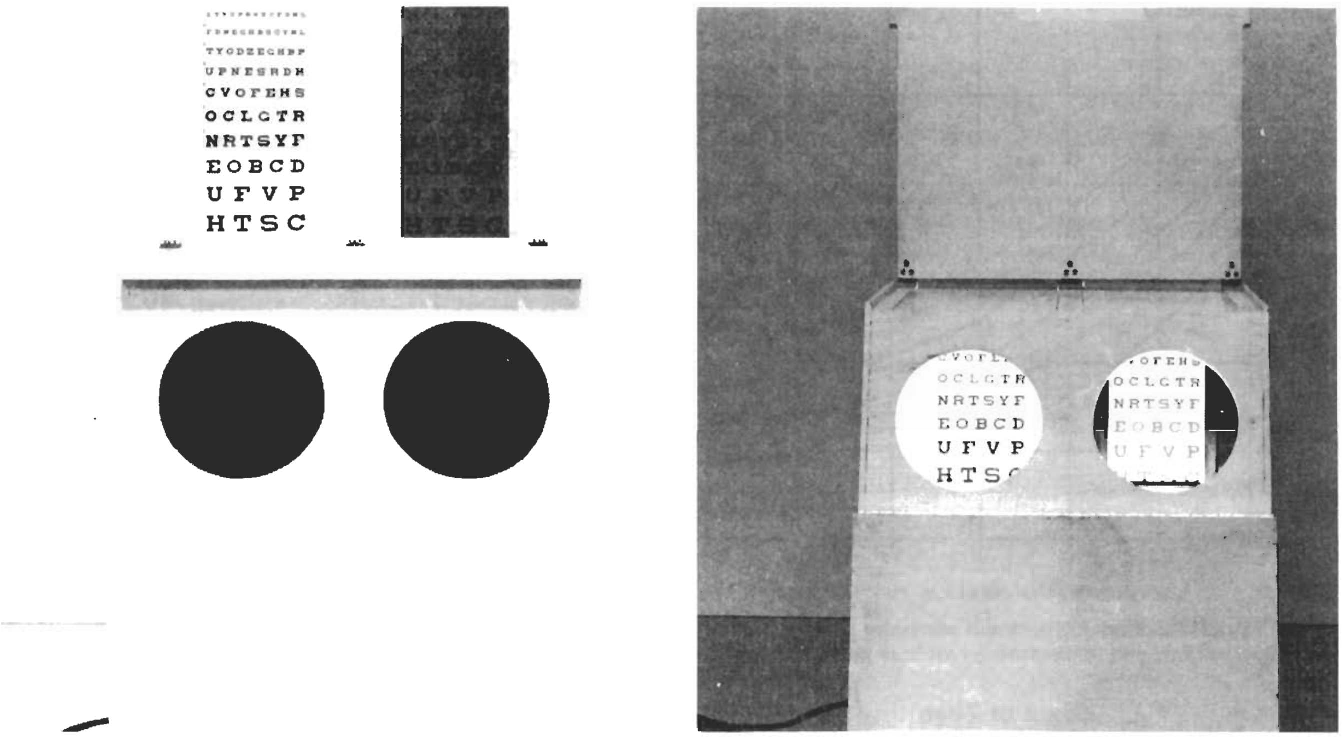
Effect of Object Size

It is accepted that larger objects are easier to see. Size is measured in terms of visual angle (fig. 42), usually in units of "minutes of arc" or degrees (60′ equals 1°). This accommodates for the effect of distance from the observer upon the apparent size of the object. Table 7 shows the visual angle subtended by objects of given overall linear dimensions (H in figure 42) at various distances from the eyes of the observer.

Table 7.—Relationship between visual angle and object dimension

Visual angle	Apparent object size at 2 distances from observer, in	
	2 ft	10 ft
2′	[1]0.014	0.07
4′	.028	.14
10′	.07	.34
60′ (1°)	.42	2.09
300′ (5°)	2.09	10.48

[1] Approximately 1/64 in.



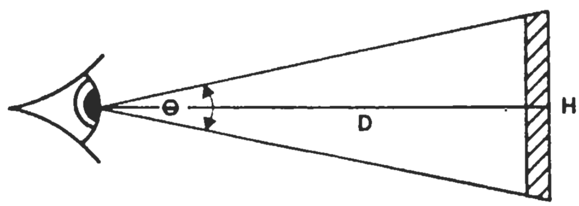
A. Equal illumination on both cards *B*. High illumination on the low contrast card

Figure 41.—Use of high light levels to illuminate low-contrast objects.

First, examine the relationship between size and level of background illumination for viewing a black object on a white background. The contrast under such a situation is at a maximum (approaches infinity) since the reflectivity of the object and background are at opposite ends of the reflectance range (0 to 100 pct). Figure 43 shows the results of such an experiment. It is obvious that there is a minimum size object that can be discerned regardless of level of illumination. This limit occurs at a visual angle of 0.4′ (28 ten-thousandths of an inch when viewed from 2 ft) and is imposed by physiological characteristics of the eye (i.e., photoreceptor size and spacing). Also notice the asymptotical nature of the curve. If one were to increase light levels from 100 to 1,000 fL (a 10-fold increase in illumination probably accompanied by a 10-fold increase in energy costs), one would only gain about a 5-pct increase in ability to see detail at this contrast level.

Object size, contrast, and illumination level are, of course, interrelated. A change in the magnitude of one variable affects the magnitude of the others necessary for perception of the object. The "spot on uniform background" experiment discussed in the previous section has been conducted with size of the spots a variable, and the results are shown in figure 44.

It is evident from figure 44 that increased levels of luminance (obtained by increasing illumination) are necessary to maintain perception as object size decreases at any given level of contrast between object and background. Notice, also, that the curves are farther apart as object size decreases. Unless contrast is very high, extremely high levels of illumination (1,000 fL or more) may be necessary in performance of tasks involving discernment of small details (e.g., certain fine assembly tasks). Localized illumination, concentrated on the task vicinity, is a practical method for attaining these levels.



$$\theta = \mathrm{ARCTAN}\left(\frac{H}{2D}\right)$$

$$\mathrm{TAN}\ \frac{\theta}{2} = \frac{H}{2D}$$

Figure 42.—Concept of visual angle.

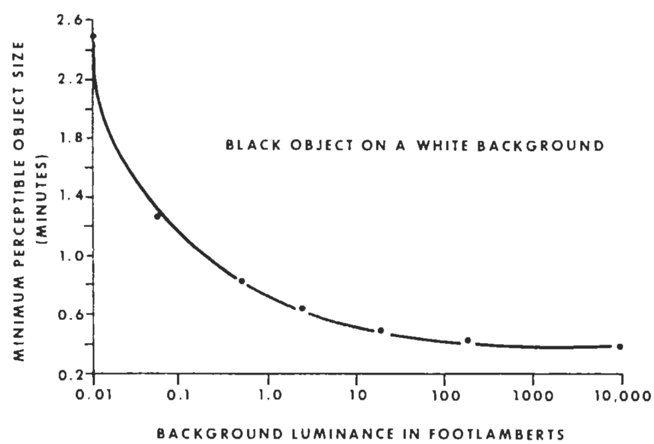


Figure 43.—Relationship between minimum perceptible object size and level of background luminance.

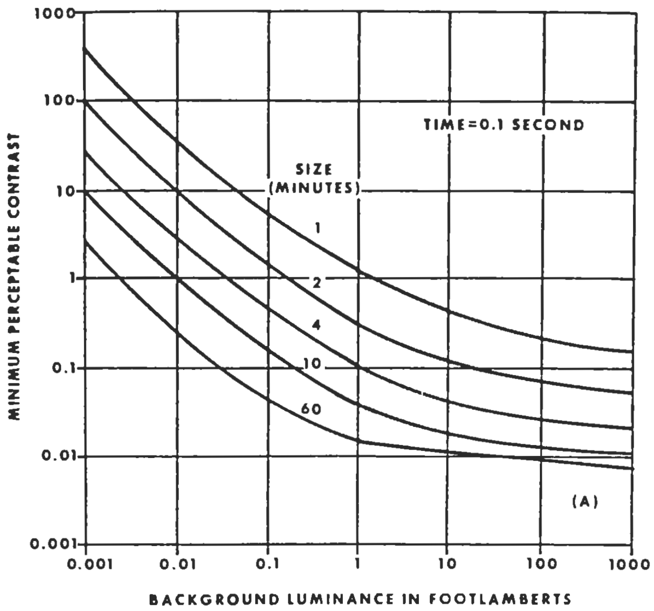


Figure 44.—Relationship between minimum perceptible contrast and background luminance for various size objects.

Effect of Time

Figure 45 shows the spot on uniform background experiment conducted for various time exposures of the dot. This figure supports the following conclusions.

1. At any given contrast level, less time is necessary to perceive an object as illumination levels are increased.
2. The effect of time becomes nearly insignificant once viewing time exceeds approximately one-third of a second.
3. Because of the steepness of the curve in the 0.001- to 0.1-fL range (also, the range of luminance revels in many mines) time for perception may tend to become critical relative to reaction times for recognizing hazards even if contrasts are relatively high. For example, if contrast between the object and background were 0.5 (a 50 pct difference in reflectivity) and illumination levels were at 0.05 fL, it would take *at least* one-third second to see the object. Although this example applies specifically to an object subtending an angle of 4′, when designing or evaluating a lighting system, the general relationship shown by the curves of figures 44 and 45 can be applied to other sized objects to obtain an indication of the "time to see." Curves equivalent to figures 44 and 45 are not currently available for a range of object sizes.

Concept of Visual Acuity

Thus far, the discussion has been directed at contrast detection and the major environment factors—contrast, illumination level, object size, and viewing time—which affect this ability. As may have been noticed, the experiments cited to explain these relationships involved very simple discriminations—was, or was not, the disk-shaped test object visible. What if the experiment were made a little more difficult and the observer was asked not only to distinguish the presence of the object but to discern whether it was a "C" or an "O." Such an experiment would yield a measure of "visual acuity" or ability to resolve fine details.

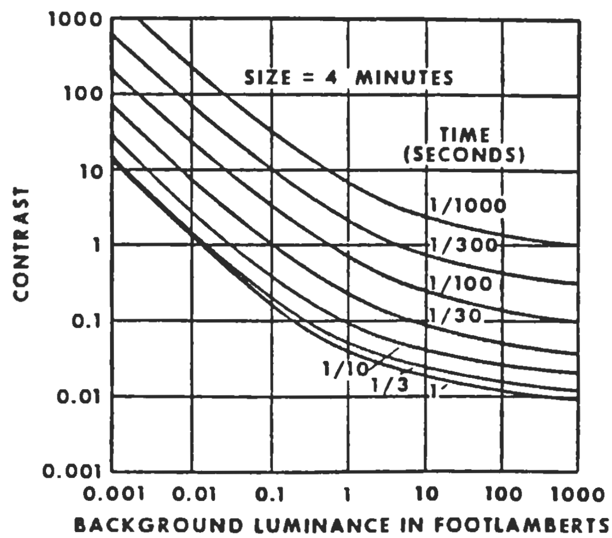


Figure 45.—Relationship between minimum perceptible contrast and background luminance for various exposure times of test object.

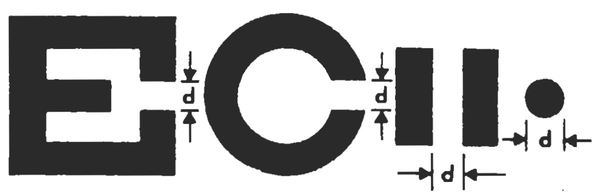


Figure 46.—Determining dimensions of critical detail for visual acuity experiments.

The size aspect of a visual acuity experiment is usually quantified in terms of the visual angle subtended by the "critical detail." Figure 46 illustrates how the dimension of the critical detail is assessed in some common experimental test objects. Visual acuity is the concept employed in the Snellen chart used in standard vision tests.

The difference between visual acuity and simple contrast detection is that perceptual processing in acuity experiments of visual information is considerably more complex. Moreover, the level of processing may differ from one acuity task to another. The level and complexity of processing involved in distinguishing between a hexagon and an octagon would differ substantially from distinguishing between a C and an O. Hence, visual acuity cannot always be directly related to contrast detection, but experiments to date show that it does vary in a similar manner with luminance level and time of exposure.

Quantifying and Measuring Visibility

An attempt to quantify the visibility of an object is an attempt to quantify the degree of difficulty in seeing it. Lighting designers define the visibility quantity, V, as the ratio of the contrast between the object or detail in question and its background under a particular level of background luminance, C_{actual}, to the minimum contrast between the object or detail and its background that would be necessary to just perceive the object at the same background luminance level, $C_{threshold}$; i.e., $V = C_{actual}/C_{threshold}$.

Figure 47 explains the concept in terms of the spot on a uniform background experiment. From the graph, it can be seen that if the contrast between the spot and background was 10.0, the visibility of the spot would be 10/1 = 10 at a background luminance of 0.1 fL and 10/0.2 = 50 at a background luminance of 1.0 fL. Note that visibility increases with increasing levels of task illumination.

Visibility meters are devices that employ a clever optical arrangement that enables measurement of the C_{actual} -$C_{threshold}$ ratio for real objects and details. These measurements form a useful tool in determining appropriate levels of illumination for actual tasks.

As noted previously, a visibility measurement is always referenced to a particular level of background luminance. The optical arrangement shown in figure 48 enables one to reduce the observed contrast between any real world object and background to the threshold for detection while maintaining a constant apparent background luminance. It accomplishes this by reducing the luminance of both the object and background by a factor, f, by passing the light through a nonwavelength discriminant filter and then adding a veiling luminance, L_V, which compensates for the filtering and maintains the apparent background luminance. Adjustment of the glass wedges and the veiling light source is interdependent such that the luminance levels seen by the observer are given by object luminance, (L'_O), = $L_V + f \cdot L_O$ and background luminance (L'_B), = $L_V + f \cdot L_B$. But as previously stated, the meter is adjusted so that $L'_B = L_B$. Under these conditions, threshold contrast is given by

$C_{threshold} - L'_O - L'_B/L'_B = (L_V + f \cdot L_O) - (L_V + f \cdot L_B)/L_B = f\,(L_O - L_B)/L_B = f \cdot C_{actual}$, but $V = C_{actual}/C_{threshold} = 1/f$.

Hence, the setting, f, defines the visibility of the task. Note that such an assessment is conveniently made without the direct measurement of contrast.

Use of Visibility Measurements

A measurement of the visibility of a particular task applies only to the level of background luminance under which the measurements were taken. One can estimate, however, how this visibility level will vary with changes in illumination level. The process is to relate field measurements to the relationship between visibility and background luminance defined by the spot on uniform background experiment. This relationship, as noted previously, has been carefully measured in the laboratory. In general terms, this is accomplished as follows.

1. The critical detail of the task is reduced to threshold by a visibility meter.
2. The threshold contrast of the 4′ test object is identified for the particular background luminance of the visibility measurement. Since both the 4′ test object and the critical detail being measured are at threshold, their visibilities are equal. That is, $V_{task} = V_{test\ object} = V_{threshold} = 1$.

Now the amount of contrast reduction that was necessary to reduce the task to threshold can be utilized to determine the equivalent contrast the test object would have had if it had undergone the same contrast reduction (see figure 49).

3. Using the procedure discussed in the previous section, this equivalent contrast can be used to define the visibility of the task at any other level of background luminance (i.e., any other level of illumination). This assumes that the relationship between the visibility of the task and the test object is constant; i.e., the shape of the threshold curves for the two objects is the same.

The value of this technique is that if one knows the level of visibility necessary one can then determine the appropriate background luminance level (and subsequently

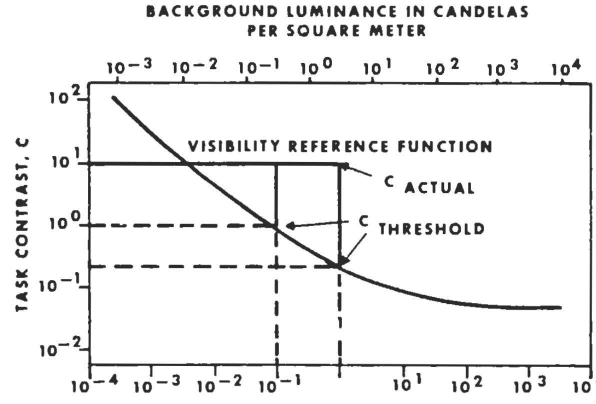


Figure 47.—Concept of visibility and how it varies with level of background luminance.

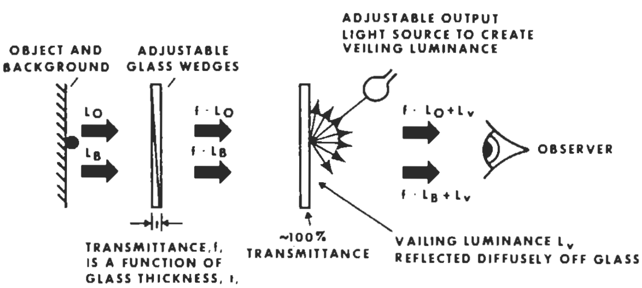


Figure 48.—Principle of visibility meter operation.

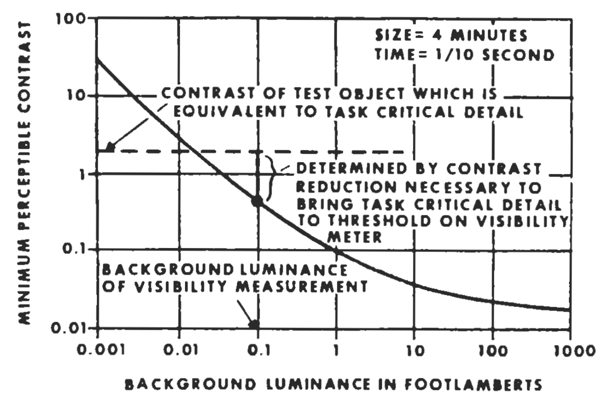


Figure 49.—Determining contrast of 4′ test object which is equivalent to real world task critical detail using visibility measurements.

the background illumination level if background reflectivity is known). Studies have been done to establish such a minimum acceptable visibility level, and it has been frequently cited in the range from 6.7 to 8.

The results obtained by this procedure, however, must be carefully scrutinized. Some of the major limitations inherent in the technique follow.

1. The fact that (a) the curve for the test object flattens in the higher background luminance level range, and (b) the scales are logarithmic, which means that slight errors yield significantly different "required" levels of background luminance.
2. There is considerable debate as to the minimum visibility level that is adequate. Factors that have been considered are knowledge of when and where the test object will appear, whether the object is moving or stationary, and determining the presence of the object with 100 pct accuracy. Designers are not sure of the applicability of the factors to each situation and whether others may be significant.
3. The degree that the visibility of real world tasks correlates with the 4′ test object curve is not known.

Regardless, this technique is a valuable tool to use in the definition of appropriate levels of illumination for a work task and is quite practical to use in many situations.

Consideration of Performance

The ultimate measure of the effectiveness of a lighting system must be the performance of the individuals working in the environment illuminated by it. This performance may be measured in terms of hazard avoidance and speed and accuracy of task performance. The problem is that several factors ultimately combine to determine performance, including vision, processing of visual information, and motor skills. The significance of vision (and hence, illumination level) is difficult to resolve independent of the other factors and may vary from task to task. For example, the speed and accuracy of typing are easily measured, but how significant was lighting to the results? Were the errors a result of not seeing the words correctly or were they a result of deficiencies in motor skills? Similarly, is it necessary to distinguish every letter, 99 pct of the time when reading, since the tendency is to reorganize the letters in "chunks" called words or phrases.

The procedure defined in the previous section provides valuable insight but not a precise definition of the optimum illumination level for performance of a particular task. The net effect on performance must be considered if the most cost effective level of illumination is going to be established. Much work is currently being carried out to define this interrelationship.

TYPES OF ARTIFICIAL ILLUMINATION

Lighting systems are frequently classified into three types on the basis of how they deploy and distribute luminous flux.

1. General lighting.
2. Localized general lighting.
3. Local or supplementary lighting.

General lighting provides an approximately uniform illumination over the entire area of the work plane. A great advantage of general lighting is that it permits complete flexibility of task location. However, if light levels for performance of a small number of tasks is high relative to the other tasks performed in the work area, it is likely not to be cost effective to accommodate these tasks.

Localized general lighting consists of a functional arrangement of luminaires giving greater weight to the visual task or work areas where most light is necessary. It also provides illumination for the entire room area. This type of illumination has the advantage of improved utilization of light compared to general lighting by concentrating on specific task areas.

Local or supplementary lighting provides lighting over only a small task area and its immediate surrounding area. It is an economical means of providing higher levels of illumination where needed. Local lighting by itself, however, is seldom desirable. It should be used in conjunction with general lighting to prevent excessive changes in adaptation.

TYPICAL TASK ILLUMINATION LEVELS

Recommended task illumination levels for a large variety of work environments are presented in the IES Lighting Handbook. To illustrate the range of these values, minimum values of illumination for a few industrial scenarios are shown in table 8.

Table 8.—IES recommended minimum illumination levels for sample industries and tasks, footcandles

Area		
High-precision inspection		1,000
Offices	70-	150
Steel rolling mills	30-	50
Machine shops, rough machining		50
Rough assembly	30-	50
Central station coal conveyor, crusher, feeder, scale areas, pulverizer, fan area, transfer tower.		10
Coal tipples and cleaning plants, breaking, screening, and cleaning.		10
Railroad yards	1-	20

Defining appropriate illumination levels for underground coal mines is a complex task. In the early 1970's, the Bureau of Mines sponsored two studies to determine recommended levels of background luminance for underground coal mines. The following are major conclusions drawn from these studies, which had significant importance in the establishment of the current regulations.

The threshold for photopic vision is approximately 0.05 fL. The luminance in any position of the visual field within 50° of the fovea (center of vision) should exceed 0.05 fL.

In one of the studies, 90 mining tasks were evaluated (visibility measurements taken) to determine the minimum luminance required for mine workers to see adequately. A sampling of results is shown in table 9 along with the luminance provided by the central portion of a miner's cap lamp. Of 90 evaluated tasks, 16 pct required luminance levels greater than 0.07 fL. The maximum luminance required by a task was 0.819 fL and the minimum required was 0.004 fL. In most cases, illumination provided by direct viewing with a cap lamp was in excess of the minimum required for the tasks. Note that these values are a small, but statistical sampling. The luminance

Table 9.—Sample of measured coal mine task luminance requirements

Task	Task distance, ft	Luminance, fL	
		Min background required	From cap lamp
Locate reset switch	3	0.819	14.9
Read methane meter	2	.786	.212
Watch loading arm (loader)	15	.361	.269
Locate base of coal face	20	.211	.189
Locate corner of loading head	12	.199	.330
Detect empty conveyor on shuttle car	4	.122	5.890
Locate red mark on rib	11	.102	.367
Track shuttle car to conveyor head	8	.098	2.100
Detect black cable against rib	30	.085	.084
Align face drill with rib	15	.074	.502
Locate ripper against roof	19	.057	.017
Locate explosive	3	.056	19.900
Detect bits on cutter chain	13	.049	.336
Align drill arm with roof bolt	4.5	.037	.951
Position front of cutter	5	.0359	2.400
Track face drill bit to rib	15	.018	.391
Locate new bit	5	.0152	2.650
Locate miner conveyor	20	0.0107	.029

required for a specific task can vary widely because of variations in task and background reflectances that can occur.

Peripheral distribution of illumination from the cap lamp is not sufficient for the illumination of the environment; consequently, additional lighting is needed.

The outcome of these studies and subsequent refinements have resulted in the current lighting regulations published in the Code of Federal Regulations, Title 30, part 75.1719 through 75.1719-4. The code specifies that the luminous intensity (surface brightness) of surfaces that are in a miner's normal field of vision of areas in working places that are required to be lighted shall not be less than 0.06 fL when measured in accordance with part 75.1719-3. The code also specifies that, each person who goes underground shall be required to wear an approved personal cap lamp or an equivalent portable light.

Current regulations often require the use of a complex combination of general, localized general, and supplementary types of lighting. The need for these systems has evolved as a result of numerous field evaluations and studies conducted by the Bureau of Mines and MSHA. The regulations also address factors including glare, equipment reflectance requirements, luminaire design, and methods for illumination measurement. The regulations are discussed in detail in IC 9074.

COLOR IN MINING

As noted in chapter 2, a color must be present in a light source if it is to be seen in the light reflected by an object. White light comes from a source (lamp) emitting radiant energy relatively balanced in wavelengths across the visible spectrum and permits all colors to be seen. Many light sources, however, emit only specific wavelengths in the visible spectrum. For example, high-pressure sodium lamps, often used in coal mines because of their high efficiency in converting electrical energy to light energy, emit wavelengths in the yellow and orange part of the spectrum. Because of this, color rendition is limited.

Coal, even under white light, has an indistinguishable hue. Therefore, accurate color rendition when viewing coal itself is usually not important. But color rendition is important for viewing of signs, color-coded wiring, etc. In general, when these tasks are being performed, miners are wearing tungsten-filament cap lamps that emit a white light. Typically, the cap lamp is the primary source of light illuminating the significant colored objects, and it is acceptable to use a nonwhite source for general lighting in such instances. However, there may be cases where nonwhite sources would be undesirable.

Using paints and surface coatings of colors at the points of high sensitivity on the spectral efficiency curve can, under certain conditions, make an object more visible. For photopic visual conditions, paints in the yellow to red band should be used. For scotopic visual conditions, as in some areas of a coal mine, paints in the green to blue band might be used (see figure 34). When selecting paints to be used to increase visibility, keep in mind that total reflectivity of the paint is generally a more important factor than color. In most instances, a highly reflective paint is preferable, regardless of color.

Colors are, or can become, associated with certain meanings. Thus, color is often used as a means of coding, or signaling. When using color codes, it is important to be consistent. Workers are more likely to respond automatically in the event of an accident if hazards are uniformly color coded. Table 10 contains some recommended color codes for signs and for painting equipment where caution must be exercised in handling.

Table 10.—Color codes

Color	*Associated meaning*
Red	Danger or stop.
Yellow	Caution.
Green	Safe or go.
Black on yellow	Hazard.

When using color codes, be sure the dimension of the color coded area subtends at least a 0.5° solid angle. This requires assumptions to be made on viewing distance (fig. 50). Smaller dimensions may make the color indistinguishable. This guideline may be applied to the marking of escape ways.

Imagine that there is a light flashing on and off at a frequency of N or hertz cycles per second. If the frequency N is greater than the *critical fusion frequency*, the impression of perfectly constant luminance is perceived. The eyes

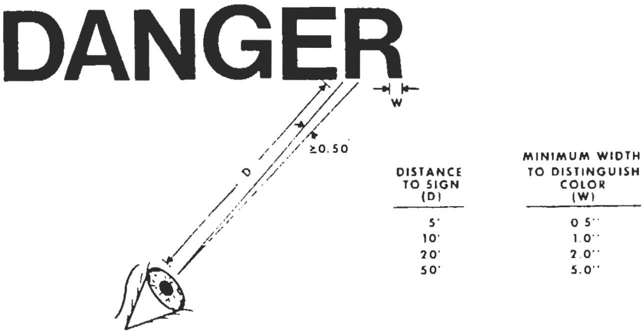


Figure 50.—Guideline for minimum dimension of letter or marking width to insure recognition of color.

are, in a sense, tricked into this perception because the retina cannot follow and signal to the brain rapidly changing intensities or events. Two examples that take advantage of this phenomenon are television and moving pictures. They present many still frames or pictures each second, which are seen as continuous action. The critical fusion frequency depends on (1) light source size, shape, color, and brightness, and (2) the adaptation state of the eye. Fusion will not greatly exceed 60 Hz regardless of the combination of these variables in question.

Now lets imagine that the flashing frequency N begins to diminish. When it is *less* than the critical fusion frequency, a flicker is noticed. Flickering light of 5 to 20 Hz can be detrimental. It can cause eye fatigue, headaches, nausea, and reduce attention span. In rare instances, these flickering lights can cause hallucinations or epileptic seizures.

Incandescent lights rarely flicker. Fluorescent lights, on the other hand, do flicker, especially if they are old and/or poorly maintained. This flickering occurs when the old or defective fluorescent tubes fail in their attempts to start. The problem of flickering fluorescent lights can be minimized by proper lamp selection, maintenance, and circuit design, as discussed in IC 9074.

Flicker can cause an optical illusion, known as the "stroboscopic effect," which could present a significant hazard. It occurs when viewing shiny, rotating objects (e.g., gathering heads on loading machine) illuminated by the fluorescent lights operating above the critical fusion frequency. Under certain combinations of lamp flicker and rotational speed, the stroboscopic effect causes the object to appear to be standing still, or moving slowly in the opposite direction. This effect can be prevented by taking proper measures in design of the lamp circuitry and/or selection of appropriate lamps.

Flicker affects the apparent brightness of a light source. At high flashing frequencies, the perceived brightness of the source is equal to the proportion of time the light was on. For example, with a 1:1 on-off ratio at high flashing frequency, the apparent brightness equals one-half of the brightness that would be perceived if the light were burning steadily. At lower flashing frequencies (2-20 Hz) however, flickering enhances brightness. A source flashing at a low frequency appears brighter than if the light source was constant. This is referred to as brightness enhancement or the Bartley effect.

Often, flashing lights are used as warning devices in coal mines. When this is the case, the flash frequency must be less than 5 c/s. A frequency of 1 c/s is common. It is best if the on-off time ratio is low (e.g., 0.2 s on and 1.0 s off).

Color can be used on warning lights. A green light is easier to detect, while a red one is slightly harder to detect than a white signal, although the difference among all three colors is not very significant. An interesting fact about colored signals is that it takes 5 to 20 times as much light to distinguish the *color* of the light than to simply distinguish the signal. In most cases, this usually is not a significant problem since the signal lights operate at a brightness well above the threshold for color detection. However, if distinguishment of signal color is important (e.g., when the light flashes red it means one thing and flashes blue it means another) and the transmissivity (see chapter 2) of the media between the signal and observer is low (e.g., dusty air), this factor may become important.

CHAPTER 4.—DISABILITY AND DISCOMFORT GLARE

Glare is addressed in this chapter from an engineering standpoint. Techniques to assess the merits of alternative illumination system concepts involving measurements and computations are presented. Application of specific methods to eliminate or reduce glare are presented in IC 9074.

Glare is a very significant factor in determining the design of underground coal mine illumination systems. It is the most frequent cause of complaint and dissatisfaction with mine illumination systems, and it may detract significantly from the benefit of these systems. It is so prevalent in the mine environment because luminaires must often be located close to the mine worker's line of sight and they are viewed against a very dark background, which results in a high contrast between the light source and its surroundings.

Glare is a visual sensation that can result in annoyance, discomfort, loss in visual performance, or reduction of visibility. Some degree of glare is constantly experienced in an illuminated environment. Out of doors, the Sun can be an extreme source of glare. The headlights of an oncoming car at night is a classic glare example. Less obviously, when driving at night, even the dashboard lights inside the car are a source of glare since they reduce the ability to see the road and can also be a distracting source of discomfort.

Glare is a complex subject. Its effect on visibility, visual performance, and comfort is dependent on many variables including the brightness of the glare source, general luminance level of the environment, sensitivity of an individual to glare, location of the glare source, and nature of the visual task. Unfortunately, no simple method is currently available to determine the acceptability of an illumination system from the standpoint of glare when light sources are in the field of view. The methods presented in this chapter are solely for the purpose of providing a means for the designer to determine the relative merits of alternative design approaches to eliminate or reduce glare.

The methods require the use of standard portable luminance and illumination photometers. Sophisticated methods and instruments, such as the glare evaluator and the visual task evaluator, are available to assess the acceptability of illumination systems with respect to glare. These instruments and their use are primarily for basic research studies from which lighting standards and guidelines are derived. The Bureau is currently conducting studies of glare in coal mine illumination systems. It is hoped that these and future studies will lead to improved methods to design and evaluate coal mine illumination systems.

There are three types of glare: disability, discomfort, and reflected. Only the first two of these types will be discussed because of their importance in the design of underground mine lighting systems. Methods to compare the glare of alternative illumination concepts using quantitative techniques are presented along with example calculations. Application of these glare reducing techniques from the standpoint of system design is further discussed in IC 9074.

DISABILITY GLARE

Disability glare is defined as glare resulting in reduced visual performance and visibility. Discomfort glare can accompany disability glare, but discomfort glare is a measure of discomfort or annoyance only. It is important to realize that these two types of glare are distinctly different phenomenon. Disability glare is caused by the action of stray light, which enters the eye and scatters within. It causes a "veiling luminance" over the retina which, in turn, has the effect of reducing the perceived contrast of the objects being viewed. This effect can be demonstrated very easily in a coal mine. Position yourself in a location where a luminaire is between you and the rib or face. Observe how well you can see a detail at the rib. Now, place a shield between yourself and the luminaire in a manner that does not change the illuminance on the face and again observe how well you can see the object. Visibility of the detail will likely improve. This difference in visibility is a measure of level of disability glare. In conducting such an experiment, it is important to realize that one should not "blame" the luminaire for a loss of visibility. Indeed, were it not there, visibility would be far less. Disability glare must be viewed as a tradeoff. Some level of disability glare is present in every illumination setting. The engineering feat is to minimize its effect while maintaining adequate net visibility levels.

Although one generally associates discomfort with the term glare, discomfort does not necessarily accompany disability glare. Imagine standing on a sunny day near the base of a hill a few hundred yards or so from the opening of a tunnel into the hillside. The tunnel appears black and no detail within the opening can be discerned. One could, however, view the tunnel opening through a tube and, if the tube was long enough, details within the tunnel opening could be perceived. The effect of the tube is to reduce the amount of stray light that enters the eye and ultimately causes a veiling of the retinal image of the tunnel. In this example, disability glare exists without noticeable discomfort. This can also be the case with underground mine lighting systems. One should not rely on a complaint of discomfort as stimulus to investigate a glare problem.

Disability Glare Relationships

The effects of disability glare have been quantified through extensive empirical study. The following are basic equations that can be used to evaluate this change in visibility. When a glare source is not in the field of view, the perceived contrast between the detail and the background luminance, as discussed in chapter 3, is represented by the equation $C' = L_d - L_b/L_b$, where L_d is the luminance, in footlamberts, of the detail, such as the surface of a timber or a mine worker's clothing, and L_b is the background luminance, in footlamberts. When the glare source is present, light from it enters the eye and may be considered to superimpose a veiling luminance, L_v, on the image of the scene being viewed. Experiments have shown that this effect can be represented by $C' = (L_d + L_v) - (L_b + L_v)/L_b + L_v$, where C' is the apparent contrast of the detail with the presence of a glare source. This expression reduces to $C' = L_d - L_b/L_b + L_v$. Expressed in this form, one can see that since L_v is in the denominator its effect is to reduce the apparent contrast. As explained in chapter 3, this reduces the object's visibility level.

To quantify this relationship, a way of establishing the magnitude of L_v is needed. Extensive empirical work has shown the following relationship to be adequately descriptive of situations where a single glare source is present (illustrated in figure 51): $L_v = K \pi E/\theta^2$. E is the illumination, in footcandles, produced by the glare source in the pupil on a plane perpendicular to the observer's line of sight; θ is the angle, in degrees, between the glare source and the line of sight, and K is a proportionality constant.

The relationship shows that L_v is directly proportional to E and inversely proportional to θ^2. As a practical matter, E can be calculated from luminaire intensity curves, based on the inverse square law presented in chapter 2, by $E = I_\theta/D^2$. If E is based on direct illumination (footcandle) measurements, the photocell should be oriented to the luminaire and the cosine law applied to calculate E: $E = E_{luminaire} \cos \theta$. Substituting these relationships in the equation for veiling luminance gives $L_v = (K\pi/\theta^2)(I_\theta/D^2) \cos \theta$. On the basis of this discussion it is evident that the effects of disability glare are greatest for high intensity luminaires that are close to the observer and, also, close to the line of sight. As the luminaire is moved away from the line of sight, the disability glare effect decreases rapidly since L_v is inversely proportional to both θ^2 and D^2.

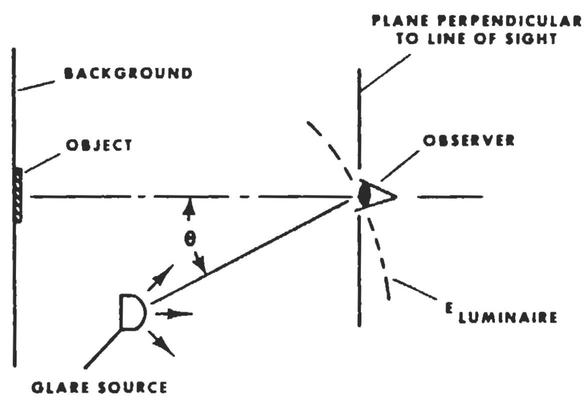


Figure 51.—Geometric parameter for disability glare.

As noted previously, the physiological basis for disability glare is light scatter within the ocular mediums of the eye. As might be expected, this will vary from one individual to another. Accordingly, the value of K has carefully been established for the "average" observer but, as discussed, rather wide variances exist. There is a significant relationship between the value of K and the age of the observer. That is, physiological changes that occur as a person ages increase light scatter within the ocular mediums and raise L_v. To accommodate this, K may be defined as a function of two variables: $K = K_{20} \times K_{rel}$. Where K_{20} is the mean value for normal 20-yr-old observers. K_{rel} is a multiplier that adjusts the value of K for the age of the observer. The relationship of K_{rel} to age is shown in figure 52. These are average values of K_{rel} for each age group. As can be seen, K_{rel} is constant at 1.0 up to an age of approximately 42 yr and then rapidly increases.

The mean value of K_{20} is a function of the background luminance. For luminance in the range of 0.06 fL, K_{20} is 17.6. For normal room lighting K_{20} is equal to approximately 10. The higher value of K_{20} in low luminances is due to the larger pupil size allowing more stray light to enter the eye.

Figure 53 illustrates the variation in K as a function of age and the variation in K within age groups when the background luminance is 0.06 fL. These data indicate that disability glare can vary widely among individuals in the particular age group and the values of K for various age groups overlap by large amounts. Note that some individuals in the 20- to 30-yr age group can be more sensitive to glare than some in the 70- to 80-yr age group.

Where multiple glare sources are in the field of view, experiments have shown that it is valid to represent the veiling luminance as the sum of the veiling luminance from each source: $L = K\pi\ E_1/\theta_1^2 + E_2/\theta_2^2 \ldots E_n/\theta_n^2$.

These equations provide a useful tool for the illumination system designers when their objectives are to compare alternative illumination system concepts from the standpoint of minimizing disability glare. The following example illustrates their application.

Application of the Disability Glare Relationships

The machine depicted in figure 54 is a continuous miner for which five lighting arrangements have been established, each capable of providing the minimum required 2-fc face and roof illumination. In each system, a fluorescent luminaire is a disability glare source along one of the operator's principal lines of sight. Each of these options will be compared from the standpoint of maximizing the visibility of a detail at the coal face.

Measured values of the important photometric parameters for each of the concepts are given in table 11. To

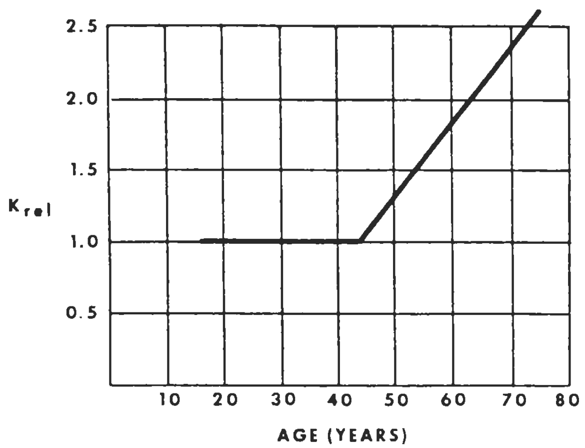


Figure 52.—Disability glare constant age factor.

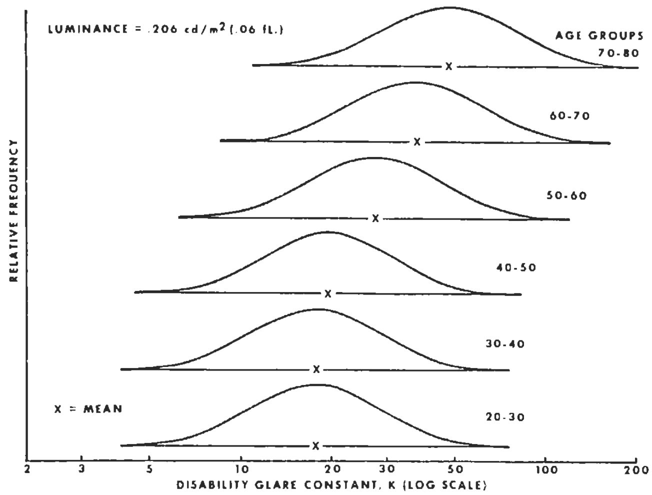


Figure 53.—Mean and distribution of the disability glare constant, K, as a function of age.

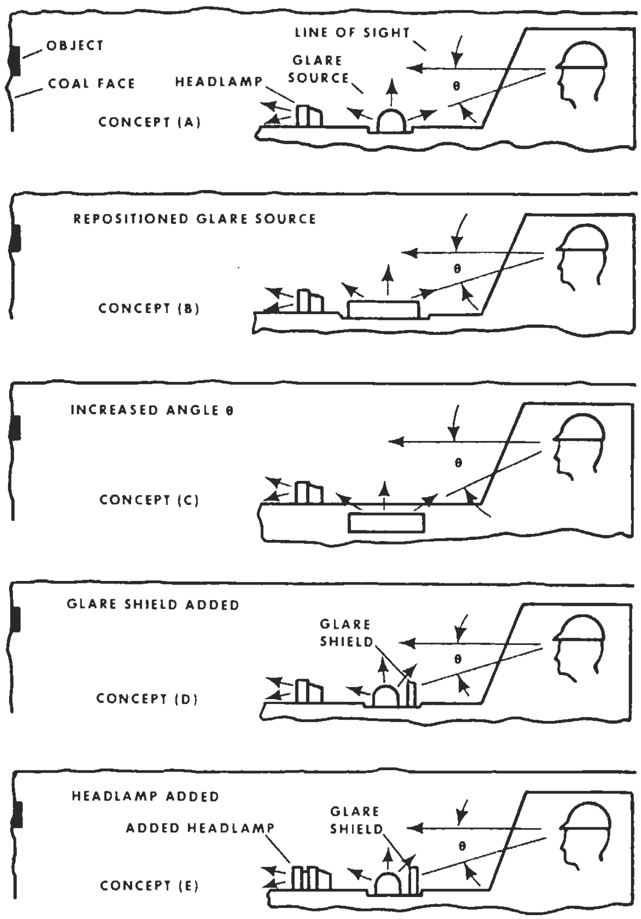


Figure 54.—Example of disability glare analysis.

Table 11.—Parameter values for suggested lighting concepts

	a	b	c	d	e
Face illumination (E) . . . . fc . .	2.0	2.0	2.0	2.0	4.0
Illumination from glare source on operator (Eθ) . . . . . . fc . .	2.0	0.5	0.5	0.1	0.1
Angle (θ)	15°	15°	30°	15°	15°

evaluate these alternatives, the computed threshold contrast, C_{task}, of the object on the coal face will be compared to an assumed threshold contrast criteria profile (the visibility reference function, see figure 47). The visibility threshold reflectances of the object, ρ_d, at the coal face will also be computed and compared for each concept.

The contrast between the object at the coal face and the coal face is expressed as $C_{task} = L_d - L_b/L_b$ and $\rho_d E - \rho_b E/\rho_b E$. The the reflectance of the background (coal face) is assumed to be 4 pct.

Concept

The illuminance, E_1, impinging on a plane normal to the line of sight of the machine operator is $E_1 = E_\theta \cos \theta$, $= 2.0 \cos 15°$ or 1.93 fc.

When the value for general luminance is in the range of 0.06 fl, the glare constant, K, equals 17.6. The resulting veiling luminance is $L_v = K \pi E_1/\theta^2$, $17.6 \pi (1.93)/15^2$ or 0.47 fL.

The apparent contrast of the perceived task (object against the coal face) is $C' = L_d - L_b/L_b + L_v$, and L_b, the luminance of the coal face, is $L_b = \rho_b E$, 0.04(2) or 0.80 fL.

Therefore the apparent contrast is $C' = L_d - 0.08/0.08 + 0.47$ or $L_d - 0.08/0.55$.

The profile (visibility reference function) depicted in figure 47 was selected as a visibility criteria curve for this analysis. The equation for this curve is $C' = [(0.482/L)^{0.4} + 1]^{2.5}/16.846$, where C′ is the apparent contrast perceived by the machine operator and L is the apparent background luminance, $L_b + L_v$, which equals 0.55 fL.

Solving the above equation for C′, $C' = 0.315$; therefore $C' = 0.315$, $L_d = 0.08/0.55$, and $L_d = 0.253$. L_d is the threshold luminance of the object. The threshold contrast for the task is therefore $C_{task} = L_d - L_b/L_b$, 0.253 −0.08/0.08 or 2.16, and the threshold reflectance of the object is $\rho_d = L_d/E$, 0.253/2.0 or 0.126.

Using this procedure, values of threshold contrast, C_{task}, and threshold object reflectance, ρ_d, for the other four lighting concepts can now be computed and compared. Note that these computed values are not meaningful in themselves because of the many assumptions and simplification of the illuminated environment. However, on a comparative basis, the values are meaningful in determining the relative effect of the varied parameters on operator visibility. The four alternate concepts shown in figure 54 are described as follows.

Concept b

The fluorescent luminaire was repositioned (rotated 90°). The change reduced the illumination from the glare source on the operator.

Concept c

The fluorescent luminaire was repositioned by lowering it within the machine structure. This change increased the angle, θ, but did not change the illuminance on the machine operator when compared with concept b.

Concept d

The lighting arrangement is the same as in concept a, however, a semitransparent glare shield has been added so that the illumination impinging on the operator's eye is reduced by 95 pct.

Concept e

The lighting arrangement is the same as in concept d with the exception that additional headlamps were added, which doubled the average face illumination level compared to the other four concepts.

As shown in table 12, concept a results in the poorest visibility. Visibility is improved progressively with concepts b through e.

Table 12.—Summary of results for suggested lighting concepts

Concept	L_v	C_{task}	ρ_d	Rank
a	0.47	2.16	0.126	5
b	.12	1.33	.093	4
c	.026	1.06	.083	3
d	0.24	1.05	.082	2
e	.024	.65	.066	1

General methods that the designer can utilize to reduce or eliminate disability glare and its adverse effect on visibility follow.

Remove the glare source completely from the field of view or shield it from view, preferably with an opaque glare shield. The advantage of shielding is shown when comparing the threshold object reflectances for concepts a and d. Adding the glare shield to concept a reduced the required object reflectance needed for visibility from 0.126 to 0.082.

Reduce the illuminance from the glare source that impinges on the observer as much as possible. Consider alternative luminaire types and orientations that minimize the illuminance. Note the position of glare source in concept b significantly reduced the glare illuminance compared with the same luminaire in concept a.

Place luminaires as far from principal lines of sight as possible. Veiling luminance values are reduced significantly as the angle, θ, is increased since L_v is a function of θ squared, $L_v = K \pi E_1/\theta^2$.

Note that when the angle was increased from 15° to 30° in concepts b and c, L_v was reduced from 0.12 to 0.026 fL. As θ approaches zero, veiling luminance values become extremely high. These values are considered valid for values of θ as low as 1° as long as the source does not impinge on the true line of sight.

Increase the illuminance of the task object and background. For example, in concept e the task illumination was doubled as compared with illumination in concept d and the threshold reflectance of the object was reduced from 0.082 to 0.066. Therefore the adverse effect of the disability glare source on visibility was reduced. This calculation ignored the effect of reducing K, which might occur if general background luminance rises significantly.

Note that factors that do not directly play an important role in reducing disability glare are luminaire size and luminaire brightness. Therefore, a small bright source and a large, less bright source that both generate the same glare illuminance on the observer are not significantly different from the standpoint of disability glare. Large sources that impinge more on the line of sight of the observer would, however, be an exception to this case.

Unfortunately, in underground mine illumination systems it is difficult to reduce disability glare to a negligible value. Luminaires are often in the field of view of machine operators and helpers. The goal of the designer should be to reduce the glare and improve visibility as much as possible while meeting the requirements of the illumination regulations.

While these equations and example problems are by no means a precise method of analysis, they do reveal the pertinent parameters, their importance in reducing disability glare, and facilitate making decisions between alternative concepts. The equations also illustrate that seemingly small changes in the design can have significant benefits in visibility improvement.

DISCOMFORT GLARE

Discomfort glare is a sensation of annoyance or in extreme cases, pain caused by high or nonuniform distribution of brightness in the field of view. As noted previously, discomfort glare is a phenomenon distinctly different from disability glare. Results from two coal mine illumination surveys conducted in 1979 indicated that discomfort glare is a major source of dissatisfaction with underground coal mine illumination systems. A recent Bureau study, confirmed that, from the standpoint of discomfort glare, underground coal mine illumination systems can be very uncomfortable. In this study, discomfort glare was measured in a simulated mine on various illumination systems mounted on a continuous miner and roof bolting machine. The results of the study also present suggested modifications to the standard equations for evaluating discomfort glare. These modified equations are presented in this chapter.

The basic relationships for quantitative discomfort glare analysis are outlined in the following discussion and a suggested method to evaluate and compare alternative illumination systems for the purpose of minimizing discomfort glare is presented. This method does not predict whether a particular design is acceptable from the standpoint of discomfort glare. To determine how much discomfort glare is acceptable is a complex task in underground coal mines since the overall benefit of improved visibility may at times outweigh the adverse effect of discomfort glare. For example, headlamps on continuous miners can at times be a source of extreme discomfort glare, yet their benefits in visibility usually outweigh the disability glare they intermittently impose on the mine worker. As in the case of disability glare analysis, the presented method of computing discomfort glare is solely for the purpose of providing the designer with a method of comparing the merits of alternative design approaches. The absolute values of computed discomfort glare are not precise because of assumptions that must be made in the analysis. These assumptions are discussed at the end of this chapter.

Discomfort Glare Equations

The following method of discomfort glare analysis is based on the IES visual comfort probability method. The standard equations of this procedure have been modified to incorporate modifications recommended in a recent Bureau study that evaluated discomfort glare in the low background luminance range encountered in underground coal mines.

Single Glare Source

A glare source within the field of view of an observer is depicted in figure 55. For a single glare source the fundamental discomfort glare formula is $M = LQ/pF_{0.32}$, where M, the index of sensation, is a measure of the level of discomfort glare. For a single glare source, M is also called the discomfort glare rating (DGR) of the scene. Higher DGR values mean increased discomfort glare.

L is the source luminance (brightness) in the direction of the observer, in footlamberts. Source luminance, L, can be computed from the luminaire photometric data or from light measurement as was discussed in chapter 2. One convenient method to determine L is to measure the illumination, E, at the observer's location that is due solely to the glare source and using the following equation compute the source luminance: $L = \pi ER^2/Ap$.

E is illuminance at the observer's location due solely to the glare source, in footcandles. If E is measured, the photometer should be aimed directly at the glare source. R is distance from the observer to the glare source, in feet. See figure 55. A_p is the projected area of glare source in the direction of the observer, in square feet.

Q is a function of the solid angle, ω, that subtends the glare source and extends to the observer as indicated in figure 55. The empirical definition of Q is $Q = 20.4\omega + 1.52\omega^{0.2} - 0.075$ and $\omega = Ap/R^2$.

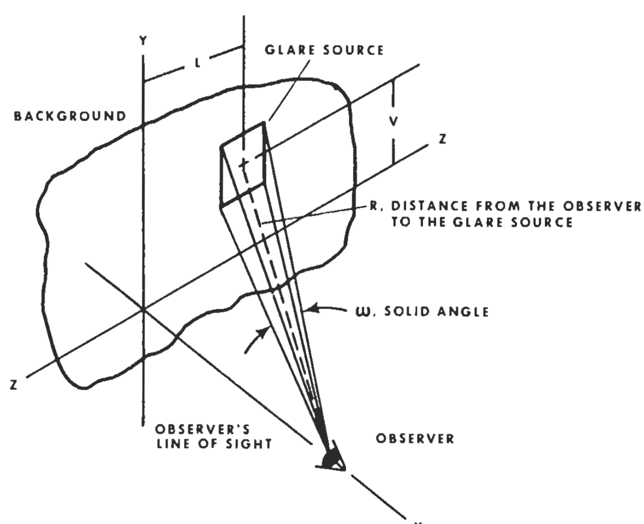


Figure 55.—Geometric parameters involved in discomfort glare evaluation.

P is the position factor. It accounts for the relative glare sensation dependent on the position of the glare source with respect to the line of sight. Position factors for glare sources above the line of sight are given in figure 56. V and L are the vertical and lateral displacements of the glare source from the line of sight and R is the distance from the observer to the glare source as illustrated in figure 55. Position factors for the entire visual field below the line of sight are not available with the exception of one location 20° below the center of the line of sight. The comparative values of P for 20° below and 20° above the line of sight are 1.58 (below) and 1.96 (above).

Until data become available for position factors below the line of sight, a suggested approximation for P_{below} would be to invert the P_{above} chart and reduce the position factors for V/R and L/R values by a factor of 1.58/1.96 or 0.8.

F is the field luminance. In the development of the discomfort glare equation, field luminance was precisely defined as the surface brightness of an 80-in^2 uniformly illuminated spherical background. Potential glare sources were evaluated by placing sources of light against this background. In the actual environment the field luminance is not precisely defined. In general, it should be a weighted average of the various backgrounds in the field of view and should include the glare sources as contributors to determine an equivalent field luminance. Three techniques to define the approximate value of field luminance follow. The first two are direct measurement techniques and the third is a computational method that provides a means to evaluate alternative designs without necessarily constructing laboratory simulations. While the derived value of F will differ for each method, if the same method is used to compare alternative lighting concepts, error will be minimized.

Method 1.—A measure of field luminance is the illuminance on the observer's eyes on a plane that is normal to his or her line of sight. This method of measuring field luminance is shown in figure 57*A*. Note that although the measurement is in footcandles, if one assumes the background to be a perfectly diffuse reflector, this value is also the field luminance, in footlamberts. The meter must be cosine corrected to accommodate for the significant luminances that impinge on it from various angles. Remember the meter measures the lumens per square foot impinging on it from all directions over a solid angle of 2π sr (a hemisphere). Since a definition of the footlambert is a diffuse source that also emits 1 lm/ft^2, one can imagine the measurement equivalent to that of a uniform diffuse field in front of the observer. Note that since the acceptance angle of the photometer is 180° (2π sr) and the field of view of an observer is less (approximately 5 sr) this approach introduces some error. Also, a meter with good cosine correction over all incident angles illumination is required.

Method 2.—With this method, a diffuse reflecting card of known reflectance is placed at the observer's location as shown in figure 57*B*. The luminance of the card is proportional to the field illumination that would have been impinging on the observer. The field luminance, F, can be calculated by dividing the measured luminance of the card by the reflectance of the card surface or $F = L_{card}/\rho_{card}$. The card surface should be normal to the line of sight of the observer.

Method 3.—This procedure permits the calculation of field luminance by averaging the various luminances over the visual field of the eye. The following approximate equation can be used: $F = L_b\omega_b + L_s\omega_s \cos \theta_s 1/5$.

L_b is the luminance of the background, in footlamberts; L_s is the luminance of each glare source, in footlamberts; ω is the angle subtended by each area, in steradians; and θ_s is the angle between the observer's line of sight and the glare source. The constant, 5, is the approximate total visual field of the eye in steradians and $\omega_b + \omega_s = 5$ sr.

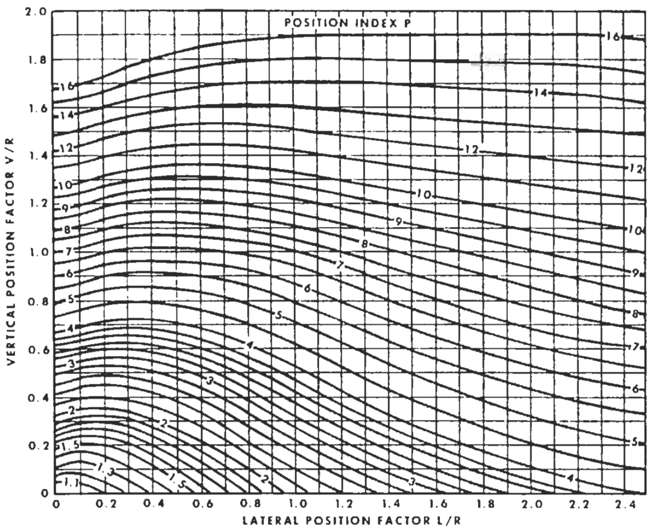


Figure 56.—Discomfort glare source position index factors for sources above the line of sight.

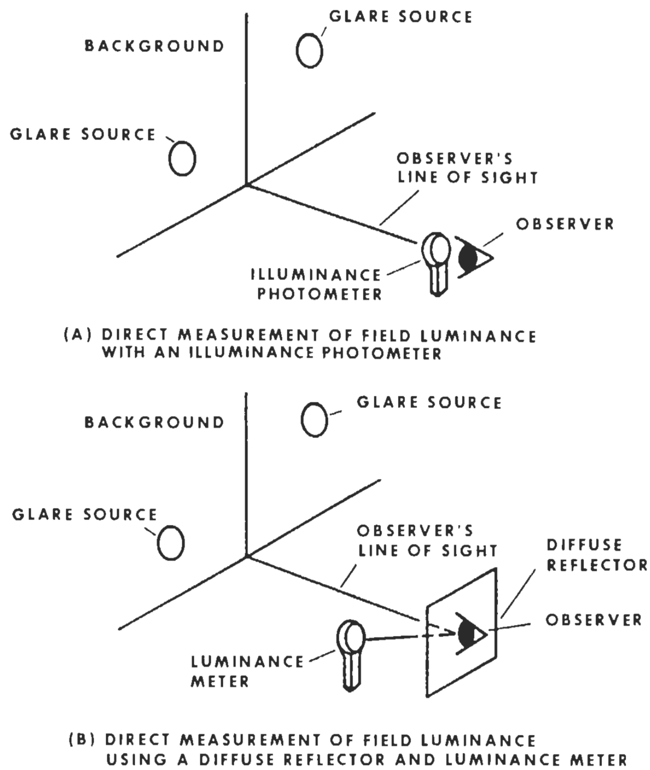


Figure 57.—Direct measurement methods to evaluate average field luminance.

For backgrounds of differing zones of brightness, the equation can be further refined expanding the $L_b\omega_b$ term as follows: $L_b\omega_b = L_{b1}\omega_{b1} + L_{b2}\omega_{b2} + \ldots L_{bn}\omega_{bn}$.

Multiple Glare Sources

The discomfort glare rating (DGR value) for a scene that consists of multiple luminaries can be computed using the following empirical equations: DGR = $M^a{}_t$ or $(LQ/PF^{0.32})^a{}_t$ and $M_t = M_1 + M_2 + \ldots M_n$, where $M_1 \ldots M_n$ are the indexes of sensation of the individual glare sources The exponent a is equal to $1/n^{\,0.0914}$ where n is equal to the number of glare sources.

The designer can compare alternative illumination system concepts for discomfort glare by comparing computed DGR values for each concept. Increased DGR values mean increased glare. Note, however, that because of the wide range of glare sensitivity in the population, DGR values cannot be readily associated with degrees of discomfort glare. To solve this problem, the visual comfort probability (VCP) method of assessing discomfort glare from the computed DGR values was developed.

Visual Comfort Probability

There are no current established standards that specify maximum discomfort glare ratings for underground coal mine illumination systems. Results from the discomfort glare study sponsored by the Bureau, however, do provide DGR data that can be useful guidelines for the illumination system designer. This is depicted in figure 58 where DGR values as calculated using the previously discussed relationship are plotted versus VCP. VCP is the percent of observers who would be expected to judge a scene to be at or more comfortable than the borderline between comfort and discomfort (BCD value). For instance

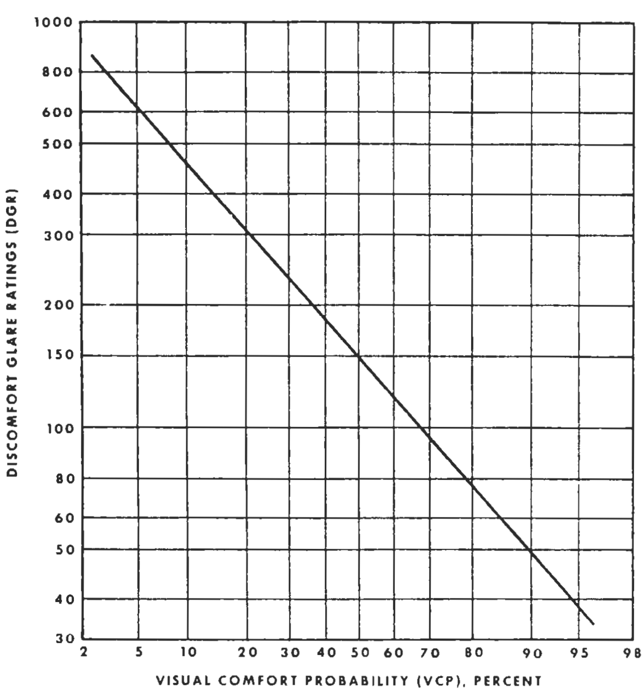


Figure 58.—Discomfort glare rating versus visual comfort probability for mining population.

if a scene has a DGR value of 100, the VCP would be 78 pct which means 78 pct of a large number of observers from the underground coal mining population would judge the scene as having less glare than the BCD value and 20 pct would judge the scene as having more glare than the BCD value.

The VCP method to evaluate discomfort glare is necessary because of the large variation in sensitivity to discomfort glare among the population. The Bureau study, suggested that an objective for the coal mine illumination system designer could be to achieve VCP ratings of 50 pct or higher. (A DGR above the BCD value may not be a particularly bad thing, since BCD is just the threshold of a discomfort sensation. It is totally impractical to design for 100 pct VCP in any application.) The goal of the illumination system designer should, of course, be to maximize VCP as much as possible within practical constraints while meeting the illumination regulations. Special attention should be paid to reducing discomfort glare at principal observer locations, and the corresponding principal lines of sight, such as the operator cab, helper stations, and machine work stations where most work activity takes place. Note from the discomfort glare equations that discomfort glare can be reduced by various methods including

Reduce source brightness, L. Note that for a constant lumen output, M values are more sensitive to a change in source brightness, L, than a change in source size, ω.

Increase position factors, P.

Increase field luminance, F.

Reduce source sizes, ω, but not at the expense of increased source luminance.

Most importantly, however, when at all possible, discomfort glare is best reduced by removing the source from the field of view of the worker.

The two following problems illustrate the application of the methods to analyze discomfort glare.

Single Glare Source.—Compare three alternative luminaire options to determine which one results in the lowest amount of discomfort glare in the location and surrounding luminance as shown in figure 59. Assume the following measured values for options 1 through 3:

		1	*2*	*3*
Area of light emitting surface	ft^2	0.25	0.5	0.5
Measured illuminance on observer due to glare source alone	fc	3.0	3.0	2.0

In each case, the light emitting surfaces are flat diffuse surfaces. The background luminance is 0.06 fL.

Solution.—The discomfort glare can be compared by computing and comparing the DGR and VCP rating for each approach. Since there is only one glare source in the field of view, the equation for DGR is DGR = M or $LQ/PF^{0.32}$. For option 1, $L = \pi ER^2/A_p$, source brightness. A_p = 0.25 cos 45° or 0.176 ft^2; R = 5/cos 45° or 7.07 ft; L = $\pi(3)(7.07^2)/0.176$ or 2,676 fL; Q = 20.4 ωs + 1.52 $\omega s^{0.2}$ − 0.075; $\omega s = A_p/R^2$, $0.176/7.07^2$ or 0.0035 sr; and Q = 20.4(0.035) + $1.52(0.0035^{0.2})$ − 0.075 or 0.487.

To solve for the position factor, P, refer to figure 56. V/R = sin 45° or 0.707, L/R = 0, and position factor, P, is 4.5.

The average field luminance impinging on the observer is $F = L_b\omega_b + L_s\omega_s \cos\theta/5$; $\omega_b + \omega_s$ = 5 sr; ω_b = 5 − 0.0035 or 4.996 sr. Therefore, F = 0.06(4.996) + 2,676 (0.0035)(0.707)/5 or 1.38 fL, and DGR = 2,676(0.487)/4.5 $(1.38^{0.32})$ or 261.

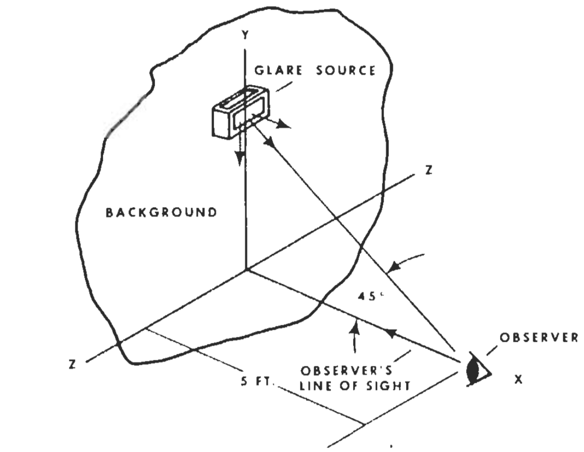


Figure 59.—Discomfort glare analysis for a single glare source.

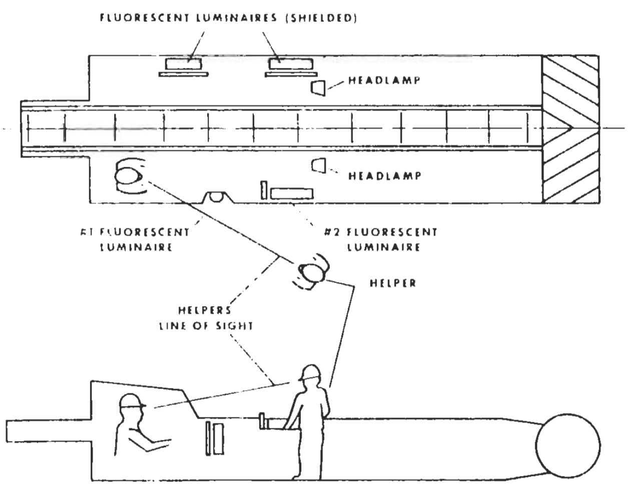


Figure 60.—Discomfort glare analysis for multiple glare sources.

VCP can be read directly from figure 58—$VCP_{luminaire_1}$ = 40 pct. The computed values of DGR and VCP for options 1 through 3 are as follows: 1—DGR 261, VCP 40; 2—DGR 169, VCP 60; and 3—DGR 127, VCP 70. Option 3 would result in the least amount of discomfort glare for the specified observer location.

Multiple Glare Sources.—A continuous miner is depicted in figure 60. Evaluate the DGR and VCP rating for the indicated line of sight of the helper. Assume the following measured parameters of the system:

Measured luminance of a diffuse reflector placed at the observer and facing his or her direction of sight is 1.0 fL. The reflectance of the reflector is 80 pct.

The locations of the glare sources as measured relative to the line of sight for luminaires 1 and 2 are as follows, in feet:

	1	*2*
Radius, R	6.0	5.5
Vertical, V	−3.0	−2.0
Lateral, L	1.0	4.0

Projected areas, A_p, of the sources in the direction of the helper, in square feet, are 1—0.25 and 2—0.40.

Illuminance on the helper, in footcandles, is 1—1.5 and 2—3.

Solution.—The field luminance at the helper station is approximately equal to the illuminance impinging on the diffuse reflector. F = E, L/ρ, 1.0/0.8 or 1.25 fL. Solving for the index of sensation, M, for each glare source, $M = LQ/PF^{0.32}$, where source luminance, $L = \pi ER^2/Ap$. For luminaire 1, $L = \pi(1.5)(6^2)/0.25$ or 678 fL, and for luminaire 2, $L = \pi\,(3)(5.5^2)/0.4$ or 713 fL. $Q = 20.4\omega s + 1.52\omega s^{0.2} - 0.075$; for luminaire 1, $\omega s = A_p/R^2$, $0.25/6^2$ or 0.0069 sr; for luminaire 2, $\omega s = 0.4/5.5^2$ or 0.013 sr. $Q_1 = 20.4(0.0069) + 1.52(0.0069^{0.2}) - 0.075$, which is 0.63, and $Q_2 = 20.4(0.013) + 1.52(0.013^{0.2}) - 0.075$, which is 0.83.

Solving for position factor, P, for luminaire 1, V/R = 3/6 or 0.5 and L/R = 1/6 or 0.17; for luminaire 2, V/R = 2/5.5 or 0.36 and L/R = 4/5.5 or 0.73.

The position factors, P, determined from figure 56 are P_1 = K(2.7), 0.8(2.7) or 2.16 and P_2 = 0.8(2.8) or 2.24. (Note that K is the adjustment factor for sources below the line of sight.)

$M_1 = L_1Q_1/P_1F^{0.32}$, $678(0.63/2.16(1.25^{0.32})$ or 184 and $M_2 = 713(0.83)/2024(1.25^{0.32})$ or 245. M_t is equal to the sum of the individual glare indexes, M_t = 184 + 245, which is 429. DGR = $M^a{}_t$ and $a = 1/n^{0.0914}$ where n is the number of glare sources. $a = 1/2^{0.0914}$, which is 0.94, and DGR = $429^{0.94}$, which is 298.

The VCP value is read from figure 58. The DGR for the scene as viewed by the helper in the indicated direction of sight is 298. This DGR value results in a VCP rating of 32 pct.

Limitations of the Discomfort Glare Analysis

The discomfort glare equations were originally developed for work environments typically encountered in offices, schools, etc., where luminaries are ceiling mounted and where the background luminance levels are far in excess of those encountered in coal mine illumination systems. Factors that limit the accuracy of this method when it is applied to underground mine illumination systems follow.

The field luminance is a complex function that, computed or measured, can be related to the basic laboratory measurements from which the glare equation was derived in an approximate manner only.

The equation for computing M_t is based on multiple luminaires in ceiling arrangements. This equation may not accurately represent multiple luminaires that occur both above and below the line of sight.

The luminaire size factor, Q, is for ω values ranging from approximately 0.0001 to 0.13 sr. When solid angles exceed 0.13 sr for a single source it is suggested that the source be treated as multiple sources each having a size less than 0.13 sr. This method of handling large sources is an approximation only.

Position factors, P, are not known for all points below the line of sight. The method recommended for positions below the line of sight is based on the broad assumption that position factors below the line vary in a manner similar to those above the line of sight.

While this method of analysis does not, nor is it intended to, predict whether a lighting system is acceptable or not from the standpoint of discomfort glare, it provides the designer with a means to objectively evaluate alternate concepts to minimize discomfort glare. The method can significantly assist in assessment of this difficult problem.

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

c	candle	lx	lux
c/in^2	candle per square inch	m^2	square meter
c/s	cycle per second	min	minute
fc	footcandle	mi/s	mile per second
fL	footlambert	nm	nanometer
ft^2	square foot	pct	percent
Hz	hertz	sr	steradian
in	inch	W	watt
in^2	square inch	yd	yard
lm	lumen	yr	year
lm/sr	lumen per steradian		

SELECTED CONVERSION FACTORS

Abbre-viation	Unit of measure	To convert to—	Multiply by—
c/in^2	candle per square inch	candle per square meter	0.000645
		footlambert	.00221
c/m^2	candle per square meter	candle per square inch	1,550
		footlambert	.2919
fc	footcandle	lux	10.76
fL	footlambert	candle per square inch	452.4
		candle per square meter	3.426
lx	lux	footcandle	.092903