Standard Guide to Properties of High Visibility Materials Used to Improve Individual Safety[1]

INTRODUCTION

For many years the problem of pedestrian–motor vehicle collisions has been a major one in the United States and the rest of the world. In the U.S., in the last three years for which data are available (1988–1990), there have been on the average about 8200 pedestrian fatalities per year, of which about 54 % occurred at night (**1**).[2] In addition, over 100 000 pedestrians were injured by motor vehicles each year (**2**).

Lack of adequate visibility and conspicuity of pedestrians at night and during the day is considered to play a direct role in many of these accidents. An investigation of pedestrian accidents lists the following six driver and pedestrian actions necessary for safe travel: search, detection, evaluation, decision, human action, and vehicle action (**3**).

Research shows that pedestrians typically overestimate their visibility (**4**). Since the average pedestrian is not likely to be able to determine means for establishing adequate visibility, guidelines are needed to improve visibility and conspicuity of pedestrians. Guidelines and, in fact, standards (**5, 6**) have been provided for other road users (for example, trucks, passenger cars, motorcycles, and bicycles) in an attempt to meet visibility needs, but not for pedestrians. This guide provides general principles for the enhancement of pedestrian visibility both at night and during the day. These principles also generally apply to anyone else exposed to motor vehicles, including construction workers, airport workers, bicyclists, and motorcyclists.

1. Scope

1.1 This guide covers the physical principles and variables involved in the performance and selection of high visibility materials for individual safety.

1.2 It is the purpose of this guide to examine the principles on which future standards relating to individual safety may be used. However, this guide does not set minimum standards for the properties of high visibility materials.

1.3 In reviewing the principles contained in this guide, it must be remembered that there are numerous factors adversely affecting visibility and safety (for example, rain, snow, road grime, alcohol, advanced age, drugs, fatigue, inattention, headlamp misalignment or breakage) that must be taken into account when dealing with actual safety requirements.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 1535 Practice for Specifying Color by the Munsell System[3]

D 2244 Test Method for Calculation of Color Differences from Instrumentally Measured Color Coordinates[3]

E 284 Terminology of Appearance[3]

E 308 Practice for Computing the Colors of Objects by Using the CIE System[3]

E 808 Practice for Describing Retroreflection[3]

E 809 Practice for Measuring Photometric Characteristics of Retroreflectors[3]

2.2 *Other Standards:*

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[1] This guide is under the jurisdiction of ASTM Committee E12 on Color and Appearance and is the direct responsibility of Subcommittee E12.08 on High Visibility Materials for Individual Safety.

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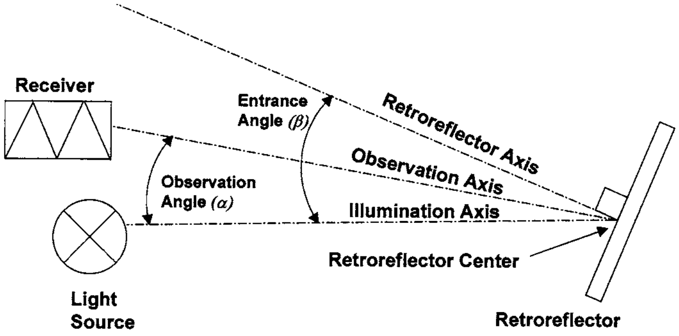
[2] The boldface numbers in parentheses refer to the list of references at the end of this standard.

[3] *Annual Book of ASTM Standards*, Vol 06.01.



NOTE 1—This figure illustrates the test geometry frequently employed when entrance angle and observation angle only are specified. The illumination axis, observation axis, and retroreflector axis are in the same plane. Although the entrance angle β is, by definition, always positive (see Practice E 808), specifying a negative value (such as –4°) for β in this geometry is intended to correspond to locating the observation axis and retroreflector axis on opposite sides of the illumination axis. The entrance angle as illustrated in this figure would then correspond to positive values of β. The observation angle is always positive. See also Fig. 3 and Fig. 4.

FIG. 1 Retroreflection Geometry

CIE S002 Colorimetric Observers[4]

SAE J579c Sealed Beam Headlamp Units for Motor Vehicles[5]

3. Terminology

3.1 *Definitions*—Terms and definitions in Terminology E 284 and Practice E 808 are applicable to this guide.

3.1.1 *brightness*, *n*—attribute of a visual perception according to which an area appears to emit more or less light.

3.1.2 *conspicuity*, *n*—the characteristics of an object that determine the likelihood that it will come to the attention of an observer.

3.1.3 *divergence angle*, *n*—use the preferred term, **observation angle.**

3.1.4 *entrance angle,* β, *n*— *in retroreflection*, the angle between the illumination axis and the retroreflector axis.

3.1.4.1 *Discussion*—This is the angle formed by a light ray striking a surface and a line perpendicular to the surface at the same point (Fig. 1). The surface is commonly depicted as a flat planar surface such as a sign face, but it applies as well to curved or irregular surfaces as when used on clothing. The entrance angle is sometimes referred to as the "incidence angle." It is desirable for retroreflective materials to remain bright through as wide a range of entrance angles as possible. This feature is especially important for retroreflective treatments worn by pedestrians because of the many positions and angles at which the pedestrian and apparel may be viewed by drivers.

3.1.5 *goniometer*, *n*—an instrument for measuring or setting angles.

3.1.6 *observation angle,* α, *n*—the angle between the illumination axis and the observation axis.

3.1.6.1 *Discussion*—This is the angle between a line formed by a light beam striking a surface (such as a sign face) and the line back to the observer's eye from the point (Fig. 1). By knowing how far one is from the light source and the surface, one can compute the observation angle. Either the sine or tangent function can be used to calculate it. This angle must be quite small (2° or less, preferably 0.5° or less) for presently available retroreflective materials to function effectively. The observation angle is sometimes referred to as the "divergence angle." The observation angle is important because retroreflected light is returned as a narrow cone with the inner part of the cone (smaller observation angles) being most intense (Fig. 2).

3.1.7 *orientation angle,* ω_s, *n*—the angle in a plane perpendicular to the retroreflector axis from the entrance half-plane to the datum axis, measured counter-clockwise from the viewpoint of the source.

3.1.8 *pedestrian*, *n*—any person on foot (standing or moving) who is located on a highway or street.

3.1.9 *presentation angle,* γ, *n*—the dihedral angle from the entrance half-plane to the observation half-plane, measured counter-clockwise from the viewpoint of the source.

3.1.9.1 *Discussion*—A full discussion of presentation angle is complicated and will not be given here. It is of importance in photometric measurement where either coplanar or perpendicular presentation geometries are used. The actual situation encountered on the roadway is usually intermediate.

3.1.9.2 *Discussion*—In laboratory measurements where components of the entrance angle are used in setting the actual laboratory goniometer settings, the presentation angle is mathematically related to these components. See Practice E 808 and Fig. 3 and Fig. 4.

3.1.10 *refraction*, *n*—change in the direction of propagation of radiation determined by change in the velocity of propagation in passing from one medium to another.

3.1.10.1 *Discussion*—The change in direction of propagation follows Snell's law (Figs. 5 and 6). When the medium containing the incident beam has the higher refractive index (Fig. 6), a critical angle can be reached beyond which light cannot be transmitted but is reflected. For angles greater than the critical angle, total internal reflection occurs. Most prismatic retroreflectors depend on this principle in order to function.

3.1.11 *rotation angle,* ϵ, *n*—the angle in a plane perpendicular to the retroreflector axis from the observation half-plane to the datum axis, measured counter-clockwise from a viewpoint on the retroreflector axis.

3.1.11.1 *Discussion*—The rotation angle is measured from a datum mark on the retroreflector and is positive in the

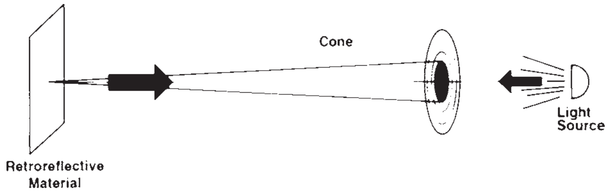


FIG. 2 Cone of Retroreflected Light

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[4] Available from the USNC-CIE Publications Office, c/o TLA Lighting Consultants, Inc., 72 Loring Avenue, Salem, MA 01979.

[5] Available from the Society of Automotive Engineers, 400 Commonwealth Avenue, Warrendale, PA 15096.

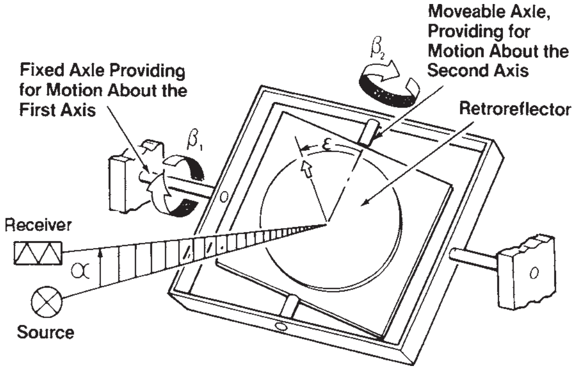


FIG. 3 Measurement Geometry (ASTM-CIE System)

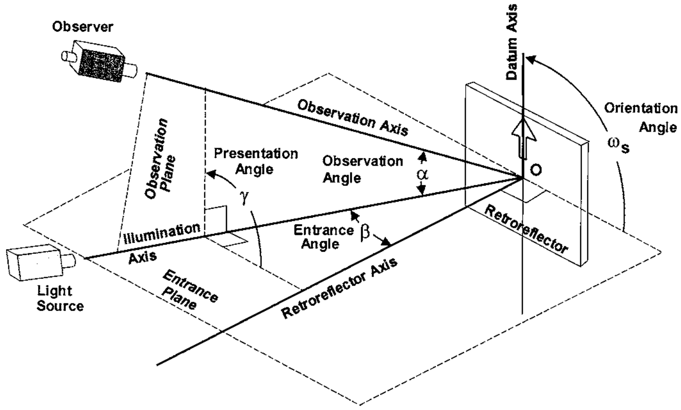


FIG. 4 Measurement Geometry (Intrinsic System)

counterclockwise direction (clockwise rotation of the retroreflector, Fig. 3 and Fig. 4). Very large rotation effects can occur without the retroreflector itself rotating by virtue of changes in distance and geometry between the observer and target. Prismatic or cube-corner retroreflective surfaces typically vary somewhat in brightness when rotated. Spherical-lens sheeting has only a minimal rotational response. On the roadway, rotational effects are usually less significant than changes in observation or entrance angles.

3.1.12 *Snell's law*, *n*—the product of the sine of the angle of refraction by the refractive index of the refracting medium is equal to the product of the sine of the angle of incidence by the index of refraction of the medium containing the incident beam.

3.1.13 *visibility*, *n*—the properties and behavior of light waves and objects interacting in the environment to produce light signals capable of evoking visual sensation.

3.1.14 *visual perception*, *n*—the visual experience resulting from stimulation of the retina and associated neural systems.

4. Summary of Guide

4.1 This guide reviews the factors affecting and gives examples of high visibility materials for individual safety.

4.2 This guide emphasizes passive high visibility materials, but certain active sources important to the functioning of passive materials are also covered.

5. Significance and Use

5.1 The principles elucidated in this guide should be carefully considered in the preparation of standards for the development and use of high visibility materials. The guide does not, however, contain specific test methods or recommended visibility levels.

6. Vision and Visibility

6.1 *General*—The terms visual perception and visibility are defined in 3.1.14 and 3.1.13, respectively. They imply a distinction between the observer and the observed object in the environment. To the observer, vision and visual perception are the important elements. Visibility, on the other hand, is a property of the object (which can be a pedestrian or other road object), its background and illumination, and the transmission of light to the eye of the observer. Thus, to improve the entire system, one might try to improve human vision or teach people to perceive and interpret signals better. Another approach would be to improve the visibility of objects by making them more conspicuous and more recognizable.

6.2 *Vision*:

6.2.1 The human eye responds to radiant energy roughly between the wavelengths of 380 and 780 nm. There are two types of photoreceptor cells in the eye, cones, and rods. Cones are concentrated in the center of the retina (light sensitive tissue) called the fovea and are responsible for color perception and the ability to distinguish fine details. Cones operate best at higher light levels (daytime, bright lights) producing what is termed "photopic" vision. Rods predominate in the retinal periphery and are quite sensitive to motion and to visual stimuli at low light levels under "scotopic" vision conditions (night, dark rooms). Intermediate to the photopic and scotopic states is the mesopic range, where both the rods and the cones are operative. Night driving, in general, produces the mesopic visual condition. The eye is remarkably sensitive; the minimum signal that can be reliably detected is said to consist of no more than about five photons for rods (**6**).

6.2.2 Central vision covers a solid angle of about 5° in the center of the fovea and is needed for such functions as acuity, judgment of speed, and color vision. Peripheral vision is the remainder, extending out to cover the forward 180° field of view. Although much less sensitive to color due to the presence of very few cones, the eye's periphery responds to bright, flashing, and moving lights. This enables a person to monitor much of the environment and selectively switch central vision to the more prominent visual phenomena as they occur.

6.2.3 The slightly different image seen by each eye and integrated by the mind give rise to stereopsis, the ability to see in three dimensions. For driving, however, this is not as important a visual cue of distance as are perspective and overlay cues which impart information by position on the terrain, size, and shadowing effects.

6.2.4 Color vision is mediated by three types of cones, responsive to short, medium, and long wavelengths in the 380 to 780 nm visible spectrum, with response functions that are extensively overlapped. The overall response of the visual system to incoming power is given by the spectral luminous efficiency function $V(\lambda)$, a bell-shaped curve peaking at about

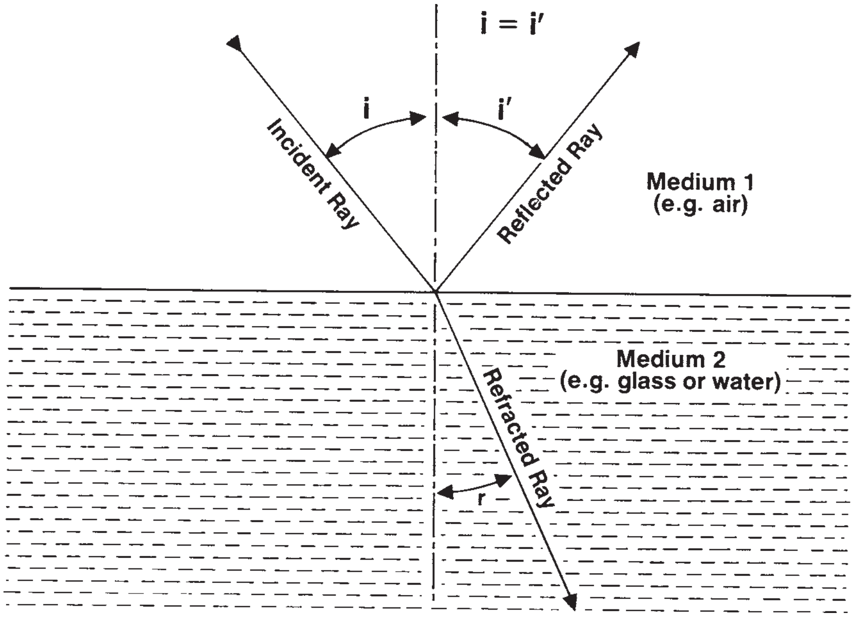


FIG. 5 Refraction—From Lower to Higher Refractive Index

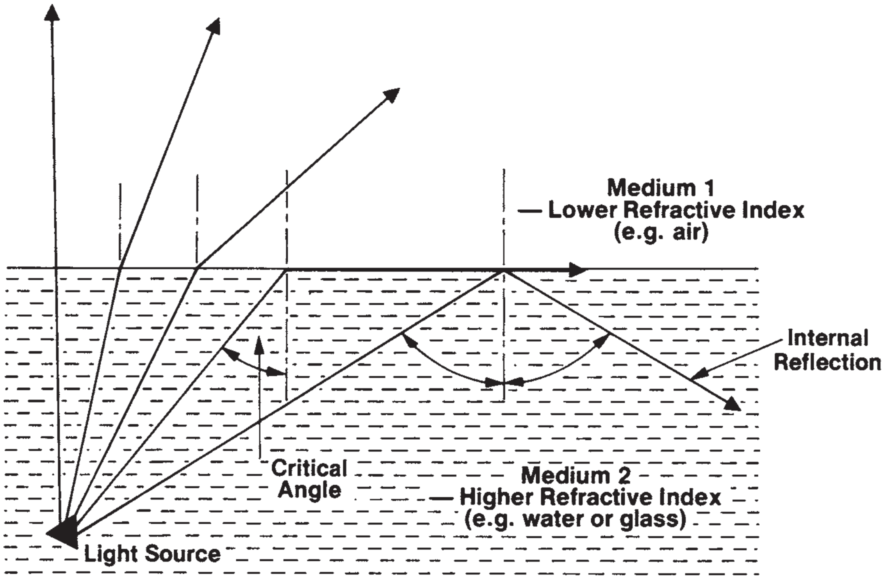


FIG. 6 Refraction—From Higher to Lower Refractive Index

555 nm for photopic (cone) vision and dropping to zero at the ends of the visible region. This function and the sets of color-matching functions characterizing the color-vision properties of the average human eye have been adopted by the CIE (Commission Internationale de l'Eclairage, International Commission on Illumination) to define standard observers for the foveal (2° field) and extrafoveal (10° field) regions of the retina (CIE S002 and Practice E 308). The sciences of colorimetry and photometry are based on these functions. They apply reasonably well to real observers except when color-vision deficiencies result from one or more types of cone being missing or inoperative.

6.2.5 An important property of the eye is its ability to judge the perceived brightness (see 3.1.1) of an object, light source, or other color stimulus. Although such judgments are subjective, they play an important role in determining conspicuity. In the CIE system described above, the psychophysical (objective, measured) correlate of brightness is luminance, Y, which is obtained by multiplying the spectral power of the stimulus, wavelength by wavelength, by the spectral luminous efficiency function $V(\lambda)$ and summing the products over the visible wavelength range, 380–780 nm. It is often assumed that luminance and perceived brightness correlate perfectly (for example, this is assumed in the Munsell system for luminance and Munsell value; see Practice D 1535). However, this assumption is not valid when comparing different colored stimuli. In that case, a correction factor known as the brightness to luminance (B/L) ratio, which is a function of hue and saturation, must be applied. Determining the B/L ratio is difficult, involving visual experiments in which two fields with different colors must be adjusted to match in brightness (heterochromatic brightness matching). Consequently, many sets of B/L ratios are reported in the literature. Those that appear to be most useful for applications involving retroreflective materials are found in ref. (**7**).

6.2.6 The eye is remarkably adaptive to a wide range of illumination levels, approximately 10^{-6} to 10^{6} cd/m^2 in luminance. No single element of the eye has such a wide dynamic operating range; it is achieved by a combination of compression, adaptation, and specialization mechanisms (**8**). One result is that, for the mesopic region (near 1 cd/m^2) associated with night driving, the subjective sensation of brightness increases by only about a factor of four for each tenfold increase in the measured luminance (**9**). Very high luminances can cause temporary or permanent loss of vision. Glaring light can produce discomfort glare which is uncomfortable to look at but does not necessarily impair vision. Glaring light can also produce disability glare which causes at least a temporary vision loss.

6.2.7 As one ages, the eye loses some of its visual acuity and sensitivity, possibly because of reduction in blood supply to the retina, reduction in maximum opening of the iris, and yellowing of the lens. As a result visual performance declines from its peak in the teens by about a factor of three by age 80 (**10**). Recovery from glare takes longer with increasing age. Older persons may perform as well in the daytime under high ambient lighting conditions but experience low acuity and contrast sensitivity at night.

6.3 *Visibility and Visual Perception:* (**11**)

6.3.1 Table 1 shows, for the highway setting, the relation of successive aspects of visibility to corresponding responses of the observer on perception.

6.3.2 The four elements of visual perception shown in Table 1 are distinct sequential phases that correspond to visibility information from the roadway and usually follow in the order shown for an unalerted driver, that is, a driver who is not expecting to encounter a pedestrian or other hazard. Thus, an object may become capable of being detected as a driver approaches but is not detected immediately. After detection, the driver needs to pay attention to the object and may or may not recognize what it is. Finally, if the object appears capable of intersecting the vehicle's path, closing rate, deceleration, headway, lateral offset, and the like, are determined by localization. In considering ways to improve visibility, all of these perceptual functions should be taken into account.

6.3.3 A system that provides only marginal detectability for properly oriented and alerted drivers, for example, should not be considered adequate since such a system fails to address the real visibility needs on the roadway. In a similar manner, conspicuity (that is, attention-getting targets quickly detected at significant distances) may not be enough if important succeeding dimensions such as recognizability and localizability are lacking.

TABLE 1 Relations of Object Visibility to Perceptual Response

Visibility of Pedestrian or Road Object	Perceptual Response
Detectability	Detection (distance dependent)
Conspicuity (noticeability)	Fixation-attention (time dependent)
Recognition	Recognition (identifying relationships)
Localizability	Localization (space-time relationships)

6.3.4 After the visual perception process has taken place, further time is needed by a driver for decision, motor response of hand or foot, and vehicle response (for example, braking action). The length of time for the visual perception-decision-motor-reaction-vehicle response sequence is variable, each element being influenced by several factors. Some of these factors are fatigue, distraction, alcohol, drugs, age, past driving experience, weather conditions, road conditions, and vehicle handling properties. As a result of this variability, one cannot assign strict times and distances for stopping or maneuvering at various speeds.

6.3.5 To cope with the variability of visual perception-decision-motor-reaction-vehicle response, traffic engineers use a measure termed "stopping sight distance" (SSD). SSD assumes a 2.5 s total perception/reaction time followed by vehicle deceleration which varies with the coefficient of friction for the roadway (that is, dry or wet conditions) and roadway grade. For 88 km/h (55 mph) on a straight roadway under wet conditions, this translates to a total of 170 m. SSD applies when the situation is one that is understood by the driver as, for example, when he knows he must stop to avoid a pedestrian in front of him.

6.3.6 Another measure that has been proposed is termed" decision sight distance" (DSD). DSD might apply if the driver is uncertain whether an object really is a pedestrian, where the object is with respect to the traveled lane, and what movements might occur. Based on longer reaction times than those normally associated with SSD, the average DSD for 88 km/h (55 mph) is about 300 m. See Table 2 for recommended decision sight distances (**12**).

6.3.7 Of the two, DSD is the more conservative, covers more of the dangerous road situations, and is the preferred distance when considering high visibility materials for improved conspicuity. It would be desirable, for example, to wear high visibility markings that are conspicuous and even recognizable at 300 m or more on roadways where speeds are 88 km/h and higher.

7. Properties of High Visibility Materials

7.1 Visibility involves light waves interacting with objects in the environment. Several aspects of this process are reviewed in 7.2-7.4.

7.2 *Primary and Secondary Light Sources*—As defined in Terminology E 284, *primary light sources* generate and emit light, that is, they are self-luminous. The sun, vehicle headlamps and taillights, fixed roadway lighting, and flashlights are some examples. Primary light sources are usually seen in the *illuminant mode*. Objects that are not self-luminous but reflect light are called *secondary light sources*. They are usually seen in the *object mode*. All surfaces reflect light to some extent. Those which are designed to reflect in a very efficient way have been termed "high visibility materials."

TABLE 2 Recommended Decision Sight Distance

Design Speed—km/h (mph)	Times (Seconds)				Decision Sight Distance (Meter)	
	Pre-Maneuver		Maneuver	Summation	Computed	Rounded for Design
	Detection & Recognition	Decision & Response Initiation				
50 (30)	1.5–3.0	4.2–6.5	4.5	10.2–14	137–188	140–190
65 (40)	1.5–3.0	4.2–6.5	4.5	10.2–14	182–250	180–250
80 (50)	1.5–3.0	4.2–6.5	4.5	10.2–14	228–313	230–315
95 (60)	2.0–3.0	4.7–7.0	4.5	11.2–14.5	301–387	300–390
110 (70)	2.0–3.0	4.7–7.0	4.0	10.7–14	335–348	335–440
125 (80)	2.0–3.0	4.7–7.0	4.0	10.7–14	383–501	380–500

1 mph = 1.609 km/h
1 ft = 0.3048 m

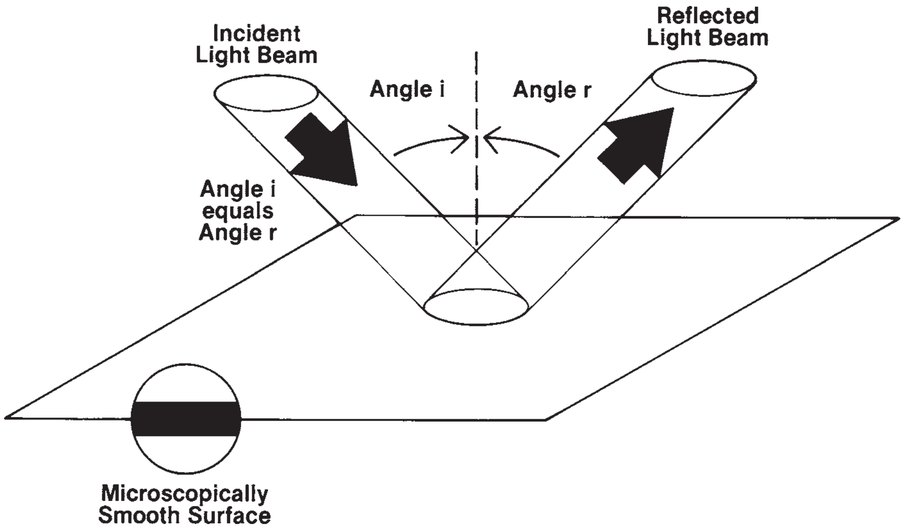
7.3 *Types of Reflection*—Materials absorb only part of the visible radiant energy falling on them. Energy not absorbed or transmitted is said to be reflected. The three basic forms of light reflection are specular reflection, diffuse reflection, and retroreflection.

7.3.1 *Specular or Mirror Reflection*— Specular reflection is possible when the reflecting surface is highly polished or microscopically smooth. The angle of reflection of the light ray is equal and opposite to its angle of incidence, similar to what occurs when light is reflected from a mirror (see Fig. 7). Specular reflection is of unreliable value to enhance visibility because the reflecting surface has to be at a precise angle to direct light into the observer's eyes. The brightness of specularly reflected light is dependent in a complex way on surface curvature, distance, and the material from which the surface is made. For example, chromium plated metal parts used in the auto industry typically reflect about 50 % of incident light.

7.3.2 *Diffuse Reflection*—Diffuse reflection occurs when the reflecting surface is microscopically rough (see Fig. 8). The ideal diffuse reflector is one which obeys Lambert's cosine law and appears equally bright regardless of where the observer stands in front of the reflector. Most materials are diffuse reflectors but are not ideal. Automobile paint, while a diffuse reflector in part, also has a specular component due to its polished surface. Normal street clothing is virtually free of specular reflection and approaches the behavior of an ideal diffuse reflector. During the day or under high artificial illumination, normal clothing can be seen readily. At night or under low illumination (for example, under car headlights at night) normal clothing's reflection may not be efficient enough to be conspicuous or even detectable. This is often true even for white clothing.

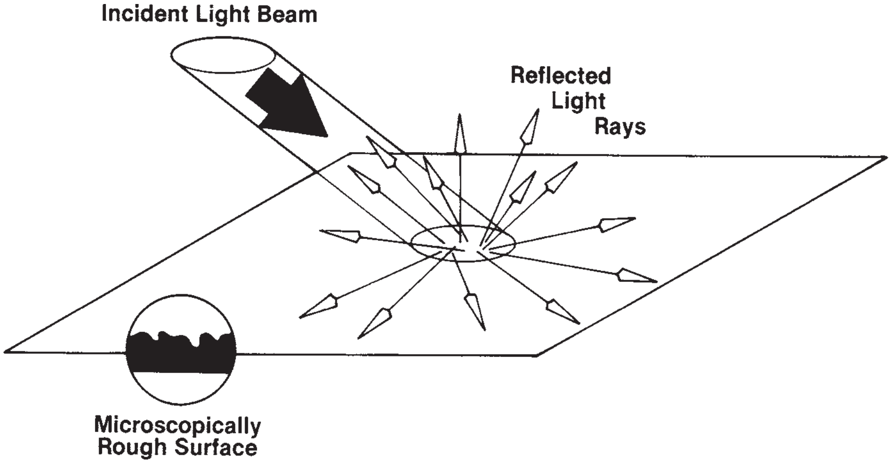
7.3.3 *Retroreflection*—Retroreflection occurs when a large proportion of the light is returned in the direction from which it comes, this property being maintained over wide variations of the direction of incident light. Fig. 9 depicts this type of reflection. It is necessary to have light directed at the retroreflective surface and the observer must be quite closely aligned to the direction of incident light (light returns in the direction from which it came) to see retroreflection from the surface. Clearly, a retroreflector is not a primary light source. Various types of retroreflectors are discussed in Section 8.

7.4 *Luminescence*—As defined in Terminology E 284, *luminescence* is a general term referring to the generation of light by other than thermal processes. An example of this kind of light, sometimes called "cold light," is seen in chemiluminescent wands. Of more interest is *fluorescence*, a type of luminescence in which light is absorbed by an object and



NOTE 1—In retroflection, specular reflection is usually accomplished by a metallized film at the back of the optical element. In some prismatic applications, total internal reflection may be used.

FIG. 7 Specular Reflection



NOTE 1—In retroflection, diffuse reflection is usually accomplished by a pigmented film such as a paint film. Randomly distributed metallic flakes in a binder can be used instead.

FIG. 8 Diffuse Reflection

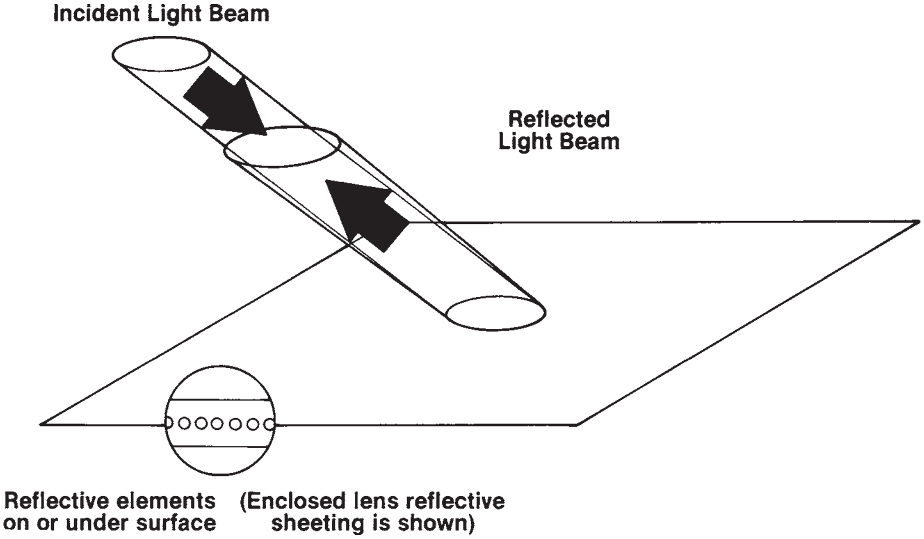


FIG. 9 Retroreflection from Sheet Material

immediately reradiated at longer wavelengths. Fluorescent objects, discussed in Section 9, combine the self-luminous properties of primary light sources with the reflective properties of secondary light sources.

8. Retroreflectors

8.1 There are two types of retroreflectors, prismatic (cube-corner) and spherical lens, both types with many variations.

8.2 *Prismatic Retroreflectors*—Prismatic or cube-corner retroreflectors are made by molding arrays of cube-corner reflective elements, each of which has three mutually perpendicular planar surfaces as indicated in Fig. 10. Cube-corner prisms are optically efficient retroreflective elements and are used in the manufacture of some of the brightest commercially available retroreflective products. Prismatic retroreflectors subdivide into two types: (*a*) rigid injection-molded plastic retroreflectors typically used as highway delineators and motor vehicle and bicycle retroreflectors (about 20 prisms per cm^2 and 3 mm thick), and (*b*) microprismatic sheetings (about 8000 microprisms per cm^2 and varying in total thickness from 0.2 to 0.5 mm).

8.2.1 *Rigid Prismatic Retroreflectors*— The most common variety of this type of retroreflector has a rigid, flat outer surface with unmirrored cube-corner prisms forming an internal layer at the rear of the retroreflector. They are available in several colors, typically clear (or silver or white), amber, and red. Incident light penetrates the front surface and is then reflected at each of the prism's planar surfaces by the phenomenon of total internal reflection. If the entrance angle at the front surface exceeds about 20° for most common unmirrored retroreflectors, total internal reflection begins to fail and brightness falls off. This entrance-angle brightness loss can be reduced by reorienting some of the prisms or mirroring prism surfaces. If the back surfaces of the prismatic retroreflectors are not mirrored, they must be protected from moisture, dirt, and scratching by a sealing film to retain the air interface necessary

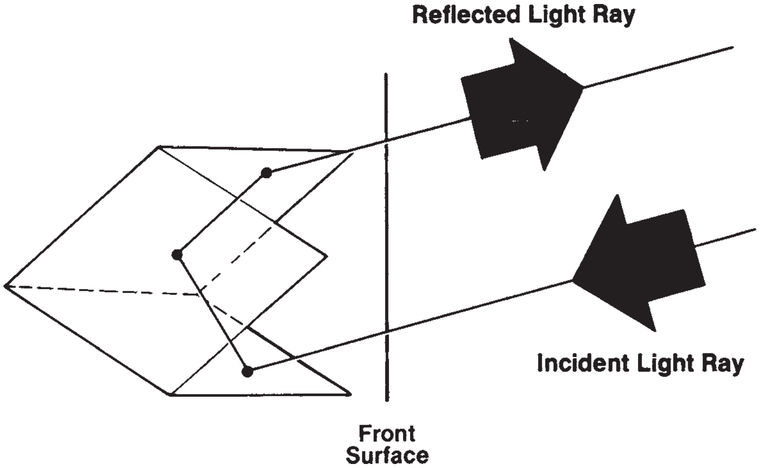


FIG. 10 Cube-Corner Reflector

for maximum reflection. Rigid, molded prismatic reflectors, properly made with smooth surfaces and precise angles, appear very bright to observers quite close to the incident light beam, that is, at small observation angles, typically experienced at longer viewing distances, but this high efficiency falls off as the observation angle increases. These reflectors are especially useful where viewing angles are constrained to narrow entrance angles, that is <20°, and small observation angles, for example, 0.2°.

8.2.2 *Microprismatic Retroreflectors*:

8.2.2.1 Microprismatic retroreflective sheetings use microscopic cube-corner prism reflective elements (approximately 0.08 to 0.4 mm in height). These microprisms can be exposed, enclosed, or encapsulated in the sheeting as with glass beads (see 8.3.2). The retroreflective and other physical characteristics can be varied widely depending on the sheeting's construction and materials used. The optical properties of these sheetings can be tailored to meet varying requirements in viewing geometry.

8.2.2.2 Microprismatic sheetings can be made in fluorescent colors, reflect colors wet or dry, and are supplied in semi-flexible and flexible forms, which can be sewn. Fig. 11 shows a typical construction of microprismatic sheeting.

8.3 *Mirrored Spherical-Lens Retroreflectors*—Mirrored spherical-lens reflectors can be of the cat's-eye type or the glass bead type, the latter being the most prevalent commercially and the most versatile.

8.3.1 *Cat's-Eye Reflector*—Fig. 12 shows a molded cat's-eye reflector. The outer spherical surface typically has a smaller radius of curvature than the inner spherical surface, which is coated with a specular reflector. Light striking the outer surface is refracted and travels through the transparent material of the cat's eye to the back surface where it is reflected back and eventually emerges from the reflector on a path parallel to the incident ray, approximately back to the light source. Cat's-eye reflectors are relatively large (3 to 10 mm) and can be molded to form multiple arrays (Fig. 12).

8.3.2 *Glass-Bead Reflectors*—Glass-bead reflectors, as shown in Fig. 13, and Fig. 14, use very small glass spheres (0.2 mm) with a high index of refraction and are generally used in retroreflective sheeting, which may be of exposed, enclosed, or encapsulated lens construction. In addition, the glass-bead

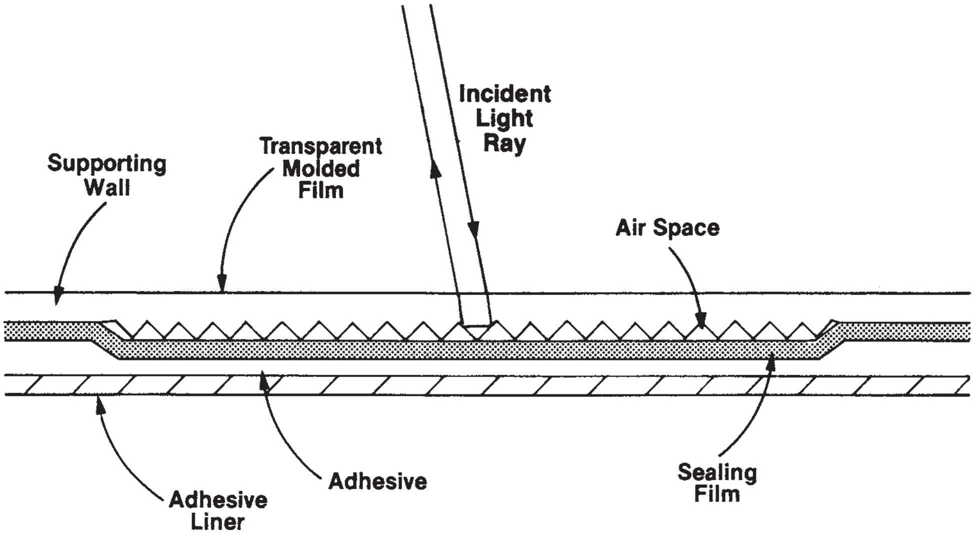
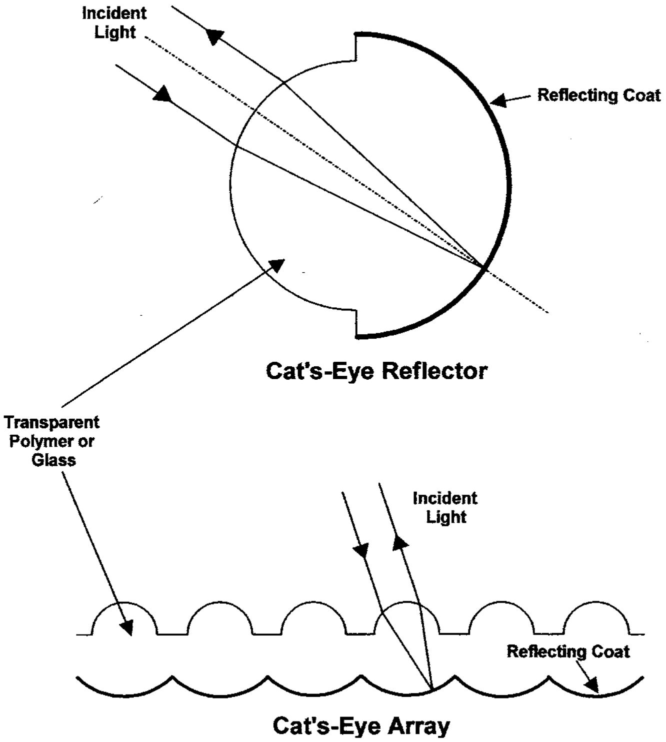


FIG. 11 Cube-Corner Sheeting



Cat's-Eye Reflector

Cat's-Eye Array

FIG. 12 Cat's-Eye Retroreflectors

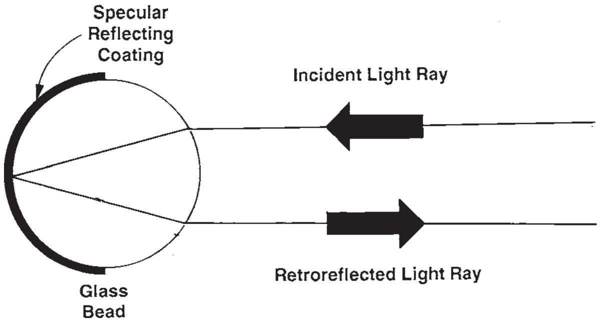


FIG. 13 Lens-Mirror Retroreflector

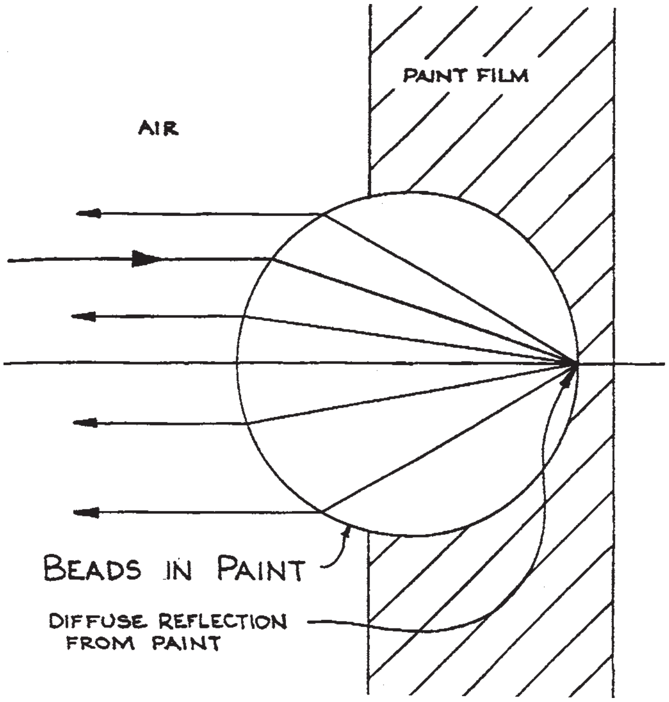


FIG. 14 Spherical Lens-and-Diffuser Retroreflector

reflectors may be used in retroreflective paint and as an exposed lens coating or finish that may be applied to garments.

8.3.2.1 *Exposed-Lens Sheeting*—This retroreflective sheeting is normally made with glass beads of refractive index *n* of 1.9 to 2.0. The construction is shown in Fig. 15. The underside of each sphere is a specular reflector. The tops of the beads are exposed to the air. The path of light through the glass bead is similar to that in the cat's-eye system except that the higher refractive index of the glass allows the front and back surfaces to have the same radius of curvature; hence, a single sphere can be used. Normally, only white or yellow retroreflection can be obtained efficiently with the exposed bead sheeting. Since moisture on exposed lens sheeting will reduce its reflectivity, it is important to choose material of a sufficiently high, dry reflectivity to allow for this loss.

8.3.2.2 *Enclosed-Lens Sheeting*—In this material, sometimes called embedded-lens sheeting, glass beads of still higher refractive index (2.2 to 2.3) are embedded in transparent films that normally have a refractive index of 1.5 to 1.6. Because the amount of refraction is dependent on the ratio of the refractive indexes of the two media (for example, 2.3/1.5 = 1.5), light is not refracted as much in this system as in exposed-lens sheeting, and it is necessary to provide a back surface of larger radius of curvature, much like that in the cat's-eye system, spaced from the glass bead. A space coat as shown in Fig. 16

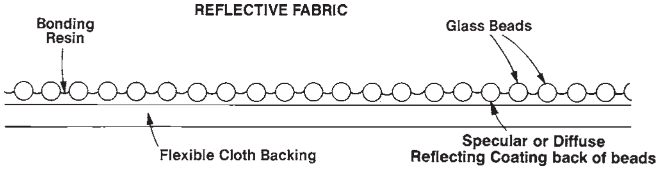


FIG. 15 Exposed-Lens Construction

with a specular reflector enables the system to be focused for efficient retroreflection. Unlike the cat's-eye system, the top surface of enclosed-lens sheeting is flat. Transparent top coatings of any color can be used, and a water film does not cause any loss of reflection.

8.3.2.3 *Encapsulated-Lens Sheeting*—This material (Fig. 17) is essentially exposed-lens sheeting with a transparent top film that is sealed in a mesh pattern to preserve the air interface. It combines the best features of both the exposed-lens and enclosed-lens types, including effective performance at entrance angles of 45° or more. Encapsulated-lens sheeting can be made to reflect any color, wet or dry, can be made in flexible versions, and is two to three times brighter than enclosed-lens sheeting.

8.3.2.4 *Beads on Paint*—Another form of glass-bead retroreflector is created by dropping glass beads of refractive index 1.5 to 1.9 into a white or yellow paint or binder. The retroreflectivity of such systems is low (with those made of beads with $n = 1.9$ being brighter than those with beads of $n = 1.5$), and consequently they are not considered to be high-visibility materials for personal use. They find utility for pavement markings that are viewed at short range.

8.4 *Retroreflectance of Retroreflectors*:

8.4.1 Measurement methods for the retroreflectance of retroreflectors are defined in Practices E 808 and E 809. The measured quantities are also defined in Terminology E 284. There are two cases of interest.

8.4.1.1 *Case I*—Here the measured quantity is the *coefficient of luminous intensity*, R_I, the ratio of the luminous intensity (I) of the retroreflector in the direction of observation to the illuminance $E_\perp$ at the retroreflector on a plane perpendicular to the direction of the incident light, expressed in cd per lux ($cd \cdot lx^{-1}$), $R_I = (I/E_\perp)$. Use of the abbreviation CIL or the inch-pound units of cd per fc (1 fc = 10.76 lx) is no longer recommended. R_I is commonly used to describe the luminance of small retroreflectors such as vehicle reflectors, dangle tags (rigid pendant reflectors which dangle on a string), and for the combined effects of reflective stripes on clothing.

8.4.1.2 *Case II*—Here the measured quantity is the *coefficient of retroreflection*, R_A, the ratio of the coefficient of luminous intensity (R_I) of a plane retroreflective surface to its area (A), expressed in candelas per lux per square metre ($cd \cdot lx^{-1} \cdot m^{-2}$), $R_A = (R_I/A)$. The use of the inch-pound units candela per footcandle per square foot is no longer recommended. These units are commonly used to define large extended reflective areas and to characterize reflective sheeting as sold by the roll.

8.4.2 Table 3 gives typical values of R_I or R_A for various retroreflective materials.

9. Luminescent Materials

9.1 Luminescence occurs when electrons fall from a higher to a lower energy state, giving up the released energy in the form of photons of light. The initial higher energy state can be created by electromagnetic radiation (for example: x-rays, ultraviolet light, visible light of short wavelengths), by chemical reactions, by electrical energy, or by radioactive emissions.

9.2 *Fluorescence*:

9.2.1 Fluorescent materials are the most important type of luminescent materials currently in widespread use as high visibility treatments. The most common forms use pigments that are activated by near ultraviolet light as well as the short end of the visible spectrum (blue light) to produce vivid reds, oranges, yellows, and greens. In addition, these pigments also reflect longer wavelength light falling on them without luminescence.

9.2.2 Fluorescence can be expressed as a component of the radiance factor, β_e, which is the sum of the fluorescence radiance factor, β_F, and the reflection radiance factor, β_S, each of which may be determined at a wavelength of interest. Luminous quantities may be calculated from each of these by summation across the visible spectral region following the usual conventions of colorimetry (see Practice E 308). For some strongly fluorescent materials, the fluorescence radiance factor may exceed the reflection radiance factor of the specimen or even that of the perfect reflecting (nonfluorescent) diffuser, the latter being assigned a value of 100. For example, a red-orange specimen had approximate values of $\beta_S = 70$, $\beta_F = 200$, and $\beta_e = 270$ at the wavelength of maximum fluorescent emission, 610 nm, when illuminated by CIE standard illuminant *D*65 (natural daylight). The corresponding values for the reflection luminance factor and fluorescence luminance factor were $Y_S = 15$ and $Y_F = 40$, respectively, yielding a total luminance factor (CIE tristimulus value Y) of Y = 55. In each case the sum of the fluoresced and reflected energy was about 3.8 times greater than the reflected energy alone (**13**). These highly fluorescent reds, oranges, and yellows appear unnatural and, hence, highly conspicuous. This effect is especially pronounced at twilight or on overcast days when the ultraviolet and blue light from the sky are present in greater proportion than in normal sunlight.

9.2.3 A common fallacy is that because fluorescent materials are so vivid during the day, especially on overcast days and in twilight, they also function well at night under car headlights. In fact, fluorescent materials at night appear the same as or only slightly brighter than normal red, orange, or yellow diffuse reflective materials because their fluorescence is not greatly excited by energy in the wavelengths of light emitted by the headlights. Thus they are not high visibility materials under car headlights, either tungsten or quartz halogen. A combination of fluorescent and retroreflective materials, however, is very useful as it covers lighting conditions over an entire 24-h period.

9.2.4 A factor to consider in the application of fluorescent materials is limited weatherability. After a relatively short period (2 to 3 months) of continuous sunlight exposure, unprotected fluorescent pigments may bleach to white. By skillful use of ultraviolet absorbers, weatherable polymers, and

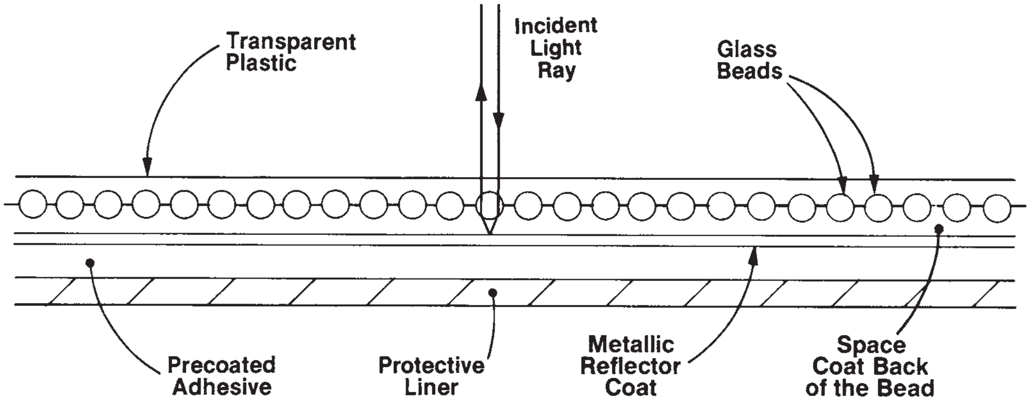


FIG. 16 Enclosed-Lens Sheeting

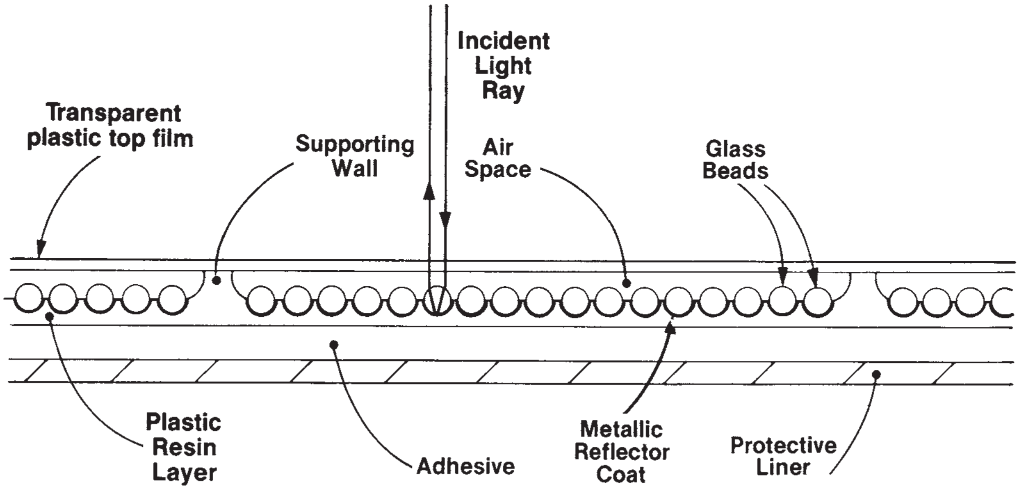


FIG. 17 Encapsulated-Lens Sheeting

TABLE 3 Retroreflectivity of Typical Materials[a]

Retroreflector Type	Case *I*, R_I	Case *II*, R_A
Vehicle reflector (red)	48	
Bicycle reflector	290	
Exposed-lens sheeting or fabric		110–550
Enclosed-lens sheeting or fabric		70–300
Encapsulated-lens sheeting or fabric		250–350
Microprismatic sheeting		110–900
Beads on paint, $n = 1.9$		12–18
Beads on paint, $n = 1.5$		2–3
Paint on cloth		0.25

[a] Observation angle, 0.2°; entrance angle, – 4°. Color is clear, silver, or white where not specified.

nonfluorescent pigments, useful lifetime can be expected to be as much as three years depending on the actual exposure to direct sunlight.

9.2.5 While susceptibility to pigment bleaching limits the use of fluorescent materials on signs and other markings that must withstand continuous exposure, it is not necessarily a serious limitation for personal use materials which may be exposed to sunlight only intermittently.

9.3 *Phosphorescence*—Phosphorescence involves a time-delayed fluorescence where the intensity of light falls rapidly with time after the energizing exposure. The absolute intensity of phosphorescent materials is too low to be of practice value except perhaps in very dark surrounds and at close range. The luminous output of these materials is generally too dim to provide adequate protection in traffic at night.

9.4 *Chemiluminescence*—Chemiluminescence is the production of light as a part of the energy transfer occurring in certain chemical reactions. Significant brightness can be achieved over a period of up to 12 h before the ongoing chemical reaction subsides. Once activated, chemiluminescent materials cannot be turned off or reused.

9.5 *Electroluminescence*—In electroluminescence, luminescent material is sandwiched between two electrical conducting surfaces, one of which is transparent, and appropriate voltage is applied. Useful light levels are obtained in extended areas, but the accompanying support hardware and power make it impractical for personal use at present.

9.6 *Radioluminescence*—A radioactive substance (for example, tritium) is incorporated into radioluminescent materials, activating them. Although light can be emitted for long periods of time without reenergizing, the levels are very low and they are not suitable as high visibility materials.

10. Contrast and Color

10.1 Objects are visually distinguished from one another principally by two mechanisms, luminance contrast and color contrast. Luminance contrast is by far the more important of the two contrast mechanisms and is almost always present. For example, the details of a scene in a black and white photograph are normally as sharp as when viewed in full color. However, color can contribute much additionalinformation and is important for both daytime and nighttime visibility.

10.2 Color, like other aspects of appearance, has both visual (subjective) and instrumental (objective) dimensions.

10.2.1 Visually, color may be described by several different sets of three properties. Over the years, the most useful of these have been the coordinates of the Munsell system, Munsell hue, Munsell value, and Munsell chroma (see Practice D 1535). Together these three coordinates constitute a Munsell color notation, which is usually assigned to a specimen by visually comparing it to the color chips in the *Munsell Book of Color* (**14**). They apply strictly to surface colors viewed in daylight. The Munsell coordinates are:

10.2.1.1 *Munsell hue, n*—an attribute of color in the Munsell system by means of which a color is judged to be red, yellow, green, blue, purple, or intermediate between adjacent pairs of these.

10.2.1.2 *Munsell value, n*—an attribute of color in the Munsell system indicating the lightness of a specimen on a scale extending from 0 for ideal black to 10 for ideal white, in steps that are visually approximately equal in magnitude.

10.2.1.3 *Munsell chroma, n*—an attribute of color in the Munsell system indicating the degree of departure of a color from a gray of the same Munsell value, in steps that are visually approximately equal in magnitude.

10.2.2 The instrumental assessment of color is carried out by the use of spectrophotometers and tristimulus (filter) colorimeters. The results are expressed in terms of CIE tristimulus values and related color coordinates.[6] The set of such coordinates providing the most useful correlations to the variables of visually perceived color are the *LCH* (lightness, chroma, hue) coordinates of the CIE 1976 $L^*a^*\ b^*$ (CIELAB) system (see Test Method D 2244):

10.2.2.1 *CIE metric lightness* L^**, n*—the CIELAB lightness coordinate, defined by the equation:

$$L^* = 116\,(Y/Y_n)^{1/3} - 16 \tag{1}$$

where Y_n is the luminance factor for the perfect reflecting diffuser (= 100) and $Y/Y_n > 0.008856$ (for use at lower values of Y/Y_n, see Test Method D 2244).

10.2.2.2 *CIE metric chroma* C^*_{ab}*, n*——the CIELAB chroma coordinate, defined by the equation:

$$C^*_{ab} = (a^{*2} + b^*_2)^{1/2} \tag{2}$$

$$a^* = 500\,[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}]$$

$$b^* = 200\,[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]$$

where X_n and Z_n are the tristimulus values of the perfect reflecting diffuser, and similar restrictions apply to the values of X/X_n and Z/Z_n as in 10.2.2.1 for Y/Y_n.

10.2.2.3 *CIE metric hue angle* h_{ab}*, n*—the CIELAB hue angle coordinate, defined by the equation:

$$h_{ab} = \tan^{-1}(b^*/a^*) \tag{3}$$

10.3 Of the wide range of colors available in reflective, retroreflective, and fluorescent materials, the bright, high chroma colors are most useful for high visibility materials, for both daytime and nighttime use (see Section 12).

11. Light Sources

11.1 *General*:

11.1.1 Although this guide focuses on reflective high visibility materials that are non self-luminous, a general knowledge of light sources is necessary to understand how such materials perform.

11.1.2 The ambient illumination in daytime, from direct sunlight and diffuse light from the sky, is so predominant that there is little need to consider auxiliary light sources. Headlamps on in daytime have proved to increase safety, not by providing better illumination of the traffic environment, but rather by increasing the conspicuity of the vehicles themselves.

11.1.3 Except for the observation that increased visibility of vehicles through vehicle lighting has definitely resulted in greater safety (**16**), extending that approach to pedestrians and bicyclists is beyond the scope of this document.

11.1.4 At night and in deep dusk, roadway illumination is provided by fixed roadway lighting and vehicle headlamps.

11.2 *Fixed Roadway Lighting*:

11.2.1 There have been many studies that indicate roadway lighting reduces accidents. A state-of-the-art review concerning pedestrian protection was conducted by the Franklin Institute in 1974 (**17**). It was found that specialized lighting at intersection crosswalks reduced pedestrian accidents by as much as 63 % as compared with the same intersections without increased lighting.

11.2.2 Roadway illumination is generally provided by mercury vapor, high-pressure sodium, and, in some cases, low-pressure sodium lighting, listed in ascending order of light to energy efficiency and descending order of accurate color rendition. If the lighting is bright enough, even diffuse reflecting surfaces can be seen readily either directly, or by dark silhouette against a brighter background. Since the amount and uniformity of illumination do not duplicate daytime levels, bright retroreflective materials are still needed and of value even in well lit areas for recognition, if not detection purposes. Roadway areas having shadows and uneven lighting reinforce the need for bright retroflective materials. On the negative side, fixed roadway lighting is expensive to install, operate, and maintain and is thus limited as to where it can be afforded.

11.3 *Vehicle Headlamps*—The required performance characteristics of headlamps in the United States is based upon SAE J579c. Several different systems are allowed involving circular or rectangular shaped lights employed in sets of two or four. All produce relatively the same beam pattern, which in the case of low beams is directed down and to the right, but with less sharp upper cut-off than is typical with European headlamps. High beams provide much greater illumination (up to 150 000 cd currently permitted) than low beams. However, surveys have shown that the bulk of night driving, even in open road, noncar-meeting situations, is done on low beams (**18**). Thus, less candlepower is typically available, often as little as

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[6] ASTM standards dealing with both visual and instrumental color measurements and their applications may be found in the *Annual Book of ASTM Standards*, Vol 06.01, and in Ref. (**15**).

3000 cd or less depending on the part of the beam considered. Headlamp intensities could be increased except that the intensified glare of oncoming cars with brighter headlamps might offset visibility gains. This trade-off must always be carefully considered. Even under somewhat favorable conditions for example, clear visibility and alerted drivers, research has shown that ordinary low beam tungsten headlamps as used in the U.S. can only be expected to result in the nighttime detection of a dark-clothed pedestrian at about 20 m and a pedestrian in a white t-shirt and blue jeans at about 70 m (**19**).

11.4 *Roadway Interactions*—Total performance of retroreflectors at night is based not only on the inherent optical properties of the retroreflector but also on distances, angles, alignments, and specific vehicle and other lighting encountered on the roadway. Although retroreflectors can be characterized by laboratory measurements, the actual performance on the roadway is based on luminance at the target, which is translated back to the viewer as illuminance at the eye. Even this is not the final measure as the human subjective perception of brightness is not linear with instrument readings. A tenfold increase in luminance, as measured by instruments, may be perceived as only about four times brighter (**9**).

12. Guides for Using High Visibility Materials

12.1 *Daytime*:

12.1.1 During the day with high light levels, the point at which a pedestrian or road object can be detected is largely a function of visual acuity (the ability of human vision to resolve small details), assuming the driver or viewer is alerted and is looking directly at the pedestrian. This can be many hundreds of metres away, well beyond the stopping sight distance (SSD) or even decision sight distance (DSD). The main problem in daytime then becomes one of conspicuity because of the wealth of other distracting details, visual clutter, glare, and camouflage effects. Once a pedestrian is noticed, problems of recognition and localization are small because of the characteristic human form with a relatively slight variation in size. Children, with a larger head to body proportion than an adult, are not usually confused with an adult farther away.

12.1.2 Conspicuity is best improved by providing high color or luminance contrast. Object shape or outline contrast and highlighted motion promote conspicuity as well. High brightness alone, for example from wearing white clothing, helps only against certain dark backgrounds and may camouflage a person against light backgrounds.

12.1.3 Research (**20**) has shown that fluorescent materials, especially orange, provide the best color and luminance contrast against most common backgrounds. Also, bright saturated colors not normally found in the environment tend to stand out even if not fluorescent. Vivid blues and greens, as well as yellows, oranges, and reds, are effective because they are not generally common in the daytime environment. Muted colors (beiges, browns, shades, greys), which are frequently chosen for reasons of style, are to be avoided if high visibility is the objective.

12.1.4 To be effective, the fluorescent color or vivid color should be used over as large an area as possible (total upper or lower garment or significant portion thereof). Small areas of fluorescent material have relatively little value. Motion, however, augments the effect; bright colors worn on arms or legs or even the head may allow smaller areas to impart some measure of conspicuity.

12.1.5 Treatments should be viewed by designers at distances of interest, usually at least 150 m under realistic lighting and background conditions, to determine effectiveness. Controlled empirical testing is recommended. Viewing at short range (indoors in an office, for example) can lead to false conclusions. Small areas and subtle color combinations seen at short range may appear to be effective, but these effects may disappear at longer distances.

12.2 *Nighttime*:

12.2.1 At night color becomes of less importance (unless standardized to have recognition meaning) and luminance contrast becomes even more important. Most aspects of visibility depend on providing more luminance contrast to the observer than otherwise available. An effective means for increasing the detectability of a pedestrian at night is some form of retroreflector that has the following characteristics:

12.2.1.1 Sufficiently bright as positioned on the pedestrian to provide conspicuity or noticeability at distances of interest (for example, SSD or DSD related to vehicle speeds).

12.2.1.2 Provides this conspicuity from all directions whether the pedestrian is in motion or not (360° protection).

12.2.1.3 Furnishes recognition cues that the object sighted is a human being, that is, a pedestrian or bicyclist and not an inanimate road object or vehicle.

12.2.1.4 Reveals the motion of the human being as much as possible but is not totally dependent on it for its effect.

12.2.2 If the high visibility materials are properly selected and located on the individual, it is not always necessary to use large areas of retroreflectivity to meet these requirements.

13. Keywords

13.1 conspicuity; high visibility materials; pedestrian; retroreflection/retroreflector; safety; visibility

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