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GUIDE TO THE PROPERTIES AND USES OF RETROREFLECTORS AT NIGHT

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SUMMARY

This Publication describes the properties, characteristics and uses of retroreflectors at night and has been written for people who, in one way or another, have to deal with retroreflectors in their professional activity. It has been edited in simple language so as to make it easily understandable to persons with a limited knowledge of optics and lighting technology. Sections 2, 3 and 4 introduce the fundamentals of the subject.

Explanations regarding the construction and the functioning of the different optical systems of retroreflectors (prismatic, spherical lens retroreflectors) are given in section 5. The effect of dew, fog and frost on retroreflectors is dealt with in section 6 and the deterioration of retroreflectors is discussed in section 7. Section 8 deals with the various tests for photometric and colorimetric performance and the resistance and durability of materials which are generally carried out as a measure of quality.

Section 9 enumerates the many typical uses of retroreflectors and retro-reflecting sheetings for road, railway, airport, waterways, sea navigation, search and rescue, vehicles, cyclists and pedestrians and safety signs at the place of work. The selected bibliography on retroreflectors is to be found in section 10.

There are 8 annexes to the publication containing drawings, charts, tables, diagrams and calculation methods associated with the equipment mentioned in the text.

RESUME

Cette publication décrit les propriétés, caractéristiques et utilisations des rétro-réflecteurs de nuit et a été écrite pour les personnes qui, d'une façon ou de l'autre, ont à faire avec les rétro-réflecteurs dans leur activité professionnelle. Elle a été rédigée dans un langage simple afin de la rendre facilement compréhensible aux personnes ayant une connaissance limitée de l'optique et de la technique de l'éclairage. Les chapitres 2, 3 et 4 traitent les questions fondamentales du sujet.

Des explications concernant la construction et le fonctionnement des différents systèmes optiques des rétro-réflecteurs (prismatiques, à lentilles sphériques) figurent au chapitre 5. Les effets de la rosée, du brouillard et du gel sur les rétro-réflecteurs sont traités au chapitre 6 et la détérioration de ces derniers est discutée au chapitre 7. Les différents essais photométriques et colorimétriques ainsi que ceux de résistance et durabilité qui sont généralement effectués pour établir la qualité des matériaux sont expliqués au chapitre 8.

Les nombreuses utilisations typiques des rétro-rélecteurs et des film rétro-réfléchissants pour les routes, chemins de fer, aéroports, voies navigables intérieures, navigation en mer, recherche et sauvetage, véhicules, cyclistes et piétons ainsi que pour la signalisation de sécurité dans les usines sont indiquées au chapitre 9. La bibliographie sélectionnée concernant les rétro-rélecteurs se trouve au chapitre 10.

La publication comprend 8 annexes contenant des dessins, tableaux, graphiques et diagrammes ainsi que des méthodes de calcul concernant les caractéristiques et les équipements mentionnés dans le texte.

ZUSAMMENFASSUNG

Diese Veröffentlichung beschreibt die Eigenschaften, Charakteristiken und Anwendungen der Retroreflektoren bei Nacht und wurde für Personen, die in ihrer Berufstätigkeit in irgend einer Weise mit Retroreflektoren zu tun haben, geschrieben. Sie wurde in einer einfachen Sprache abgefasst, damit Personen mit beschränkter Kenntnis der Optik und der Lichttechnik sie leicht verstehen können. In den Kapiteln 2, 3 und 4 werden die grundsätzlichen Fragen des Themas erörtert.

Erklärungen über die Struktur und das Funktionieren der verschiedenen optischen Retroreflektorensysteme (prismatische, sphärische Linsen) sind unter Kapitel 5 aufgeführt. Die Wirkung von Tau, Nebel und Frost auf die Retroreflektoren wird in Kapitel 6 und die Verschlechterung derselben in Kapitel 7 behandelt. Die verschiedenen Tests zur Kontrolle der photometrischen und farbmétrischen Leistung sowie der Widerstandsfähigkeit und Haltbarkeit des Materials, die gewöhnlich zur Festsetzung des Gütemasstabs durchgeführt werden, werden in Kapitel 8 dargelegt.

In Kapitel 9 werden die zahlreichen typischen Anwendungsmöglichkeiten der Retroreflektoren und retroreflektierenden Folien für die Strassen, Eisenbahnen, Flughäfen, Binnenwasserstrassen, See-Navigation, Such- und Rettungsaktionen, Fahrzeuge, Radfahrer und Fussgänger sowie für die Sicherheitsmarkierungen in Fabriken angegeben. Die ausgewählte Literatur über Retroreflektoren ist in Kapitel 10 aufgeführt.

Der Veröffentlichung sind 8 Zeichnungen, Tabellen, Diagramme und Rechenmethoden über die im Text erwähnten Eigenschaften und Einrichtungen beigelegt (Beilagen 1 bis 8).

1 SCOPE

A publication for the information of transport and traffic engineers, police and fire executives, mariners, airport officials, legislators and administrators concerned with marking and signalling and with the night-time safety of people and equipment.

2 TERMINOLOGY

The terms used in this Guide are based on the CIE International Lighting Vocabulary 4th Edition and CIE Publication No. 54, 1982 (Retroreflection, Definition and Measurement).

The various geometric parameters involved in retroreflection are shown in figures No. 21 and 22.

General photometric terms used are:

- Candela (cd)

SI unit of luminous intensity. As an indication, it is approximately the luminous intensity of a candle flame.

- Illuminance (E) (at a point of a surface)

Quotient of the elementary luminous flux falling on an element of the surface around the point being considered by the area of this surface element. Unit: lux (lx). i.e. lumens per square metre

- Luminance (L)

Quotient of the luminous intensity dI of the surface element in the given direction by the area dA of the orthogonal projection of this surface element on a plane perpendicular to the considered direction (projected or apparent area).

$$L = \frac{dI}{(dA) \text{ proj.}} \quad \text{or} \quad L = \frac{dI}{dA \cos \theta}$$

where θ is the angle between the direction of observation and the normal to the surface element.

Unit: candela per square metre (cd m^{-2}).

- Luminance factor (β_v)

(at a point on the surface of a non-self-radiating body).

Ratio of the luminance of the body to that of a perfect reflecting or transmitting diffuser identically illuminated.

- Luminous intensity (I) (of a source in a given direction)

Amount of light emitted by a source in a given direction.

Unit: candela (cd).

- Lux (lx)

SI unit of illuminance: illuminance produced at a distance of 1 m by a source of 1 candela on a surface perpendicular to the direction of the incident light.

VISION AND VISIBILITY

The human being does not see well in darkness. In a completely black location, for example in a cave where there is absolutely no light, he does not see anything at all. For man to see, some light must enter his eyes.

At night, one sees a lamp, a fire, vehicle headlamps or a glow-worm because of the light they emit directly. They are self-luminous and are thus primary light sources.

Objects which are not self-luminous can also be seen in darkness by the light which is reflected from their surface. These objects are secondary light sources.

Non-luminous and non-reflecting bodies (black bodies) are visible in the dark through contrast with a lighter background against which they stand out.

In other words, for a human being to see, either direct light rays from a light source, or indirect (reflected) light rays must enter his eyes.

The special receptors in the eye which permit vision are:

- the cones, predominantly located at the centre of the retina (fovea),
and
- the rods, more numerous than the cones and distributed outside the
fovea in the retina.

The cones are mainly activated under normal day-time conditions (photopic vision); they are sensitive to colour and give a high visual acuity by day.

The rods are colour blind, but they are activated by small amounts of light. They are very sensitive and work under conditions of low illuminance (scotopic vision).

In mesopic vision (i.e. at dusk and dawn), both types of receptors are more or less activated; bright lights and retroreflectors are viewed photopically with the cones activated.

Both the cones and the rods are part of a co-ordinated system and they supplement each other.

Moving in darkness is not a natural activity for man. His visual system has its highest performance characteristics in normal daylight conditions. In darkness, conditions are quite different and the performance of the human eye is greatly reduced.

At a low level of ambient illumination, the contrast sensitivity and colour discrimination of the eye are drastically lowered with the result that colours merge into the background, the entire scene becomes indistinct and details are no longer perceptible. This is a major disadvantage in any human activity.

In addition to this basic visual deficiency, the eyes of many people are also affected by a great sensitivity to glare (e.g. sudden illumination, oncoming vehicle headlamps) accompanied by a slow re-adaptation process during which vision is impaired. Night myopia is another weakness which afflicts a great many people and reduces their vision in the dark.

To sum up, the human eye is inadequate for driving and other operations under conditions of low-level illumination.

4 LIGHT SOURCES AND RETROREFLECTION

4.1 Light sources (primary light sources)

Light sources used after dark as a substitute for daylight are of two main types, viz.:

- omni-directional luminaires used to illuminate an area or a road,
- directional lights such as headlamps and searchlights with a narrow beam.

The purpose of the first category of light sources is to give, over a wide area, a light level high enough for people to see the surrounding scene distinctly and to work and move with ease and safety. Public lighting in towns and highways varies greatly from one location to another; it generally gives the road surface a luminance between 0.5 and 2 candelas per square metre (cd m^{-2}).

Lights of the second category are constructed so as to emit a narrow beam. The luminous intensity of such directional lights varies extensively from one type to another, for example:

- | | |
|--|-------------------------------------|
| - hand torches, miner's cap lamps | 400 - 800 cd |
| - bicycle headlights | 600 - 1 000 cd |
| - car passing lights (2 European, above cut-off) | 800 - 1 500 cd |
| - car passing lights (2 American sealed beam lights) | 1 500 - 2 500 cd |
| - car driving lights (2 European highbeam headlamps) | 75 000 - 200 000 cd |
| - ships signalling lamps (Aldis lamps) | about 300 000 cd |
| - air plane landing lights | each lamp from 100 000 - 900 000 cd |
| - searchlights on ships and aircraft | from 1 million to 10 million cd |

In spite of their high luminous intensity, the ability of these directional lights to provide adequate visibility is limited firstly by the "inverse square law" which states that the illuminance on a surface decreases with the square of the distance from the light source. Secondly the surface reflectance characteristic of the illuminated object will limit the perceived brightness.

4.2 Reflection

4.2.1 Various types of reflection

People, objects of all sorts, plants and rocks are not clearly visible at a distance in the dark, even when illuminated by strong vehicle headlights or powerful searchlights. This is because they are poor reflectors which absorb part of the light impinging upon them and scatter a great part of the rest; the amounts of each depending on their structure and colour. These bodies are diffuse reflectors.

In fact, there are four different types of reflection, namely:

- diffuse reflection

where the light rays are scattered and reflected in all directions. (see Fig. 1)

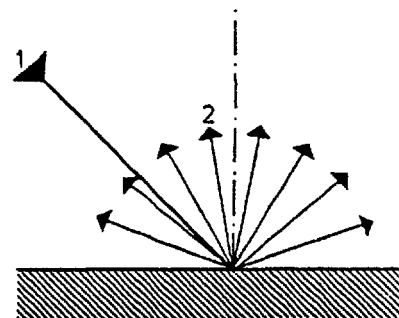


Fig. 1 Diffuse reflection

- specular reflection (mirror reflection)

where the light rays are not scattered, but reflected in one direction only.

If the axis of the incident light is perpendicular to the surface, the reflected rays are returned to the light source.

If the incident light strikes the surface at an angle, the light is reflected in another direction and the angle of reflection is always equal to the angle of incidence. (see Fig. 2)

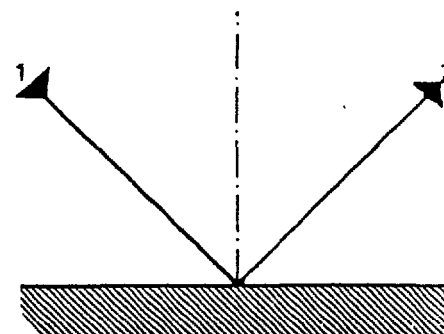


Fig. 2 Specular reflection

- mixed specular and diffuse reflection

where more or less of the light is reflected specularly, the rest being reflected in all directions (see Fig. 3).

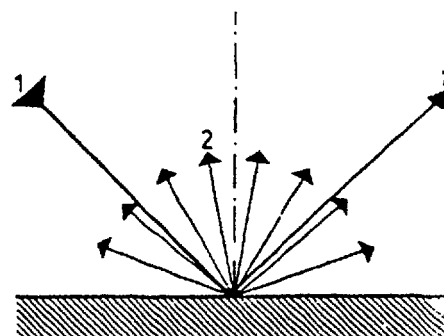


Fig. 3 Mixed specular and diffuse reflection

- retroreflection

where the light is returned back to its source in a narrow cone, irrespective of the direction of the incident light in relation to the perpendicular. There is little scattering of the light (see Fig. 4).

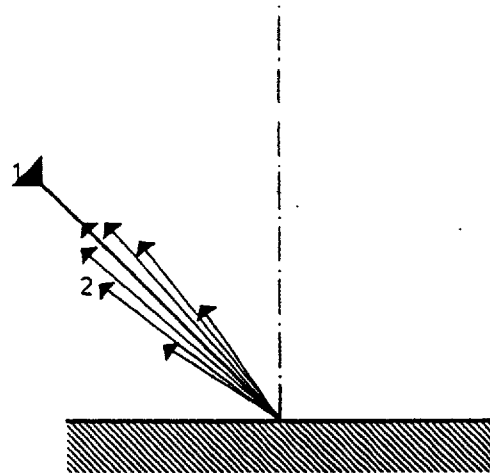


Fig. 4 Retroreflection

4.2.2 Visual signalling devices

Many visual signalling devices used to mark hazards, identify places, delineate routes, give warning, impart instructions and communicate information are more or less diffuse reflectors. In general, they are adequately conspicuous by day but at night they are only visible when illuminated with their individual light source or when placed in an area well lit by public lighting.

Pedestrians, cyclists, road workers, personnel of public utility companies, navigation buoys and life-saving appliances are also diffuse or mixed reflectors.

Even when illuminated by a directional light, these targets may not be sufficiently conspicuous at a distance because they scatter the light rays falling upon them, and only a small part of the light is returned to the observers close to the light source. It is in this case that retroreflectors are most valuable.

Due to their unique characteristic of returning the incident light back to its source in a narrow cone, retroreflectors appear very bright and in full colour to observers close to the light source. They are visible from a large distance with a directional light beam and are thus most suited for making people and objects visible, and signalling devices understandable in the dark.

By day and when illuminated by omni-directional lighting or in heavy fog, the retroreflective property is inoperative for a vehicle driver and retroreflectors will be seen as diffuse reflectors.

5 PRISMATIC AND SPHERICAL LENS RETROREFLECTORS (secondary light sources)

There are two types of retroreflectors in common use, viz. the prismatic (tri-hedral) retroreflector and the spherical lens retroreflector.

5.1 Prismatic retroreflector (corner-cube or cube-corner retroreflector)

The principle of this type of retroreflector, commonly called a corner-cube retroreflector because it looks like the inside part of a cube, is shown in Fig. 5 and 6 below. Reflection is due to the phenomenon of total internal reflection.

A light ray falls successively on three plane surfaces set at 90° with respect to each other and is returned parallel to its initial direction.

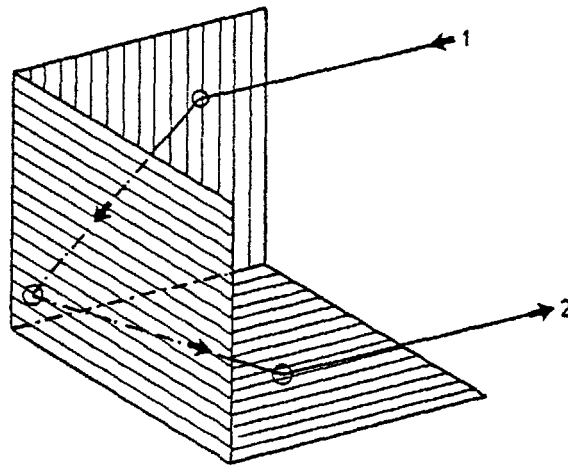


Fig. 5

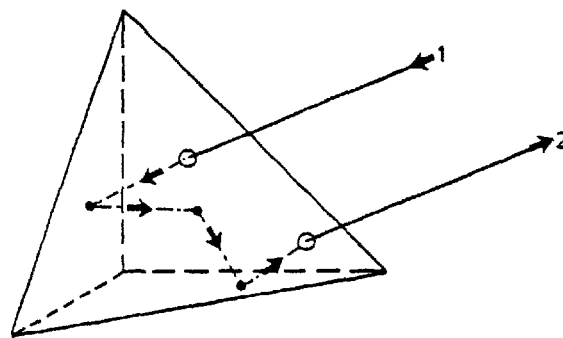


Fig. 6

Path of the light ray in a prismatic retroreflector

With corner-cube retroreflection, there are two principles involved, the principle of refraction and the principle of total internal reflection.

5.1.1 Refraction

When a light ray travelling in a transparent medium, for example in air, falls on another transparent medium such as glass or plastic material, part of it is reflected and part enters the second medium and is deviated. This phenomenon is called refraction. The magnitude of the deviation depends on the velocity of light in the various transparent media. There is a constant ratio between the sines of the angle of incidence and of the angle of refraction which is called the refractive index. When one of the media is air, which has a refractive index of unity, this ratio becomes the refractive index of the material, for example glass which has a refractive index of about 1.5. The index is identified by the letter n .

The law governing the phenomenon of refraction is SNELL's law which is expressed as follows:

$$n_i \sin i = n_r \sin r$$

where: i = angle of incidence

r = angle of refraction

n_i = refractive index of the medium of the incident ray

n_r = refractive index of the medium of the refracted ray.

See Fig. 7 and 8

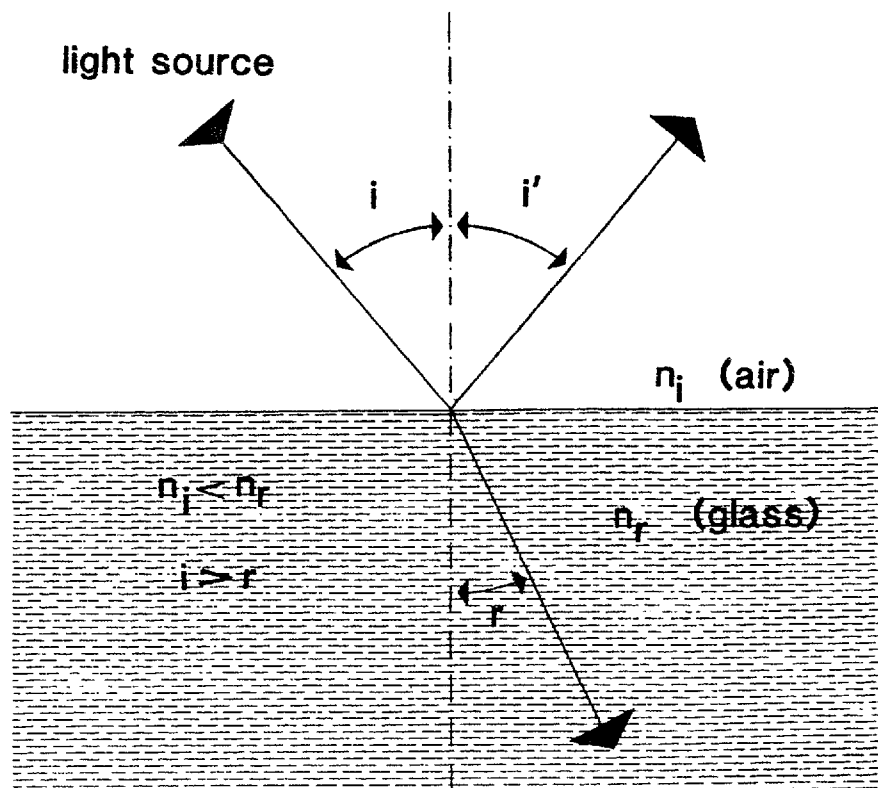


Fig. 7 The phenomenon of refraction from air to glass

5.1.2 Total internal reflection

Light passing from a dense to a less dense medium is refracted away from the normal to the surface and the angle of refraction in the less dense medium increases more rapidly than the angle of incidence. For a certain angle of incidence, the angle of refraction will be 90° , that is, the refracted beam will be just grazing the surface. This angle of incidence is called the critical angle related to the two media. Light meeting the surface at an angle of incidence greater than the critical angle cannot therefore enter the second medium and the whole of the light will then be reflected at the surface (specular reflection). This is known as total internal reflection. See Fig. 9.

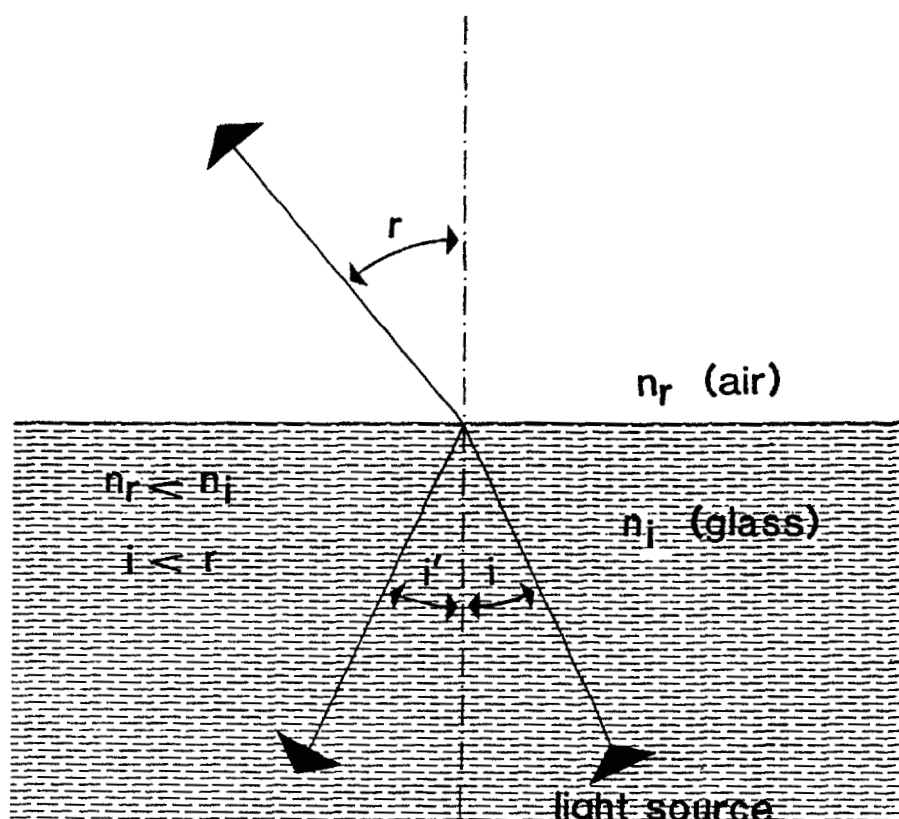


Fig. 8 The phenomenon of refraction from glass to air

For example, the critical angle for some transparent plastic materials in air is about 42° . Thus, for a plastic corner-cube all the rays striking the plastic-air interface at an angle larger than 42° are reflected specularly inside the material; those striking the interface at less than 42° partially go through the plastic boundary surface into the air.

These principles are illustrated for a two dimensional case in Fig. 10 and Fig. 11.

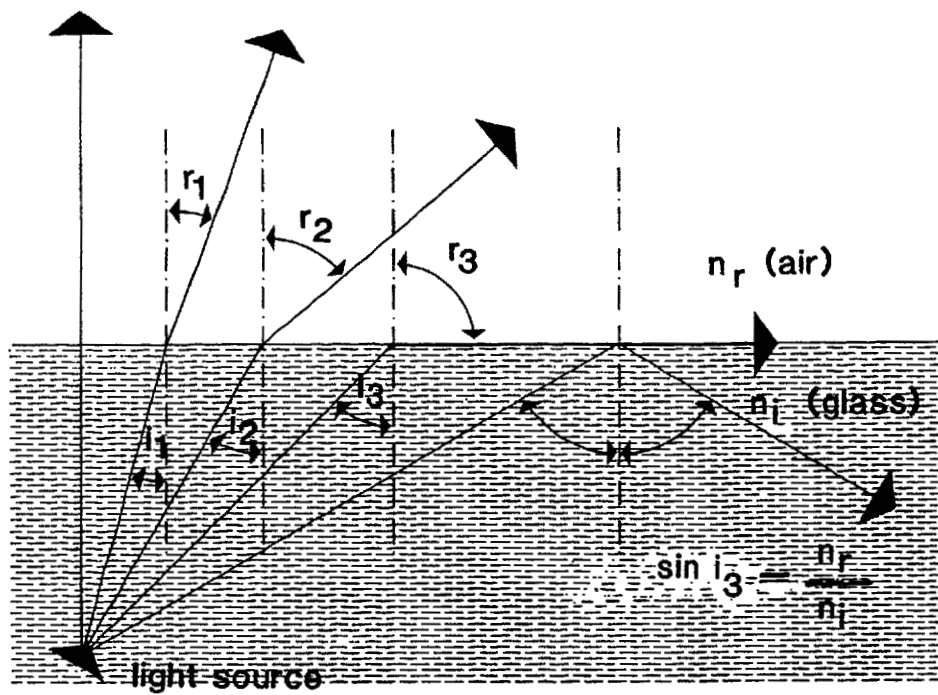


Fig. 9 The phenomenon of total internal reflection

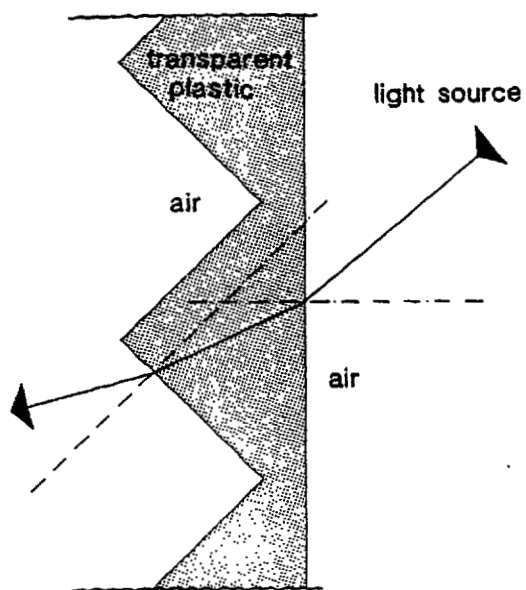


Fig. 10

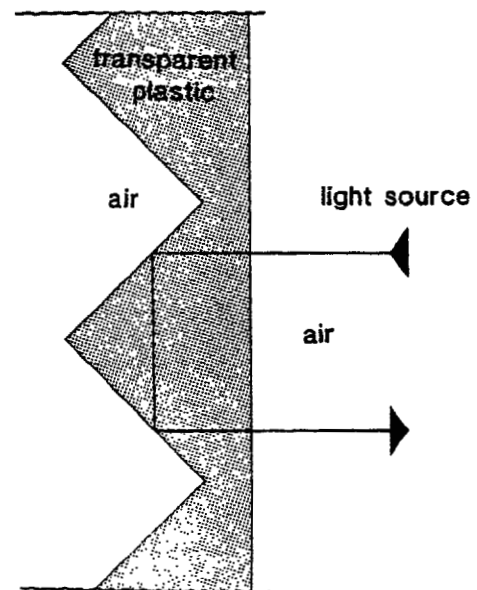


Fig. 11

Path of the light rays striking a prismatic (corner-cube) retroreflector

5.1.3 Construction

Typical single corner-cube retroreflecting elements are small and usually have a side length of about 2 to 4 mm. These are not used separately, but assembled side by side to form a composite retroreflector of any shape (square, circular, triangular, rectangular) or retroreflective letters, figures and symbols (Fig. 12).

The cone of the retroreflected light beam is rather narrow and the light intensity is maximum along the illumination axis (see Annex 5)

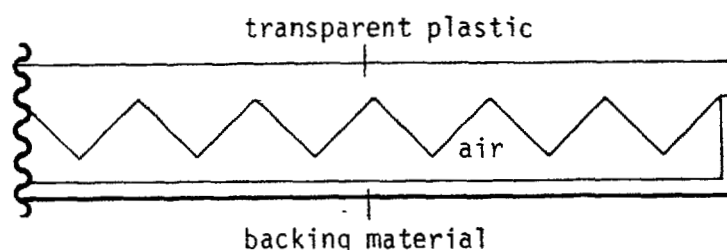


Fig. 12 Cross-section of a prismatic (corner-cube) retroreflector

Since the optical system of corner-cube retroreflectors is based on the principle of total internal reflection, the rear faces of the cubes must be in direct contact with air. This means that the cubic elements must be protected so as to remain always dry and clean. If this protection is not watertight, or if the device itself is cracked, dust and moisture can enter and interfere with the total internal reflection phenomenon with the result that retroreflection of the incident light is much reduced.

5.1.4 Performance

The retroreflection from corner-cube retroreflectors decreases rapidly as the entrance angle increases and is generally no longer useful when the entrance angle is larger than about 25° (see Annex 4). It is, however, possible to construct wide-angle retroreflectors by using a series of corner-cube elements orientated towards the right or the left, or upwards and downwards, so as to face the light beams coming at an angle. In this way, it is possible to manufacture corner-cube retroreflectors giving a useful retroreflection of the light coming from any direction over an angle of up to 50° .

The back of the corner-cubes is sometimes provided with a reflective coating. Reflection is then not due to the total internal reflection principle, but to specular reflection; such coated retroreflectors are not affected in their performance by dirt or moisture behind the cubes. The coefficient of retroreflection R' of such devices is, however, lower than that of normal corner-cube retroreflectors by about 25 %. This is due to the successive specular reflections at the three surfaces, each with a reflection factor of about 0.9, resulting in an overall loss of about 25%. However, they provide wide-angle performance over entrance angles up to about 40° .

When based on the total internal reflection principle, the optical performance of corner-cube retroreflectors is outstanding. The coefficient of retroreflection R' of colourless retroreflectors of high quality is about 700 candelas per lux per m^2 ($\text{cd lx}^{-1} \text{m}^{-2}$) at 20' observation and 5° entrance angles. Under these conditions, a surface painted with diffuse white paint would have a coefficient of retroreflection R' of about 0.3 candelas per lux per m^2 . The coefficient of retroreflection R' of coloured retroreflectors is, as a percentage of colourless retroreflectors, approximately as follows:

Blue	5%
Green	15%
Red	25%
Orange	40%
Yellow	60%

It should be noted that some commercially available corner-cube retroreflectors may have substantially lower R' values than those indicated above, due to poor manufacture. A visual inspection at close range does not enable such a retroreflector to be detected and the poor performance is only revealed when viewed under retroreflective geometric conditions.

5.2 Prismatic (micro corner-cube) retroreflecting sheeting

Nowadays, it is possible to manufacture corner-cube retroreflectors in the form of a thin (about 0.4 mm), flexible sheeting with a high coefficient of retroreflection R' . The coefficient R' of the white material is of the order of 550 $\text{cd lx}^{-1} \text{m}^{-2}$ at 20' observation and 5° entrance angles:

Corner-cube retroreflecting sheeting is generally manufactured with an air space behind the cubes so that they function by total internal reflection. The coefficient R' of this type of material is very high up to about 20° entrance angle, then decreases rapidly as the entrance angle increases.

Corner-cube retroreflecting sheeting can also be produced with a mirror-type coating at the back of the cubes which thus function by specular reflection. The wide-angularity is excellent, but the performance is reduced by about 25% and the day-time appearance of the white material is greyish because of the mirror coating.

Corner-cube retroreflecting sheeting can be made in various colours.

5.3 Spherical lens retroreflectors

A solid glass or plastic sphere has the property of focusing the light rays, the focal point being determined by the index of refraction of the material. If a perfect transparent sphere has an index of refraction which is exactly twice that of its environment, it will focus the incoming light on to the sphere surface (neglecting spherical aberration).