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COMMISSION INTERNATIONALE DE L'ECLAIRAGE  
INTERNATIONAL COMMISSION ON ILLUMINATION  
INTERNATIONALE BELEUCHTUNGSKOMMISSION

# TECHNICAL REPORT

## HOLLOW LIGHT GUIDE TECHNOLOGY AND APPLICATIONS

**CIE 164:2005**

UDC: 628.953

Descriptor: Light guides as part of illuminating devices

## THE INTERNATIONAL COMMISSION ON ILLUMINATION

The International Commission on Illumination (CIE) is an organisation devoted to international co-operation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of the National Committees in 38 countries and one geographical area and of 4 associate members.

The objectives of the CIE are :

1. To provide an international forum for the discussion of all matters relating to the science, technology and art in the fields of light and lighting and for the interchange of information in these fields between countries.
2. To develop basic standards and procedures of metrology in the fields of light and lighting.
3. To provide guidance in the application of principles and procedures in the development of international and national standards in the fields of light and lighting.
4. To prepare and publish standards, reports and other publications concerned with all matters relating to the science, technology and art in the fields of light and lighting.
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1. De constituer un centre d'étude international pour toute matière relevant de la science, de la technologie et de l'art de la lumière et de l'éclairage et pour l'échange entre pays d'informations dans ces domaines.
2. D'élaborer des normes et des méthodes de base pour la métrologie dans les domaines de la lumière et de l'éclairage.
3. De donner des directives pour l'application des principes et des méthodes d'élaboration de normes internationales et nationales dans les domaines de la lumière et de l'éclairage.
4. De préparer et publier des normes, rapports et autres textes, concernant toutes matières relatives à la science, la technologie et l'art dans les domaines de la lumière et de l'éclairage.
5. De maintenir une liaison et une collaboration technique avec les autres organisations internationales concernées par des sujets relatifs à la science, la technologie, la normalisation et l'art dans les domaines de la lumière et de l'éclairage.

Les travaux de la CIE sont effectués par 7 Divisions, ayant chacune environ 20 Comités Techniques. Les sujets d'études s'étendent des questions fondamentales, à tous les types d'applications de l'éclairage. Les normes et les rapports techniques élaborés par ces Divisions Internationales de la CIE sont reconnus dans le monde entier.

Tous les quatre ans, une Session plénière passe en revue le travail des Divisions et des Comités Techniques, en fait rapport et établit les projets de travaux pour l'avenir. La CIE est reconnue comme la plus haute autorité en ce qui concerne tous les aspects de la lumière et de l'éclairage. Elle occupe comme telle une position importante parmi les organisations internationales.

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Die Ziele der CIE sind :

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2. Grundnormen und Verfahren der Meßtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
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Die Arbeit der CIE wird in 7 Divisionen, jede mit etwa 20 Technischen Komitees, geleistet. Diese Arbeit betrifft Gebiete mit grundlegendem Inhalt bis zu allen Arten der Lichtenwendung. Die Normen und Technischen Berichte, die von diesen international zusammengesetzten Divisionen ausgearbeitet werden, sind von der ganzen Welt anerkannt.

Tagungen werden alle vier Jahre abgehalten, in der die Arbeiten der Divisionen überprüft und berichtet und neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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This Technical Report has been prepared by CIE Technical Committee 3-30 of Division 3 "Interior Environment and Lighting Design" and has been approved by the Board of Administration of the Commission Internationale de l'Eclairage for study and application. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory. The latest CIE proceedings or CIE NEWS should be consulted regarding possible subsequent amendments.

Ce rapport technique a été élaboré par le Comité Technique CIE 3-30 de la Division 3 "Environnement intérieur et étude de l'éclairage" et a été approuvé par le Bureau de la Commission Internationale de l'Eclairage, pour étude et emploi. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tout les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire. Il faut consulter les plus récents comptes rendus de la CIE, ou le CIE NEWS, en ce qui concerne des amendements nouveaux éventuels.

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The following members of TC 3-30, "Hollow Light Guides" took part in the preparation of this technical report. The committee comes under Division 3 "Interior Environment and Lighting Design".

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‡ See minority opinion statement in Chapter 6.

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## HOLLOW LIGHT GUIDE TECHNOLOGY AND APPLICATIONS

### SUMMARY

CIE initiated a Technical Committee "Hollow Light Guides" for the purpose of developing new terminology and dissemination of information in the field of illumination with hollow light guides. This report is a first step in that direction, representing the state of the art at the time of its substantial completion in 1999.

It includes a brief history of the field of hollow light guides, reviews the different solutions and describes the basic physics behind them. The pros and cons of each of the solutions are summarized and the terminology is given. System design and the photometry of hollow light guides are detailed. Finally, a review of four example projects is given.

## TECHNIQUE ET APPLICATIONS DE CONDUITS DE LUMIERE CREUX

### RESUME

La Commission Internationale de l'Eclairage a mis en place un Comité Technique sur le thème "Guides des conduits de lumière creux" afin de développer une nouvelle terminologie et de diffuser l'information spécifique au domaine de l'éclairage par conduits de lumière creux. Ce rapport est la première étape de la démarche qui représentera l'état de l'art au moment de son achèvement substantiel en 1999.

Un bref historique de l'éclairage par conduits de lumière creux recense les différentes solutions et décrit les propriétés physiques qui les sous-tendent. Les avantages et inconvénients de chacune des solutions sont mis en évidence et la terminologie est précisée. Le concept des systèmes et la photométrie des conduits de lumière creux sont détaillés. Enfin, il est présenté une évaluation de 4 projets-type.

## TECHNIKEN UND ANWENDUNGEN VON HOHLLICHTLEITERN

### ZUSAMMENFASSUNG

CIE hat das Technische Komitee "Hohllichtleiter" ins Leben gerufen mit dem Ziel der Entwicklung einer neuen Terminologie und der Verbreitung von Informationen auf dem Gebiet der Beleuchtung mit Hohllichtleitern. Dieser Bericht ist ein erster Schritt in diese Richtung: Er gibt den Entwicklungsstand zu dem Zeitpunkt wieder, als die wesentlichen Arbeiten zu dem Bericht ihren Abschluss gefunden hatten (1999).

Der Bericht enthält eine kurze Beschreibung der Entwicklung der Hohllichtleiter, gibt einen Überblick über die verschiedenen Lösungen und beschreibt ihre physikalischen Grundprinzipien. Die Terminologie wird angegeben und das Für und Wider der einzelnen Lösungen zusammengefasst. Die Photometrie von Hohllichtleitern und die Planung der Beleuchtung mit dieser Technik werden ausführlich erläutert. Abschließend werden vier Beispielprojekte vorgestellt und bewertet.



## 1 INTRODUCTORY COMMENTS

### 1.1 Outline of this report

In April, 1994, the CIE initiated a Technical Committee TC 3-30 (Hollow Light Guides) for the purpose of developing new terminology and dissemination of information in the field of illumination with hollow light guides. This report of TC 3-30 is a first step in that direction, representing the state of the art at the time of its substantial completion in June 1999.

This chapter contains introductory information which provides a context for the technical information presented in the rest of the document. It includes a brief history of the field of hollow light guides and a summary of advantages and areas of application of illumination with these devices.

Chapter 2 presents a review of the basic physics of hollow light guides. These can be classified into four basic types according to the four optical phenomena used to guide light: metallic reflection, multi-layer partial reflection, refraction and total internal reflection. This is then followed with a discussion of the basic system design, in which light is directed into, and subsequently uniformly emitted by, the hollow light guide structure.

Chapter 3 discusses the need for standardized terminology in this field. There are a few ideas in this field that cannot be uniquely and unambiguously described with the current set of CIE terms, and some new terms are therefore proposed as an aid to communication in this field.

Chapter 4 is a treatment of the photometry of hollow light guides. It is shown that standard photometric report formats can be used to characterize their light output. This information can be used with standard lighting design methods. The one special challenge for hollow light guides is that their great length requires the use of non-standard photometric equipment – a problem that can be solved in several ways.

In Chapter 5, a method is presented for summarizing the important quantitative features of a hollow light guide lighting installation. This method is well suited to comparing the features of various projects. Based on this method, four example projects are reviewed and compared.

Chapter 6 includes a minority opinion statement.

The references and a comprehensive bibliography are appended.

### 1.2 Brief history of hollow light guide illumination

The idea of illumination with hollow light guides has a long history. Many scientists who have experimented with optics designs have realized that an internally mirrored pipe will transport light, and that this could permit separation of the light source from the location where the light is used. Many have speculated on the practical application of this idea.

Especially, during the 1880's, there was a surge of work in this area. This was no doubt motivated by the advent of high output electric carbon arc lamps, which, without a means for distributing their large luminous flux, were too powerful for use in ordinary interior illumination applications. Work was pursued by V. N. Chikolev (1880) in Russia, in Germany, and by Professor William Wheeler (1881) in the USA, who patented the idea. All of this early work related to a system of indoor illumination by "piping" light throughout a building using a centralized very intense light source.

However, such early light guide plans were impractical because conventional metal-on-glass mirrors are both expensive and inefficient. The expense arises from the complexity of the batch process required for metal deposition and the thickness of material necessary to achieve a robust, good quality mirror. The inefficiency is due to light absorption associated with the metallic reflection in ordinary mirrors, which is usually greater than 10%. This is significant because in a typical light guide the light rays must be reflected numerous times. If the average light ray undergoes  $N_g$  reflections, each with reflectivity  $R$ , then the maximum efficiency of the light guide itself is about  $R^{N_g}$ . Typically,  $N_g$  is of order 10, and  $R$  for the most practical reflector (aluminum) is about 0,85. Together, these imply an efficiency in the range

of 20%. By reducing the number of reflections, it is possible to improve the efficiency, but this also reduces the relative benefit of the light guide itself.

These limitations, together with the increasing commercial availability of practical small light sources for general illumination, caused the idea of illumination with guided light to be forgotten for a long time. However, two developments in the last fifty years yielded partial solutions to these problems associated with the early concept.

The first was the advent of the solid dielectric light guide, which guides light with high efficiency because it employs total internal reflection (TIR). Unlike metallic mirrors, TIR introduced no loss of light reflection efficiency through absorption. In a 1946 publication, Henry Pearson (1946) of Rohm and Haas Company described the use of both acrylic rods and sheets to transmit light from one place to another. He proposed to provide distributed illumination by introducing materials or structures along the guide, which caused light to emit continuously along its surface. Pearson suggested such guides for providing distributed room illumination, but noted that it was difficult to inject a large enough quantity of light into such guides to make them useful. With the recent improvements of optical fibers, many more researchers have considered the possibility of using them for efficient distribution of light for illumination, and several applications of this type have evolved. However, such applications are limited to a rather small size scale, because these guides are generally too expensive to be made large enough to carry the large luminous flux required for conventional illumination.

A second important development was the advent of low cost optical surfaces resulting from the mass production of continuous high quality polymeric films, which can be optically treated in a variety of ways. For example, vacuum metallization of polyester films yields a flexible mirror that is almost as specular as ordinary glass mirrors, but at a fraction of their cost.

The first large scale application of hollow light guides was in the former USSR. In 1965, Gennadi Bukhman (1965) proposed the use of a metallic mirror light guide, which emitted light along its length through a non-metallized aperture, which he named an "optical slit". In 1975, in conjunction with his colleague Julian Aizenberg, they patented a device (Aizenberg et al., 1978) which employed a thin aluminized plastic film and structures for guiding not only both sunlight and artificial light, but also the heat generated by light sources as well (Aizenberg and Bukhman, 1974 and 1975). In collaboration with Vladimir Pjatigorsky and Alexei Korobko this research yielded a new light guide design (later patented) which they termed the Slit Light Guide. Under the leadership of Julian Aizenberg, over 47000 of these metallic mirror light guides were installed in the former USSR. Additionally, 5000 guides were produced utilizing extruded aluminum. The films used were in the range of 20  $\mu\text{m}$  - 50  $\mu\text{m}$  thick aluminized polyester, and were typically formed into 275 and 600 mm diameter cylinders which were 6 m or 18 m long, illuminated with one or more 700 W metal halide lamps.

Meanwhile, in 1978, Lorne Whitehead of the University of British Columbia in Vancouver, Canada independently initiated research on illumination with optical fibres, which had the advantage of employing the highly efficient effect known as total internal reflection. However, it quickly became clear that the high cost and absorption in the bulk dielectric material would limit the cost effectiveness of this approach. The challenge was to find a way to preserve the surface reflection efficiency of an optical fibre while making it hollow. This reasoning led to his invention of a fundamentally new form of hollow light guide that incorporates total internal reflection rather than metallic mirrors to guide the light (Whitehead et al., 1982). This patented concept (Whitehead, 1982) is now called the "prism light guide". The prism light guide has a transparent wall containing precise longitudinal right angle prisms. Light rays incident on the inside surface of the wall may undergo TIR at the prismatic exterior surface, and then re-enter the central air space to continue propagating along the pipe. In this design, the prisms need only be large relative to the wavelength of light, so, in principle, the material can be thin and low cost.

Based on this concept, Whitehead and his colleague Roy Nodwell, founded TIR Systems Ltd. in Vancouver in 1983 to begin manufacturing prism light guide lighting systems (Whitehead et al., 1986). Since that time, the company has sold over 15000 such systems in North America, Asia, and Europe. These fixtures incorporate a wide range of sizes and shapes utilizing a variety of light sources with power levels ranging from 50 W to 100 000 W. The prism light guide was able to overcome the previously incompatible requirements of high

efficiency, high uniformity, and high length to diameter ratio, and was, therefore, well suited to a wide range of demanding illuminating applications. Initially, however, this work was substantially constrained by one remaining key problem: the precise prisms required in the polymeric wall material of the prism light guide represented a significant fabrication challenge which resulted in high manufacturing costs and quality control difficulties.

At about the same time, two researchers at 3M Company (USA), Roger Appeldorn and Sandy Cobb, were working in the area of precision prismatic film design and fabrication. After becoming aware of Lorne Whitehead's development in 1983, the problem of fabricating the prism light guide material was solved in 1985 utilizing a new 3M technology platform known as "microreplication". This technology makes it practical to do large scale manufacturing of micro-prismatic structures with surface irregularities that are precisely controlled and substantially smaller than the wavelength of light. Cobb reasoned that such precision would allow the production of high quality films with the right angle prisms required for the prism light guide. He proposed and patented (Cobb, 1989) the idea of such thin prismatic films and their application to prism light guides having a variety of curved cross-sectional shapes. Under a licensing agreement with TIR Systems Ltd., this prismatic film was made available to interested lighting manufacturers (Saxe and Whitehead, 1982) for incorporation into a wide variety of prism light guide based products in order to accelerate the growth of this industry.

Presently, more than 15 organizations offer or are currently developing hollow light guide fixtures utilizing the technical advances described above. Work is underway in at least Australia, Belgium, Canada, France, Germany, Italy, Japan, the Netherlands, Norway, Russia, Spain, Switzerland, the UK, the Ukraine and the USA.

### 1.3 Overview of hollow light guide applications

In most of the applications that are currently being pursued, the guided light approach is chosen because of the benefits associated with locating the light source remotely from where the light is used. In other words, there is value in "separating the light from the bulb". Such advantages include the following:

**Maintenance** – Lamps placed remotely can often be positioned in locations where lamp maintenance is more convenient, safer, and less expensive. In some applications, an additional maintenance advantage is the implementation of a lighting solution which uses fewer lamps.

**Safety** – Because the lamps can be located remotely, it is often possible to locate electrical connections, sources of heat, and electromagnetic interference outside of a hazardous or sensitive area. This may also simplify or reduce building heating and air conditioning requirements.

**Improved lighting quality** – Diffuse light emitted from a hollow light guide can result in less glare, better user acceptance, and improved perceived lighting quality at lower absolute light levels.

**Design freedom and aesthetics** – In both interior and exterior applications, the use of hollow light guides permits unique, aesthetically pleasing fixture designs and provides total lighting solutions which would be difficult or impossible to achieve by some other approach. The fixtures may be of variable length and diameter, can often require less structural support because of their lightweight construction, and can provide new dimensions in special effects using light intensity, uniformity, and colour.

The benefits highlighted above have led to lighting solutions in a variety of both interior and exterior lighting applications. Some of these diverse applications include the following:

**Building lighting** – This includes both interior and exterior spaces of buildings. In many applications, the spaces to be lit are large in area and of medium height (about 4 m to 8 m). Typical advantages include optimum placement of lamps for ease of maintenance, reduction in the number of required fixtures, improved lighting quality and energy savings. In addition to lighting building spaces, there is increasing use of

fixtures that can be used to highlight the exterior architectural features of specific buildings, throughout North America, Asia, and Europe.

*Display and advertising lighting* – This area includes unique applications such as in the lighting of museum artifacts where elimination of both heat and ultraviolet radiation is crucial to conservation efforts. In addition, standardized thin back-lit signs for advertising and graphics display purposes have been fabricated. Some of the benefits include a thinner and less expensive sign design with improved lighting uniformity which also incorporates placement of lamps for easy maintenance.

*Hazardous area lighting* – An example of this application is the lighting of specific spaces where heat sources or electrical components are not permitted. Examples could include lighting in explosion or food handling environments or rooms used for medical diagnostic or imaging purposes.

*Pole lighting* – Several manufacturers have introduced pole lights products which contain the lamp and electrical components near the base for ease of maintenance. In addition to being functional, these products are also popular because of their aesthetic appeal.

*Roadway lighting* – The application of hollow light guides has been implemented in several ways in the roadway environment. Back-lit highway signs, lighted delineation products, linear lighting products which effectively illuminate the roadway, and tunnel lighting systems are examples.

*Miscellaneous applications* – As more people become familiar with the potential benefits of hollow light guide technologies, the type of applications become increasingly diverse. Examples of special applications include the development of a workstation task lighting system that delivers light with reduced glare and unwanted reflections from shiny surfaces. Another example is the use of hollow light guides to replace high glare point light sources in the interior patient care compartment of emergency vehicles.

Emerging technological developments in several areas may offer further improvements in hollow light guide design and operation. Included are improvements in the efficiency and optical control of high output, compact, electrodeless light sources, such as the recently introduced microwave powered high pressure sulfur discharge. Other lower wattage, compact and efficient high intensity discharge reflector lamps are also becoming more readily available from a variety of manufacturers. Additional improvements or refinements in the optical design of hollow light guides, and in the methods for injecting light into and extracting light from a guide, offer the potential for both increasing the energy efficiency and reducing the overall cost of hollow light guide solutions. A particularly exciting research area involves concentrating and directing sunlight into light pipes to provide daylighting in the core regions of buildings. Such improvements will no doubt expand the potential for this technology and make it more attractive for many diverse general lighting applications.

It is apparent from a look at some of the initial applications, and from the recent and ongoing technological improvements in this area, that the field of illumination with hollow light guides is rapidly evolving and growing.

## 2. OVERVIEW OF HOLLOW LIGHT GUIDE TECHNOLOGY

### 2.1 Review of the four basic hollow light guide types

At first glance, many people wonder why there is any difficulty in transporting light at all. After all, light moves very rapidly and efficiently through open air and can travel great distances. The problem is that all practical light sources produce light that is highly divergent and this means that the space occupied by light expands as it travels along. As a result, only a small fraction of the light emitted from a source can arrive at a distant location without first interacting with other surfaces. The problem of guiding light, therefore, consists of designing a system containing special optical surfaces that do not absorb light, but instead interact with light in such a way that it continues along in the desired direction within a desired area until it reaches its destination.