



ISBN 978 3 902842 40 4

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

TECHNICAL REPORT

TUBULAR DAYLIGHT GUIDANCE SYSTEMS

CIE 173:2012 (including Erratum 1)

UDC: 628.92
628.953

Descriptor: Daylighting of interiors
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 about 40 countries.

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.
5. To maintain liaison and technical interaction with other international organisations concerned with matters related to the science, technology, standardisation and art in the fields of light and lighting.

The work of the CIE is carried on by seven Divisions each with about 20 Technical Committees. This work covers subjects ranging from fundamental matters to all types of lighting applications. The standards and technical reports developed by these international Divisions of the CIE are accepted throughout the world.

A plenary session is held every four years at which the work of the Divisions and Technical Committees is reviewed, reported and plans are made for the future. The CIE is recognised as the authority on all aspects of light and lighting. As such it occupies an important position among international organisations.

LA COMMISSION INTERNATIONALE DE L'ECLAIRAGE

La Commission Internationale de l'Eclairage (CIE) est une organisation qui se donne pour but la coopération internationale et l'échange d'informations entre les Pays membres sur toutes les questions relatives à l'art et à la science de l'éclairage. Elle est composée de Comités Nationaux représentant environ 40 pays.

Les objectifs de la CIE sont :

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.

DIE INTERNATIONALE BELEUCHTUNGSKOMMISSION

Die Internationale Beleuchtungskommission (CIE) ist eine Organisation, die sich der internationalen Zusammenarbeit und dem Austausch von Informationen zwischen ihren Mitgliedsländern bezüglich der Kunst und Wissenschaft der Lichttechnik widmet. Die Mitgliedschaft besteht aus den Nationalen Komitees in rund 40 Ländern.

Die Ziele der CIE sind :

1. Ein internationaler Mittelpunkt für Diskussionen aller Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik und für den Informationsaustausch auf diesen Gebieten zwischen den einzelnen Ländern zu sein.
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.
4. Normen, Berichte und andere Publikationen zu erstellen und zu veröffentlichen, die alle Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik betreffen.
5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

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 Lichtanwendung. 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.

Published by the

COMMISSION INTERNATIONALE DE L'ECLAIRAGE
CIE Central Bureau
Kegelgasse 27, A-1030 Vienna, AUSTRIA
Tel: +43(1)714 31 87 0, Fax: +43(1)714 31 87 18
e-mail: ciecb@cie.co.at
WWW: <http://www.cie.co.at/>

© CIE 2012 – All rights reserved



ISBN 978 3 902842 40 4

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

TECHNICAL REPORT

TUBULAR DAYLIGHT GUIDANCE SYSTEMS

CIE 173:2012 (including Erratum 1)

UDC: 628.92
628.953

Descriptor: Daylighting of interiors
Light guides as part of illuminating devices

This Technical Report has been prepared by CIE Technical Committee 3-38 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 3-38 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 tous 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 modifications éventuelles.

Dieser Technische Bericht ist von CIE Technischen Komitee 3-38 der Division 3 "Innenraum und Beleuchtungsentwurf" ausgearbeitet und vom Vorstand der Commission Internationale de l'Eclairage gebilligt worden. Das Dokument berichtet über den derzeitigen Stand des Wissens und Erfahrung in dem behandelten Gebiet von Licht und Beleuchtung; es ist zur Verwendung durch CIE-Mitglieder und durch andere Interessierte bestimmt. Es sollte jedoch beachtet werden, daß das Dokument eine Empfehlung und keine Vorschrift ist. Die neuesten CIE-Tagungsberichte oder das CIE NEWS sollten im Hinblick auf mögliche spätere Änderungen zu Rate gezogen werden.

Any mention of organisations or products does not imply endorsement by the CIE. Whilst every care has been taken in the compilation of any lists, up to the time of going to press, these may not be comprehensive.

Toute mention d'organisme ou de produit n'implique pas une préférence de la CIE. Malgré le soin apporté à la compilation de tous les documents jusqu'à la mise sous presse, ce travail ne saurait être exhaustif.

Die Erwähnung von Organisationen oder Erzeugnissen bedeutet keine Billigung durch die CIE. Obgleich große Sorgfalt bei der Erstellung von Verzeichnissen bis zum Zeitpunkt der Drucklegung angewendet wurde, ist es möglich, daß diese nicht vollständig sind.

© CIE 2012 – All rights reserved

The following members of TC 3-38, "Tubular daylight guidance systems" took part in the preparation of this technical report. The committee comes under Division 3 "Interior Environment and Lighting Design".

Members:

J. Aizenberg	Russia
G. Bracale	Italy
S. Bottiglioni	Italy
J. Callow	UK
D. Carter	UK (Chair)
I. Edmonds	Australia
B. Ford	UK
M. Fontoynt	France
V. Hansen	Australia
E. Lee	South Korea
A. Mingozi	Italy
T. Muneer	UK
T. Payne	UK
W. Pohl	Austria
A. Rosemann	Germany
L. Shao	UK
A. Tsangrassoulis	Greece
L. Whitehead	Canada

Corresponding members:

D. Jenkins	UK
T. Kolas	Norway

CONTENTS

SUMMARY	VI
RESUME	VI
ZUSAMMENFASSUNG	VI
ERRATUM 1	E-1
GLOSSARY OF TERMS	1
1. INTRODUCTION	4
2. COMPONENTS OF TUBULAR DAYLIGHT GUIDANCE SYSTEMS	4
2.1 Types of light collection system	4
2.1.1 Zenithal systems with active collection	4
2.1.2 Passive zenithal light guides	6
2.1.3 Horizontal guide systems	7
2.2 Light transport methods	8
2.2.1 Beam/lens systems	8
2.2.2 Hollow mirrored guides	9
2.2.3 Hollow prismatic guides	9
2.2.4 Solid core systems	10
2.3 Light output methods	10
2.3.1 Combined transport and output	10
2.3.2 Discrete output components	11
3. METHODS OF PHOTOMETRY OF SYSTEMS AND COMPONENTS	12
3.1 Performance indices for passive zenithal guides	12
4. DESIGN METHODS	13
4.1 Passive zenithal systems	15
4.1.1 Approximate sizing method	15
4.1.2 Daylight transfer characteristic method	18
4.1.3 Guide transmission efficiency method	18
4.2 Active zenithal systems	22
5. MAINTENANCE OF TUBULAR DAYLIGHT GUIDANCE SYSTEMS	23
6. THERMAL PERFORMANCE OF TUBULAR DAYLIGHT GUIDANCE DEVICES	24
7. COST AND VALUE OF GUIDED DAYLIGHT	24
7.1 Cost and value of daylight guidance systems	24
7.2 Value issues	25
7.3 Cost issues	25
7.4 Cost versus value?	26
8. HUMAN WELL-BEING	26
9. ARCHITECTURAL DESIGN ISSUES	27
9.1 Geographical location	27
9.2 Integration with space planning	28
9.2.1 Plan depth	28
9.2.2 Boundaries to activities and number of floors	28
9.3 Integration with environmental strategy	28
9.3.1 Daylight strategy	28
9.3.2 Ventilation strategy	28
9.4 Building codes	28
9.4.1 General issues	28
9.4.2 Fire protection	29
9.5 Application to existing buildings	30
10. CASE STUDIES	30
10.1 Case study - Arthelio	31
10.2 Case study - Carpiano	35
10.3 Case study - Heliobus	39
10.4 Case Study - Bopartshoff school	40

10.5	Case study - Riverside college	42
10.6	Case study - Eurosped – Tavazzano (Italy)	45
10.7	Case study - South Charnwood school	51
10.8	Case study - Sutton Sports Arena	54
10.9	Case study - Underground kitchen - Environment Park, Torino	57
REFERENCES		60
APPENDIX A. FURTHER DESIGN METHODS FOR PASSIVE ZENITHAL SYSTEMS		62
APPENDIX B. RECOMMENDATIONS FOR GOOD MAINTENANCE PRACTICE		63
APPENDIX C. TUBE TRANSMISSION EFFICIENCY (<i>TTE</i>)		65

TUBULAR DAYLIGHT GUIDANCE SYSTEMS

SUMMARY

Tubular daylight guidance systems are linear devices that channel daylight into the core of a building. They consist of a light transport section with, at the outer end, some device for collecting natural light and, at the inner end, a means of distribution of light within the interior. Collectors may be either mechanical devices that actively focus and direct daylight (usually sunlight), or be passive devices that accept sunlight and skylight from part or whole sky hemisphere. The transport element is usually a tube lined with highly reflective or prismatic material or may contain lenses or other devices to redirect the light. Light is distributed in an interior by output components, commonly diffusers made of opal or prismatic material. The major emphasis of this Report is on passive zenithal systems, the most commercially successful type of daylight guidance being installed in many parts of the world.

The Report includes a contextual review of the technology of all generic types of daylight guidance system. The major part of the report is concerned with photometry of components and systems, design methods, maintenance issues in both design and use, energy aspects, cost and benefits, human factors and architectural issues in the context of passive zenithal systems. The report includes case studies showing good practice.

LES TUBES DE LUMIÈRE NATURELLE

RESUME

Les tubes de lumière naturelle sont des systèmes linéaires qui conduisent la lumière naturelle au cœur des bâtiments. Ils sont constitués d'une section de transport de la lumière avec, à l'extrémité extérieure, un dispositif de collection de la lumière naturelle, et à l'extrémité intérieure, un dispositif de répartition de la lumière naturelle. Les collecteurs peuvent être soit des systèmes actifs, mécaniques, qui concentrent et dirigent la lumière du jour (essentiellement la lumière du soleil), soit des systèmes passifs qui utilisent la lumière du soleil et tout ou partie de celle de la voûte céleste. La section assurant le transport de la lumière naturelle est constituée soit d'un tube dont la paroi intérieure est revêtue d'un matériau prismatique ou à réflectivité élevée, soit d'un tube contenant des lentilles ou d'autres systèmes permettant de rediriger la lumière. Le plus souvent, la lumière est répartie à l'intérieur de la pièce par un diffuseur fait d'un matériau opalin ou prismatique. Ce rapport se concentre essentiellement sur les tubes de lumière naturelle utilisant des collecteurs passifs zénithaux. Ce sont les systèmes les plus vendus dans le monde.

Ce rapport passe en revue les différents types de systèmes permettant de conduire la lumière naturelle. Il est essentiellement consacré à la photométrie des composants et des systèmes, aux méthodes de conception, aux problèmes de maintenance, aux aspects énergétiques, au coût et aux avantages, aux facteurs humains et à la prise en compte architecturale des systèmes passifs zénithaux. Ce rapport présente des réalisations exemplaires.

HOHLE TAGESLICHTLEITSYSTEME

ZUSAMMENFASSUNG

Hohle Tageslichtleitsysteme sind lineare Baugruppen, die Tageslicht in das Gebäudeinnere leiten. Sie bestehen aus einem Lichttransportmodul, an dem sich außenseitig ein Modul zur Einkopplung von Tageslicht und innenseitig ein Leuchtenmodul zur Lichtverteilung anschließt. Tageslichteinkopplungsmodul werden entweder als eine bewegliche Baugruppe, die aktiv das Tageslicht (üblicherweise direktes Sonnenlicht) fokussiert und einleitet, oder eine passive Baugruppe, die das direkte Sonnenlicht oder auch Himmelslicht (vom gesamten Himmel oder nur von Teilen des Himmels) nutzt, ausgeführt. Das Transportmodul ist üblicherweise ein Hohlkörper, der mit hochreflektierendem Material oder einem prismatischen Film ausgekleidet ist. Zusätzlich kann es optische Linsen oder andere Komponenten zur Umlenkung des

Lichtes enthalten. Das Licht wird im Gebäudeinneren durch ein Leuchtenmodul verteilt. Dieses Modul besteht in den meisten Fällen aus diffus transparentem Material oder prismatischen Strukturen. Im Rahmen dieses technischen Berichts wird vornehmlich auf passive Zenithsysteme eingegangen, die die derzeit erfolgreichsten Typen hohler Tageslichtleitsysteme am Markt darstellen und in vielen Teilen der Welt installiert werden.

Der Bericht beinhaltet einen Überblick über gängige Typen von hohlen Tageslichtleitsystemen. Ein großer Teil dieses Berichts beschäftigt sich mit Messungen von Komponenten und Systemen, Auslegungsmethoden, Wartungsaspekten in den Bereichen Auslegung und Nutzung, energetischen Aspekten, Kosten und Nutzen, menschlichen Faktoren sowie architektonischen Fragestellungen im Zusammenhang mit passiven Zenithsystemen. Der Bericht enthält zudem eine Sammlung von Fallstudien, die gute Auslegungsbeispiele aufzeigen.

Copyright International Commission on Illumination
Provided by IHS under license with CIE
No reproduction or networking permitted without license from IHS

ERRATUM

(August 2012)

to CIE 173:2006 Tubular Daylight Guidance Systems1. Page 21:**Table 3. Utilisation factors for output devices.**

For Room index 5,0, Effective ceiling reflectance 70 %, Reflectance of floor or working plane 30 %, Reflectance of wall 50 % the utilization factor is 1,00.

Therefore replace the value 10,0 by 1,00 in the respective cell.

2. Page 65:**Appendix C. TUBE TRANSMISSION EFFICIENCY (TTE)**

In the formula used to derive an approximate value of TTE the square root is missing in the denominator.

Therefore replace the existing formula by the following:

$$TTE = \frac{e^{\frac{L}{D} \tan \theta \ln R}}{\left(1 - \frac{L}{D} \tan \theta \ln R\right)^{0,5}}$$

Copyright International Commission on Illumination
 Provided by IHS under license with CIE
 No reproduction or networking permitted without license from IHS
 Full document details: CIE 173-2012

GLOSSARY OF TERMS

active daylight collector ("heliostat")

device consisting of all the apparatus necessary to track the sun, collect and concentrate light, and direct light of the correct angular distribution into the input aperture of a light guide

daylight (ILV 845-09-84)

part of global solar radiation capable of causing a visual sensation

daylight factor (ILV 845-09-97)

ratio of the illuminance at a point on a given plane due to the light received directly and indirectly from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky

The contribution of direct sunlight to both illuminances is excluded.

Note 1: Glazing, dirt effects, etc. are included.

2: When calculating the lighting of interiors, the contribution of direct sunlight must be considered separately.

daylight penetration factor

ratio of the illuminance at a point on a given plane due to the light received directly and indirectly via a light guide from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky

The contribution of direct sunlight to both illuminances is included.

Note 1: Glazing, dirt effects, etc. are included.

2: When calculating the lighting of interiors, global horizontal illuminance is used as the basis of the calculation.

extractor

structure in a hollow light guide which causes light to escape from the guide in a controlled manner

global horizontal illuminance [E_{vg}] (ILV 845-09-89)

illuminance produced by daylight on a horizontal surface on the earth

unit: $lx = lm \cdot m^{-2}$

hollow light guide

hollow light distribution structure, through which the average light ray propagates mainly in air and is guided by means of numerous optical interactions before exiting

lens light guide

hollow light guide in which light is confined by refraction by lenses which are located periodically along of the guide

maintenance factor (MF) (ILV 845-09-59)

ratio of the average illuminance on the reference plane after a certain period of use of a lighting installation to the average illuminance obtained under the same conditions for the installation considered conventionally as new

Note 1: The term **depreciation factor** has been formerly used to designate the reciprocal of the above ratio.

2: The maintenance factor (MF) takes into account dirt accumulation on luminaire (LMF) and room surfaces ($RSMF$) and lamp depreciation ($LLMF$).

metallic mirror light guide

hollow light guide in which light is confined by metallic reflection by metallic surfaces at the guide wall

multi-layer light guide

hollow light guide in which light is confined by multiple partial reflections by multi-layer dielectric structures at the guide wall

output component

apparatus, similar to a luminaire, located at the end of a passive guide that distributes, filters or transforms the light transmitted by a guide

Output components for tubular daylight guidance systems are commonly referred to as "diffusers".

passive daylight collector

static device that is capable of capturing daylight and directing it into the input aperture of a light guide

prism light guide

hollow light guide in which light is confined by total internal reflection by prismatic surfaces in the transparent material comprising the guide wall

prism light guide film

optical film containing right angle prisms running parallel to a longitudinal direction, which reflect light by total internal reflection in a manner which preserves the component of a light ray's propagation in the longitudinal direction

A prism light guide can be made by forming such film into a tube, with the prisms running parallel to the tube axis.

skylight (ILV 845-09-83)

part of sky radiation capable of causing a visual sensation

slit light guide

mirror hollow light guide with a longitudinal optical slit (or slits), through which light passes out from the guide

solar factor; total (energy) transmittance (of glazing material) [g] (ILV 845-09-106)

ratio of the quantity of heat penetrating into an interior through the glazing, to the solar radiant energy incident on that glazing

Note: This ratio is the sum of two quantities: the radiant transmittance τ_e of the glazing and the quantity equal to the ratio of the convected and radiated heat gain from the glazing into the interior Q_2 to the solar radiant energy Q_1 incident on the glazing

$$g = \tau_e + Q_2/Q_1 .$$

standard light transfer characteristic

ratio of the illuminance at the guide input to the luminous flux leaving the guide output

unit: m^2

sunlight (ILV 845-09-82)

part of direct solar radiation capable of causing a visual sensation

U-value

thermal transmittance of a material

unit: $\text{W/m}^2\text{K}$)

Copyright International Commission on Illumination
Provided by IHS under license with CIE
No reproduction or networking permitted without license from IHS
Full document details: CIE 173-2012

1. INTRODUCTION

Traditional vertical windows can provide adequate daylight within about six metres of a window but, since daylight levels decrease asymptotically with distance from a window, a disproportionate amount of solar radiation must be introduced into the front of the room to achieve small increases in daylight at the back. While this will contribute to energy savings by offsetting electric lighting, the corresponding increase in cooling due to solar heat gain, and/or heating due to structural heat loss, can negate these savings. Atria, rooflights and roof monitors may light areas remote from vertical windows but are of little use in lighting deep core areas. A number of systems exist to redirect daylight into areas of buildings that cannot be lit by conventional glazing. One major generic group known as "beam daylighting" redirects sunlight by adding reflective or refracting elements to conventional windows. This work is concerned with the second major group of redirecting devices known as tubular daylight guidance systems.

Tubular daylight guidance systems are linear devices that channel daylight into the core of a building. They consist of a light transport section with, at the outer end, some device for capturing natural light and, at the inner end, a means of distribution of light within the interior. The light capture device may be located at roof level of a building enabling light from the zenithal region of the sky to be gathered. Alternatively, light may be gathered from a device mounted on the building façade. Zenithal openings allow intensive use of daylight but may cause glare or overheating due to penetration of direct solar radiation especially during summer. For a horizontal aperture the quantity of solar flux entering through a façade mounted collector depends on façade orientation and season and these systems are more likely to be influenced by external obstruction than zenithal systems. Collectors may be either mechanical devices that actively focus and direct daylight (usually sunlight), or be passive devices that accept sunlight and skylight from part or whole sky hemisphere. The transport element is usually a tube lined with highly reflective or prismatic material or may contain lenses or other devices to redirect the light. Light is distributed in an interior by output components, commonly diffusers made of opal or prismatic material.

The major emphasis of this Report is on passive zenithal systems. These are by far the most commercially successful types of tubular daylight guidance, being manufactured and installed in large numbers in numerous countries. The design related material in this Report relates to passive zenithal systems only. The Report includes a contextual review of the technology of all generic types of daylight guidance system and includes case studies. The sections on performance indices, photometry of components and systems, design methods, cost and benefits, human factors and architectural issues relate to passive zenithal systems.

2. COMPONENTS OF TUBULAR DAYLIGHT GUIDANCE SYSTEMS

Tubular daylight guidance systems consist of a light transport section with, at the outer end, some device for capturing natural light and, at the inner end, a means of distribution of light within the interior. Figure 1 shows a general classification of daylight guidance systems.

2.1 Types of light collection system

The light collection device is either located at roof level to gather light from the zenithal region of the sky or is a device that is part of, or attached to, the building façade. Zenithal collectors are either mechanical devices that actively focus direct daylight (usually sunlight) or are passive devices or building elements that accept sunlight and skylight from part or the whole sky hemisphere.

2.1.1 Zenithal systems with active collection

A "heliostat" tracks the sun and collects and concentrates sunlight. A tracking mirror or Fresnel lens usually located on the roof uses light sensors, pulse motors, and computers to track the sun. A second mirror or lens directs a concentrated beam of sunlight into the transport device that may be a light guide, atrium or rooflight (see Figure 2). The necessity to concentrate the light means that diffuse daylight is much less suitable as a light source for this method of light capture since there are theoretical limits on how much concentration can be achieved (Rabl, 1980). If narrow light guides are used for transport strongly collimated

sunlight is necessary to achieve the necessary concentration ratios. The size of tracking mirrors or lenses required can be large. It is estimated that a total mirror area of about 40 m², or a lens area of half this value, would be required to light a 1000 m² office to 500 lx (Ngai, 1983). Collectors of this size would have high capital cost, require costly control and structural systems and maintenance, and have implications for the external appearance of the building.

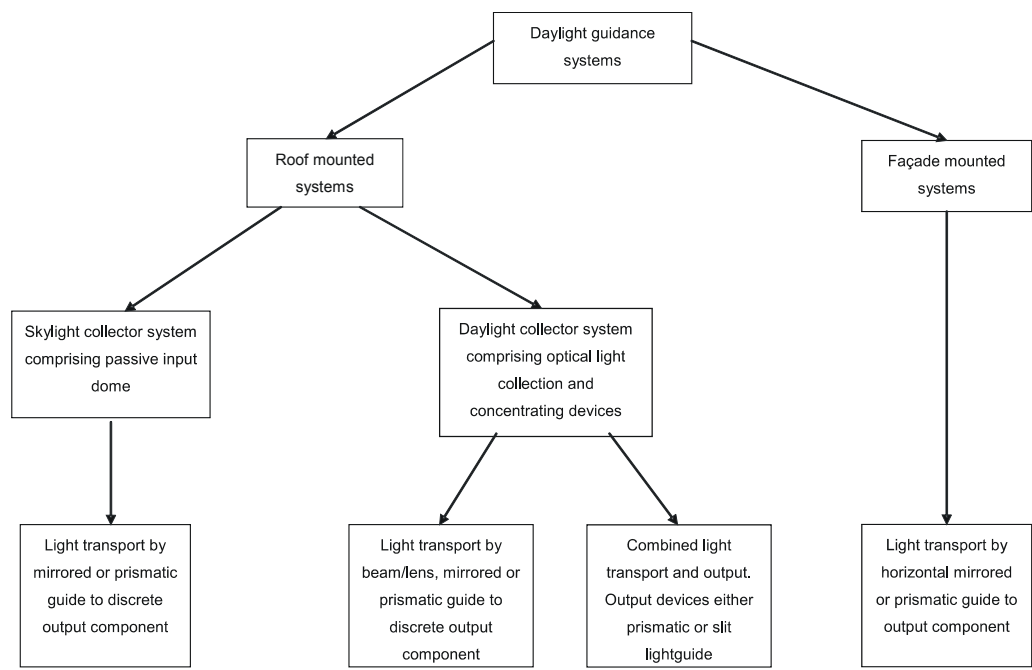


Figure 1. General classification of daylight guidance systems.

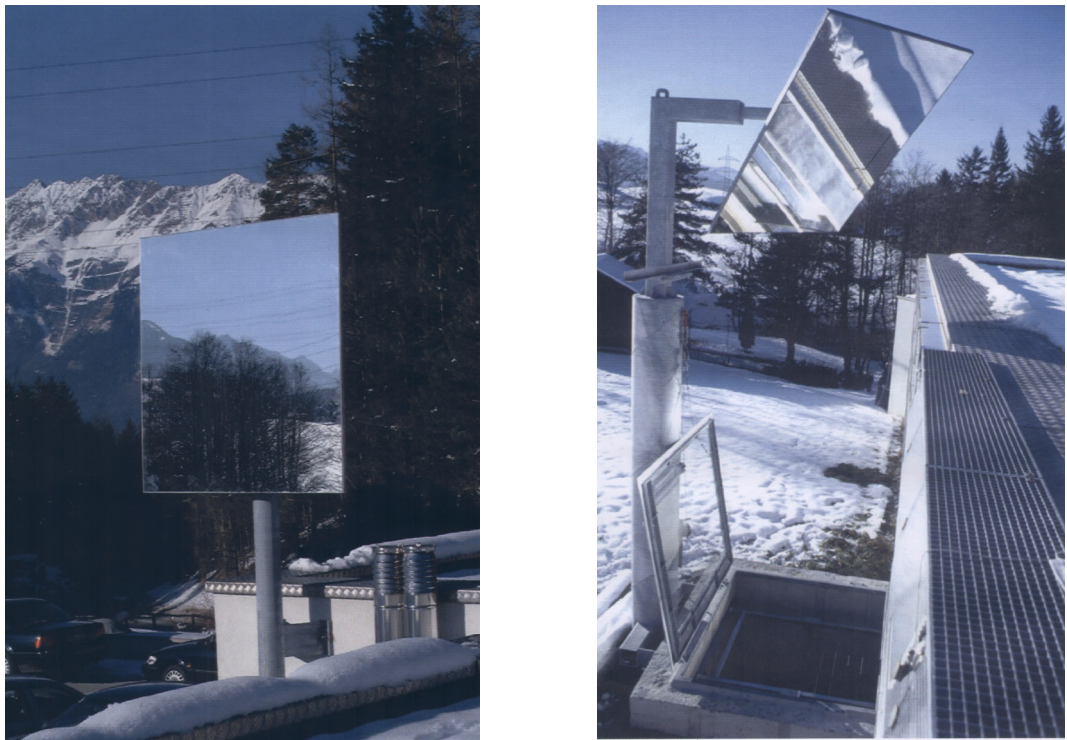


Figure 2. Light collector for active systems.

Inexpensive and less sophisticated rooflight tracking systems have been used for the lighting of single storey buildings usually in areas where clear skies predominate. These utilize tracking reflectors mounted on the roof to reflect light through a prismatic rooflight or some other device to spread the light over the area below to where it is needed (Figure 3). The majority of light transport systems used for active collector systems are hollow mirrored or hollow prismatic light guides.



Figure 3. Tracking reflector.

2.1.2 *Passive zenithal light guides*

Passive light guides are the most commercially important form of light guidance system being widely used for amenity lighting mainly in domestic buildings. They have not yet become a major light source for functional or task lighting in commercial, industrial or storage buildings despite their potential as a substitute for electric lighting with accompanying environmental benefits.

When daylight falls on an unobstructed horizontal surface from the full sky hemisphere light from various directions will intercept a collecting surface in proportion to the area it presents to the incoming rays. The proportion of the global incidence actually collected depends on the portion of the sky "seen", that is, on the cone of acceptance of the incident area (dependant on its construction and geometry) and its orientation. If acceptance is over the full hemisphere all light is processed but if acceptance is within a 120° cone facing the zenith some 82% of light from a CIE overcast sky is collected. If the surface is tilted 30° from the vertical on an azimuth exposed to direct sun this value reduces to 73% (Smith and Ruck, 1986). To light the 1000 m^2 office referred to earlier to 500 lx, some 50 m^2 of passive collector area would be required assuming typical system efficiencies and 20000 lx external.

Passive hollow guides consist of an essentially vertical light transport section with, at the upper end, some device for capturing natural light whilst preventing ingress of wind and rain and, at the lower end, a means of distribution of light within the interior. The upper end of the guide may be horizontal or inclined at some angle to the tube axis and consists of a clear polycarbonate dome which may include in its construction a refractive device intended to redirect light in a near axial direction (Figure 4). Modifications to the basic systems include laser cut deflecting panels to redirect light in an axial direction and reflectors known as "light scoops", located outside or inside the collector dome, to intercept direct sunlight (Figure 5). The latter have the effect of increasing the luminous flux output of the tube by a factor of up to two under clear sky plus sun but have a negative effect on output under overcast conditions. An oblique angled opening has a similar effect to the "light scoops". Laser cut panels will improve the transmittance of a mirror light guide under clear sky conditions by reducing the number of reflections a light beam encounters before reaching the illuminated space. However, under overcast sky they may have a negative impact on light capture. The transport section is a rigid or flexible hollow mirrored or prismatic guide. Rigid tubes may include bends or elbows.

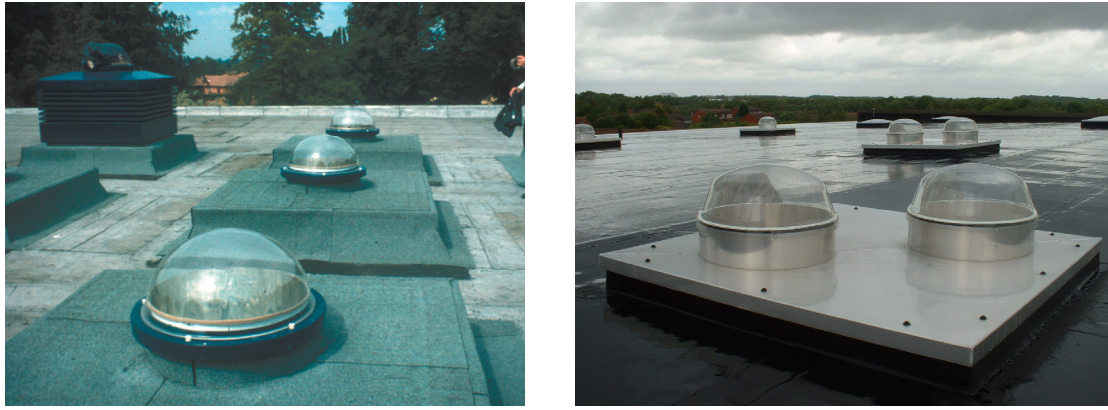


Figure 4. Passive hollow guide collectors.

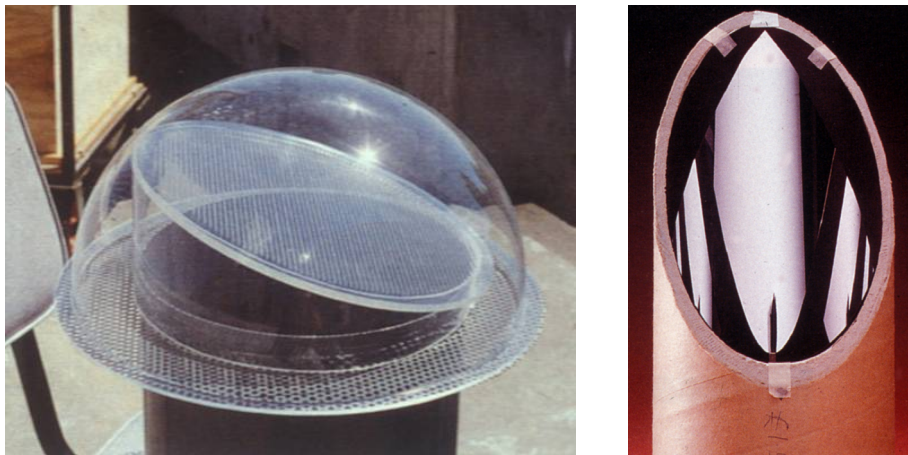


Figure 5. Laser cut deflecting panels and "light scoops".

Prismatic materials are not widely used in passive light guides because they only accept light within a defined cone. Although high transmissions can be obtained by total internal reflection for radiation from some incident directions, there may be very little from others. Since the range of incident directions necessarily utilised in daylight systems is large, and will include many angles from directions outside the acceptance cone, this could be seen as a major drawback. Prismatic materials are however used for several reasons: firstly, although they only accept light from a narrow range of incident angles, daylight entering at near axial incidence is more efficient because it undergoes less reflection; secondly daylight from the zenith is likely to come from the relatively bright part of the sky; thirdly buildings are commonly overshadowed meaning that in practice little horizontal light reaches the collector in the first place.

2.1.3 Horizontal guide systems

A horizontal daylight guidance system is integrated into a suspended ceiling, its light gathering device being part of the building façade and the output end located deep in the room. The systems are usually designed for use in conjunction with a conventional lower window. The light collector is generally located on the façade orientated toward the equator and consists of a curved mirror or some other means of deflecting sunlight into the duct that is lined with highly reflective material. Limiting dimensions of the duct are determined by the space available in the suspended ceiling zone. The majority of applications of this technology are for office buildings. Horizontal light ducts may be used both in high latitude regions, where the sun altitude normally allows direct solar penetration into the duct with minimal reflections, and also in equatorial regions where high angle solar radiation may be redirected into the duct by a mirror, laser cut panel, or other device (Figure 6).

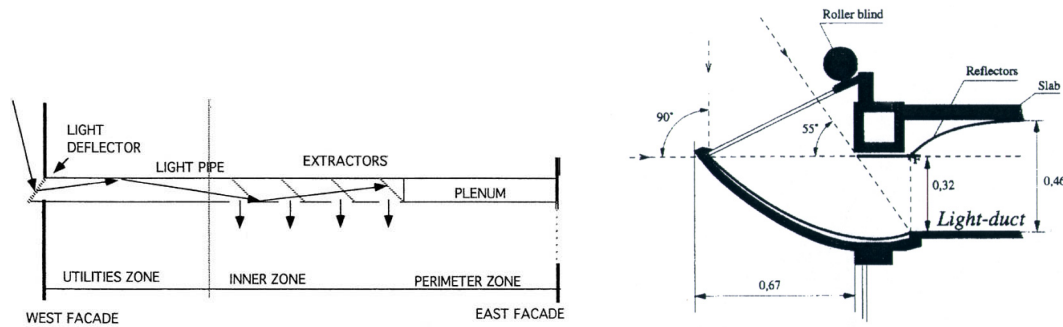


Figure 6. Façade mounted collector and horizontal guide systems.

2.2 Light transport methods

Light transport is the feature that sets tubular guidance systems apart from other daylight systems. Transport elements deliver light from the collector to the point of exit but some may additionally act as output components. Recently considerable research effort has been directed at transport systems, a major factor being the availability of new low cost light redirection materials. The four different transport methods, namely, beam/lens systems, hollow mirrored guides, hollow prismatic guides and solid core systems are examined in turn.

2.2.1 Beam/lens systems

In these systems, light from the source is collected and collimated by a heliostat and transported via an arrangement of lenses and mirrors (see Figure 7). A physical "guide" between the lenses is not necessary from the optical point of view, but in practice may be necessary to provide protection. The spacing of lenses is determined by their focal length. These systems have two drawbacks that limit practical application. Firstly, light redirecting equipment such as lenses and mirrors tend to be more expensive than the other methods. Secondly, there are high levels of light loss in the optical processes. Whilst a clear lens can transmit a maximum of 92%, losses increase with dirt deposition on surfaces. Efficiency is also dependent on accurate alignment so that in systems consisting of several components losses due to misalignment become significant.

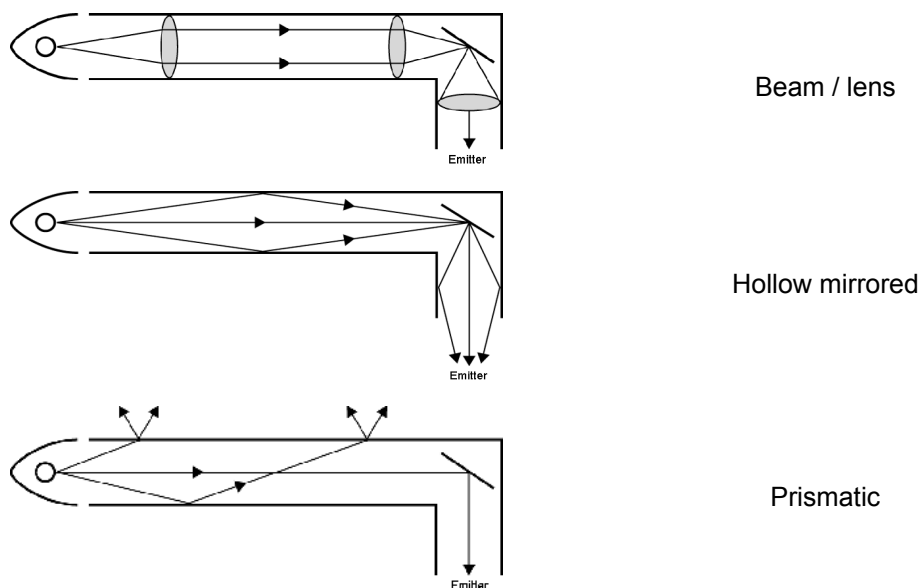


Figure 7. Light transport methods.

The few examples of this type that have been realised are based on the work of Dugay (Dugay and Edgar, 1977). A building at the University of Minnesota, for example, uses heliostats on the roof to capture sunlight that is concentrated and collimated before being beamed through a vertical duct in the building containing lenses and mirrors to a working space 35 m below ground. A total of 13 optical processes give a maximum system efficiency of 28% in a clean state. The main advantage of this approach is that concentrated sunlight permits the use of smaller ducts than other transport methods such as a hollow guide containing mirrors delivering the same light flux. However, high capital and maintenance costs combined with low efficiencies suggest that these methods would almost certainly be uneconomic compared with other transport methods.

Using this technique the sunlight is concentrated during transport and the duct thus occupies less floor area than capable of delivering the same flux. Taken together the above suggest that although a beam/lens system may be superficially attractive using "free" sunlight as a source the level of possible losses suggest that these methods would almost certainly be uneconomic, particularly, when used with skylight as a source.

2.2.2 Hollow mirrored guides

These use multiple specular reflection at the inner wall surface to transmit light (see Figure 7). Overall light transmission is a function of the surface reflectance, the luminous intensity distribution of light entering the system and the proportions of the tube in terms of the ratio of length to diameter. If the light paths are long compared with the axial length of the guide the number of reflections are necessarily large and thus light losses depend to a great extent on the reflectance of the wall material. To attempt to minimise the number of reflections, light must enter the guide as a near collimated axial beam. The ratio of length to effective diameter is the projection onto a plane perpendicular to the guide axis of the average distance between two reflections. The ratio thus depends not only on the area and geometric form of the guide but also on the directional properties of the source. The light transmittance of the guide is highly sensitive to the reflectance of the mirror material, with variations of as little as 0,1% causing noticeable changes in performance. Additionally, the transmission along a mirrored guide can induce large variations in spectral properties of light - that from silver coated guides exhibiting a red shift and that from aluminium coated guides being blue shifted. Mirror light guides may contain bends that may significantly reduce the transmittance of the light guides depending on the severity of the bending.

A recent development has been the introduction of reflecting materials based on polymeric multi-layer optical stacks having a specular reflectance of the order of 99%. The multiple thin film layers of transparent dielectric material create a tuned interference stack that in aggregate produce the high reflectivity for a wide range of incident angles. The availability of these materials will greatly increase the distances over which transmission of light is economic.

The above transport elements are of rigid construction. Flexible transport elements consisting of metallised polyester film covered with aluminium foil stretched over a spring steel skeleton are available. Whilst the specular reflectance of the lining material is of the order of 90%, the irregular internal surface of the concertina-type guide shape means that the effective reflectance is less than 90%.

2.2.3 Hollow prismatic guides

These are structures in which light is totally internally reflected from a prismatic dielectric surface which traps the light and redirects it down the inside of the guide (see Figure 7). Incident light is totally internally reflected twice at the prismatic surface and operates like a mirror for certain angles of incidence. Unlike a mirror, however, the prismatic structure is transparent to light at off-axis angles of incidence. The existence of prismatic light guides is due to the development over the last couple of decades of reliable methods of production of precision structured surfaces. Of particular interest for lighting applications are the range of optical materials made from acrylic or polycarbonate that have a 90 degree prismatic ridge structure on the exterior surface. These materials, when used to line a light guide with the prisms orientated parallel to the axis transmits light by the process of total internal reflection providing that the incident light does not exceed 27,5 degree. In theory all light would be

reflected by this process but irregularities in the film cause a small proportion of light to exceed the maximum angle and leak out of the guide to give an overall reflectance of the order of 98%. This effect can make the guide glow and for this reason the prismatic guide acts as both a transport and output component. Hollow prismatic guides are detailed in CIE 164:2005 (CIE, 2005).

2.2.4 Solid core systems

The major practical examples of solid core systems are optical fibres that transport light through thin flexible solid fibres with high efficiency by total internal reflection at a dielectric interface. Optical fibres consist of two coaxial regions: an inner core which acts as the light transport medium and an outer cladding of lower refractive index which prevents leakage of light from the core. The process of total internal reflection in an optical fibre is very efficient and light transport is essentially a function of length and not of diameter as in the case of mirrored or prismatic transport systems. Some light will be lost due to absorption and scattering and this is expressed in terms of attenuation in decibels/m. This varies according to wavelength and means that there is a danger that the spectral composition of the transported light may change. Typical values of attenuation vary from 0,1 dB/km to 0,4 dB/km for plastic and from 0,2 dB/km to 0,6 dB/km for glass fibres. Optical fibres have an individual diameter of some 50 μm - 150 μm and a large number are usually clustered together to form a flexible bundle and encased in a protective tube. The cross section size of the bundle varies depending on the number of fibres but commercially available examples suitable for light transport purposes are typically of the order of 10 mm diameter. The main design considerations with optical fibres are at the coupling to the light source and the utilisation of the light at the termination of the fibre. At the entrance end of the fibre light must be confined to a certain acceptance angle if loss by refraction through the cladding is to be minimised.

Fibre optical transport may be used as part of systems that collect solar radiation using heliostats and use concentrators to focus light onto the ends of the optical fibre. In this way sunlight may be transmitted many tens of metres from the collector. Major advantages are the relative ease of installation of optical fibre and the absence of the need for large vertical ducts.

A variation of the optical fibre daylight system is the optical rod set up where a rod of an acrylic or another clear light transmitting material is used as the light carrying medium. The system also works on the principle of total internal reflection and enjoys the advantage of less transmission loss but has the additional benefit of having a less stringent accuracy requirement for solar tracking.

2.3 Light output methods

The physical and optical properties of daylight output components are heavily influenced by the transport system to which they are connected. They may be described as "combined transport and output" in which light is extracted continuously along its length, or "discreet output components" which operate in a manner similar to conventional luminaires.

2.3.1 Combined transport and output

Two of the generic types of lighting transport system described in Section 2.2 may be used as output components.

2.3.1.1 Hollow prismatic guides

Light transport within a hollow prismatic light guide is by total internal reflection within the prismatic material (Whitehead et al., 1982). Output is caused by imperfections in the prismatic structure and to the presence of non-collimated light that exceeds the acceptance angle. The loss is approximately 2% per 300 mm of guide length and the effect is to cause the guide to glow. The relative luminous flux output of a guide declines with distance from the source and luminous intensity distribution may not be symmetric in the axial plane. A number of devices are used to control the light output variation of "size" of the output window. For a constant light output this "size" must vary over the guide length. A reflective material may be used to cover the exterior surfaces of the prismatic tube that are not used as an output component and the effect of redirecting rays back through the guide so that the maximum useful light is emitted.

Other control techniques are extractors and mirror ends. An extractor is a strip or wedge of diffusing material placed inside the tube which causes incident light to be scattered and escape through the transport tube walls. Control of light output along the length of the output component is achieved by varying the width and shape of the strip. Mirrors placed at the end of the tube reflect some of the light that would otherwise exit and this has the effect of increasing the useful light output of the output component. The large prismatic output components used for interior illumination range from 100 mm to 300 mm in diameter and have an appearance similar to large conventional prismatic panel area sources. Their large size and low brightness gives diffuse light with few shadows and little glare.

2.3.1.2 Slit lightguides

These are tubes which have a high reflectance (0,85 - 0,95) mirrored internal coating except for a longitudinal slit running the length of the tube (Aizenberg et al., 1975). Light transmission along the guide is by mirror reflection and light is emitted through the slit which may be transparent or diffusing. The angular size of the slit varies from 30° to 110° subtended by the axis. Slit lightguides are large, diameters ranging from 250 mm to 1200 mm, and optimal aspect ratios are between 30:1 and 40:1. Mirrors placed at the end of the tube reflect some of the light that would otherwise exit and this has the effect of increasing the useful light output of the output component. Some descriptions of the guides allude to solar source versions but no working applications of these are described in the literature.

2.3.2 Discrete output components

There are several types of commercially available discrete output component that distribute light emerging from the ends of a light guide. They are generally circular flush or domed diffusers made of opal or prismatic material of diameters corresponding to the light guides. An alternative is 600 mm square components fitted into suspended ceiling systems in commercial buildings. These are connected to a 500 mm mirrored guide via a transition box and light is distributed within the building interior by either a diffuser or an array of Fresnel lenses (Figures 8 and 9).



Figure 8. Installation showing discrete output components and fire protected shafts housing guides.



Figure 9. Internal and external view of large installation.

Laser cut panels have been proposed as output components either at the end of the light guide to direct light towards desired surfaces, say ceiling, or at selected positions inside a light guide where they extract a proportion of the light and direct it to spaces to be illuminated. The latter option is suitable either for horizontal guides or vertical guides spanning more than one floor.

3. METHODS OF PHOTOMETRY OF SYSTEMS AND COMPONENTS

Section 2 of this report describes the many types of tubular daylight guidance system that are available. In general, the systems comprise combinations of components each having a defined optical purpose. Each system is tailored to the needs of the individual application and/or the building into which it is fitted. The system components are characteristically of large size - much larger than electric lighting devices offering a comparable light output. However, if photometric data for daylight guidance components were available, conventional illuminating engineering calculation processes could be used for evaluation. There are a number of problems concerned with photometry of these systems, notably that specialist photometers capable of accepting components of large size are necessary and only a limited number of these exist (Rosemann et al., 2005). A second problem is specification of a suitable standardised light source for testing daylight systems, natural skies being unsatisfactory for this purpose. These could be either an integrating sphere to create a constant luminance (Lambertian radiator) or an artificial sky with a CIE overcast sky luminance distribution.

Many of the limitations alluded to above do not apply to the passive zenithal light guide systems that are the main concern of this Report. These systems consist of combinations of a limited number of standard components. However, because of their worldwide manufacture and use the necessary specialist photometric facilities may not be available locally. Also these systems are commonly specified and installed by non-lighting specialists and thus a simpler method of performance evaluation may be appropriate. The "performance indices" described in the following section can be used by manufacturers of passive zenithal light guides to produce design information in a standard format. This data can subsequently be used to predict illuminance resulting from the daylight guidance system output within a building and comparison of information in this format enables designers or potential users to make informed choices between alternatives.

3.1 Performance indices for passive zenithal guides

For a given tubular light guide system, consisting of a daylight input window, a length L of light guide having a diameter, D and a light output window, the "standard light transfer characteristic" is determined as follows: a diffuse light source is placed near the input window, and the illuminance, E , is measured at the input window. The luminous flux leaving the guide output, Φ , is also measured. The "standard daylight transfer characteristic" is simply the ratio Φ/E which has units of m^2 . This is the equivalent area of an open-sky aperture that would be needed to produce the same amount of light, if there were no losses in the system.

The source consists of a diffusing material illuminated by tubular fluorescent lamps as illustrated in Figure 10. This must fulfill a luminance uniformity requirement when viewed from the guide window. Specifically, when viewed from any point at the guide input, for any direction up to an angle of 70° , relative to the axial direction of the pipe, the observed luminance must be within $\pm 20\%$ of the mean value. (This implies a minimum required size for this diffusely luminous source.) In this case, the illuminance at the guide input will be very uniform, so it will be sufficient to measure the value E at the centre of the guide input using a calibrated illuminance meter.