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"Lighting Loads and New Transparent Materials"

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LIGHTING LOADS AND NEW TRANSPARENT MATERIALS

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Abstract

The paper discusses the relevance of the natural light to reduce energy consumption in buildings, particularly commercial ones, both in terms of electric energy and thermal energy.
In addition, it presents some data and information on materials, both traditional and new, necessary to understand and evaluate the complex phenomena associated with the transmission and distribution of light inside a building.
Finally, a simplified integrated energy analysis computer code, meant to provide estimates of monthly and annual energy consumption for heating, cooling and lighting, is briefly described.

1. Introduction

There is a growing interest among architects and designers for the use of natural light, particularly in commercial (non residential) buildings.
Daylight is correctly perceived as a way not only to save energy, but also as a mean to create better living and working conditions.
The choice of materials play an essential role in determining the actual capability of a building to take full advantage of the available light from the sun and the sky.
Most of the information reported in this paper has been derived from the activity of the European Concerted Action Programme on Daylighting, which is coordinated by the author [1].
The European Concerted Action Programme on Daylighting was initiated in September 1986. It is a three-year programme, involving six main research groups from various EEC countries, with participating researchers from sixteen European institutions, funded by the Commission of the European Communities.
Objective of the Programme is to provide designers with updated and reliable information and tools, as to enable them to use daylighting concepts and components in the design of large, non residential buildings, with predominantly diurnal occupation, in order to improve the visual quality of the working environment and to save energy from non-renewable sources.

2. Lighting Loads

Electric lighting is a source of heat for the conditioned spaces.
During the cold seasons such heat represents a "free" gain, and thus it helps in reducing the need for heat from the heating system. Of course, it would not be wise to heavily rely on such "free" source, for instance increasing the illuminance task level above standards, as electric energy is very expensive, both economically and in terms of primary energy consumption.

During the hot season, the heat generated by electric lighting represents a problem, either in terms of cooling load for the HVAC system, or in terms of human comfort, or both.

The instantaneous rate of heat gain from electric lighting can be expressed as [2]:

$$q = W\ UF\ SAF$$

where W is the total light wattage, UF is the Use Factor, which expresses what fraction of the total wattage is actually in use at that time, and SAF is the Spatial Allowance Factor, which takes into account the fact that most fixtures require more energy than their rated wattage, mostly due to ballasts.
Typical values of SAF are:

Fixture	SAF
Sodium Lamps	1.04 - 1.37
Rapid-start lamps	1.18 - 1.30
32W single-lamps	up to 2.19

The total wattage, W, depends on the desired illuminance level, E_{SET} (lux, i.e. lm/m^2), on the area to be illuminated, A (m^2), and on the luminous efficacy of the light sources K (lm/W) (see following chapter):

$$W = (E_{SET}\ A)/K$$

In conclusion, the cooling load due to electric lighting depends on a number of parameters, which, in turn, depend on the following factors:

a. local luminous climate: the Use Factor depends on available daylight;

b. user's requirements: area to be illuminated, A, and required level of illuminance, E_{SET}, which is related to the task to be performed;

c. architectural design and materials: which determine the capability of the building to take advantage of available natural light, and thus affect, again, UF;

d. control system: UF is smaller than unity only as long as the lighting system is provided with control and regulation characteristics enabling it to adapt its output to the spatial and temporal distribution of daylight inside the building;

e. electric lighting hardware, that is, lamps and luminaires, with their performance: luminous efficacy, and Special Allowance Factor.

3. Luminous Efficacy of Natural and Artificial Light

The spectral luminous efficacy of a radiant source is defined as the ratio of the luminous flux at a wavelength to the radiant flux at that wavelength (lm/W). The maximum possible value, K_m, is 680 lm/W. Integrating over the whole spectrum, one obtains the luminous efficacy of the source, K:

$$K = E/E_e$$

where E is the illuminance (lux) and E_e is the irradiance (W/m^2). As the spectral composition of sunlight at ground level depends on the atmosphere it passes through, its luminous efficacy is variable, depending on the air mass, and on the content in ozone, gases, water droplets, dust, other particles, etc.

The luminous efficacy of global solar radiation, for a solar altitude greater than 10 degrees, varies between 70 and 110 lm/W for clear sky conditions, and between 100 and 130 lm/W for overcast skies (see Table I).

For the diffuse radiation component, values of the luminous efficacy found by various authors [3] are between 84 and 173 lm/W (see Table II).

For direct radiation, values range from 50 to 120 lm/W.

TABLE I

Authors	Place of measurements	Values obtained (lm/W)
Drummond	Pretoria, South Africa	106
Krochmann	Washington, USA	115
Blackwell	Kew	120±5
Blackwell	Kew	115
Bartenava and Poljakova	Repeteke, Karakuma, USSR	103
Dogniaux and Lemoine		110
Evenich and Nikol'skaya	Moscow, USSR	60 - 92 fn of h
Lofberg	Stockolm, Sweden	111±18
Rattunde	Berlin, Germany	116±10
Petersen	Vaerlose, Denmark	121±7
Page		112 - 128 fn of h

TABLE II

Authors	Place of measurements	Values obtained (lm/W)
Drummond	Pretoria, South Africa	132 (average)
Blackckwell	Kew	130
Bartenava and Poljakova	Repeteke, Karakuma, USSR	118
Krochmann	Washington, USA	130 - 133
Kuhn	Plateau Sta. Antartica	122 - 156 increases with h
Evenich and Nikol'skaya	Moscow, USSR	60 - 92 fn of h
Liebelt	Karshruhe, Germany	113.3 ± 8.0
Chandra	Roorkee, India	84
Arumi-Noe	Golden, USA	140
Petersen	Vaerlose, Denmark	146 ± 14

An expression proposed by Aydinli [4], of the luminous efficacy of direct radiation, K_S, as a function of solar altitude h_S, is the following:

$$K_S = 17.72 + 4.4585\, h_S - 8.756\, 10^{-2}\, h_S^2 + 7.3948\, 10^{-4}\, h_S^3 + \\ - 2.67\, 10^{-6}\, h_S^4 - 8.4132\, 10^{-10}\, h_S^5$$

Artificial light sources are usually characterized by much lower values of the luminous efficacy, as shown in the following Table:

Type of lamp	Luminous Efficacy (lm/W)
Incandescent	
General Service	8-14
Tungsten/Halogen	20-30
Tubular fluorescent	40-100
High pressure discharge	
Mercury	50-55
Metal halide	80
Sodium	up to 120

In conclusion, in principle, daylight can play a beneficial role not only as far as saving energy for illumination is concerned, but also in reducing energy consumption for cooling purposes, as the amount of heat introduced in the ambient for a given lighting service is generally smaller in the case of daylighting, because K is greater and SAF is always equal to one. Of course this is not so true in real life, as the assumptions to be made are seldom provided in actual buildings and situations. These assumptions are:

a. illuminances provided by daylight, E_{DL}, are never allowed to be greater than E_{SET}, otherwise the amount of heat introduced might exceed the heat produced by the less efficient, but more controllable, electric light sources;

b. the electric lighting system only provides an integration to daylight when and for the amount strictly necessary; this implies the use of "perfect" controls, which is far from normal in present buildings and design practice.

4. Example of Simplified Thermal and Luminous Analysis Code

A simple microcomputer code (HEATLUX), developed within the framework of the European Concerted Action Programme on Daylighting is presented here as an example of integrated energy analysis tool [5] (See Fig. 1).
The integration of the thermal and luminous aspects is obtained by including the heat corresponding to the artificial lighting requirements among the heat gains in a simplified thermal analysis code.
The simplified thermal analysis code used here (SMEEC [6]) is based on analyses performed by means of the NBSLD code and permits the evaluation of energy needs for heating and/or cooling of any zone in commercial or residential buildings, on a monthly basis, keeping into account the influence of HVAC system's control laws.
Thus, HEATLUX firstly computes the levels of illumination provided by natural light in a room, then estimates the necessary artificial light integration, converts it to heat, and finally performs the thermal analysis including such heat among the heat gains, together with the gains due to other sources, such as solar, occupants, appliances, etc..

The required input data are as follows:

a. room function and occupancy characteristics;

b. geometry of each surface;

c. thermal and optical properties of each surface;

d. HVAC and artificial lighting systems operating characteristics: set points, operating hours, efficiencies, Special Allowance Factors, etc.

e. climatic data: monthly averages of: daily total solar radiation on horizontal surface, H_h; sunshine ratio, I_S; air temperature, t_a.

The code computes, for each hour of the average day of each month, for each of the five sky types proposed by CSTB [7], the ratio:

$$K_d = H_{dh}/H_h$$

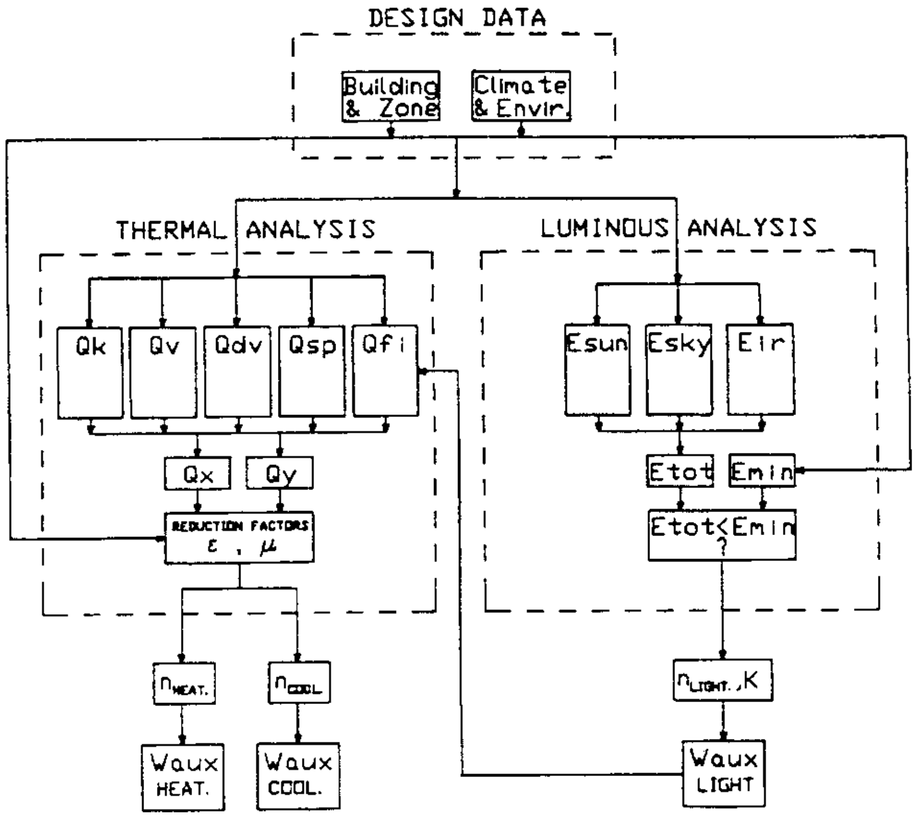


Fig. 1 Block Diagram of HEATLUX

where H_{dh} is the monthly average daily diffuse radiation.
Using the Liu-Jordan procedure [8], $K_T = H_h/H_0$ is computed as a function of K_d, where H_0 is the extraterrestrial daily radiation.
Then, hourly fractions of the direct solar radiation, I_B, are evaluated.

The hourly illuminance of node 'j' of work surface 'i', E_{ij}, is given by [9,10]:

$$E_{ij} = E_{Dij} + E_{Rij}$$

where E_{Dij} is the direct illuminance, and E_{Rij} is the internal reflected illuminance:

$$E_{Dij} = \sum_{k=1}^{N} E_{s\text{-}ijk} + \delta\, C_{ijk}\, \tau\,(\theta_{S\text{-}ijk}) E_{Si} \cos(\theta_{S\text{-}ij})$$

where E_{Si} is the illuminance on surface 'i' given by sunlight, and $E_{s\text{-}ijk}$ is the illuminance on point 'j' of surface 'i' provided by the portion of the sky seen through aperture 'k':

$$E_{Si} = K_S I_{Bi}$$

where K_S is the luminous efficacy of direct radiation, already mentioned, and I_{Bi} is the direct irradiance:

$$I_{Bi} = A \exp(-B/\cos\theta_h) \cos\theta_{S\text{-}ij}$$

- $\delta_{Cijk} = 1$ if sunlight strikes node 'ij' trough aperture 'k'
- $\delta_{Cijk} = 0$ if not
- $\tau(S_{\text{-}ijk})$: transmission coefficient of the transparent material of aperture 'k' in the direction Sun-node 'ij';

$$E_{s\text{-}ijk} = \int_{\phi k1}^{\phi k2} \int_{\phi zk1}^{\phi zk2} L_s(\phi, z)_{s\text{-}ijk} \cos(\theta_{s\text{-}ij}) \sin(z)\, d\theta\, dz$$

where the sky luminance distribution, is computed by the expression developed by CSTB [7]:

$$L_s = f(\Gamma) g(z_P) h(z_S)$$

where:
- z_p : zenithal angle of point P;
- z_0 : solar zenithal angle;
- Γ : angle between P and sun:

According to the split-flux method, the daylight transmitted by the window is split into two parts, a downward-going flux, which falls on the floor and portions of the walls below the imaginary horizontal plane passing through the center of the window ("window mid-plane"), and an upward-going flux, which strikes the ceiling and portions of the walls above the window mid-plane; the zone behaves like an integrating sphere with perfectly diffusing interior surfaces and no internal obstructions; it therefore works best for rooms which are close to cubical in shape. The resulting illuminance, E_{Rij}, due to internal reflections is, thus, uniform:

$$E_{Rij} = E_R = \left(r_F A_F \sum_{k=1}^{N} (E_{s\text{-}k} + E_{S\text{-}k}) + r_C A_F \sum_{K=1}^{N} E_{g\text{-}k}\right) / (A(1 - r))$$

where A_F is the window's area, and:

$$E_{s\text{-}k} = \int_{\phi k1}^{\phi k2} \int_{\phi zk1}^{\phi zk2} L_s(\phi, z)_{s\text{-}k} \cos(\theta_{s\text{-}k}) \sin(z)\, d\phi\, dz$$

$$E_{S\text{-}k} = \tau_{S\text{-}k} E_{S\text{-}k}$$

$$E_{g\text{-}k} = 0.10 L_{sM} 0.5\ \tau(\theta_g)$$

The daily energy consumptions for electric lighting can be expressed as:

$$W_{AUX,L} = \sum_{n=1}^{Nsky} (p_n \sum_{m=1}^{Nwh} (\sum_{l=1}^{Np} f_{nml} A_l))$$

where:

- $f_{nml} = 0$ if $(E_{SET,l} - E_{nml}) < 0$
- $f_{nml} = (E_{SET,l} - E_{nml})\eta_L/K_L$ if $(E_{SET,l} - E_{nml}) > 0$
- $E_{SET,l}$: minimum required level of illumination in nodal point 'l';
- E_{nml} : hourly level of natural illumination in a nodal point for a certain sky type;
- N_{sky} : number of sky types;
- p_n : probability of sky type 'n';
- N_{wh} : maximum number of working hours for lighting systems;
- N_p : number of sub-surfaces (nodal points) on the working surface where level of illumination has been evaluated;
- A_l : area of subsurface;
- η_L : efficiency of electric lighting system, it includes the Special Allowance Factor, as well as other losses (distribution, transformation, etc.);
- K_L : luminous efficacy of lighting system (lm/W);

The code computes thermal energy needs on a daily basis, month by month, taking into account the heat contribution from the artificial lighting system, by including $W_{AUX,L}$ among the heat gains due to internal sources, Q_{FIt}.

The total annual energy consumption for heating, cooling, and lighting, F_{tot}, is finally computed as:

$$F_{tot} = \sum_{t=1}^{12} N_t(W_{AUX,H} + W_{AUX,C} + W_{AUX,L})_t$$

where:

- N_t : number of days in a month;
- $W_{AUX,H}$: average daily energy need for heating;
- $W_{AUX,C}$: average daily energy need for cooling:

$$W_{AUX,H} = Q_{AUX,HEAT} / n_H$$

$$W_{AUX,C} = Q_{AUX,COOL} / n_C$$

where n_H and n_C are the average global efficiencies of the heating system and of the cooling system, respectively.

5.Classification of Materials

Designers need data and information about new and traditional materials useable in daylighting solutions. A detailed photometric analysis would be too complex to manage to that purpose, but the knowledge of some photometric properties is essential to evaluate the performance of daylighting components [11].

In order to characterize a material from the point of view of its interaction with light, it would be necessary to determine the light intensity distribution curve, that is, to know the intensity of the reflected and/or transmitted light in all direction, as a function of the direction of the incident light (see Fig. 2). This would require a complex test procedure and a very large number of data. For most purposes, a simpler characterization is sufficient.

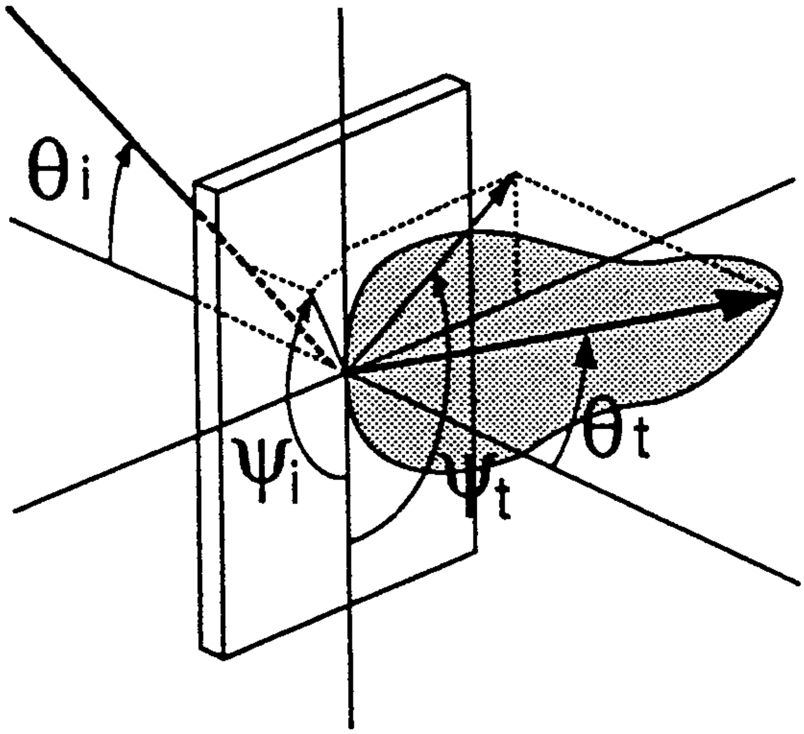


Fig. 2 Characterization of materials

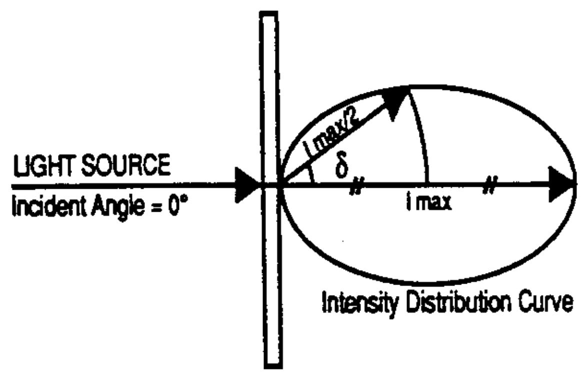


Fig. 3 Definition of "HalfValue Angle"

This is based on the concept of "Half Value Angle", or "Dispersion Angle", Delta, shown in Fig. 3: it is defined as the angle between the direction of maximum intensity (I_{max}) and the direction of intensity equal to $I_{max}/2$, the incident light being perpendicular to the surface. This quantity can be quite easily be defined using a simple test procedure, or even assessed by means of visual observation.

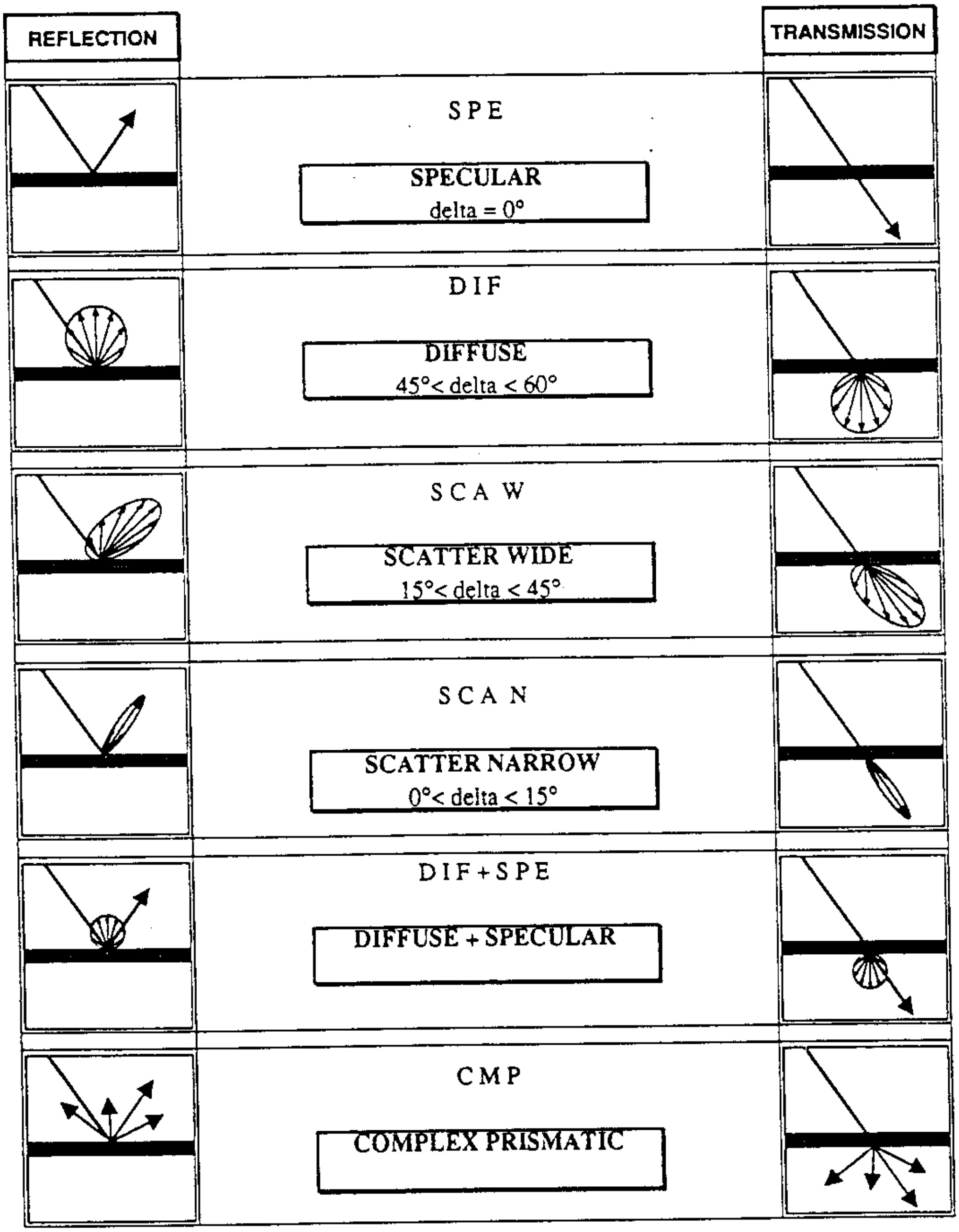


Fig. 4 Classification of materials based on Half Value Angle

A general classification of materials, both reflective and translucent, based on this concept, into six categories is shown in Fig. 4. Examples of reflective materials belonging to the different categories are:

a. Specular: glass mirror, anodised aluminium, polished steel,etc.

b. Diffuse: carpets, velvet, mineral fiber panels, porous concrete.

c. Wide spread: most building materials; in particular: mate paints and surfaces, concrete, polyester fabric, etc.

d. Narrow spread: satiny paint, glossy surfaces.

e. Specular + diffuse: lacquered and varnished surfaces.

f. Complex: corrugated and irregular reflective surfaces, prismatic surfaces, etc.

6. New Materials

Many new materials for daylighting purposes have been developed recently. Most materials deal with the problem of taking advantage of direct sunlight, without the disadvantages associated with it (glare), that have prevented its use in traditional daylight solution.

Here is a short review of some of them.

Prismatic Devices

A way of controlling sunlight penetration is to generate Fresnel type lenses with glass or acrylic material, thus increasing the sensitivity of the transmission factor to the incidence angle, and especially to the sun altitude angle. Fig. 5, 6 and 7 show different applications of such a concept: Prismatic Panels, to redirect incident sunlight towards the ceiling, which would be highly reflective, and Light Guides, to transmit sunlight deep into core spaces.

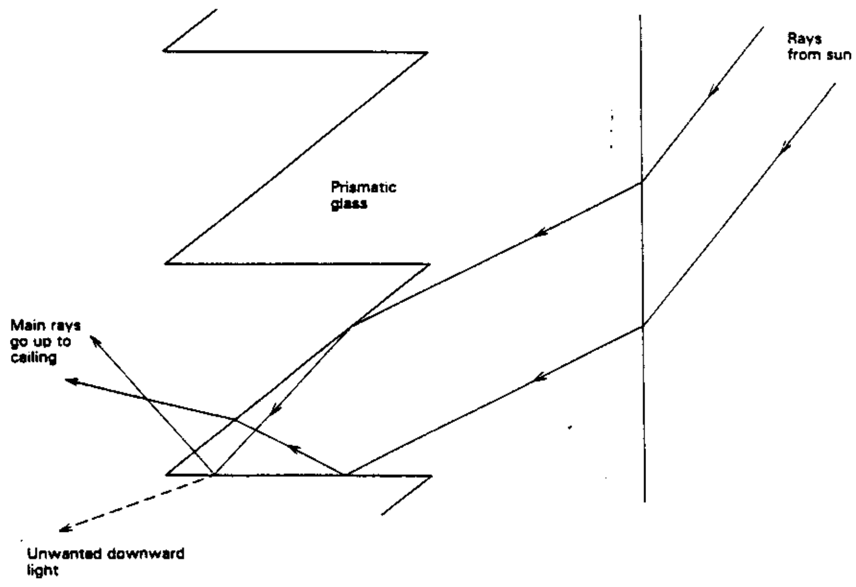


Fig. 5 Schematic of Prismatic Device

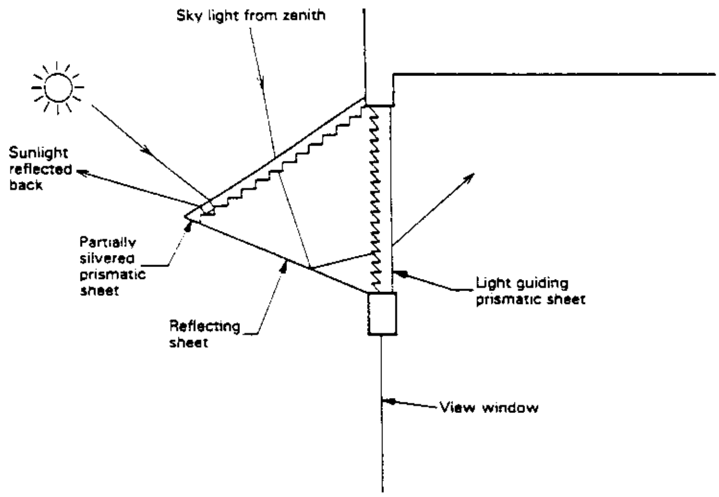


Fig. 6 Prismatic Panel coupled with reflecting sheet

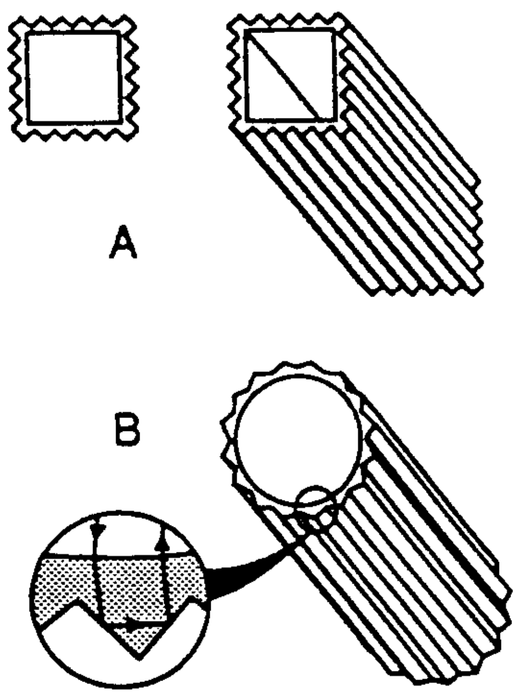


Fig. 7 Light Guides based on prismatic material

Holographic Films

It is possible to use holographic films on glass to tack passively the sun as it moves across the sky, redirecting light to a fixed position [12], for instance the ceiling. Holograms are made creating a given interference pattern on an emulsion (usually silver-halide) on a glass substrate, by means of a computer-controlled laser, based on building's latitude, orientation and tilt angle of glazings.

Main problems are costs, still very high, limited dimensions, and rainbow-effect, as they are wavelength-sensitive.

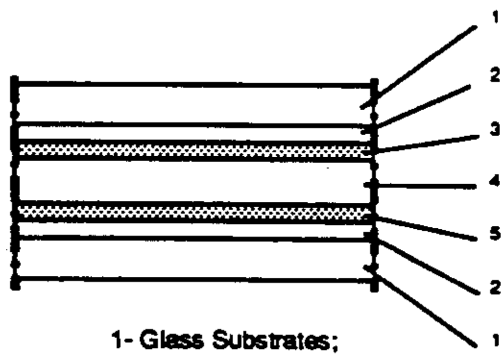
Electrochromic Devices

The principle is of changing the optical properties of a transparent element by means of an externally applied electric field. Typical transmission change would be between .15 and .70 in the visible spectrum. Fig. 8 shows a schematic section of such a system, composed by a number of successive layers.

Costs are quite high, but the idea seems very promising, as the control of such components could be made by the automatic general control system.

Thermochromic Devices

These are materials that remain transparent until they reach a preset temperature, which can be fixed over a wide range. Above this temperature, the material turns into a highly reflective white. The composition is usually either tungstene trioxide, or vanadium dioxide. The transmission factor can vary in a range 1 to 3. An example is the product called "Cloud Gel".



1- Glass Substrates;
2- ITO transparent electrical contacts
3- Cathodically coloring a-WO3,
4- Transparent proton (H+) conductor (e.g. polyAMP s)
5- Anodically coloring IrO2
(The layer thickness are not drawn to scale)

Fig. 8 Section of Electrochromic Panel

Photocromic Devices

They work like sunglasses, darkening in bright light, and going back to transparent in low light. They may be used to reduce eccessive glare and heat gain in windows exposed to direct sunshine.

Fiber Optics

Like Light Pipes, fiber optics can transmit light to great distances, thanks to very limited transmission losses, with the advantage of their easy installation an absence of mirrors at bends. Due to their cost, small sections can be used, provided a suitable concentration of sunlight is realized. For instance, a component has be developed in Japan, consisting of a protective acrylic capsule, which tracks the sun, containing hexagonal Fresnel lenses, which capture and focus sun rays onto highly polished ends of a fiber-optic cable.

Fluorescent Concentrators

Like fiber optics, these devices are based on the total reflection that can be achieved when light comes from a medium with higher index of refraction than the medium toward which is directed, provided the angle of incidence is greater than a critical value, dependent on the ratio of the indexes. This effect can be use to concentrate and transmit diffuse light through a thin layer of material (see Fig. 9).

Problems: low efficiency and color associated with the dies used.

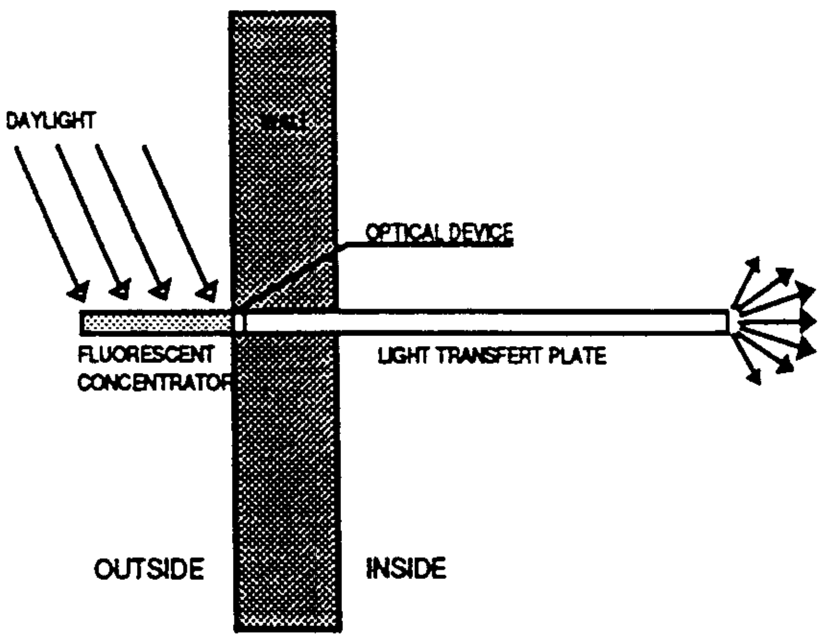


Fig. 9 Fluorescent Concentrating Panel

7. Conclusions

The daylight designer has to take into account all consequences created by the adoption of design solutions.

In particular, the impact on energy consumption for the different requirements of a building must be assessed in an integrated way, looking at the advantages and disadvantages in terms of comfort and energy performance, Heating, cooling and lighting energy needs must be evaluated concurrently.

To this end, the understanding of the behaviour of materials is essential to meet luminous, as well as thermal, specifications of an architectural project. This is particularly true for new materials, some already available on the market, others still at the research and development stage.

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