3.1.0 Introduction

Energy Efficient Windows

1. Choice of glazing types

Usually, glazing is the less efficient component of the building shell from an insulation point of view even with the most high-tech components such as low emissivity glasses and triple glazing. The high U value and low inertia of the components gave it a bad thermal effect except when solar gains permit a positive balance between losses and gains.

• the choice of glazing type will be function of several parameters :
  - the climate which determine irradiation and temperature.
    In northern septentrional climates efficiency have to be the best as possible. Low emissivity, large air void.
    In southern, mediterranean climates where temperature and irradiation are high, glazing type is function of comfort conditions more than thermal efficiency. Double glazing would be the general rule, but in south coastal regions single glazing can be acceptable.

• the second main aspect to be considered is building and facades orientation. Even in Southern countries, the most efficient glazing type shoud be installed on the north, east and west facades. For south orientation, a single glazing or a double clear glazing can be installed in place of low emissivity for the others orientations to maximize solar gains.

• the optimal choice would be an technico-economic solution. The challenge would be : « Not to much glazing but well glazed ». a glazing surface is about three times the cost of an insulated wall. Apertures in it have to be designed as a function of :
  - orientation (more or less).
  - view from inside to the land
  - position of people in the room and activity.
Objectives: Comfort and energy saving

- The two first functions of glazing are to permit day lighting and in corollary to communicate with external spaces. Then glass properties (to trap the irradiation) can be used to save energy and to give a new function to the windows: solar collector. In fact to assure daylighting in all spaces (if it is occupied daily) is anyway a good design process because of electricity saving and comfort conditions. An efficient glazing allow thermal losses reduction: low emissivity products.
- The choice of glazing can also have an influence on overheating:
  - more insulation limits also the internal temperature when external temperature is high.
  - the solar factor of the glazing (i.e. 75 %) indicates the quantity of irradiation which penetrate through the window.
- Reflecting glazing is a solution to limit or prevent dazzling effects.

The choice of glazing types are also determined by architectural considerations (low emissivity for example have a light blue tint) and in function of mask effects and reflection effects.

2. Efficient glazing

For a recent period, glazing efficiency largely increase their performances, by new concepts, the addition of materials between two glasses and on the glass itself. Research has been made in the idea to decrease U Value to limit thermal losses, but also to limit overheating, using the glass as solar protection by reflective, or photo-chemical and electrical adaptation of the properties.

At the opposite, we try to manufacture super transparent glazing to increase the solar factor to benefit both of passive solar gains, and a high daylighting.
- double low emissivity glazing: U = 1,5 to 2,3 W/m2K
- solar transmission factor (double glazing): 70 to 90 %.

- The electrochromic glazing:
  This is the only glazing with "memory effect" with a multilayer electro-chemical sensor. Its effect is modulable and proportional to the electric charge. It changes from a coloured state to a transparent state.
  The main interest of electrochromic glazing is to optimize directly in function of meteorological conditions the use of solar gains and daylighting.
  Solar transmission: 25 to 75 %

- Other physico-chemical properties have to be exploited for new glazing components:
  - photochromism: the optical properties move when the glass is exposed to irradiation.
  - thermo-chromism: the properties change when the temperature increase and glass find it initial state again when temperature decrease.
  These products are not available in the standard building market.
- Parieto-dynamic windows and breathing glazing are very efficient because they are used both as solar collector and air preheating system.
  Fresh air taken in through the triple glazing frame is introduced at a comfort temperature, almost the temperature of the room. This component is associated with a mechanical extract-air ventilation system.
  These breathing glazings have also several qualities:
  - acoustic property of the wall is increased (no direct vent)
  - it is possible to build large windows without condensation.
  These qualities are due to the large air strip.
- Amongst the future high efficient components, the best is (for thermal consideration)
Aerogels.

This material, high insulating and transparent as glass allows a very high U value almost identical as an insulated wall. \( U = 0.5 \, \text{W/m}^2\text{K} \).

3. Clever windows

A « clever window » is a component which integrate other functions than those in standard windows. A sum, not restrictive, of principles and functions are available through the frame, glass and window scope.

• The movable components such as solar protections, shutters, and transparency of the glass are commanded by computer controlled by climatic sensors.
• The clever window component integrate external and/or internal shading devices such as venetian blind, screen, roller....).
• As the windows have also a ventilation role, ventilation flow modified by internal hygrometry and occupation of the rooms, presence of smoke, etc... The ventilation through the window components is associated with a mechanical extract air system.

Solar gain controls:

The window integrated « clever » system permits a solar gains control to optimize the heating/cooling, lighting effects.
- in winter passive solar heating is having priority,
- in Summer solar shading is move to assure sufficient daylighting and limit temperature to solar irradiation.

We also can introduce new glazing features such as electrochronic and heating leaves systems usable with high efficient components.

As an industrial complex component, the « clever » window’s frames integrates a set of leads to command from computer and sensors the different functions and control operations.

3.1.1 General remarks

3.1.1.1 Introduction

Windows and in general glazings play a significant part in our houses. These multi-purpose elements of architecture have several important functions in the building envelope. Most prominent is the effect on visual and thermal comfort in the building, but also sound reduction, weather protection, security, aesthetical appearance and similar issues are to be considered in the selection of a window. In the following chapter we emphasize the properties of a window that influence the energy flows between the interior of a building and the environment. With respect to energy flows the function of a window is, in general terms, to transmit a controlled amount of luminous radiation (for vision) and solar radiation (for space heating) at a specific - usually minimized - heat transfer. The heat transfer comprises contributions from thermal radiation, conduction in solids and gases, and gas convection.
Radiation is relevant in three different wavelength regions, the visual region from 0.4-0.7 µm, the solar region from 0.3-3.0 µm, and the thermal region with wavelengths larger than 2 µm. Luminous, solar and thermal radiation are confined to these specific wavelength intervals, as can be seen in Fig. 1. The right hand part depicts Planck spectra for two temperatures of practical significance for windows. Both spectra are confined to the thermal range. The peak in the spectrum for 50°C lies at a shorter wavelength than the one for 0°C, which is a manifestation of Wien’s displacement law. At room temperature the peak occurs at about 10µm. Thermal radiation from a material is obtained by multiplying the Planck spectrum by the emittance, which is generally wavelength dependent and is less than unity. The solid curve in the left-hand part shows a typical solar spectrum for radiation that has passed already the earth's atmosphere. The curve has again a bell shape corresponding to the sun's surface temperature of about 6000°C. The minima in the spectrum are caused by atmospheric absorption, mainly by water vapour, carbon dioxide and ozone. In addition scattering by aerosols - or in the case of bad weather by clouds - is responsible for the specific structure of the irradiance spectrum.

The dashed curve shows the relative spectral sensitivity of the human eye in its light-adapted (photopic) state with the maximum at 0.555 µm. In the darkness-adapted (scotopic) state, the latter one is displaced about 0.05µm towards shorter wavelengths.

A key concept to improving window energy efficiency is therefore spectral selectivity, implying that the radiative properties should be qualitatively different for different wavelength ranges, so that, for example, it is possible to combine high transmittance of luminous radiation with reflection of thermal radiation.

But what is energy efficiency? An energy efficient window should provide good lighting during the day and good thermal comfort both during day and night at minimum demand of paid energy. This implies that overheating as well as excessive cooling should be minimized, that draught and cold surfaces should be avoided. It should be emphasized that good thermal insulation improves energy efficiency directly by lowering the U-value. Additionally, it lowers indirectly the heating requirements by raising the inner surface temperature close to room air temperature. This means reduced draughts and increased thermal comfort. The set-point temperature of a heating system may be lowered by 1-2 degree according to the area of glazing without reducing comfort. In general, however, energy efficiency may be suitably discussed only with respect to the climate considered. Cold, moderate and warm climates pose different requirements on the windows.
In a warm climate frequently the solar radiation transferred through the window and absorbed by the room causes overheating. Space conditioning then needs air cooling equipment. Clearly it is effective to have "solar control" windows which keep the infrared part of the solar spectrum (0.7<\(\lambda\)<3\(\mu\)m) out of the room without lowering the luminous transmittance too much. In principle it is possible considering the spectral distribution of solar radiation to exclude about 50% of the energy without any decrease in luminous transmittance. In many situations a larger reduction is possible as a decrease of luminous transmittance may even be desirable.

In a cold climate a window usually causes an undesired loss of thermal energy, and hence a need for space heating. The heat transfer through windows may be effectively reduced by the use of multiply-glazed windows incorporating one or more layers of essentially non-convecting gas of low conductivity. Noble gases are a good choice for such layers. Further reduction in heat transfer may be achieved by lowering the thermal radiative exchange. This is usually due to a transparent low-emissive coating of the glass surfaces. With these techniques the thermal losses of a glazing may be reduced by a factor of eight when starting from a double-glazed unit, going to a triple-glazed low-e coated unit with noble gas filling.

In a temperate climate the situation changes temporarily. Sometimes overheating must be prevented, at other times one wants to gain as much solar radiation as possible to reduce space heating demands (passive solar). A dynamic throughput of energy may be accomplished using conventional mechanical regulation - shutters for night time insulation, shades, blinds and roller curtains for shading are known. A more elegant solution is to invoke chromogenic materials\(^1\), often additional layers on a glass substrate which may change their optical properties according to the varying demands over a day or season.

### 3.1.1.2 Quantitative characterisation of windows

A quantitative description of a window has to comprise physical quantities for the radiation gains in the different wavelength regions and for the thermal heat flow through the window. The heat flow due to a temperature gradient across the window has several components. Thermal radiation, conduction through gas and solid parts, and convection in closed gas-filled spaces as well as at the interior and exterior surface. Usually the exterior convection is enhanced by wind.

The heat transport in a double pane glazing is shown schematically in Fig. 2. The net radiative heat transfer between the two glass panes is influenced by the emissivities of the two surfaces adjacent to the gas. The lower the emissivities the smaller this part of the heat transfer. The second part of the heat transfer is by convection and conduction of the gas filling. This is dependent on gas properties like conductivity and viscosity, on the distance between the panes and on the temperature difference. A third part, conductive heat transport occurs at the glazing edges, where spacer materials represent thermal bridges.

Generally the U-value is mainly influenced by the quality of the glazing, but also by the type of frame or sash used. The heat flow and surface temperature distributions are not uniform over the window area. With the improvement on the glazing units through the use of low-emissive transparent coatings and the filling with argon and other gases the traditional frame, sash and sealing products represent considerable thermal bridges and have to be improved as well.

Quantitatively the total heat flow across a window is characterized by the total coefficient of heat transfer or U-value $U_w$. It is defined by the following equation:

$$Q_T = A \cdot U_w \cdot (T_{ai} - T_e)$$

- $Q_T$ heat flow through window [W]
- $A$ window area [m²]
- $T_{ai}$ inside air temperature [°C]
- $T_e$ outside air temperature [°C]

The better the U-value of a window, the higher the temperature on the inside surface of the window (s. Fig. 3). This is often a better argument for the inhabitants or builders, as this is intimately connected to the thermal comfort! Windows with lower surface temperatures result in a lower radiation temperature, radiation asymmetries and possibly draught.
Fig.3: Inside surface temperature distribution with varying glazing quality for ambient temperature -10°C

In practice different U-values are used for windows. Usually brochures and catalogues give either the glazing U-value $U_{cg}$ (glazing industry) or the window U-value $U_w$ (window industry). It is well-known that $U_w$ increases with decreasing window area for well insulating windows due to the frames. Thus for advanced windows with improved glazings the frames become more and more the weak part of the thermal envelope!

The solar and light gain through a window is mainly determined by the optical properties of the glazing. The light transmittance $\tau_v$ (or $\tau^L$) gives the percentage of transmitted radiation in the wavelength region 0.38-0.78 $\mu$m, taking into account the eye’s (photopic) daylight sensitivity. The solar transmittance $\tau_e$ (or $\tau^S$) gives the percentage of all transmitted solar radiation from 0.28 to 2.5 $\mu$m. This, however is not a complete description of the energetic flows. The part of the solar radiation not reflected to the outside or not transmitted into a room is absorbed by glazing components, i.e. this energy is converted to heat. Depending on the position of the component a certain percentage of this heat flows into the room, the other part to the ambient. These heat flows are considered as a superposition on the thermal loss heat flow $Q_T$ and are in good approximation proportional to the solar irradiation. The dimensionless proportionality factor $q_i$ ($q_e$) is called secondary internal (external) heat transfer factor. Therefore a total solar energy transmittance $g$ (g-value) is defined by

$$g = \tau_e + q_i$$

The total energy gained through a window is a product of the glazing area, the g-value and the solar irradiance. Usually the optical properties listed in product sheets are given only for the transparent part of a window, i.e. the glazing. However, similar to the U-value, an exact treatment should consider also frame, edge and centre-of-glass areas.
3.1.2 Multiple Glazings

3.1.2.1 Glass types

3.1.2.1.1 Standard Window Glass

The purpose of this section is to present a few selected optical data on standard window glass in order to give a baseline for subsequent discussions of means to improve the energy efficiency.

Normal windows are made by the float process in which the glass is solidified on a bath of molten tin. The uniformity and flatness of this glass are excellent. Fig. 4 illustrates spectral transmittance in the solar range for three types of float glass. It is seen that \( \tau_{\text{L}} \) is large. The transmittance in the infrared as well as in the ultraviolet are significant and dependent on the glass type. In the thermal infrared - not shown in Fig. 4 - glass is virtually opaque. The major difference among the glass types in Fig. 4 is their iron oxide content. With regard to energy efficiency, its most salient influence is to produce a broad absorption band centred at \( \lambda \sim 1 \mu m \), extending somewhat into the visible and giving a greenish tint. If a maximum solar gain is desired, a low oxide content is preferrable. Solar passive gains are increased by the use of white glass!

![Graph of spectral transmittance with different iron-oxide content](image)

Fig. 4: Spectral transmittance of float glass with different iron-oxide content

We now consider the reflectance of the glass. In the spectral range where the absorption is weak, and at normal incidence, each air/glass interface has a reflectance governed by \( (n-1)^2/(n+1)^2 \), with \( n \) being the refractive index of the glass. In practice \( n = 1.5 \), so that each interface produces \( \sim 4\% \) reflectance. It is inferred that \( \tau_{\text{L}} < 92 \% \) is valid for a single pane. The overall transmittance is further diminished by multiple glazing. In the thermal infrared, the transmittance is low, which leads to a high emittance - in practice \( \varepsilon_{\text{th}} \approx 84\% \).

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Laminated windows may be used for safety and other reasons. This glass comprises an interlayer of tough and resilient polyvinyl butyral (PVB) sandwiched between two glass panes and bonded under heat and pressure. The most salient optical effect of the PVB lies in the ultraviolet, which can be almost completely rejected.

3.1.2.1.2. Diffusing glass

Although in about 90% of all cases a clear view through a window element is desired\(^3\), glasses and windows with diffusing character have a growing market. Traditionally confined to areas where privacy or secrecy was important, diffusing glass with geometrical patterns is becoming a part of architectural design, and diffusing glazings in non-view parts of a radiation transmitting building envelope (sky-lights, top or bottom light bands in rooms up to complete diffusing walls) may be used energy-efficient. The latter applications usually combine the effects of good daylight distribution in a room or building (no direct glare, no hard shades) with the now possible improved thermal transmittance of modern glazings. The architectural glass usually exhibites regular patterns such as dot or square matrices, strips and lines from white or metallic diffusing surface coatings. These patterns can be applied to a float glass in a printing process and in principle would allow also more complex patterns. Of course these glazings are much harder to characterize, especially when the user wants to know the very special light distribution in a room utilizing such glazings! The traditional numbers given in leaflets and defined by standards are usually not satisfactory, and in fact may be wrong. For example the procedure to evaluate a g-value of a glazing with diffusing patterns is not yet developed neither in national nor international standards, although research work is heading towards this aim.

3.1.2.2 Coated glass

3.1.2.2.1. Coating Technology

Surface coatings with thicknesses in the range 0.01 to 1μm can improve the radiative surface properties of glass. Two techniques are in widespread use for preparing such coatings on the scale of square metres, viz. sputter deposition and spray pyrolysis. A detailed description of the technologies is not attempted there, but their operating principles and pros and cons will be outlined.

Sputter deposition

\[\text{vacuum chamber} \quad \text{sputter cathodes}\]

\[\text{sputter plasma} \quad \text{unheated glass}\]

Fig. 5: Principle of sputter deposition

Fig. 5 shows the principle of sputter deposition. The surface coating is prepared inside a vacuum chamber which contains an inert gas (usually argon) to a pressure on the order of one Pascal. The chamber holds one or more sputter cathodes whose lower parts comprise plates - known as targets - of the raw material for the coating. The glass passes in and out of the chamber by means of a load-lock system, and is transported a few cm below the targets. The deposition process involves a magnetically confined self-sustained plasma set up in such a way that energetic ions (usually Ar+) bombard the target surface and dislodge atoms via complex momentum transfer processes. The atoms travel at high speed and stick to the glass, whose surface becomes uniformly coated. Use of direct current to power the plasma is customary and energy-efficient; it requires targets with some electrical conductivity. Radio frequency powering is an alternative for non-conducting targets. Dielectric thin films, for example of oxides, can be prepared by reactive sputtering in the presence of oxygen. A multilayer coating is conveniently produced by letting the glass pass under severl cathodes which, if cross-contamination is feared, can be placed in separate chambers.

**Spray pyrolysis**

![Spray nozzle](image)

Fig. 6: Principle of spray pyrolysis

Fig. 6 illustrates spray pyrolysis as a technique for making surface coatings. A solution, typically containing a metal chloride or acetylacetone, is transported and dispersed through a system of nozzles by means of a carrier gas (air, nitrogen, argon, etc.) and, if required, a reactive gas. An aerosol is thus formed pneumatically and is sprayed towards the surface of a hot glass. The aerosol becomes vapourized before reaching the glass, and hence spray pyrolysis is a form of chemical vapour deposition. A typical reaction, of large significance for window coatings, is the hydrolysis of tin chloride to form tin oxide, shown schematically as SnCl₄ + 2H₂O→SnO₂ + 4HCl.

Sputter deposition as well as spray pyrolysis can be carried out by fully automatic equipment up to widths of several metres. Sputtering is notable for its versatility, possibilities to accomplish process control, multilayer facility, and low substrate heating for so-called "soft coatings" (which makes it possible to coat plastic web and other temperature sensitive materials); on the negative side we note that high investment costs may be needed for equipment. Spray pyrolysis lends itself almost ideally to the production of extremely durable metal oxide based coatings ("hard coatings") by deposition onto the surface of a hot glass as it comes out from the tin bath of a float line. Multilayer deposition is possible. For more details on surface coating technology, the subject is covered to some depth in\(^4\),\(^5\),\(^6\). Practically, durability and solar gain characteristics are the main differences between the two coating types. Up to now, no solar control films have been produced as hard coatings. On the other hand, the maximum solar gain with glazings utilizing soft coatings is restricted.

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\(^6\) H.K. Pulker, Coatings on Glass, Elsevier, Amsterdam, 1984
3.1.2.2. Noble metal coatings (soft coatings)

Very thin noble-metal coatings produced by sputtering are, at least in principle, the simplest solution for reaching a significant short wavelength transmittance combined with long-wavelength reflectance. The best optical properties are obtainable with copper, silver, and gold\(^7\). Alternative materials may be TiN\(^8\) and aluminium. Thin silver coatings stand out as the superior material on account of their low absorption of luminous and solar radiation\(^9\) and are mainly used for commercial coatings.

It is necessary to improve the transmittance by additional antireflection layers. Dielectrics with high refractive indices - such as Bi\(_2\)O\(_3\), In\(_2\)O\(_3\), SnO\(_2\), TiO\(_2\), ZnO and ZnS - give the largest enhancement of the transmittance. By selecting the thicknesses of the three-layer configuration properly, one can optimize for a warm climate (minimum solar gain with high visible transmission) or a cold climate (maximum solar gain combined with low emissivity). Fig. 7 shows the spectral optical properties of two silver-based coated glasses, one optimized for high solar gain, the other one for reasonable solar rejection with similar visible transmission.

![Fig. 7: Spectral transmittance and reflectance of glass with silver-based coatings](image)

Solar control coating: High visible transmittance with maximal solar reflectance
Solar gain coating: Increased solar gain in the solar infrared (above 0.7 \(\mu\)m)

\(^7\) E. Valkonen, B. Karlsson and C.-G. Ribbing, 'Solar Optical Properties of Thin Films of Cu, Ag, Au, Cr, Fe, Co, Ni and Al', Solar Energy \(32\), p.211, 1984


Doped oxide semiconductor coatings by spray pyrolysis offer an alternative to the earlier discussed noble-metal based coatings. The materials which are known to be useful are oxides based on zinc, cadmium, indium, tin, thallium, lead and alloys of these. The required doping is often achieved by the addition of a foreign element; particularly good properties have been obtained with SnO$_2$:F, SnO$_2$:Sb, In$_2$O$_3$:Sn and ZnO:Al. The industrial products are based on tin oxide, where the coating is directly done in the float process. A specific and important advantage of the doped oxide semiconductors is their excellent chemical and mechanical durability, which allows their use on glass surfaces exposed to the air.

The required coating thickness $t$ is usually around $t \sim 1$ µm, much thicker than the multilayer soft coatings! This is done to avoid iridescence with unpleasant coloured fringes. The human eye then senses a uniform colouration. However, the use of a much larger thickness than the one demanded for a low $\varepsilon_{\text{th}}$ is clearly inefficient in terms of materials utilization, coating time, and cost. Further, thick oxide semiconductor coatings can display some light scattering, sometimes referred to as haze. This phenomenon is associated with the occurrence of large crystallites as well as surface roughness.$^{10}$

![Graph showing transmittance and reflectance for a thick pyrolithic tin oxide coating](image)

**Fig. 8:** Transmittance and reflectance for a thick pyrolithic tin oxide coating

### 3.1.2.3 Plastic films

In order to suppress convection and radiation heat transport within the gas layer, additional highly transparent plastic films (often with a low-e coating) are sometimes used to compact the gap even further. Apart from constructive problems - the plastic films have to be tightly fixed in order to avoid undulations or wrinkles - this is an optimization problem: The solar and light transmittance decrease too for every additional film. HIT-windows from Switzerland and HEAT MIRROR® products from the US are the most prominent representatives utilizing this approach with coated plastic films.

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3.1.2.4 Gas filling

While the usual filling gas for uncoated glazings is air, for glazings with a low-e coated surface gases with lower thermal conductivity are being used. Here the effect on the already rather low U-value is especially pronounced. The noble gases Argon and Krypton are used today in most low-e glazing units. Krypton has the advantage of allowing the use of very thin gas layers, as the conductivity is extremely low. Due to the temperature drop across the glazing, the gas will in most cases rise at the warm surfaces while warming up, and fall at the colder surface. This convective motion has been investigated in experimental and theoretical studies, showing that the thickness of the gas layer does influence this motion.

![Graph showing convection heat transfer across a gap for different gas fillings](image)

Fig. 9: Convection heat transfer across a gap for different gas fillings

Fig. 9 shows the calculated thermal heat transfer coefficient for a vertical glazing filled with air, argon or krypton depending on the layer thickness. Because of the onset of convection it is not sensible to increase the thickness of the gas layer beyond 14-18mm. The convective conductance usually increases beyond that local minimum, reaching a better value only at distances above 40-50mm. Thus the air layer in double windows is actually superior to that of a typically insulating double glazed unit. Nowadays also non-purified Xenon is also used for glazings. It is even superior to Krypton, but also more expensive. But still the costs for the filling of a typical glazing unit are below 2-3% of the consumer price!

3.1.2.5 Edge seal

An important part of a glazing unit is the edge seal, which keeps the gas filling between the panes, and which protects coatings from environmental stresses. A sketch of a typical sealed glazing unit edge seal is shown in Fig. 10. Its construction consists of two glass sheets, a spacer and sealant(s). The primary sealant is not always present, in which case the spacer makes direct contact with the glass (single seal, Fig. 10b). The remaining sealant is a secondary sealant. If both sealants are present, the construction is called double seal (Fig. 10a). The functions of a seal is manifold, they may be attributed to the two different sealants in a double seal. Chemical attachment to the glass surface is a prerequisite of a stable and elastic connection. At least one of the sealants should provide a gas tight seal and a barrier against water vapour diffusion.
Fig. 10: Edge seal technology
a) Double seal
b) Single seal

The thermal resistance of glazing system edge seals plays an important role in glazing system heat transfer. Highly conductive edge seals cause excessive edge-glass energy loss. In addition to this, the thermal short-circuit caused by conductive edge seals is also known to aggravate condensation problems in cold climates because it lowers the interior surface temperature near the perimeter of the glazing.

Due to the thermal bridging at the edge seal, the edge seal may have a noticeable impact on the overall thermal performance for window designs, especially for well insulating windows. Aluminium and steel spacers are available from a large number of manufacturers. Alternative spacers try to improve the thermal resistance by using non-metallic materials. It is important that they provide the same tightness as the conventional edge-seals. A practical problem for their market penetration is the different machinery for this edge-seal technology which would be needed.

3.1.2.6 Complete glazing units

Glazing units with coated glass exist in many variations. The glass layer thicknesses vary due to mechanical and sound insulation properties, hardened glass or two-layer glued safety glass has to be used e.g. in overhead applications. Special products for fire hazard and safety glass is being sold. From the energy conscient builder, however, these glazings have not too much impact on the energy flows from and to the environment. Although thick safety glasses with high iron content absorb a lot of solar radiation, this is not too important an issue.

It is on the other hand decisive to distinguish between the two main categories of coated glass units, the transparent heat mirror and the solar control glazings. Depending on the building design, the choice of these glazings is important for with regard to user comfort and energy costs produced by heating and cooling equipment.

3.1.2.6.1. Transparent heat mirror glazings

Transparent heat mirror glazings are optimized for high solar gains. This includes high visible transmittance, of course, but also very low U-values. They are preferably used in buildings and climates which are dominated by the heating demand. There exist many products utilizing soft or hard coatings. It is important to know, that the coating has to be on the inner pane of the glazing - for a double glazed unit the coating is on surface 3, by convention the counting starts at the outmost surface. Therefore a substantial part of the solar radiation absorbed by the coating itself may still be utilized as solar gain in the room.

3.1.2.6.2. Solar control glazings

The counter design for minimized solar gain is a solar control glazing. These exist with either coloured glass with strong absorption or reflection properties, or with colour neutrally coated glass.
The latter ones are soft coatings with a narrow visible transmittance band. It is essential to have the coloured glass or the coated glass as the outer glass pane. Absorbed solar radiation converted to heat will be mainly cooled away by the ambient, preferably in situations exposed to wind. Only marginal fractions lead to a warming of the inner glass surface and of the room.

3.1.2.6.3. HIT-windows

As glazing utilizing plastic films can be somewhat different in construction, a particular product is presented here. The HIT-windows (HIT=high insulation technology) of the Geilinger company, Zürich, use coated plastic films with low emissivity to compart a large space between inner and outer glass pane. The films have to be fixed in the frame under tension to avoid wrinkles. Because of the large air volume pressure compensating openings are built into the frame. Therefore exchangeable drying agent containers are needed to protect the film coating against humidity. With this type of window (Fig. 11) $U_{CG}$-values around 0.5 W/(m$^2$K) are possible, however the $g$-value is low. The light transmission is high, therefore these windows are suited to office buildings, where internal heat sources are abundant and solar gains have to be avoided.

![HIT-window diagram]

3.1.2.5.4. Overview

The market of advanced glazings expands steadily due to raised comfort requirements and to increased pressure from the legislative bodies. The latter certainly has its origin not only in the efforts to save fuel imports but also in the international commitments to reduce the CO$_2$ production. Therefore a vast number of products with slightly different properties are available. The following table tries to give a rough indication of typical performance.

Table: Typical key parameters for different glazings

(center values)
3.1.3 Transparent insulation materials

3.1.3.1 Optical and thermal characterisation

Even lower U-values may be achieved when using so-called transparent insulation materials as a filling material. In most cases these materials allow no clear view because they are geometric structures (slats, honeycombs, tubes) made from plastic or glass and distort any image, or because they exhibit light scattering up to very high levels. For the latter class of materials the so-called aerogel is the most promising candidate.

3.1.3.1.1. Heat transport

The heat transport in transparent insulation materials is usually dominated by the radiative heat transport. The reason is the semi-transparency of most materials to radiation in the thermal wavelength range. This is rather pronounced in cellular structures like honeycombs and capillaries, but even in aerogel which is optically thick at most thermal wavelengths, a radiative window exists where the extinction is relatively small. The dominance of the radiative mode results in a heat conductance varying approximately with $T^3$, where $T$ is the absolute temperature. Another consequence of this semi-transparent quality is that the equivalent heat conductivity including all heat transport modes (i.e. heat conductance multiplied by sample thickness) is not constant with thickness. These properties are illustrated in Figure 12a and 12b, where the equivalent heat conductivity is plotted over sample temperature and thickness, both for a typical transparent insulation material (TIM) and for a typical insulation material like Styrofoam.
Fig. 12: Illustration of directional-directional, directional-hemispherical and hem.-hemispherical transmittance

Clear glazings are being compared by the normal transmittance. In comparison with them TIM have rather dissimilar optical properties. For example granular aerogel is a scattering layer with small angular variation of the transmittance function. On the other hand, for a good honeycomb material the transmittance for normal incidence is close to 100 percent, as the parallel light passes the cells independent of the length. Thus this number is rather meaningless and tells little about the honeycomb quality! It seems difficult to produce a single figure of merit.

However, a reasonable quantity for material comparisons is the transmittance for diffuse irradiation $\tau_{hh}$, as has been proved by many practical studies. To a good approximation this value is equivalent to a yearly average transmittance - nearly independent of orientation and tilt of the material plane! Figure 13 shows the monthly averages of two samples oriented South, where the hem.-hemispherical transmittance $\tau_{hh}$ is indicated.

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3.1.3.2 Capillaries, tubes and honeycombs

3.1.3.2.1. Small-celled plastic honeycomb and capillary structures

The small-celled structures described here have been designed not only to suppress convection but also to reduce the radiative heat exchange appreciably. This is achieved by absorption and reemission of heat - the IR-photons "diffuse" through the structure. Therefore the material content of these products is high, around 30-40 kg/m$^3$. Rectangular celled extruded polycarbonate honeycombs and capillary materials (with tubular cells) from various plastics have been developed, but only some of them are on the market.

The commercial products use PMMA and PC, which exhibit also UV-stability behind a cover glass. PES is rather instable with respect to UV, other materials have bad optical quality (HFL, TPX). The only candidate for higher temperature, e.g. for use in a solar fluid collector for process heat, is the APEC capillary. A polyacrylate variation called KAMAX® had been produced successfully with similar temperature stability and good optical properties and was used in some TIM-projects. However, the plastic granulate is not available any more.
Table 2: Characteristic data of capillary (cap) and square-celled honeycomb layers

<table>
<thead>
<tr>
<th>type</th>
<th>plastic</th>
<th>density [kgm⁻³]</th>
<th>cell width [mm]</th>
<th>max. temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>cap/PMMA</td>
<td>polymethylmethacrylate</td>
<td>31</td>
<td>3</td>
<td>90-105</td>
</tr>
<tr>
<td>cap/PC</td>
<td>polycarbonate</td>
<td>30</td>
<td>3</td>
<td>120</td>
</tr>
<tr>
<td>cap/TPX</td>
<td>polyethylene</td>
<td>18</td>
<td>3</td>
<td>160</td>
</tr>
<tr>
<td>cap/HFL</td>
<td>polytetrafluorethylene</td>
<td>48</td>
<td>3</td>
<td>150</td>
</tr>
<tr>
<td>cap/APEC</td>
<td>polyestercarbonate</td>
<td>30</td>
<td>3</td>
<td>175</td>
</tr>
<tr>
<td>cap/PES</td>
<td>polyethersulfone</td>
<td>36</td>
<td>3</td>
<td>215</td>
</tr>
<tr>
<td>hc1/PC</td>
<td>polycarbonate</td>
<td>36</td>
<td>4.2</td>
<td>120</td>
</tr>
<tr>
<td>hc2/PC</td>
<td>polycarbonate</td>
<td>33</td>
<td>3.4</td>
<td>120</td>
</tr>
</tbody>
</table>

Production uniformity and cell quality sometimes may be a problem for the small-celled materials in general. This is even a problem for characterisation, as the quality of tested sample varies. The question has been addressed and results for solar transmittance and heat conductance are available for the most important material classes\textsuperscript{12,13}. Figure 14 shows schematically the problem areas which might be overcome to some extent in future.

Fig.14: Production irregularities for small celled materials

Corrugation of cell walls, optical and heat transport within these materials, especially the non-rotational symmetry of the rectangular cells as well as light scattering has been treated also theoretically in some detail\textsuperscript{14}. The spectral transmittance of the materials has been measured\textsuperscript{15} and


modeled\textsuperscript{16,17}. Figure 15 gives the hemispherical-hemispherical transmittance for the commercial products of the structures listed above.

![Hem.-hemispherical solar transmittance as a function of layer thickness for important plastic small-celled structures](image)

**Fig. 15:** Hem.-hemispherical solar transmittance as a function of layer thickness for important plastic small-celled structures

### 3.1.3.2.2. Glass capillary structures

One serious shortcoming of plastic structures used in flat-plate collectors is that they do not withstand the collector stagnation temperature in most cases. Careful design utilizing additional air gaps and plastic films may prevent melting for the best plastic materials. The stagnation temperature depends, of course, on the U-value of the collector and hence on the honeycomb thickness. Glass is an ideal substitute for plastic in such an application. It does not soften below 600°C which is more than required. However, glass has higher density and heat conductivity. Therefore one has to optimize glass structures quite carefully with respect to material content. Early experiments using available glass tubes\textsuperscript{18} resulted in relatively large U-values. But recent initiatives to develop glass capillary structures for transparent insulation proved to be successful\textsuperscript{19,20}. Especially the large diameter tubes (7-8mm) can be produced very uniformly. The regular pattern that may be obtained with filled glazings is rather attractive for architectural purposes. At the moment production, handling and filling techniques are being improved in order to reach competitive prices in comparison to plastic materials.

<table>
<thead>
<tr>
<th>geometry</th>
<th>results</th>
</tr>
</thead>
<tbody>
<tr>
<td>cap1.7/PC</td>
<td>—</td>
</tr>
<tr>
<td>cap3/TPX</td>
<td>—</td>
</tr>
<tr>
<td>cap3/PC1</td>
<td>—</td>
</tr>
<tr>
<td>cap3/HFL</td>
<td>—</td>
</tr>
<tr>
<td>cap3/PMMA</td>
<td>—</td>
</tr>
<tr>
<td>hc/PC_1</td>
<td>—</td>
</tr>
<tr>
<td>hc/PC_2</td>
<td>—</td>
</tr>
</tbody>
</table>

**Table 3:** Overview glass capillary layers (solar transmittance values: boldface: value from literature; first value without glass panes, second lower value as double glazed unit $d_{W}$: cell wall thickness; $r$: tube diameter; $L$: tube length)


<table>
<thead>
<tr>
<th>Material</th>
<th>d&lt;sub&gt;w&lt;/sub&gt; (µm), r (mm)</th>
<th>L (mm)</th>
<th>(\tau_S (60^\circ))</th>
<th>U (W/(m&lt;sup&gt;2&lt;/sup&gt; K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buchberg/Edwards</td>
<td>200, 4-5</td>
<td>103+2x2</td>
<td>47%</td>
<td>1.65</td>
</tr>
<tr>
<td>Infraconsult</td>
<td>30, 1.5</td>
<td>50+2x2</td>
<td>61%</td>
<td>1.24</td>
</tr>
<tr>
<td>Schott</td>
<td>100-120, 3-4</td>
<td>80+2x4</td>
<td>63%</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Regular appearance, uniformity of production, fire resistance and very good optical properties make glass tubes an interesting product for transparent walls or special windows for daylighting.\(^{21}\)

### 3.1.3.3 Aerogel

Aerogel is a microporous "silicate foam" with pore sizes of some 10nm, light is scattered within the material, comparable to the Rayleigh scattering of blue sky. The utilization of these transparent and well insulating materials in window and cover systems started about 10 years ago. Up to now two different forms of aerogels are being produced, the monolithic tiles and the granular filling material.

![Nanoporous structure of aerogel](image)

**Abb. 16:** Nanoporous structure of aerogel

### 3.1.3.3.1 Monolithic aerogel

Silica aerogel in its monolithic form (MSA) is a fascinating nanoporous medium with many interesting physical and chemical properties.\(^{22,23}\) Densities between 3 and 500 kg/m<sup>3</sup> may be obtained. The material typically used for solar energy is produced from alcogels with supercritical drying and has densities around 100-150 kg/m<sup>3</sup>. Apart from problems to produce flat tiles larger than 60cm x 60cm x 2cm without cracks, handling and water resistance have to be improved. Optically the material is clean enough to read a book below a tile, however bulk scattering at the small pores - similar to Rayleigh-scattering - gives the material a reddish hue in transmission and blue in reflection. The solar transmittance is very high and has been improved over the past few years substantially.\(^{24}\) Light transmittance is lower due to the bulk scattering.

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\(^{21}\) *J. Geisler, 'TWD aus Glasröhrchen', Sonnenenergie No 20/4 (1995), pp. 10-12*

\(^{22}\) *J. Fricke (Ed.), Proc. of the 3rd Int. Symposium on Aerogels, Elsevier Science, North-Holland (1992)*

\(^{23}\) *M. Rubin, C.M. Lampert, "Transparent silica aerogels for window insulation", Sol.En.Mat. 7 (1983) 393-400*

\(^{24}\) *A. Nordgaard, Performance prediction of solar thermal systems and the use of monolithic silica aerogel to improve collector efficiency, PhD-Thesis NTH Trondheim, VVS-rapport 1991:1 (1991)*
Fig. 17: Normal-hemispherical transmittance of monolithic silica aerogel (ref. 24)

The heat transport is rather well understood in its principles. Gaseous conduction is largely reduced by the Knudsen effect within the small pores. Evacuating down to 1mbar is enough to exclude gas conduction totally. The radiative heat transport is the main part, which is influenced by water adsorption. A typical equivalent conductivity of MSA (Airglass, Sweden) is $16-19 \cdot 10^{-3} \text{ W/(mK)}$ at room temperature unevacuated. Xerogels - which are being dried in a different way - seem to be much clearer than aerogels. Xerogels due to the higher densities have higher values above $30 \cdot 10^{-3} \text{ W/(mK)}$, but a minimum of $18 \cdot 10^{-3} \text{ W/(mK)}$ has been reported\(^\text{27}\).

3.1.3.2. Granular aerogel

Granular aerogel:
* diameter 1-10mm
* cheap production
* voids
* surface scattering (spheres)

Fig. 18: Schematic of granular aerogel glazing

A granular silica aerogel (GSA) may be produced as a mass product. The supercritical drying is a part of the continuous production process. The granule sizes range from dust to 10mm diameter. The product has been developed within a large European project by the company BASF for the application as a filling material for double-glazed translucent glazing units.28

Fig. 19: Performance of glazings with granular aerogel

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28 J.J. Dengler, V. Wittwer, cit. above
Granule distribution, mechanical stability and hydrophobicity have been improved using a pilot plant with capacity 100m³/year. The granule size influences heat transport and optical properties, however mainly through the small dust particles. If these are sieved out and the granules withstand the filling process of the glazing unit, the properties are very good. Although the light is diffused, the glazing units are interesting for daylighting applications and for transparent insulation of walls. The heat conductivity is somewhat higher for granules than for monolithic tiles because of the voids. A typical equivalent conductivity of GSA is 21-24·10⁻³ W/(mK) at room temperature. Meanwhile the glazing company Interpane has taken up the idea and produces glazings filled with GSA commercially ("ipawall").

![Graph showing normal-hemispherical transmittance of granular silica aerogel (granules 2-6mm) as a function of the filling thickness D.](image)

**Fig. 20:** Normal-hemispherical transmittance of granular silica aerogel (granules 2-6mm) as a function of the filling thickness D

### 3.1.3.4 Material comparison

Because of the different nature of the material types treated it is difficult to compare materials in a fair way. Similar optical and thermal properties may be achieved with different thicknesses. Normal incidence transmittance is a good indicator of aerogel quality but not for honeycombs. Therefore in the following graph the total solar energy transmittance for diffuse irradiation $g_h$ is plotted against the U-value.

![Graph showing optical and thermal characteristics of material types.](image)

**Fig. 21:** Overview over optical and thermal characteristics of material types
In the previous sections the most promising transparent insulation materials have been presented. For each type listed at least one current product is commercial or close to commercialisation. Each material may be adapted more or less to a specific application. It is impossible to physically optimize one single product for such differing requirements as needed e.g. for a daylighting light wall and a flat-plate solar collector. However, because price and hence production capacity is a key parameter, it is often reasonable to have just one product specification being sub-optimal for some purposes. The deterioration of the system performance usually is not dramatic.

3.1.3.5 Summary on transparent insulation materials

These data show the high potential of these materials for high temperature or storage systems. Further improvements might be possible in the future, mainly in transmittance as a result of better production technologies but also in the U-value due to optimisation of the geometry. All these materials may not be used in ordinary windows. There is nevertheless an increasing market for non-view glazings such as sky-lights, light shelves below or above a view-window. No direct shades, reduced direct glare, rather constant light distribution even for changing environmental conditions combined with low heat losses and additional light gains are the key issues with these applications. If regular structures are used within the glazings also aesthetical considerations, or just the puzzling optical appearance may stimulate the use.

Although there exist alternative structures, the materials described seem to be the most promising ones. It must be stated, however, that the success of a new material is the combination of good optical and thermal properties with a cheap production technique. The big disadvantage of honeycomb structures is that they need unusually wide gaps to obtain U-value or in the order of 1.0-1.5 W/m²K. 60-120mm thick materials must be accommodated. This cannot be accomplished with a sealed glazing unit. Special spacer and edge seal technology is needed. Granular aerogel on the other side has been shown to achieve good energy efficiency with conventional glazing thicknesses. The additional requirement here is the careful filling and sealing after lowering the pressure to about 0.1 atmosphere inside. The pressure then exerted on the filling is sufficient to avoid granule settlement due to wind pressure and temperature rises.

3.1.4 Highly insulating glazings: edge effects

U-values for the centre of the glazing systems are seriously degraded by the edge components of glazing systems: spacers and frames. New advanced glazings require new types of frame and edge seal products. As the insulation properties of the glazing itself reach a performance close to that of well-insulated opaque walls, the thermal bridging caused by the spacer bars and the frames is unacceptable, even for wooden windows.

Window edge components with lower heat loss characteristics are becoming available which almost match improvements in centre of pane performance. Spacers used in the manufacture of insulated glass units are traditionally aluminium but insulating alternatives now exist (stainless steel, metal reinforced butyl rubber, silicon foam, thermally broken aluminium or steel, etc). Insulating frame materials are also available (vinyl and now fibreglass) and existing wood and aluminium framed products are being redesigned to minimise heat loss.

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Figure 3.1.4.1: Typical window spacers, traditionally aluminium (a), have been redesigned for improved thermal performance. Options include thermally broken metal (b), foam or butyl spacers (c), U-shaped spacers (d), or spacers made of stainless steel with a longer path length (e). (Source: Arasteh\textsuperscript{31})

The thermal losses through the windows frames are similar to the losses through uninsulated edge spacers. Today's thermally broken metal frames will reduce the risk of condensation, but heat loss will still be excessive. Wood frames insulate only as well as ordinary double glazing. Better insulating materials than wood or metal are necessary to match the performance of multi-pane, low-e, gas filled windows, and the insulated walls which surround them.

Figure 3.1.4.2: Typical window frames can be redesigned for improved thermal performance. A typical aluminum frame (a) has a thermal break added to it. A typical aluminum clad wood frame (b) has reduced cladding on the exterior. A typical vinyl frame (c) uses smaller cavities, some of which may be foam-filled. (Source: Arasteh
d

Higher performance frames using reaction injected moulding (RIM) technology are being manufactured. The technology makes it possible to form a graded density foam frame from urethanes (or fireproof phenolics) so the interior is porous and resistant to heat flow, while the exterior is dense and hard enough to resist wear and tear and to take on a finish. The frame can be strengthened with an

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interior longitudinal steel rod to maintain dimensional stability, particularly when the outdoor temperatures rise.

Wood and plastic, and wood and aluminium composites frames are becoming available.

Fibreglass frames have been available in North America for some time and are now marketed in Europe. In an Owens-Corning product, a dense fibreglass core acts as the insulator with a U-value of 1.41 W/m2K. The mechanical strength and the finish skin is provided by an outer sheath of gel-coated, glass-reinforced polyester, which is integrally bonded to the fibreglass core. The material is formulated to have the same temperature coefficient of expansion as wood. This practice guarantees that the frame continues to mate well with the glass glazing throughout the year. Dimensional stability is good because of the extra fibreglass reinforcing at the core-to-skin bond.

The Tables 1 to 3 below show how the centre of glazing U-value, UCG, is degraded by the presence of spacers (as represented by the insulating glass unit U-value, UC) and frames (as represented by the overall window U-value, UW). Data is shown for traditional and improved materials. Three different glazing systems, double glazing, double low-e with argon, and triple 2 low-e krypton, are used to illustrate the effect. (The WINDOW software was used to calculate U-values.)

Table 1. Effects of edge component heat flow on window U-value, Uw (W/m2K): Double glazed, 1m2 window, 3-12-3

<table>
<thead>
<tr>
<th>Frame material</th>
<th>Spacer material</th>
<th>Frame material</th>
<th>Insulating glass only, UIG</th>
<th>Centre of glass, UCG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>aluminium</td>
<td>aluminium with thermal break</td>
<td>Wood</td>
<td>PVC</td>
</tr>
<tr>
<td>fibreglass</td>
<td>4.55</td>
<td>3.45</td>
<td>2.69</td>
<td>2.54</td>
</tr>
<tr>
<td>glass</td>
<td>4.63</td>
<td>3.53</td>
<td>2.77</td>
<td>2.62</td>
</tr>
<tr>
<td>butyl/metal</td>
<td>4.60</td>
<td>3.49</td>
<td>2.73</td>
<td>2.59</td>
</tr>
<tr>
<td>aluminium</td>
<td>4.65</td>
<td>3.55</td>
<td>2.79</td>
<td>2.64</td>
</tr>
</tbody>
</table>

Table 2. Effects of edge component heat flow on window U-value, Uw (W/m2K): Double low-e, argon, 1m2 window, 3-12-E3

<table>
<thead>
<tr>
<th>Frame material</th>
<th>Spacer material</th>
<th>Frame material</th>
<th>Insulating glass only, UIG</th>
<th>Centre of glass, UCG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>aluminium</td>
<td>aluminium with thermal break</td>
<td>Wood</td>
<td>PVC</td>
</tr>
<tr>
<td>fibreglass</td>
<td>3.50</td>
<td>2.40</td>
<td>1.70</td>
<td>1.55</td>
</tr>
<tr>
<td>glass</td>
<td>3.57</td>
<td>2.47</td>
<td>1.77</td>
<td>1.62</td>
</tr>
<tr>
<td>butyl/metal</td>
<td>3.57</td>
<td>2.47</td>
<td>1.77</td>
<td>1.62</td>
</tr>
<tr>
<td>aluminium</td>
<td>3.69</td>
<td>2.59</td>
<td>1.89</td>
<td>1.74</td>
</tr>
</tbody>
</table>

34 WINDOW 4 Program Description, Window and Daylighting Group, Lawrence Berkeley Laboratory, Berkeley, California, USA, Mar. 1992.
### Table 3. Effects of edge component heat flow on window U-value, $U_w$ (W/m²K): Triple, 2 low-e, krypton, 1m² window, 3-10-E3-10-E3

<table>
<thead>
<tr>
<th>Spacer material</th>
<th>aluminium</th>
<th>aluminium with thermal break</th>
<th>Wood</th>
<th>PVC</th>
<th>Insulating glass only, $U_{ig}$</th>
<th>Centre of glass, $U_{cg}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>fiberglass</td>
<td>2.89</td>
<td>1.79</td>
<td>1.13</td>
<td>0.98</td>
<td>0.73</td>
<td>0.65</td>
</tr>
<tr>
<td>glass</td>
<td>2.91</td>
<td>1.81</td>
<td>1.14</td>
<td>0.99</td>
<td>0.75</td>
<td>0.65</td>
</tr>
<tr>
<td>butyl/metal</td>
<td>3.02</td>
<td>1.92</td>
<td>1.25</td>
<td>1.11</td>
<td>0.90</td>
<td>0.65</td>
</tr>
<tr>
<td>aluminium</td>
<td>3.20</td>
<td>2.09</td>
<td>1.42</td>
<td>1.27</td>
<td>1.12</td>
<td>0.65</td>
</tr>
</tbody>
</table>

It can be seen that, as the glazing technology becomes more advanced than double glazing, that it is vital to pay attention to edge heat loss effects if a low window U-value is to be achieved. Edge effects are more pronounced the smaller the dimensions of the windows. For high performance windows low profile frames and large glazing area units give the lowest U-values, especially when combined with insulating spacers and frames.

**Promising products:**

Silicon foam spacer, from Edgetech, UK Ltd, Highclec, Newbury RG 9PB, UK
Tel./Fax. 01635 253530

Fibreglass window frames, from - for example - Glaslite Building Products Ltd, The Grove, Geddington Road, Corby, Northants NN18 8EW, UK
Tel. 01536 406238 - Fax. 01536 406255

### 3.1.5 Daylighting and Solar Control Glazing Systems

**Introduction**

The window as a light source element is not necessarily an efficient component in the building structure. Being a transparent part of the building envelope, it establishes contact with the exterior world but it also produces glare and thermal problems. Traditional shading devices and low transmittance, heat-absorbing or heat-reflecting glasses are used to restrict solar heat gain and to reduce the glare component of sky brightness. However, reflective and solar-control glasses also reduce the transmittance of light.

**3.1.5.1 Cool Daylighting Systems**

Not all buildings in climates such as that of the UK or warmer benefit from passive solar gains. Indeed these may best be avoided in some non-domestic buildings, such as offices with high occupation and high casual and computer heat gains.

Daylight, however, is almost universally desirable, as over reliance on electric lighting increases the heat input to the building - potentially leading to overheating or high cooling loads - and can result in an unpleasant luminous environment for occupants to work in.

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Figures quoted below illustrate the relative efficacy of different sources of light. It can be seen that natural light produces the least amount of heat (measured in Watts) for a given amount of light (measured in lumen):

<table>
<thead>
<tr>
<th>Source</th>
<th>Efficacy lumens/Watt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten filament</td>
<td>10 - 15</td>
</tr>
<tr>
<td>Fluorescent</td>
<td>45 - 60</td>
</tr>
<tr>
<td>Sodium high pressure</td>
<td>80 - 90</td>
</tr>
<tr>
<td>Daylight</td>
<td>100 - 130</td>
</tr>
</tbody>
</table>

Attempts to control solar gains in the past, using tinted glazing, were misguided and often resulted in insignificant reductions in solar gain compared with clear glazing and the subsequent need to switch on electric lights (see Figure 3.1.5.1). Absorption of solar gains in the tinted glass turns the pane into a huge panel radiator in summer. It can be seen that in summer the tinted glass stops 86% of the solar heat gain, compared with 93% for the clear glass - just 7% less solar energy finds its way into the building. Closing internal blinds has little effect as they can heat up too. Double glazing with the tint on the outside can improve matters by reducing the shading coefficient by about 15-20%. (Note: shading coefficient of a glazing is the ratio of the solar heat gain through the glazing to that through clear single glazing.)

Major improvements result from reflecting solar heat away and transmitting the visible part of the solar spectrum; cool daylighting low-e coatings do just this.

Spectrally selective “cool daylight” low-e coatings exist which allow a high proportion of the visible light in the solar spectrum to be transmitted but block much of the other wavelengths responsible for solar heat gains (see Figure 3.1.5.2).
The effect of these spectrally tuned soft low-e coated double glazed units, with the coating positioned on the inside surface of the outer pane, is to allow good daylighting without the penalties of overheating or increased cooling load.

The positioning of the coating is important for reducing heat gain. With the coating on the outer pane, most of the absorbed energy will be dissipated to external ambient, rather than re-radiated inwards.

Different products exist with different visible (Tvis) and total solar energy transmittances. A key characteristic is the ratio of solar to visible transmittance - the lower this ratio the cooler the daylighting provided. One of the current best performing products (in a double glazed unit) is Tvis = 66% and total solar transmission = 34% (Interpane Iplus Neutral figures). The physical theoretical limit is roughly Tvis=60% and total solar transmission = 22%, so there is still room for development.38

![Figure 3.1.5.2 Ideal commercial low-e characteristics compared with ordinary glass. (Source: Johnson39)](source)

**Figure 3.1.5.2** Ideal commercial low-e characteristics compared with ordinary glass. (Source: Johnson39)

**Cool Daylight with Green Glass**

The pyrolytic low-e coatings are used in solar heating applications because their solar transmission is almost as high as clear glass. But often it is desirable to minimise solar transmission, particularly in office applications where the heat from people, lights, and equipment is already excessive, even during the winter. The solar gain is reduced in two ways: by reflecting more solar heat to the outside with a thicker silver-based coating, and by absorbing more solar heat in the outer layer of the double glazing, where the heat can be dissipated by air movement, without significantly reducing the daylight transmission. Normal tinted glass does not work well because of the overheating issues.

already discussed. Tints also do not work well because the daylight transmission falls off as fast as the solar gain (a 50% tint usually implies a 50% daylight transmission).

The coupling of solar gain and daylight transmission in tints is favourably overcome by high-iron ("green") glass. Unlike ordinary tints, green glass is a selective absorber - it absorbs more solar energy than daylight energy. An uncoated outer light of green glass in an otherwise clear, double-glazed window transmits almost as much light as triple glazing, yet it rejects as much solar heat as a bronze tint. Using this with a double layer silver low-e sandwich, and the double glazing solar gain goes down to almost that of reflecting glass, while the daylight transmission remains high, at 60% (about the same as four layers of clear glass). The daylight that filters through this material is termed cool daylight because it contains up to 60% less heat than fluorescent light of an equal brightness, or about the same as light from metal halide lamps.

Cool daylight glazing lowers both the daytime air conditioning and the lighting bill because the luminaries are not necessary, and the heat from the daylight is as low as the most efficient lamps made.

**Light and Heat Performance Criteria**
Performance is best evaluated against a set of absolute standards. Since low-e products are beginning to reach the limiting laws of physics, it is interesting to measure various products in terms of their ultimate performance bounds.

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**Figure 3.1.5.3** The possible combinations of solar shading coefficients and daylight transmissions for double-glazed windows. The ratio of the shading coefficient to the daylight transmission, Dx, is the transmitted daylight's index of coolness - the lower the number, the cooler the light (ie. less solar heat gains accompany the daylight transmission). (Source: Johnson\(^{40}\))

Figure 3.1.5.3 shows the combinations of solar shading coefficients and daylight transmissions that are possible for double-glazed windows. The corresponding total solar transmission, the fraction of solar radiant heat at normal incidence that is transferred through the

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glazing by both direct transmittance and inward flowing absorbed energy, is given on the opposite axis. The shading coefficient is also given (the total solar heat gain of the glazing divided by 0.87, the total solar transmission of single clear glazing). All insulated glass (IG) units must lie inside the envelope. The upper right hand corner of the envelope represents two panes of high-transmission, 3 mm water-white glass. (Water-white glass does not appear green even at its edges because of its extremely low iron content.) The envelope edge that slopes upward from zero shows the minimum amount of inward flowing solar heat that can possibly accompany a given amount of daylight, assuming all of the near infrared component is rejected. For instance, the graph shows that the lowest possible shading coefficient for a product with 50% daylight transmission is 0.18.

Considering only transmission aspects, products used for solar heating should lie near the envelope's top right corner of Figure 3.1.5.3. But depending on the application considered, a compromise between solar transmission and thermal insulation must be found. Windows used for light and heat control should lie near the bottom sloped line. The single square near the top right corner represents some of the low-e products designed for maximising solar gain and daylighting in residences. The four triangles in the middle occupy the range covered by ordinary tinted glazings, which is limited and far from the envelope's edges. Reflective office glazing, shown as orthogonal crosses, covers a wider range nearer the bottom edge; but the solar gain is too high for a given daylight transmission. The low-e coatings coupled with various tints skirt are represented by filled triangles. The low-e and green glass combinations are represented by crosses; they perform well, skirting the envelope's bottom edge.

The ratio of the shading coefficient to the daylight transmission, Dx, is the transmitted daylight's index of coolness - the lower the number, the cooler the light. Four reference lines - for Dx = 2.00, 1.00, 0.66, and 0.50 - are shown as dashed lines radiating from the origin of Figure 3.1.5.3. The lowest possible Dx value is 0.36, which forms the bottom edge of the envelope. Figure 3.1.5.3 shows that reflective IG generally has the highest Dx values, followed by lowering values for tinted IG units, clear units, and green IG units. A low-e coating added to the inside of the outside light or a low-e film suspended in the airspace lowers Dx dramatically. The lowest Dx value on the graph of 0.61 corresponds to the new double silver low-e coating on a light green IG unit.

3.1.5.2 Daylighting Glazing Systems

In a conventional side-lit space the daylight distribution falls off rapidly with distance from the window wall. Some form of supplementary (artificial or natural) lighting system is necessary therefore if the depth of such a room exceeds about 2.5 times the window height, not only to provide an adequate illumination level but also to provide an optimum visual environment.

The aim is to provide a system of illumination to light deep spaces economically and simply, and to conserve energy. In order to achieve this goal, four major issues need to be addressed:
- increasing the daylight illuminance level
- improving the illumination distribution
- reducing glare due to sky brightness
- control of direct sunlight.

It is possible to use sunlight and to control it directly, by reflecting, refracting or diffracting its rays with a light-directing system on to a ceiling of high diffuse reflectance to provide better illumination deep inside a room.

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Beyond the energy-related issues of daylighting, there are important qualitative issues to be addressed. The primary purpose of lighting is to enhance visual performance while providing comfort. Deep spaces lit by conventional window systems can produce intolerable glare due to contrast between sky brightness seen through the window and the relatively dark areas of the interior space. Additional reflected sunlight will increase the ambient light level by lighting the ceiling. This will reduce contrast and therefore reduce discomfort due to glare.

The daylighting effect of control elements can be based on different physical phenomena: reflecting (lightshelf, louvre blinds), refracting (prism) or diffracting (holographic elements) daylight from its natural path.

**Need for control elements**

Direct sunlight in the workplace causes discomfort. Control can be provided by appropriate choice of glazing system or shading devices. However, shading devices, especially fixed devices, reduce the quantity of light entering the space and thus increase the electric lighting load. If properly designed, control elements offer the possibility of reducing the use of electric lighting by redirecting natural light.

The use of Visual Display Terminals, i.e. computer screens (VDT) in office spaces is becoming more and more common. In rooms with large side windows it can be difficult to orient VDTs to avoid both unwanted reflections on the screen and uncomfortable contrasts between the dark screen and a bright window. Control elements such as blinds, lightshelves, prismatic or holographic optical elements can reduce these problems by directing most of the incoming light onto the ceiling.

Control elements discussed in this section are limited to those which form an integral part of the glazing system.

**3.1.5.2.1 Integral blinds**

Blinds placed between the panes of a glazing system are more effective at controlling solar gains than internal blinds as the solar energy is reflected before it enters the building envelope. For a double glazed window with integral blinds solar heat gains will be 30% of those through a single glazed window (25% of incident solar energy).

Integral blinds also have a role in the control of glare and providing visual comfort. However they are not good components of a daylighting strategy. Their use frequently leads to the “blinds down, lights on” syndrome resulting in poor use being made of available daylight, and consequent reliance on electric lighting with the associated overheating problems or increased cooling loads. For a double glazed window with integral blinds the light transmission is less than 10% when adjusted for maximum solar control.

**3.1.5.2.2 OKASOLAR insulating glass with optical sun control louvres**

Okasolar is double-glazing with integral miniature louvre blinds encased within the cavity. These blinds, however, are rather more sophisticated and must be carefully positioned to precisely control solar gains. It was calculated that if fixed pre-set miniature sun-deflecting chromed steel louvre blades were set within the sealed cavity, angled to take account of the varying paths of the sun over the building, it should be possible to seasonally control the amount of solar heat gain. Greater transmission is allowed in winter when passive gains may be required, and reduced gains in summer to reduce overheating.

The 23mm thick blades, which have three slightly concave reflector faces, can be positioned within the cavity at centres from 13 to 17mm. The sealed units are normally 16mm thick for vertical facades and 18mm when used as roof cladding. The outer leaf of glass has to be toughened to handle the greater stress resulting from deflected solar heat. The blades’s spacing and orientation must be
accurately predetermined by computer modelling, taking into account the site’s location, the orientation of the building, and angles of the cladding, before the units are fabricated, in Germany.

Figure 3.1.5.4 Schematic of Okasolar solar control glazing. (Source: Okalux product literature)

Key Features:
- OKASOLAR is an insulating glass with fixed reflecting louvres in the air gap.
- Any kind of flat glass may be used but preferably safety glass (laminated or tempered).
- The reflecting louvres have been designed in such a way that the quantity of light and solar energy transmitted depends on the elevation of the sun. In winter, with low sun, transmittance is high. In summer, with high sun, most of the radiation is reflected to the outside.
- It can be used for vertical and sloped glazing. Depending on the orientation of the glazing area to the sun different types of louvres are used.
- The daylight is partly reflected to the outside by the louvres and partly reflected and diffused to the inside giving a soft undistorted light, well spread in depth.
- Light transmission is 5 - 50% for parallel light depending on the elevation of sun and 14% for diffuse light.
- OKASOLAR can also direct the light within the building interior.
- Sun protection depends on the orientation of the glazing area to the sun. Shading coefficients of 0.29 to 0.52 can be achieved. The shading coefficient can be varied within certain limits by choosing different types of louvres.
- The U-value for a standard construction of OKASOLAR is 2.5 W/m²K. Used with low-e glass, the U-value can be reduced to 1.3 W/m²K.
- Dimensions cannot exceed unit sizes of 1000 x 3000 mm.
- The manufacturers recommend that to ensure that OKASOLAR glass is used to its full advantage, use should be made of their experience at the project design stage.

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Background

One way to control sunlight penetration into a building is to increase the sensitivity of the transmission factor as a function of the incidence angle, and especially as a function of the solar altitude. This may be achieved by employing Fresnel-type lenses made of glass or acrylic material. Devices can consist of a single prismatic layer or two successive layers.

Prismatic elements for daylighting were in use in cities at the beginning of this century. Poor quality electric lighting at that time encouraged the investigation of deeper daylight penetration techniques, especially in densely built-up cities. The prisms were designed to be used in heavily obstructed rooms to redirect diffuse light from the sky zenith towards the back of the room, which would otherwise receive no direct sky light. They were applied in spaces facing narrow streets, basements, industrial buildings, hospitals and greenhouses.

Prismatic devices can be made inexpensively but distortion by the prisms prevents their use where a view is required, restricting application to industrial buildings or specific locations such as the upper parts of facade windows.

Function

There are two forms of prismatic glazing: sunlight directing prisms and sunlight excluding prisms.

Prismatic panels control transmitted light by refraction. The direction of the incoming daylight is altered by passing through a prism or a triangular wedge of glass. Normally a prismatic system which will refract the light to the ceiling consists of two sheets of prismatic panels, with the prismatic faces placed internally for dust protection.

Figure 3.1.5.5 Function of prismatic glazing: daylight redirection (Source: Daylighting in Architecture\textsuperscript{42})

Application
The need to install light re-directing elements has to be established. The fields of application can be where:
- requirements for visual comfort are demanding (i.e., office space with VDTs, classrooms)
- large external obstructions with low reflectance are located outside the room (i.e., urban space, street, atrium)
- the availability of sunshine is high (south-facing glazing)
There is a need to direct light away from work surfaces different from computer screens, or encourage deeper penetration of daylight.

Sunlight Directing Prisms
These prismatic systems direct sunlight using a movable tilted prismatic panel.

Sunlight Excluding Prisms
These prismatic systems reject direct sunlight while admitting near-zenithal sky light. These systems work on the principles of both reflection and refraction.
The main functions of such systems are:
- sun-screening
- daylight control and distribution.

Figure 3.1.5.7 Prismatic devices used in conjunction with window material. (Source: Siemens product literature)
Prismatic panels are designed to be also used within double glazed units and are available in different types, each designed to perform a different task. Four different angles of prism, used according to their location in the building, are produced either unsilvered or with a part-silvered prism for solar rejection.

The diagrams in Figure 3.1.5.8 demonstrate various design options for sidelighting using prismatic elements.

![Figure 3.1.5.8 Use of prismatic elements for sidelighting (Source: Siemens product literature)](image)

**Advantages of Prismatic Systems**

- Sky remains perceptible: Prismatic elements are translucent; the sky cannot be seen through these elements, but it remains perceptible. Thus, this control element does not disturb the overall appearance of a window seen from the inside.
- Reduced glare: Due to the sky brightness seen through a conventional window is greatly reduced: sun-excluding prisms have a luminance, viewed from below, of only 100-300 cd/m² compared with 2000-6000 cd/m² for overcast sky viewed through a conventional window; therefore it becomes an appropriate daylighting system for rooms with VDT use.

**Disadvantages of Prismatic Systems**

- With fixed prism systems the view out is permanently obscured if installed below head height.
- Constructional aspects can be problematic: the single prism requires a 20mm space between panes of glass, increasing to 48 mm for the three prism version.
- The cost can be considerably higher than conventional systems: however, some of this cost may be offset by savings in building costs (no sunshading devices, reduced HVAC system, reduced installation of luminaires) and also by potential energy savings (lighting and air conditioning running cost).

The daylight systems are a joint development of Siemens AG, Lichtplanung Christian Bartenbach GmbH and Glaszentrale Abenber GmbH.

Prismatic daylight systems reject light coming from certain angles and transmit the light coming from all other angles. They have a cut-off range and a transmission range.
The cut-off range prevents the transmission of direct sunlight to the interior, thus providing a sun-shielding effect.

**Figure 3.1.5.9** (a) redirection of daylight and the avoidance of direct beam radiation, (b) transmitted light being guided on to an appropriately formed ceiling. (Source: Siemens product literature)

In the transmission range, the optical refraction of the prism changes the direction and intensity of the transmitted zenith light. At the same time, this light also becomes controllable. The daylight entering through a window can be directed up towards the ceiling in the interior. If suitable forms and materials are used for the ceiling, the system can distribute the daylight uniformly over greater room depths. Figure 3.1.5.9 shows (a) the redirection of daylight and the avoidance of direct beam radiation, and (b) transmitted light being guided on to an appropriately formed ceiling.
Prismatic daylight systems offer the architect new ways of using light to create atmosphere. They:

- make better use of the effective zenith light from the sky
- direct the daylight deeper and more uniformly into the interior
- have the sun-screening effect of external sun-shielding
- are available in configurations for sidelight and toplight systems
- allow lower room temperatures to be maintained in summer and/or reduce air-conditioning costs due to the lower external heat gain
- avoid nuisance glare from sunlight and sky
- reduce energy costs for artificial lighting
- allow controlled distribution of the daylight in the interior by an appropriately structured, reflective ceilings

Colour dispersion is sometimes a problem with prisms, though provided a wide beam of sunlight is refracted by a number of small prisms, coloured areas should only be visible at the very edges of the beam of light reflected onto the ceiling.

In Figure 3.1.5.10, the example shown in S3 rejects direct sunlight but admits skylight from near the zenith. The tilted prismatic sheet has one face of each prism silvered, so that light from the areas of sky where the sun could be (up to 60° altitude in SE England) will be reflected back outside. Diffuse light from higher altitudes is admitted and refracted onto the ceiling by the inner, vertically fixed prismatic sheet.

Such a system has been analysed and it was found that under overcast conditions slightly less daylight reached the interior than with a clear window, although it was more uniformly distributed over the working plane. The main advantage of the system occurs under sunny conditions when blinds would be drawn on conventional windows, blocking off skylight as well as sunlight. The prismatic system, while rejecting sunlight, would still allow skylight to enter.

Systems of this type have been installed in a few buildings in Europe, and are now being marketed by Siemens. Prismatic sheets for rooflights are also available.
Figure 3.1.5.10 (a) Applications of prismatic glazing systems. (Source: Siemens product literature)
Figure 3.1.5.10 (b) Applications of prismatic glazing systems. (Source: Siemens product literature)
Example:
The reconstruction of Billingsgate fish market into a dealing hall was the first example in the UK of a prismatic glazing system for daylight control. The building is essentially a single top-lit space covered by nine glass barrel vaults. The system used is manufactured by Siemens and comprises acrylic tiles measuring 206mm square that are clipped together to form the required size of panel. These are enclosed in sealed double-glazed units.

The number and angle of the tiles varies with aspect: maximum daylight control on a south face requires a silvered prism face with two additional panels forming a treble-thickness sandwich, while on a north face there is only a single panel.

The prism system of solar control is a customised solution for particular problems and has value for atria and other top-lit spaces where natural light is required without the accompanying problems of glare and solar gain.

One of the main advantages of these systems is their suitability for use in rooms with visual display terminals (VDTs). Conventional guidance tends be that daylight and VDTs do not mix, however the ability of innovative daylighting systems to cope with this problem may be a major factor in their uptake.

Solar Control
According to DIN 67507, the solar heat gain coefficients (g-values) of sun-shielding fittings on buildings are always determined with a vertical direction of incidence of the radiant energy. Since the cut-off and transmission ranges depend on the angle of incidence, daylight systems cannot be expected to have a constant g-value over all angles in the room. It has proven best to determine the g-value in natural sunlight to compare with normal insulating glass. In such a comparison measurement, a total energy transmittance value, of 0.19 was determined when the sun was at its highest point at 1.00 pm on an August day.

Thermal transmittance
Plastics are good heat insulators. The heat transmission of insulating glass is reduced by the installation of a layer of prismatic panels made of plastic (polymethyl methacrylate. Normal insulating glass has a U-value of 3.0 W/m²K, normal insulating glass with one prismatic layer a value of 2.2 W/m²K, and with two prismatic layers, 2.1 W/m²K. The heat transmission coefficient is improved by some 35%. The U-value is improved even further by using heat insulation glass.

3.1.5.2.4 Prismatic Blind System
Huppe's Daylight Technique makes use of a novel, transparent, solar-protective venetian blind constructed from prismatic slats which only transmit diffuse light. An inner anti-dazzle blind made from partially perforated, deflecting slats with a reflective coating, directs overhead light towards the ceiling, helping to provide a uniform light level throughout the interior. The aim of the system is to reduce operating costs for both artificial lighting and air-conditioning systems.
Figure 3.1.5.11 The anti-dazzle venetian blind consists of partially perforated, deflecting slats with a reflective coating on the inside and reflection inhibiting matt paint on the outside. The solar protection venetian blind, made from transparent prismatic slats, selectively reflects direct sunlight. (Source: Huppe product literature.)

The operation of the Huppe/Bartenbach Daylight Technique system is based on the combination of prismatic and deflecting slats. In accordance with the law of total internal reflection, the prismatic slats act as an optical filter by almost completely reflecting direct solar radiation and only transmit the diffuse, cooler overhead light.

Partially perforated, parabolically shaped deflecting slats - made from aluminium - direct the daylight upwards toward the ceiling. They produce a scatter effect to prevent dazzle in the vicinity of the window. This effect can be increased still further by means of additional reflecting panel under the ceiling.

The system is useful for providing solar protection to the interiors of those buildings which are 'listed' or classified as ancient monuments and whose facades cannot be altered by the addition of external solar protection systems.

Figure 3.1.5.12 Schematic of prismatic blind system redirecting beam radiation (Source: Huppe product literature)
Daylight and solar protection

Huppe's Daylight Technique achieves a lower total energy solar transmission (about 0.3) than conventional, internal solar control systems (about 0.5). (External solar protection venetian blinds have a total energy solar transmission of about 0.2 but with the penalty of severe internal darkening). The blinds of the daylight system can be lowered and raised separately so that it can be adapted to the prevailing external light conditions.

Automatic adjustment of blind angle is made using a difference sensor mounted to permanently monitor the relative angle of incidence of the sun's rays to the blind and provides the parameters for automatic adjustment.

The slats of the anti-dazzle venetian blind are mounted at a precisely defined, fixed angle of incidence. In contrast, the angle of inclination of the prismatic slats is variable. With the aid of the electronic difference sensor, the slats are continually moving in relation to the position of the sun so that they are always automatically aligned at right angles to it. The system is equipped with a BUS interface and can be integrated into modern building control systems.

Even interior lighting.

Huppe Daylight Technique is claimed to create an even distribution of light throughout interiors under every sky condition. The system offers new possibilities for light planning compared with conventional external blinds (see Figure 3.1.5.13).

Intense brightness and blinding glare near windows are reduced to a sensible level that does not create dazzle while the level of brightness further into the room is increased by reflected, directional lighting.

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Figure 3.1.5.13 Comparison of the performance of conventional venetian blinds and Huppe Daylight Technique by the Christian Bartenbach Office for Light Planning. (Source: Huppe product literature)
3.1.5.2.5 High Transmittance Materials

Glass and polyester films treated for anti-reflection or anti-soiling can improve performance in glazing applications where solar and/or daylight transmission must be optimised. These are described below. Other high transmittance materials are low iron glass and plastic films, which have been described earlier in section 3.1.

**Anti-reflection Films**

Transparent covers and films used in solar energy conversion systems and architectural windows can have visible reflection losses reduced by anti-reflection treatments.

Reflection losses are caused by optical interference from the boundary formed between two media with different optical properties eg. air and glass. As an electromagnetic wave propagates from one medium to another, there is a change in phase velocity, wavelength, and direction. Because of interaction between the incident wave, and the atoms of the new medium, a reflected wave is formed.

The incident reflectance losses are about 3.5-4.5% per surface for most untreated polymers and glasses for solar use. By anti-reflecting the glazing surfaces the maximum increase in performance for each glazing would be about 7-9%. This gain in transmittance can be significant if multiple glazings are used. Certain anti-reflective coatings can also serve as durable overcoating materials. Some polymer overcoatings, having a low refractive index (n), can anti-reflect glass (n=1.5) and other high-refractive index plastics. Dispersions of fluorinated ethylene propylene (n=1.34) can be used for this purpose.

Fluorosilicic acid can give a graded-index, anti-reflective coating to glass. It primarily roughens the surface by etching out small pores, in non-silica regions. Silica films deposited from sodium silicate or colloidal silica can be used for acrylic, polycarbonate, and some glasses.

For cover materials for photovoltaics, certain polymeric and elastomeric materials can be used if the coating is thin enough, although protective coatings are generally used in thick-film form. Popular protective materials are silicones, fluorocarbons, halocarbons, and acrylic resins which have protective and anti-reflective functions.

Inorganic thin films have been used for a wide range of single and multiple interference-coating applications. Compounds such as MgF₂, CeO₂, TiO₂, SiO, SiO₂ are used for anti-reflection applications. Many of these coatings are deposited by physical vapour deposition (PVD) techniques (e.g. sputtering and vacuum evaporation).

A number of oxides can be deposited by the Solgel dipping and drying process. Solgel coatings are formed by hydrolysis and polycondensation of metal alkoxides which transform into transition metal oxide coatings. Solgel coatings have been used to anti-reflect glass, changing transmittance from T=0.91 to 0.96 and for photovoltaics to reduce reflectance from R=0.36 to 0.04. Specialised anti-reflection coatings for transparent low-emissivity films have been devised. Silicon oxynitride films can be made with varying indices of silicon oxynitride (n=1.46 to 3.4).

**Anti-reflection coatings: key points**

- Visible light transmission through glazing is reduced by reflection losses
- Antireflection coatings have been available for many years: this act to reduce, not eliminate reflection reflection
- This change in glazing properties can be desirable for:
  - appearance
  - improved daylight & solar energy transmittance for solar collectors
Properties of coatings to be considered are:
- durability
- wavelength response
- cost-benefit trade-off

For untreated glazing, reflectance losses are about 4% per surface
- so for multiple pane glazing systems the increase in transmission can be significant

Low-e glass has an antireflection coating to improve transmission and act as a durable overcoating material

Complex coatings such as those for electrochromic films require antireflection coatings

Surface etching is an alternative approach to antireflection, with superior mechanical properties and broader wavelength response.

**Anti-soiling Coatings for Glass and Plastic**

Surface treatments to improve visibility of glazings during rain storms have been researched for over 15 years at the US Naval Research Labs. Some of this technology is becoming available for commercial applications. These surface treatments act to change the surface tension of the glazing so water totally wets the glazing rather than forming spots. Surface treatment of polymer glazings are common in greenhouses to prevent condensation and dripping of water onto plants. Also, a wide variety of surface treatment products to prevent soiling have been developed for polymer and natural fabrics and painted surfaces.

Fluorocarbon coatings have been used commercially to treat glass on buildings and ships. The fluorocarbon coatings tend to wear off with time and have to be replaced. The Clear Shield product made by Ritec (UK) is an example of a surface fluorocarbon treatment. Window manufacturers, Viracon and Musselman, are to produce a window glazing with the Ritec technology. Nippon Sheet Glass has also licensed this technology, and filed a patent on Stay-Clean window glass based on a pyrolytic coating of TiO2 with dopants of Platinum, Rhodium or Palladium. The action of UV light on this coating tends to catalyse surface organics to become oxidised. Also, the water contact angle to glass is reduced, promoting a sheet action. Another coating has been developed by Asahi Glass which also provides anti-reflection for glass. This coating is based on polyfluorocarbosilane made by a dipping and drying technique. Further work is being undertaken at LOF and Toyota Motors on slippery or hydrophobic glass coatings. This is an area for further development.

**Anti-soiling coatings for glass: key points**

- Glazing is often difficult and expensive to clean
- Important problem, as surface soiling:
  - reduces daylight transmission (and solar energy transmission)
  - affects appearance
  - reduces efficiency of solar collectors, PV arrays
- High demand for glass with self cleaning or reduced cleaning properties
- No superior process has yet been devised
- Key to this technology is the permanent chemical modification of the surface characteristics of the glazing
- Some coatings allow water sheeting action
  - change in surface tension of glazing prevents droplets and spots forming
- Fluorocarbon coatings can be applied to building glass for this effect
  - wears off and needs replacing
- Examples: Ritec International’s product “Clear Shield”, a silicon treatment for existing or new glass
- Important area for future development
3.1.5.3 Maximizing Daylighting Benefits by Control of Electric Lighting

This section summarise the relevant sections of “Energy Efficient Lighting in Buildings”, 1992.\textsuperscript{43} This very useful publication is available from the EU, see reference for further details.

Daylight within a building has a major effect on the appearance of the space, and can have considerable energy efficiency implications. Building occupants generally prefer a well daylit space, provided that problems such as glare and overheating are avoided.

The major factors affecting the daylighting of an interior are the depth of the room, the size and location of windows and rooflights, the glazing system and any external obstructions. These factors usually depend on decisions made at the initial design stage of the building, e.g. whether the building is deep or shallow plan, whether it is single storey, allowing the use of rooflights, or multi-storey. Appropriate planning at this early stage can produce a building which will be more energy efficient as well as having a pleasing internal appearance.

In a well daylit building, daylight often provides sufficient illumination for activities such as circulation for the majority of the day and can provide adequate working lighting for a substantial part of the year. However to fully utilise the benefits of daylight in an interior it is important to ensure that the electric lighting is turned off when daylight provides adequate illumination. This is achieved by the use of appropriate lighting controls and may involve some degree of automation.

**Lighting Controls**

Appropriate lighting controls can yield substantial improvements in lighting energy efficiency. These improvements arise principally from the utilisation of available daylight to reduce electric lighting use and from switching off electric lighting when a space is unoccupied. In addition they can increase user satisfaction by allowing occupants to have more control over their working environment through the use of localised switches.

The most cost effective control strategy for a particular space will depend on the daylight availability and the type and pattern of occupation. If sufficient daylight is available to meet lighting requirements for a significant part of the day, energy savings can be considerable. Research has shown that the probability of switching on electric lighting on first entering a space correlates closely with the daylight availability, but switching off rarely occurs until the last occupant has left. The control strategies given in the decision chart (Figure 3.1.5.14) aim to invite the switching decision to be remade at times when daylight availability will have improved (time switching) or aim to place the switch in a location where the occupants perception of daylight adequacy will be more relevant to their needs than a switch location at the entrance to the space (localised switching). Further improvements in energy efficiency can be achieved by using automatic sensing of daylight levels (daylight linking) or occupancy (occupancy linking). For spaces with negligible daylighting, a combination of time switching and localised switching will cover most situations, although care is necessary to ensure that the lighting is not automatically switching off to leave dangerous blackout conditions. For installations with sparse and intermittent occupancy such as a warehouse, localised switching will eliminate the need for the whole space to be lit when only a small part is in use; occupancy detectors are particularly suitable for such spaces.

\textsuperscript{43} Energy Efficient Lighting in Buildings, CEC DGXVII Thermie Maxibrochure, 1992.
The occupancy pattern of a space is important in determining lighting use. This can be broadly divided into types:

- **variable occupation**: occupants spend part of their time in the space and part elsewhere, e.g. a sales office where workers spend part of their time visiting clients
- **intermittent scheduled occupation**: people occupy the space for relatively short but defined periods, e.g. a school classroom, a sports hall
- **full occupation**: occupants are in the space for the entire working day, e.g. a factory space where occupants are at their machines the entire time
- **intermittent occupation**: an area visited only occasionally for short periods during the working day, e.g. storerooms, a warehouse.

The four basic methods of lighting control (i) time based control, (ii) daylight linked control, (iii) occupancy linked control and (iv) localised switching, can be achieved in a number of ways.

Time signals may be derived from a variety of devices ranging from the simple multi-position electromechanical switch to solid state switches. Time signals may also be derived from building management systems. These signals must be transmitted to the luminaires through a communications channel. This can be the mains wiring itself or a dedicated low voltage wiring bus connected to receivers in each luminaire or group of luminaires. It is important to include local override so that lighting can be restored if the occupants need it.

Photoelectric daylight linking can take two forms, either simple on/off switching or dimming. The photocell may either be mounted externally or facing out of the window to sense the daylight only or mounted inside the space to measure the total daylight and electric light. It is important to incorporate time delays into the control system to avoid repeated rapid switching caused, for example, by fast moving clouds. Photoelectric switching causes sudden and noticeable changes in lighting level and can lead to occupant complaints; it is therefore best used for areas which are well daylit and where switching frequency will be low, for example close to windows.

Unlike photoelectric switching, photoelectric dimming control is relatively unobtrusive. The control system ensures that the sum of daylight and electric lighting always reaches the design level by sensing the total light in the controlled area and adjusting the output of the electric lighting to top-up the daylight as necessary. If daylight alone reaches the design level the electric lighting is dimmed to extinction. The energy saving potential of dimming control is greater than for simple photoelectric switching and the mode of control is more likely to be acceptable to the occupants. The recent developments in electronic ballasts have facilitated the use of photoelectric dimming systems for fluorescent lighting, particularly in commercial interiors.

Occupancy linking can be achieved using infra red, acoustic, ultrasonic or microwave sensors, which detect either movement or noise in the space. These usually switch the lighting on when occupancy is detected and off again once they have failed to detect occupancy for a set time. It is important to have a time delay built into the system, since the occupant may remain still or quiet for short periods while remaining in the space but would not wish the lighting to be extinguished before s/he has actually left.

Localised switching is important where only part of a large space requires the electric lighting to be on, either because the other parts are unoccupied or because daylight there is adequate. Studies in open offices have shown wide variations in user preference for lighting with some occupants switching their lighting on under almost all conditions and others doing so only on rare occasions. This produces noticeable energy savings compared with the common situation where the lighting in the entire space is controlled with a single switch. In general, the area controlled by a particular switch should have a similar daylight level in all parts. It should also be related to the occupancy pattern, for example in an office where individual occupants may be absent it should cover the space of a single occupant or small working group, in a factory it could be related to a particular production line or process.
Lighting control systems can combine a number of the strategies outlined above. For example, successful office installations have combined centralised time switching, including a lunchtime switch off to reduce lighting use in the afternoon, with daylight linking on luminaires close to the windows and localised switching so that only those areas which are occupied at the time need be lit.

It is important that the occupants of a space are aware of the existence of an automatic lighting control system, how it works and how they can interact with it. This is particularly important in retrofit installations where considerable resistance to the introduction of controls can be produced if the occupants are not consulted and fully informed about the new system.

Substantial cost effective savings in energy used for lighting can be realised by appropriate lighting controls. Lighting energy consumption in offices can typically be reduced by 30% to 50%. Simple pay back can often be achieved in 2-3 years. One installation in a warehouse resulted in a 70% energy saving with a simple payback in less than 2 years.

<table>
<thead>
<tr>
<th>Yes</th>
<th>DAYLIGHT AVAILABLE</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCCUPANCY PATTERN</td>
<td>OCCUPANCY PATTERN</td>
<td></td>
</tr>
</tbody>
</table>

### Multi-occupant occupancy types
- **Variable occupation**
  - * * * Time switching
  - * Localised switches
  - * Photoelectric daylight linking
  - * Occupancy linking
- **Intermittent scheduled occupation**
  - * * * Time switching
  - * Localised switches
  - * Photoelectric daylight linking
  - * Occupancy linking
- **Full occupation**
  - * * * Time switching
  - * * Photoelectric daylight linking
  - * Localised switches

### One or two occupants
- **Variable occupation**
  - * * * Localised switches
  - * Occupancy linking
  - * Photoelectric daylight linking
- **Intermittent occupation**
  - * * * Localised switches
  - * Time switching
  - * Photoelectric daylight linking
- **Full occupation**
  - * * * Localised switches
  - * * Photoelectric daylight linking
  - * Time switching

### Very low occupation
- **Variable occupation**
  - * * * Localised switches
  - * Occupancy linking
  - * Photoelectric daylight linking
- **Intermittent occupation**
  - * * * Localised switches
  - * Time switching
  - * Photoelectric daylight linking
- **Full occupation**
  - * * * Localised switches
  - * * Photoelectric daylight linking

### All
- **Variable occupation**
  - * * * Localised switches
  - * Occupancy linking
  - * Photoelectric daylight linking
- **Intermittent occupation**
  - * * * Localised switches
  - * Time switching
  - * Photoelectric daylight linking
- **Full occupation**
  - * * * Localised switches
  - * * Photoelectric daylight linking

### Key
- * * * Definitely recommended to produce savings
- * Could be expected to provide economies but rate of return on investment would not be as high
- * Needs consideration; might depend on a detailed examination of the installation

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Figure 3.1.5.14 Selection of lighting control strategy - decision chart\(^{44}\).

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3.1.6 Near Market Glazing Technologies

Low-e performance is reaching its theoretical and economic limits. Soft coat emissivity has been lowered from 10% to 3%. Further decreases would not noticeably improve the glazing’s thermal resistance.

Pyrolytic coatings have lifted the solar gain by 4%, to only 2% to 3% of clear double glazing. A 4% rise in the shading coefficient is important for solar heating applications, but pyrolytic technology does not lend itself to much more improvement in the shading coefficient.

The desirable low-shading coefficient, high daylight transmission combination for offices has reached new performance levels. The lowest shading coefficient available with soft coat technology is now 38% at a 60% daylight transmission. The lowest theoretical shading coefficient for this daylight transmission is 21.6%, so improvement is still possible. Further advances in this area will depend on advanced low-e coatings with sharper cut-offs in the near infrared spectrum and better heat absorbing glazings that maintain a high daylight transmission.

While the above sections discussed technologies which have been commercialised into mainstream manufacturing processes, several products still in research laboratories offer the potential for increased energy savings or are new approaches to controlling heat losses and gains through building envelopes.

3.1.6.1 Evacuated Glazing

Convective heat losses in double-glazed windows are completely eliminated if the air space is evacuated. The glass must be internally supported or the atmospheric pressure will cause implosion. One approach is to provide support with 0.3mm glass beads arrayed over the inner glass surface on a 5cm grid (Figure 3.1.6.1). Current research indicates that this approach can achieve a U-value of about 0.5W/m²K in double-glazed units with a good low-e coating to greatly reduce the radiant heat losses. The U-value is not lower because of the heat loss via thermal bridging through the glass beads and edge seal.

A high vacuum must be maintained over 20 years in order for the window to become a viable product. Only all-glass seals can currently do this job. A laser has been used experimentally to seal the borosilicate glass edges. Most of the soft coat low-e coatings cannot withstand the high heat of laser welding. The pyrolytic coatings can withstand these temperatures but their emissivities are too high for effective vacuum windows.

Another problem arises because of the glass’s tendency to bend over the glass beads causing disturbing reflections. Closer bead spacing minimises these optical distortions, but the denser spacing increases the thermal bridging and view interference.

So evacuated windows pose new technical problems for the window industry. For structural reasons, small gas gaps (fractions of a millimetre) at very low pressures (10⁻⁷ atm) are the focus of current research efforts. At this spacing, the sealing technology becomes a critical factor and getters are required to trap gasses (i.e. helium) which diffuse through the glass.
3.1.6.2 Chromogenic Glazing Systems

Technological Advances in Controlling Window Solar Heat Gains

Solar heat gains through windows can either contribute positively or negatively towards a building's energy efficiency. The impact of solar gains will vary with building type and use, climate, season, and even time of day. Unlike window U-values, where lower U-values are almost always better, there is not a universal goal for Solar Heat Gain Coefficients. For some applications, SHGCs should be maximised, for others, SHGCs should be minimised. Controlling solar heat gain is also related to other human comfort factors (i.e. thermal and visual comfort and UV fading). Often, as with the case of direct solar radiation, visual comfort concerns will dominate over the need for solar gains.

Switchable Glazing: Temporal Control of Solar Heat Gains

In some applications, it may be beneficial to use a glazing system with time dependent solar-optical properties. Main applications will be in commercial buildings where the benefits of solar gains and daylight will vary on a daily or hourly basis but could also include residential applications where the desirability of solar gains varies seasonally.

Such functions have typically been covered by shading systems—however, optically coated glass offers the potential for more effective solutions. Glazings with variable properties are typically called “chromogenic” or “switchable” glazings or, sometimes, smart windows. Chromogenic glazings offer a significant opportunity for reduced building energy use. They are just beginning to become commercialised.
The focus of research efforts in this field has been to produce glazings which control the intensity of transmitted solar gains and daylight. Such systems could be used in commercial buildings to provide an optimum amount of daylight with minimal adverse effects such as unwanted solar gains, thereby reducing the energy and peak demands imposed on buildings by electric lighting cooling. Since daylight is an ambient energy source and is typically a more efficient source of light than electric lights, it is advantageous to use daylighting as much as possible to provide the necessary illumination in internal spaces. However, the transmission of too much daylight, and the associated heat gains, can increase cooling loads dramatically; thus the need for switchable glazings.

**Control Mechanisms**

While there are several different types of switchable glazings, they all have several features in common. All switchable glazings are activated by a physical phenomena (light, heat, electricity). Once activated, they switch, either incrementally or completely, to a different state. The state with the highest solar transmittance (typically the inactivated state) is called the bleached state and the state with the lowest solar transmittance is called the coloured state.

Three control mechanisms exist. These are photochromic (or light sensitive), thermochromic (or heat sensitive), and electrochromic (electrically activated) systems. Each control strategy will have different effects on the building's thermal performance. For example, photochromic glazings may be appropriate for the control of daylight; however, they are insensitive to solar heat gain effects. Thermochromics can respond well to thermal effects, but may not necessarily allow the proper transmittance of daylight and may not be able to distinguish between high ambient temperatures and incident solar radiation. Electrochromics offer the greatest potential for energy savings since their control can be integrated into total building energy management systems, optimising the trade-offs between lighting energy and cooling consumption.

**Photochromic materials** alter their optical properties when exposed to light, typically UV, and revert to their original state when the light is removed. This phenomenon is widespread, occurring in organic and inorganic materials. Probably the most widespread use of photochromic materials in consumer goods is for sunglasses. Since this photochromic glass cannot as yet be produced using the float glass process, it would be prohibitively expensive to be used in building applications. Current research is aimed at developing photochromic plastic layers; as yet these have not exhibited the necessary durability.

**Thermochromic materials** show a change in optical properties when subjected to a change in temperature. Thermochromism is seen in both organic and inorganic materials with the primary commercial interest to date in inks, paints, security devices, temperature indicators, and even clothes. Criteria for the development of a suitable thermochromic for window applications include durability, switching or activation temperatures, switching range (intensities and wavelengths), and optical clarity in the coloured state. Suntek Co. of Albuquerque New Mexico has developed a thermochromic polymer (“Cloud Gel”) which becomes diffuse in the bleached state; this product is currently undergoing demonstration and durability testing.

**Thermochromatic Devices**

The objective is to produce a material that will passively switch between a heat-transmitting and a heat-reflecting state at specific design temperatures within the human comfort range. The composition is usually either tungsten trioxide or vanadium dioxide. On windows, it could have the appearance of a thin film on the glass.

This product seems attractive for the reduction of cooling loads, and offers ways to provide sunshading in response to solar gain. The inconvenience may be the blocking of potentially useful solar beams during the heating season. The transmission factor can vary by a range of 1 to 3, which makes this product attractive. Durability is questionable at the moment.
**Electrochromic glazings** are complex multi-layer coatings whose optical properties vary continuously from a highly transmitting or bleached state to a low transmitting or coloured state. A small potential difference, typically 1-5 volts, is all that is required to trigger a change in state. The longer the potential difference is applied, the more the electrochromic layer will switch, until it reaches its maximum or minimum. A schematic diagram of an electrochromic is shown in Fig. 3.1.6.2. Electrochromics can be tied into building energy management control systems, thereby allowing the glazings to be controlled by a pre-defined algorithm which best suits each application. For this reason, electrochromics are viewed as having a greater potential for energy savings and user comfort than photochromics or thermochromics.

Currently, glass companies and research organisations throughout the world are working to commercialise electrochromic technology. Much of this research is proprietary, although sample electrochromics are on display in Japan. Manufacturers have developed an electrochromic for use in automobile rear-view mirrors which is controlled by a photo-sensor.

**Liquid-crystal devices** are offered by several manufacturers, which change from a low-transmitting translucent state to a transparent high transmission state. Because of the large and continuous voltage required to keep these devices in the clear state, they are typically not energy-efficient products; their primary purpose is as privacy screens in offices, limousines, etc.

It is important to note that it is not necessary to optimise the properties of the electrochromic glazing but rather to optimise the properties of the glazing system or window which incorporates an electrochromic layer. Since electrochromics, in their coloured state, are intended to minimise solar gains, it is important that the solar gains not directly transmitted do not find their way into the building by another route. The best way to accomplish this is to use an electrochromic layer which switches from transmitting to reflecting. However, such a requirement is a limiting factor in the development of electrochromics. Another alternative would be to use an electrochromic device which switches from transmitting to absorbing and is placed in the IG unit in such a way that the inward flowing fraction of the absorbed component is low. The use of an absorbing layer may require the use of heat strengthened or laminated glass. Different electrochromic devices may also have different spectral responses. In commercial buildings, the primary target application for electrochromics, solar gains outside the visible portion of the spectrum should be excluded virtually all the time. Therefore, an electrochromic layer could either be designed to reflect the solar infrared with modulating transmittance properties over the visible portion of the solar spectrum, or it could be designed to be used in conjunction with a spectrally selective glazing layer with the only requirement on its switching capabilities being in the visible portion of the solar spectrum.
When lithium atoms are stored in the passive counter electrode, the window becomes transparent, allowing both radiant heat and light to pass through.

When the direction of the current is reversed and lithium atoms pass to the electrochromic layer, the window has reduced transmission of heat and/or light.
**Figure 3.1.6.2: Schematic cross-section of an electrochromic glazing.**

**Performance criteria & the state of the art**

Target performance characteristics of an electrochromic glazing have been estimated and are shown in Table 1, from Selkowitz and Lampert\(^45\).

<table>
<thead>
<tr>
<th>Spectral Response</th>
<th></th>
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<tbody>
<tr>
<td>Solar transmittance, (T_s)</td>
<td>(T_s) (Bleached)=50-70%</td>
</tr>
<tr>
<td>(T_s) (Coloured)≤10-20%</td>
<td></td>
</tr>
<tr>
<td>Visible transmittance, (T_v)</td>
<td>(T_v) (Bleached)=50-70%</td>
</tr>
<tr>
<td>(T_v) (Coloured)&lt;10-20%</td>
<td></td>
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</tbody>
</table>

**Table 1. Desired performance characteristics of an electrochromic glazing\(^46\).**

\(^{45}\) Selkowitz S E and Lampert C M, Application of large area chromogenics to architectural glazings, SPIE IS Vol 4, pp22-45, 1988

Applications, energy benefits & control

The lack of availability of smart windows outside of the research laboratory has meant that to date little real experience has been gained in their use and operation in buildings. It is likely that the progress achieved by industry in realising large area electrochromic and thermochromic windows will enable demonstration projects to be set up in different climatic zones in the near future. Such projects will yield valuable information on possible control strategies to be implemented in linking the window optical properties to the building environmental conditions, provide experience on integrating the control system to the building heating, ventilation and air conditioning services and contribute to the advancement of intelligent buildings.

Present investigations of potential energy impacts and control strategies have largely been studied through the use of building simulation tools and much of the detailed work has been carried out by the Windows and Daylighting Group at the Lawrence Berkeley Laboratory, University of California. Much of the emphasis has been on cooling-dominated buildings where it is expected that a switchable glazing will help reduce cooling and lighting loads.

The performance characteristics listed in Table 1 together with additional factors which will influence the market acceptance of electrochromic windows have been reviewed by Selkowitz et al47 48. Expected energy savings were calculated and compared with the performance of conventional glazings. Different glazing configurations and control strategies were studied for electrochromic glazings using representative optical properties data obtained from current prototype devices and for improved devices which one may reasonably expect will be developed in the future, e.g. a low-e electrochromic device. The study raises interesting issues in regard of predictive control, the reduction of peak demand, occupant comfort and the architectural and aesthetic appeal of a dynamic coating. The results indicate that electrochromic windows can be highly effective in reducing peak electricity demand and electricity consumption in commercial buildings in southern California.

3.1.6.3 Holographic Optical Elements

Spatial Control of Daylight Distribution

In a daylit commercial building, there is often a surplus of daylight; unfortunately it is typically not distributed evenly throughout the floor space. While skylights are an effective means to daylight a building, their use is limited to the top floor of a building. As a result, other approaches must be explored to redistribute daylight incident on the side of a building.

Holographic optical elements (HOEs) redirect light by diffraction.

Holographic Films

The principle of such films is to intercept sunlight and to diffract part of the radiation in another direction giving a similar effect to prismatic systems. When applied to a window incoming sunlight can be redirected deeply into a room. In addition, the luminous efficacy of this radiation can be increased by tuning the holographic film to reflect non-visible radiation wavelengths which contribute to the solar heat gain.

Holographic films are generated by a photographic process on a dichromate gelatin, which at present imposes a limitation on the maximum size of the films. Furthermore, such films are wavelength sensitive and create rainbow reflections.

The major field of applications seems to be currently far removed from the building domain. Holographic devices are used to produce low-cost and light-weight optical systems for "head-up" displays in military jets, or light concentrators. The possibility of use in windows offers the best large-scale potential. Although tests and simulations have been performed, there is no production of such films in large dimensions.

**Function of HOE**

The principle of this technology is that windows have a transparent coating applied in which an invisible diffraction pattern has been "printed" by a holographic technique. The window will then deflect transmitted direct and diffuse solar radiation over a certain angle (which is defined by the diffraction grid characteristics) deep into the building. Similar grids can also be used to reflect away solar light which impinges on the window from well defined angles.

One of the main advantages of HOEs is the fact that, unlike conventional optical elements, their function is essentially independent of substrate geometry. Another advantage is the possibility of spatially overlapping elements, since several holograms can be recorded in the same layer. Volume holograms, recorded in dichromated gelatin, can take up to four different images with specific information.

**Design of HOEs**

The diffraction pattern of transmittance and reflection holograms has to be defined before recording. Light then emerges at set exit angles, but only if the angle of incidence and wavelength of the incident light satisfy a particular relationship. It is possible to obtain a diffraction efficiency of 90%, which means that 90% of the incoming light can be redirected to a specific point in the space.

The diffraction of light waves - the way in which they bend when they pass an obstruction - is a well known phenomenon. Light waves resemble ripples on water: when one encounters another, interference patterns are created. Such an interference pattern, refined by the coherence (single wavelength) of laser light, is frozen on a recording material to create a hologram. The recording process is similar to the recording procedure of display holograms, but without the use of an object. A split laser beam is aimed at the recording material to create the interference pattern.

**Conclusions**

The performance of the HOEs tested for diffuse light was very poor. No significant effect is visible because light waves of diffuse light are coming from various directions; if there was any specific light directing effect it was so small that it could not be detected.

When using the HOE for direct sunlight there is high potential for application in design. HOEs can be designed as sunshading and light-directing devices in combination, without altering the distribution of window area. However, at certain viewing angles rainbow effects are created.

There is a very high potential for the application of HOEs in buildings for improving the luminous environment. Among the advantages are:

- the conventional appearance of a building does not need to be changed when using HOES: there is a high potential for its application in building retrofits
- HOE elements can fulfil several functions of building aperture in one element: light admitting element, sunshading, passive control of energy consumption
- HOE elements can also be combined with various functions of the glazing material: insulating glazing, security glazing, acoustic glazing, etc
- for properly designed HOEs there is no need for sun-tracking
- the design of the HOE integrates the requirements of the user and the architecture.