CENTRE FOR WINDOW AND CLADDING TECHNOLOGY

Use of Advanced Glazings

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Centre for Window and Cladding Technology 1997

This research report was written by the Centre for Window and Cladding Technology (CWCT) as a review of advanced glazing technology, with particular attention paid to those factors which will influence the up-take of advanced glazing technologies.

Whilst every care has been taken in the preparation of this report, the CWCT cannot be held responsible or liable in any respect of the use to which the information in this report is put. It should be noted that because many of the advanced glazings described in this report are still under development any problems reported here may have been resolved by the time of publication, or may be resolved in the near future.

The research work was funded by the Department of the Environment under research contract number 39/3/181.

Centre for Window and Cladding Technology
January 1997

ISBN 1 874003 08 4

Published by
Centre for Window and Cladding Technology University of Bath, Claverton Down, Bath BA2 7AY

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INTRODUCTION

This report is based on the findings of a project to assess the potential use of advanced glazings. The following objectives were specified at the start of the project:

- to identify potential barriers to the use of advanced glazings including their technical risks and durability
- to identify necessary supporting technology for advanced glazing systems (this will include framing technology, aspects of volume manufacturing, handling, installation and maintenance)
- to evaluate and propose feasible measures to remove or overcome the potential barriers identified

To achieve these objectives a number of discussions were held with potential users, manufacturers and researchers involved in the development of advanced glazing technologies in several countries, including the UK, Germany, Australia, Japan, Canada and the USA. The results of these discussions are presented in the following report, which has been divided into three Parts for convenience

- Part A A review of advanced glazings and technical performance criteria
- Part B UK issues affecting the uptake of advanced glazing technologies
- Part C World-wide issues affecting the uptake of advanced glazing technologies

Whilst the authors hope that this report is reasonably comprehensive at the time of publication it is recognised that there are many types of advanced glazings under development at the present time, and many variations within each generic type. However, general performance issues are the same for all types of advanced glazing, and this report attempts to describe all of the factors that will influence the use of different generic types of advanced glazing.

As most advanced glazings are being developed for reducing energy usage, and are still in the development stage, it is only in issues of energy and thermal behaviour that sufficient information is available to describe the performance of many advanced glazings. It is not yet possible to consider issues of fire or acoustic performance although some general comments are made (these issues are also specialised and complex subjects in their own right).

Energy issues

The Commission of the European Communities published a report in 1993 (Thermie [1993]), as part of its Thermie programme of funding, which examined the best available technologies (BATs) for reducing energy usage in the EC. It is estimated that 28% of primary energy use in the EC is associated with buildings. The consumption of energy for space heating accounts for about 20% of EC primary energy consumption, but around 30% of this amount could be eliminated by better insulation of buildings. Further reductions are possible with the active and passive use of solar energy. It is also important to reduce the production of CO_2, SO_2 and NO_x gases, and the use of better insulation, active solar energy and more efficient electrical appliances and lighting will have the greatest impact in this area.

The better use of day-lighting and the development of glazings with a higher insulation rating is therefore highly important in the reduction of energy use and emissions. Advanced glazing technology has the potential to make far greater savings than if the insulation content of walls and roofs alone were increased.

Fenestration 2000

In 1987 approval was given for a study into the long-term requirements for fenestration. The Fenestration 2000 study included interviews with experts world-wide, studies of current and new glazing technologies and assessment of potential energy savings.

The Phase I Fenestration 2000 report by Button and Dunning [1989], the Phase II report by Halcrow Gilbert Associates [1992] and the Phase III report by Lampert and Ma [1992] discuss many types of advanced glazing technology, and the findings from those reports are considered here.

International Energy Agency (IEA)

Advanced glazings are currently being developed world-wide by a number of organisations. An umbrella project which helps to co-ordinate research efforts is the IEAs 'Task 18 Advanced Glazing Materials'. Operated by Professor Mick Hutchins of Oxford Brookes University, IEA Task 18 brings together experts from all around the world in the field of advanced glazings. Most of the work to develop and test advanced glazings is drawn together by Task 18, and results from the work are published in a series of internal reports. However, although Task 18 is ideally placed to assess the physical performance of advanced glazings there is still a considerable gulf between academic research and practical application. It is the intention of this report to consider advanced glazings from an applications point of view, and to raise some of the key issues that are asked of components in modern facades, such as is it durable?, is it easy to use? and how will it improve the building?

Acknowledgements

The authors acknowledge the support of those individuals and organisations who contributed to this project, whether through provision of data, informal discussion, formal interview or review of this report.

The project was funded by the Department of the Environment under research contract number 39/3/181.

Part A A review of advanced glazings and technical performance criteria

A1 Performance issues

This section concentrates on an introductory description of advanced glazing technologies, and summarises the basic physical relationships that govern the performance of glazings and advanced glazings. Techniques of performance assessment (existing and under development) relevant to advanced glazings are also discussed.

A1.1 Light and heat

The visual and thermal conditions within a building are two of the most important factors affecting a person's comfort, and it is the building envelope which plays the most important part in achieving an acceptable indoor environment. The building envelope acts as a barrier to the harsh conditions which exist in the natural environment, and may be used to completely isolate the internal environment from that outside or to act as a filter which allows some heat and light energies to pass between the two.

Although a massive and well-insulated building envelope would provide excellent thermal isolation from an external environment, it would be considered unacceptable by most people if it did not also provide the opportunities to enjoy the warmth of the sun and delight in a view through a window. However, the advantages of a window are not provided without cost. The massive well-insulated envelope has been punctured and no longer will it provide the same degree of thermal isolation; heat will now be required to make up for that which is lost through the window in winter, and cooling may be needed to reduce the overheating from sunlight in a hot summer.

Adding a window does not inevitably result in additional energy costs however; light through the window will reduce the energy needed for electric lighting and sunlight on a cold winter day will help keep the building warm. The complex balance between energy gains and losses through a window considerably increases the complexity of designing a facade and it can be quite difficult to accurately predict the nett balance between the energy gains and energy losses.

The window is rarely a static building element and its characteristics are modified to make the most of particular features of the glazing. Because ordinary window glass transmits solar heat as effectively as it does light, an external shutter may be used to limit the sunlight entering a building in midsummer and the poor insulation of such glass may be compensated for by using the shutters to keep in the heat on a cold winter night. Curtains may be drawn at night to retain heat, and this also softens the interior decor to make a room more comfortable than it would appear with black windows harshly reflecting the electric lights. Net curtains may be used to alter the appearance of the window and obscure the view into a building, and thus provide more privacy than possible with clear transparent glazing on its own.

These techniques are all examples of modifying the overall behaviour of the window so that favourable aspects of the glazing are exploited whilst the consequences of some of the less attractive features of glazing are ameliorated. Advanced glazings are being developed so that some of the selectivity possible in the overall window design can be incorporated within the glazing itself.

The physics of light and heat, as it relates to buildings, can be divided into two clear subject areas - *solar radiation* and *heat transfer*.

- Solar radiation is energy in the form of the electromagnetic spectrum. The parts of the spectrum that are of interest to the building engineer are the ultraviolet (wavelengths from approximately 300×10^{-9} m (300 nm) to about 380×10^{-9} m (380 nm)), visible light (wavelengths in the region of 380×10^{-9} m (380 nm) to 780×10^{-9} m (780 nm)) and near infra-red (wavelengths from 780×10^{-9} m (300 nm) to approximately 3000×10^{-9} m (3000 nm)).

- Heat transfer comprises three basic processes by which energy is transferred from one point to another - conduction in solid and stationary fluids, convection in moving fluids and radiation heat transfer in the far infra-red.

A1.1.1 Near- and far-infrared

The distinction between near- and far-infrared is important. All surfaces at a temperature above absolute zero emit electromagnetic radiation. For a surface which behaves as a black body the wavelengths at which radiation is emitted is a function of the surface temperature, with a peak energy emitted at some wavelength which is directly related to the surface temperature by Wien's law

$$\lambda_{\max} T = 2.896 \times 10^{-3}\,\mathrm{mK}$$

- λ_{max} is the wavelength of maximum radiation intensity, in m
- T is the surface temperature, in K

and a distribution across wavelengths which is given by Planck's law

$$E_\lambda = \frac{c_1 \lambda^{-5}}{e^{c_2/\lambda T} - 1}$$

- $E_\lambda d\lambda$ is the energy flux density emitted in the wavelength range λ to $\lambda+d\lambda$, in W/m^2
- λ is the wavelength of radiation, in m
- T is the surface temperature, in K
- c_1 and c_2 are constants ($c_1=3.74\times10^{-16}$ Jm^2/s, $c_2=1.4388\times10^{-2}$ mK)

The total energy flux emitted per unit area of a 'black' surface is given by Stefan's law

$$q = \sigma T^4 \text{ W/m}^2$$

- q is the energy emitted per unit area across all wavelengths, in W/m^2
- σ is the Stefan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8}$ W/m^2K^4)

A surface at a temperature of 6000 K (the surface temperature of the sun) will emit radiation in a distribution around a peak wavelength of 483 nm, which is in the visible light region. A surface at a temperature of 1000 K will emit radiation at a wavelength of 2896 nm, which is at the edge of the near-infrared. A warm building surface, at a temperature of 313 K (40°C) emits radiation around a peak wavelength of 9252 nm, which is deep into the far-infrared.

The distribution of radiation is shown in Figure A1.1.1 for solar radiation at high altitude, and for a black body at 6000 K and 313 K. Note that the vertical axis of the 303 K line has been greatly magnified - a black body at 313 K emits 544 W/m^2 whilst a black body at 6000 K emits 73.5 MW/m^2, some 135,000 times more energy. Heat transfer, which is concerned with energy transfers at low temperatures, is clearly concerned with the far-infrared, whereas solar radiation is concerned with the near-infrared.

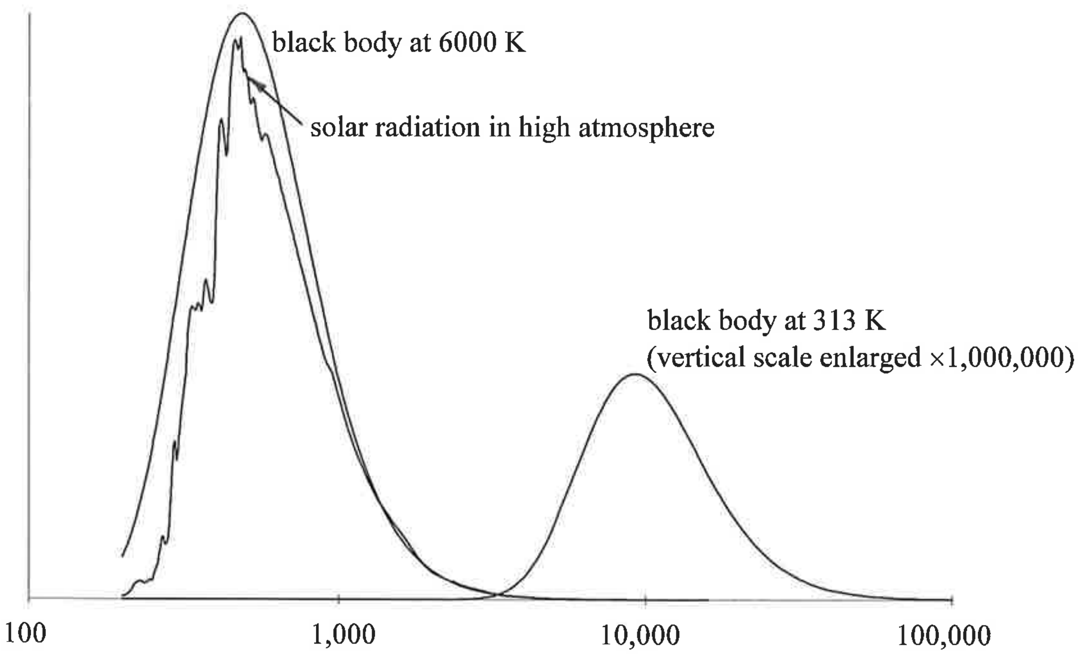


Figure A1.1.1 Distribution of radiation for selected surfaces

It should be noted that dust, water and other chemicals in the atmosphere absorb some of the solar radiation before it reaches the ground. The distribution of energy at sea level is therefore slightly lower than the distribution shown in Figure A1.1.1.

A1.1.1.1 Emissivity

For a real surface the emission of energy does not follow the black-body curve - less energy is radiated but over the same range of wavelengths. The ratio of the actual emitted energy to the energy that would be emitted by a black body at the same temperature is termed the emissivity of the surface

$$\varepsilon = \frac{q}{\sigma T^4}$$

- ε is the emissivity
- q is the actual radiation emitted per unit area of the surface, in W/m^2

Emissivity is a function of the wavelength of the radiation, and is also a function of the direction from which the surface is viewed. If it assumed that a surface has the same emissivity at all wavelengths then the surface is termed 'grey', and this assumption is usually made for building surfaces. The effect of viewing direction (i.e. the direction in which the radiation is emitted - radiation is emitted in all directions from a surface) is then allowed for either by obtaining a true emissivity spectrum, by considering only a normal viewing direction, or by taking an average over a solid hemisphere.

Some typical values of emissivity for surfaces at room temperature are given in the table below (note that emissivity is not strongly affected by the colour of a surface - colour is only relevant to visible light, whereas these emissivity values are for surfaces at room temperature, where radiation is emitted in the far-infrared):

Surface material	Normal emissivity
polished aluminium[1]	0.04
oxidised aluminium[1]	0.10
anodised aluminium[1]	0.72
polished steel, mild[1]	0.08
oxidised steel, mild[1]	0.79
polished steel, 316 stainless[2]	0.28
glass[1]	0.88
surface painted with white oxide-based paint[2]	0.9-0.95
surface painted with black oxide-based paint[2]	0.96
[1] from CIBSE Guide Part C3 [1986] [2] hemispherical emissivity from CALEX [1980s]	

The emissivity of a surface is usually either high (0.7 to 1.0) or low (0.02 to 0.4). As a rule of thumb a surface which conducts electricity has a low emissivity (e.g. polished metals, some metal oxides), and a surface which resists electricity has a high emissivity (glass, concrete, some heavily oxidised metals).

Figure A1.1.2 shows typical distributions of emissivity at a single wavelength with viewing angle for a low emissivity surface and a high emissivity surface.

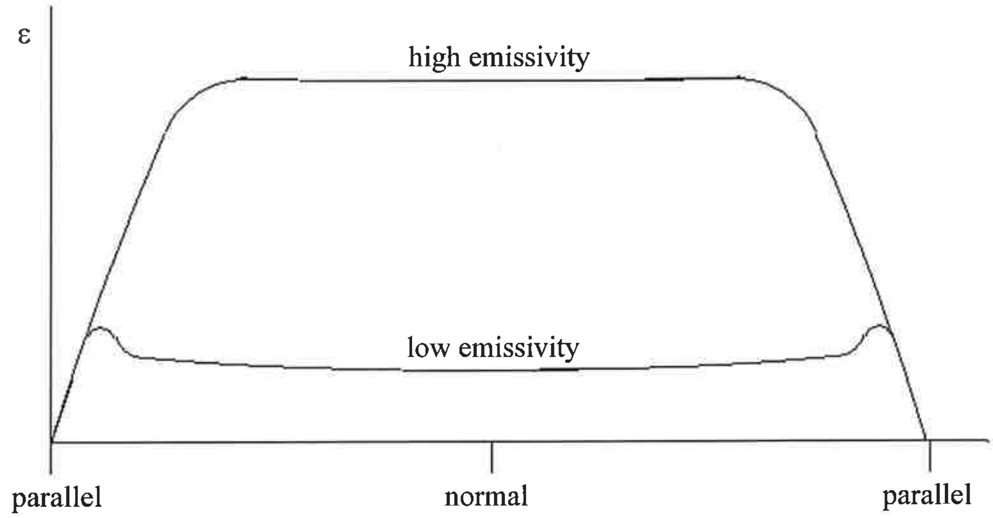


Figure A1.1.2 Variation of emissivity with viewing angle

A1.1.2 Solar-radiated energy

All solar radiation is energy. When solar radiation strikes a surface a proportion of the radiation, whether it is ultraviolet, visible light or near-infrared, is absorbed, thus increasing the energy content of the surface. The absorbed energy causes the surface temperature to increase, and this then increases the emission of energy by the surface in the far-infrared.

All solar radiation therefore increases the energy content of a building. This can give rise to overheating in summer, but it is not possible to exclude all of the solar energy from a building because visible light is also energy. If 100% of the light is admitted, but none of the ultraviolet or infrared, then 54% of the total solar energy would still be admitted (Button and Pye [1993] pp166). This represents the best performance in terms of admitting all of the light but rejecting unwanted heat. Further gains in performance require that some of the light is also excluded, but this can then lead to an increase in the requirement for artificial lighting.

There are of course important issues beyond energy performance. The admission of ultraviolet and visible light at the blue end of the spectrum may lead to the fading of some colour finishes (it is not sufficient just to exclude the ultraviolet; the blue component of visible light also influences fading (Button and Pye [1993] pp101-103). Ultraviolet can also lead to problems with degradation of materials, particularly some polymers. The admission of natural light is essential to human comfort, but too much strong direct light can lead to problems with glare. The admission of infrared may lead to overheating in summer, but can be very beneficial in winter.

A1.1.2.1 Reflection, absorption and transmission

When any form of radiation strikes a surface three things can happen - the radiation is either reflected, absorbed or transmitted, and usually a mix of all three. Furthermore, reflection, absorption and transmission can be wavelength- and angle-dependent. Additionally, any radiation that is absorbed will increase the temperature of the surface and result in greater emission of radiation in the far-infrared. A surface can also have a diffusing effect, so that specular radiation becomes diffusely reflected and transmitted.

The selective nature of reflection, absorption and transmission can cause problems, but can also be highly desirable. Natural light appears white because it contains an even mix of colours. Tinted glasses filter out some of the light, changing the spectral composition, and this is what gives them their colour. However, changing the colour of transmitted light can have detrimental effects on the colour rendering of surfaces.

The spectrum of light from the sky can vary a great deal and our eyes have developed to adapt to a range of correlated colour imperatives. Therefore problems should only occur where there is a gross distortion or sudden change in transmission; ideally a glazing material should change the spectrum of the visible part of the solar spectrum gradually, so that the light passing through the glazing gives a true rendition of colours, although brightness may be limited. However, reducing brightness too much can lead to a feeling of isolation, because the human eye and brain are used to high levels of natural light (there is evidence from physiological studies that gross distortion of the light spectrum can affect biological development, but there is no evidence that the modifications to light passing through current glazing types adversely affects human biology).

The fact that reflection, absorption and transmission depend upon the angle of incidence of the solar radiation can be used to improve the performance of the glazing. Button and Pye [1993, pp161] give the example of a south-facing glazing at 54° latitude, with the sun at 60° elevation, for which the direct solar energy transmission is 73% with the glazing vertical, but only 51% with the glazing tilted outwards by 15°. In this way the peak solar gain is reduced, but when the sun is at low altitudes in the winter the transmission is better.

A1.2 The analysis of solar radiation

Consider a simple surface on which the sun may shine at some moment in time. The surface receives ultraviolet, light and infrared, in a proportion that depends upon the angle of the surface, its geographical position (latitude, longitude and altitude), the time of day, the time of year and the condition of the sky and any shading elements between the sun and the surface.

The total radiation reaching an exposed surface may comprise a direct component from the sun (sunlight), a scattered component from the clear sky (skylight), a reflected and diffused component from clouds (daylight) or radiation reflected from the ground and other buildings (ground light), as shown in Figure A1.2. Within a building these various components may directly irradiate a surface or reach it after reflection from internal surfaces in the room.

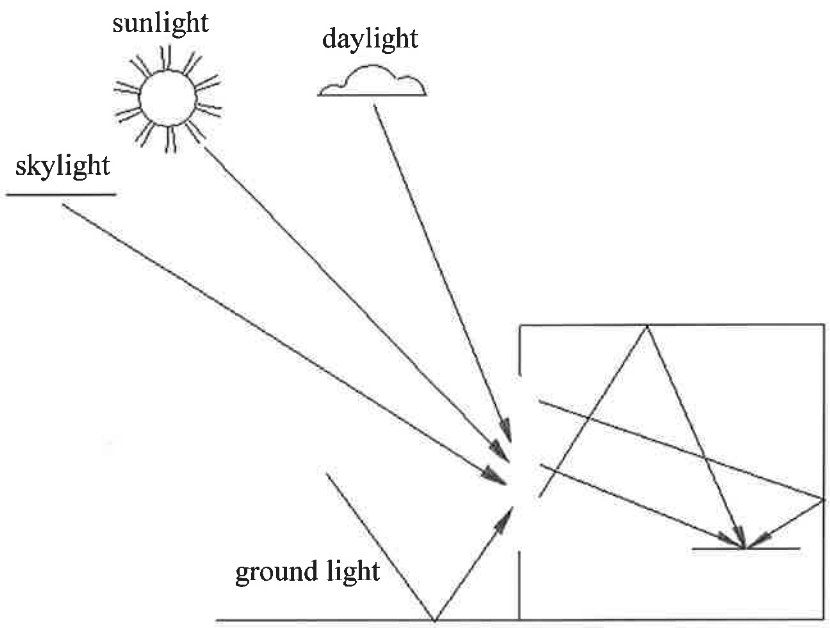


Figure A1.2 Radiation components reaching a surface inside a building

The radiation I that falls on any surface must be either reflected, absorbed or transmitted, and usually some combination of the three. The fraction that is reflected is

ρI	whilst
αI	is absorbed and
τI	is transmitted, where

$$\alpha + \rho + \tau = 1$$

However, the parameters α, ρ and τ are dependent upon the angle of incidence θ and the wavelength of the radiation. Thus light and infra-red will behave differently when striking a surface, and the behaviour of the surface at near-normal incidence (incidence perpendicular to the surface, $\theta \approx 0$) can be very different to near-parallel incidence ($\theta \approx 90°$). Furthermore, the path that the sun makes through the sky is not simple, and the solar altitude and solar azimuth are complex functions of other parameters.

A1.2.1 Solar radiation on a layered structure

The structure shown in Figure A1.2.1 is a simple layered component, such as a multiple glazing unit with a suspended film:

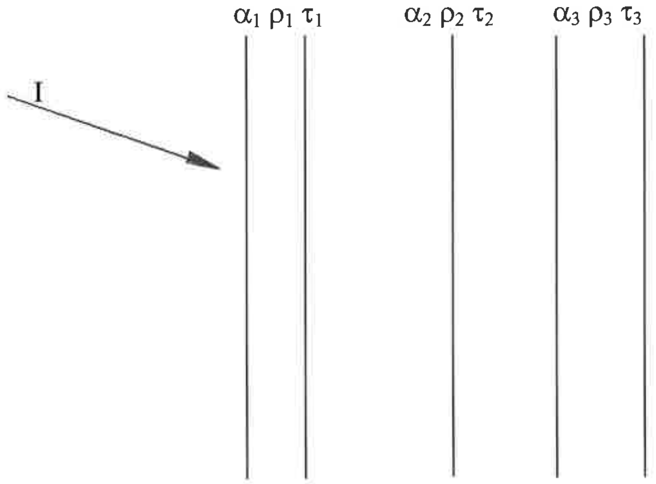


Figure A1.2.1 Layered component with incident solar radiation

Each layer has a known reflection, absorption and transmission characteristic, together with a known characteristic for the emission of far-infrared. Of the incident radiation I a total part ρI is reflected and a total part τI is transmitted. The remainder αI is absorbed, but each layer may absorb a different amount, depending upon its particular properties. Note also that the part that is reflected consists of direct reflection from each of the layers, together with the transmitted part of each repeated reflection between layers - i.e. each pair of adjacent layers may reflect light and infra-red between them, losing a proportion of the energy by absorption and transmission each time a surface is encountered.

To analyse the multiple reflections between layers, and the absorption and transmission at each surface, is difficult. However, it can generally be assumed that only solid parts of the structure absorb any energy directly (the gaseous parts of a structure absorb energy by heat transfer) and that the absorption, reflection and transmission at each surface is independent of wavelength and direction. This at least allows an estimate to be made of the total energy reflected, transmitted and absorbed.

A1.3 The analysis of air infiltration

Air infiltration is a frequently-neglected issue in glazing energy performance. This is because air infiltration requires an assessment of framing systems, and yet glazing manufacturers are only concerned with promoting the benefits of their glazings, which can be done by considering only the centre-part of a glazing.

Air infiltration results in energy exchange by mass transfer.

A1.3.1 Mass transfer

Mass transfer is the simplest form of energy transfer to deal with. If some solid or fluid is transferred from one side of a facade to the other then it will probably undergo some temperature change. The temperature change represents a change in the energy of the substance, and so represents an energy transfer (another way of looking at this is to say that if a volume of conditioned air is lost from a building then it must be replaced with an equal volume of unconditioned air from outside a building - the energy 'exchange' is that energy required to condition the air entering the building).

Under steady conditions if air passes through a facade at a mass flow-rate of m kg/s and has a specific heat capacity of C_P J/kgK then the energy transfer for a ΔT temperature change is

$$\Delta E_m = \dot{m} C_P \Delta T$$

If the volumetric flow-rate Q (in m^3/s) of the air is known then the mass flow-rate is the volume flow-rate multiplied by the air density

$$\dot{m} = \rho Q$$

The air flow-rate may be a function of the pressure difference across the facade, in the case of natural ventilation or air leakage, or may be reasonably steady, in the case of forced ventilation.

Methods of installation of glazings should be chosen after taking into account the detrimental effect that air leakage will have, which is far more significant if the glazing is particularly energy-efficient. A common design aim is that all air movements through the facade must be designed for, and incidental air movements avoided.

A1.4 The analysis of heat transfer

Heat transfer is the only form of energy transfer which is present at all times - any absolute temperature difference between two points and heat transfer will then occur between those two points.

There are three basic processes for heat transfer - conduction, convection and radiation.

A1.4.1 Conduction

Conduction is entirely responsible for heat transfer within opaque solids, and also plays a role in heat transfer in transparent solids and small bodies of fluid. Consider a simple uniform slab of material, as shown in Figure A1.4.1:

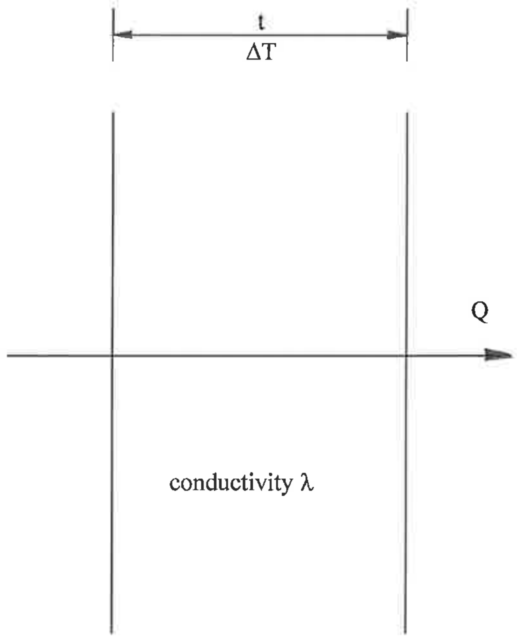


Figure A1.4.1 Conduction through a uniform slab of material

The defining equation for one-dimensional conduction heat transfer through a uniform slab of material is

$$Q = \lambda A \frac{\Delta T}{t}$$

- Q is the heat transfer, in W
- A is the area of the slab, in m^2
- t is the thickness of the slab, in m
- T is the uniform temperature difference across the slab, in °C
- λ is the thermal conductivity of the material, in W/mK

Some typical values of thermal conductivity are

Material	Thermal conductivity [W/mK]
aluminium	201
steel, mild	55
steel, stainless	15
glass	1
polycarbonate	0.2
air	0.025
argon	0.017

The heat transfer per unit area is

$$q = \frac{Q}{A} = \lambda \frac{\Delta T}{t}$$

From this equation it is easy to see that for a given temperature difference the least conduction heat transfer will occur through a thick layer of a material with a low thermal conductivity. If a vacuum can be created then it will have zero thermal conductivity and there will be zero conduction heat transfer. Otherwise, the lowest thermal conductivities are those of gases or highly-porous materials, but the thickness of a gas layer (gas-space, because the layer must be entrapped between two solid layers) cannot be increased too far or convection heat transfer will occur and the heat transfer will start to increase. A highly porous material, such as an aerogel, has a significant advantage over a gas, because increasing the thickness of the material does not encourage convection heat transfer.

A1.4.2 Convection

Convection heat transfer occurs in a fluid when the fluid moves over a surface that is at a different temperature. The mechanism for the fluid movement may be naturally induced buoyancy forces resulting from a conduction temperature gradient, in which case the terms natural or free convection are used, or the fluid movement may be caused by some external agency, such as a pressure difference or fan, in which case the term forced convection is applied.

Convection heat transfer between a surface and a body of fluid is defined by the relationship

$$Q = hA\Delta T$$

- Q is the heat transfer, in W
- A is the surface area, in m^2
- ΔT is the temperature difference between the fluid and the surface, in °C
- h is the convective heat transfer coefficient, in W/m^2K

Generally the heat transfer coefficient h can be predicted theoretically if the fluid movement is laminar, but must be determined experimentally if the fluid movement is turbulent. The value of h depends on the surface size and orientation, the relative velocity of the fluid and the fluid material properties.

Convection heat transfer through a gas-space is always greater than the conduction heat transfer through the same gas-space. It is desirable that the gas-space should be of the width where conduction is about to give way to convection, but this often limits the gas-space to 10-15 mm in width. Multiple gas-spaces in glazing units using gases such as air require more glass, and so are heavier and more expensive. Gases which limit the onset of convection heat transfer (or ordinary gases at lower pressures) and solids with low thermal conductivity values are therefore desirable as means of eliminating convection heat transfer in advanced glazing systems.

For convection heat transfer in an enclosed gas-space the value of the heat transfer coefficient is usually obtained from an empirical correlation based on many hundreds or thousands of previously reported measurements. Correlations for natural (free) convection in an enclosed gas-space are based on the use of the dimensionless Nusselt and Rayleigh numbers, with a correction for the height of the gas-space

$$Nu = C(Ra)^n\left(\frac{t}{L}\right)^p \quad \text{where} \quad Nu = \frac{ht}{\lambda} \quad \text{and} \quad Ra = \frac{\beta g \theta t^3 \rho^2 C_P}{\mu \lambda}$$

- Nu is the Nusselt number (dimensionless)
- Ra is the Rayleigh number (dimensionless)
- t is the thickness of the gas-space, in m
- L is the height of the gas-space, in m (the width of the gas-space may also be important)
- h is the convective heat transfer coefficient, in W/m^2K
- λ is the thermal conductivity of the gas, in W/mK
- β coefficient of cubic expansion of the gas, in K^{-1}
- θ is the temperature difference across the gas-space, in °C
- ρ is the density of the gas, in kg/m^3
- C_P is the specific heat capacity of the gas at constant pressure, in J/kgK
- μ is the dynamic viscosity of the gas, in Ns/m^2
- C, g, n and p are constants ($g=9.80665\ m/s^2$, C, n, p depend on geometry)

This correlation is applicable regardless of the actual gas that is used. More importantly this correlation can be used to predict the transition from conduction to convection heat transfer - if the Nusselt number from this equation is less than unity (Nu=1.0) then conduction heat transfer is occurring. If the orientation of the gas-space is known (coefficients C, n and p depend on the orientation of the gas-space) and a suitable gas is identified then it is straightforward to identify the thickness of the cavity for which the transition from conduction to convection occurs at a given temperature difference θ.

In order to use this correlation it is necessary to know the value of the property

$$\lambda\left(\frac{\beta\rho^2 C_P}{\mu\lambda}\right)^n$$

Some values of this group are given below (at atmospheric pressure and a mean temperature of 10°C), based on horizontal heat transfer through a vertical gas-space for which n=0.38 (BS 6993:Part 1 [1989])

Gas	Property $\lambda(\beta\rho^2 C_P/\mu\lambda)^{0.38}$ [W/mK]
Kr (krypton)	7.9
Ar (argon)	8.9
air	12.3
SF_6 (sulphur hexafluoride)	25.3

Sulphur hexafluoride has been used in multiple glazing because it has a higher density and lower viscosity than other gases and so gives better sound insulation. However, it should also be noted that from a purely thermal point of view the use of a gas such as sulphur hexafluoride also allows thinner gas-spaces than with other gases (the thermal conductivity of SF_6 is about half that of air) - this is often preferred as a reduction in the volume of gas means that the build-up of pressure due to gas heating is reduced. It is known that the gas in the gas space becomes hotter as the panes of glass heat up. The relative expansion of the gas is roughly the same regardless of the actual type of gas - they all have about the same value for the coefficient of cubic expansion β (about 0.0035 $°C^{-1}$ at 10°C) and so these gases each try to expand their volume by about 3.5% for each 10°C increase in mean temperature. However, a 3.5% increase requires double the absolute volume change for a 12 mm gas-space as for a 6 mm gas-space. Any expansion of the gas must be accommodated by deflection of the glass, and so a thicker gas-space will require more expansion, which requires more deflection of the glass, which creates higher stresses in the glass (which could lead to glass failure) and generates higher pressures in the gas (which could lead to failure of the edge seal). The failure rate will be highest in small glazing units (the glass is more stiff and so less able to deflect, leading to higher pressures) with large gas-spaces (more initial volume so more volume increase). Failure will be manifested as either glass failure (the hotter pane of glass will usually fail, because the thermal stresses in the glass are also higher) or as failure of the edge seal, which may take two or three years to become visible (failure of the edge seal is eventually seen as condensation in the gas-space).

A1.4.3 Radiation

The fundamentals of radiation heat transfer have already been discussed above. However, there are some specific issues which are worth considering in slightly more depth.

The amount of radiation that is emitted by a flat surface is limited by the physical law

$$Q = \sigma \varepsilon_h A T^4$$

- ε_h is the hemispherical emissivity of the surface (the average emissivity over all viewing directions, dimensionless)
- A is the area of the surface, in m^2
- T is the absolute temperature of the surface, in K
- σ is the Stefan-Boltzmann constant (σ=5.67×10^{-8}W/m^{2}K^4)

However, the exchange of radiation between two flat surfaces is a more complex problem. Infrared radiation is just another part of the electromagnetic spectrum, and behaves in an identical manner to light - thus infra-red radiation may be reflected by a surface, absorbed, transmitted, scattered or prevented from reaching a surface if there is some obstruction which casts a thermal shadow. If two surfaces are in direct line of sight of one-another then there can be multiple reflections between the surfaces, and not all of the radiation leaving one surface will strike the other.

This complex interaction between surfaces means that radiation heat exchange can only be calculated in a number of special cases. Where the infra-red exchange between two surfaces can be calculated it is usually in the form

$$Q_{12} = \sigma A_1 \Phi \left(T_1^4 - T_2^4 \right)$$

- Q_{12} is the net amount of energy leaving surface 1 which arrives at surface 2, in W
- A_1 is the area of surface 1, in m^2
- T_1 is the absolute temperature of surface 1, in K
- T_2 is the absolute temperature of surface 2, in K
- Φ is some combination of the surface emissivities together with a factor for the visibility of surface 1 form surface 2

Although this relationship appears complex it can be factorised into the form

$$Q_{12} = \sigma A_1 \Phi \left(T_1^2 + T_2^2 \right)\left(T_1 + T_2 \right)\left(T_1 - T_2 \right)$$

Now, T_1 and T_2 must be absolute temperatures, in degrees Kelvin, and so in buildings they will have values typically in the range 263-313 K (-10 to +40°C). The term

$$\left(T_1^2 + T_2^2\right)\left(T_1 + T_2\right)$$

can then be replaced with the term

$$4T_m^3$$

- T_m is the mean surface absolute temperature, in K

$$T_m = \frac{T_1 + T_2}{2}$$

This then gives

$$Q_{12} = 4T_m^3 \sigma \Phi A_1 \left(T_1 - T_2\right)$$

This substitution gives an error of just 0.75% if T_1=263 K and T_2=313 K.

The relationship for radiation heat transfer can now be expressed in the form

$$Q_{12} = h_r A_1 \left(T_1 - T_2\right)$$

- h_r is the radiative heat transfer coefficient, in W/m^2K

$$h_r = 4T_m^3 \sigma \Phi$$

A1.4.4 Combined heat transfer relationships for simple layered structures

The relationships for the individual forms of heat transfer can often be combined to determine an overall relationship for the heat transfer through a component. Usually a glazing system is in the form of uniform layers of several materials. The heat transfer through the combined structure can be determined using the principle of thermal resistance.

The thermal resistance of an object is defined as

$$\Re = \frac{\Delta T}{Q}$$

- $\Re$ is the resistance, in m^2K/W
- ΔT is the overall temperature difference across the object, in °C
- Q is the resulting heat transfer through the object, in W

For a uniform layer (a layer of constant and uniform thickness with constant and uniform properties) in which only conduction heat transfer is occurring the heat flow is defined by

$$Q = \lambda A \frac{\Delta T}{t}$$

The thermal resistance of a conduction layer is therefore

$$\Re = \frac{\Delta T}{Q} = \frac{t}{\lambda A}$$

For a convection process between a surface and a fluid the heat flow is defined by

$$Q = hA\Delta T$$

and so the thermal resistance is

$$\Re = \frac{\Delta T}{Q} = \frac{1}{h_c A}$$

For a radiation process between two surfaces the heat flow is given by a relationship of the form

$$Q_{12} = h_r A_1 (T_1 - T_2)$$

The thermal resistance of a radiation process between two surfaces can therefore be expressed as

$$\Re = \frac{T_1 - T_2}{Q_{12}} = \frac{1}{h_r A_1}$$

For a number of layers placed together (they are described as being in series because the heat must transfer from one to the next in sequence) the overall temperature difference is equal to the sum of the temperature differences across each layer, whilst, under steady conditions, the heat flow through each layer is the same. Therefore

$$\frac{\Delta T}{Q} = \frac{\Delta T_1 + \Delta T_2 + \Delta T_3 + \ldots}{Q} \quad \text{or} \quad \Re = \Re_1 + \Re_2 + \Re_3 + \ldots$$

For a cavity between two flat surfaces radiation heat transfer can occur in parallel with either conduction or convection heat transfer (depending on the thickness of the cavity). In either case the heat transfer processes are parallel - the temperature difference is the same for each process but the total heat transfer is the sum of the individual heat transfers.

Thus

$$\frac{Q}{\Delta T} = \frac{Q_1 + Q_2}{\Delta T} = \frac{Q_1}{\Delta T} + \frac{Q_2}{\Delta T} \quad \text{or} \quad \frac{1}{\Re} = \frac{1}{\Re_1} + \frac{1}{\Re_2}$$

For combined conduction and radiation processes through a gas-filled cavity

$$\frac{1}{\Re} = \frac{\lambda A}{t} + h_r A$$

- λ is the thermal conductivity of the gas in the cavity, in W/mK
- h_r is the radiative heat transfer coefficient, in W/m^2K

The cavity could also be represented as a conduction layer with an equivalent thermal conductivity, such that

$$\frac{\lambda_{eff} A}{t} = \frac{\lambda A}{t} + h_r A \quad \text{or} \quad \lambda_{eff} = \lambda + h_r t$$

For a cavity with combined convection and radiation processes

$$\frac{1}{\Re} = h_c A + h_r A = (h_c + h_r) A$$

Again this can be expressed in the form of an equivalent thermal conductivity

$$\lambda_{eff} = (h_c + h_r) t$$

A1.4.5 Environmental temperature

At the exposed surfaces of a structure there will be combined convection and radiation processes, but the temperatures associated with the convection process (surface and air) and the temperatures associated with the radiation process (surface and surrounding surfaces) are different. The total heat transfer is therefore

$$Q = h_c A (T_s - T_a) + h_r A (T_s - T_{surr})$$

A typical solution to this dilemma is to define an overall heat transfer coefficient

$$h = h_c + h_r$$

and then to define a temperature, generally called the environmental temperature, which gives the correct heat transfer

$$(h_c + h_r) A (T_s - T_{env}) = h_c A (T_s - T_a) + h_r A (T_s - T_{surr})$$

so that

$$T_{env} = \frac{h_c}{h_c + h_r} T_a + \frac{h_r}{h_c + h_r} T_{surr}$$

The only difficulty with this approach is that the size and shape of the environment on either side of the structure affects the temperature of the various surfaces, and so T_{surr} is variable in practice even if the same structure is monitored. A simpler approach is to assume that the environmental temperature is roughly equal to the air temperature - this at least allows a first approximation to the heat transfer through a structure.

The overall heat transfer coefficient at a surface is often defined in national regulations, and may be very different in different parts of the world.

Note that all of the relationships described above are based on steady-state conditions. Although temperature and heat flow varies continuously in real systems this is difficult to allow for in any simple manner, and it is usually assumed that the rate of structural temperature variation follows environmental temperature fluctuations sufficiently rapidly that a steady-state method applied at some instant in time gives a reasonable estimate of the heat transfer.

A1.4.6 The U-value

The overall thermal resistance of a layered structure, which may include cavities, is given by

$$\Re = \sum_{i=1}^{n} \frac{t_i}{\lambda_i A} + \frac{1}{h_{si} A} + \frac{1}{h_{se} A}$$

where h_{si} and h_{se} are the internal and external surface heat transfer coefficients. In the UK these are presently taken as 8.33 and 16.7 W/m^2K respectively.

The overall heat transfer may also be expressed in the form of a U-value, which is defined as

$$U = \frac{Q}{A \Delta T}$$

The U-value and overall thermal resistance are therefore related by

$$U = \frac{1}{A \Re}$$

It is interesting to note that in layered structures the area of each surface is identical, and so the U-value is given by

$$U = \frac{1}{\sum_{i=1}^{n} \frac{t_i}{\lambda_i} + \frac{1}{h_{si}} + \frac{1}{h_{se}}}$$

It is sometimes simpler to calculate resistances based on unit area for layered structures, but for irregular structures the area of each element must be introduced. Note that surface resistances are independent of area!

It is always possible to represent a conduction layer with an equivalent convection or radiation layer, and vice-versa, using the equality

$$\frac{1}{h_{eff}} = \frac{t}{\lambda_{eff}}$$

A1.4.7 An example of a calculation for two layered glazing units

A1.4.7.1 Aerogel-filled 28 mm (4/20/4) glazing unit

Consider the glazing unit shown in Figure A1.4.7.1:

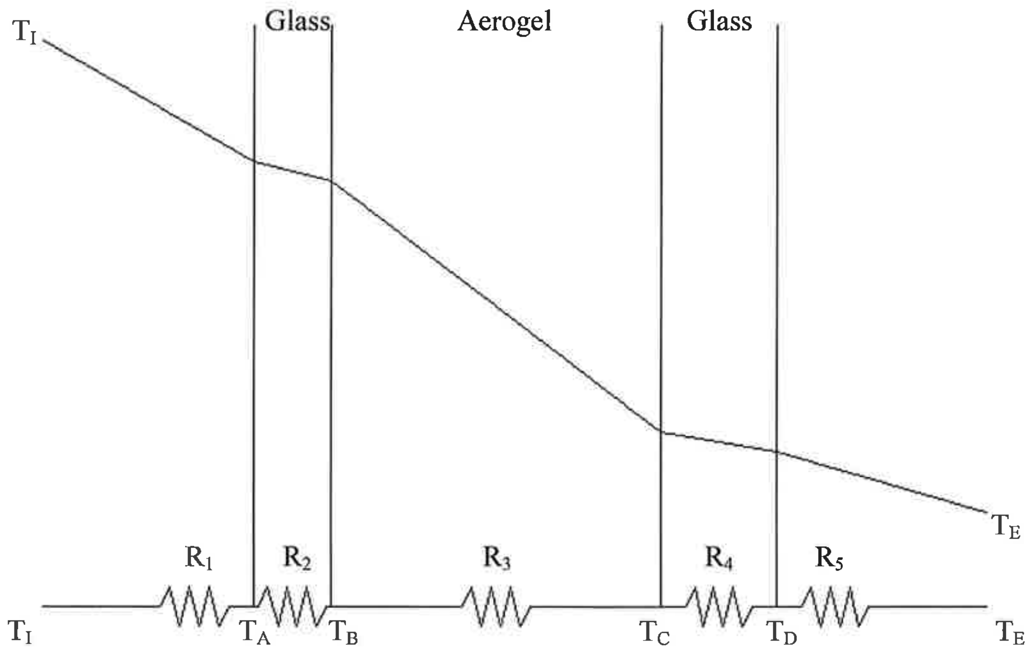


Figure A1.4.7.1 An aerogel-filled double glazing unit

This structure comprises three layers, plus two surface heat transfers. Assuming a unit area the thermal resistances of each layer are

inner surface: $R_1 = \frac{1}{h_{si}} = \frac{1}{8.33} = 0.12\ \text{m}^2\text{K/W}$

inner pane of glass: $R_2 = \frac{t}{\lambda} = \frac{0.004}{1.0} = 0.004\ \text{m}^2\text{K/W}$

aerogel layer: $R_3 = \frac{t}{\lambda} = \frac{0.02}{0.02} = 1.00\ \text{m}^2\text{K/W}$

outer pane of glass: $R_4 = \frac{t}{\lambda} = \frac{0.004}{1.0} = 0.004\ \text{m}^2\text{K/W}$

outer surface: $R_5 = \frac{1}{h_{se}} = \frac{1}{16.7} = 0.06\ \text{m}^2\text{K/W}$

The U-value is therefore

$$U = \frac{1}{\sum_{i=1}^{5} R_i} = \frac{1}{1.188} = 0.84\ \text{W/m}^2\text{K}$$

The temperature at each interface between layers is readily determined when it is realised that the temperature drop across each layer is proportional to the resistance of the layer. The temperature drop across layer 3 must therefore be related to the overall temperature difference ΔT by

$$\delta T_3 = \frac{R_3}{\sum_{i=1}^{5} R_i}\Delta T = \frac{1.00}{1.188}\Delta T = 0.842\Delta T\ {}^\circ\text{C}$$

The temperature drop across the other layers is:

$$\delta T_1 = \frac{R_1}{\sum_{i=1}^{5} R_i}\Delta T = \frac{0.12}{1.188}\Delta T = 0.101\Delta T\ {}^\circ\text{C}$$

$$\delta T_2 = 0.003\Delta T\ {}^\circ\text{C}$$

$$\delta T_4 = 0.003\Delta T\ {}^\circ\text{C}$$

$$\delta T_5 = 0.051\Delta T\ {}^\circ\text{C}$$

For any internal and external temperature difference it is possible to predict the temperature at the surface of each layer. Thus for an internal temperature of 20°C and an external temperature of 0°C

$$T_A = 20 - \delta T_1 = 17.98\,°\text{C}$$

$$T_B = 20 - \delta T_1 - \delta T_2 = 17.92\,°\text{C}$$

$$T_D = 20 - \delta T_1 - \delta T_2 - \delta T_3 = 1.08\,°\text{C}$$

$$T_D = 20 - \delta T_1 - \delta T_2 - \delta T_3 - \delta T_4 = 1.02\,°\text{C}$$

A1.4.7.2 Gas-filled 28 mm (4/20/4) glazing unit

Now assume that the glazing unit is gas-filled. The resistances of layers 1, 2, 4 and 5 remains the same as before.

For radiation heat transfer between two parallel plates (the panes of glass) the radiative heat transfer coefficient is given by

$$h_r = \frac{4T_m^3\sigma}{\dfrac{1}{\varepsilon_1} + \dfrac{1}{\varepsilon_2} - 1}$$

The glass surface emissivities could be taken as normal emissivities or as hemispherical emissivities. However BS 6993:Part 1 [1989] indicates that an effective emissivity should be taken, which for a glass surface has a value of 0.845 (the corresponding normal emissivity is 0.88). Assuming a mean temperature of 283 K (10°C) and emissivities of 0.845 therefore gives

$$h_r = 3.76\ \text{W/m}^2\text{K}$$

The behaviour of the gas in the unit will depend on the convection correlation

$$Nu = C(Ra)^n\left(\frac{t}{L}\right)^p \quad \text{where} \quad Nu = \frac{ht}{\lambda} \quad \text{and} \quad Ra = \frac{\beta g \theta t^3 \rho^2 C_P}{\mu\lambda}$$

In the UK BS 6993:Part 1 [1989] indicates that for a vertical glazing unit with horizontal heat flow the constants are

$$C = 0.035 \qquad n = 0.38 \qquad p = 0$$

The limitation with this type of correlation is that the temperature difference θ needs to be known - until the glazing performance is calculated it is necessary to guess at a value of θ. BS 6993:Part 1 [1989] recommends taking θ=15 K initially, and then iterating the solution using the calculated temperature difference at the end of each step. However, in many cases the result is based on the assumption of a 15 K temperature difference.

The convection correlation can be rearranged into the forms

$$Nu = 0.035\left(\frac{\beta\rho^2 C_P}{\mu\lambda}\right)^{0.38} g^{0.38}\theta^{0.38}t^{1.14} \qquad h = 0.035\lambda\left(\frac{\beta\rho^2 C_P}{\mu\lambda}\right)^{0.38} g^{0.38}\theta^{0.38}t^{0.14}$$

For a 20 mm gas-space (t=0.02 m) with an assumed 15°C temperature difference across the gas-space (θ=15°C) the values for the property group $\lambda(\beta\rho^2 C_P/\mu\lambda)^{0.38}$, the Nusselt number and the resulting heat transfer coefficient are

Gas	Property group $(\beta\rho^2 C_P/\mu\lambda)^{0.38}$	Thermal conductivity λ [W/mK]	Nusselt number Nu	Convection heat transfer coefficient h [W/m^2K]
krypton	850	0.0093	2.29	1.06
argon	530	0.0168	1.43	1.20
air	492	0.025	1.33	1.66
SF_6	1977	0.0128	5.33	3.41

The heat transfer coefficients determined from this first approximation can be used to estimate the overall resistance and the U-value for each gas-fill. This can then be used to determine the temperature difference across the glazing, and the true performance gradually obtained by iteration. If this procedure is followed for environmental temperatures of 20°C and 0°C then the following results are obtained

	First guess			Final iteration		
Gas	Nu	h [W/m^2K]	U [W/m^2K]	Nu	h [W/m^2K]	U [W/m^2K]
krypton	2.29	1.06	2.54	2.02	0.94	2.51
argon	1.43	1.20	2.57	1.26	1.05	2.55
air	1.33	1.66	2.69	1.16	1.45	2.65
SF_6	5.33	3.41	3.06	4.44	2.84	2.96

It is important to note that with the 20 mm gas-space taken in this example the krypton- and SF_6-filled units are showing significant convection heat transfer. An alternative method of analysis is to identify the gas-space which gives optimum performance (Nu=1.0) for each gas, with all other parameters staying the same:

Gas	Optimum gas-space [mm]	U-value [W/m^2K]
krypton	11.0	2.49
argon	16.5	2.54
air	17.5	2.64
SF_6	5.5	2.87

A similar analysis can be obtained for a gas-fill between two panes of glass, one of which has a low-emissivity coating with an effective emissivity of 0.05 (this is about the best available). The results for a 20 mm gas-space are

	First guess			Final iteration		
Gas	Nu	h [W/m^{2}K]	U [W/m^{2}K]	Nu	h [W/m^{2}K]	U [W/m^{2}K]
krypton	2.28	1.06	1.06	2.34	1.09	1.07
argon	1.42	1.19	1.14	1.45	1.22	1.16
air	1.33	1.66	1.41	1.33	1.66	1.41
SF_6	5.32	3.40	2.17	4.96	3.17	2.09

and the optimum gas-spaces are now

Gas	Optimum gas-space [mm]	U-value [W/m^{2}K]
krypton	9.5	1.01
argon	14.5	1.12
air	15.5	1.38
SF_6	5.0	1.89

A cautionary note is required here - the values given above are based on environmental temperatures of 20°C and 0°C, which are typical for a UK winter. For a North American winter the external temperature can fall to -20°C or below, which doubles the overall temperature difference and will cause convection to occur in smaller gas-spaces - for colder climates the optimum gas-space width is less. In climates which have colder winters there is an additional factor to be taken into account - the external surface resistance will be less (North American practice uses an external overall heat transfer coefficient of 34.1 W/m^{2}K, which gives a surface resistance of 0.029 m^{2}K/W, one-half of that used for the UK).

A1.5 Interaction between light, infra-red and heat transfer

When solar radiation is incident on a glazing system the heat transfer through the system is disturbed because some solar energy is absorbed. The result of energy absorption is an increase in temperature, and the resulting steady-state energy transfer and temperature distribution depends on the resistances between the layer where the energy is absorbed and the environments on either side of the glazing. Some of the absorbed energy is radiated into the building as far-infrared.

It is important that the engineer can calculate the effect of energy absorption on the temperature of glazing systems because this determines whether the glass needs to be strengthened in some way in order to withstand higher thermal stresses.

A1.5.1 Effect of absorbed energy on a single-sheet glazing

Consider a single pane of glass, such as shown in Figure A1.5.1.

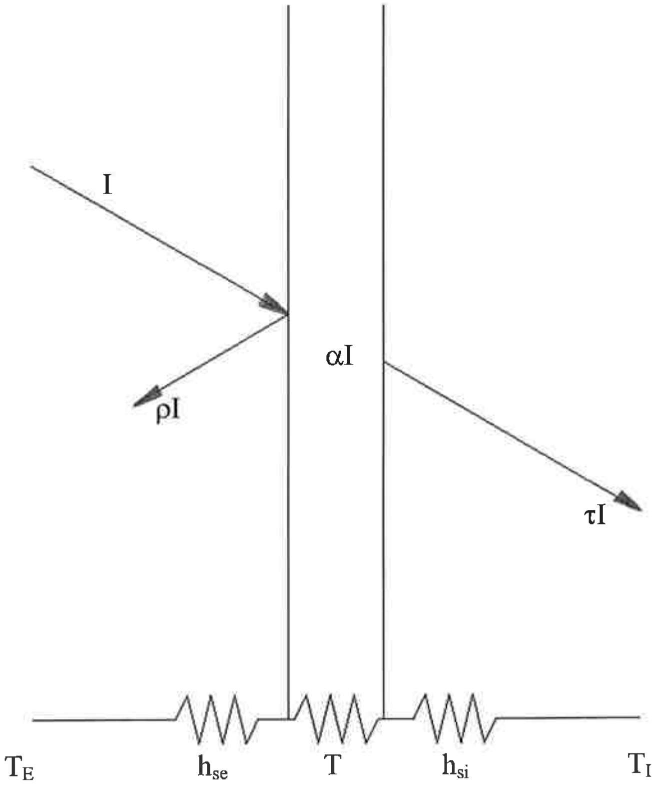


Figure A1.5.1 Absorption of solar radiation by a single glazing

Assume that the glass absorbs a fraction α of the incident radiation I. Assume also that the thermal resistance of the glass is negligible, such that the pane of glass can be assumed to be at a uniform temperature. This problem is then reduced to a two-layer problem, with an amount of energy αI absorbed at the interface of the layers. The energy balance for the interface is such that the energy lost from each side of the interface must equal the energy absorbed at the interface, under steady-state conditions, or

$$\alpha I = h_{si}\left(T - T_i\right) + h_{se}\left(T - T_e\right)$$

where the energy loss from the interface is by combined convection and radiation heat transfer at the surfaces of the glass.

This formula can be rearranged to determine the resultant interface temperature as

$$T = \frac{\alpha I + h_{si}T_i + h_{se}T_e}{h_{si} + h_{se}}$$

For the UK the surface heat transfer coefficients are h_{si}=8.33 W/m^{2}K and h_{se}=16.7 W/m^{2}K and a sensible peak solar radiation incident on a vertical surface is about 700 W/m^2.

Ordinary clear float glass absorbs about 11% of the incident solar radiation. If the environmental temperatures on either side of the glazing are assumed to be 25°C then the glass will reach a temperature of

$$T = 28.1\,°\mathrm{C}$$

This temperature is very close to the environmental temperature, and plain annealed float glass is unlikely to be at risk of failure form thermal stressing.

Now consider the case where a reflective solar control film is applied to this glazing. Reflective films will increase the amount of energy that is absorbed by the glass. A typical commercial product can increase the amount of energy that is absorbed to 50% or more. Assuming 50% absorption then the glass will reach a temperature of

$$T = 39.0\,°\mathrm{C}$$

This is considerably higher than before the film is applied, and advice should be sought as to possible problems. More importantly it should be noted that the hot glass will radiate significant heat onto anyone seated near the glazing. Radiation of heat from glazing can be a significant problem if the glazing is not selected carefully.

A1.5.2 Effect of absorbed energy on a double-sheet glazing

Now consider the example of Figure A1.5.2.

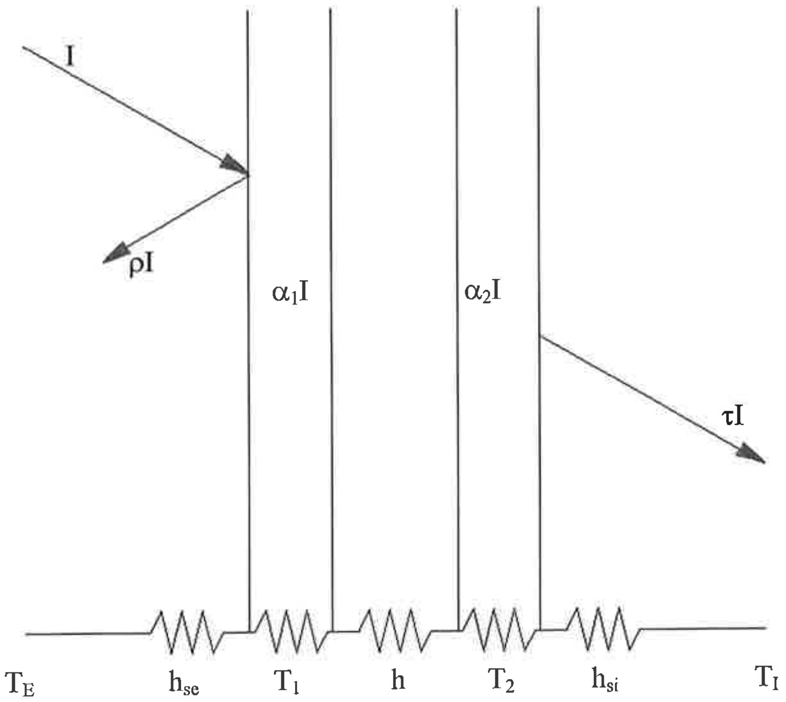


Figure A1.5.2 Absorption of solar radiation by a double glazing

In this double glazing unit each pane of glass will absorb some of the incident radiation (the fraction that is transmitted or reflected is not important). The energy balance at the outer pane of glass is

$$\alpha_1 IA = h_{se} A(T_1 - T_e) + hA(T_1 - T_2)$$

Again it is assumed that the glass is at a uniform temperature. It is also assumed that heat transfer through the gas-space is represented with a combined heat transfer coefficient h.

The energy balance at the inner pane of glass is

$$\alpha_2 IA = h_{si} A(T_2 - T_i) + hA(T_2 - T_1)$$

These two formulae can be rearranged and solved to give

$$T_1 = \frac{UI}{h_{se} + h}\left[\frac{\alpha_1}{U} + \frac{h\alpha_1}{h_{si}h_{se}} + \frac{h\alpha_2}{h_{si}h_{se}} + \frac{\alpha_2}{h_{si}}\right] + \frac{U}{h_{se}}(T_i - T_e) + T_e$$

and

$$T_2 = \frac{UI}{h}\left[\frac{h\alpha_1}{h_{si}h_{se}} + \frac{h\alpha_2}{h_{si}h_{se}} + \frac{\alpha_2}{h_{si}}\right] + \frac{U}{h_{si}}(T_e - T_i) + T_i$$

where the U-value is given by

$$\frac{1}{U} = \frac{1}{h_{si}} + \frac{1}{h} + \frac{1}{h_{se}}$$

These formulae are general, and combine heat transfer with solar radiation - at night I=0 and the formulae revert to their usual forms

$$T_1^* = \frac{U}{h_{se}}(T_i - T_e) + T_e \qquad \text{and} \qquad T_2^* = \frac{U}{h_{si}}(T_e - T_i) + T_i$$

With the absorption of heat by the glazing the energy loss from a room due to heat transfer is reduced by the amount

$$Q = h_{si}A(T_2 - T_2^*) \qquad \text{or} \qquad Q = UA\left[\frac{\alpha_1}{h_{se}} + \frac{\alpha_2}{h_{se}} + \frac{\alpha_2}{h}\right]I$$

If the temperature of the internal glass pane is increased above the room temperature then heat transfer losses become heat transfer gains, and are added to the direct solar gains.

A1.5.3 Solar gain

The building gains solar energy by directly transmitted radiation through glazings. However, some radiation is absorbed by the glazings and then released into the building through heat transfer. Solar gain is the total part of the incident solar energy that reaches the interior of the building.

Solar gain can be quantified by a g-value

$$g = \tau_s + \alpha_s f_s$$

- τ_s is the direct solar transmittance (dimensionless)
- α_s is the solar absorptance (dimensionless)
- f_s is the fraction of the absorbed energy that is released into the building (dimensionless)

The value of the fraction f_s depends on the nature of the glazing system and upon the surface heat transfer coefficients. The surface heat transfer coefficients have different standard values in different countries, and so the solar gain through a particular glazing may be quoted as a slightly different value in different countries.

It is very important to recognise that heat transfer and solar gain are inextricably linked - the solar gain modifies the temperature variation through the glazing and so the conventional use of the U-value is no longer possible. Heat transfer and solar gain are not simply additive - they are combined in a complex manner. Glazing manufacturers may identify the performance of a glazing in terms of the amount of heat that is transmitted, and this usually includes a term for the re-radiation of heat through heat transfer mechanisms. It is not necessary to use the formulae above, as the glazing performance is given in simpler terms. Only at night-time does the U-value come into effect as the principal measure of energy movement.

The term shading coefficient (abbreviated SC) is sometimes used to rate glazings. The shading coefficient is the proportion of solar radiant energy that is transmitted through a particular glazing compared to the proportion of the ratio that is transmitted through a single 3 mm (originally 1/8") thick pane of clear float glass. A 3 mm pane of clear glass transmits 87% of the incident solar radiation, but has a shading coefficient of 1.0. The amount of radiation that is transmitted through a glazing unit with a shading coefficient of 0.65 is therefore 0.65 times 0.87 times the incident radiation.

Note that the amount of the incident solar radiation that is transmitted through a glazing unit is made up of a direct component (the directly transmitted energy) and an indirect component - the part of the incident radiation that is absorbed by the glazing and then convected and radiated into the building.

The way in which solar radiation is used in a building can vary considerably. In some cases the requirement is to stop the solar radiation, whilst in others it is desirable only to stop one component, usually the direct solar radiation which causes glare. It might also be desirable to draw natural light into a room in a way that gives more uniform light levels.

Figure A1.5.3 shows different ways in which light can be stopped, selectively stopped or redirected:

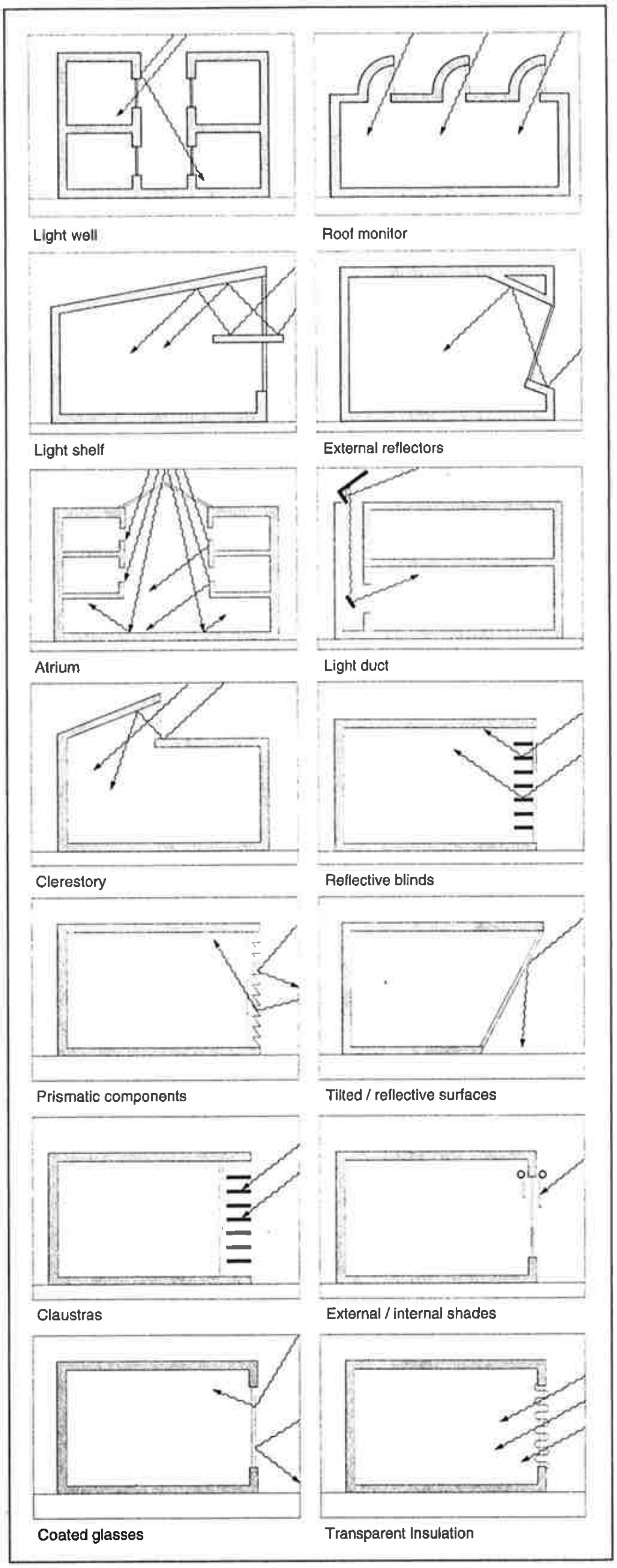


Figure 7: Daylighting devices.

Figure A1.5.3 Methods for intercepting light (from UCD-OPET [1994])

A1.5.4 Visible light and solar energy transmission

An important design parameter for glazing system is the amount of visible light that is transmitted compared to the total amount of solar energy that is transmitted. Glazings are often identified using a two-number system of the form

89/86

The first number is the percentage of light that is transmitted, and the second number is the total solar energy transmission. These values apply for clear 4 mm float glass in the UK.

A full description of a glass might be

12 mm 27/47 bronze body tinted

Indicating that it transmits 27% of light and 47% of the total incident solar radiation. Note that, as stated above, the best that can be achieved with 100% light transmission is 100/54, assuming that all ultraviolet and infrared components of the solar energy are stopped.

A1.5.5 Summary of heat transfer, light and infra-red

Heat transfer through a glazing system can be reduced by using thick layers of materials with low thermal conductivities (conduction through solids) or by using suitable gases in gas-spaces of the optimum width. The emissivity of a surface can also be changed to reduce the amount of radiation heat transfer at the surface, although low-emissivity coatings generally need to be protected from abrasion and dirt by sealing them into a hermetic space.

Solar light and heat transmission through a glazing can be reduced by intercepting the radiation at some point (use a shading device), reflecting the radiation or absorbing the radiation. However, light is desirable, and if light is required to pass through a glazing system then some heat is also transmitted (light and heat are both energy).

Guidance on designing buildings for daylight is given by Bell and Burt [1995].

A1.6 Performance testing

An important aspect of any product is the requirement to be able to compare products through some sort of performance rating. For advanced glazings there are usually two performance criteria that are important; 'how much solar energy is admitted?' and 'how much heat is transferred?'. Heat transfer is an issue on winter nights, when the energy required to heat a building is very significant. Solar energy transmission becomes important during summer days, when the energy transmission through a glazing system must be controlled or the building will overheat.

A1.6.1 Heat transfer assessment

Heat transfer depends on the temperature difference across the glazing and on the surface resistances on each face of the glazing. The temperature difference across the glazing can also be ignored if the material properties and surface resistances are assumed to be independent of temperature (this is a reasonable assumption).

Most countries have standards relating to the assessment of heat transfer through glazing systems. Glazing can be measured separately, or complete glazed systems can be assessed.

A1.6.2 Solar transmission assessment

Assessing the transmission of solar energy through glazings is slightly more complex, because the transmission, reflection and absorption of solar energy is dependent on both the wavelength of the energy and the angle of incidence. The behaviour of many advanced glazing systems also depends on whether the light is direct or diffuse.

The assessment of solar energy is usually based on a system whereby energy with a known spectral energy distribution is directed at a sample of the glazing and the transmitted and reflected energy are measured on a hemispherical basis, and converted to overall parameters.

A1.6.3 Product assessment

For the architect or specifier the best type of product assessment is one which gives a single parameter which describes the performance of the product in full. However, it is rarely possible to achieve this, because the performance of many products actually depends on the location where the product is to be used. As a result there tend to be separate performance parameters for heat transfer (the U-value, sometimes called the 'night-time' U-value), solar energy transmission (the shading coefficient) and air infiltration, even though these all affect the energy balance of the building. There is now a trend towards trying to combine these parameters into single performance ratings, but there is still uncertainty as to the suitability of these combined performance ratings (it may still be necessary to take separate performance criteria for heat transfer, solar gain and air infiltration in order to predict whole-building performance).

A1.6.3.1 The National Fenestration Rating Council (NFRC) in the USA

In 1989 the NFRC was founded by the USA fenestration industry 'to develop a fair and accurate system for rating the energy performance of windows, doors and other fenestration products, and to ensure the rating system's uniform application on a national basis' (NFRC [1993]). At present the NFRC rating procedure comprises a standard method for assessing product U-values (NFRC 100-91 [1991]), although work is underway to determine a standard method for rating the solar heat gain coefficient (SHGC) of a fenestration product (NFRC 200-93 [1993]).

The NFRC rating system is particularly well organised, and comprises clear guidance for laboratories that wish to be accredited assessors (NFRC LAP 1-92 [1992]), for companies that wish to have products certified (NFRC PCP 1-92 [1992]) and for organisations that wish to be able to issue certificates on the basis of assessments (NFRC CAP 1-92 [1992]). Furthermore the NFRC provides a 'technical interpretation' service, so that queries about the rating system can be answered, and the response to each query is published (NFRC 100-91 [1994]).

Finally, the result of every certification is published in a handbook (NFRC [1995]), so that architects and specifiers can simply look up the performance of a particular product - in many cases a product will not be used on a project unless it appears in this 'bible'. Each product range that is certified is then supplied with an energy label, such as that shown in Figure A1.6.3.1, so that the end-user knows the expected performance of the product.

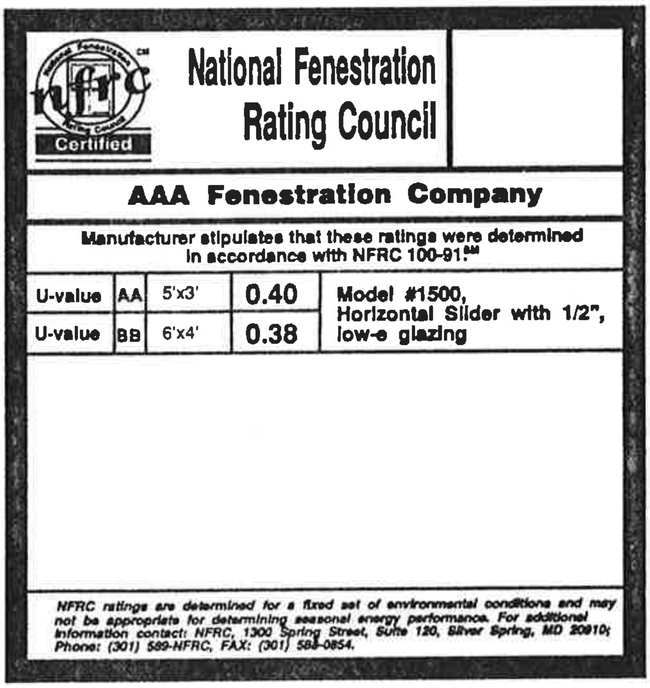


Figure A1.6.3.1 An NFRC energy rating label (from NFRC [1995])

The NFRC procedure is particularly attractive to product manufacturers because it is based on computer prediction (simulation) of the U-value of two representative sizes (defined by NFRC) of each product in a range backed up with measurement of the product with the highest U-value in one standard size, and the product with the lowest U-value in the other standard size. The simulations can be carried out quite easily using standard low-cost software that has been specially developed for the task, and the minimal number of measurements then used to confirm the analyses, thereby reducing costs of certification significantly.

The development of methods for assessing solar gain in conjunction with heat transfer is described by Crooks *et al* [1995]. The method makes use of a fenestration heating rating (FHR) and a fenestration cooling rating (FCR), which each account for heat transfer and solar gain relative to some basic window type. The relative nature of the FHR and FCR mean that they can be used to estimate the energy cost savings that will be achieved by replacing one window with another. The FHR and FCR values can be added to the energy rating labels already issued by the NFRC, and so each window would carry a clear statement of its energy performance.

The extension of the NFRC method to include durability information is also being considered, and Garries and Mathis [1995] discuss issues relating to durability of fenestration systems and their effect on performance.

Some issues that Garries and Mathis [1995] report are

- U-value influences
    - gas loss in ig units
    - changes in low-e coatings
    - frame conductivity changes
    - seal failure
    - suspended film degradation
- air leakage influences
    - wear of weatherstrips
    - weatherstrip material changes
    - frame stability
    - installation
    - glazing loss of performance
    - frame sealant loss
    - hardware loss of performance
- solar heat gain influences
    - permanent surface degradation (glass and frame)
    - coating/tint loss of performance
    - frame/glass U-value changes
    - laminated or suspended film degradation
    - dirt

These issues are quite complex, but must be considered if the long-term performance of a building is to be ensured. The need to replace advanced glazings if they degrade can seriously change the costing of a building and the balance between energy use and capital and maintenance costs.

The NFRC rating method is also described by Mathis (1991).

A1.6.3.2 Energy rating in Canada and the ER number

The Canadian Standards Association defines an energy rating (ER) which combines solar heat gain, heat transfer and air infiltration to obtain an overall energy rating for a product (CSA A440.2-93 [1993]).

The energy rating is given by

$$ER = \left[F_W F_\theta H_t\right] - \left[(t_{bi} - t_{bo})U_W\right] - \left[(t_{bi} - t_{bo})\left(\frac{0.138 PFL_{75}}{A_W}\right)\left(\frac{\rho C_P}{3.6}\right)\right] \text{ W/m}^2$$

where

- F_W is the window solar heat gain coefficient (dimensionless)
- F_θ is an off-normal solar incidence factor for solar radiation (dimensionless)
- H_t is the average solar radiation incident on vertical windows facing the four cardinal directions during hours of the year when solar heat gains influence heating load, in W/m^2
- t_{bi} is the average indoor temperature during hours of the year when daily average outdoor temperature is below 12°C, in °C (assumed to be 20.0°C)
- t_{bo} is the average outdoor temperature during hours of the year when daily average outdoor temperature is below 12°C, in °C (assumed to be -1.9°C)
- U_W is the window U-value, in W/m^{2}K
- L_{75} is the window air leakage rate at a pressure difference of 75 Pa, in m^3/h
- C_P is the thermal capacitance of air, in kJ/m^3°C
- A_W is the area of the window

The calculation is based on a reference window size, which depends on the style of the window. The first term in the ER equation is the solar heat gain, the second terms represents heat transfer, and the third term represents air infiltration. If the energy rating number is greater than zero then there is a net gain in energy to the building during the heating season.

A simplified form of the ER formula can be used, which gives an average energy rating for all climates and all cardinal compass directions, which is

$$ER = \left[72.20 F_W\right] - \left[21.90 U_W\right] - \left[\frac{0.54 L_{75}}{A_W}\right] \text{ W/m}^2$$

The energy rating needs three items of information which are product-dependent:

- solar heat gain coefficient, F_W, which can be obtained by measurement or simulation
- U-value, U_W, which can be obtained by measurement or simulation
- air leakage rate, L_W, which must be obtained by measurement

The solar heat gain coefficient is the ratio of the solar heat gain through the product to the solar radiation incident on the product, assessed for a realistic solar energy spectrum. This depends on the angle of incidence of the solar radiation and on various environmental parameters (which affect the amount of heat that is absorbed by the product and then released into the room). The U-value is the amount of heat transfer through the product per unit area per unit overall temperature difference. This depends on the materials from which the product is made, and on the environment around the product. The air leakage rate is a function of the various joints within the product.

Energy rating can be a useful means of comparing two similar products. However, the energy rating described above is only a measure of the performance of the product during the heating season, and a full assessment of the building performance is still required through a full yearly cycle. More importantly the ER measures the average solar gain, less the average heat transfer, less the average energy loss due to air leakage. As such it does not give the user information about what will happen on overcast windy days, when the ER for the day is tipped towards the negative, or on sunny clear days, when the ER is tilted towards the positive.

Henry [1995] discusses the ER method and also describes the development of Canada's National Energy Code (NEC) for new housing, which identifies minimum required ER values for various regions of the country, as shown in Figure A1.6.3.2. The requirements are different for opening and fixed windows (opening windows generally have higher rates of air leakage), and according to whether electric or gas/oil fired heating is used (electric heating is generally more expensive than oil or gas, although in remote areas it may be cheaper to use hydroelectricity than to fly oil or gas in), but they generally show that the ER should be less negative in colder parts of Canada.

There may also be a significant difference between products tested in the laboratory and products installed in buildings, because performance measures such as air leakage can be deliberately improved on laboratory samples by more careful alignment of hardware and careful installation of gaskets and weatherstrips.

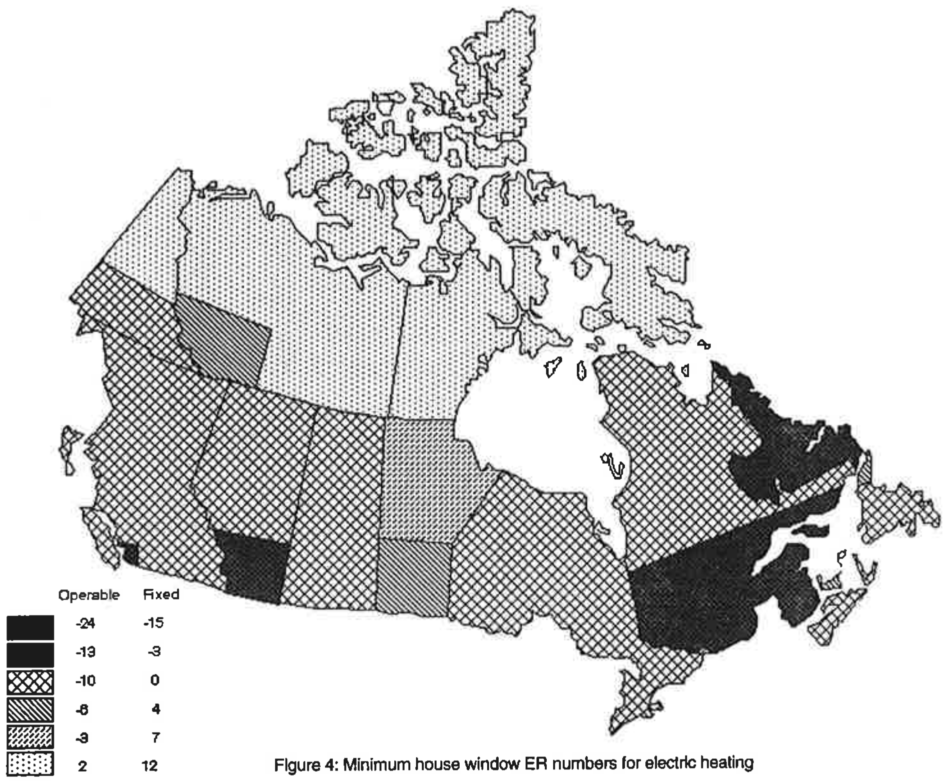
A1.6.3.3 Summary of the NFRC rating method and the ER system

The Canadian ER system is presently more advanced than the USA's NFRC rating, in that it already allows for solar gain and air leakage. However, the NFRC method is being developed continuously and the two methods should converge in their treatment of the energy balance of fenestration. It is possible that when both systems are well established they may be unified, although with the emphasis of both systems on using computer simulation for assessment this may not be necessary - perhaps only the air leakage through a product will need to be measured and solar gain and heat transfer can be predicted, allowing ratings to be readily converted between different systems.

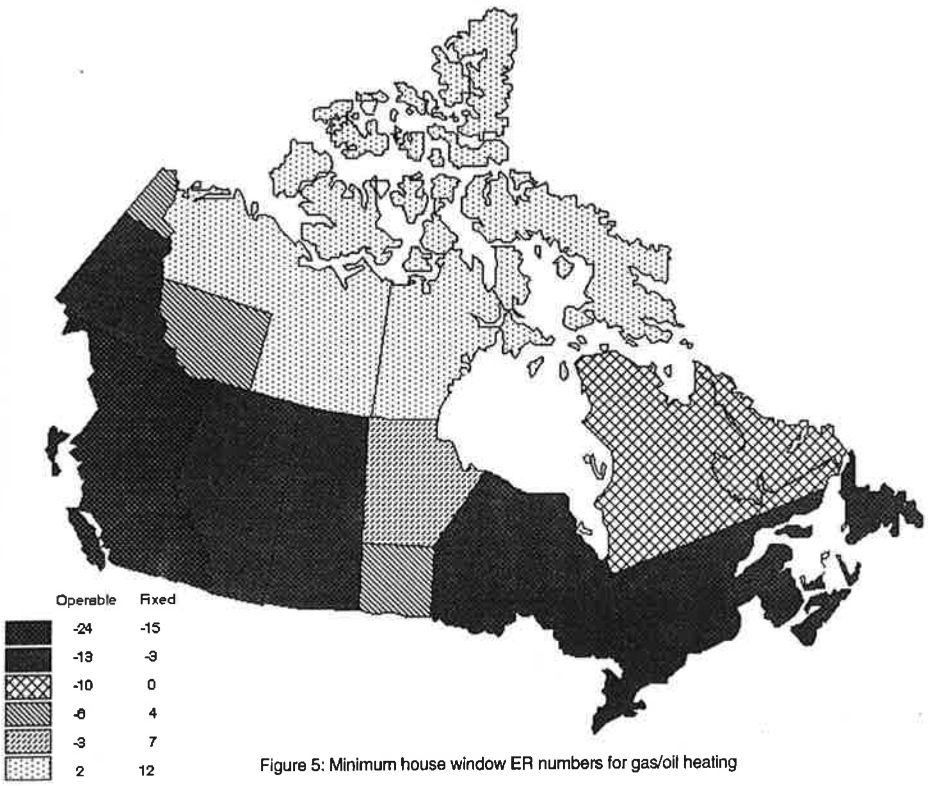
A1.6.3.4 The Window Information System (WIS) in Europe

Europe does not, at the present time, have a rating system for fenestration, and standards are still in preparation for the assessment of thermal, solar and optical properties. However, a project has is now well underway to develop a Window Information System (WIS), which will comprise a software package linking all of the issues relating to the thermal performance of fenestration in buildings. The project is co-ordinated by TNO Building and Construction Research in the Netherlands, with input from several other European organisations.

van Dijk and Bakker [1995] discuss the development of the WIS program, and Figure A1.6.3.4 is taken from their paper. It can be seen from this figure that the WIS software will be a comprehensive tool for the assessment of fenestration, and will link into other software for the assessment of specific issues.



(a) for homes with electric heating



(b) for homes with gas/oil heating

Figure A1.6.3.2 Minimum ER numbers for Canadian fenestration products (from Henry [1995])

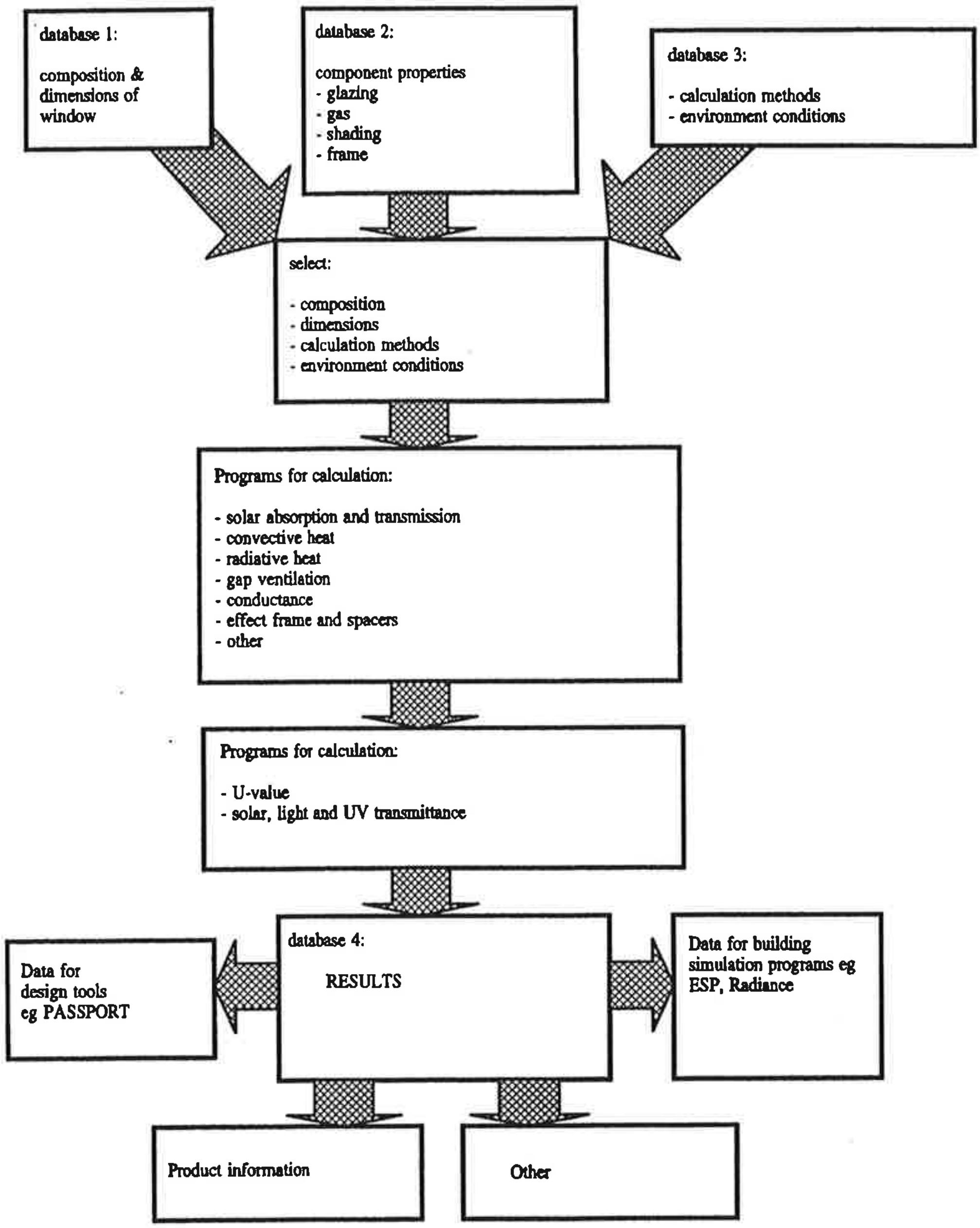


Figure 1: Diagram with main WIS structure

Figure A1.6.3.4 The Window Information System (WIS) (from van Dijk and Bakker [1995])

A2 Types of advanced glazing

Each type of advanced glazing works in a different way with regard to their use of light, infra-red and heat transfer. The following types of advanced glazings are currently in use, or under development. This section also describes more conventional forms of glazing, starting with ordinary single glass as a useful point of reference:

A2.1 Single-sheet un-coated glasses

A2.1.1 Clear glass

Clear glass transmits a high proportion of the incident light, but absorbs the infra-red. The temperature of the glass is dominated by ordinary heat transfer processes at the surfaces of the glass, because the thermal resistance of a single thin glass layer is insignificant.

Some typical performance values are:

Clear float glass (from Button and Pye [1993] pp163)						
	Light		Direct solar radiation			Total solar radiation
Thickness	T	R	T	R	A	T
4 mm	0.89	0.08	0.82	0.07	0.11	0.86
6 mm	0.87	0.08	0.78	0.07	0.15	0.83
10 mm	0.84	0.07	0.70	0.07	0.23	0.78
12 mm	0.82	0.07	0.67	0.06	0.27	0.76
T=fraction transmitted, R=fraction reflected, A=fraction absorbed						

Note that these values are for the UK, where one-third of the absorbed radiation is released into the building by heat transfer.

Single clear glass has been in use for a considerable period of time. Installation is not a problem, being possible by dry- or wet-glazing techniques. The only significant limitation of single glass is its limited strength, particularly with regard to impact. However, this can be improved by toughening or laminating the glass.

A2.1.2 Coloured/body-tinted/stained glass

Coloured single glass absorbs a much higher proportion of the incident light. Coloured glass transmits more light in one particular part of the visible spectrum - for example green-tinted glass transmits proportionally more of the green component of light.

The temperature of coloured glass is higher than for clear single glass, because of the absorbed solar radiation, and coloured glasses are usually toughened to enable them to survive the higher stresses that may be developed during use.

Some typical performance values are:

Body tinted float glass (from Button and Pye [1993] pp163)						
	Light		Direct solar radiation			Total solar radiation
Thickness and colour	T	R	T	R	A	T
6 mm green	0.72	0.06	0.46	0.05	0.49	0.62
6 mm blue	0.54	0.05	0.46	0.05	0.49	0.62
6 mm bronze	0.50	0.05	0.46	0.05	0.49	0.62
12 mm bronze	0.27	0.04	0.23	0.04	0.73	0.47
T=fraction transmitted, R=fraction reflected, A=fraction absorbed						

The absorption of solar radiation is almost 50% for the thinner body-tinted glass, and can approach 80% for thicker body-tinted glasses. Whilst body-tinted or coloured single glass is no more difficult to install than ordinary single glass care must be taken to ensure that the glass is not used with any feature on the room-side (such as additional blinds or curtains) which reduces heat loss from the glass surface and causes transmitted energy to be reflected back onto the glass.

The higher temperatures experienced with coloured glasses can also cause discomfort, due to heat being radiated from the glazing onto the occupants of the room. Coloured glass is often used as the outer pane of a multiple glazing unit so that the gas-space, and any coatings on the inner panes of glass, reduce the transmission of heat into the building.

A2.1.3 Low iron 'Clear white' glass

If viewed edge-on a pane of ordinary float glass has a distinctive greenish colour, due to the presence of iron oxides in the raw ingredients. By using a low iron oxide mix it is possible to produce glass that is clear when viewed edge on, known as 'clear white' glass (the term 'water white' has also been used). Clear white glass has an almost uniform transmission characteristic throughout the visible light and infra-red parts of the spectrum (Button and Pye [1993] pp63-64). Daylight transmission is higher, but so is infra-red transmission.

This glass can be treated as an ordinary float glass. It is often used where there is a need to give a clear view through several layers of glazing. This glass may absorb slightly less energy than ordinary clear float glass.

A2.1.4 High iron 'Cool green' glass

Increasing the amount of iron in the glass mix has the opposite effect - daylight transmission is reduced, but infra-red transmission is reduced even more so (Johnson [1991] pp42). A typical such product is 'EverGreen' glass, from Libby Owens Ford in the USA. A 6 mm pane of this green-coloured glass has a daylight transmission of 65% but a total solar energy transmission of only 34%, whereas a conventional 6 mm tinted glass of any other colour would have a total solar energy transmission of at least 60% for the same daylight transmission.

This glass can also be treated as an ordinary float glass, although it absorbs slightly more solar energy and will become slightly warmer.

A2.1.5 Etched and patterned glass

Glass may be etched or patterned to distort or diffuse light passing through the glass. Although usually intended for privacy such glasses may also be used to provide shading from direct light. These glasses will absorb slightly more solar energy than clear glass, depending upon the nature of the patterning.

Etched and patterned glass is no more difficult to use than ordinary single glass, although there are issues related to the cleaning of textured surfaces, and to the edge sealing of textured surfaces if they are to be used in multiple glazing units - patterned and textured glasses are usually used with the patterned surface on the room-side of a glazing unit.

A2.1.6 Stone-faced laminated glass

An interesting new product which has come to the authors attention is a thin stone pane laminated to a sheet of glass using a conventional lamination technique. This product is manufactured by laminating a reasonably thick piece of stone (usually a granite or a marble with an intricate internal pattern) to a piece of glass, and then machining the stone down to a thickness at which light can pass through the stone. The resulting effect is rather like a stained glass window, but it can be considered an advanced glazing in that a greater proportion of the light is absorbed by the translucent stone.

This type of glazing is comparatively new, and little information is available on its performance characteristics. The stone-side of the glass probably cannot be installed into a glazing unit, because many types of natural stone contain small fissures which would make a hermetic seal impossible. Similarly the stone-side of the pane probably cannot be on the exposed outside face of a glazing unit, because of the possibility of water penetration and possible freeze-cracking (a principal concern is for the inter-layer that is used to bind the stone to the glass).

The amount of solar energy that is absorbed by the stone is likely to vary significantly with the type of stone, and generalisations are not possible.

A2.2 Coatings and films on glasses

Films and coatings are discussed thoroughly in the book by Johnson [1991], and are also discussed in some depth in the article by Valdes [1988]. The following notes summarise the information provided by Johnson and Valdes and also raise some additional issues.

Coatings with different optical or thermal properties may be applied to the surface of the glass as chemical coatings during manufacture (either as part of the on-line manufacturing process or as a second-stage operation) or may be added in the form of adhesive-backed sheets during refurbishment. Many coatings could be applied to single glazings, and so are discussed in this section, but may be referred to in the next section on multiple-pane glazings.

It should be noted here that most coatings and films consist of several layers of different materials, and a full discussion of each possible combination is beyond the scope of this report. Furthermore there is a wide variability in the properties of some types of coating, and two coatings which share one property may vary considerably in others. Therefore this section only considers coatings in general terms.

A2.2.1 Glass with a mirror (optically reflective) coating applied during manufacture

A mirror coating (light reflective) may be used to create glazing which reflects a substantial part of the incident light (note that a coating may be selective, so that a coating which reflects light need not necessarily reflect heat, and vice-versa). Mirror coatings are principally decorative (thin gold-plating for example) or functional (to prevent a view in under day-light conditions) but they should allow a view out, although the view may be coloured and will appear darker. Note that when back-lit (at night for example) light-reflective coatings may allow a view in (in some cases this effect has been used to dramatically enhance the architectural effect).

Reducing the amount of light that enters through the glass helps to reduce the heat generation within a building, at the expense of slightly lower natural light levels.

Mirror coatings may be produced as an on-line part of the float glass manufacturing process, or may be added to the glass after manufacture.

Some typical performance values are:

Reflecting glass (from Button and Pye [1993] pp167)						
	Light		Direct solar radiation			Total solar radiation
Thickness and mirror colour	T	R	T	R	A	T
6 mm silver	0.10	0.38	0.08	0.32	0.60	0.23
6 mm silver	0.20	0.23	0.16	0.18	0.66	0.34
6 mm bronze	0.10	0.19	0.06	0.21	0.73	0.24
10 mm bronze	0.10	0.18	0.05	0.19	0.76	0.24
T=fraction transmitted, R=fraction reflected, A=fraction absorbed						

The light reflection of these glasses is not particularly high. A 6 mm reflective glass only reflects three to four times as much light as a clear float glass. However, a 6 mm clear float glass transmits 87% of the building light outwards, and this is significant when compared to the 8% of daylight light that is reflected. With the reflective coating the reflection of daylight (at least 19% for the 6 mm glasses above) is much greater than the light transmitted from inside the building (10%)

The proportion of energy that is absorbed by these coated glasses is similar to that of body-tinted glasses - an optically-reflective coating does not necessarily reflect heat. These glasses can therefore reach high surface temperatures, and the same precautions are required as for coloured glass - shield the building occupants from radiated heat and toughen the glass.

Coatings generally have to be protected from damage - although single panes of coated glass are possible they are rarely used, and when they are used the coating is usually on the room-side of the glazing. Mirror coatings should also be applied to flat glass surfaces or distorted reflections will occur. The deflection of glass due to thermal expansion or contraction should always be considered, as this will also distort the reflected image, and unevenness in the framing system will also be apparent for large expanses of reflective glass.

The colour shift of transmitted light experienced with many reflective coatings cannot be avoided, nor can the fact that the coating is still present in winter and may prevent useful winter solar gains.

The reflective nature of these coatings does extend into the infra-red region (although not necessarily uniformly), and optically-reflective coatings can help to reduce the U-value of glazing units.

A2.2.2 Glass with a mirror (optically reflective) coating applied as part of an adhesive film

A reflective coating may be applied in the form of a pre-coated adhesive film (this is the only option for retrofit, but it can also be used on new-build). However, if the glass has a film applied during or after installation then the glass is unlikely to be toughened, and so may be more likely to fail through thermal stresses. Furthermore the film is thicker than an on-line coating (there is a substrate and an adhesive layer involved) and this will generally let less light through and absorb more solar radiation.

As with any product that can be used in retrofit there is a tendency for the installer to use the product without fully understanding its true implications in terms of absorbed solar energy. The addition of a film to the room-side of a double-glazed unit is particularly undesirable, as the higher thermal resistance of the glazing air-space prevents the loss of heat from the warmer pane of glass.

Putting a film on the external surface of the glazing will reduce problems of energy absorption, but the film must be resilient, and the user must allow for the accumulation of dirt on the film and possible damage to the film by the cleaning process.

Another issue with adhesive films is the durability of the adhesive. If the film is applied after the glass is installed then the film is only likely to be fitted up to the edge of the glazing gaskets, leaving a path for cleaning fluids and water to reach the adhesive layer and the edge of the film. Delamination of the film and separation of the film for the glass could then occur. The effect of fire should also be considered - if a film has a plastic substrate then it should be of a material that does not give of poisonous films or burn freely in the event of a fire.

Films can also be sold on the basis that they improve the security of the glazing and hold the glass together in the event of an explosion. Both of these issues require that the film is applied carefully and extends to the very edge of the glazing (the glazing must be removed). If the film is only installed up to the glazing gaskets then in the event of an explosion the glass can be punched out of its frame as a single piece.

A2.2.3 Float glass with a low-emissivity (thermally reflective) coating applied on-line during the manufacturing process (hard coatings)

Un-corroded metal surfaces generally have a low radiation emissivity and a high radiation reflectivity; some metal oxides also have this property. If a metal-based coating is applied to the surface of the glass then infrared radiation can be reflected, and heat transfer is reduced. The metal coating may only be a few tens of atoms thick, and so it appears transparent when viewed from either side (the coating is thermally-reflective but not optically-reflective). A typical coating will reduce the amount of infra-red that the surface emits by 80%.

Coatings can be applied during the float glass manufacturing process. On-line coating has obvious cost advantages over the alternative of having to transport the glass to a coating plant, and higher rates of production are possible. Coatings which are applied on-line are referred to as pyrolitic coatings, and they form an integral part of the glass surface, being baked onto the glass during production. These coatings are often referred to simply as 'hard' coatings, because they are difficult to remove and can be bonded to directly (this type of coating does not have to be removed when the glass is fabricated into a multiple glazing unit).

Some work has been performed on the etching of hard coatings to produce a grid (spacing on the scale of μm). This modification of the coating increases transmittance and reduces reflectance. Lampert and Ma [1992 pp56] suggest that a typical grid etched onto an indium tin oxide (ITO) film saw the total solar energy transmittance increased from 0.8 to 0.9, whilst the reflectance reduced from 0.91 to 0.83. However, this extra step in the manufacturing process increases the cost of the coating.

The coating material is already an oxide (usually tin oxide or indium tin oxide) and so cannot corrode when exposed to the atmosphere. These coatings can therefore be used on the exposed surfaces of glass, but this raises issues related to cleaning. If an exposed low-e coating becomes wet or dirty it quickly becomes a high-e coating because water and dirt have a high radiation emissivity - cleaning may be difficult because hard low-e coatings have a rough surface, and repeated cleaning may result in damage and erosion of the coating. Erosion of exposed coatings on the outer surface of the glazing will be more rapid due to wind-borne dust and debris. Hard low-e coatings are therefore usually used within multiple glazing units.

For the exclusion of solar energy low-e coatings in double glazing units are best used on surface 2 (the convention is to count from the outside, so that surface 2 is on the back of the outer pane of glass). However, small variations in the thickness of the coating may lead to a slightly oily appearance (iridescence), and this effect is usually hidden by putting the coating on surface 3. The difference in thermal performance is that extra solar radiation is absorbed at the glass pane which has the low-e coating, and if this pane is on the room-side of the glazing unit then more of the extra heat is radiated into the room. It is suggested however that the iridescence of hard low-e coatings is less of a problem now that multi-layered hard coatings have been developed (Lampert and Ma [1992 pp55]).

A key gain in performance from using a low-e coating is the increase in the room-side glazing temperature. The reduction of condensation on such glazings can actually be a better selling point than the reduction of energy usage because condensation is a visible problem and energy usage is not.

A2.2.4 Glass with a low-emissivity (thermally reflective) coating applied after the manufacturing process (soft coatings)

Low-e coatings may also be applied after the glass has been manufactured, by the process of sputtering (also referred to as vacuum deposition). In this process the cooled glass is placed into a vacuum chamber and a pure metal target is bombarded with a beam of ionised gas to produce a stream of metal atoms which then condense onto the surface of the glass. The resulting coating has a very low emissivity (about 0.04, which is as low as is practically possible - any further reduction in emissivity would not give a significant reduction in heat transfer). This type of coating can also be applied to plastics materials, because it is produced at a low temperature.

The sputtering process occurs at a much lower temperature than pyrolysis and so the coating does not bond itself to the surface of the glass. As a result the soft coating must be removed from the edge of the glass (it is burnt off) before assembly into a multiple glazing unit. Applying the coating onto hot glass would not work because the coating metal would corrode during deposition, and its effectiveness would be significantly reduced.

At one time using a soft coating on an exposed surface was not possible, because the coating corroded (tarnished) when exposed to atmospheric moisture. Soft coatings therefore had to be protected by being hermetically sealed into a dry environment (such as the cavity of a multiple glazing unit). Now, however, multi-layer soft coatings are possible, in which the low-e layer is protected between layers of a metal oxide (a typical layer arrangement is bismuth oxide-silver-bismuth oxide). The metal oxide is selected to be transparent to infrared (otherwise the low-e properties of the silver coating would be lost) and cannot corrode (because it is already an oxide).

Soft coatings may be more expensive than hard coatings, because the glass must be transported to the coater and because the coating must be removed from the edge of the glass before it can be used. The glass may also have to be cut to size before coating. A useful refinement would be to improve the bond between the soft coating and the glass, although the ease of removing the coating may make this unnecessary. Advances in processing speed will also reduce the cost difference between hard and soft low-e coatings.

A2.2.5 Glass with a low-emissivity (thermally reflective) coating applied as part of an adhesive film

Low-e coatings can be applied first to a plastic film, and then fitted to the glazing. In this case the low-e coating will probably be protected with a clear coating that transmits infra-red (otherwise the properties of the low-e coating will be lost).

Adhesive films may be applied to single glass in order to cut down solar heat transmission or to improve privacy. However, these films do increase the amount of energy that is absorbed by the glass, which is often annealed and more likely to break due to thermal fracture. These films should not be applied to ordinary double glazed units or the risk of failure is very high.

A2.2.6 Glass with a diffractive coating (holographic)

A diffraction grating comprises a series of parallel lines with uniform spaces between them. The lines are of some material that does not transmit radiation. When solar radiation strikes the diffraction grating radiation which passes close to the edge of a line is bent. If 'waves' of radiation are considered, as shown in Figure A2.2.6, then it is apparent that one of the diffracted waves must travel an extra distance x in order to reach the target surface - if the distance x is equal to one-half of the wavelength of the light then the two waves will cancel each other out (destructive interference) and there will be no illumination of the target surface at that particular wavelength. Similarly if the distance x is equal to the wavelength then the two rays will add together (constructive interference) and there will be bright illumination of the target surface.

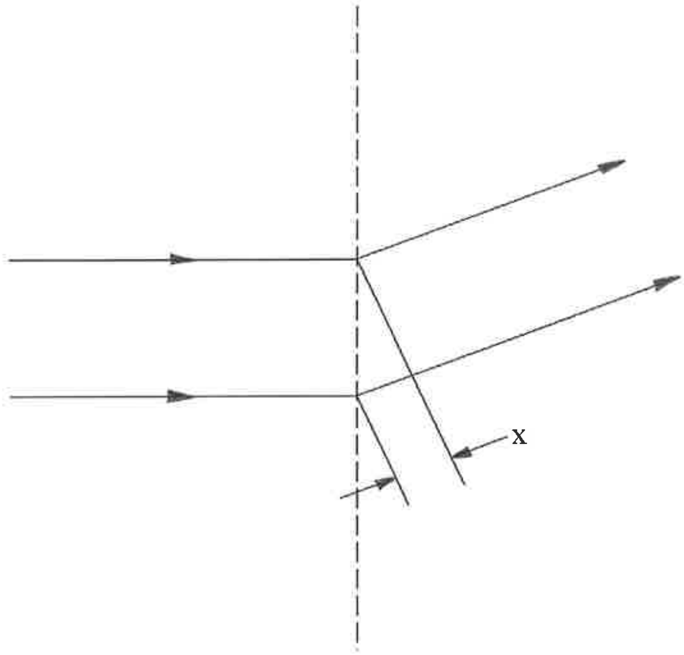


Figure A2.2.6 Diffraction of radiation through a narrow grating

Clearly the angle α is important, and the distance x need not be only one-half or one whole wavelength - reinforcement occurs at any whole number multiple of the wavelength and interference occurs at any whole number multiple of the wavelength plus one-half wavelength. The light passing through the diffraction grating therefore appears as a series of bands of light and dark. It should be noted that this effect is only visible if the spacing of the parallel lines is small - typically around the wavelength of the radiation - and that different wavelengths of radiation behave slightly differently. This can cause the transmitted visible light to be separated into a colour spectrum as each colour favours a slightly different viewing angle to its neighbours.

Holographic coatings work on the basis of a diffraction grating - a 3-dimensional network of parallel lines is created which have a uniform spacing similar to the wavelength of solar radiation. Only light of the same wavelength as the spacing of the grid is allowed straight through - nearby wavelengths are diffracted whilst distant wavelengths are reflected.

By varying the spacing of the holographic grid it is possible to refract incoming solar heat and light through different angles, so that one part of the spectrum is transmitted and another is diverted. Holographic films can thus be used to create shading devices, or to redirect light to where it is best used.

Holographic films may also be produced which can have several layers, so that light can be selectively used when the sun is at several positions in the sky.

An interesting use of holographic films is described by Müller [1994] in which holographs on sliding glass panels are placed over a glazing system with clear glass bands delineated with strips of photovoltaic cells - most of the direct incident light is focused onto the photovoltaic cells and about half of the diffuse light passes between the cells to provide natural light within the building.

Holographic coatings work well with direct light, but do not work properly if the light is diffuse. There may also be a rainbow effect when the glazing is viewed from some angles (UCD-OPET [1994]).

A2.2.7 Plastic glazing sheet with a low-emissivity (thermally reflective) coating applied during manufacture

Low-e coatings can also be applied to plastics. The application of a soft-coating to a film which is then suspended in the gas-space of a multiple glazing unit is described in the next section, but it is also possible to produce thick plastic sheets with an integral low-e coating.

'Plexiglas X Heatstop' (Endres and Benz [1994]) is a plastic sheet which is co-extruded with an infrared-reflective coating. The active ingredient of the coating is mica platelets enclosed in a metal oxide layer, the thickness of which is controlled to preferentially reflect infra-red radiation. This coated product can be used in single sheets - the coating is an integral part of the sheet, and should not corrode.

It is reported by Endres & Benz [1994] that 'Plexiglas X Heatstop' has a reddish-blue 'shimmer' in incident light, and that transmitted light has a green tinge. As with other low-e coatings the daylight is also slightly reduced. However, the coated plastic can be curved and bent after manufacture, to create components such as skylight domes. The product typically has 51% light transmittance and 38% total solar energy transmittance, which compares to 92% light and 85% total solar energy transmittance for the clear un-coated product.

A2.2.8 Other issues relating to coating and films

Coatings are far more complex than has been described above. Multi-layer coatings are being produced in more and more forms, and development of new coatings is ongoing. Many of the problems associated with coatings will probably be solved, and in some countries glasses with coatings form a major part of the new-glazing market.

A subject that has not been described above is the development of coatings specifically for the purpose of excluding ultraviolet radiation. Such coatings are particularly useful because of the detrimental effects of ultraviolet on some materials and pigments.

Some films are applied to glass for the purpose of holding the glass together should it break (particularly as the result of an explosion). Such films will also modify the thermal performance of the glass, even if the film is transparent. Patterned films might be used to create privacy, and this too can modify thermal performance. Generally the application of any adhesive film to a window will result in more heat being absorbed by the glass, and care should be taken to check that the glazing system can tolerate any additional thermal expansion that occurs as a result.

A2.3 Multiple-sheet glazings

There are several reasons why glass may be used in a sandwich assembly (multiple glazing unit). Generally two or more panes of glass, separated by a gas-space, will have better thermal properties (the insulation value will be greater, although light transmission will be reduced further by each additional layer of glass, plastic or coating) and give better acoustic attenuation (which is particularly important for domestic dwellings which may be situated close to busy roads). However, some of the various coatings that can be applied to glass must be protected from attack by atmospheric moisture, cleaning agents or abrasion, and sealing them into multiple glazing units is the only solution. It is also important, where some solar control glasses are used, that the solar control glass is kept away from the building occupant - solar control glasses generally absorb excess solar radiation and can become very hot to the touch.

A2.3.1 Double-glazed clear glass, air- or gas-filled, with or without low-e coating

Multiple glazing units were originally all air-filled, with ordinary glass. However, it was soon realised that heat transfer through these units could be reduced if a better gas could be found (one which suppresses convection better and has a lower thermal conductivity) and the glass surfaces could be coated to give them a lower emissivity.

In a gas-filled unit the air is purged from the unit during manufacture and replaced with a gas such as include argon, krypton or sulphur hexafluoride (SF_6). These are generally selected to have a greater resistance to heat transfer than air, although SF_6 is used because it has better resistance to acoustic transmission.

The gas-fill may be used in conjunction with any of the glass options described above, to give even lower heat transfer, and the combination of gas-fill with a low-e coating is more usual than just a gas-fill on its own.

Low-emissivity coatings are available as hard coatings, which have a comparatively high emissivity, up to 0.2, or as soft coatings, which have lower emissivities, down to 0.04 - ordinary un-coated glass surfaces have a normal emissivity of about 0.88.

It should be noted that a coating is rarely applied to both panes, as the additional gain from a second coating is rarely worth the additional cost - the use of one soft low-e coating gives a lower U-value than a single hard coating.

Some typical values of double glazing units with various gas-fills and plain glass surfaces are

Fill gas	Density	Thermal conductivity	U-value [W/m²K]		
	[kg/m³]	[W/mK]	4-6-4 mm	4-12-4 mm	4-16-4 mm
Air	1.23	0.025	3.20	2.80	2.68
Argon	1.7	0.0168	2.95	2.64	2.54
Krypton	3.6	0.0093	2.67	2.50	2.51
SF_6	6.36	0.0128	2.88	2.92	2.94

With a single hard low-e coating the following performance values are possible

Fill gas	Density	Thermal conductivity	U-value [W/m²K]		
	[kg/m³]	[W/mK]	4-6-4 mm	4-12-4 mm	4-16-4 mm
Air	1.23	0.025	2.62	1.95	1.73
Argon	1.7	0.0168	2.22	1.66	1.53
Krypton	3.6	0.0093	1.73	1.44	1.47
SF_6	6.36	0.0128	2.17	2.25	2.29

and with a soft low-e coating

Fill gas	Density	Thermal conductivity	U-value [W/m²K]		
	[kg/m³]	[W/mK]	4-6-4 mm	4-12-4 mm	4-16-4 mm
Air	1.23	0.025	2.42	1.63	1.38
Argon	1.7	0.0168	1.94	1.26	1.13
Krypton	3.6	0.0093	1.35	1.03	1.05
SF_6	6.36	0.0128	1.91	2.01	2.05

These values have been calculated in accordance with BS 6993:Part 1 [1989], and an iterative procedure used to determine the correct heat flow through the gas-space based on environmental temperatures of 20°c and 0°C. The effective emissivity of a plain glass surface is taken as 0.845, that of a hard low-e coating as 0.2, and that of a soft low-e coating as 0.05.

There are two key issues with gas-filled units: was the correct amount of gas put into the unit in the first place? and: will the gas stay in the unit over a period of time?

Gas-filling is subject to the quality control systems used by the sealed unit manufacturer. In one method of manufacture the sealed unit is assembled and gas is then injected into one opening in the perimeter of the unit whilst air is vented off at another - the process is stopped when the concentration of the fill-gas at the exhaust vent reaches some pre-defined level. However, it is possible, if the injection opening and the exhaust opening are opposite one-another, for gas to pass directly from the injector to the exhaust, or for significant mixing of the fill gas with the air within the unit. An alternative approach to filling is to assemble the unit and then withdraw the air in a vacuum chamber - the fill gas is then introduced to the sealed unit as air is introduced to the chamber outside the unit (thereby equalising the pressure difference across each pane of glass and preventing the unit from imploding or exploding). A third method of manufacture is to assemble the unit using robots in an atmosphere saturated with the fill gas.

Gas filling must be controlled carefully if the units are to be properly filled. There is also a need for reliable non-invasive techniques which can be used to assess the amount and type of the fill-gas in the unit. Customer confidence in gas-filled units will quickly disappear if there are cases of units being supplied without the appropriate fill-gas; at the moment it is only possible to identify the gas with destructive testing techniques, although surface temperature measurements may give some indication of incorrect filling - the customer presently has no assurance that the specified gas-fill is actually provided, other than the word of the supplier.

The concentration of gas in a unit may also decrease over a period of time, either due to diffusion through the edge seal, or due to a failure of the edge seal. The latter condition will usually lead to interstitial condensation, but the former will only lead to a gradual increase in the U-value and may go undetected for some time.

Double glazing is now reasonably common in the UK and there are a clear set of recognised problems. Principally if the glazing unit is hermetically sealed then there is a need to ensure that the unit is installed in a way that does not impair the durability of the hermetic edge-seal. It is already recognised that wet-glazing can be a problem if the glazing sealant fully encapsulates the edge of the glazing unit - if the glazing sealant comes away from the glazing it may allow water to penetrate by capillary action and stay in close contact with the glazing edge seal, leading to degradation and eventual failure of the edge seal. The probability of failure is however related to the initial quality of the edge seal, and proper examination of the glazing unit edge during manufacture should help to reduce the incidence of this type of failure. The effect of service temperature on the glazing edge seal is also important, as is possible attack degradation of the polymer sealant materials by ultraviolet.

A2.3.2 Double-glazed unit, coloured glass, gas-filled

The use of coloured glass in double glazing units is possible. Usually only the outer sheet of glass will be coloured, as this results in the lowest stresses (glass-cooling heat loss from the outer pane is always likely to be higher than from the inner pane). Furthermore the occupier of the building is protected from contact with the hot glass pane.

The use of coloured glass requires that the glass be toughened, and care must be taken to ensure that the glass is installed the right way round - it is however generally easy to tell which is the coloured pane of glass! The higher temperature of coloured glass when exposed to solar radiation may also have implications for the durability of the edge seal, and will also lead to greater expansion of the glass - the mounting of the glass is therefore important (there must be a reasonable clearance between the edges of the glazing unit and the glazing frame).

A2.3.3 Double-glazed unit, suspended coated film between panes, gas-filled

Instead of coating one of the panes of glass it is possible to suspend a thin film of some coated polymer (usually polyester) between the panes of glass. This approach sub-divides the air-space, reducing convection currents within the glazing unit, and the suspended film may have coatings on both sides. The film must however be pierced at one edge or corner, to ensure that the temperature difference across the glazing unit does not generate a pressure difference across the film, which could lead to rupture of the film. This type of system also generally uses glazing edge spacers with better thermal properties, such as that shown in Figure A2.3.3:

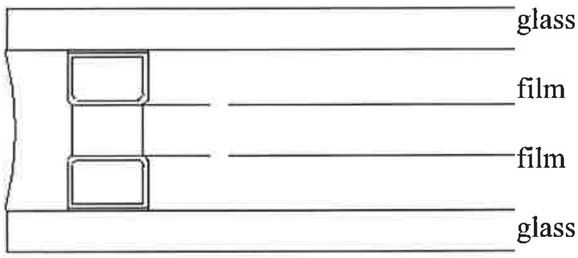


Figure A2.3.3 A glazing spacer with suspended polyester films

A typical suspended film is Southwall Technologies 'Heat Mirror', which had been used for more than 70 million square feet of glazing by 1993 (Southwall Technologies [1993]). A double glazing unit with two 6 mm panes of clear glass, a single Heat Mirror 88 suspended clear film and a 12 mm air-filled gas space has a centre-glass U-value of 1.76 W/m^{2}K, and transmits 70% of daylight but only 44% of the total solar energy (shading coefficient 0.62). At the other end of the range using a Heat Mirror 33 clear film reduces the U-value slightly to 1.70 W/m^{2}K, transmits 28% of daylight but only 13% of the total solar energy (shading coefficient 0.22). This demonstrates the range of performance that can be achieved simply by varying the coating on the plastic film.

This type of suspended film has been used for some time in the USA. There are obvious issues regarding the installation of such films, to ensure that the film does not wrinkle, and the glazing edge seal must not become soft (either as a result of age or high operating temperatures) or the tension in the film could pull the glazing edge spacer inwards.

Generally the polymer used for the suspended film can creep, and keeping the film taut is extremely important. It should be noted that a European manufacturer of suspended films withdrew the product after experiencing problems with the film-tensioning mechanism. Tensioning can be achieved either by pre-tensioning the film using the perimeter glazing spacer (which is an integral part of the suspended film system) or by heating the glazing unit after production so that the film shrinks slightly and pulls itself taut. However, at high temperatures expansion and creep of the film may lead to wrinkles, and it may be difficult to ensure that the film is initially flat at corners.

Increasing the number of films will subdivide the gas-space even further without a weight penalty, but as the number of films is increased so the light transmission decreases. More films may also be more difficult to tension properly.

A2.3.4 Double-glazed unit, liquid-filled

McKee [1994] reports the development of a fluid-filled glazing system. The system comprises a triple glazing unit, but with the cavity next to the room-side glazing filled with a special fluid. The fluid is formulated to transmit light but trap infrared. The visual light transmission is reported as 70%, whilst the shading coefficient is less than 0.2.

By circulating the fluid summer heat can be recovered using a heat exchanger or winter heat can be added and used to warm the building. The fluid can be dyed, and a photochromic dye can be added so that the glazing reacts to ambient light levels.

There are obvious concerns regarding the sealing of these units, particularly if a network of pipes is required. Replacing a damaged unit may cause problems if the system needs to be drained, and there must be concerns about possible expansion and contraction of the fluid. The amount of energy that is absorbed by a coloured liquid will be high, and positioning the liquid on the room side of the glazing could lead to problems with thermal radiation from the glass. Although circulation of the fluid will reduce the risk of overheating there is the question of what will happen if the circulating system fails in some way (presumably the liquid will get very hot).

The weight of the unit is also significant, and special framing sections may need to be developed. The possible development of biological matter within the system must be considered; whilst chemicals can be added to the liquid to inhibit the development of algae and similar organisms there is then a need to consider what will happen if a problem occurs say five years after installation - the building owner may call in a local engineer to fix the problem, who could then inadvertently refill the system with the wrong liquid.

A2.3.5 Double-glazed unit, evacuated with surface coating

The most effective alternative to the units described above is to remove the air from the glazing unit altogether. Conduction and convection heat transfer cannot occur through a vacuum, and so the only mechanism for heat transfer would be by infrared radiation. A surface coating can then be used to significantly reduce the radiation component of the heat transfer.

Simko *et al* [1995] describe the manufacture and performance of evacuated glazings. A typical evacuated glazing might comprise two panes of 4 mm glass, with a 0.15 mm space, held apart by 0.25 mm diameter spacers on 25 mm centres. It is suggested that the spacers are difficult to see with the unaided eye, and that the optical clarity of such a unit is nearly as good as a conventional double glazing unit.

The small gap between the sheets means that a hard vacuum is required, and the edge seal must be strong enough to withstand this. Typically the edge seal is formed from sintered glass, which requires that the units are baked at high temperatures (about 500°C - Simko *et al* [1995]) during production. The air is pumped out of the units through a special tube, which is then sealed over with solder glass. The general layout of such a unit is shown in Figure A2.3.5.

Simko *et al* [1995] indicate that a centre-glass U-value of 0.9 W/m^2K can be routinely achieved using two hard low-emissivity coatings (soft low-e coatings cannot be used because the process of forming the edge seal occurs at a temperature that would destroy a soft coating). In this condition about 40% of the heat transfer through the unit is due to conduction through the support pillars, whilst the remaining 60% is due to radiation heat transfer. The optical properties of the unit should be similar to those obtained for an air-filled unit.

Evacuated glazings require good edge seals, and the sheets of glass must be supported to prevent them from being pulled together by the vacuum. This is generally achieved by using glass spacers between the panes and by sealing the edges of the unit by glass-sintering. However, the units are still very fragile, and early indications have been that even transporting the units can lead to fracture.

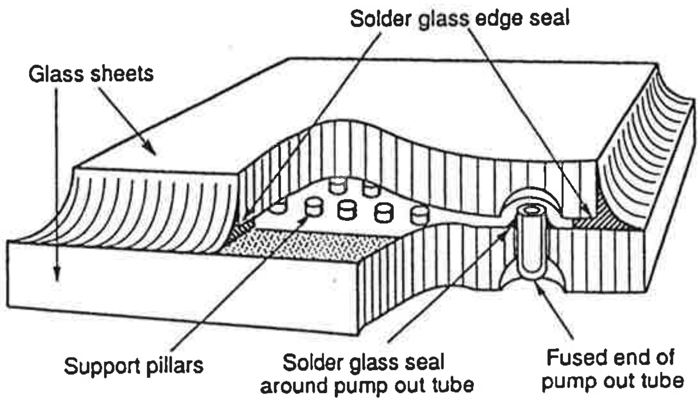


Figure 1 Schematic diagram of vacuum glazing as currently manufactured at the University of Sydney.

Figure A2.3.5 An evacuated glazing unit (from Simko *et al* [1995])

The low-e coating must be selected carefully - the process by which the edge seal is formed will burn a sputtered, soft, coating off the glass, and so a hard pyrolitic coating must be used. This requires two pyrolitic coatings to achieve the same level of performance as a single sputtered coating.

The spacers that are used to separate the panes of glass may be visible under some lighting conditions (it has been suggested that the optical clarity of evacuated glazings are 'nearly as good' as ordinary double glazing units!). The spacers are also the limiting factor in determining the performance of these units - sufficient spacers must be used to prevent local distortions of the glass (this causes higher thermal stresses in the glass and distorts reflections).

In terms of thermal stresses Simko *et* al [1995] indicate that unit have survived glass-to-glass temperature differences of 70°C, although it is uncertain whether units would survive this temperature differential superimposed on fluctuating wind-loads.

Ideally this type of glazing would last longer in small units (wherever small panes of glass have been used traditionally - for example Georgian sash windows in the UK). However, the nature of the edge seal - sintered glass - means that the heat transfer path at the edge of the glazing is very significant when compared to the centre-glazing heat transfer; this means that the average U-value of a small sample is entirely dominated by the edge performance. Although it has been suggested that increasing the bite of the edge gasket would help to shield the poorer-performing glazing edge this would also reduce the vision area of the glazed system, in contrast with most architects' ever-growing desire for more glass and less frame.

A2.3.6 Triple glazing and beyond

Triple glazing, and glazings with four or more panes of glass, may be used with any combination of glass type, surface coating and gas-fill described above. As a general rule however coloured glass will be outermost and surface coatings will be placed facing into the gas-spaces with one per gas-space. It is also possible that a sealed double glazed unit will be used with a separate sheet of glass for the third pane.

Where a double glazed unit is placed in parallel with a single pane of glass it is typical in Scandinavian practice that the extra pane of glass is on the outside of the unit. This stabilises the temperature range of the glazing unit (by eliminating the highs and lows of the annual and diurnal temperature variation) and reduces the likelihood of the edge seal coming into contact with water. The space between the glazing unit and the third pane is then vented to the outside, eliminating the risk of condensation in the space without compromising the thermal performance of the system. Conventional UK practice on the other hand is to add extra panes of glass to the room-side of windows!

A2.3.7 Multiple glazing with 'electric glass'

The coatings that are usually applied to glass have a significant metal content. As a result the coating is electrically conductive, but because the coating is very thin it has a high electrical resistance. If a voltage is applied across the coating, through electrodes running along the top and bottom of the glass, then the low-e coating becomes hot. If the low-e coating is on the room-side of a gas-space the insulating properties of the gas-space ensure that most of the heat is transmitted into the room. Electric glass is already being produced in Finland under the trade-name EGlas.

'Electric glass' is already used in applications where condensation is undesirable (the glass only has to be heated to a fraction of a degree above the adjacent air temperature and condensation cannot occur). Electric glass is also useful for avoiding the formation of ice and for clearing snow from a glass surface.

The obvious drawback with electrical glass is the need to provide an electrical sub-system. However, this will become more straightforward as the relevant technology is already being developed for photovoltaics. Photovoltaics could even be combined with electric glass to provide a system that completely eliminates glazing heat loss whilst also heating the room and eliminating cold-radiation and cold down-draughts from the glass. The elimination of cold down-draughts would then allow simple changes to room layout, such as moving radiators and other heating systems away from their usual location below the window to a location against an internal wall, where all of the heat can be retained within the building.

A2.4 Transparent insulation materials (TIMs)

These materials have very good insulating properties combined with good light transmission. On the whole these materials do not offer a good enough optical performance to be used for view windows, but are ideal for use where the desire is to increase the level of ambient light. TIMs are ideal for use in constructions such as Trombe walls.

Many transparent insulation materials are actually translucent, and they also act to diffuse direct light. TIMs have been classified by some authors using a scheme such as that shown in Figure A2.4:

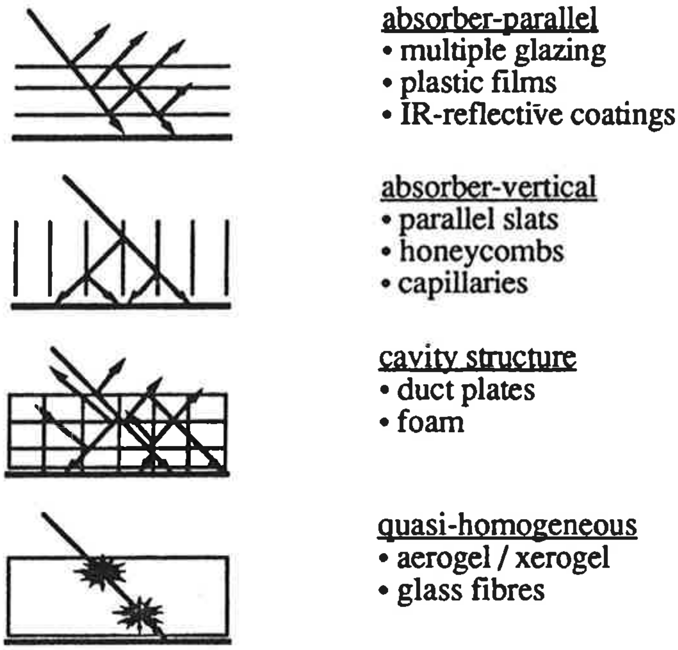


Fig. 1: Geometric classification of TIM[7]

Figure A2.4 Classification of transparent insulation materials (from Platzer and Braun [1995])

A number of projects have been completed in which TIMs have been used on demonstration buildings. A useful summary of some of these projects is given in ETSU-OPET [1993].

A2.4.1 Aerogels, xerogels and carbogels

Aerogels, xerogels and carbogels are silica-based materials which contain a significant volume of air-filled voids (Duer *et al* [1995]).

These compounds are produced by mixing an organic silicon compound with water, alcohol and catalysts into an 'alcosol'. The alcosol gradually develops a silica structure containing small voids filled with solvent - the 'alcogel'. The critical part of the manufacturing process is to remove the solvent without damaging the fragile silica structure, leaving behind a cellular material containing as much as 95% air-filled voids. The manufacture and properties of these materials are discussed in depth in books such as that by Brinker and Scherer [1990].

Aerogels are produced by drying out the alcohol solvent at high pressures (typically 90 atmospheres) and high temperatures (typically 280°C) in order to prevent collapse of the silica structure (collapse occurs due to high surface tension forces - if the alcohol is removed at a temperature and pressure above the critical point then the surface tension forces disappear). An alternative to this is first to replace the alcohol with CO_2, which can then be evaporated safely at low pressure and low temperature (any temperature above 31°C) - the resulting material has been called a carbogel. Another alternative is to add other monomers to the alcogel, in order to strengthen the silica structure, which allows drying to take place at atmospheric pressure and temperatures below 100°C - this results in a xerogel, which is denser than an aerogel or carbogel.

Duer *et al* [1995] describe two aerogels (densities 90 and 150 kg/m^3), a carbogel (density 173 kg/m^3) and a xerogel (density 500 kg/m^3), and the optical properties are discussed. It is generally found that the xerogel has slightly better optical properties, although slightly poorer thermal properties due to its higher density. However, the carbogel and aerogels are similar in performance.

Aerogels may be produced in monolithic form (slabs) or as granules, typically 2-6 mm diameter. The thermal conductivity of an aerogel is typically 0.02 W/mK or less (Field [1994]). Xerogels are believed to have a higher thermal conductivity, perhaps in the range 0.03-0.06 W/mK. This suggests that a panel comprising two 4 mm sheets of glass and a 16 mm aerogel-filled cavity will have a U-value of 1.0 W/m^{2}K or less. To attain a U-value of 0.45 W/m^{2}K, which is the current level required for walls in the UK, would only need an aerogel layer 41 mm thick. Lower thermal conductivity values can be obtained if air is pumped from the unit to create an evacuated aerogel (typically the absolute pressure should be reduced below about 10% of atmospheric pressure). Evacuating the unit (the aerogel is strong enough to withstand the forces due to evacuation of the unit) typically lowers the thermal conductivity down to 0.008 W/mK (Yannas [1994a]), which would allow a U-value of 0.45 W/m^{2}K with just 16 mm of aerogel.

Aerogels produced by some processes are hydrophilic - they absorb ambient moisture and subsequently break down. However, aerogels can be produced in a form that repels water (hydrophobic) (Field [1994], Brinker and Scherer [1990]).

It is suggested that aerogels should not be subjected to repeated movement because the material is fragile and can be ground down into powder. However, with the development of hydrophobic forms of aerogel it is possible to vent the aerogel to atmosphere, thereby using pressure equalisation to limit deflections of the glass surfaces (although the thermal performance would not be as good as with evacuated units and the question of contamination of the aerogel with biological material would need to be considered).

Light transmitted through aerogels is filtered and appears yellow in colour (the reflected light appears blue). Furthermore there is a small amount of light diffusion and the view through an aerogel appears slightly cloudy.

A2.4.2 Capillary glass - 'Okalux'

'Okalux' is a commercially-available (since 1965) advanced glazing comprising a slab of parallel hollow acrylic capillaries, which is installed fitted between two panes of glass in a sealed unit. Okalux is a translucent material which does not permit a view-through, but which acts to diffuse incident light by a process of multiple reflection - the acrylic 'capillaries' behave as short optic fibres with highly reflective walls. The capillaries are attached to a translucent woven fabric mat, and this is then installed between the panes of glass, which are sealed with a conventional edge sealant. Thicker insulating panels can be produced, with a thermally-broken aluminium edge (Kümpers and Link [1994]).

This type of advanced glazing material can be used to give more even light levels within a room, and also has better heat transfer properties than the air which it typically replaces in the double glazing unit.

The Okalux slab is fairly rigid, and appears to be used without any form of edge spacer - the Okalux material itself is in contact with both sheets of glass, and only needs to be sealed at the edges of the unit. Whilst this has obvious implications in terms of thermal performance (the edge of the unit does not compromise the overall performance) it should be noted that if the Okalux is in contact with both sheets of glass then it can be expected, over a period of time, to undergo a fairly strenuous cycle of movement due to wind-loading. The durability of the plastic capillary structure under cyclic loading is not clear and should be assessed - although this type of glazing has been used for some time it is not clear whether service units have been dismantled and checked for damage, nor is it clear that units have been performance-tested after several years in service.

It should also be noted that as a translucent material Okalux cannot be used to glaze a facade in its entirety, but if used in areas above head height it could be used to give a more even light level whilst cutting out direct solar radiation. The transmitted light from these devices is concentrated in a cone, and glare may be a problem unless suitable precautions are taken. Okalux is supplied with the capillaries layered between two sheets of a translucent woven mat, and this may reduce glare problems.

As this product is already available commercially it is possible that the technical issues raised above will be resolved.

A2.4.3 Honeycomb materials

Honeycomb assemblies of hollow rods may also be used to redirect solar energy. Again solar energy is transmitted through the assembly by a sequence of multiple internal reflections.

Honeycombs also tend to be made of plastic materials with lower thermal conductivities than glass, such as polycarbonate or polymethylmethacrylate. The rods are hollow because air has much better insulating properties than solid materials and plastics have the advantage that they can be readily extruded into small hollow rods with uniform cross-sections.

As with capillary glass these structures are best protected between panes of glass. The risk of contamination with dirt and infestations by biological organisms is otherwise too great. The transmitted light from these devices is also concentrated in a cone, and glare may be a problem in some positions.

If plastic-based TIMs are used for solar collectors or as retrofit over existing opaque walls then care should be taken that the plastic can withstand the high temperatures that are likely to be generated (Peuportier [1994]). It is normal when fitting TIMs over an opaque wall to paint the wall surface black in order to maximise the absorption of energy. This may also have implications for the framing system, because thermal expansion of the material will be greater - the use of conventional glazing-rebate dimensions may not be sufficient in some applications.

A2.4.4 Thin-wall polycarbonate sheet

Polycarbonate is also used in the form of thin-walled sheet, produced by an extrusion process. The cross-section of the sheet is divided into small cells which limit the occurrence of convection heat transfer. A number of cross-sections are commercially-available, and a selection is shown in Figure A2.4.4:

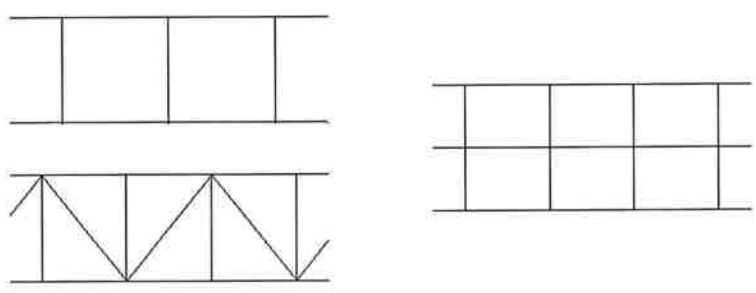


Figure A2.4.4 Typical cross-sections of thin-walled polycarbonate glazing sheet

This type of sheet has found a significant use in domestic conservatories in the UK, and a range of colour-tints are available. The strength of the plastic and the in-built edge seal makes the cost very favourable when compared to a double-glazed unit, whilst the thermal performance is very similar. However, light transmission through these products is distorted and a clear view is impossible. For overhead glazing these products are ideal.

The polycarbonate sheets are used directly, and there have been concerns raised about the compatibility of the polycarbonate with certain materials used to seal the sheets into framing systems. Durability of the plastics may also need to be considered carefully, and plastics are also more prone to scratching.

A2.4.5 Glass blocks

Glass blocks may seem an unusual item to include here but they can be considered as transparent insulation. The light transmission through a glass block is distorted, and the thick walls of the glass block also provide a shading effect when the sun is high in the sky. In future the insulation content of glass blocks may be increased by replacing the air within the block by a material such as an aerogel.

Glass blocks are already used where light transmission is desired but the view should be limited. The addition of an aerogel to the glass blocks will allow these components to be used in greater amounts, and the strength of the glass will prevent mechanical damage to the aerogel. Glass blocks also have the advantage that they are self-supporting, doing away with the need for expensive framing systems.

A2.5 Directional glazings

Directional glazings work by changing the path of incident radiation, either reflecting the radiation away from the building or redirecting the transmitted radiation to where it is of most use (or least inconvenience) within the room. Whilst many of these products are sometimes described as transparent insulation materials they are placed in a separate section here because their behaviour under direct light is generally specular - they do not diffuse or disperse incident light.

A2.5.1 Prismatic panels

A prismatic panel has a surface that is cut into a wedge pattern. The surfaces of each wedge refract or reflect direct light, depending upon the angle of incidence. Generally these panels are designed and arranged so that strong direct sunlight is reflected, whilst some of the diffuse light is admitted into the building. Some typical prismatic panel arrangements are shown in Figure A2.5.1.

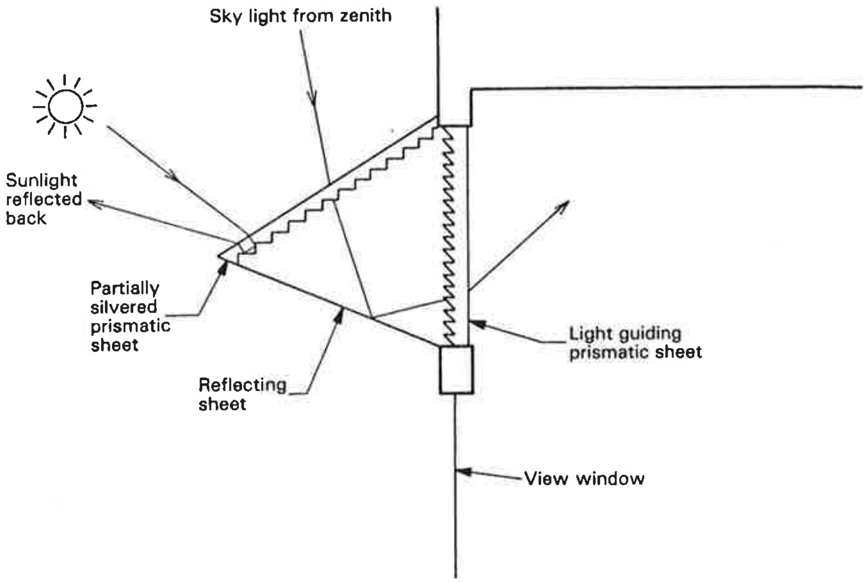


Figure 73 A sunlight-excluding prismatic glazing system

Figure A2.5.1 Typical arrangements of prismatic panels (from Littlefair [1996])

An innovative use of prismatic panels is demonstrated by the Hüppe Form 'Daylight Technique' system, in which small prismatic panels are used to form the slats of a Venetian blind, thereby giving a high level of control over lighting levels. Light which passes though the prismatic blind is then directed onto a second reflecting blind, which redirects the light onto the ceiling. By co-ordinating the position of both blinds it is possible to obtain a uniform light level within a room whilst still permitting a limited view out.

Prismatic panels, and their effect on room lighting levels, are discussed by Bartenbach and Klingler [1994].

The angular surface of a prismatic panel is liable to gather dirt and dust, and this reduces the effectiveness of the panel. The panel is usually either cleaned regularly or protected by being enclosed in a sealed glazing unit.

The nature of the prismatic panel is to prevent direct light transmission - by the same mechanism any view out is prevented. The double-blind system used by Hüppe Form does allow a limited view out, in the form of horizontal strips of view, and this is preferable to no view.

Glazings which work on a refractive principal also tend to cause some separation of the light into a coloured spectrum - prisms are traditionally used to demonstrate the polychromatic nature of 'white' light. However, where a large number of small parallel prisms are used this problem tends to disappear as the separation of the transmitted light is only visible at the edges of the transmitted light beam.

A2.5.2 Louvre panels

Siemens market a daylight system which comprises a rigid plastic louvre system mounted between two panes of glass. A cross-section is shown in Figure A2.5.2:

Fig. 1:
Operating principle

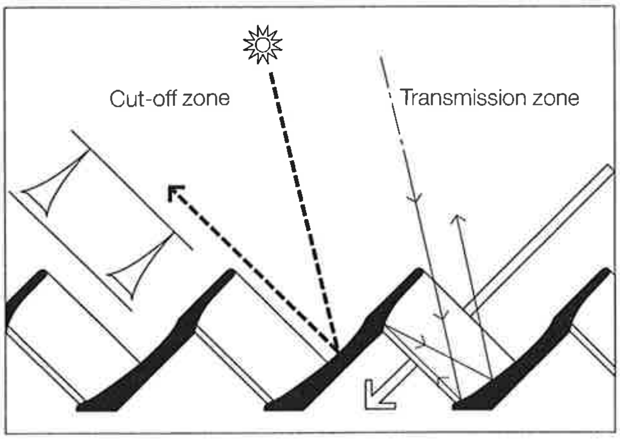


Figure A2.5.2 Typical section through a louvre panel (from Siemens [undated])

The curved plastic louvre is coated with a highly reflective aluminium layer, and the louvres are sloped so that light is reflected back from the louvre at some incident angles but reflected through the louvre at other angles. The louvre system is usually arranged so that the direct path through the louvre is protected from direct solar radiation (facing north in the northern hemisphere). This type of system can be used to give more uniform overhead lighting.

This is a simple passive technology, and is subject to the same issues as for an ordinary double glazing unit. Durability of the plastic louvre may need to be considered.

A2.5.3 Laser-cut panels

An alternative to prismatic and louvred glazings comprises a transparent plastic sheet which is cut through with a laser to give a series of parallel reflecting surfaces, as shown in Figure A2.5.3. Light striking the cut surfaces is reflected onto a suitably positioned surface, and by installing this type of panel in a moveable frame it can be adjusted to follow the sun.

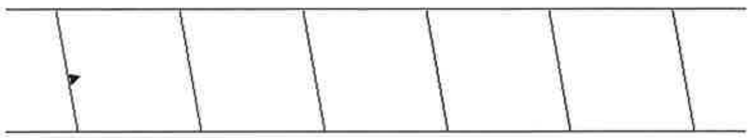


Figure A2.5.3 Section through a laser-cut panel

As with any plastic-based products there are concerns about durability. However, this type of device should be easy to produce and simple to use. The only other limitation is that the angle of the cut is fixed, and the transmitted light will change position as the sun moves. Fitting this type of system into a tiltable frame will allow the sun to be tracked, giving a more even light distribution within the room.

A2.5.4 Angular selective glazings

All surfaces reflect, absorb and transmit solar radiation by differing amounts for different angles of incidence. It is already known that tilting a glazing forward means that less solar energy is transmitted when the sun is higher in the sky. However, it is possible to accentuate this effect by developing coatings with a non-symmetrical internal structure. Figure A2.5.4 (taken from Lampert and Ma [1992] pp70) gives cross-sections through coatings in which a columnar structure has been deposited at an angle to the substrate. Radiation striking the surface at an angle β can pass straight through, whilst at other angles the radiation is diffusely scattered by the columns.

A system like this can be used to block sun at some solar altitudes whilst allowing solar energy through at others.

The biggest problem with this type of coating is likely to be in installing the glass the right way around. Information on the technical aspects of these types of coating is difficult to obtain, and the short review by Lampert and Ma [1992] is the only significant source of references. It is considered however that a possible development of this technology is to develop angular selective liquid crystal coatings.

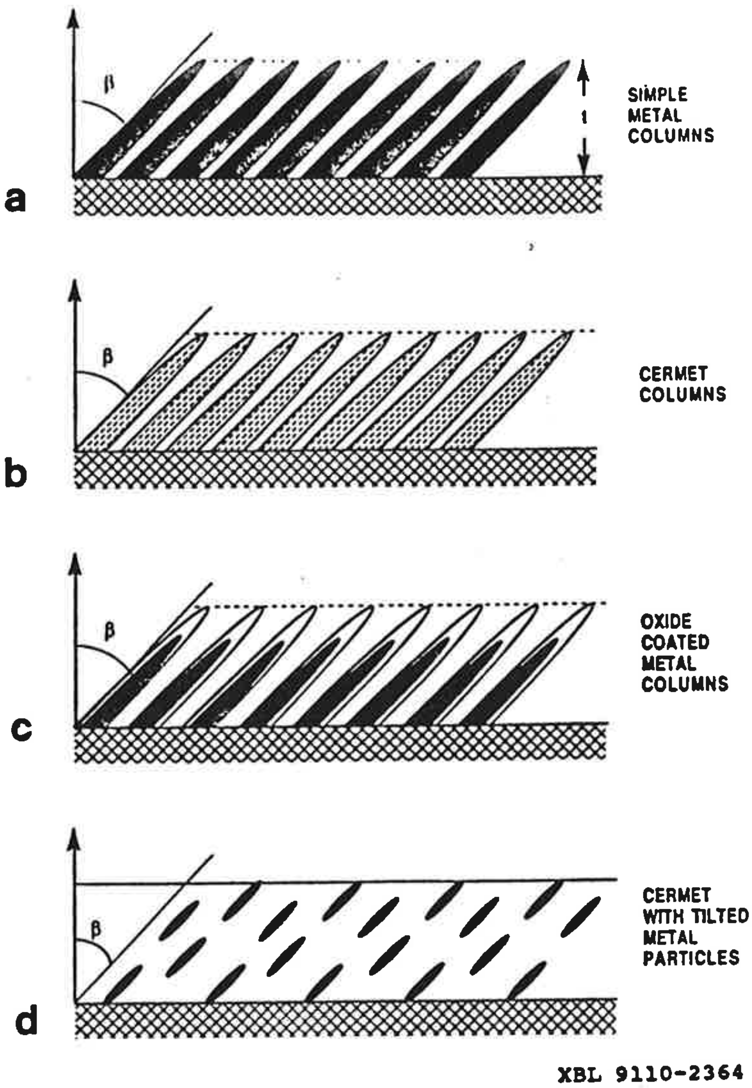


Fig 11.1. Schematics of different types of coating microstructures showing four types of angle selective structures (after Smith et al., 1991).

Figure A2.5.4 Cross-sections through angular selective coatings (from Lampert and Ma [1992])

It is also important to know whether angular selective coatings can be applied to adhesive films, and if so what happens if the film is stretched during installation?

A2.6 Variable (chromogenic) glasses

Chromogenic glasses change their appearance (indicated by a change of colour) in response to some external stimulus. A number of stimuli can be used, but the most common are light (or some other part of the electromagnetic spectrum), heat and electricity.

Chromogenic glazings are discussed in considerable detail by Lampert [1995]. This paper has 76 references, which cover many of the issues relating to the technical development of chromogenic glazings. This paper also lists 70 organisations world-wide which are active in the development of electrochromic switchable glazings and 23 organisations world-wide which are developing switchable glazings of other types (this list is growing continuously).

A2.6.1 Electrochromic glass

Electrochromic coatings may be applied to the surface of a pane of glass (the electrochromic coating must be protected by being sandwiched between two panes of glass, usually as laminated glass).

These multi-layered coatings (Lampert and Ma [1992 pp30] identify 16 different layer-structures for electrochromic coatings) respond to an electric potential by changing colour. In simple terms such coated glasses may be switched between a high transmission state (bleached) and a low transmission state (coloured) state. However, Selkowitz *et al* [1994] identify three idealised forms of electrochromic coating

- coatings which switch from high transmission to low transmission across the whole spectrum of solar energy
- coatings which have a permanently low transmittance in the infra-red, but switch from high to low transmittance in the visible part of the spectrum
- coatings which have a permanently high transmittance in the visible, but switch from high to low transmittance in the infra-red part of the spectrum

Selkowitz *et al* [1994] also discuss the range of performance available from current electrochromic glazings; for a typical electrochromic glazing used in a double-glazed unit with a single low-e coating the shading coefficient varied from 0.67 (bleached) to 0.20 (coloured), whilst the visible light transmittance varied from 0.65 (bleached) to 0.08 (coloured).

It is important to note that in the coloured state a chromogenic glazing may absorb a considerable amount of solar radiation, with the result that the glazing temperature is very high. This requires that the glazing is used as the outer pane of a multiple glazing unit. However, there may still be a considerable problem with heat being radiated into the room from the coloured glazing, and so a low-e coating is often used on the adjacent pane of glass to reflect this radiated heat away from the room.

The time for the glazing to switch states depends on the direction of the switch, and times have been reported as low as 5 seconds and as high as several hundred seconds; this probably depends upon the size of the sample. The potential at which electrochromic glazings switch can be as low as 2 V (Nagai *et al* [1994]), compared to perhaps 50 V for liquid crystals, and once switched the devices have a memory which means that the potential can be removed and the device will remain switched for several hours, or until a reverse potential is applied.

Potential benefits of electrochromic glazings in various USA climates are demonstrated by Warner *et al* [1992] and by Selkowitz. *et al* [1994].

Electrochromic glasses are presently very expensive, and are not yet available in sizes greater than about 1m by 1m because of difficulties in obtaining an even colour across the opacified glazing. There is also an issue of durability, as repeated switching of the units, and switching with too high a potential, can cause the coating to degrade.

Although electrochromic glazings have a 'memory', so that the material remains in its switched state after a single application of a potential, there is little information as to how the performance varies as the memory fades.

The colour of electrochromic glazings is presently limited to blue, with the bleached state generally being transparent or slightly yellow. Glazings which change from light blue to dark blue might be more aesthetically acceptable, but other colours are certain to be requested; photovoltaic cells were also available initially only in blue, but after repeated demands from clients and architects other colours are now available.

When coloured these glazings will absorb a significant amount of energy and become hot, which is recognised by Selkowitz. *et al* [1994], who indicate that the electrochromic glazing should always be on the outside of a glazing unit. For this same reason it is unlikely that electrochromic glazings can be used other than in sealed units. Since the electrochromic coating is usually protected by being laminated between two panes of glass these units will be heavier than double glazing units and, combined with the need to fit electrical cables, the installation process may be considerably more difficult.

Selkowitz. *et al* [1994] also note that it can be difficult for researchers to identify the voltage that can be applied across an electrochromic film. Higher voltages result in faster switching, but can also lead to premature breakdown of the film.

When these issues have been resolved it is probable that electrochromic glazings will be heavily used. Selkowitz. *et al* [1994] note particularly that because electrochromic windows must be controlled they offer guaranteed levels of performance that user-controlled systems cannot. Furthermore, it is possible to use far larger areas of electrochromic glazing in a facade than is currently accepted for passive glazings.

Issues of high cost will gradually be resolved, more so now that electrochromic glazings are being offered in the automotive industry. However, the use of electrochromics will be tempered by the need to determine the optimum switching strategy - at what point is the glazing changed from bleached to coloured - because this affects the energy balance of the building. Electrochromics also have the advantage that, as switchable products, they can also be used for privacy.

Nagai *et al* [1994] state that Asahi Glass in Japan are aiming to develop a glazing system 'by 1996' which has durability under sunshine of at least 10 years, can operate for 100,000 cycles and be available in sizes of at least 40×60 cm. Indeed, a device has already been cycled 100,000 times at 60°C without loss of stability. However, the limited size and durability may discourage the use of these products in precisely those areas where they will be most attractive - tall office buildings - because those buildings are often prestigious (the owner of such a building does not want to replace the glazing after 10 years, which is a highly visible process and sure to be commented on by competitors).

A2.6.2 Catalytically-switched glass

The Fraunhofer Institut Solare Energiesysteme reports the development of glasses with coatings similar to those used in electrochromic glass but which change state in response to the presence of a chemical catalyst (Fraunhofer ISE [1995] pp30). The colour of the reactive film changes from bleached to coloured in the presence of hydrogen gas, and from coloured to bleached in the presence of oxygen gas. The coating is positioned on one pane of glass, with a small gas-space separating another pane. The oxygen and hydrogen pass through the gas-space.

At present little is known about this type of chromogenic glazing. However, there are certain to be issues related to the production of the oxygen and hydrogen gases, and the need to seal the system must be considered.

A2.6.3 Photochromic glass

Photochromic glass (or photochromic plastic) changes its colour in response to light levels. Such glass automatically darkens when the light is strong (it is usually the UV component of the light that causes the response - Lampert [1995]). Photochromic materials are already used in sunglasses.

Lampert and Ma [1992 pp40] suggest that a typical photochromic glazing developed for sunglasses has the properties

visible light transmittance:	89% uncoloured	26% coloured

and takes 3-4 minutes to fade from coloured to 57% visible light transmittance at room temperature. It is suggested that the total solar energy transmittance varies from 85% to 50%.

It is suggested by Lampert [1995] that the durability of photochromic glass under continuous colour/bleach cycling and resistance to chemical attack are excellent, and that photochromic glass is probably the most chemically stable of the chromogenic materials. However, the limited rate of colour change may be a problem.

It should also be noted that the behaviour of the photochromic glazing is in-built and the architect and occupier are unable to define the control strategy beyond the initial selection of the glazing. This may cause the building occupiers to feel that they have no control over their working or living environment.

A2.6.4 Thermochromic glass

Coatings can also be produced which change their colour in response to changes in the ambient temperature. These thermochromic glazings can be made to change their colour over about 5°C ambient temperature change. Materials can also be produced which physically change phase at some temperature - these are known as thermotropic materials (Lampert [1995]). Lampert also discusses the thermotropic 'hydrogels', which are used in layers typically 1 mm thick, and which respond to changes in ambient temperature.

Thermochromic and thermotropic glazings may be used to provide some form of over-temperature protection for other advanced glazing systems (Fraunhofer ISE [1995] pp31, Wilson *et al* [1995]). The temperature at which the colour change occurs can be determined during the manufacturing process.

It is suggested by Lampert [1995] that the hydrogels may suffer from problems with UV stability, limited cyclic lifetime and inhomogeneity during switching. However, an interesting possibility is the addition of a transparent conductor next to the thermochromic/thermotropic material so that the transition can be induced by electrical heating - this at least gives the occupier some control over the glazing.

A2.6.5 Liquid crystals

Liquid crystals work on the basis either of a molecule changing its orientation in the presence of an electric field, or of some needle-like suspended particle changing its orientation. Liquid crystals are opaque until a potential is applied (the molecules/particles are randomly oriented) and require a continuously-applied potential for the liquid crystal to switch to and stay in the bleached state.

It is indicated by Lampert [1995] that the largest chromogenic glazings yet produced are based on liquid crystals - sizes of 1 m by 2.5 m have been produced using NCAP (nematic curvilinear aligned phase) technology (Lampert and Ma [1992] pp37). Lampert and Ma [1992 pp36-39] discuss liquid crystal devices in some depth. They identify typical performance values for a polymer dispersed liquid crystal (PDLC) device as

total solar energy transmittance	53% off	77% on
total solar energy reflectance	20% off	14% on
visible light transmittance	48% off	76% on
visible light reflectance	27% off	18% on

Suspended particle (electrophoretic) devices use multi-layered films in which needle-shaped particles of polyiodides or paraphathite, typically 1μm long, are suspended in an organic fluid or gel laminated between two parallel conductors. An electric field causes the particles to align themselves with the field (Lampert and Ma [1992 pp39]). It is indicated that the switching voltage depends on the thickness of the device, and may be between 0-20 V, or even up to 150 V AC.

It is suggested by Lampert [1995] that liquid crystal glazings typically operate at around 60-100 V AC (although this may become lower in future, perhaps 20 V or less). The power consumption is suggested as less than 20 W/m^2, but power must be continuously applied. It is also indicated that in the 'clear' state these glazings are hazy, and that UV stability may be poor.

The development of suspended particle devices has been delayed by problems of long-term stability, cyclic durability and particle settling, amongst others, as indicated by Lampert and Ma [1992 pp39].

A2.7 Edge details and framing issues

The Phase I Fenestration 2000 report (Button and Dunning [1989] pp6, pp59, pp84) identified that

> "The majority of problems arise at the interface of components, but this does not seem to be generally appreciated; there are insufficient design specification mechanisms for dealing with the interface problems. The industry appears unwilling to collaborate internally to tackle these problems"

> "The window, glass, glazing, frame and facade components are typical of this lack of integration"

and reported the question

> "Why do we not have integrated forms of fenestration involving framing, sealing and installation?"

and the statement

> "It's not standardisation of components we need; it's standardisation of fixing"

At the present time a typical advanced glazing is usually a component with good thermal performance, mounted in a well-insulated wall, with a poor glazing edge and a poorly performing glazing frame. Whilst improving the performance at the centre of a glazing system is important, because designers prefer to use as much glazing as possible, as the centre-glazing performance is improved the significance of the edge of the glazing and of the glazing frame becomes more significant.

Lowe and Olivier [1995] discuss issues relating to the edge of glazing, and rate glazing frames in terms of the ratio of overall U-value to centre-glazing U-value. A ratio of 1.0 or lower indicates that the window frame is not compromising the heat transfer through the system. However, the influence of solar gain is also important on the overall energy balance, and this simple performance ratio does not tell the whole story.

O'Catháin and Howrie [1994] indicate that for best solar performance the ratio of frame to opening should be minimised. However, the effect of the window rebate should also be considered, as this can overshadow the edge of the glazing quite considerably.

A2.7.1 Warm edge technology

A principal shortcoming in many multiple glazing systems is the heat transfer that occurs through the aluminium spacer used to keep the panes of glass apart. To reduce this heat transfer a number of manufacturers now offer spacers with a significant insulating performance. This can reduce the interaction between frame and glazing, and in a study by Harris [1995] the best warm edge spacers were found to reduce the heat transfer through a simple window by 7.5% with conventional air-filled double glazing, and by 11% with air-filled low-e double glazing (the improvement in performance gets better as the centre-glazing U-value is increased).

The other advantage of warm-edge technology is that the temperature of the warm-side glass edge is increased; the best case assessed by Harris [1995] showed a 3°C increase in the lowest glass surface temperature, for an inside temperature of 20°C and an outside temperature of 0°C. In a typical UK winter this can mean the difference between visible condensation and clear glass. In a colder climate, such as Canada and mid-USA, where outside temperatures might drop below -20°C, the warm-edge spacer can make the difference between condensation and ice!

Typical types of warm edge technology glazing spacer include

- aluminium spacers with pour-and-de-bridge resin thermal break (Azon 'Warm Light', Helima 'Helitherm')
- thin-walled stainless steel spacers (Allmetal 'SST Spacer')
- butyl sealant spacers with metal reinforcing strip (Tremco 'swiggle strip')
- silicone foam rubber spacers (Edgetech 'Super Spacer')
- extruded plastic spacers (Inex Spacer Industries 'INEX')

A number of different types of spacer are illustrated in Figure A2.7.1(a):

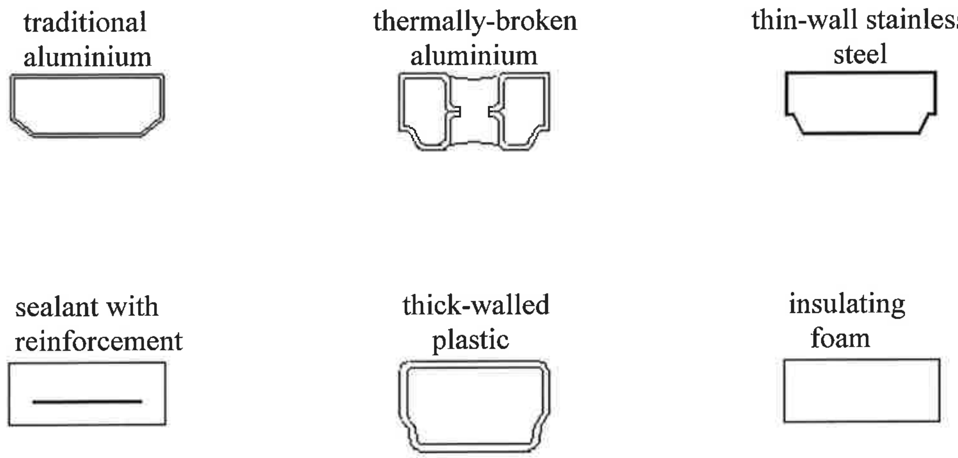


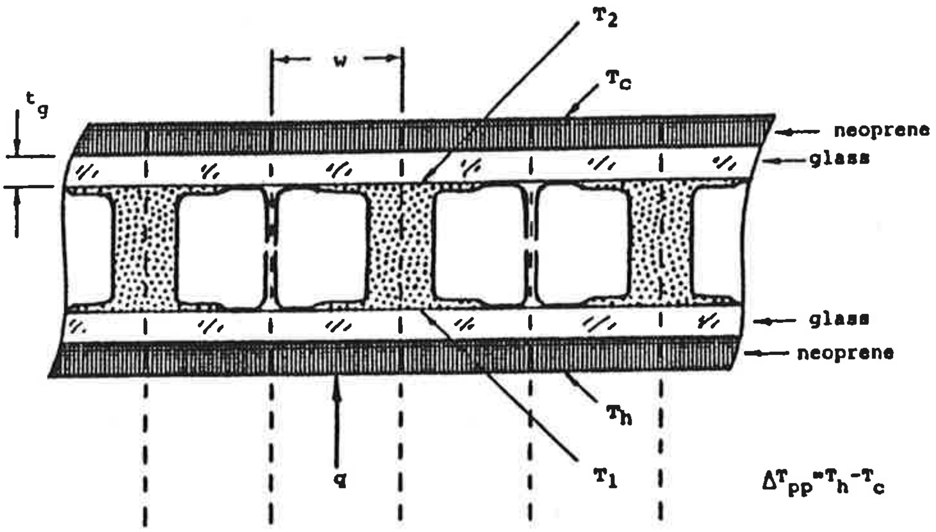
Figure A2.7.1(a) Warm edge technology glazing spacers

In some cases the spacer is produced with the desiccant incorporated into the matrix of the spacer material, and for some materials there are a range of colour options. The Tremco 'Swiggle Strip' does not require any additional sealant, and the Edgetech 'Super Spacer' is supplied with self-adhesive tapes already in place.

Warm edge technology is also discussed by Blower [1996] and Watts [1996].

Most of the warm-edge spacers include some kind of polymer material, which raises the usual issues of colour stability, compatibility with sealants and reaction to UV. The softness of some warm-edge spacers may also cause problems if glazing units are made with thick gas-spaces - the thermal expansion of the gas can generate significant pressures inside such units, which may damage the spacer. However, the makers of such spacers are generally aware of these issues and can give guidance.

An important issue in the use of warm-edge glazing spacers is the significance that is now placed on the glazing-edge sealant. The high thermal conductivity of a traditional aluminium edge spacer means that the heat transfer through the edge sealant is insignificant; the low effective thermal conductivity of a warm-edge spacer means that the heat transfer through the sealant may be a significant proportion of the overall heat transfer. Sullivan and Wright [1995] made a series of measurement of heat transfer through glazing spacers, in which several parallel strips of each spacer were sealed between plates of glass, as shown in Figure A2.7.1(b), and the heat transfer was measured per unit length of spacer. In the case of a warm edge spacer which comprised a reinforcing strip in a sealant base it was found that increasing the width of the sealant by 50% increased the heat transfer by 25%. Computer simulation methods are usually used to assess the impact of the glazing spacer on fenestration performance (the change in heat transfer may be less than the experimental error in a typical hot-box), and it so is essential that the correct amount of sealant is used (too much sealant means too much heat loss, too little sealant may lead to premature failure of the glazing unit) and that its thermal conductivity is accurately known.



Dashed lines mark planes of symmetry.

Figure 1: Cross Section of Edge-Seal Test Sample[13]

Figure A2.7.1(b) Mounting of glazing spacers for performance assessment (from Sullivan and Wright [1995])

Warm-edge technology glazing spacers are already used in Canada and the USA and a large amount of information is being gathered on issues such as durability. It is probable that other types of spacer will be developed (this is essential if glazings are to be produced with even lower centre-glazing U-values).

A2.8 Summary of types of advanced glazing

There are many types of advanced glazing either on the market or at various stages of development. What is apparent is that the architect, engineer and building owner/occupant must be provided with understandable, unbiased and accurate information about the performance of advanced glazings if they are to be used with confidence. Issues of durability, installation and long-term performance are also important and must be explored further.

A3 General and personal issues

Sections A1 and A2 have considered theory and types of advanced glazing. However, some issues affecting the use of advanced glazings are general (they apply to a number of different types of glazing) and others are personal (they depend upon the personal tastes of the architect, owner or occupier).

A3.1 General issues

A3.1.1 Health and safety

In 1994 the UK construction industry underwent a significant change in legislation with the introduction of the Construction (Design and Management) Regulations 1994 (CDM). These regulations, and the associated approved code of practice (HSC [1995]), relate to all things that are designed, and require designers to pay adequate regard to health and safety risks when considering their design. Moreover the definition of 'designer' is very loose and includes (CONIAC [1995])

- architects and engineers contributing to, or having overall responsibility for, the design
- building services engineers designing details of fixed plant
- surveyors specifying articles or substances or drawing up specifications for remedial works
- contractors carrying out design work as part of a design or build project
- anyone with authority to specify, or alter the specification of designs to be used for the structure
- temporary works engineers designing formwork and falsework
- interior designers, shopfitters and landscape architects

The designer can be an individual, a partnership or a firm which employs a number of 'designers'.

It is clear that this definition includes anyone who could possibly influence the use of a particular glazing system, and so different advanced glazings will have to be considered in terms of their health and safety. As an example framing systems may need to be selected so that they can be glazed from the inside of the building, or so that they can be demounted and reglazed, and glazings may be preferred which are lightweight and do not require special equipment for installation or replacement. There is a need for the developer of an advanced glazing to alert the user/specifier to possible health and safety risks, and the user of advanced glazings must consider these issues and may allow them to influence the choice of a particular glazing.

Health and safety issues may also change the way in which responsibilities are handled in the construction process. Previously, as identified by Button and Dunning [1989 pp66-68], the increase in litigation related to building failures has provoked a resistance to innovation and a desire to spread the design contribution to the contractors, sub-contractors and material suppliers (thereby offloading the risk of failure and its subsequent problems to third parties). However, the advent of the CDM regulations define responsibilities for all designers and should ensure that design is carried out more thoroughly and on the basis of proper information. The requirement for systems and materials suppliers to provide information relating to health and safety issues, which may necessarily include performance specifications as these will influence the interfaces with other components, may allow the design process to become centralised again. This then allows the designer to make proper integrated decisions about the building, which could encourage the use of some advanced glazings.

A3.1.2 Fire performance

Behaviour in fire is a significant concern with transparent and translucent media, because the radiant heat from a fire can be sufficient to ignite materials on the other side of a glazed partition. Button and Dunning [1989 pp88] indicate that the transfer of fire between adjacent buildings is a particular issue in Japan.

The use of plastics in advanced glazings may cause concern with fire for two reasons - firstly plastics may give off poisonous or noxious fumes when ignited but, more importantly, a plastic glazing may resist attempts to break the window (either to allow egress or to allow entry to fire-fighters). Safety issues with advanced glazings must therefore be considered, and the designer may be required to ensure that plastic sheets can be removed easily from glazing units to allow passage of humans.

Fire is a complex performance criteria to assess and specialist consultants should be approached for advice. It is usually recognised that glazing will fail in a fire, but the glazing should be sufficiently resilient to discourage the spread of fire between rooms, and should last sufficiently long enough for the occupants of a building to escape. A particular concern is if a window in one room breaks allowing flames to pass over the surface of the building and into an adjacent room. A highly-stressed glazing, such as an evacuated glazing, may break at lower temperatures and help to spread a fire.

A3.1.3 Labelling and replacement

A very important issue, and one that does not appear to have been considered previously, is one of replacement - what does the building owner or occupier do if a glazing unit is broken?

Breakage or some other failure of a glazing unit poses two main problems - identifying a suitable replacement and gaining access to the system to make the replacement.

Whilst access is an issue for the designer (an important one in terms of health and safety, because glazing units are heavy, liable to be caught by the wind and in many cases installed from the outside of the building!) it is generally not a concern for the owner/occupier, who will usually call in a specialist contractor to make the replacement. Framing systems are, in most cases, of very similar designs, and even a contractor who is unfamiliar with the particular framing system can usually work out how to dismantle the system to replace a glazing unit.

Identifying a suitable replacement unit is a much greater issue for the owner/occupier, and has three main implications

- the broken/damaged/failed unit must be disposed of safely
- the new unit must be of similar (preferably identical) appearance
- the new unit must be of similar (preferably identical or possibly better) performance

Disposal is important where unusual materials are concerned - for example if an aerogel-filled unit breaks a contractor may be unwilling to get involved in the replacement because of concerns over the safety of the aerogel material. A simple label identifying the health risks of the material is essential, or the owner/occupier must be made aware of the materials used in the glazing system.

Appearance is important if a glazed facade is to retain its aesthetic qualities - replacing a broken glazing with one of a different colour, or one with a different coating, may destroy the uniformity of appearance. It is not possible to match the appearance of the remaining glazings if the original glazing type is unidentifiable. A cautionary note should be added here - in the Fenestration 2000 Phase I report Button and Dunning [1989 pp26] record the requests

> "Glass manufacturers should be providing a greater variety of colours, appearances and textures - almost a bespoke service"
>
> "Glass which could be coloured to the customer's choice would be attractive"

If a bespoke-colouring process were to be developed then it is essential that glass be clearly marked to identify its colour on some internationally accepted scale. It would also be desirable to the customer that all glass manufacturers have the knowledge to produce glass to any colour.

The performance of the glazing is most important to the occupants of a room - if a new glazing unit allows a different amount of light or heat to be transmitted then this will be noticed. The use of holographic or angular selective coatings and films may lead to problems if they are replaced with ordinary coatings which do not redirect light in the same way. The performance of the glazing is also important to the building services - the building air conditioning and heating may have been designed using a computer model of how the building will perform, based on the expected performance of the glazing. Replacing one or two glazing units may not cause problems, but replacing all of the units on a particular floor of the building, perhaps due to unforeseen problems of noise from the street or for privacy reasons, may seriously affect the performance of a building.

A3.1.3.1 Labelling

Current practice is that the occupier of a building has little idea of the systems incorporated in the building facade - buildings rarely come with a users handbook or a maintenance manual (although perhaps they should!). Replacement of broken or damaged parts either relies on the availability of 'as-built' drawings (both the specification and the original architects drawings may have little relevance to the finished building) or the skills of the repair contractor in identifying broken units.

One option is for the building owner to create a stockpile of replacement units at the time of construction. However, this requires a suitable space to store the 'spares', and the size of the space depends on how much the glazing units are standardised. For a typical rectangular building each of the four elevations of the building may use a different type of glazing, and the glazing type may vary from ground floor to penthouse. The number of different glazings in even a simple building may be too much to justify allocating space in the building to store the parts.

Labelling of glazings is a better option and would make replacement much simpler. A simple reference number could be engraved on a glazing unit, perhaps identifying the key performance parameters, the fabricator of the unit and the suppliers of the key parts. Line call-out labels are used in a variety of industries, and a simple identification code could be devised for any type of building component. This code might also include information about country of origin for components - the building owner may not know that the glazings were sourced on the other side of the world because there are no local producers and this has a significant impact on replacement.

A3.1.4 Durability of plastics

Plastics materials are always subject to some concern over issues of durability, particularly with regard to moisture, ozone, ultraviolet radiation and atmospheric pollutants. Exposed plastics may also scratch or erode.

Many advanced glazing systems which use plastics rely on the plastic being protected within a glass enclosure, otherwise the material can be damaged by the frequent cleaning needed to maintain acceptable levels of performance. The technology to do this has been available for many years in the form of hermetically-sealed multiple glazing units. However, whilst this removes concerns about durability it introduces the issue of the compatibility of plastics with glazing edge sealants, and this needs to be researched. Furthermore, some sealant materials are degraded by ultraviolet, which is normally minimised by relying on the glazing edge spacer to shade most of the sealant from direct light and recessing the glazing edge deeply into the glazing frame - the light which is transmitted down the glazing into the edge of the unit is then assumed to be insufficient to cause serious degradation of the sealant. However, using a transparent or translucent plastic may remove the need for the glazing spacer and allow more light onto the edge sealant, increasing the rate of degradation.

By sealing plastic materials into a glazing unit the only durability problem that remains is that of UV radiation. However, suitable selection of the plastic should minimise this problem.

A3.1.5 Installation guidance

Some types of advanced glazing are sensitive to the way that they are installed. Multiple glazings using tinted glass or chromogenic glass must be installed so that the unusual glass is on the outside of the building, and glazings using low-e coatings are usually installed so that the low-e coating is not on the back of the outer pane of glass. Prismatic glazings and holographic glazings must be installed the right way up and the right way around.

There is a clear need for suppliers of advanced glazings to mark products clearly to indicate 'this way up' and 'this side inside'. It is not sufficient to provide installers with special tools to identify which side of a glazing is which because these tools are easily misplaced (or borrowed and not returned) and are often separated from the operating instructions. Furthermore, knowing which side of a glazing unit has a low-e coating is of no benefit to the installer if the site supervisor doesn't know whether the coating should be on the inside pane of the outside pane.

As an example the author was recently involved in a project to measure heat transfer through three windows with low-e glazing. The frames and glazing were delivered separately to the test house, and each frame manufacturer sent an installer to fit the glazing - in one window the glazing units were all installed the same way around, but not the right way, whilst in another window only one of the units was the right way around. In both of these cases neither installer noticed that the glazing units were actually 2 mm thicker than had been specified, despite one installer spending more than an hour trying to install the glazing. (which should only have taken a few minutes). A simple adhesive label on each glazing unit could have avoided all of these problems.

A3.1.6 Night views

In a typical northern European winter office buildings are occupied for three to four hours each evening without daylight. The use of tinted glazings or glazings with certain coatings may result in the view out being either eliminated or obscured (partially or fully) by reflections from the room-side glass surface. The amenity value of the building is therefore reduced. Under these circumstances switchable glazings or clear glazings may offer benefits to the occupant in permitting a view out. This depends of course on the location of the building - a rural location will not permit a significant view out even with a clear glazing, because of the lack of external lighting. However, an urban building will allow some view out because streetlights and car lights provide a reasonable level of background illumination.

A3.1.7 Pot plants!

Johnson [1991 pp42-43] notes that the growth of plants is affected by red and blue light. Whilst this may seem irrelevant to the building designer it is worth noting that the use of plants in an office building or in the home significantly improves the amenity and comfort of the work or living space. However, glazings which filter out certain light components may limit the growth of plants, with the result that the comfort level of a room is reduced, and this can add to the burden of occupying a space which may already have diminished view (pot plants are probably most desirable where view out is limited by the type of glazing).

It is useful to consider the effect that glazing type will have on plant growth, particularly where comfort issues are emphasised by the selection of glazings which reduce natural light levels.

A3.2 Personal issues

A3.2.1 Cost

Publications on advanced glazing technologies often include analyses of the potential energy and cost savings that may occur as a result of using a particular advanced glazing. This approach has not been followed here, however, for several reasons

- such an analysis must be based on a 'typical' building - which usually bears little resemblance to the architects particular project
- the analysis often assumes that the same glazing is used on every elevation of the building, but more cost-effective solutions may be available for different elevations and the number of possible combinations is limitless
- the life of a building and its glazings must be guessed at (it is all too easy to base costs on the assumption that components will last 50 years, when the building is probably going to be extensively refurbished in 25 years)
- capital costs of the glazing are not known and may be project dependent
- energy costs are not known in advance (in the UK they have reduced in recent years)

Some issues that affect the uptake of advanced glazings, such as improved comfort or aesthetics (real or perceived), are difficult to quantify. There are also issues with some types of glazing which depend upon their orientation or setting - for example angular selective glazings can be chosen to use morning light, evening light or midday light, and electrochromic glazings must be set to 'switch' under specified conditions. There is also a problem due to the wide range of countries in which advanced glazings are being developed - for example evacuated glazing is being developed in Australia, and the developers of the technology are likely to use a 'typical' Australian building for comparison, which cannot be compared to a typical Japanese building for the use of electrochromic glazings or a typical North American building for warm-edge glazing spacer technology. Unless a 'Universal' reference building is defined (and a universal reference climate) it is therefore very difficult to compare glazings on the 'building' level.

It is interesting to note that Button and Dunning [1989 pp28] record a variety of conflicting responses to questions about cost preferences, such as

> "Most customers prefer lower capital cost to reduced running cost"

against

> "Higher capital costs are acceptable if it improves running costs"

What is certain is that unless costs can be reliably estimated, based on realistic and unconditional performance data, this conflict of ideas will not be resolved - too many parties have a vested interest in supporting one side or another of the cost 'equation' and in the absence of agreed and proven methods of cost assessment the owner/occupier may be none the wiser.

A3.2.2 Comfort

Button and Dunning [1989 pp12-13] identify that in the 1990s comfort needs will concern

- higher, or more dependable, comfort conditions
- a greater sensitivity and reaction to the artificial 'high technology' environment and a reactive desire for the natural environment
- personal and reliable control over the immediate environment

They also note that

> "The technology explosion has obscured occupants spiritual needs, light and fenestration are key factors"

> "Technology in building over the last 50 years, and notably the last 10 years, has obscured the real spiritual needs of people"

Comfort is a difficult issue for the building designer to allow for, because comfort can neither be represented as a simple equation nor can it be assumed that two people will feel equally comfortable in the same environment. Whilst there are measures of 'thermal comfort' these are often based on statistical observations, and carry the proviso that 'within this band 90% of people will feel comfortable 90% of the time', or somesuch.

Comfort issues relate to the occupants perception of light, heat and sound. A high light level is often acceptable if the light is diffuse and evenly spread, but a strong direct light may cause problems with reflections from light-coloured surfaces (glare). The temperature of the environment is also important, and is strongly affected by solar gains or heat losses through the glazing system. The occupant of a room may often change the characteristics of the glazing system by introducing curtains or blinds to moderate the environment within a room.

The need to control heat and light is important, and may dominate the decision-making process. If the architect or client wants a deep room but with natural light at the back then an angular selective glazing becomes useful, but if the client wants a shallow room without significant solar gain then solar control glazings are more desirable.

The issue of sound may not be considered particularly appropriate when discussing advanced glazings, but it must be remembered that in the UK multiple panes of glass were first introduced to combat traffic noise, and this is still an advantage of double glazing units. Glazings such as evacuated glazings (which have small spacers to separate the panes of glass and a low internal pressure to hold the assembly together) and single sheet electrochromic glazings (which protect the electrochromic film in a laminated pane) will not give the same levels of acoustic attenuation as glazings which have a significant gas-space between two or more panes of glass. If evacuated and electrochromic glazings need to be used in multiple-glazed units to provide sound attenuation then there are obvious weight penalties and glazings which use 'weightless' coatings to achieve similar levels of performance will be preferred.

The issue of colour-shift through a glazing, due to selective transmission of light, and of the dimming of external scenes as a result, can be acceptable to the human eye as long as there are no natural light references available, such as a view through an open window (Button and Pye [1993] pp61). The human eye and the human brain appear to be able to adjust rapidly to changes in the spectrum of light. However, the reaction of pot plants to lower light levels may be poor, and this influences the occupants sense of comfort.

A3.2.3 Image

The building owner always has a personal vision of the building. This vision may label the building as a purely functional living space or work-place, but it may also make a statement about the owner, in terms of education, ideology and wealth. Factors such as 'Green issues' may then play a significant role in the use of an advanced glazing - cost is not as significant as the statement that 'I am saving energy' or 'I am saving the planet'. In this case an advanced glazing is more likely to be taken up if it is visibly different from ordinary glazing systems - low visibility products such as warm-edge technology glazing spacers are less likely to be used to make a statement (issues such as elimination of condensation are more significant with WET).

Another side to the image coin is that there may be a certain kudos in being the first to use a particular technology in a prestige building (both for the owner and for the architect), although the risk of failure must be weighed carefully.

A3.2.4 Appearance

An electrochromic or photochromic glazing, or a transparent insulation material, is highly distinctive in appearance, and so may be more desirable. It should also be noted that a visibly different glazing system can be used to make a strong architectural statement, and may be used regardless of its performance - chromogenic glasses may be used simply because they change appearance and attract attention. Some materials, such as aerogels, have a reasonably uniform white colour when viewed from the outside (although there may be a tinge of some other colour). These materials may actually find more applications if they can be tinted or coloured in some way - although this will cut down the effectiveness of the material it will give the architect more scope for variation of the appearance of the building.

The choice of glazing might also be dictated by the orientation of the building. It is unlikely that the same advanced glazing will be used on all four elevations of a traditionally rectangular building. The sun-facing aspects of a building may have requirements for some form of solar-control glazing, but the shaded side of the building is more likely to want glazing with good insulating properties. The mix of different glazing types becomes more critical for east- and west-facing elevations.

Another factor which may influence the use of an advanced glazing is whether or not the glazing can be supplied in non-rectangular and non-plane shapes. Curved glazings are particularly useful architecturally, and round glazing units may be required in some applications. It is uncertain however whether a circular or curved evacuated glazing could be made or would last very long.

The appearance of a building can be influenced in other ways by the selection of the glazing type. Multiple glazing units are hermetically sealed, and so the glass is influenced by the pressure difference between the outside world and the gas-space in the glazing unit. The gas-space pressure is dominated by the temperature and pressure at which the hermetic seal was created, together with the heating effects of solar radiation and heat transfer with the surroundings. The outside pressure is governed by the weather. As the weather changes so the gas-space pressure changes, and the pressure acting on each pane of glass changes. This will cause the pane of glass to bow, which is instantly recognisable by the distorted reflections of adjacent buildings.

Toughened glass, which must be used in some forms of glazing, has the disadvantage that during the toughening process a surface ripple is created as the glass is passed over rollers. This too can create distorted reflections. Of course, this may not be a problem if the whole facade demonstrates this effect - old buildings are often considered to have more character because the glass is clearly not uniform. However, the use of toughened and non-toughened glass in the same facade may be evident from the change in the nature of the reflections.

A3.2.5 Design

The use of an advanced glazing will always depend on the ease with which it can be incorporated in the design, and this generally means the ease with which it can be framed. Although it might be thought that electrochromic glazing is less likely to be used because it requires some form of wiring this is no longer the case with the increasing use of photovoltaic glazings - indeed there is even the possibility of using photovoltaic cells on the opaque insulated parts of the facade and electrochromics for the vision areas - the electrochromics are often only required at the same times that the photovoltaic units are generating power!

The traditional shape of buildings may also affect the uptake of advanced glazings - with better shapes of building the issues of heat loss and solar control change. For example, in the extreme latitudes (close to the poles) buildings are sensibly aligned with a long axis pointing east to west - this ensures that the maximum amount of light and heat is received. However, at latitudes nearer to the equator the building may be aligned north-south, so that morning and evening sun is caught but midday sun is rejected. his need not be followed of course - in India and Australia the traditional methods of building used the verandah to hide the windows and provide a cool, shady, area. With this type of construction advanced glazings are irrelevant, but there has been a shift world-wide towards typical European designs of building with windows on exposed walls.

The effect of neighbouring buildings is also significant - a building in a city centre is much more likely to be overshadowed by one of its neighbours for part of the day, and this reduces the effectiveness of advanced glazings. If part of the sunward elevation of a building is permanently shaded from direct light then for that part of the elevation it may not be appropriate to use an advanced glazing - the selection of the type of advanced glazing for the remainder of the facade then becomes related to the ability to match the appearance of the glazing types (or architecturally design the building to use the shaded area as a feature). Chromogenic glasses are more likely to be used if they can cover the whole elevation, or if they can be used in a visually pleasing uniform pattern (perhaps as horizontal bands between insulated panels).

A3.2.6 Installation

It should be noted that there may be legislation relating to the introduction of electrical facade elements, and there is also a need to have specialist electrical installation contractors on the building site. The management of the construction process becomes more difficult as a result, and delays are more likely.

The thickness of an advanced glazing is also a factor. In curtain walling systems for example the framing system is designed to be uniform, and each component that fits into the system is usually expected to have the same thickness, at the edge at least, as the glazing unit.

There is also a need to control the installation process much more closely with some types of advanced glazing - it has already been noted that evacuated glazings may be fragile and electrochromic glasses require electrical installations, but there is also a need to ensure that angular selective glasses are installed 'green side up' and that coated glazings are installed the right way round.

A3.2.7 Durability

The use of an advanced glazing must always be tempered by the thought that the system with the advanced glazing installed may need to undergo a whole battery of performance tests. The commonest performance tests are those related to wind-loading, air- and water-tightness testing. These are generally performed on all glazed systems, and they usually involve the generation of a pressure difference across the glazed system Some advanced glazings, for example evacuated glazings, may not be strong enough to withstand the deflections expected of the framing systems. As an example a curtain walling frame is allowed to deflect by 1/175 of its length between supports. For a 1 m long advanced glazing unit this equates to a deflection of 5.7 mm out of plane.

Another issue of durability is the effect of the high pressure that may be generated in an enclosed volume of gas as a result of solar radiation, or the low pressure that may be generated during winter conditions. The expansion and contraction of the gas-fill in a multiple glazing unit is a function of the temperature and atmospheric pressure change from the time when the seal was made, assuming that the seal remains intact and does not leak. The change in volume of the gas for a given temperature change is a fixed percentage of the initial volume, which means that if the gas-space is doubled in thickness then the absolute increase in volume will double. The stiffness of the glass is a limiting factor in allowing the gas to expand, and as a result the pressure within the unit will increase - this may cause the glazing unit edge spacer to be pushed out of the unit, or if the edge seal is sufficiently strong will cause the glass to fail. This is more likely in small glazing units where the glass is relatively stiffer in terms of its ability to bend out-of-plane.

A3.3 Summary of general and personal issues

The issues raised above will all have an impact on the up-take of advanced glazings. Architects and owners are already asking more questions about durability and long-term performance, and there is a growing awareness of the technical issues associated with products for use in the building facade. The advent of the CDM regulations in the UK, and a desire to avoid future litigation is focusing attention on products which have less perceived risk, and innovation may become more difficult in future unless proven methods of performance evaluation can be developed.

A4 Advanced glazings in refurbishment

Many advanced glazings are perceived as being suitable for new-build but an equally important market is the refurbishment of old buildings. A major aspect of refurbishment is improving the energy efficiency and comfort of a building, both of which are dominated by the use of solar radiation.

Button and Dunning [1989 pp37] consider refurbishment to be a major opportunity for advanced glazings, but suggest that

> "The industry has yet to grapple properly with the problem of what products are required and how these are to be marketed as fenestration systems for refurbishment"

Refurbishment is an ongoing process, with a continuous and expanding market potential. The use of advanced glazings in refurbishment projects should not be discounted, and the manufacturers of such products should consider how to demonstrate the performance improvements achieved by increasing the specification of the glazing.

A case in point is the uptake of double glazing in the UK. The UK Building Regulations now place a limit on the U-value of fenestration systems at 3.3 W/m^2K (or 3.0 W/m^2K for poorly insulated buildings) which pushes the builder into using double glazing. However, most contractors will not use low-e double glazing because they do not believe that they can recoup the additional cost simply by adding it to the purchase price of the building. It is then up to the 'double glazing salesman' who is not only trying to persuade home-owners to replace their existing single glazed windows with double glazing but is also trying to persuade the home-owner to go one step further and buy low-e double glazing. It is not surprising to find that low-e glazing is not being sold on the basis that there will be lower heating bills, but on the basis that because the room-side glass is warmer there is a much lower risk of condensation - the home-owner can see condensation, but cannot see heat loss. There is a clear need to develop tools by which the full performance improvements due to particular types of advanced glazing can be demonstrated.

A5 Competing technologies

There are a number of other technologies which cannot be called advanced glazings but which do have an impact on the use of advanced glazings - in some cases the use of these technologies may outweigh the benefits of an advanced glazing, and in others the alternative technology may be used to boost the behaviour of a less-advanced (but perhaps more durable or lower-cost) glazing.

A5.1 Photovoltaics

It might be argued that with the advent of photovoltaic technology it is no longer necessary to use advanced glazings. However, passive advanced glazings will always have the advantage that they work regardless of the weather; photovoltaics only generate power when the sun is shining, and may ultimately lead to significant problems of demand management because the greatest power output is often generated when it is least needed. Controlling the energy input to a building is often preferable to allowing the energy in and then using generated power to remove it (using free summer power to cool a building for example may lead to a demand for the same levels of comfort in winter, therefore increasing the wintertime power demand).

This is not to say that photovoltaics should not be used, but they should be part of an integrated solution to the building design. Indeed, the combination of photovoltaics on the opaque facade and electrochromics on the transparent facade may be a highly desirable way in which to clad a building.

Photovoltaics have found another application which impacts directly on the use of advanced glazings - photovoltaic modules are readily mounted on external shading devices, so that the intercepted solar energy is used to provide useful electricity for the building occupants (Goethe and Kwasny [1993]). Ultra-thin photovoltaic cells have also been developed so that glazings containing photovoltaics can be used directly - this is particularly valuable for overhead glazings, where the patterns caused by the photovoltaic cells do not detract from the view.

For more information a useful guide to photovoltaic technology is given in EAB-OPET [1993], and some of the issues are discussed by Schmid [1994], Toggweiler [1994], Goethe [1994] and Benemann [1994].

A5.2 Light-pipes and light-shelves

Light-pipes are used to channel natural light from the outside of a building to the inside, through a duct with suitable reflectors. A light-pipe may be used to channel light from the roof of a building into a basement area, but may also be used to channel light into the back of a deep room or office. This could have an impact on the use of refractive glazings, and the designer must consider the relative value of using the glazing to divert light to the back of the room against the use of a duct system which will possibly use up valuable commercial space. Issues of cleaning and maintenance will also need to be considered.

A light-shelf is a somewhat simpler device to install, comprising a reflective shelf mounted across the glazing and used to reflect light up towards the ceiling whilst also shading the area below the light-shelf. The principle issue with light shelves is one of cleanliness - dust will gather on the shelf and will need to be cleaned off regularly, whilst a shelf that is fixed will quickly become a home for potted plants. A good light-shelf therefore needs to be hinged so that it is not used as storage, but this may create conflicts over control - the light-shelf could be angled in such a way that it is used primarily for shading and so reflects the useful light straight back out of the window. It is suggested that a light-shelf is more efficient when placed on the outside of the window, has reflective surfaces that diffuse the light and is combined with a room ceiling that has a high reflectance (UCD-OPET [1994]). However, an external light-shelf, as with any external shading device, may limit access to the window for cleaning. A light-shelf is also of little use for dealing with low winter sun. Better control can be achieved with adjustable blinds which have a reflective surface - this also gives a degree of control to the room occupant, allowing cloudy days to be dealt with.

Light-pipes and light-shelves are discussed in some detail by Littlefair [1996].

A5.3 Shutters, blinds and curtains

A traditional approach to modify the performance of a glazing system is to use some device to block solar radiation (and reduce heat transfer by creating an additional trapped air-space). In the UK this takes the form of curtains, which are pulled across the inside of the window at night to reduce heat loss, and may remain in place during summer days to prevent excessive solar heat gain (to the detriment of pot plants!). In other European countries shutters may be used to cover the outside of the window and perform the same function. Alternatively blinds can be used, which may be installed on the room-side of the glazing or between the panes of a sealed glazing unit.

The use of shutters, curtains and blinds depends on the application. In domestic housing cost is often the governing factor - it costs less to fits shutters, blinds or curtains than to buy better glazing - although privacy issues may be of equal importance. For commercial buildings there are issues of control, which may mean that although blinds would reduce direct light and solar gain they can become the subject of a control struggle with those seated nearest the blind insisting that they remain closed, whilst those seated away from the glazing wanting the blinds to be left open. Blinds in commercial and public buildings are also more likely to be damaged by careless use.

An important point is that the best place for a shading device is on the outside of a glazing system, to prevent the solar radiation from even reaching the glazing. However, this requires consideration of possible shading lines across the glazing, and may also prevent access to the glazing for cleaning (of course, if designed sensibly a shading device may also provide a safe working platform for cleaning - if the shading device stops rain from reaching the glazing surface then this may also influence the rate at which the glazing becomes dirty). Shading devices fitted between the panes of a double glazing unit introduce issues of maintenance, although the control may be taken out of the hands of the room occupier. Shading devices on the room-side suffer from damage, accumulate dirt and lead to control struggles.

In the UK curtains or blinds are only used on the room-side of the window, creating an additional insulation layer on the warm-side of the glazing (in winter and at night). In winter although this reduces heat loss is also has the effect of lowering the temperature of the room-side glass, increasing the risk of condensation. This is particularly undesirable where the fabric of the curtain or blind comes into contact with the wet glass and becomes stained or otherwise damaged as a result. In summertime the use of blinds or curtains on the room-side to reduce solar gain leads to a build up of heat adjacent to the glazing, and this might cause glass to fail due to higher levels of thermal expansion. In other European countries shutters and blinds are used on the outside of the building, preventing solar radiation from reaching the glazing and resulting in higher room-side glass surface temperatures during winter night-time conditions!

The use of blinds between the panes of a glazing unit, or between coupled lights in a casement window, offers an intermediate level of performance, and introduces control issues - facility must be provided to adjust the blinds, and this may require additional operations on the part of the window fabricator and installer. However, sealed units containing blinds are already widely available.

A5.4 Low-energy artificial lighting

A simple alternative to advanced glazings is to combine some form of external shading device with energy efficient lighting to compensate for reductions in natural light levels. A shading device can be arranged to block out summer sun, which is at a high elevation in the sky, whilst allowing the sun into the building during winter, when it is lower in the sky. In this case some artificial lighting may be needed to compensate for low natural light levels on cloudy summer days, and low energy lighting will be preferred.

A reasonable introduction to energy efficient lighting, including a number of cost-based case studies, is given in BRECSU-OPET [1992].

A5.5 Design

As well as using other low-energy technologies it is also sensible to consider design issues - i.e. how can we design to minimise problems:

A5.5.1 Glare

Glare arises when the light entering a room has a strong direct component. Reflections of direct light from adjacent buildings and from surfaces within the room will compound matters. However, glare is a problem of contrast - strong light is more of a problem if it contrasts with dull adjacent surfaces, or is the only light entering an otherwise dark room.

Glare from a window can be minimised by reducing the contrast. Button and Pye [1993, pp100-101] suggest using deeper windows or windows in more than one wall to increase general light levels, and using light-coloured matt finishes around windows, with splayed reveals to decrease the contrast between window and wall. Using glazings with diffusing glasses may not be helpful, because the incident light is scattered and the whole of the glazing may become illuminated. This can cause a significant glare problem that can then be seen from anywhere within the room, because the glazing is diffusing the light.

A5.5.2 Artificial lighting

Button and Pye [1993, pp181-2] note that

> 'Using daylight to save artificial lighting can be a substantial means of saving energy. The deeper the daylight penetrates into a building, the more the artificial lighting can be reduced. Large windows and shallow buildings offer potential for significant savings, especially in offices, where the provision of artificial lighting often expends more energy than the heating'.

However, Button and Pye also note that

> 'Passive solar gains through windows are wasted if all the lights are permanently on and the radiators in sunny rooms continue to provide heat, irrespective of the levels of daylight and solar heat admitted. Heating and lighting systems must be controlled so that they respond to variations in heating and lighting levels if the energy provided by the window is to be used effectively'

Proper use of daylight and passive solar gain can allow the designer to provide an energy efficient building without the expense of advanced glazing systems. The balance between natural and artificial lighting is not well understood, and should be researched further.

Part B UK issues affecting the uptake of advanced glazing technologies

There are three basic types of building - domestic dwellings, commercial buildings and public buildings. In the UK the relationship between architect, contractor, owner and occupier is very different for each, and this has significant implications for the way in which each can respond to the development of advanced glazing technologies.

B1 Domestic building

The following text refers to domestic buildings in general and privately-owned dwellings in particular. There is also a significant amount of housing in the UK which is not privately-owned but is rented from a landlord (either a private owner or a group (commercial or public) owner), and issues relating to this type of occupation are discussed in section B1.2. There is also a possibility in many cities in the UK that the dwelling is in a 'conservation area', and this is discussed in section B1.3.

The domestic building industry in the UK is marked by the isolation that exists between the building contractor and the eventual home-owner. The construction process, and the decision as to what technology should be used in the dwelling, is controlled not by the eventual owner of the property but by the contractor or the architect (where one is used - domestic housing is often built from the contractors' 'pattern book'). The contractor is then driven by cost, in that a new technology or new process will not be used unless it either costs less than the existing technology or process, or alternatively adds sufficient value to the dwelling that the additional costs can be recovered. The contractor sees little benefit to himself in introducing any new technology or new process which reduces the running costs of the dwelling. Consequently new technologies such as double glazing or low-emissivity double glazing are introduced through retrofit. Indeed, the building contractor often deliberately uses the lowest-cost timber windows in a new-build dwelling on the basis that the owner will replace the windows within a few years anyway - in this way the contractor can make even more profit and shifts pass the cost of better technology onto the owner.

The only system by which better technology can be drawn into the UK new-build housing market at the present time is through legislation. In recent changes to the UK Building Regulations Approved Document L (which set out acceptable standards for thermal insulation and heat loss) it is now necessary that the majority of the windows used in new-build dwellings are double glazed. However, even this simple change met with resistance from the construction contractors lobby, as it introduced requirements for different processes and does not add value to the dwelling. It should also be noted that the increased use of sealed double glazing also has implications for the replacement of failed units - the home-owner must go to a specialist retailer to obtain a replacement glazing unit, and can no longer make running repairs as needed.

B1.1 Improving up-take of advanced glazings in the domestic building market

The up-take of advanced glazings in the domestic dwelling market is only likely to be affected by three issues - legislation, direct selling and insurance.

B1.1.1 Legislation

The UK Building Regulations already make statements about preferred levels of thermal insulation. Tightening these requirements will force the up-take of more advanced glazing technologies. It might also be possible to force the use of better glazings by tightening regulations covering issues such as acoustic transmission, but this could cause problems in terms of health and safety issues - the use of triple glazing instead of double glazing may increase the weight of a glazing unit by 50%, requiring a sturdier glazing frame and an installer with a strong back!

B1.1.2 Direct selling

Direct selling usually means selling the product to the home-owner rather than to the contractor. However, this requires that the product be retrofitted, because the owner has no influence on the initial construction process, and costs may play a decisive role. It also requires good sales skills, and yet the UK double-glazing salesman is often despised for a heavy-handed sales pitch and aggressive tactics.

It may also be possible to sell the idea of an advanced glazing directly to the project architect. However, many contractors simply have a 'pattern book' from which they take their plans, and an architect is not involved in the project. Furthermore the architect may be overruled by the contractor on the grounds of higher costs or perceived difficulty with the construction process as the result of using a new technology. Contractors have also been known to change the design of the building or to select other components if they will reduce construction costs.

B1.1.3 Insurance

The role of insurance in the up-take of any advanced technology is variable. Generally companies that insure buildings may be willing to reduce the insurance premium if the building is made more secure or more durable by the use of some technology (the risk of paying out on the insurance is decreased).

Insurance could however be used to discourage the up-take of advanced glazings - if a particular type of advanced glazing acquires a reputation for having a limited life-span, or requires the introduction of more complex systems into the home, then the insurance premium may rise, either because the rate of failure is higher or because the cost of repair and replacement is higher.

On the whole insurance companies may play a leading role in the up-take of new or better technologies. Insurance companies may also be actively involved in the development of standards for product assessment, because this offers a means to rate products and define clear levels of acceptable performance. There have been instances of insurance companies not being prepared to wait for the industry to develop standards and requesting compliance of products with draft standards where this can be used to reduce the risk of paying out.

It should also be noted that the insurance on a dwelling is paid by the occupier, which isolates the building contractor from any requirement to use safe or durable technologies.

B1.1.4 Contractor feedback

An understanding of the issues involved in the UK market can be gained from the report by O'Catháin and Howrie [1994]. O'Catháin and Howrie carried out a number of case studies based around the design of domestic housing to utilise passive solar gain. In the report the building contractor is referred to as the 'quasi-client' - the price of the house is determined by the area in which the house is built, and so the contractor has a major interest in deciding which technologies to use in the building (the contractor wants a house that is cheap and easy to build, because the profits are then maximised).

To support his arguments the contractor often refers to 'feedback' from the house-buyer. For example, it was suggested that the use of roof-lights to light a room should be avoided, because most homeowners wanted a view out. Another statement is that if a building has a large area of south-facing glazing then the occupier will use curtains and blinds to protect fabrics from fading.

It is suggested by one contractor that larger north-facing windows should be used to improve the view out, although O'Catháin and Howrie point out that all glazing that does not face south is thermally bad (they suggest that non-south facing window area should be reduced to the minimum level that gives a reasonable day-lighting level and an acceptable view out). This emphasises the view of O'Catháin and Howrie that few contractors and developers have a proper understanding of energy issues.

B1.2 Domestic buildings not in private ownership

A precautionary note should be added here about domestic buildings that are not in private ownership. Generally this type of housing falls into two categories - privately owned and rented to another party, or group-owned and rented to another party.

B1.2.1 Privately-owned dwellings rented to another party

Some dwellings may be owned by a private individual and rented to another party for occupation. In this case the dwelling may be of a basic quality, and the costs of running the dwelling may be met entirely by the occupier. However, the occupier must ask permission of the landlord to change or modify the dwelling in any way, and the landlord may not be willing to bear the costs incurred by the use of advanced technology. Work on privately-owned rented property is often only carried out where there is a risk of failing to meet required basic standards of habitation, and sometimes not even then. Advanced glazings are unlikely to find their way into such properties.

B1.2.2 Group-owned dwellings rented to another party

In some cases rented dwellings are owned by a group or organisation which looks after the properties as a whole. Traditionally in the UK large numbers of dwellings were owned by local councils, and managed as a single resource; now it is also possible that the buildings are owned by a 'housing association', which may have bought the plot of land, put up several buildings and now rents the buildings to private tenants. In either case the costs of running the property may be met by the tenant but the building owner has more of a responsibility to the tenants, who can form a 'residents association' to deal with problems collectively - this would have no impact if the properties were privately owned but can be very powerful where a large number of properties are in common ownership.

Where a large number of properties are owned and managed by a single organisation issues of scale become more important, and in the case of publicly-owned buildings it may be desirable for the owning authority to make a statement about environmental issues by refurbishing buildings as a group. The introduction of advanced technologies may be more cost effective on a large scale, and there are also organisations which allow local authorities to pool resources related to the assessment of products - if one local authority has found a product to be satisfactory there is an established grapevine for passing this information on, through organisations such as LAPFAG (Local Authority PVC-U Fabrication Advisory Group).

B1.3 Conservation areas

In the UK a large number of buildings are considered to be of historical interest, such that restrictions are placed on their renovation and repair. The general requirement placed on such buildings is that any modification to the exterior of the building (even a coat of paint) may only be permitted if it does not change the appearance of the building.

A significant amount of research is already underway into ways to refurbish existing fenestration products without altering their appearance. This has particular implications where the owner wishes to employ double glazing - traditional windows in the UK use single glazing, and the incorporation of double glazing usually requires wider window frames to cover the edge seal of any sealed units, thereby changing the appearance of the building.

Another issue is the division of the glazed area of a window into small panes with timber glazing bars; replacing the small lights with a single large pane and then using glazing bars over the surface of the glass or within a double-glazed unit is usually highly apparent because the reflection of light and images from the surface of the glass is too uniform with modern float glasses.

The modification of glazing in listed buildings is often limited to the addition of secondary glazing on the room-side of the window. However, if advanced glazings could be developed which can be used in small panes in existing frames then there would be a ready market. Unfortunately evacuated glazings, which would be better used in small panes (thermal expansion and the effects of wind-load are less likely to generate failure stresses in small panes) suffer from the fact that the edge seal is no better thermally than the aluminium edge-spacer in an ordinary double glazing unit and so would swamp the better performance of the centre-glazing.

B2 Commercial building

Commercial building is different from domestic building in that the client is often heavily involved in consultation processes from the first conceptual design to the ultimate detailed design and construction. The client may even be encouraged to take the lead in specifying which technologies are to be used, although the specification may be reined-in when the capital cost implications are discovered!

There are still variations within the commercial building market however. Principally there are two kinds of client - the owner-occupier and the landlord. The owner-occupier has some interest in the technology used in the building, as the costs of running the building are seen directly. The landlord has no such interest however, because the rental is usually dominated by the quality of useful space available and the location of the building. A landlord is more likely to use advanced technologies if the building is in a prestigious location where advanced technologies may add to the marketability of the building. Advanced technologies will not be used where the building is in an area with traditionally low rents unless they offer some clear benefit to the environment within the building.

It should also be noted that building energy costs may only be a small part of the running costs of a business - the company management may be more concerned with the type of company car that they allow their sales reps!

B2.1 Improving up-take of advanced glazings in the commercial building market

This may generally be achieved through similar routes as for the domestic building market. However, insurance issues are easier to police and the architect becomes a more important route for direct-selling.

What is more important with commercial buildings is that true performance values are available - the design process for a commercial building is likely to include detailed predictions of energy usage, as these affect the design of the building services. Maintenance costs may also be more important, as is the time to first maintenance.

B3 Public building

Public buildings are those buildings to which the public has general access, such as schools, libraries, hospitals and local government buildings. In some cases the environment within the building is considered important to the welfare of the building users (for example in schools and hospitals), or in others the building may be in a highly visible location and the local authority wishes to use the building to make a statement (for example in libraries and administrative buildings). In either of these cases the local authority, although constrained by costs, may be willing to use an advanced technology as part of a commitment to environmental issues (pay a little bit more to save the planet).

The only drawback with using advanced technologies in public buildings is one of durability - if a building is in a highly visible location then it is not desirable that passers-by see maintenance work occurring on a continuous basis. The technology used in public buildings should therefore be reasonably well understood, and will be expected to last for a considerable period without replacement or repair. Specifiers may ask that all of the systems used in public buildings can be proven to last at least 50 years.

B3.1 Improving up-take of advanced glazings in the public building market

The issues are again similar to those for domestic or commercial buildings, although the local authority, as the client, may be as concerned about issues such as durability as the insurance company are.

B4 Light and climate

The design of a building facade is dominated by two issues - what is the local climate and what is the day-light requirement.

B4.1 Day-light requirements

There are two reasons for having glazed areas in a building facade - to allow a view out and to let natural light in. Both of these are comfort issues; humans do not feel comfortable in dark enclosed spaces. It is therefore important to consider the effect of light on the use of advanced glazings, because many artificial glazings reduce light in their bid to reduce solar heat gain and so lead to an increased use of artificial light, which subsequently reduces the energy savings of the advanced glazing.

B4.1.1 Natural versus artificial light

In a recent article in Building Services Journal [1995] the balance between artificial and natural lighting was considered, in part of a report on the findings of the European Low Energy Design Forum.

It was considered that in a typical office building around 25% of the energy use was due to artificial lighting. Moreover, the basic problem was identified as natural light levels which are too high near the glazing, and too low deeper in the building. Although light shelves are a possible solution to this they were perceived as being in some way inefficient and costly to maintain. A suggested solution was to use windows with two kinds of glazing - the lower glazing type to permit a view, and an upper glazing type to collect and distribute light. Issues such as glare from VDUs were considered to be the responsibility of the computer manufacturers, not of the building designers (the design of day-lighting for display-screen equipment is discussed by Littlefair [1995]).

There is a clear need for glazings which can divert light to the back of a deep room, and so angular selective glazings and glazings which diffuse light have a clear market use. However, there is a clear need for guidance on how these types of glazing affect natural light and solar heat - if all of the heat and light is allowed into the room, but in a more diffuse manner, then the issue of solar gain is still not resolved.

B4.1.2 Day-light in the UK

In the UK, with its northern latitude, the position of the sun in the sky is very variable. During summer the sun is high in the sky, with the result that light often does not penetrate deeply into a room. However, during winter the sun is at a low angle in the sky, and deep penetration is available for south facing elevations. This variability encourages the use of external shading devices to reduce glare at the window during summer, but this does not resolve the problem of poor light penetration. Products which incorporate a light-shelf, such as the Colt 'Interactive Window System' (shown in Figure B4.1.2) may improve light penetration, but there is a potential market for advanced glazings which perform the same function.

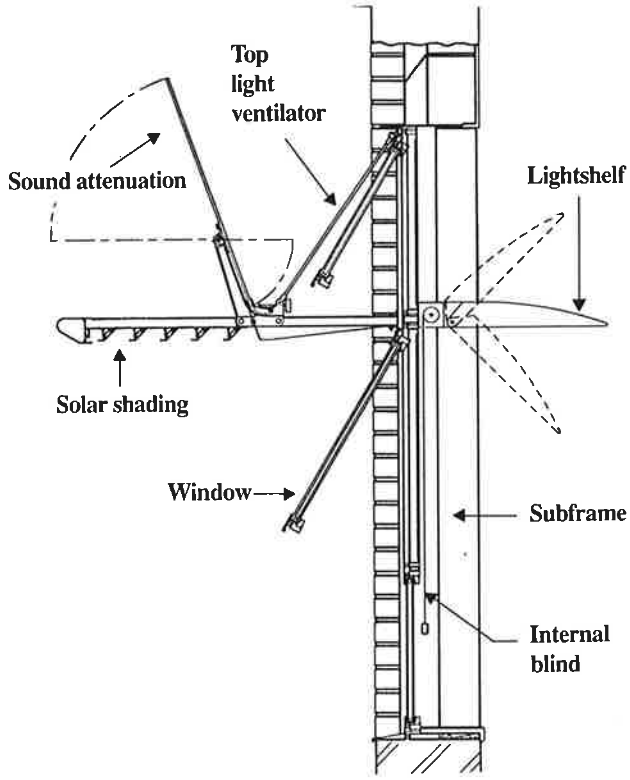


Figure B4.1.2 The Colt 'Interactive Window System' (from Colt [1993])

The UK climate also influences the use of advanced glazings, because broken cloud cover and overcast days with diffuse natural light are commonplace, even during the summer months. It is important, from an energy point of view, that simulations of building performance allow for the proper balance of direct and diffuse day-lighting.

B4.2 Climate

Climate should always be expected to play a role in the use of advanced glazings, in terms of temperature variation (annual and diurnal) and solar radiation.

The UK is a comparatively small land area, on the edge of the Atlantic ocean, and covers approximately 9° of latitude (50-59°N) and 10° of longitude (9°W to 1°E). The climate is generally dominated by the gulf stream and the North Atlantic Drift, being reasonably uniform and without the extremes experienced in landlocked regions. Consequently prolonged winter temperatures below 0°C are unusual, and summer temperatures do not often reach 30°C.

Technologies such as warm edge technology in glazing units are likely to be seen as luxuries (there is no ice risk on multiple glazings in the UK), and may only be used where the glazing already has low-e coatings with a gas-fill. However, the use of solar radiation to heat homes in winter may be more desirable, and the use of transparent insulation materials to over-clad homes might be a useful refurbishment option for the many homes which have poorly insulated walls.

B5 Preferred improvements in glazing

Although advanced glazings may offer better energy performance for the building there are other issues which are more significant in the eyes of the UK architect, owner and contractor. Principal amongst these is the desire for glass which does not require cleaning, which was identified by Button and Dunning [1989 pp33] as being one of the most significant concerns relating to glass in buildings. It is suggested that developing a coating which sheds dirt is more attractive to many architects and owners than a coating which reduces heat loss or solar gain, although combining the two would be even better, providing the cost is not too high! A related issue, highlighted by Lampert and Ma [1992 pp77] is one of water sheeting - the development of coatings that cause water to form a sheet over the surface of the glazing, rather than droplets. This type of coating has the benefit that a clear view can be maintained even after rainfall.

B6 Summary of issues affecting the up-take of advanced glazings in the UK

The up-take of advanced glazings in the UK is likely to be limited by three factors

- the isolation between the capital-cost-dominated contractor and the running-cost dominated occupier (in many cases only legislation will force a contractor into using a particular technology)
- concerns about the durability of new and innovative technologies
- the small range in climatic conditions through the year (no extremes of hot summers or cold winters)

It is essential that if advanced glazings are to be used in the UK then proven and realistic performance parameters are made available (including durability under real operating conditions) and legislation encouraging better technologies is strengthened. Unless this happens then the present level of glazings (air-filled double glazings, some with low-e coatings) is unlikely to change, and use of advanced glazings will be limited to prestige buildings and commercial clients with an image to advertise.

Part C World-wide issues affecting the uptake of advanced glazing technologies

C1 Climate

The local climate plays a crucial role in selecting the right glazing. It is difficult to generalise on something as variable as climate, but Button and Dunning [1989 pp73] define two key climates - 'hot' and 'temperate'. They say that for a hot climate the glazing should

- provide high levels of solar control to minimise solar heat gains and risk of overheating
- control glare arising from reflection off the ground or from surrounding buildings and in some instances from bright areas of sky (excluding direct sunlight)
- provide some natural lighting and sunlight
- insulate the building from heat conducted from outside
- provide a view of the outside

It is suggested that to achieve these needs the total solar transmission should range from 10% to 40%, whilst light transmission will be from 5% (to provide a view) to around 60% to control reflected glare, and to allow natural lighting.

For a temperate climate it is indicated that the glazing should

- provide good thermal insulation to reduce conductive losses from indoors to outdoors
- provide high levels of natural lighting
- provide solar control to reduce the risk of summertime overheating
- provide some control of glare from bright areas of sky and reflections from surrounding surfaces
- have a balance between solar and lighting performance to allow 'passive solar design'
- provide a view of the outside

To achieve these needs it is indicated that total solar transmission should range from 10% up to 70%, and light transmission should range from 10% up to 90%. To allow 'passive solar design' the performance range is defined as total solar transmission 20% to 70%, light transmission 35% to 90% and a U-value of 2.0 W/m^2K or lower.

These criteria are obviously very general, and the selection of a particular glazing must allow for the particular location and orientation or the building. Moreover it will probably be necessary to select different glazings for different elevations of the building.

The following sections describe issues which are known to be relevant in specific countries. The information given here is not intended to be comprehensive, as it is based on a limited number of interviews and reports:

C2 USA

Frost, Arasteh and Eto [1991] carried out an important survey of USA energy efficient windows, which included a survey of the use of different types of glazings and window frames over the period from 1974 to 1991. An important observation is that by 1991 some 30% of new multiple glazing units combine low-e coating with argon gas-fill. The move towards multiple glazing units has gone from 14% market share in 1970 to 90% of the market share in 1993, and there is a growing market for super-windows (three or more panes of glass and multiple low-e coatings). The mean U-value of windows has decreased from about 4.6 W/m^2K in 1974 to about 3.2 W/m^2K in 1991 (the mean centre-glass U-value fell from about 5.0 W/m^2K to 2.8 W/m^2K over the same period).

The improvement in glazing technologies is driven by many agencies. For example Selkowitz. *et al* [1994] indicate that some USA utilities (power companies) were offering rebates of around $10 per m^2 of glazing, for passive, spectrally-selective glazings. The NFRC rating scheme for fenestration products is also implicated in improving the basic level of glazing systems - when performance can be measured by some standard method then mechanisms such as neighbour-envy become significant in encouraging up-take of better products, particularly if the product carries an officially published performance label.

C2.1 Government support

The USA Department of Energy (DoE) is actively supporting research in striving for technical excellence. This is aimed at developing a higher knowledge of technical issues, both to prevent imports and to encourage exports. As an example the DoE is funding the development of software for glazing and glazing frame thermal analysis.

The voluntary NFRC rating scheme is continuously monitored by the USA Department of Energy on the basis that if the DoE is not satisfied then a mandatory rating scheme will be introduced. However, the fact that all NFRC ratings are published encourages manufacturers to chase after better ratings (nobody wants to be seen to be producing a less-than-average product) and so the average performance improves. In January 1995 there were 16,000 windows and doors in the NFRC's product directory (NFRC [1995]).

Interestingly the NFRC method as it currently stands (U-value assessments only) is believed to be presented at a lower level than the technical knowledge of the better US fenestration producers would allow - producers have the technical expertise to improve their products. The extension of the rating scheme to include solar and optical properties is unlikely to be opposed by the industry. It is also considered possible to extend the scheme to include durability information, so that reliable life-times of materials and products can be given.

An important aspect of US construction is that all new government buildings are designed on the basis of whole-life costs. Energy savings are offset against initial costs for a 10 year pay-back period, and all fenestration products are NFRC-rated. This led-by-example approach will encourage the use of advanced glazings if they can be shown to be cost effective, but it may not take issues such as occupant comfort into account (simply because the value of comfort cannot be easily expressed in $ per square foot).

Use of the NFRC rating scheme is currently mandatory in the building codes of some states, and is referenced by the building codes in others. Hogan [1995] indicates that the states of California, Minnesota, Idaho, Oregon and Washington directly reference NFRC in their state energy codes. The state of Arkansas indirectly identifies NFRC ratings as one means of demonstrating compliance with energy codes, and in Alaska some financial institutions require the use of NFRC ratings before giving house-buying loans. Some counties and cities also refer to NFRC ratings.

Another aspects of the NFRC rating method is that the US government is encouraging their use in other countries (principally Canada and Mexico, with which there is a substantial amount of trade) and is actively visiting other countries to provide technical advice and support, and to encourage the use of the NFRC rating method. The uptake of advanced glazings in the USA will only be increased by ensuring that they are assessed to the NFRC rating method, and this may be required for other countries also.

C3 Japan

Interviews with individuals in Japan and Australia found that Japan is often considered to be the least developed country in the developed world in terms of its fenestration. Most glazing in Japan comprises single glazing in aluminium frames (perhaps 90 % of the total, with about 10% PVC-U frames) and building standards are generally low. Domestic housing is small, and of timber construction. Consequently the design life of a house is short (20-30 years) and replacement windows/glazing is not an issue. This lack of development crosses-over into other areas of building.

Glass manufacturers in Japan are actively lobbying their government to introduce building regulations which require double glazing, although their obvious desire is to sell more glass, rather than conserve energy. There is also a failure to understand framing issues, and the glass suppliers would happily put double glazing into non-thermally-broken aluminium frames. It was anticipated by one glass producer however that double glazing would be commonplace in about 10 years time.

It was found that the one place where double glazing and PVC-U frames are currently used is on the northern island of Hokkaido, where winter temperatures may fall below -10°C. However, the general climate in Japan is temperate, with temperatures in the main conurbations seldom falling to 0°C, and overheating only being a problem in August. In these circumstances the retention of single glazing but with better sound attenuation properties is preferred (Button and Dunning [1989] pp57).

C3.1 Cultural issues

The different significance of window frames in Japan was identified by Button and Dunning [1989 pp59], who noted that, whilst Europeans prefer frames that look solid and secure, the Japanese would prefer no frame at all.

It is also noted that in Japan the average temperature of a house is lower than in other countries, and energy usage is less as a result. The principal concern that the average Japanese has is about earthquake and subsequent fire.

Housing in Japan is both specification-built and bespoke. To introduce double glazing widely it will be necessary to convince builders, occupiers and housing authorities of the advantages.

Offices and public spaces in Japan are usually kept much warmer than houses, although the temperature is not always well controlled.

Button and Dunning [1989 pp32] make some important comments about Japan regarding the quality of construction:

> "Quality control is stricter in Japan than in the US"
>
> "The Japanese think of the building industry as a service industry and provide it with all appropriate support and guarantees"
>
> "Contractors survey buildings several years after completion to learn lessons"

This approach towards construction has significant implications for new technologies - if a technology is used before being properly developed and proven it will almost certainly be found out and this may discourage its future use.

C4 Australia

In Australia heat loss from buildings is generally not a problem, except for Tasmania and some mountain regions. In most other locations the problem is one of overheating, and efforts are being directed towards reducing solar heat gain. The U-value of a system is not of concern from a point of view of energy usage, but there are comfort issues where a non-thermally-broken metal frame can radiate heat into a room. However, there is now a thinking that lower U-values would be a benefit in northern Australia, where the outside temperature is always above the desired indoor temperature.

The traditional style of domestic house in the state of Queensland uses verandahs and awnings to reduce solar gain, and is built on stilts with through ventilation. With this type of building the use of structures with lower U-values will then allow heat transfer into the building to be reduced. However, there is a tendency towards building new homes in a European style, with no shading and poor cross ventilation. These homes then require air conditioning to achieve a comfortable environment.

At the present time Australian windows do not use thermally-broken frames, and few are double glazed. Low-e coatings have no market, and are not currently being produced in Australia. The use of heavier multiple glazings would also require sturdier frames.

C4.1 Energy rating - the NatHERS scheme

Australian building codes vary from state to state, and they do not emphasise energy efficiency. Wall and roof insulation are required in domestic housing (to reduce overheating) but there is no requirement relating to glazing systems. The Nationwide House Energy Rating Scheme (NatHERS) is available but its use is not mandatory within building codes - this scheme gives a star rating, based on energy savings compared to a base case. NatHERS makes use of computer predictions of energy usage, but it has been suggested that NatHERS is currently only applied to 10% of building designs.

NatHERS is discussed by Ballinger *et al* [1995], who describe the simulation programme CHENATH, which is used for the development and implementation of NatHERS. This package simulates energy requirements for houses based on the design (including orientation), occupancy patterns and local climate. The climate of Australia has been reduced to 27 discrete weather patterns which cover all of the continent. The NatHERS rating uses a 'star' system, with a 5 Star house being best.

The possibility of a 'carbon tax' has been explored in Australia, but this is believed unlikely to occur in the current political climate. Advanced glazings will only be used if they are encouraged by voluntary guidance and rating schemes.

The labelling of appliances for energy use is now familiar in Australia, and there is an understanding that better windows will reduce energy use. SOLARCH, the National Solar Architecture Research Unit of the University of New South Wales, is currently developing a window energy rating scheme (WERS) which may label windows with a heating rating and a cooling rating. Climate data can then be used to combine these ratings and show how a particular window will perform in a given site. This could then lead to a simple star rating for glazed systems (AAWG [1994]). It is suggested however that such a rating scheme is most likely to lead to increased use of coated glasses to prevent solar heat gain.

Air conditioning is not common in domestic properties. However, the use of air conditioning in homes is increasing. This does not encourage the use of better glazings.

C4.2 Commercial buildings

Commercial buildings in Australia take one of two forms - high rise 'glass towers' in main business areas of cities, and low-rise (typically three storey) suburban offices. Offices are generally built to just meet the building codes, which have few requirements for energy efficiency, although advisory guides are available.

Although offices are air conditioned there are no requirements in the building codes for better glazing, even though this might allow air-conditioning plant to be down-sized. The use of double glazing might be better encouraged by emphasising the comfort issues - less heat radiated from the glazing. Low-e coatings may also be of use, but reflective coatings are restricted in many business city districts because they can cause glare and they also redirect heat onto other buildings. External shading devices tend not to be used on new offices because they are difficult to maintain and clean.

In winter it is often desirable to use solar heat gain and natural light. The use of tinted glass is often avoided and passive shading devices are used instead. Where blinds are used they are often apart of the fit-out, rather than part of the building. However, if the blinds were treated as part of the building cost there may be a case for the use of switchable glazings.

A problem that was reported in Australia was the fact that low-e glass is imported, and often ordered for a building before the facade contractor is involved. In some cases it was suggested that the structural frame of a building may be completed and the facade contractor simply shown the frame and told to clad it!

Photovoltaics have a special significance in Australia, where the low population and large land area make local electricity generation more viable than importing power. The use of photovoltaics will compete with the use of better glazings.

Awareness of energy issues is increasing in Australia, but with the current standard in domestic housing being single glazing with lightweight frames there is little hope for selling considerable amounts of advanced glazings, beyond perhaps double glazing with low-e coatings.

C5 Summary of world-wide issues affecting the up-take of advanced glazings

There are many issues affecting up-take of advanced glazings in any country. Key issues are

- the current level of building facade technology
- the presence of a national energy rating scheme
- variation of the local climate
- local cultural attitudes towards fenestration

It is not easy to predict the up-take of advanced glazings. It is to be expected that the producers of such technology will have to sell their products on the basis of proper technical performance data, and long-term issues must be considered. Selling of products will be easier in those countries which have performance ratings systems already in place, and the advanced glazing producers may find encouraging the up-take and standardisation of rating schemes to be to their advantage. This will also heighten customer awareness of advanced glazing products.

REFERENCES AND BIBLIOGRAPHY

The following publications are referenced in this report:

AAWG, 1994, *A window to the future*, Newsletter of the Australasian Advanced Windows Group, volume 2 no 4, November 1994, 8pp

Ballinger J., Cassell D., Prasad D. and Lyons P., 1995, *The integration of window labelling in the nationwide house energy rating scheme (NatHERS) for Australia*, Proceedings of Window Innovations '95, Toronto, 5-6th June 1995, pp300-308

Bartenbach C. and Klingler M., 1994, *Daylight management and integrated artificial lighting*, European directory of energy efficient building 1994, James & James Science Publishers, pp108-121

Bell J. and Burt W., 1995, *Designing buildings for daylight*, BRE report BR288, Building Research Establishment, 95pp

Benemann J., 1994, *Photovoltaic facades*, European directory of energy efficient building 1994, James & James Science Publishers, pp85-88

Blower N., 1996, *Insulating glass trends*, Glass Age, v39 n4, April 1996, pp36

BRECSU-OPET, 1992, *Energy efficient lighting in buildings*, A Thermie Programme Action - Rational Use of Energy, Commission of the European Communities, Brussels, 16pp

Brinker C.J. and Scherer G.W., 1990, *Sol-gel science: the physics and chemistry of sol-gel processing*, Academic Press Limited, London, 908pp

BS 6993:Part 1, 1989, *British Standard Thermal and radiometric properties of glazing Part 1. Method for calculation of the steady state U-value (thermal transmittance)*, British Standards Institution, 10pp

Building Services Journal, 1995, *Advancing the cause of low energy design - Artificial and natural lighting*, Building Services Journal, January, pp40-41

Button D.A. and Dunning R., 1989, *An investigation into the long-term requirements for fenestration A market context study*, Fenestration 2000 Phase I report, Pilkington Glass Limited, 106pp

Button D. and Pye B. (eds), 1993, *Glass in building*, Butterworth Architecture, 370pp

CIBSE A2, 1982, *Weather & solar data*, CIBSE Guide Part A2, CIBSE

Colt, 1993, *Interactive window system*, Colt international Holdings, 8pp

CONIAC, 1995, *Designing for health and safety in construction A guide for designers on the Construction (Design and Management) Regulations 1994*, Construction Industry Advisory Committee, Health and Safety Commission, HSE Books, HMSO, 42pp

Crooks B., Larsen J., Sullivan R., Arasteh D. and Selkowitz S., 1995, *Progress in the development of NFRC's residential fenestration annual energy rating method*, Proceedings of Window Innovations '95, Toronto, 5-6th June 1995, pp202-217

CSA A440.2-93, 1993, *Energy performance evaluation of windows and sliding glass doors*, Canadian Standards Association, 70pp

Duer K., Svendsen S., Chevalier J.L., Chevalier B., Platzer W.J., Stangl R. and Wittwer V., 1995, *Aerogel windows - material evaluation within IEA SH&CP Task 18*, Proceedings of Window Innovations '95, Toronto, 5-6th June 1995, pp563-571

EAB-OPET, 1993, *Photovoltaic technologies and their future potential*, A Thermie Programme Action - Renewable Energy, Commission of the European Communities, Brussels, 30pp

Endres B. and Benz V.W., 1994, *Infrared-reflective glazing*, European directory of energy efficient building 1994, James & James Science Publishers, pp63-66

ETSU-OPET, 1993, *Transparent insulation technology*, A Thermie Programme Action - Renewable Energy, Commission of the European Communities, Brussels, 16pp

Field A., 1994, *Super-insulation from sand*, Building Services Journal, October, pp45-46

Fraunhofer ISE, 1995, *Achievements and results*, Annual Report 1995, 87pp

Frost K., Arasteh D. and Eto J., 1993, *Savings from energy efficient windows: Current and future savings from new fenestration technologies in the residential market*, paper LBL-33956 WG-300 UC-350, Energy & Environment Division, Lawrence Berkeley Laboratory, University of California, April 1993, 51pp

Garries R. and Mathis R.C., 1995, *Instant, annual, life: A discussion on the current practice and evolution of fenestration energy performance ratings*, Proceedings of Window Innovations '95, Toronto, 5-6th June 1995, pp196-201

Goethe R., 1994, *Photovoltaics in buildings*, European directory of energy efficient building 1994, James & James Science Publishers, pp81-84

Goethe R. and Kwasny R.J., 1993, *Value-added sun shading The integration of photovoltaics in buildings*, European directory of energy efficient building 1993, James & James Science Publishers, pp61-65

Halcrow Gilbert Associates, 1992, *Review of advanced glazing technology and study of benefits for the UK*, Fenestration 2000 Phase II report ETSU S 1342, Energy Technology Support Unit, Department of Trade and Industry, 130pp

Harris R.M., 1995, *Guide to the design of thermally improved glazing frames*, Centre for Window and Cladding Technology, 200pp

Henry R.P., 1995, *Canada's energy rating systems for windows and doors now implemented in a national energy code for houses*, Proceedings of Window Innovations '95, Toronto, 5-6th June 1995, pp231-241

Hogan J., 1995, *The use of NFRC ratings in U.S. energy codes*, Proceedings of Window Innovations '95, Toronto, 5-6th June 1995, pp309-324

HSC, 1995, *Managing construction for health and safety*, Construction (Design and Management) Regulations 1994 Approved Code of Practice, Health and Safety Commission, HSE Books, HMSO, 53pp

Johnson T.E., 1991, *Low-e glazing design guide*, Butterworth Architecture, USA, ISBN 0-7506-9147-6

Kümpers R. and Link A., 1994, *Capillary-structured transparent insulation for passive solar energy gain*, European directory of energy efficient building 1994, James & James Science Publishers, pp97-98

Lampert C.M., 1995, *Chromogenic switchable glazing: towards the development of the smart window*, Proceedings of Window Innovations '95, Toronto, 5-6th June 1995, pp348-364

Lampert C.M. and Ma Y-P., 1992, *Advanced glazing materials study*, Fenestration 2000 Phase III report ETSU S 1215, Energy Technology Support Unit, Department of Trade and Industry, 87pp

Littlefair P.J., 1995, *Daylighting design for display-screen equipment*, BRE Information Paper IP10/95, Building Research Establishment, June 1995, 4pp

Littlefair P.J., 1996, *Designing with innovative daylighting*, BRE Report BR305, Building Research Establishment, 66pp

Lowe R. and Olivier D., 1995, *The ins and outs of low energy glazing*, Building Services Journal, April, pp49-51

Mathis R.C., 1991, *What NFRC means to manufacturers of windows and doors*, Fenestration, November/December, pp16-21

McKee F.B., 1994, *Fluidized glazing and cladding*, McKee Fluidized Glazing and Cladding, 6pp

Müller H., 1994, *Innovative use of light-directing holograms with solar cells*, European directory of energy efficient building 1994, James & James Science Publishers, pp67-69

Nagai J., McMeeking G.D., Seike T. and Noutomi Y., 1994, *Smart electrochromic glazing*, Glazing Today, December 1994, pp33-36

NFRC, 1993, *Technical, operational and administrative foundations for fenestration rating, certification and labeling: The NFRC multi-year plan*, National Fenestration Rating Council, Maryland, USA, 50pp

NFRC, 1995, *Certified products directory*, 4th edition January 1995, National Fenestration Rating Council, Maryland, USA, 320pp

NFRC 100-91, 1991, *Procedure for determining fenestration product thermal properties (currently limited to U-values)*, National Fenestration Rating Council, Maryland, USA, 23pp

NFRC 100-91, 1994, *Technical interpretations*, 5th edition November 1994, National Fenestration Rating Council, Maryland, USA, 47pp

NFRC 200-93, 1993, *Procedure for determining fenestration product solar heat gain coefficients at normal incidence*, draft, National Fenestration Rating Council, Maryland, USA, 18pp

NFRC CAP 1-92, 1992, *Certification agency program*, National Fenestration Rating Council, Maryland, USA, 50pp

NFRC LAP 1-92, 1992, *Laboratory accreditation program*, National Fenestration Rating Council, Maryland, USA, 80pp

NFRC PCP 1-92, 1992, *Product certification program*, National Fenestration Rating Council, Maryland, USA, 43pp

O'Catháin C. and Howrie A.J., 1994, *Passive solar house design studies: Northern Ireland Final reports*, report ETSU S1299-P1, Energy Technology Support Unit, Department of Trade and Industry, 400pp

Peuportier B., 1994, *Transparent insulation Architectural creativity and energy efficiency*, European directory of energy efficient building 1994, James & James Science Publishers, pp91-96

Platzer W.J. and Braun P.O., 1995, *Transparent insulation technology for buildings - a review*, Proceedings of Window Innovations '95, Toronto, 5-6th June 1995, pp588-597

Schmid J., 1994, *Integrated photovoltaics in architecture*, European directory of energy efficient building 1994, James & James Science Publishers, pp73-74

Selkowitz S.E., Rubin M., Lee E.S. and Sullivan R., 1994, *A review of electrochromic window performance factors*, paper LBL-35486 UC-1600, Energy & Environment Division, Lawrence Berkeley Laboratory, University of California, April 1994, 23pp

Siemens, undated, *Creative fashioning of daylight - the sun shielding louver*, Siemens AG Drives and Standard Products Group, Lighting Systems Division

Simko T.M., Collins R.E., Turner G.M., Tang J-Z., Fischer-Cripps A.C., and Garrison J.D., 1995, *An overview of the technology of vacuum glazing*, Proceedings of Window Innovations '95, Toronto, 5-6th June 1995, pp578-587

Southwall Technologies, 1993, *Heat mirror insulating glass*, product brochure, 20pp

Stokdyk J., 1996, *Shady operators*, Building - Doors and Windows Supplement, 12th January, pp4-6

Sullivan H.F. and Wright J.L., 1995, *Guarded heater plate measurements in support of warm-edge technology*, Proceedings of Window Innovations '95, Toronto, 5-6th June 1995, pp263-272

Thermie, 1993, *Best available energy technologies for our environment*, Commission of the European Communities, Brussels, 20pp

Toggweiler P., 1994, *Building-integrated photovoltaics*, European directory of energy efficient building 1994, James & James Science Publishers, pp76-79

UCD-OPET, 1994, *Daylighting in buildings*, A Thermie Programme Action - Renewable Energy, Commission of the European Communities, Brussels, 24pp

Valdes N., 1988, *Low E glass Increased performance/greater design freedom*, The Construction Specifier, August, pp73-78

van Dijk D. and Bakker L., 1995, *Development of a European advanced Window Information System (WIS)*, Proceedings of Window Innovations '95, Toronto, 5-6th June 1995, pp337-346

Warner J.L., Reilly M.S., Selkowitz S.E., Arasteh D.K. and Ander G.D., 1992, *Utility and economic benefits of electrochromic smart windows*, paper LBL-32638 UC-350, Energy & Environment Division, Lawrence Berkeley Laboratory, University of California, June 1992, 21pp

Watts D., 1996, *Tremco gets warmer*, Glass Age, v39 n4, April 1996, pp38

Wilson H.R., Raicu A., Nitz P. and Ferber J., 1995, *Thermotropic glazing*, Proceedings of Window Innovations '95, Toronto, 5-6th June 1995, pp489-498

Yannas S., 1994a, *Solar energy and housing design Volume 1: Principles, objectives, guidelines*, Department of Trade and Industry, Architectural Association Publications, 145pp

The following are publications which contain general information relating to advanced glazings:

Button D., 1993, *Glazing for the future*, Architect, Builder, Contractor and Developer, February, pp31

CIBSE, 1987, *CIBSE Applications Manual: Window Design*, Chartered Institution of Building Services Engineers, London, 66pp

Collins B., 1996, *To E or not to E, that is the question*, Glass Age, April, pp56

Conolly S., 1995, *Towards the transparent envelope*, the architects journal, 15 June, pp42-44

Crowther R.L., 1983, *Sun/Earth alternative energy design for architecture*, Van Nostrand Rheinhold, 255pp

Gläser H.J., 1988, *Control of solar transmission using special Venetian blinds*, Glaswelt special export edition, April ,pp4-10

Goulding J.R. and Lewis J.O., 1993, *Passive solar building design*, European directory of energy efficient building 1993, James & James Science Publishers, pp27-31

Goulding J.R., Lewis J.O. and Steemers T.C. (eds), 1992, *Energy conscious design A primer for architects*, Commission of the European Communities, Batsford, 135pp

GPG35, 1993, *Energy efficiency in offices. A guide for the design team*, Good Practice Guide 35, Energy Efficiency Office, Department of the Environment

GPG79, 1993, *Energy efficiency in new housing. Low energy design for housing associations*, Good Practice Guide 79, Energy Efficiency Office, Department of the Environment

Hastings S.R. (ed), 1994, *Passive solar commercial and institutional buildings A sourcebook of examples and design insights*, International Energy Agency (Task XI), John Wiley & Sons, 454pp

Hutchins M. and Shaw M., 1995, *Advanced glazing materials*, Building Services Journal, April, pp53

Jahn K., 1993, *Transparent insulation materials A new technique for solar architecture*, European directory of energy efficient building 1993, James & James Science Publishers, pp82-88

Kristensen P.E., 1994, *Daylighting technologies in non-domestic buildings*, European directory of energy efficient building 1994, James & James Science Publishers, pp33-39

Lindsell A., 1995/6, *Step on the gas*, Window fabricator and installer, December 1995/January 1996, pp16-17

Lund-Hansen K., 1993, *Why solar control?*, European directory of energy efficient building 1993, James & James Science Publishers, pp48-49

Minne A., 1993, *Advanced glazing*, European directory of energy efficient building 1993, James & James Science Publishers, pp32-35

Parry M., 1993, *Designs on daylight*, Architect, Builder, Contractor and Developer, February, pp16-18

PSA, 1975, *Solar heat and the overheating of buildings*, Directorate of Building Development, Property Services Agency, HMSO, 44pp

Schmidt J., 1994, *Windows and heat insulation*, Finestra International, n1, pp54-58

Tatum R., 1987, *The evolution of energy-saving windows*, The Construction Specifier, USA, August, pp33-34

Winter S. and Ridout G., 1991, *Top of the glass*, Builder, 15 March, pp64-65

Yannas S., 1994b, *Solar energy and housing design Volume 2: Examples*, Department of Trade and Industry, Architectural Association Publications, 127pp

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