INTELLIGENT SKINS FOR BUILDINGS

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ABSTRACT

The development of improved visual and thermal performance of glazing during the last 30 years is reviewed. Complementary glazing devices, such as blind systems, are discussed and examples given of how automatic control systems have been or might be used to optimize the visual and thermal performance with regard to the varying external climate in achieving specified building management strategies, such as energy economy.

Variable performance and glazing products are described and discussed. The current situation or potential for commercial development is summarized.

Current developments in further improving the thermal performance of glazing materials are discussed and the latest advances in low-emissivity (low-e) glass technology presented and the potential for future applications discussed. Finally, the international project "Fenestration 2000" is described and the findings of the first stage presented.

REVIEW OF GLAZING PERFORMANCE

The thermal performance of glazing is principally defined by its shading coefficient or total transmission—its ability to reject solar radiation—and by its U-value or thermal transmittance—its ability to insulate. These performance criteria are required for combating the summer and winter climates in northern, cold, and temperate regions or whole-year climates in hot and tropical regions. At the same time there has been a demand for associated light transmissions to be high where daylighting was deemed important or relatively low where glazing was intended purely for visual contact with the exterior.

The response of glass manufacturers from the 1950s until recent times has been improvement in the sense of reducing the shading coefficient of products while at the same time offering products which architects could use in buildings to develop the aesthetic context.

Figure 1 illustrates how the solar heat rejecting performance has developed. The figure shows the boundary of physical possibility enveloping three groups of products starting with a range of absorbing glasses, followed by reflecting glasses, to the most recent development of high-performance, low-emissivity products.

The response to serious consideration of the insulating properties of glazing came considerably later than the development of improved solar products, although production equipment (high-volume off-line magnetron sputtering equipment) had been used for putting solar reflecting coatings on glass substrates for some years. Hitherto the option was double or multiple glazing, originally in separate sashes, leading to hermetically sealed units in the 1960s.

By the 1970s it was clear that successive energy crises, determined by the unstable political situation in the Middle East, but reflecting the progressive diminution of worldwide fossil fuel reserves, stimulated industry to the serious development of low-e products.

The physical principles of improving the insulation of glazing in this way had been understood for many years (Owens and Barnett 1974); however, production techology was needed to manufacture the products at a high volume and low cost.

To this end, magnetron sputtering of low-emissivity coatings was developed and commenced marketing highly transparent, low-emissivity coatings in 1981 in Scandinavia (Owens 1984).

Figure 2 shows how the U-value is reduced by reducing the emissivity for double- and triple-sealed units, while Figure 3 shows how the introduction of certain gases, namely inert monatomic gases, further reduces the U-value. The practical limits are about 1 W/m^2K and 0.5 W/m^2K for double- and triple-glazed units, respectively.

Low-emissivity products have been further developed and are combined with solar-absorbing products to provide insulation and enhanced solar control, providing a family of products such as the group shown in Figure 1, labeled low-emissivity H.P. glass.

The recent development of low-emissivity glass made on line, directly on the float glass production plant, opens the potential for further product innovation.

COMPLEMENTARY WINDOW DEVICES

The chosen performance characteristics of the glazing are essentially a compromise to meet certain design criteria such as air-conditioning load. The glass performance is constant so that in this case the reduction of solar load occurs at all times, including times when it might be beneficial. Traditionally, variable control has been achieved by using movable shading devices to complement the glazing performance.

In the vast majority of buildings these shading devices

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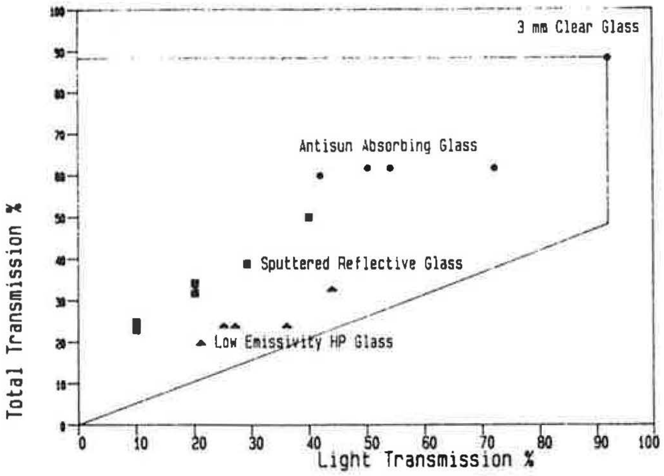

***Figure 1** Control of heat and light—generic glass types*

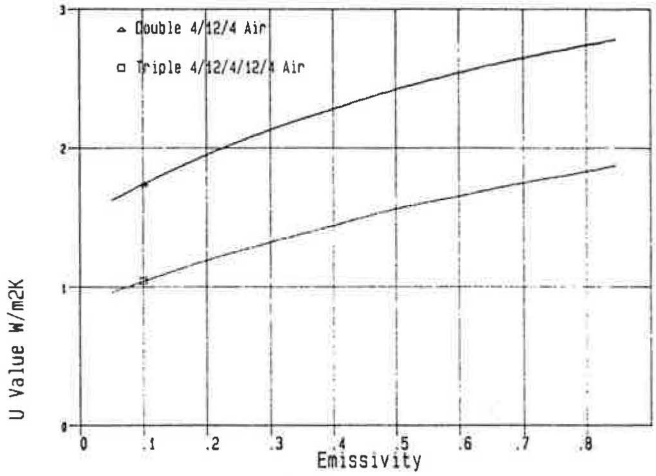

***Figure 2** U-value—emissivity*

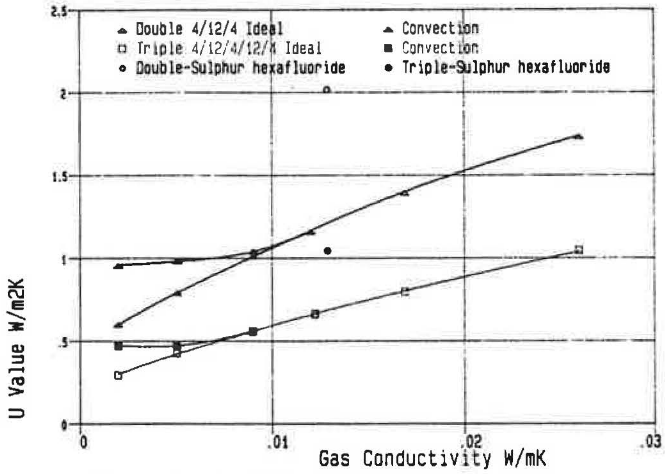

***Figure 3** U-value—gas conductivity (E = 0.1)*

are operated manually in response to individual perception of the adequacy of the internal environment. These may be subjective criteria for the visual or thermal environment. In the majority of ordinary buildings this individual control extends to the opening of windows to increase the ventilation to remove unwanted solar heat.

In large, multiple-occupancy buildings (for example, high-rise office buildings), manual control creates conflict without easy options of compromise either between individuals or the efficient management of the building as a whole. Some designers have sought to optimize the variable performance of the the windows and shading by automatic control of the shading by a centralized control system. At this time, through the use of computer control of building energy management systems, it would be relatively simple to optimize the control to any set of strategic management principles.

For example, a control system might be optimized to reduce energy consumption. This, in practice, might mean lowering the blinds or controlling the pitch of the louvers so that solar radiation is excluded when cooling is called for but maximized when heating is called for. More complicated control strategies can easily be envisaged. For example, if daylight control were to be incorporated where lighting energy is displaced by dimming control of the internal illumination, additional lighting energy needs to be balanced against reduced cooling load and the associated electrical power consumption.

There is no doubt that modern computer management systems in buildings can readily be programmed to achieve the most complicated management strategy. The question is why such systems are not popular in buildings. The answer is probably that such control systems are not robust enough, particularly mechanized shading, to occupancy misuse.

VARIABLE-PERFORMANCE GLAZING

The possibility of devising a glass which in some way responds automatically to an environmental stimulus has been the dream of many an architect for decades. In principle, there are two ways to achieve this—with a glass which responds directly, or through an intermediate control stimulus. The former, direct-response products are the so-called thermochromic and photochromic glasses, responding to temperature or solar radiation, respectively.

Photochromic Glass

Photochromic glass has been used successfully for ordinary sunglasses for a number of years and in principle could be used in windows.

Typical properties of a single-glazed product are given in Table 1 as an example. Notably, the product performs better at lower temperatures, contrary to usual precepts, and the visual response is much better than the response to the complete solar spectrum when ideally the reverse might be the better option.

However, the decisive factor mitigating against its use is cost. Typically, one might expect the cost to be 10 times that of a simple absorbing glass. Conceivably, the product might find an application where visual requirements dominate the considerations, as is the case in airport control towers but, to my knowledge, there has been no serious use of photochromic glass in buildings.

Electrochromic Glass

Indirect response to an environmental stimulus is characterized by this product. Early work was done to

TABLE 1
Photochromic Glass

Sample	Visible Light Transmittance %	Solar Radiant Heat: Reflectance %	Absorbtance %	Direct Transmittance %	Total Transmittance %	Shading Coefficient
Rapide 5 mm Unexposed	89	8	5	87	89	1.02
35°C after 20 min exposure	15	5	49	46	61	0.70
25°C after 20 min exposure	8	5	57	38	56	0.64
10°C after 20 min exposure	4	4	64	32	52	0.60

develop optical displays, and coatings sputtered on float glass are now being developed. A wide range of inorganic compounds is known to exhibit electrochromic properties and principal contenders in this research are multi-layers based on tungsten oxide (Christie and Hutchins 1988).

Figure 4 shows how such a coating responds to a signal of 4 or 5 volts with solar transmittance significantly reduced. These results are encouraging but there is a long way to go before a suitable solid, transparent electrolyte is developed to make these applications practicable for architectural glazing. Figure 5 shows the target performance data proposed by Lambert (unpublished).

FURTHER IMPROVEMENT IN INSULATING GLAZING

Figures 2 and 3 show how the practical limits that can be achieved with low-emissivity coatings and low-conductivity gas fills are 1 W/m²K and 0.5 W/m²K, respectively. The principal limiting factor is the onset of convection in the space between the bounding glass layers. This fact leads to the consideration of ways in which convection could be stopped so that, by increasing the separation of glasses, the thermal insulation could be improved, while, of course, retaining transparency.

There are two current practical possibilities. The first is a honeycomb matrix (Hollands et al. 1984) made of polycarbonate in the space. This product, presently being developed commercially, does not exhibit absolute transparency although it has a high light transmission, unless it is viewed at right angles due to the walls of the honeycomb. The light losses are small due to total internal reflection in the honeycomb and convection is avoided.

The thermal conductivity is 0.089 W/mK, giving U-values of 1.3 W/m²K and 0.75 W/m²K for 50 mm and 100 mm glass separations, respectively, with about 85% light transmission. Compared with the target figures for existing commercial low-e products, these figures aren't very exciting. However, this is a comparatively low technology concept and has the potential of being inexpensive. There are many possible applications, including the development of the "Trombe" wall principle, skylight glazing in factories, etc.

Aerogel

Aerogel is the name given to a transparent porous matrix of silica—the principal component of ordinary glass. It was first reported by Kister at a U.S. university and further developed for nuclear research as a component of particle detectors in high-energy particle acceleration equipment in Switzerland. The production process for industrial manufacture was developed at a Swedish university in the late 1970s (Henning and Svenson 1982).

The pore size of the matrix is of submicron dimensions, which means that the dimension is below the size for Rayleigh scattering and the material is transparent, albeit a little cloudy. The small pore size also means that the mean free path of oxygen and nitrogen molecules in the pores is of a corresponding length. Elastic collision at the walls of the pores tends to reduce the overall conductivity to the conduction through the matrix of the material. The Swedes reported overall conductivities of 0.021 W/mK.

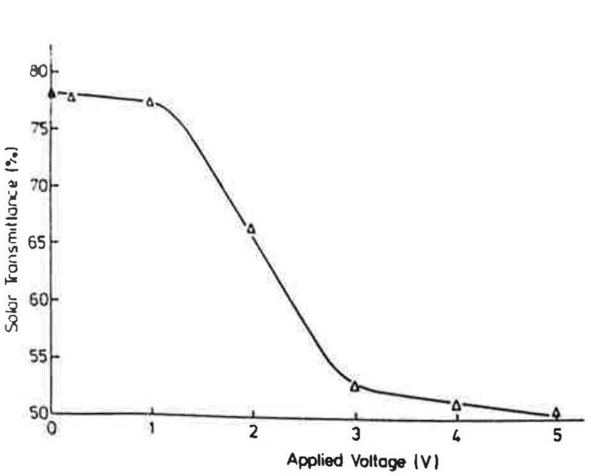

Figure 4 Electrochromic glass transmittance—voltage

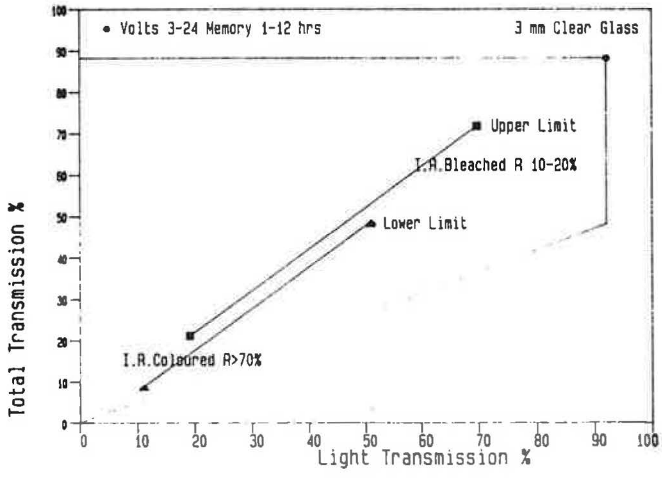

Figure 5 Control of heat and light—Lampert's criteria

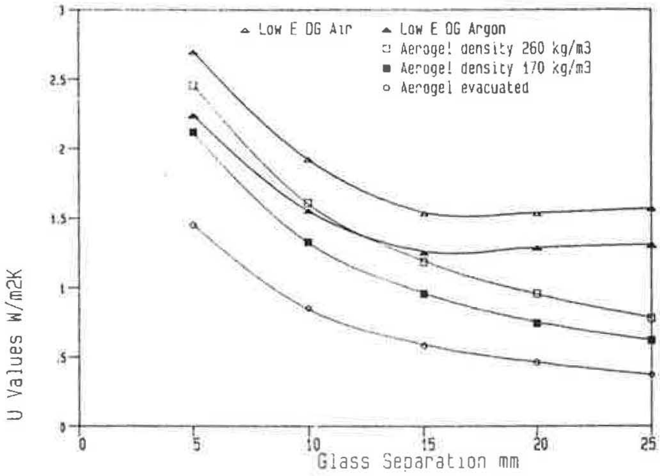

***Figure 6** U-values DG with low-e compared with aerogel*

A research laboratory has measured conductivities of 0.023 W/mK and 0.0175 W/mK at densities of 260 kg/m^3 and 170 kg/m^3, respectively, at a mean temperature of 10°C.

Figure 6 makes the comparison of a sealed double-glazing unit with a low-emissivity coating or with aerogel for increasing glass separation. The lower curve represents what might be expected with the aerogel evacuated, further reducing the conductive component of the entrapped air.

The material is very brittle and friable but is strong enough to withstand the atmospheric pressure on the bounding glass panes so that the glazing unit does not collapse.

Prospects for Commercial Production

The challenge is to develop high-volume, economic production of what is now a well-established technology. The original Swedish production is dangerous because of the use of highly flammable alcohols used in an autoclave process. The production plant was completely destroyed by explosion, fortunately without loss of life, and was subsequently rebuilt.

Currently research is being pursued to develop a process for manufacturing granular aerogel with a grain size of 3 to 4 mm, which could be used to fill sealed glazing units. Unfortunately, such a product, while retaining high overall light transmission, would lose its transparency.

Hard Low-e Coating

Magnetron sputtered low-e products based on S_nO_2-Ag-S_nO_2 multilayers are relatively soft coatings. They are therefore confined to use in sealed glazing units where the coating is protected from abrasion and oxidation. There is a need for a durable low-e coating not requiring such protection, and in practice gives greater flexibility in the manufacturing process.

The on-line pyrolytic coating has such durability, indeed the tin oxide coating is harder than the glass substrate. This opens up possibilities for glazing it monolithically in glazing systems, with many other non-architectural possibilities. An example is passive de-icing of vehicle windows.

Again the material component cost is low, there is no extra time required for processing and, provided the yield could be improved to levels approaching normal production yields, there is commercial potential for a product which is only marginally more costly than the basic glass.

A scenario is opened where all windows are "high-performance" glazed as a matter of course with durable low-emissivity glass or components based on it. This would herald a revolution in the design of windows and indeed the walls of buildings.

FENESTRATION 2000

This is an international project (Button and Dunning 1990) supported by both the U.S. and U.K. Departments of Energy and the glass industry. The objective is to provide targets for marketing and product development and direction to commercial, institutional, and government bodies in the long term.

The first stage, which has been completed, involved interviews with a broad range of specialists in Europe, North America, and Japan to develop future scenarios for the construction industry.

The principal conclusions are:

1. In the 1990s an aging and smaller working population and competition among employers for staff will produce expectancy in the built environment for higher standards of thermal, visual, and aural comfort; provision of better amenities; improved workplaces; privacy; trouble-free services; simple controls; and personal control over the worker's local environment.

2. The capacity to process, store, and transmit information will grow enormously. Communications systems will be an integral part of the building in the same way as mechanical and engineering services. High-tech electronics will have facilitated the emerging intelligent building, which integrates the traditional mechanical and engineering services and communications systems. New partnerships will emerge between owners and suppliers of automation, communication control systems, and building systems.

3. Technology has obscured the spiritual and amenity needs. Future employees will be in a stronger position to bargain for amenities. They will demand customized, high-quality goods and services geared to variety, self-expression, and style. Visual amenities will become essential means to assist the introduction of new technologies and innovation in the workplace.

4. The building occupant, investor, developer, or corporate financier will be more enlightened in his or her financial appraisal of long-term costs, amenities, productivity, etc. New research and understanding into occupant productivity will be made and become important in the financial appraisal of the design and innovation in commercial buildings. The commitment to quality in all its aspects in construction will be an important feature in marketing and design in the next 30 years. A growing tendency for people to go to litigation will put increasing pressure on suppliers and designers to be more responsible in their attitudes, but this will have constraints on innovation.

5. In the Western world, as the inventory of existing buildings in the 20th century grows both older and larger each year, there is a built-in growth for refurbishment.

The 1990s will see a shift from the era of building to the era of renovation. This factor, in conjunction with the need for commercial building refitting to accommodate changes in technology, will have developed new refurbishment industries, specialists, designers, and contractors.

6. Safety and security will continue to have a major impact on current developments in commercial building design. The modern world continues to grow more hostile and dangerous. Criminals are more ready to use force and terrorist activities touch all our lives.

7. Current predictions suggest that up to the year 2000 dramatic increases in oil prices are unlikely but, regardless of energy prices, worries about the greenhouse effect will exert considerable pressure in design for energy conservation.

8. Concern for energy efficiency in buildings will be affected by: more sophisticated methods of investment appraisal, greater concern for long-term running costs, and sensible energy strategies for buildings (e.g., computer control). These will generate new interest in innovative materials and a new regard for passive solar design and natural daylighting.

9. The intelligent building will integrate traditional services with communications systems. The use of computers and the level of control possible through microprocessors will have developed more sophisticated building control systems which can handle more than energy. They will include security, life safety, communications, etc. They will also encompass the control of daylighting, thermal insulation, building tightness, and indoor air quality.

The importance of a linkage between the intelligent building and an intelligent, dynamic, performing facade will have been well established by the year 2000. The combination of computer technology and advanced materials will facilitate this for energy efficiency and a better sense of control and comfort, leading to improved health and productivity.

LONG-TERM FENESTRATION PRODUCT DEVELOPMENT

From these general conclusions and scenarios for the building industry more specific development targets for fenestration are identified as follows:

1. The function of the window as a transmitter (and filter) of solar and visible radiation will be enhanced. Specifically, there is a real need for variable transmittance.

The development of super insulation will occur, incorporating insulating translucent or transparent products such as silica aerogels. The development of glass with optimized solar optical performance for temperate climates will continue.

2. Decoration will be integrated with the information technology and communications functions so that walls become displays of information or simply color and pattern, creating the possibility of changing the whole character of the building. Glass, with its new developments (coatings, electronics, holography, etc.), is placed in a position to play a key role in this technology while performing its traditional light-giving functions.

3. There is a trend in the building industry for off-site fabrication, increasing industrialization, and larger, factory-fabricated facade components which will assist in solving failures due to incompatibility of materials and components.

This trend is limited by a paucity of long-run standard unit demand, the fragmented nature of the building industry, and contracting legislation. There will be innovations in facade design, bringing together industrialized, factory-produced components of glass, framing, and cladding.

4. Information and computer-aided design technologies will have a profound effect on components, documentation, specification, performance prediction, design detailing, and costing.

Further stages of this project are planned.

The second stage will be two parallel studies examining the energy benefits of future requirements that fenestration would offer and a materials option study. The benefits study will use analytical computer programs developed by the Departments of Energy in the U.K. and U.S. The materials options study will be carried out by a national laboratory and will be funded by the two Departments of Energy and the glazing industry.

The final stage will bring together the results from these three projects to assess whether investment will be justified in developing products and the directions those developments should take.

CONCLUSIONS

This paper has sought to put in perspective the reality of practical glazing products available for devising high-performance skins for buildings. In conclusion, current and ongoing product development for future products has been exemplified:

(1) Continued improvement of solar control products for selective heat rejection with good visible transmission.

(2) Accelerating applications of low-emissivity products for highly insulating windows and facades.

(3) Development of insulating products with transparent or translucent visible properties.

(4) Longer-term development of variable transmission with more promising electrochromic materials.

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DISCUSSION

R. Sheng, Senior Engineer, University of Manitoba, Winnipeg, Canada: Please comment on the cost differences among the three types of glasses you showed.

P.G.T. Owens: This type of question is difficult to answer precisely. First of all, I presume the questioner really relates to prices to the consumer and not to costs. Bearing in mind that actual prices are strongly influenced by the volume of the order and perhaps the difficulty of executing the order in terms of sizes and supplementary requirements, an indication can be given in a relative way. Thus, for comparison, observe the following price ratios:

Absorbing glass in a sealed glazing unit	—	1.0
Reflecting glass in a sealed glazing unit	—	1.4
High-performance glass in a sealed glazing unit	—	1.7

The last named is available only in the sealed glazing unit product, whereas the former may be single-glazed.