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ADVANCED GLAZING TECHNOLOGY: Fenestration 2000 Project- Phase III: Glazing Materials

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FENESTRATION 2000

An investigation into the
long-term requirements
for fenestration

PHASE THREE

Advanced Glazing Materials
Study

by

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I. EXECUTIVE SUMMARY

The future holds many challenges for the fenestration industry. Just as new types of coated glass are becoming common place today even more advanced wonders await in the future. This industry has the opportunity to redefine the function of the window and to advance its technology into the electronic age. The key to the future appears to be the use of intelligent control systems in home and businesses. This will increase along with advances in a very wide range of appliances and office products. Now the big question remains is the fenestration industry ready to plan for these products? Some changes are certainly being made, but probably too slowly. The future will definitely see further integration of glazings into the building skin and the building skin becoming a dynamic element. The future building skin will be dynamic, incorporating sensors to determine a variety of information. It is not unreasonable to expect the building to sense human presence and a variety of climatic factors. One of the key growth areas over the next 10-20 years will be in sensor technology. Many types of distributed neural net sensors will be developed along with multipurpose intelligent discrete sensors. Sensors will use microprocessors locally coupled to the sensing region.

Steady movement will be made to integrate microelectronics and photonics with the macro glazing or building skin. If we look back, building technology and electronics have had very little in common. In the future, the glazing and the building skin will become one large electroprocessor or photoprocessor. Another important issue is the increased attention to safety and more stringent fire codes concerning fire resistance. Increased litigation cost and insurance rates make issues of safety even more important in the future.

The future will bring a merger of wall and glazing elements. Major change in production methods will fully integrate wall and glazing technology. This implies that as the complexity increases many walls and large glazing portions will be constructed in the factory. It may be that less field installation from the minimum components will occur in the future. It is likely that a variety of glazings or wall elements will be used in the future. With an increased use of factory constructed elements the quality of the glazing will rise on a consistent basis. The thermal performance of glazed assemblies will increase approaching the thermal properties of the wall. The use of super glazing will become common place. The use of materials such as aerogel and translucent insulation will be fully integrated into future window design.

Switchable films for glazings present one of the largest future changes. There are a wide variety of products ranging from electrochromic, dispersed liquid crystal, photochromic polymers and gel thermochromic materials. Electrochromic films offer the widest range of opportunity for application and design. The development of this technology is steady with about 200 patents filed per year, with Japan leading the technology. The complexity of materials and fabrication issues slows the introduction of this technology. Fortunately these issues are not insurmountable. Following the current trends in thin polymer batteries, considerable advances will be made in ion conductive lamination polymers. One of the major costs of electrochromic and dispersed liquid crystal devices are the transparent conductors. This cost will fall as pyrolytic on-line tin oxide processes improve. Also, the improvement in the properties of transparent conductors on plastic will bring about a new generation of low cost switchable devices.

Materials with modified angular properties and possibly switchable properties will be used for buildings and specific auto glazing applications. Holographic films will continue to mature with the development of more stable substrate and better understanding of its processing technology. Antisoiling technology will develop for glass and plastics. Light transport systems will become more efficient and may become centralized using a range of light transport technologies. New types of design tools will allow glass products to be fully imagined. The future looks very promising for the glazing industry, and this industry will certainly experience a strong learning curve in the years to come to be able to produce the products of the future.

II. SCOPE AND LIMITATIONS

This study discusses some new glazing ideas that are being developed for the future and introduces new ones that may have significance in future building fenestration systems. Some of the technology is drawn from sources beyond the glazing field such as electronics and aerospace. Some information is taken from allied fields involved in glazing such as automotive, marine and aerospace. Many of these fields are far ahead of fenestration in the complexity and refinement of technology. Some of these fields may help lead fenestration from a passive brutish technology to a highly refined energy and communication window or portal to the outside world or between working areas. The scope of our study covers two large topical areas: (1) Glazing Technology (Glass and Plastics) and (2) Lightwave Technology. These topical areas are divided into 14 categories. The categories of the study are as follows:

1) Advanced manufacturing can give us the means to produce quality complex glazing and building skins in a cost effective manner. Coating technology provides a method for depositing optical quality films on glazings.

2) Advances in automotive, aerospace and marine glazing technology can help guide the way to future building technology.

3) Smart building technology, can allow the window or the whole building skin to become a dynamic, adjustable sensing element. Smart building technology could have control over heat, light, fire warning, communication, and security.

4) Glazing as a communication medium for the transmission of messages and control of electromagnetic transmission.

5) Computer based design and prediction methods for the rapid and intelligent design of structures and the determination of energy performance of glazing and fenestration.

6) Optical switching technology can be used for dynamic glazing and can be adjusted automatically or according to the users wishes. Technologies include electrochromic, liquid crystals, suspended particles, photochromic, and thermochromic glazing.

7) Translucent and transparent insulation include the characteristics and performance of new insulating glazing materials, glass-like aerogel, and cellular and capillary shaped polymers.

8) Wavelength selective materials can be low-emittance coatings for the control of heat transport by radiation. Radiative cooling surfaces can transport heat by radiative processes through gaps in the atmosphere. Spectral splitting coating can separate regions of solar and visible radiation.

9) Super windows combine several materials to make a highly insulating glazing.

10) Conductive polymers and their use as conductors and potential for window coating to replace metals or provide properties not seen in other materials.

11) Materials with modified angular properties, which can be used for the selective control of transmittance for solar and light control and security applications.

12) Antireflection coatings to reduce the reflectance loss from glazing and to reduce glare.

13) Antisoiling coatings for glass and plastics to control soiling of glazing surfaces.

14) Light concentration and distribution materials including fibers, hollow pipes, fluorescent concentrators and holographic films. Holographic films have the potential for the concentration and redirection of light through a glazing into a room.

Information for these categories came from a wide range of sources including buildings, electronics, materials, automotive, space and defense articles. Additional information comes from conversations with trade people, engineers, scientists and architects. In all of areas listed above we initiated the study with a computer data base search. We have searched the literature from 1970-90, with concentration on the last ten years. The Data bases searched are Inspec, Chemical Abstracts (CA), NTIS, Compendix, Engineered Materials, Avery Architecture Index, Ceramics, Aerospace, Soviet Science and Technology, World Patents, Dept. of Energy, U.S. Patents, Foreign Patents Index and the U.S. Defense and Aerospace data base. Also several journals were searched in addition to the data bases. The journals searched included Photonics Spectra, Schott Information, Glastechnische Berichte, Proc. of SPIE, Solar Energy Materials, Semiconductor International, NASA Tech Briefs, Ceramic Bulletin, IEEE Spectrum, Advanced Materials and Processes, Popular Science, Information Display, Journal of Metals, Physics Today, Research and Development, Paper and Film Converter (1991 only) and Laser Focus World. Many of the categories developed from this data base are only presented with enough information here to give a picture of the concept. Each identified area could be developed into considerable detail. However, two areas covered in great detail are optical switching and low-e materials because of their popularity. Some areas covered may not be currently practical or possible, and others require innovations in allied fields to become viable. They are presented here to give the reader a sense of what may be possible and may in turn stimulate innovation to realize some of this exciting technology.

III. CURRENT INNOVATION AND TRENDS IN THE GLASS INDUSTRY

Innovation in the glass industry over the last few years has been chiefly in two categories: (1) the basic glass making process and (2) value-added products that are modified or coated glass products (OECD, 1988; U.S. Glass, 1989). The glass making process consists of the primary glass float line, composition, melting, forming and pyrolytic coatings. In one year the worldwide production of flat glass is roughly 1 billion m^2 per year, with about half of it produced in USA (AGR, 1988). In the glass making process, innovation has been in the development of the direct delivery float system (LOF Process), in which a wide ribbon of glass is directed into a tin bath of smaller than normal size, saving on the size of the bath. Another innovation is the AFG mini-float process to produce glass in smaller quantities (100 Tons per day compared to 600 Tons per day). Another trend is to reduce waste, scrap and energy in all aspects of the glass making process. Economics strongly drives this trend. Smaller float lines allow faster glass-melt composition changes and smaller runs of specialized glass products, reducing waste and down time. Innovations in electric melting and boost melting in float baths of clear and heat absorbing glass are being made. Automated numerical control of glass fabrication equipment is being used. Computer control and computer aided processes (CAD, CAE, CAM and CIM) are being used for all aspects of the glass making and forming process. Research is going into making glass furnaces more energy efficient to reduce the consumption of fuel, overall operational cost and scrap. Also, the increased collection and use of recycled architectural glass in melts is being studied. Improvements in glass edge grinding machines have allowed for changes in glass thickness without reducing output efficiency. The demand for flat glass products to the year 2004 will increase at a rate of about 2.5% per year in Europe. The increase in the U.S. will be about 3% per year. This corresponds with the growth in the Gross National Product. Plastics are predicted to have about 10-11% of the total market in 2004 (Hammel, 1985).

New architectural products include a range of very successful low-emissivity (low-e) products to reduce thermal radiative loss. This is possible by the development of large-area deposition systems. Large conveyor type reactive d.c. sputtering systems, made by Airco Coating Technologies (Concord, CA) and Leybold AG (Hanau, Germany), have been purchased by every major glass maker and some glass fabricators in the world. Typically, a coater can coat a 3 x 4 m sheet of glass. Also high deposition rates and better cathode usage are available with the rotatable and metamode (OCLI, Santa Rosa, CA) sources. High rate flexible web coating equipment is being offered by Airco Coating Technologies (Manchester, UK) and Leybold AG. The two major classes of coatings produced now are (1) a limited transmission solar control coating, and (2) High visible transmittance coatings with high infrared reflectance (low-e). The solar control coating is usually darkly colored and gives some degree of privacy and provides shading to both solar and daylight. This type is very popular for automotive and window glazing in the warmer climates. This can be a solar absorbing glass or be coatings with moderate to high reflectance, although the trend is to move towards less reflective glass. The highly transmitting coatings can be selective coatings that pass only the visible or pass most of the solar spectrum. They can serve as electrical conductors and used for example for electrically heated windshields. Currently these products are being improved to give higher thermal performance. Quality of coatings, reduction of defects, distortion, improved surface condition and strength are all issues. The use of statistical process control for the improvement of coating processes is also important for improved quality and reduced waste. There is a trend to reduce visible reflectance of glass products. New glass products that simulate the appearance of other building materials such as marble and granite are being developed. Work has gone into developing glass to withstand breakage during fires. This is very important in large buildings, especially in Europe and Japan, whose building standards for fire propagation are becoming strict.

New Pilkington (K-Glass) and LOF tin oxide coated low-e products have shown considerable improvement in thermal emissivity properties; this is done by reducing the effect of visible iridescence in thick coatings by optical interference, these coatings are produced by atmospheric chemical vapor deposition (CVD) on the glass float line. A whole new class of spectrally selective coatings (high visible transmission with UV, NIR and IR rejection) is expected to emerge in the near furture. Other improvements are related to better window design such as gas filled double glazing using low-e coatings (such as Andersen Corp., Bayport, MN). Another development is the Southwall (Palo Alto, CA) "Superglass System". This is a window with two suspended low-e coated polyester films and a fill gas in the gap of a double glazed window. A wide variety of low-e and solar control coatings are being produced. For example, manufacturers such as 3M Co. (St. Paul, MN), Courtaulds (Canoga Park, CA), Deposition Technology Inc. (San Diego, CA), Madico (Woburn, MA), Teijin (Tokyo, Japan), Southwall, and Toray (Tokyo, Japan) are producing a variety of window products on polyester substrates. Currently they are working to improve durability and visible selectivity. New bent and curved insulated glass units have been introduced by many including Marvin Windows (Warroad, MN). This allows for greater architectural styling with energy efficiency. Other improvements are being made in the reduction of frame conductivity, which become significant as the thermal performance of the glazed portion of the window improves. New interlayers in place of PVB have resulted in glass with improved acoustical damping. These materials could be polyvinyl chloride, polyurethane and composite polymers (Sekisui, Japan). It is expected that by 2004, acoustic properties of glazings will be about 60 db damping compared to 30 db damping today (Barton, 1985). Bilaminate glass is being experimented with to increase impact safety in automotive applications.

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IV. INTRODUCTION TO THE FUTURE OF FENESTRATION

This study is a product of the Fenestration 2000 Phase I project (Button and Dunning, 1989) and explores its conclusions that first phase addressed the overall trends in future glazing. It looked deeply into the current building industry and how it must change to meet the needs for future fenestration. The goal of the Fenestration 2000 Phase III project is to search for and examine new products and processes that have application to future building fenestration. The time frame is 10 years or greater from the present time.

Before we discuss future technology it is important to summarize the results of the Phase I project. The study found that the current building industry is inefficiently organized, generally fragmented and not innovative enough to meet the needs of the twenty-first century. The problems have to do with industry organization where many building components are not designed with the building system in mind. In the future there needs to be a much higher level of component integration and standardization. The study also looked at trends and the needs of future glazings for a variety of functions. The first phase study had several conclusions. All buildings can be more energy efficient, which means interactive lighting, heating, and cooling control systems using smart sensors are necessary. A higher overall quality of materials is needed for future buildings than are currently available. Renovation of inadequate or sick buildings is growing. Currently about half of the U.S. window market consist of replacement glazings (U.S. Glass, 1989). Renovation is expected to increase due to the rising expense of building new buildings. Fenestration must also prevent electronic eavesdropping and provide personal security. Future fenestration has to be responsive to the needs and wants of the customer. This includes the designer builder, building owner, community surrounding the building, the occupants who pay the lease, mortgage or rent and the needs and requirement of maintenance workers who maintain the building.

The major needs of the future commercial building occupant are increased comfort and visual amenity. Improvements in lighting, heating and cooling are needed. This has a direct effect on productivity and health. Smart control systems will have both programmed and learning abilities using fuzzy logic. Fuzzy logic is a machine process by which decisions are made on intermediate conditions between yes and no or on or off. Both exterior and interior glazings are expected to serve multiple functions and become more highly integrated into the building as a whole. Local-area networks (LAN) for communications will become standard for offices. Fenestration will probably include functions of display and communications.

The future of residential buildings appears to be on a parallel course with commercial buildings, with increased security systems, communication and smart building thermal and lighting control systems. Also, entertainment and appliances may be integrated into a centralized smart control system. Smart appliances are currently being developed. Another important issue is affordable cost for residential buildings. In every developed country, the building costs are increasing at a rapidly. The average family is finding it harder to own a home or even rent an adequate one. Because of increased cost and complexity, there will be greater interest in prefabricated components and manufacturing techniques to integrate window and wall systems.

Other areas of technical advances might be in quality improvement, cost and weight reduction of glass or glazing units, increased use of laminated or protective coated glass for safety and better design of glazings for increased manufacturability with increased awareness to ease of assembly. A new wider range of glass compositions is expected to improve tinted glass, high transmittance glass, and low alkali glass for large area display use. More shaped glass products are expected too. Also, it is expected that more multiple function glass will be used in the future, such as the incorporation of solar control, communication, safety and decoration. The building skin will be better integrated with glazing and non glazing components. Future glazing will have properties such as expansion matching to reduce breakage. Glazings will be better designed to avoid the contaminates that frequently run-off causing streaking or staining of the non-glazed portions.

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V. TECHNOLOGY OF THE FUTURE

In several areas of advanced technology we are seeing progress being made, some areas are moving rapidly while others more slowly. The areas of technology we have selected appear to have major impact on the future of building and vehicle glazings. In the following several sections each subject is developed giving a review of current commercial technology and prospects for future technology as indicated by research developments. Many of these technical developments will probably be combined to form multifunctional glazing components.

The following technological areas are directed toward the improvement of glazing and building skins. These technologies used in the proper way have the potential for the development of highly integrated fenestration. Also the integration of smart systems and controls will make integrated fenestration effective. Many of the following technologies will provide methods and materials to make this possible. For advanced glazings several factors have to be taken into account. Glass is becoming important for a variety of related functions including energy conservation, climatic comfort, security, safety, visual amenity and fire protection. Many building codes are requiring better performance from glazing. Thin laminated glass for security and safety uses such as store windows is increasing in demand in cities with increased crime and insurance rates. This trend will increase well into the future. A new project that will study the building envelope and lighting systems for the twenty-first century is being developed by the California Institute of Energy Efficiency (CIEE), LBL, Berkeley, CA, USA. It is designed to look at methods to increase energy efficiency of building envelope and lighting systems.

Fire protection for future glazings is also important. In the Hong Kong and Shanghai Bank in Hong Kong a special sealed glazing was used with fusible seals built into the window so in the case of fire the air trapped between the glass panes would escape rather then shattering the window as they do in normal double glazings (Sewell, 1987). Loss of life and property by fire is an increasing cost that effects insurance rates. Even in modern building there is a very strong chance of quick fire propagation and smoke filling escape routes. Building regulations in much of Europe and Japan are requiring that glazing give greater protection and containment from fire propagation and heat radiation (Ader, 1986). Two types of glazings exist for fire protection. The first type, Type F, contains a heat sensitive lamination layer that becomes opaque to infrared with heat; the glass portions crack when exposed to fire but the pieces are held by the intumscent lamination layer. The second type, Type G, remains fully transparent and does not shatter during exposure to fire; an example product is wired glass (Scheidler, 1982).

This trend is expected to continue, increasing the demand for heat resistant glass and glazed systems. Commonly borosilicate glass is used to prevent breakage by thermal shock. Currently glass of this type has resistance to fire of 30, 60, 90 or 120 minute rating. For the higher ratings special frames are used which have an expandable compression fitting. Currently, to control heat radiation Type F glass is used to control heat radiation that is hazardous to humans. It is possible that low-e glazings may be used in the future. Regular float glass shatters within the first few minutes of exposure to fire because of high tensile stresses set up in the cold areas around the edge of the pane that is covered by the frame while the hot middle area of the glass expands. Borosilicate glass (such as Schott Glass Pyran) has a low coefficient of expansion and tempering that makes it resistant to breakage and it is more resistant to sagging than regular glass.

Another important area of development is window frames with increased thermal resistance. This development is lagging behind that of super windows, but without it the properties of super windows are degraded in over all fenestration thermal performance. Frames are discussed in Section 7.2. Another interesting development is a Russian process to produce a double glass panel by a special downward drawing process (Rudoi, 1989). This process can produce tubes or flat parallel sheets for a variety of window, wall and electronic display products. The process is adaptable for inside surface coating of pyrolytic SnO_2.

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Sources for chemical technology information on new products are:
Dr. Michael J. Smith, Rohm & Hass Co., Research Labs. 727 Noristown Rd., Spring House, PA 19477, (215) 641-2005.

General Licensing opportunities for new technologies:
Licensing Executive Society, 71 East Ave., Norwalk, CT, 06851-4903 (203)852-7168.

Technology transfer meetings:
Technology Transfer Conferences, 325 Plus Park Blvd., Suite 108 Nashville, TN 37217 (615) 366-0679.

1) ADVANCED MANUFACTURING ENGINEERING

The economics of manufacturing play a very important role in determining which new fenestration materials will be produced. Many new technologies will bring the need for new manufacturing techniques to be developed. It will take much innovation and renovation to supply adequate manufacturing processes (Marley, 1981). Certain processes such as used in aircraft or automotive industries can be modified for buildings. The use of industrial robotics could replace labor intensive functions. Some technologies are incompatible or nonexistent compared with existing window manufacturing technology. Economic manufacturing is the key to many of these technologies. Some future products are much closer to the market place than others. Global production of building products for export is expected to increase in the future.

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1.1) Deposition Technology

Probably the most advanced technology in the window industry is that of coating processes such as the large conveyor type reactive d.c. sputtering systems made by Leybold AG and Airco Technologies (as discussed in Section III). New simultaneous control technology can regulate several coating chambers or several regions within a process chamber at once. It is expected that large-scale deposition technologies will continue to be improved with increased efficiency, yield and throughput. The connection of several different types of coating processes has been done at Nippon Steel (Japan) (Hashimoto, Ito and Ito, 1989). The process makes continuous multilayer coatings using plasma-assisted CVD and ion plating and sputtering all in sequence. Different techniques are used to obtain the optimum chemistry and microstructure of the multilayer coating. It is expected that future process technology will move towards more integration of different processes. New types of assisted coating processes such as ion, UV, photo, laser assisted can be used to promote reactions, and favorable energy conditions on the substrate. High-rate cathodic arc technologies will be improved in the future. On-line CVD technology needs to be further developed to be more versatile to deposit many types of multilayer and thick coatings not currently possible. Low-capital intensive non-vacuum processes such as solgel and catalytic deposition and direct chemical deposition are receiving attention, especially in Japan, for glass coating and modification. There is an under-current of low-capital intensive coating processes that will probably increase due to the large capital expense of the vacuum processes. Various process breakthroughs are expected in this area in the future. Further developments in sensor and control technology are very important for the manufacture of glass to keep a high level of quality control and yield. Electrochemical techniques are being developed for the analysis of glass melt during the glass making process.

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1.2) Integrated Wall and Glazing Technology

The future holds great promise for integration of wall and glazing technology. Two driving forces for this are the reduction of overall cost of residential construction by prefabrication and the need for increased building quality (for comfort and productivity). One large contributing factor in the U. S. and Europe is high labor rates. It is projected that labor rates will continue to rise substantially over the next 20 years. There is considerable political and public force to lower the cost of residential housing in the U.S. (Olson and Kurent, 1988). Another factor affecting further integration of window and wall technology is the movement toward smart houses or smart buildings. The future holds even more integration of control systems sensors, communication networks, detection networks for intrusion, surveillance, fire and safety. Another factor favoring integrated wall and window technology for all buildings is the increased complexity of assembly and potential for super windows, which may be difficult to assemble properly at the building site. It is expected that in the near-future, the quality of windows will improve and approach the thermal performance of walls. It is also expected that wall insulation will improve with new types of gas-filled closed-cell fiber glass insulation and coated fibers in low density insulation (Barton, 1985). A new type of gas filled insulating panel (GFP) has been developed at LBL. It consists of a baffled polymer structure filled with low conductivity gas. The polymer structure has a low emittance coating and gas barrier layers. The insulation can be made to be rigid or flexible with thermal conductance (U) values 0.40-0.47 W/m^2K (thermal resistance (R) values up to R-12 to R-14/ in.) ((Arasteh, Griffith and Selkowitz, 1990). This can be compared to conventional insulation of U=1.53-2.27 W/m^2K (R-2.5 to R 3.7/in.) for fiberglass and U=0.79-1.4 W/m^2K (R-4.0 to R-7.2/in.) for foam. Also, it is expected that new types of evacuated closed cell polymer insulation are to be developed (Jewett, 1990).

In Europe, the use of transparent insulation or translucent insulation for walls is increasing. Currently there are many projects in Europe. This type of insulation is being studied for walls and limited window applications. Transparent insulation includes: honeycomb polymers, granular and powdered aerogels and gas cells in multilayer coated polymer sheet insulation. The properties of transparent insulation will be discussed in Section 7. It is possible that the European manufactured building industry (prefabricated buildings and sections) will lead the path to further the introduction of transparent insulation into the building market. Before this will happen in the U.S., the building industry will have to improve fabrication quality. Also, the public perception of this industry has been characterized with low quality products, although there are exceptions. In Europe and Japan the manufactured buildings industry is characterized as having high quality products; with some of the best buildings made this way. It may be easier in Europe to bring about technological change and public acceptance to smart and energy efficient manufactured buildings. The wall and window industries in the U.S. are not currently integrated, but will have to become so if this advanced technology is to be fully utilized. There is a large institutional barrier that will have to be overcome in the U.S. In the meantime, there is increased foreign import of high quality prefabricated building sections and components into the U.S. (OTA, 1986).

There are other technologies that might affect how future buildings are constructed and which could influence the integration of wall and window. Composite metal matrix polymers and ceramic materials can provide unparalleled strength to weight ratios compared to conventional materials (Clark, 1987). Advanced polymers will continue to be used in future buildings. Also the advances in adhesives and sealing materials are leading to very secure and long-life structures. A method of shaping graphite epoxy fabric into wrinkle free and void free shapes has been developed by NASA for the space shuttle payload doors. This technique involves the application of a vacuum bag and oven. Lightweight structural members can be made using this process. This material and forming process could be used for light-weight high-strength wall construction or to support fabric roof structures (Cupp, 1980). A new type of processed wood, Parallam, (Macmillian Bloedel, Ltd., BC, Canada) is adhesive bonded multiply wood. Parallam is three times stronger than regular wood and can be used as structural members. A new strong wood pane material called "stress skin" has a pre-formed insulating core. These new materials can improve performance and reduce construction costs.

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2) ADVANCES IN AUTOMOTIVE, AEROSPACE AND MARINE GLAZING

One key development area to watch is in automotive applications of glazings. Much technology is tested out in this industry. Because of the perceived short life of a car (6-7 years in the U.S.) and the car replacement philosophy, many new technologies are tested and developed by this industry. Some of these technologies can be transferred to building applications. Some product ideas go the other way, such as double glazing technology. However, one thing that can be learned from the auto industry is that car makers are very good at the integration of the glazing into the structure. It is possible that such technology advances can be taken advantage of for the combined wall-window concept for a building. Also the idea of easily replaceable glazing from autos could be transferred to building glazing. If the level of innovation in the glazing industry picks up over the next ten years it may become important to design windows with replaceable glazings in mind. This would allow for improved glazing to be installed during the life of the building. Replacement technology advances could be picked up from the auto industry.

Anti-lacerative polymer laminates on the interior surface of the windshield have been explored by LOF. It is expected that bilaminate protective glazings will continue to evolve over the years to come. The idea is relevant to building glazings for safety, but durability appears to be the biggest obstacle. Electric ice defrosting laminated windshields have been developed by Ford, LOF and Airco Technologies. This technology is an integration of an antireflected metallic film with the PVB (polyvinyl butyl) lamination layer. Additional developments have been in the incorporation of car antenna and information displays in windshield glazing. It is expected that the future glazing will serve multiple functions. Research is trying to make auto glass tougher for theft resistance. Other work is to make glass acoustically dampened and more energy efficient by introducing double pane glass side windows. Designs for double pane auto windows are being developed for the Volvo, BMW, Audi and Mercedes cars (Trier, 1988). The first showing of cars using double glazing (3 mm gap) was at the Spring 1991 European Auto Show (Geneva, Switz.) The windows were made by Plikington and Flachglas AG (Gelsenkirchen, Germany). With the introduction of double pane windows, multilayer selective coatings can be used to reduce the solar thermal loading of cars. In single glazing there is a problem of durability of multilayer coatings. Hard coating is one solution to this problem, but still requires further development and has some limitations. The thermal load problem in cars creates the need for larger air conditioning units in cars. Because of chlorofluorocarbon reduction legislation in many countries, many air conditioners will be reduced in size or eliminated. Products are being developed for cars with wavelength selective properties that have high transmission for visible light but reduced solar UV and near-infrared heating of the car's interior. This coated glazing product must be able to withstand the damage most car windows withstand. The effect of different glazings on thermal loading and air conditioner performance has been studied (Sullivan and Selkowitz, 1990).

Other concerns are safety from occupant ejection through the side glazings in accidents. Side-ejection is the largest cause of loss of life and major disfiguration in U.S. auto accidents. Laminated and double glazed designs may help reduce this problem. Related to these developments is the use of reaction injection molding to make complex frames for car windows. This simplifies installation of the window and can extend to architectural glass applications. A related development is making automotive glass easier to install with less additional parts in the factory and during replacement. Head-up displays are being introduced for cars and combiner units (display area) and are expected to be integrated with the windshield. Also PPG Industries and other companies have developed moisture sensors that are integrated with the glazing to activate the windshield wipers.

The trend in switchable glazings for cars is to develop mirrors first, and gain some experience with their operation and durability characteristics. They will be followed by larger-area glazings, sun-roofs and side and rear glazings. More on the details of this technology is in Section 3.1. Switchable electrochromic mirrors are being developed and used on a variety of cars. The current trend appears to be that just about every automotive manufacturer will offer them on their more expensive cars as an option. So far, companies such as Ford, General Motors, Volvo, Saab, Fiat, BMW, Mercedes, Nissan, Toyota, and Citroen have offered this product or expressed interest in it. A leader in switchable mirror products produced is the Gentex (Zeeland, MI) electrochromic mirror. This mirror is based on an organic liquid system and is available on GM and Ford cars. Some experimental switchable glazings have been experimented with by Gentex. LOF has formed an agreement with Gentex to develop mirror products. The Donnelly Corp. (Holland, MI) offers a competitive mirror product and is working on an all-inorganic mirror design based on Nickel oxide and tungsten oxide (Lynam, 1987; Lynam and Agrawal, 1990). Electrochromic auto mirrors based on a-H_xWO_3 have been developed for the European automotive use by Schott Glass (Weisbadden, Germany) (Baucke, 1987; Baucke, 1990). The Schott mirror has the distinction of being the only true field-effect device using seven layers. It also represents a very successful proton based device. Nikon (Tokyo, Japan) has developed an all solid state mirror for cars based on tungsten oxide and iridium tin oxide (Niwa et al., 1986). These electrochromics are the only all-inorganic-solid state electrochromic designs to become products. Another mirror is being developed by Toyota Motors using tungsten oxide and polyaniline. Potentially a sun-roof product will also be developed by Toyota.

Sun-roofs followed by side glazings for cars are being developed by several companies in Japan. So far the most impressive sun-roof products have come from Japan. Nissan Motors and Central Glass of Japan have jointly developed a prototype a-$LiWO_3$/Prussian Blue ($Fe_4(Fe(CN))_6)_3$ complementary electrochromic sun-roof (Kase et al., 1990). Windows at least as large as 80x60 cm have been demonstrated by at least 4 companies in Japan and a few in Europe. At the Tokyo Auto Show in 1985 Nissan displayed their electrochromic sunroof on the Cue-X concept car (Kase, Kawai and Ura, 1986). This prototype received considerable interest by both General Motors, Ford and European automotive manufacturers. Another sun-roof product is the dispersed liquid crystal device. Currently Taliq (Sunnyvale, CA) is the only commercial producer of this product type. It is being evaluated by both Ford and General Motors for car and van side windows. Also General Motors research labs have been consistently improving this product. There are plans to produce this as a product for future GM cars. Other companies such as Ashai Glass and Nippon Sheet Glass have been working on dispersed liquid crystal devices too and more information on this product is given in Section 5.2.

Many of the advances in aerospace are in the field of smart skins and structures that are covered in another section. PPG has shown an electrochromic glazing for use in commercial aircraft. In its design it incorporates tungsten oxide and Poly-AMPS as a proton conducting polymer and a copper grid counter-electrode structure. The grid serves as an RFI shield for unwanted electromagnetic radiation. This grid has 8 lines/cm spacing with a linewidth of 63.5 μm (Greenberg, 1988). This prototype is being tested at Boeing Aircraft for their next generation of commercial aircraft (5-10 years away). At the 1991 Paris Air Show, another prototype window was shown without the grid lines. Also for aircraft there is interest in the development of switchable transparent visors and sunglasses (Harris and Greenberg, 1989). A very stable, but expensive window device based on a-WO_3 and a-IrO_2 has been developed for NASA space applications (Cogan et al., 1987; Cogan and Rauh, 1990). This is another example of a stable proton based solid state device. In the defense field, there is considerable interest in switchable windows to provide sun control for sensors in the visible and infrared. Examples of work at the Naval Weapons Center (China Lake, CA) include studies on viologens, tungsten oxide, polyaniline and Prussian Blue (Miles et al., 1990).

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Source for advances in composite and honeycomb materials for aircraft, space and defense applications:

SAMPTE, Soc. for the advancement of material and process engineering, P.O. Box 2459, Covina, CA 91722, phone: (818) 331-0616, Fax: (818) 332-8929.

3) SMART BUILDING TECHNOLOGY

The idea of the smart house has been with us for sometime and there have been several demonstrations of computer controlled technology (Gouin and Cross, 1986). Since about 1984 there have been coordinated efforts to create a standard smart system for the home (Klein, Bernaden and Neubauer, 1988). Developments in intelligent systems are starting to occur in the commercial building sector too. (Payne, 1988; AEE, 1986). In this direction NTT (Tokyo, Japan) is developing building automation systems (BAS) that integrate all telecommunication, office and building control automation functions (Kujuro, 1988; Morishita, 1987). Currently home automation promoters have developed standards for use by several of manufacturers. In 1984, the Electronic Industries Association formed the Consumer Electronics Bus (CEBus) Committee to develop standards for a variety of home automation products. As of 1990, eleven companies have joined this project, including AT&T, Carrier, Lennox and Pioneer. The standards for CEBus are expected to be final by Spring 1991. Homes of the future are proposed to have central control and distribution network incorporating video, telephone, security, and electrical. A demonstration house using this technology has been built by the National Association of Home Builders (NAHB) at the NAHB National Research Center in Baltimore, MD (Gilmore, 1990). This is a hard wired house, but it is probable that optical fiber links will be used in the future because of their reduced size, increased reliability and resistance to electrical interference. Smart systems have been proposed for building HVAC system diagnostics and control (Haberl, Norford and Spadaro, 1989; Harrold and Lush, 1988).

A Smart House has been built in Japan at the University of Tokyo (Normile, 1990). Over 100 experiments are being performed on this house. It has interior and exterior sensors that detect temperature, lighting level, humidity, airflow, human presence and number of people and even carbon dioxide levels. Outdoor sensors detect wind velocity and direction, air pressure, and level of solar radiation. For security the owner could view any part of his house and grounds through a television, using distributed video cameras. Various control functions can also be performed by telephone. A schematic of the control system is shown in Fig. 3.1. The Japanese have formed the TRON Association with 140 member companies, including Apple, IBM, Siemens, Motorola and Olivetti as foreign members. This organization is developing electronics and software for use with a common real-time TRON operating system. The Electronic Industries Association of Japan is working on standards known as the Home Bus Standard and Domestic Digital Bus Standard that is working to link different brands and products in smart homes. In Europe, an effort to standardize is underway for smart appliances, called ESPRIT II Home Systems Project. Work is in progress to develop remote control units that can govern a variety of electronics, security, drapes, and lighting functions. Future plans are to apply the technology to office buildings and automotive applications. A communication control link connects all appliances and sensors to three computers. Also motor driven devices like windows and blinds can be controlled. A variety of devices in the house also contain microprocessors and can exchange information with the control computer. For the home dweller, various scenarios can be used for leaving the house, going to bed, or having a party. The number of people in the house is determined by thermographic sensors, used to adjust heating or cooling. Air velocity sensors adjust HVAC fan speeds.

Another Smart house was built in Rosmalen, The Netherlands in 1988 (Scott, 1990). This house was designed by Chreit Titulaer and uses a large amount of glass. The control systems used in the house are a network of small computers that communicate with each other. The house includes a complete climate control system and water management system. It has a full security and fire system that knows the status of every window and door in the house. Another system monitors fuel usage and gives indications on how to reduce fuel consumption at any time. Many functions can be controlled by remote control or by voice. An interesting photochromic wall paint that changes from green to yellow color is used on the interior of this advanced house. It is designed to change with increased interior lighting levels. For example, the day and night colors of a wall could change. A dispersed switchable liquid crystal window is used for light control in part of this house. Another interesting aspect of the design is that a steel shell serves as the structure to eliminate load bearing walls, so all the interior walls can be moved or modified according to the owner's needs and changes in family size.

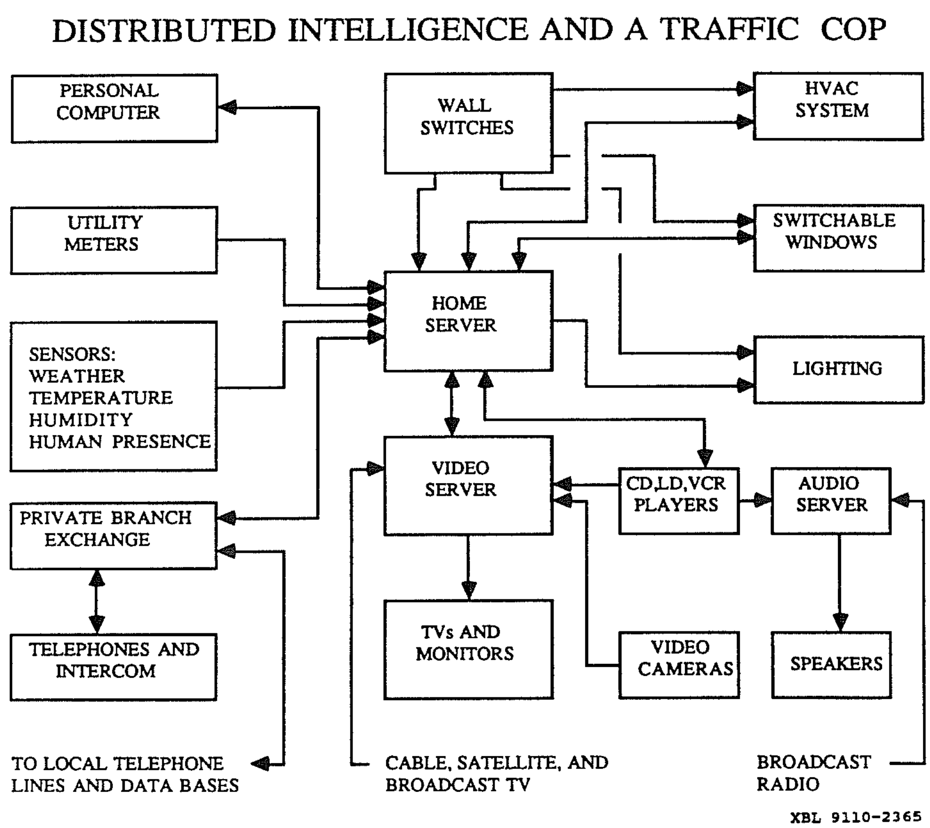

Fig. 3.1. The TRON smart control system shows the interaction of all home electronics, communications, lighting and heating systems (after Normille, 1990).

The field of smart fiber optic structures and skins is moving very rapidly for aerospace applications. Some of these developments are being studied for buildings (Udd, 1989; Udd, 1988a; Udd, 1988b). Joint work at Brown University and University of Iberoamericana, Mexico City, Mexico is studying embedded fiber optic sensors in concrete used for buildings (Mendez, 1989). These sensors can be used for a variety of structures to measure stress and structural integrity. They can be used to give information regarding seismic activity, condition of the structure, thermal stress, monitor creep and crack growth.

The market for building and heavy construction is 700 billion U.S.$/year (Eng. News, 1989). Once a fiber is embedded into a structure many changes in the structure are interpreted by change in intensity, phase or polarization of light traveling through the fiber. This can be done continuously or at intervals as necessary. Three main areas of applications for fiber optic networks are: (1) structural monitoring of the mechanical properties of the building; (2) stress monitoring for experimental building designs; (3) management and control of building systems for the monitoring of electrical power, lighting, security, fire and temperature. Fibers are embedded using metal tubes, which are withdrawn during setting of the concrete, or attached to steel reinforcement rods using tape spacers. In the future it is expected that fiber optic grids will become common. Multiplexed grid systems can overcome the effects of broken fibers.

In the U.S. Air Force "Project Forecast II" report, a number of future technologies have been identified and are being acted on; one is Smart Skins. This project is expected to continue beyond 2010. Currently there are studies by the U.S. Air Force Astronautics Lab (Edwards Air Force Base, CA) and NASA on the design of embedded skin structures including microprocessors, sensors and actuators for the dynamic sensing of large space structures. Large-scale testing of structures will be performed at The ASTREX facility at Edwards Air Force Base over the next few years. This work involves several major companies (for example, TRW and Boeing) and U.S. and Canadian Universities (Michigan State, MIT, Virginia Tech, Univ. of Toronto, Texas A&M, and Florida Institute of Technology). Texas A&M is working on embedded sensors using mirrors placed directly into the fiber to measure wavelength, temperature, acoustical frequencies, and strain built in to the fiber (Lee and Taylor, 1989). LTV Aircraft Products has evaluated and developed baseline performance values for a wide range of sensor types (Barrick, 1989). All fiber optic sensors are immune to electromagnetic interference, making them much more reliable then electronic systems. (DeHart, 1989). A long-term goal of this project is to develop skins that monitor the complete status of the surface including information processing at the sensor location and complete communications and surveillance systems through the skin (Ehrenfeuchter and Claus, 1987). A twin mode fiber can be used to measure temperature without a sensor. When coherent light is launched into one of the cores, symmetric and antisymmetric modes having different phase velocities are excited. These two modes exhibit periodic interference along the length of the fiber that results in back and forth coupling of light from one core to the other. External changes such as stress and temperature influence the characteristics of the cross-talk between the cores. Operation at two different wavelengths allows simultaneous determination of temperature and strain (Meltz, 1983; Meltz, 1988). The fiber optic sensors can be used to control the flow of water or air in heating and cooling system. The fiber optic systems can also be coupled to electrical power distribution networks to control load and correct power factors according to the time of day. Fibers coated with a heat sensitive polymer can be used as heat sensitive fire detectors in fire alarm systems. Piezoelectric fibers of ceramic and polymers are being developed as deformation sensors; they produce a voltage change by deformation. Physical actuation can be obtained by the use of fiber optics coupled to a temperature dependent shape memory alloy such as NITINOL. By heating with a laser beam down the fiber the NITINOL element will heat up causing it to change its shape to make a control change (Grossman, et al., 1989; Bowden et al., 1989). Acoustical waveguides can be imbedded into composite structures. They can sense the impact of even a few grains of sand on the surface. For a building, the impact of dust, dirt, rain, and human interaction with the building skin can be detected (Harrold and Sanjana, 1989). It is possible to use Nichrome, polyester-fiberglass or even optical fibers as acoustical waveguides. Much of this technology could be adapted to building applications.

All of these smart skins, structures and systems point the way to more dynamic homes in the future. The large activity in the space and aerospace areas should provide buildings with considerable smart technology in the future. With standards forming for a number of products it appears that this technology is moving closer to the marketplace.

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J. of Intelligent Material Systems and Structures, Technomic, Pub., Lancaster, PA, , Phone: 717-291-5609, FAX: 717-295-4538.

4) GLAZING AS A COMMUNICATION MEDIUM

Glazing has for many centuries supplied visual communication with the outside world. People at both work and home enjoy the view to the outside world that a glazing can provide. With the electronic age, glazing is beginning to provide additional forms of communication to the building or vehicle occupant. Heads-up holographic displays are beginning to be used in automotive and aerospace applications. Developments are being made at Pilkington, PPG, LOF and Nissan /Central Glass companies. For this purpose the glazing serves as a holographic combiner surface for the display system. Future communication glazing may incorporate synthetic vision systems, which would allow the viewer to see under adverse weather or in the dark or into other areas of the building. This could be very useful in vehicle glazings.

In automotive applications, there are strong efforts to integrate antennas into glazing using metal patterns or etched films of transparent conductors. This effort is expected to increase following the growth in cellular phones, fax machines, TV and satellite navigation for cars. Unfortunately, communication can not be as discriminating as it needs to be. Electronic eavesdropping and electronic jamming of on-board computers and communication interference are of concern to aircraft pilots. High energy radiated magnetic field (HERF) radiation has been known to jam guidance computers and is suspected to be the cause of a few military aircraft crashes (Harvey, 1990). As glass products become multi-purpose it is expected that the use of glass as a communication medium will increase, and along with it there have to be some controls and safeguards for communication. Also, as more optical technology is used for smart structures, fiber optical communications or sensing links can be coupled in and out of glazings. Flat panel display for television will be used in the future. A laminated display screen project called PolyVision is being undertaken by Corning and Alpine. The first topical meeting on intelligent glass has been conducted at the SPIE Hague conference, March 1991. The size of display panels for liquid crystal display is now at 45 x 45 cm and is expected to be at 1 m (diagonal) by 1996. The size of displays has been increasing at a rate of 75 mm a year (Teves, 1987; Schneider and Resor, 1989). Also the productivity is increasing, lowering cost. It is expected in the future information panels will be integrated with glazing systems.

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5) COMPUTER BASED DESIGN AND PREDICTION METHODS

5.1 Computer Based Design

The use of computer aided design (CAD) is becoming very commonplace in design and is being used in the glass and glazing industry. It can be used to simplify cutting and to rapidly supply glazing characteristics for a number of glazing products. Information on a CD-ROM InfoDisk system is used to store building product information that can be called up when needed by the CAD system (Thompson, 1991). Other CAD systems are available including Kawneer Partnerpak, Vistawall AutoCAD, Amarlite architectural products, Cadcel drafting program, Aluminum shapes, Inc. CAD/CAM is used for the design of aluminum frame extrusions. Sixteen Bit Software (Surry, UK) and I.P.C Computer Services (Tempe, AZ) supply window design software. ECHIP (Hockessin, DE) software includes provisions for coating and glazing design. CAD is being used in design of nested and shaped glass for automotive production at several companies including the Albat+Wirsam Co. (Germany). A CAD system can provide the codes needed to control the CNC numerical control glass cutting and grinding machines (Schmidt and Maass, 1990). Glasstech (Perrysburg, OH) is a leader in CAD glass bending design for architectural and automotive glass. The application of computers to glass problems has been studied by Prof. Lehman at Rutgers University (New Brunswick, NJ). Personal computers can be used for glass batch formulation, raw material selection, and glass property prediction. The idea of knowledge based artificial intelligence building design has been studied (Papamichael and Selkowitz, 1990).

There is significant development of scientific visualization programs using Cray Supercomputers (Cassidy, 1990). The National Center for Supercomputing Applications (NCSA) at the University of Illinois, Urbana-Champaign, (Champaign, IL), and the Electronic Visualization Lab. (EVL) at the University of Illinois (Chicago, IL), have become useful centers for the solving of complex problems and the development of new products. Applications include, visualization of crack growth in brittle materials and creep in plastics. Electrogig (Amsterdam, NL) has developed 3D design software for the glass industry. Objects and glazing can be visualized incorporating color, textures, diffuse and specular transmittance and reflectance and viewed under various lighting conditions. Volume visualization displays are being developed by Texas Instruments (Dallas, TX) (Williams and Garcia, 1989). This system allows the display of objects in a dome shaped 3-D monitor. The images are generated using X, Y scanned lasers writing on an angled spinning disk. It is being developed for applications such as combat control, air traffic control, medical imagery.

The use of computer generated virtual reality is being promoted for a wide range of interactive design evaluations. This technology is still evolving but has strong possibilies for the future designer. In the future, it is expected that the designer could see and physically interact with the design of a building through the cybernetic eyes of the computer (Carrabine, 1990). Virtual reality or CyberSpace is also being developed at NASA-Ames Research Center (Moffet Field, CA). With this technology the user has special interactive gloves and stereoscopic goggles. Scott Fischer of NASA has created the Virtual Environment Interactive Workstation (VIEW). This system allows the user to directly interact with a three dimensional image. This system has been used to "step inside" the vortex fuel stream of the space shuttle engines. There are various versions of quasi-virtual reality coming to the marketplace. A 3D computer mouse called the Flying Mouse allows the user to move it in space to view and manipulate a 3D design image on the computer (Sim Graphics Engin., S. Pasadena, CA). Another version of this is the Space Ball (Spatial Systems, Billerica, MA). The VPL Power Glove for Nintendo Games is another example of this technology (Carrabine, 1990). In the future, it is expected that this technology will be well integrated into engineering and architectural design.

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Mr. Jaron Lanier, VPL Research, (Virtual Reality) Redwood City, CA.

Mr. Richard-Dunn Roberts, University of Central Florida, Institute for Simulation and Training (Virtual Reality), Orlando, FL.

5.2) Energy and Performance Modeling

The field of energy performance modeling for buildings and fenestration elements has been under considerable development over the last two decades. Many of the computer programs that exist have been going through an evolution to become more user-friendly, more versatile and run on smaller computers such as personal computers (PCs). There is a trend for many of these programs to become more compatible with other programs, such as a frame program interacting with a glazing program which in turn interacts with a whole building program. They will continue in the future to become more user friendly and more interactive with other programs. Also artificial intelligence systems in the future will allow the user to interact with all programs and data bases and design tools of their choosing.

DOE-2 is a mainframe program for total building analysis. Its capabilities have been reviewed (BESG, 1985). DOE-2 is a public-domain computer program that calculates an hour-by-hour simulation of a building's expected energy use and energy cost, given a description of a building's climate, architecture, materials, operating schedules, and HVAC equipment. DOE-2 is widely used in the United States and in 36 other countries for designing energy-efficient buildings, for analyzing the impact of new technologies, and for developing energy conservation standards. The current version of the program, DOE-2.1D, was released to the public in 1989 (BESG, 1989). Major new features include: (1) User defined functions for custom modeling of HVAC and control system; (2) modeling of building-envelope components and systems; and (3) simulation of desiccant cooling and associated control systems. A PC version of this program is available, MICRO-DOE-2. Figure-of-merit performance indices: heating energy, cooling energy, cooling energy peak, thermal comfort and visual comfort has been developed for non-residential buildings using DOE-2 and other simulation models (Sullivan et al., 1988; Sullivan and Selkowitz, 1989). A new version of DOE-2 is expected in the near future. SERI-RES, ESP, and HTB2 building energy simulation models are also used by many researchers. As part of the U.S. energy labeling program for the National Fenestration Rating Council (NFRC) two PC based programs, RESFEN and COMFEN are being developed at LBL. RESFEN is for residential buildings and COMFEN is for commercial buildings. The programs calculate heating and cooling energy use, peak loads and cost due to varing fenestration system parameters.

There are three popular glazing performance simulation models. They are WINDOW 4.0 developed at the LBL, VISION 3.0 developed at University of Waterloo (Ontario, Canada) and MULTB (Pilkington Glass, UK). WINDOW has been adopted by the majority of the U.S. Glazing industry. MULTB is an in-house glazing model developed by Pilkington Glass and is not generally available outside of Pilkington. These three simulation models were evaluated in a UKDOE study (Robinson and Littler, 1988). Studies of experimental data from The Mobile Window Thermal Test Facility (MoWiTT) tests, suggest a high level of consistency between all the models. This gives us confidence in the modeled predictions of window performance. The WINDOW program is currently used as a standard by the glazing industry. The program serves as a standard tool for calculating the heat transfer indices through different combinations of coatings, glazings, gas fills, window tilt, spacer and frame materials. The program uses an iteration technique to calculate one dimensional heat transfer across a user defined window. From this result one can obtain performance characteristics such as U-values and shading coefficient. The latest version of WINDOW (4.0) takes account of spectral bands, so switchable glazing can be simulated and the program has full compatibility with the Canadian frame modeling program FRAME 3 (Enermodal, Engin., Waterloo, Canada). LBL have improved some of the window algorithms relating to the spectral and angular dependencies of glazing materials and to two-dimensional heat transfer around window edges. Edge and frame analysis in WINDOW use a data library of predetermined values. Another Software program, AAMASKY1, is a PC based program for skylight analysis. AAMASKY1 and a Skylight design handbook are available from the American Architectural Manufacturers Assoc. (AAMA).

The prediction of lighting quantity and quality in the luminous environment is essential for energy-efficient lighting design. A daylighting simulation program, SUPERLITE PC 1.01, was developed to model more sophisticated daylighting systems such as complex sun-control systems and shading systems (Schuman et al., 1988; Schuman and Selkowitz, 1989). The SUPERLITE model was selected by an International Energy Agency (IEA) task group as the primary tool for a multinational daylighting research effort. A Daylighting Design Tool Survey is available from LBL (WDG, 1988). A synthetic imaging program, RADIANCE, 1.4 uses a ray tracing program to accurately predict the behavior of light in design spaces. The user defines the geometry of the space and the characteristics of the surface materials and light sources. The program then predicts the behavior of light in the scene giving a realistic color image. RADIANCE is available from the LBL Windows and Daylighting Group.

Currently, a project at LBL is underway to develop a hypermedia system called the Building Envelope Design Tool. This system will integrate a complete collection of building design software and data bases and educational modules. This system uses an expert system linking CAD programs, and design and performance software using CD-ROM and video disk data base libraries. The expert system allows for a very friendly user interface.

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American Architectural Manufacturers Assoc (AAMA), 2700 River Road, Des Plaines, IL, 60018

DOE-2.1D is available from F. Winkelman, Building Technologies Group, Lawrence Berkeley Laboratory, MS 90-3147, Berkeley, CA 94720, (510) 486-5711.

Prof. John Littler, Research in Building Group, Polytechnic of Central London, 35 Marylebone Road, London, UK, NW1 5LS.

Lighting Systems Research Group, Mail Stop 46-125 Lawrence Berkeley Laboratory Berkeley.,CA 94720, (510) 486-5388.

Mr. Paul Robinson, Halcrow Gilbert Assoc. Inc., Burderop Park, Swindon, Wits., SN4 0QD UK, Tele: 0793-815020, Fax: 0793-815020.

SUPERLITE PC is available from Jong-Jin Kim, Assistant Professor, College of Architecture & Environmental Design, Arizona State University, Tempe, AZ 85287.

WINDOWS 4.0 and RADIANCE, 1.4 is available from the Windows and Daylighting Group, Lawrence Berkeley Laboratory, MS 90-3111, Berkeley, CA 94720 , (510) 486-6845 Fax: (510) 486-4089.

MICRO-DOE-2 (PC Compatible) is available from Acrosoft Int., 3120 S. Wadsworth Blvd. No.1, Denver, CO 80227 , (303)969-0170.

VISION 3.0 is available from Prof. John Wright, University of Waterloo, Dept of Mech. Engin., Waterloo, Ont. Canada. and Enermodule Co. Waterloo, Ont., Canada , N2L 3G1, 519-885-1211 x6849.

FRAME 3.0 is available from Mr. Steve Carpenter, Enermodal Engineering, Ltd., 368 Philip St., Unit 2, Waterloo, Ont, Canada N2L SJ1, 519-884-6421.

6) OPTICAL SWITCHING TECHNOLOGY

Optical switching technology has a very natural place in future glazings, it is probably one of the most exciting areas in glazings and has the potential to change the view of glazing from a fixed element to a dynamic one (Swanson, 1987: Selkowitz and Lampert, 1990). There are various physical optical techniques that can be used for the regulation of incident solar energy, daylight and glare in buildings and vehicles. Optical switching materials or devices can be used for windows in a variety of applications where optical and thermal modulation is required. The purpose of this material is to control the flow of light and heat into and out of a window, according to an energy management scheme. Optical switching devices could also regulate lighting and heating levels for energy load functions. In the last few years there has been growing interest in this technology. The basic property of an optical switching material or smart window is that it shows a large change in optical properties upon a change in either light intensity, spectral composition, heat, electrical field, or injected charge. This optical change results in a transformation from a highly transmitting state to a partly reflecting or absorbing state, either totally or partly over the solar spectrum. Another use for switchable glass is in the specialty glass market. There is considerable demand for special glasses for use as artistic and stained glass. This market has been increasing in Europe (Hoffman, 1983).

The physical phenomena of interest for optical switching processes can be classified in one of two categories, either discrete mass movement or collective physical movement. Discrete mass movement includes ion and localized electron motion as seen in photorefractive, photochromic, electrochromic, and thermochromic materials. Collective physical movement includes dispersed and homogeneous liquid crystals, and suspended particles, deformable membranes and adjustable diffraction gratings. All of these processes are classified as "chromogenic" (Lampert and Granqvist, 1990).

In this study we will cover chromogenic switching processes including photochromism, thermochromism, electrochromism, dispersed liquid crystals, guest-host liquid crystals, and suspended particle devices. A switching wavelength matrix is shown in Table 6.1. Here the ranges of spectral possibilities for solar and thermal modulation are shown. However, it is not presently known if materials exist that have all the properties depicted.

One of the most significant issues is the cost of these devices and the trade-off between cost and benefit and cost and lifetime. The range of potential electrochromic window costs has been estimated to be from 100-1000 US\$/m^2 (10-100 US\$/ ft^2). The related issue for all electrically activated devices is the quality and cost of transparent conductors, In_2O_3:Sn (also known as ITO) and SnO_2:F (Kaneko, Nagao, and Miyake, 1988). Currently the transparent conductors are the largest cost of the electrochromic device (Lynam, 1990). Large-area (over 2 m^2) ITO coated glass (with low haze and 9 ohms/sq) is being developed at Asahi Glass (Yokohama, Japan). There is considerable development on the production of low-resistivity ITO or ZnO transparent conductors onto plastic substrates at low temperatures using ion-assisted evaporation (Dobrowlski, 1984) and by r.f. sputtering using external d.c. magnetic fields applied to the substrate (Nato, 1988). Current research is aimed at long-life devices with durability similar to regular coated windows. A different approach is the development of low-cost limited-life switching devices. This is an area of important parallel development activity. It is expected that with further research and new materials, such as low-resistivity pyrolytic tin oxide made on the glass float line, doped ZnO and polymer conductors, this cost will decrease.

Table 6.1. Optical Switching Materials Matrix

Visible	NIR	IR*	Description	Example	Solar Usage
F	F	V	Changeable IR Emissivity	Switch. Abs-Ref. Thermochromic/	Research Electrochromic
F	V	F	Tunable Solar NIR	Electrochromic	Future glazings
V	F	F	Tunable Solar Visible	Photochromic/ Electrochromic/SPD	Future glazings
F	V	V	Broadband IR	Thermochromic	Future glazings
V	F	V	Two-band adj. (VIS & NIR)	None	None
V	V	F	Broadband Solar	Electrochromic/ Liquid crystals	Future glazings
V	V	V	All Band Variable	None	None

Codes:
F: Fixed properties over the range specified; V: Variable properties over the range specified.
VIS:Visible = 0.39 - 0.77 μm, NIR:Near-infrared = 0.77 - 2.5 μm and
IR:Infrared = 2.5-100 μm.
*IR: Infrared properties are largely dependent upon the substrate; most substrates are opaque.
SPD: Suspended Particle Device

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6.1) Electrochromic Materials and Devices

Electrochromic windows are a very popular area of research; over the last ten years about 200 U.S. and international patents have been granted per year. Japan leads in patents granted in this area by about 4:1 to the rest of the world. Electrochromism is exhibited by several inorganic and organic (including some polymer) compounds. Electrochromism is of current research interest because of its application to optical switching windows and mirrors for buildings and vehicles and large-scale electronic information display devices. The major advantages of electrochromic materials are: they only require power during switching, have a long term memory (12-48 h), require small voltage to switch (1-5 V), are specular in all states and have the potential for large scale fabrication. Electrochromic materials change their optical properties due to the action of an electric field and can be changed back to the original state by a field reversal. There are two major categories of electrochromic materials: transition metal oxides including intercalated compounds, and organic compounds. The electrochromic effect occurs in inorganic compounds by dual injection or ejection of ions (M) and electrons (e^-). A typical reaction for a cathodic coloring material is: WO_3 (transparent) + yM^+ + ye^- <-> M_yWO_3 (blue) where $M = Li^+, H^+, Na^+, Ag^+$, etc. A typical anodic reaction might be : $Ni(OH)_2$ (transparent) <-> NiOOH (bronze) + H^+ + e^- or NiO (transparent)+OH^- <-> NiOOH (bronze) + e^-. An electrochromic device must use an ion-containing material (electrolyte) in proximity with the electrochromic layer as well as transparent layers for setting up a distributed electric field. Devices are designed in such a way that they shuttle ions back and forth into the electrochromic layer with applied potential.

Organic electrochromics are based on the viologens, anthraquinones, diphthalocyanines, and tetrathiafulvalenes. With organic compounds, coloration is achieved by an oxidation-reduction reaction, which may be coupled to a chemical reaction. The viologens are the most studied of the organic electrochromics. Originally, organic electrochromics tended to suffer from problems with secondary reactions during switching, but recently more stable organic films are being developed. There is a considerable effort at Sony and Sharp in Japan and IBM in London and other investigators to develop a multicolor computer display screen using organic electrochromics (Elliott and Redepenning, 1986). The Gentex Co.(Zeeland, MI) has commercially developed organic electrochromic materials for automotive mirrors. This is the most commercially developed electrochromic product to date. New techniques for the electrodeposition of polymer electrochromics from solution have been reported by Toyota of Japan (Onishi, 1987). Uniform films of polythiophene, polyaniline and polypyrrole have been deposited by this oxidation polymerization technique. Polyaniline has recently become one of the favored organic polymer electrochromics (Jiang and Dong, 1989; Yang, 1990). Toyota is basing an automotive sun-roof on polyaniline.

The inorganic materials that have gained the most research interest are amorphous (a) and crystalline WO_3, MoO_3, and IrO_x, and NiO films. These compounds, among other transition metal oxides, are the subject of a few research reviews (Fanghan and Crandall, 1980; Dautremont-Smith,1982; Lampert, 1984; Oi, 1986; Donnadieu,1989; Lampert and Granqvist, 1990). A solid-state window device can be fabricated from five (or less) layers consisting of two transparent conductors (TC), electrolyte or ion conductor (IC), counter electrode (CE), and electrochromic layer (ED). Research is needed to develop better electrochromic materials with high cycle lifetimes, and short response times. New types of ion conductors and solid electrolytes also require development for this technology. The most promising ion conductors are certain immobile solvent polymer systems, ionic glasses and open channel structures such as Perovskites. Example electrochromic device structures are given in Table 6.1.1.

Table 6.1.1 Electrochromic Device Structures

Electrochromic	Ion Cond./Electrolyte	Ion Storage	Maker.
a-Li_xWO_3	$LiClO_4$+ PC	Redox Cple	Asahi
a-WO_3	Ta_2O_5	$Ir_xSn_yO_2$:F	Nikon
a-Li_xWO_3	$LiClO_4$+ PC	Prussian Blue	Nissan
a-H_xWO_3	Polymer	Polyaniline	Toyota
a-H_xWO_3	SiO_2/metal	WO_3	Schott
Viologen	PMMA+Organic	none	Gentex
a-WO_3	Poly-AMPS	Cu Grid	PPG
a-WO_3	Ta_2O_5	a-IrO_2	EIC
c-WO_3	Li-B-SiO Glass	IC/$Li_xV_2O_5$	EIC
a-WO_3	Li-PEO	CeO_x	St. Gobain
a-WO_3	MgF_2	Gold film	SERI
a-Li_xWO_3	PPG-$LiClO_4$-MMA	$Li_yV_2O_5$	Chalm. U.
a-H_xWO_3	Ta_2O_5	NiO	Donnelly
a-WO_3	Li-PEO	NiO	St. Gobain
NiO	a-PEO copolymer	Nb_2O_5, WO_3:Mo	LBL
Polyaniline	HCl		U.of RI.

Much of the current activity on electrochromic windows is for automotive applications such as sun roofs. This is an ideal entry market because of the smaller size and shorter lifetime required of the window, although the upper temperature limits are higher (90-120 C, according to desert static soak temperatures for cars). Automotive applications are discussed in Section 2. Several research groups are investigating electrochromic materials and devices. Asahi Glass (Yokohama, Japan) has introduced 30x30 cm prototype windows for testing and evaluation. Work is on-going at LBL to evaluate the thermal and daylight control properties of this window using the MoWiTT mobile window test facility (Klems, 1984). Energy performance data is shown for a 9 pane matrix of 30x30 cm Asahi electrochromic windows compared to a bronze single glazed window in Fig. 6.1.1. The electronically controllable window has a considerable cooling energy advantage over that of a conventional bronze window. In this test the daylight illumination level inside the test chamber was regulated by the window to a constant value. Energy modeling of electrochromic windows has shown that electrochromic windows can provide significant energy performance improvement conpared to conventional double glazed windows (Reilly, Gottsche and Wittwer, 1991).

The Asahi window uses Li^+ ions for coloration of amorphous WO_3, with a redox couple as part of the electrolyte (Nagai, 1986; Mizuhashi, Nagai and Kamimori, 1990). The optical response of this window is shown in Fig 6.1.2. The problem of the use of liquid electrolyte has been reduced by using UV or thermally curable acrylic polymer as a binder (Nagi, Kiyoya and Kamimori, 1989). This development could make the use of liquid phases significant in the manufacture of large-area devices while reducing the device fabrication cost. About two hundred (40x40 cm size) prototype electrochromic windows have been installed in the Seto Bridge Museum (Kojima, Okayama-Pref., Japan), shown in Fig 6.1.3. Also, 50 windows have been installed in the Daiwa House (Mita-city, Hyogo-Pref., Japan). The use of polymer electrolytes opens possibilities of exploiting the benefits of adhesiveness, making for a safer and stronger window. It is possible to construct the device with two separate glass or polymer substrates. Other groups have developed polymer electrochromic devices incorporating tungsten oxide (Andersson and Granqvist, 1990; Passerini et al., 1990) and Prussian Blue (Honda et al., 1988). The characterization and testing of electrochromic glazings are being carried out under an International Energy Agency Program (under Task 10 and Task 18) (Lampert, et al., 1991; Czanderna and Lampert, 1990).

Crystalline WO_3 offers near-infrared modulation, which has the potential to control the infrared portion of the solar spectrum. Crystalline WO_3 is being researched by several investigators (Cogan et al., 1985; Goldner et al., 1986; Goldner et al., 1987; Svensson and Granqvist, 1985). Peak near-infrared switching levels from 20% to greater than 75% was achieved with crystalline WO_3 (Goldner et al., 1989). The reflectance properties of tungsten oxide films produced so far seem to lie rather far from the theoretically limiting behavior. Studies on sputtered Li-W-O layer structure compounds for devices have been performed (Kitabatake, Hirochi, and Wasa, 1985; Hirochi, Kitabatake, and Wasa, 1986, Kaneko, Nagao and Miyake, 1988). Research has been conducted on plasma enhanced CVD deposited amorphous MoO_3 and WO_3 aimed at increasing coating deposition rates (Benson, 1985).

Electrochromic NiO is being developed by several groups (Lampert, Omstead and Yu, 1986; Yu, Nazri and Lampert, 1987; Svensson and Granqvist, 1987; Morisaki et al., 1988; Yamada et al. ,1988; Bendert and Corrigan, 1989; Yu and Lampert, 1989, Lampert, 1990, Wruck, et al., 1991). Nickel oxide devices using a polymer electrolyte are also being studied (Pennisi, Lampert, 1988; Ma, Yu and Lampert, 1991). An example of the optical response of electrochromic NiO is shown in Fig. 6.1.4. Further improvements in optical response are expected in the future. Under specific conditions the solar transmittance can switch from 74-37% and the visible from 75-24%, however even deeper coloration is possible. Pilkington with European partners under the 1990-93 EC Joule program are also involved in electrochromic materials developement.

There are many other candidate electrochromic materials, primarily among the transition metal oxides and among several classes of organic compounds. In fact, the study of "unconventional" inorganic or organic electrochromic materials will be a fertile area for research and development for years to come. The overall thermal performance of these windows is very dependent on the window design and placement of the layers. In an actual design to get the maximum benefit from the window, low emissivity layers may be required for thermal insulation purposes.

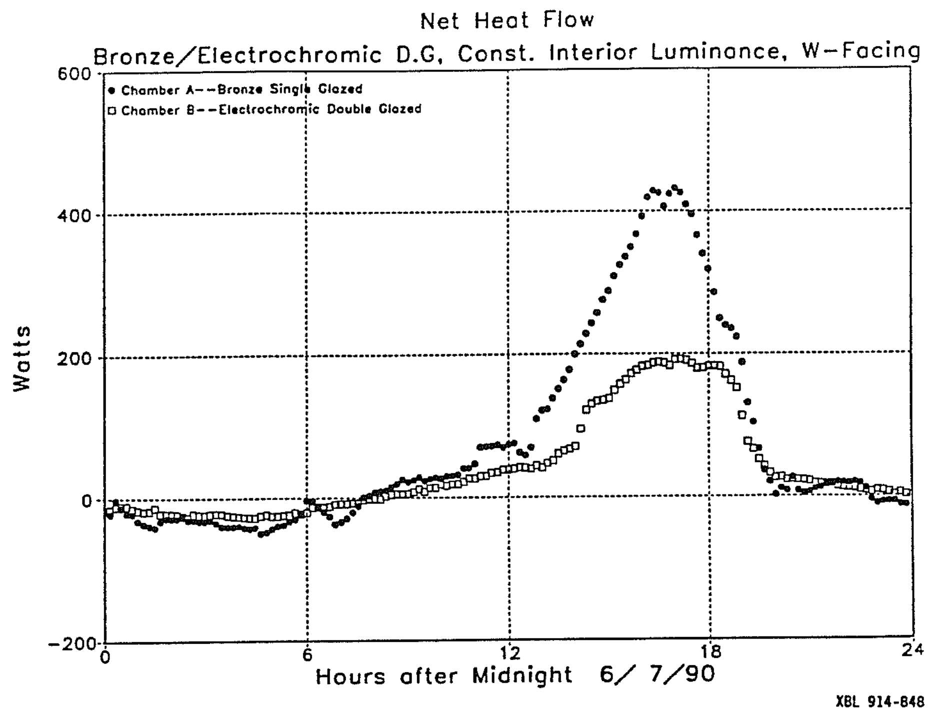

Fig. 6.1.1. Energy performance data is shown for a 3 x 3 matrix of 30x30 cm Asahi ECW electrochromic windows compared to a bronze single glazed window.

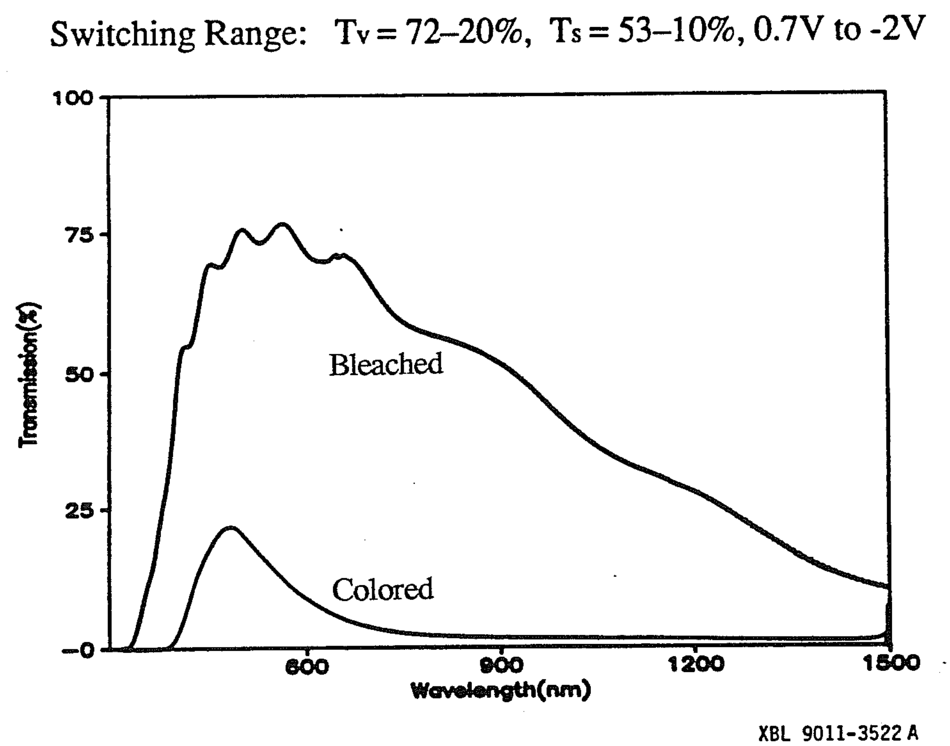

Fig. 6.1.2. Solar transmittance of an Asahi ECW electrochromic window based on tungsten oxide, using a lithium polymer gel electrolyte. Both the bleached and colored conditions are shown.

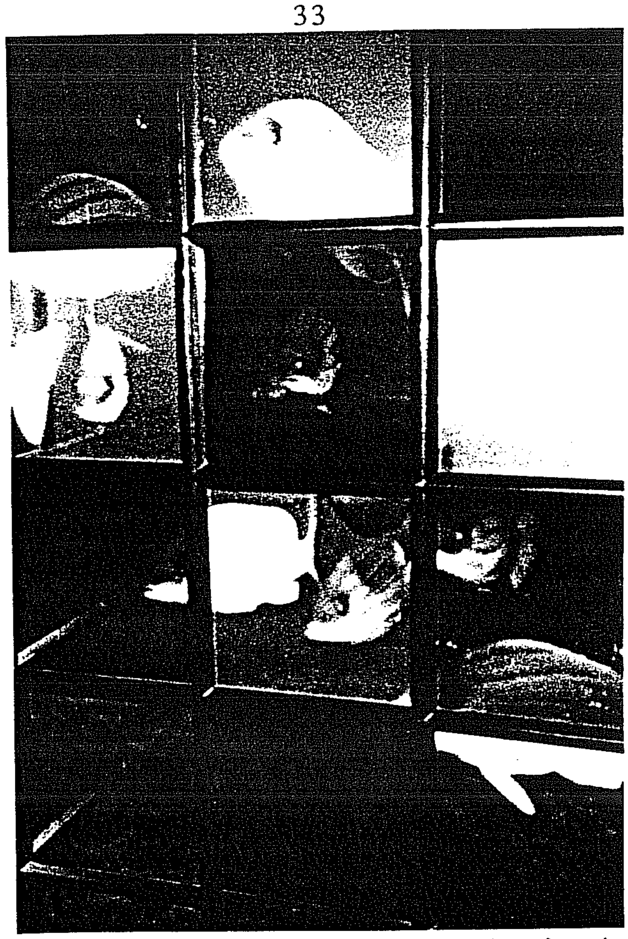

Fig. 6.1.3. Photograph of the inside of the Seto Bridge Museum showing Asahi ECW electrochromic glass windows.

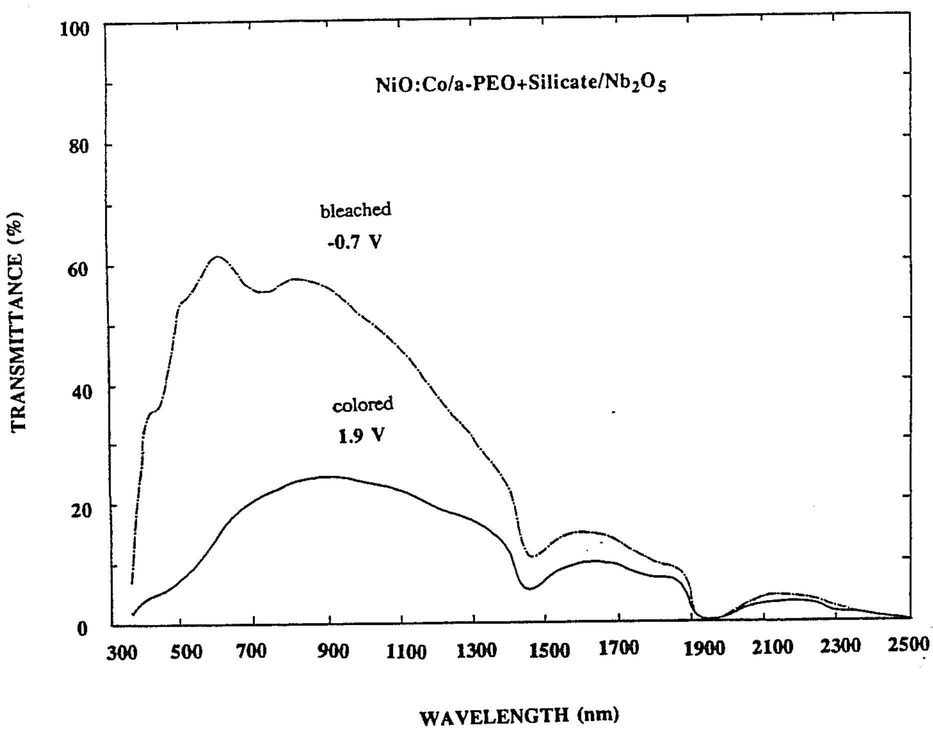

Fig 6.1.4. Solar transmittance of a LBL nickel oxide/niobium oxide electrochromic device using a laminated polymer ion conductor. This device colors to a deep bronze.

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6.2) Liquid Crystals

Liquid-crystal-based systems offer another approach to chromogenic electrically activated devices. The basic classes of liquid crystal light switching devices are the twisted nematic, guest-host, surface stabilized ferroelectric, and polymer dispersed liquid crystals. The mechanism of optical switching in liquid crystals is to change the orientation of liquid crystal molecules interspersed between two conductive electrodes with an applied electric field. The orientation of the liquid crystals changes with the field strength that alters the overall optical properties of the device (Chandrasekhar, 1977; de Gennes, 1974; Blinov, 1983). Open circuit memory is not possible with liquid crystals. The most widely used type for electronic displays is the twisted nematic type (Sherr, 1970; Bahadur, 1984). For windows, the twisted nematic type is not a good choice since it requires polarizers that reduce transmission and have fabrication size limitations, because of stringent gap spacing requirements. Twisted nematics have been used for electrically controlled welding goggles made by Optrel, AG, Wattwil, Switzerland. Recently considerable work has been done on surface stabilized ferroelectric liquid crystals. These are being developed for electrooptic switches by Displaytech Inc, Boulder, Co. They are bistable and switch in 0.15 mS with +/-15 V d.c., but unfortunately exhibit high contrast ratios (about 50) in a narrow temperature range. They are very difficult to manufacture. With further improvements in the liquid crystal it is expected that this type will become more useful.

The guest-host and polymer dispersed liquid crystals are the best choice for large-area glazing. The guest-host types use dichroic dye molecules mixed with liquid crystals (Heilmeier and Zanoni, 1968). The guest-host type is being developed mainly for display applications, but has been considered for optical shutter applications (Busturk and Grupp, 1990). The Cholesteric-nematic phase change guest-host type of liquid crystal has the greatest chance of being used for large-area optical switching. This type of liquid crystal switches by a field induced phase change. It exhibits a continuous gray scale operating from 2-12 a.c. with a contrast ratio of 5 and uses no polarizers. The upper temperature stability is 100 C. Guest-host liquid crystal devices are being developed by Asulab in Switzerland for eyeglasses and car mirrors. A car mirror based on this technology can switch R_v = 48-12% with switching times of 15 and 360 ms for on and off respectively. This has been possible with the development of improved UV and electrochemical stability of the liquid crystals by Mitsui Toatsu Chemicals, Japan and E. Merk, Corp., Germany.

The polymer dispersed liquid crystal (PDLC) or encapsulated liquid crystal (NCAP) consists of nematic liquid crystals distributed in microcavities (Drzaic, 1986).This cavity structure can give modulated light scattering known as the Christiansen effect. PDLC and NCAP materials have very similar characteristics but are defined in the patent literature differently according to preparation procedure. NCAP films are formed from an emulsion and PDLC films are formed from an isotropic solution which phase separates during curing. General Motors Research Labs and Kent State University (Kent, OH) are developing PDLC technology for automotive glazing (Montgomery, 1990).

Currently plans for production of glazing devices are being made. The typical solar and photopic transmission and reflectance hemispherical values for a PDLC device are $T_{s(off-on)}$= 53-77%, $R_{s(off-on)}$=20-14%, $T_{v(off-on)}$=48-76% and $R_{v(off-on)}$27-18%.

Devices based on NCAP (nematic curvilinear aligned phase) technologies are being produced by Taliq (Sunnyvale, CA) as optical shutter materials for glazings and information displays (known as Varilite and Vision Panel). Nippon Sheet Glass markets this product in Japan as the "Umu" Device. At least two other major companies in the U.S. are developing NCAP automotive sunroofs. Large-area devices have been fabricated in 1 m x 2.5 m sheets. With NCAP the liquid crystals are encapsulated within an index matched polymer matrix. The composite polymer is fabricated between two sheets of ITO coated polyester that serves as electrodes. The device can also be fabricated between one sheet of glass and one sheet of plastic or two sheets of conductive glass. The switching effect of this device spans the entire solar spectrum, up to the absorption edge of glass. In the off-state, the device appears translucent white. Since the off-state in these devices is diffusely transmitting the device has application for privacy and security. An example of its optical properties is shown in Fig. 6.2.1. The hemispherical transmittance property of a dyed NCAP device is shown in Fig. 6.2.2. The dyed film shows considerable control over visible transmittance compared to the undyed film in Fig. 6.2.1. When an electric field is applied, the liquid crystal droplets align with the field and the device becomes transparent (Fergason, 1985). Typically these devices operate between 50-100 V a.c., (potentially 20 V in the future) at less than 20 W/m^2 but require continuous power to be clear. Pleochroic dyes can be added to darken the device in the off-state (van Konynenburg, Marsland and McCoy, 1989). In general, compared to electrochromics, the power consumption is higher because of the need for continuous power in the activated state. Dispersed liquid crystal devices have a very good future but are restricted by three characteristics: the unpowered state is diffuse, haze remains in the activated (transparent) state and UV stability is poor. Many of the devices made to date are used in interior building applications. The residual haze problem can probably be alleviated by better control over the formation and processing of the liquid crystal emulsion. The UV stability is being improved. For widespread use of NCAP devices the cost will have to decline.

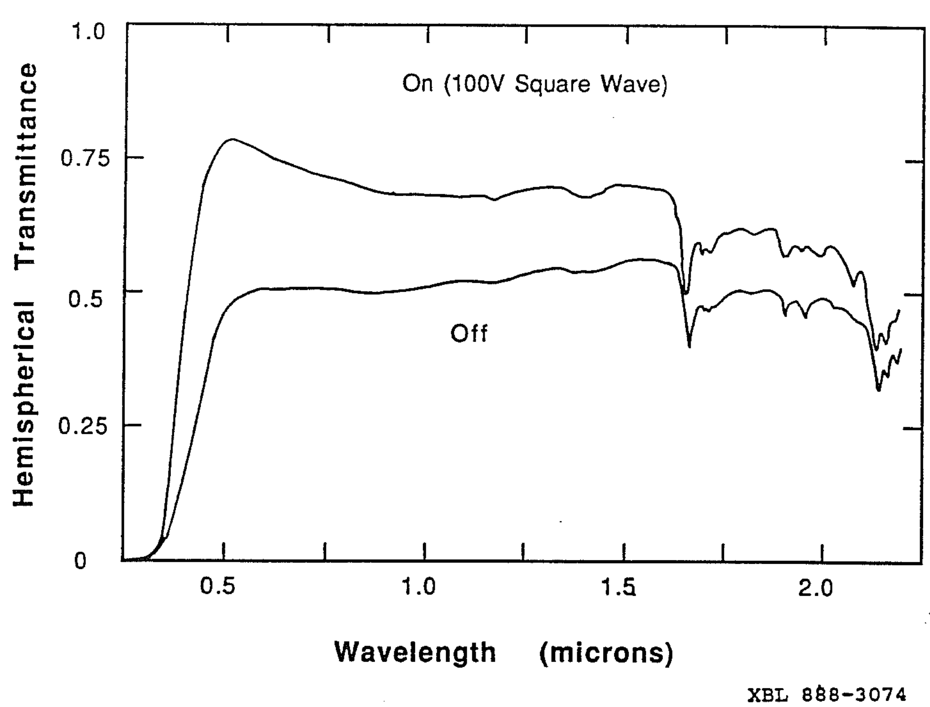

Fig. 6.2.1. Hemispherical transmittance of an undyed Taliq liquid crystal window film. Both the fully transparent (on at 100 V) and fully scattering (off at 0V) states are shown.

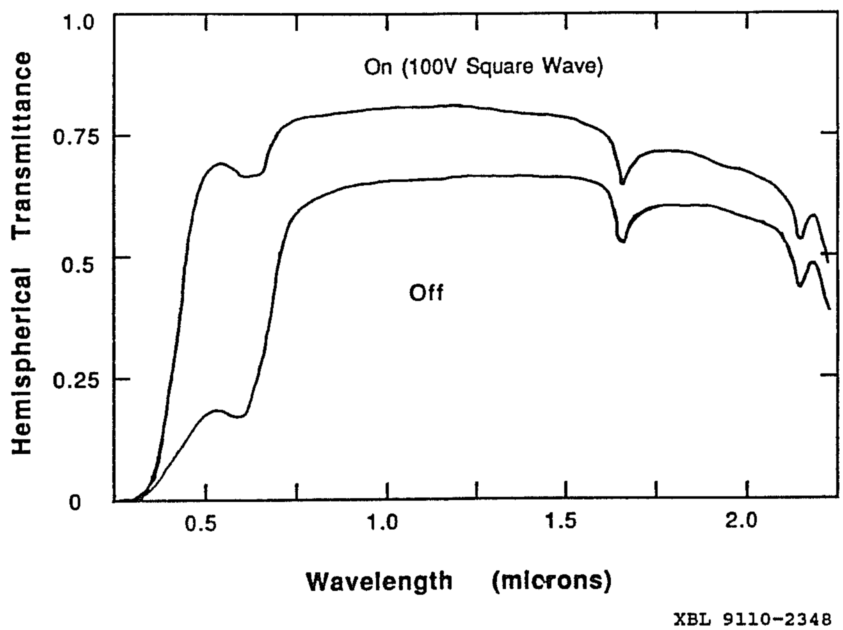

Fig. 6.2.2. The hemispherical transmittance properties of a dyed NCAP window made by Taliq. Both the fully transparent (on at 100 V) and fully colored scattering (off at 0V) states are shown. The color is grey.

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6.3) Suspended Particles

The development of suspended particle or electrophoretic devices have spanned several years. Their development has been slowed by a number of technological problems including long-term stability, cyclic durability, particle settling and agglomeration and gap spacing control for large-areas. In recent years many of these problems have been reduced or controlled (Thompson and Saxe, 1978; Beni et al., 1981; Saxe, 1988). Commercial development of these devices for eye glasses, goggles and windows is being done by Research Frontiers (Plainview, NY).

A suspended particle device consists of 3-5 layers. The active layer has needle shaped particles of polyiodides or paraphathite (1μm long) suspended in an organic fluid or gel. This layer is laminated or filled between two parallel conductors. In the off-condition the particles are random and light absorbing. When the electric field is applied, the particles align with the field, causing transmission to increase. Typical transmission ranges are 20-60%, 10-50%, 0.1-10%, with switching speeds of 100-200 ms. The voltage required for the device depends on thickness and ranges from 0-20 to above 150 V a.c. An interesting version of this technology is being developed by Nippon Sheet Glass in Japan. They have combined particles inside a polymer droplet (Tada, 1990). This idea has merit if scattering can be reduced in the on-state.

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6.4) Photochromic Materials

Photochromic materials have a place in advanced glazings. They have passive switching properties that only require UV light to darken them (Smith, 1967). For glazings there are two types of photochromic materials: photochromic glass based on metal halides and photochromic plastics. There exist other classes that have not been explored for glazings and building skins. They are dispersed photochromic inorganic compounds in plastics and paints and photochromic polymers that can be used for coatings (Chu, 1977). Another possibility is photochromic insulating aerogels. Still another is photochromic glass coatings made from solgels. There has been some experimentation with silica-silver chloride gels (Hoffman, Komarneni and Roy, 1984).

Photochromic materials change their optical properties when exposed to light and revert to their original properties in the dark. Generally, photochromic materials are energy-absorptive. Basically, the phenomenon is the reversible change of a single chemical species between two energy states having different absorption spectra. This change in states can be induced by electromagnetic radiation. Scientific discussions of photochromism date back to the 1880's. The phenomenon is widespread and occurs in many organic and inorganic materials (Brown, 1971). Photochromic materials have been reviewed by several authors (Brown and Shaw, 1961; Exelby and Grintner, 1964; Smith, 1967; Dorion and Wiebe, 1970; Durr, 1990).

Probably the best known photochromic material is photochromic glass for ophthalmic glasses and goggles (Hoffmann, 1990). Suitable inorganic compounds include HgCNS, HgI_2, Li_3N, TiO_2, ZnS, and alkaline earth sulfides and titanates. Many of these compounds are not pure phases as they require additions of a heavy metal or halogen such as AgCl or AgBr, to be photochromic. Special heat treatment of photochromic glass causes the formation of silver halide crystals of about 15 nm in size to exhibit the photochromic effect. UV energy of wavelength between 300-400 nm causes the crystals to breakdown into metallic silver and the halide. This effect causes visible absorption to take place. When the UV light is removed, the metal-halide molecule recombines by thermal processes and the glass becomes more transparent. Glasses that exhibit photochromism are hackmanite, silver halide Ce, and Eu doped glasses. Photochromic glasses have been developed for ophthalmic use by companies including Pilkington (UK), Corning Glass (Sullivan Park, NY); Schott Glasswerke (Mainz, Germany); Asahi Glass (Yokohama, Japan). These glasses are the most widely known of all photochromic materials (Araujo, 1982; Panysheva, 1984). The typical optical response for a photochromic glass in the bleached and colored state is shown in Fig. 6.4.1. Corning products are known as Photogray and Photobronze. The glass shows good durability and fatigue-resistance during color/bleach cycling (Araujo, 1980). Photochromic glass has also been developed by Desag (Germany). Typical values for Photosolar Super gray-brown eyeglasses are T_v(uncolored) = 89% and T_v(colored) = 26%. Fading of the colored state to about T_v = 57% takes 3-4 minutes at room temperature (Lowitzki, 1988). A typical solar value might be T_s = 85-50%. Photochromic glass is not presently produced in sufficient sizes to allow its use in buildings and cars. Fairly large, thin prototype sheets (approximately 1 m^2) have been made by Corning for use as a glass laminate to regular float glass. To be effective the photochromic glass must be at least 1 mm thick. Lamination is one of the ways to reduce the cost of the glass. The glass is now manufactured by rolling, drawing and fusing, followed by a special heat-treatment process. The float process has not been demonstrated for photochromic glass. As soon as there is sufficient demand, photochromic float glass could become a reality. This assumes the processing conditions could be met. Durability under extended color/bleach cycling, and resistance to chemical attack, are excellent for photochromic glass.

Photochromic organic compounds include certain dyes, stereoisomers, and polynuclear aromatic hydrocarbons. Photochromism in organic materials is associated with heterolytic and homolytic cleavage, cis-trans isomerisation and tautomerism. A photochromic plastic has been developed by American Optical Corp. (Southbridge, MA) using derivatives of spiroinodolinonaphthoxazine dissolved in a plastic matrix material (Chu, 1986; Chu, 1990). Its spectral properties are shown in Fig. 6.4.2. Following these developments, PPG introduced in 1991, a new line of plastic photochromic eyeglasses called "Transitions". The polymer host material is CR-39 poly(diethylene glycol bis(allyl carbonate)). This material has been developed for ophthalmic use but with future research may become useful for energy regulating glazings for solar energy control. A few patents have been filed concerning this application (Washida, 1984; Rickwood and Hepworth, 1987). Photochromic plastic and electrochromic windows were used in the GE all-plastic model house (Lees, 1988). Improvement is needed in durability, and the loss of photochromism at elevated temperature should be reduced.

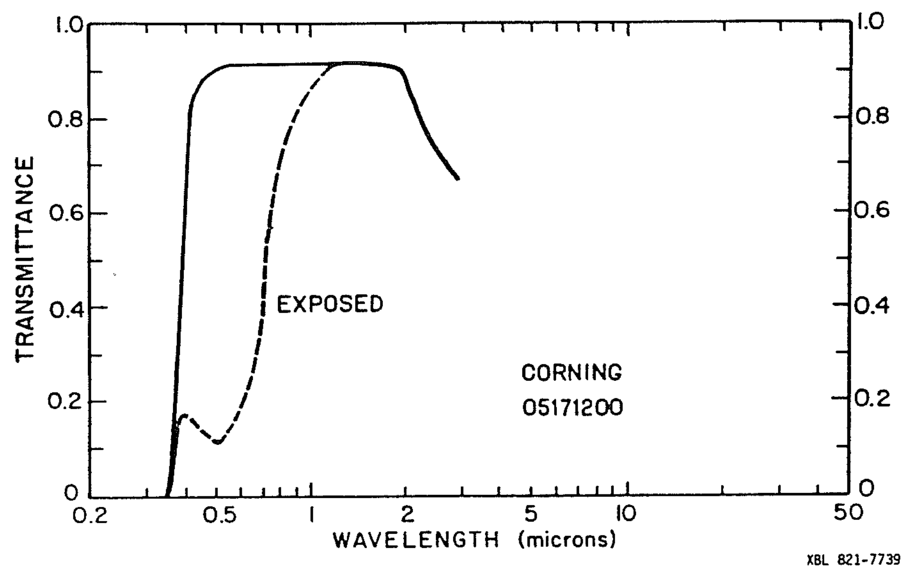

Fig. 6.4.1. The near-normal solar transmittance properties of a Corning photochromic glass.

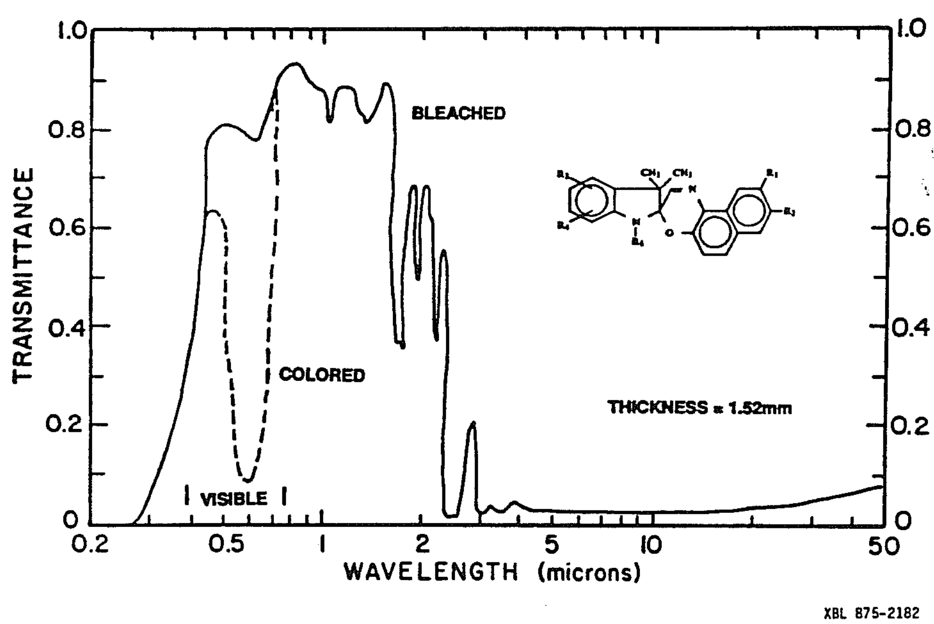

Fig. 6.4.2. Normal solar transmittance properties of an American Optical spiro-oxazine photochromic plastic.

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6.5) Thermochromic Materials

Thermochromic materials show a large optical property change with change in temperature. They return to their original properties when cooled to the starting temperature. Systematic studies of this phenomenon date back at least to the 1870's. Thermochromic materials change their properties by going through a thermally induced chemical reaction or by a phase transformation. Thermochromism can be due to equilibria between different molecular species, cis-trans isomerisation, crystal phase transitions, etc. Thermochromism is seen in a large number of organic compounds (Day, 1963, Day, 1977; Day and Willett, 1990). Organic compounds in the anil, spiropyrans, polyvinyl acetal resins, and hydroxide groups exhibit thermochromism. Many compounds have been formulated for paint and microencapsulated compositions for color copying paper and for fabric that change color with body temperature. Another common use is for inks that change color with temperature as indicators. Thermochromic materials are used for document security. Another interesting material is thermochromic fluorescence, where a material will change its fluorescence emission wavelength with temperature (Day and Willett, 1990). Thermochromic gel polymers are being developed for window applications (Germer, 1984; Boy and Meinhardt, 1988; Rozova, 1986). Fig. 6.5.1 shows the optical properties of a polymer gel material for a window application. Also, the Suntek Co. (Albuquerque, NM) is developing a cloud-gel thermochromic window. The thermochromic gel polymers also offer some interesting possibilities for glazings if they can be made to be UV stable.

Reviews have been written on thermochromism in inorganic compounds (Day, 1968; Sone and Fukuda, 1987). Inorganic thermochromic compounds include AgI, Ag_2HgI_4, Cd_3P_3Cl, HgI, HgI_2, $SrTiO_3$, along with several cobalt, copper and tin complexes (Day, 1977). Inorganic fiber/liquid composites (Andersson et al., 1987) can show thermochromism using the Christiansen effect.

Of considerable interest are thin films of certain transition metal oxides and related compounds, which transform from semiconducting to metallic state when a certain "critical" temperature is exceeded (Adler, 1968). These are known as the Mott transition compounds (Mott, 1974). Such materials, when perfected, can be used to control both the solar transmittance and infrared emissivity of a glazing or surface. Some of these compounds are Fe_3O_4, $FeSi_2$, NbO_2, NiS, Ti_2O_3, Ti_4O_7, Ti_5O_9, VO_2, and V_2O_3 (Adler, 1972). The key issues concerning these compounds are control or modification of the transformation temperature, transmission in the bleached state and magnitude of the optical density change and electron concentration change after switching. For window applications some research has been done on VO_2 (Babulanam et al.,1987). By substitutional doping of vanadium in VO_2, alteration of the transformation temperature can be achieved. Compounds of $V_{1-x}W_xO_2$ have shown large changes in transition temperature but unfortunately smaller changes in conductivity during switching compared to VO_2 (Jorgenson and Lee, 1986; Jorgenson and Lee, 1990).

It may be possible to directly incorporate thermochromic materials into polymer films and coatings. Such materials could have a wide use in shading devices and greenhouse glazings. Inorganic thermochromic coatings have a potential for being developed so that they can be used in large-area devices. Vanadium-dioxide-based materials seem to be the best ones. Their metal-insulator transition should be close to a comfort temperature. By combining different methods for diminishing the metal-insulator transition temperature and for lowering the luminous absorptance, a practically useful thermochromic coating, suitable for large-area devices, could be developed.

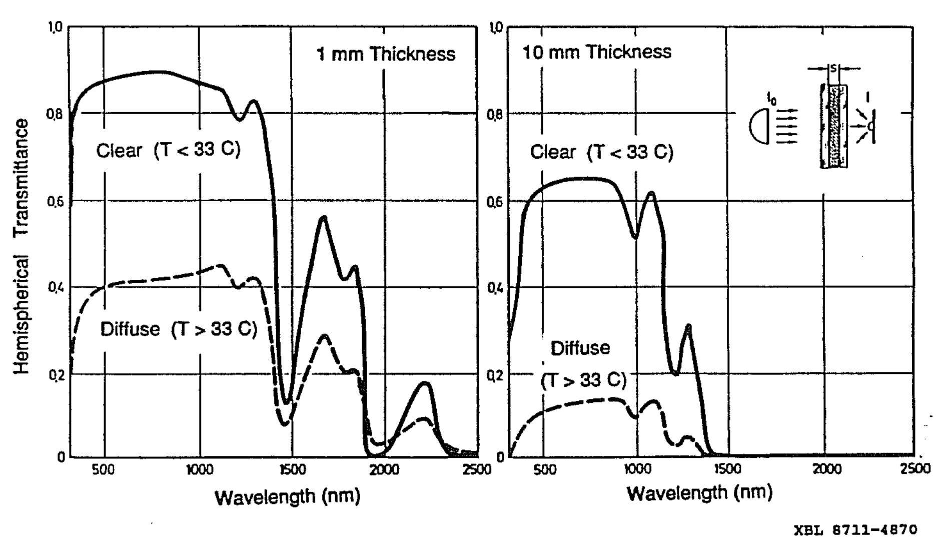

Fig. 6.5.1 Optical properties of the TALD thermochromic polymer gel window.

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6.6) Electronic Control Technology

Electronic control technology is very important for the proper application of electrochromic or liquid crystal glazing. Although a central control system may be used to set the window for the best energy savings or follow a master plan, local control is equally important for view windows. To have local control, it is possible that the driving electronics will be integrated onto the glazing. Either a photoelectric or photovoltaic could be used for sensing. A photovoltaic array could also be used for the activation of the window. The future control system will probably be interactive, smart, learning neural networks using fuzzy logic. Currently, fuzzy logic systems are being developed in Japan for manufacturing processes and control system for the control of electric passenger trains. These fuzzy logic systems have many levels of gray or fuzzy logic that can make decisions regarding the magnitude or probability of necessary change, using a variety of sensor information. This type of control system could be applied to buildings which monitor temperature and light profiles, office use and time of day and incorporate any changes that might occur. Neural networks can learn and modify their own programs by many environmental factors. For example several different types of businesses may occupy an office building, but because of differences in the business of each one, they may have different requirements for solar energy, light, heating, and cooling control. Also, they could have differences in the level of security, fire safety and internal communication. A neural network can learn to adapt to these changes (Farhat, 1989). These systems also tend to be fault tolerant and adaptive, giving a much higher degree of reliability compared to simple digital or analog control systems. Complete optoelectronic systems are being developed. Currently small-scale prototypes using non-volatile spatial light modulators are being applied to form neural networks with capabilities including associative storage and recall, self organization and adaptive learning (self-programming) and fast solution of optimization problems (Farhat and Shae, 1989). Further developments rest on the refinement of totally integrated electrooptic chips. Currently the Japanese are developing this type of chip for optical communications (Shabata and Kajiwara, 1989). It is also expected that fast efficient algorithms for neural networks will be developed.

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Prof. Nabil H. Farhat, University of Pennsylvania, Electrical Engineering Dept., Philadelphia, PA.

Journals of Neural Networks and Neural Computation.

7) TRANSLUCENT AND TRANSPARENT INSULATION

Translucent insulation or transparent insulation is composed of solid and granular silica aerogel, a low density glass and a variety of cellular polymers. The cellular polymers are usually a honeycomb, capillary or closed cell construction. The generic types of transparent insulation are shown in Fig. 7.1. These polymers are not to be confused with conventional foamed polymers, which are generally considered to be opaque. Silica aerogel in a sheet form does have some unique advantages because it has high clarity in its transmission and does not have highly oriented properties. All other products tend to have strongly oriented structures with a high amount of scattering or diffuse transmittance. These materials can be used in a variety of ways as windows, skylights, solar collector covers and as opaque wall insulation. The latter application is being widely investigated in Europe. A future area of development, is an aerogel analog using a polymer media that can develop a network skeleton structure.

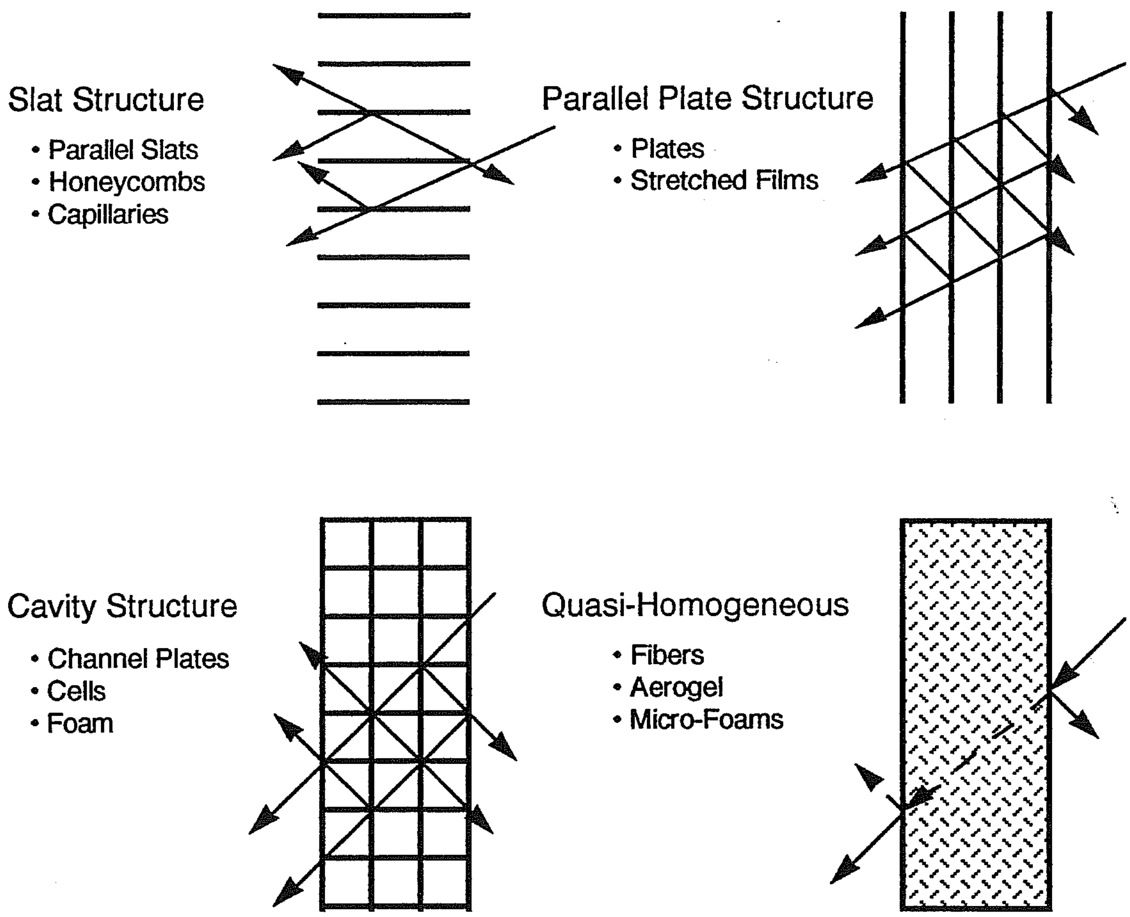

Fig. 7.1. Four generic types of transparent/translucent insulation structures (XBL 9111-2429)

TIM materials have thermal properties rather different to conventional opaque insulation materials, e.g., the equivalent thermal conductivity (k_e) is dependent on the thickness of the sample. Also optical properties are different to conventional glazing units, e.g., some materials have coarse structures with dimensions of several millimeters, they are up to 15 cm thick and very often show scattering. Honeycomb structures also split up the incoming beam radiation in a complicated manner. This leads to problems when measuring the thermal and optical properties of these materials. Measurement schemes that have been developed for other materials do not necessarily qualify for transparent insulation materials.

Although there are many different material types, a classification can be given (modified from Platzer, 1988). One may classify the materials according to the nature of the optical path of an incoming beam. Clear glasses for instance can be viewed without distortion of images on the other side, but diffusing structures can not. Also, there are materials structures that preserve the incidence angle but still do not allow a clear view. Both criteria are physically meaningful, but there is a continuum of materials between the extreme cases. However, mixed types also exist with respect to the optical behavior. A honeycomb structure produced from weakly scattering plastic films does not fully preserve the incidence angle for the transmitted beam, but also has a small diffusing component. A classification according to the geometric structure of the materials is very useful. Four generic types are defined, which show different physical behavior and include most real materials (Fig. 7.1).

One of the best known is the Parallel-Plate structure with multiple glazings or plastic films, which may be either transparent or translucent. The specular multiple glazed window even fits in this category (even though it is not considered translucent insulation). The Geilinger (Winterthur, Switzerland) super window is an example. High optical reflection losses prohibit the use of a large number of layers. The glass panes or plastic films have defined temperatures (approximately constant), but because of convection in the gaps between, a one-dimensional temperature distribution cannot be given.

The Slat structures include honeycomb or capillary materials with different cross-sectional geometry, and slit structures (plastic films stretched parallel across the glazing). As the incoming beam is reflected and transmitted by the structure walls towards the absorber, optical losses are very small. Only a little scattering and absorption within the films reduces the overall transmittance. For clear films with low absorption, the transmission properties are nearly independent of the material thickness, therefore very thick samples may be used. Contrary to the first type, the Parallel-Plate structures, convection can be suppressed, if the aspect ratio is chosen well.

If the previous types are combined, one gets a cavity structure, represented by transparent multiple duct plates or transparent foam with bubble sizes on the order of millimeters. From the optical viewpoint these materials have approximately the same transmittance as an equivalent multiple film cover. Reflection is the dominant loss mode. However, they have the advantage of being even more effective in suppressing convection losses, but conduction paths are increased over the first two structure types.

Quasi-homogeneous layers are characterized by similar optical properties, but the loss mechanisms are namely scattering and absorption. Aerogel, a microporous silica foam, belongs to this class. Because of pores with sizes of some 10 nm, light is scattered within the material, comparable to the Rayleigh scattering of blue sky. This structure is very effective in the reduction of convective loss. Glass fiber materials do not have this homogeneity, but they can be treated and analyzed with similar methods.

For each of the four generic types, theoretical approaches exist which satisfactorily describe the basic features of the materials. Of course, transition materials exist which cannot be strictly classified. Folded or V-corrugated films are one example. If the corrugation angle is small, the glazing behaves essentially like a Parallel-plate material; if the angle is large, it behaves nearly like a Slat structure. Honeycomb structures with cells not vertically oriented with respect to the glazing plane are a transition between the Parallel-plate and the Cavity structure type. Nevertheless, the generic types provide a useful approach to classification of these materials. The energy modeling and optical characterization of these materials still requires considerable work. It is expected that in the future more of these materials will be used in the development of super glazings. An evaluation has been made of several transparent insulation materials for building facades (Van Dijk et al., 1990; Wittwer and Platzer, 1990) Interlaboratory testing is currently being performed on these materials under an International Energy Agency project (Task 10C-Glazings) (Platzer, 1990).

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7.1) Aerogel

One of the major drawbacks of conventional windows is their high thermal loss characteristics compared to building walls. Transparent low-emissivity surface treatments and modified window design can do much to lower the radiative portion of heat transfer (covered in Section 8). Another way of decreasing overall heat lossis to reduce overall conduction through the glazing. An example of this approach is to develop a highly transparent material that by virtue of its bulk macro or microstructural properties has low thermal conductivity. Aerogel is such a material. Its properties have been investigated and reviewed by several authors (Rubin and Lampert, 1984; Mazur and Lampert, 1984; Fricke, 1985; Russo and Hunt, 1986; Henning, 1990). The commercial manufacturers of monolithic aerogel are Airglass (Lund, Sweden) and Thermalux, L.P. (Richmond, CA). The commercial cost of producing monolithic aerogel is as little as 20 US$/m^2 (2$/ft^2) (Kahn, 1991). Granular aerogel is made by BASF in Germany and Monsanto in the U.S. Other types of aerogels exist; recently the first organic aerogel was made at the Lawrence Livermore Lab (Livermore, CA) consisting of carbon, hydrogen and oxygen.

Silica aerogel is close to being a specular transmitting insulating material. This material has a microstructure of bonded fine silica particles surrounded by porous microcells. Aerogel is a microporous structure with pore size of approximately 10 nm. Only 2-5% of the volume is solid silicate with 95-98% filled with air. The thermal conductivity of aerogel is lower than still air because the microcells are smaller (their diameter is less than 10 nm) than the mean-free-path of an air molecule (about 66 nm). Since most of the particles are smaller than a wavelength of visible light, they are not strongly scattering. However, one effect of the microporosity can be the scattering of light in the visible, so to obtain a transparent areogel the microstructure has to be closely controlled. Density fluctuations of the closely packed scattering centers produce a spectral and angular scattering distribution very close to Rayleigh scattering, resulting in a small amount of haze. However, haze can be effectively reduced by process control. Aerogel has optical properties similar to silica glass except that the index of refraction ($n = 1.03$-1.1) is much lower than glass. The optical spectra for aerogel made by two methods is shown in Fig. 4.1.1. This material has been modeled optically by Rayleigh Theory. Silica aerogel is made by producing a colloidal silica gel from hydrolysis and a polycondensation reaction of an orthosilicate. This gel is solidified into the form of its mold by CO_2 substitution for the alcohol solvent, followed by supercritical drying. This chemical process was developed by Tewari, 1985, and Russo and Hunt, 1986. The advantage of the CO_2 substitution process is that much lower temperatures and pressures can be used to form the aerogel making it a much safer, economical and faster process. The disadvantage of aerogel is that it must be protected from shock and moisture. It is possible to form aerogel between two sheets of glass to make a window. The volumetric density of aerogel is around 135 kg/m^3.

For a window of aerogel (20 mm thick), the thermal conductance (U) is calculated (Rubin and Lampert, 1984) to be about 1 W/m^2K (0.176 Btu/h ft^2°F or thermal resistance R=5.7). For a double glazing without aerogel (20 mm spacing), U = 2.8 W/m^2K (0.49 Btu/h ft^2°F or R=2). The solar hemispherical transmission properties for aerogel are better than $T_S = 0.67$ (20 mm thick) and $T_S = 0.9$ (5 mm thick). The thermal properties for aerogel used in different window designs are shown in Fig. 7.1.2. A very low thermal conductance of U = 0.5 W/m^2K (0.088 Btu/h ft^2°F or R=11.4) can be achieved for a double glazing by evacuating the aerogel to about 0.1 atm. (Buttner et al., 1984; Hartmann, Rubin and Arasteh, 1987). An evacuated monolithic aerogel window of 0.57 x 0.57 x 0.2 m has been constructed at the Thermal Insulation Laboratory in Denmark (Jensen, 1990).

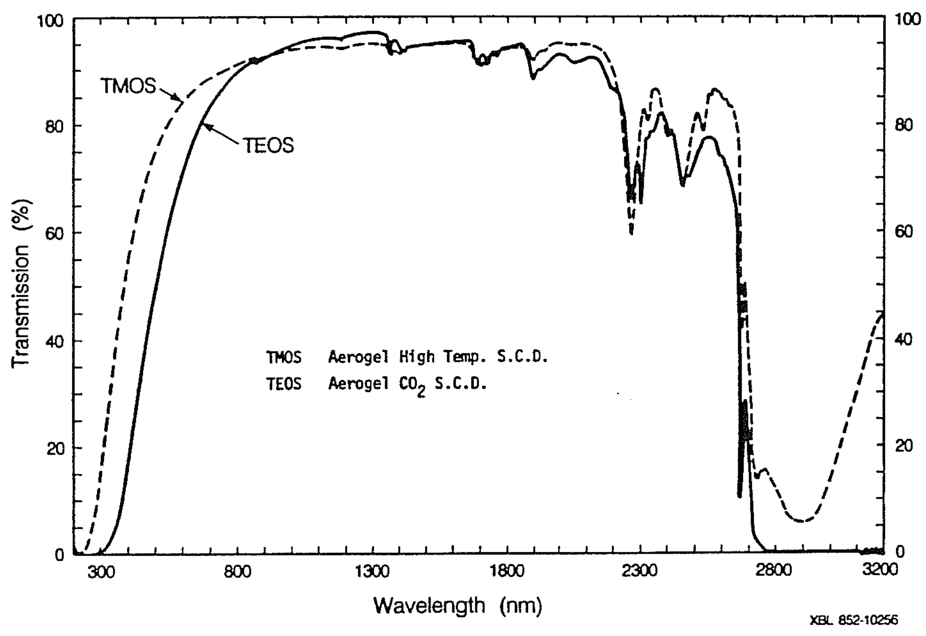

Fig. 7.1.1. The hemispherical transmission properties of silica aerogel.

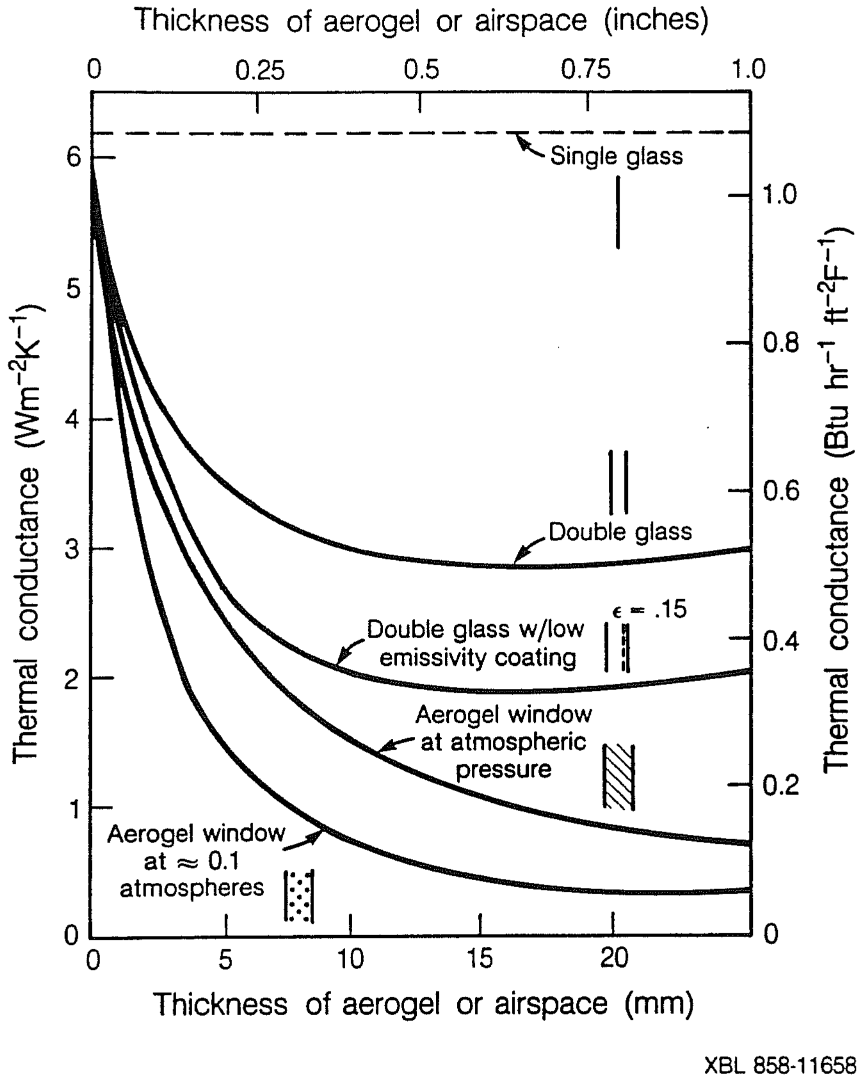

Fig 7.1.2. The thermal properties of different silica aerogel windows compared to conventional window types as a function of aerogel thickness or airspace. The best performing window is the one with aerogel under a partial vacuum (0.1 atmospheres).

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7.2) Polymers

Different polymeric materials with macrostructures containing open or closed cells and oriented micro-channels have been experimented on as translucent or transparent insulation. (TIM) (Platzer, 1987; Pfluger, 1987). There has been considerable interest in the development of translucent insulation in Europe as thermal insulation for windows and walls. Although these materials generally provide a distorted view for window applications they can be used for building insulation or skylights. Also, these materials can be used for the insulation of solar collector covers and thermal storage tanks. Many types of microstructures exist ranging from capillaries to honeycombs to cavity structures. These materials are typically made from polycarbonates and acrylic polymers. U values of 0.8 W/m^2K (0.141Btu/h $ft^2{}^\circ F$) have been achieved with diffuse transmission values of greater then 70%. (Wittwer and Platzer, 1990) Measurement techniques for these optically complex materials are being developed at the Fraunhofer-Institute for Solar Energy Systems (Freiburg, Germany) (Platzer, Apian-Bennewitz and Wittwer, 1990). The morphological effects on the transparency of these materials have been studied (Alexander-Katz, 1990).

TIM materials combine high solar transmittance with good heat insulation properties when compared to conventional single or double glazings. Of course it is difficult to give an exact criterion when a material is belonging to that class. A certain number of research type materials exist and some of them are sold commercially (e.g., AREL polycarbonate honeycombs, OKALUX capillary structures). The materials available have solar transmittance values for diffuse irradiation of about 0.4 to 0.7 including necessary cover glazings and U values of 0.7 W/m^2K to 2.0 W/m^2K (0.12-0.35 Btu/h $ft^2{}^\circ F$).

The Israeli AREL polycarbonate honeycomb structure with approximately square cross-section of the cells is commercially available. The structure has cell widths of about 4.5 mm, cell walls between 20 and 100 micron (mean thickness 55 micron) and a volumetric density of approximately 36 kg/m^3. The structure is produced from many tube strips (4 cells for 16 mm strip thickness) which are glued or thermally molten together. For an IEA round-robin test, AREL sample thicknesses of 5 cm and 10 cm were evaluated (Platzer, 1990).

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8) WAVELENGTH SELECTIVE MATERIALS

8.1) Transparent Low-Emissivity Coatings

Transparent low-emissivity or low-e, coatings continue to be developed and will in the future play a major role in reducing radiative heat transfer (Lampert, 1981; Kostlin, 1982; Lampert, 1982; Glaser, 1989). The major trends in low-e coatings are the development of selective low-e coatings that reduce the radiative portion of heat transfer for architectural and vehicle windows. With increasing concerns over the destruction of the atmospheric ozone layer by chlorinated fluorocarbons (e.g., freons) there is growing pressure to reduce air conditioner size and use, especially in cars. Air conditioner redesign and substitute refrigerants will solve part of this problem but coatings appear to be the most viable solution since they can reduce the existing problem at the glazing. This is very important for the reduction of solar heat gain.

Other developments are occurring in the durability of multilayer thin film coatings and the design of color into these coatings. In the future, we will see a range of very well tuned low-e coatings suited both in performance, durability, and color for their specific application. We expect this coating to be fully integrated into future glazing technology. The low-e coating has also importance to greenhouse windows (Brambly and Goder, 1982), transparent electronic conductors for defrosting windshields, electrochromic devices and liquid crystal devices. For greenhouse windows an example commercial product is Hortaplus glass made by Glaverbel (Belgium). For transparent conductors we expect to see properties improve and costs to fall as large-area processing techniques begin to be used for electronic grade coatings. Because this is an important subject we will go into some detail on the technology. For reference, a number of commercial glazing optical properties are shown in Fig. 8.1.1. Both uncoated glass products are represented with durable (pyrolytic tin oxide) coated low-e glazing and nondurable (D/M/D) coated low-e glazings (Rubin, 1990). The highest visible selectivity is shown for the point with the highest visible transmittance and lowest shading coefficient.

Low-e is defined as a coating that is predominantly transparent over the visible wavelengths (0.3-0.77 µm) and reflective in the thermal infrared (2.5-100 µm). In the near-infrared (0.77-2.5 µm) the coating may exhibit combined properties depending upon design or application requirements. A selective low-e film will show a strong transmission cut-off at 0.77 µm and a strong reflection cut-on at 0.77 µm. Low-e films for windows derive their usefulness from their low thermal emissivity (or high reflectance) in the infrared. The lower the emissivity, the less the magnitude of radiative transfer by the window. The emissivity of glass is $e = 0.84$; many plastics also have high emissivity values. The selective coating is useful to reduce solar heat gain loads in cars and buildings. Much of the solar infrared energy (0.77-100 µm) is reflected to help reduce needed air conditioning capacity and overall cooling loads. The coating allows only transmission of visible energy through the window. Several companies are developing selective coatings for vehicles. A selective windshield of the GM (Warren, MI) APV Van is being designed by PPG (Pittsburgh, PA). LOF (Toledo, OH) is developing a selective windshield for the GM Corvette windshield. Also, Ford Glass (Dearborn, MI) is developing selective windows for automotive use. Asahi Glass is working with Japanese automakers in selective glazing.

Transparent low-e films can be classified into two categories: multilayer dielectric/metal/dielectric (D/M/D) or (D/M/D/M/D), and highly-doped semiconductor films. These categories are becoming less defined as semiconductor films are used more in multilayer designs. Multilayer films have an advantage of broad wavelength tunability over the doped semiconductors. Doped semiconductors have the advantage of durability. Characteristics are shown for typical window configurations using low-e coatings in Table 8.1. The design and theory of D/M/D films are well understood (Liddell, 1981; Eckertova, 1986; Macleod, 1986). Historically, the D/M/D films are not durable enough in window designs to be used on exposed surfaces because of atmospheric corrosion problems. However it may be possible to make this class of coating more durable by better material design. Multilayer D/M/D low-e coatings are typically deposited on glass and plastics by physical vapor deposition (PVD), which includes vacuum evaporation and sputtering techniques. Also, solgel deposition has been used for the formation of the dielectric oxide layer (Chiba, 1973). The wavelength selective properties of D/M/D films are derived from both the optical properties of the metal and dielectric layers and the interference effects caused by the film stack. Metal films less than approximately 10 nm thick exhibit partial visible and solar transparency. The optical properties of thin metal films have been determined for a range of thicknesses (Karlsson and Ribbing, 1978). The dielectric layers serve to both protect and to partly antireflect the metal film in the visible region, thereby increasing transmission. The dielectric film, usually a metal oxide, and when used to overcoat a metal, must exhibit high infrared transmittance in order to preserve the infrared reflectance of the metal. Additional designs include polymer dielectrics such as infrared transparent polymers of polyethylene, polyvinylidene chloride, polyacrylonitrile, polypropylene, and polyvinyl fluoride. The metal layer is typically silver, gold or copper although most use silver. Other metals have been experimented with such as Sn, Zn, ZnSn, Cr, Ni, Pd, Rh and stainless steel. Durability improvement of multilayer films still remains an important research area for the materials scientist. One method of stabilizing this design is by substituting a non-metal such as TiN, TiN_xO_y, SnNiOx (Howson, 1983; Szczyrobowski et al., 1989) for the fragile noble metal layer.

The most common of commercial D/M/D coatings are $In_2O_3/Ag/In_2O_3$, $SnO_2/Ag/SnO_2$ and ZnO/Ag/ZnO. Other coatings of the same type are $TiO_2/Ag/TiO_2$ and ZnS/Cu/ZnS. Many of these coatings use barrier layers at the Ag/dielectric interface to prevent oxidation of the silver layer during oxide deposition. Typical barrier materials are aluminum oxide, chromium oxide and lead oxide. Greater selectivity is achieved by making a D/M/D/M/D stack (Woodard and Zeable, 1990). Developments in these types of low-e coatings have been in durable oxides, nitrides, silicides and oxynitrides. Some of these materials also show solar selectivity such as ZrN:Ag (Nakai et al., 1990). Durable dielectric layers include $MoSi_2O_7$, (Kawaguchi et al., 1990), AlN (Iida, et al., 1990), AlN_xO_y, $AlSi_xN_y$, and $AlSi_xO_yN_z$ (Murata, 1989). Examples of makers of multilayer coatings are Southwall (Palo Alto, CA) and Renker (Switzerland). Southwall has just received the 1990 product of the year award from Popular Science for their "Superglass" window. It uses two low-e suspended polymer films inside a double glazing, with a krypton gas fill. This window has a center-of-glass U= 0.71 W/m^2K (0.125 Btu/h ft^2°F or R=8) rating; with the frame it is probably U=1.14-1.4 W/m^2K (0.2-0.25 Btu/h ft^2°F or R=4-5). Other companies are starting to introduce gas filled low-e window products too; these are expected to become a standard in the future. Properties of commercial low-emissivity coatings have been compared (Dolenga, 1986; Bakke, 1991).

Examples of highly-doped semiconductors are SnO_2:F, SnO_2:Sb, In_2O_3:Sn (ITO), Cd_2SnO_4, ZnO:Al and ZnO:In. Characteristic spectral transmission and reflectance for three of the best research-grade films are shown in Fig. 8.1.2 (Kostlin, 1975; Haacke, 1977; Van der Leij, 1979). Large-scale high-rate deposition techniques of low-emissivity coatings on glass and plastic (polyester film) substrates are of significant importance. Obtaining a reproducible high-quality commercial coating is considerably more difficult than making research grade films (Howson and Ridge 1982; Itoyma, 1979). Present techniques need to be improved to deposit coatings at low temperatures to get very low sheet resistance (10 ohm/sq.), high mobility and high transmission on polymeric substrates. Doped semiconductor films are typically deposited by chemical vapor deposition (CVD) either on or off the glass float line and have been limited mostly to glass because of the temperatures involved (400-600 C). Of the highly doped semiconductors the tin oxide pyrolytic coatings produced on the glass float line have been very successful. An aqueous tin chloride or tin organometallic liquid or powder is sprayed onto the surface of the glass as it leaves the float bath. The spray reacts with the glass surface at about 600 C forming tin oxide in air. This is probably the most efficient coating process for glass coating. Problems of iridescence have hampered the use of this glass compared to the multilayer coated glass with much more controllable optical properties and lower emissivity.

Recently these coatings have been improved by Pilkington (K-Glass) and LOF glass by the use of a two layer coating to reduce the iridescence of thicker tin oxide coatings. Significant developments on iridescence reduction were also made with the help of Prof. Roy Gordon, (Harvard Univ., Cambridge, MA). This allows products with even lower sheet resistance to be produced with excellent optical properties. ITO coatings on glass have been color modified by metal ion implantation (Tsutsuki, 1989). Also, doped semiconductors can be deposited by PVD, but at lower deposition rates. The thermal, mechanical and chemical stability of the substrate is significant in determination of the proper deposition technique and conditions. With CVD, secondary and competing reactions must be suppressed by control of reaction kinetics and knowledge of the system thermodynamics. Also, thermal durability and property stability of substrate and film is significant for long-life designs. There is considerable commercialization in both multilayer and semiconductor low emissivity coatings in Europe, North America, Japan, and USSR. Saint Gobain Glass has been working with a TiC underlayer for ITO to provide selective transmission for vehicle glazing. The coating has been developed to improve solar heat rejection.

Table 8.1 Commercial Low-e Glazing Properties
(Bakke, 1991)

Type	Shading Coeff.	T_{vis}	U-Value, Wm^2/K (R-Value)
Double-Pane (for comparison)	0.89	82	2.8 (2.0)
Low-e , Double Glazed (SnO_2)	0.84-85	74-78	1.72-2.27 (3.3-2.5)
Low-e ,Double Glazed (D/M/D,Argon Filled)	0.72	76	1.83 (3.1)
2 Low-e/Plastic, Double Glazed (D/M/D, Argon Filled)	0.52	62	0.71 (8.0)
Laminated Glass (D/M/D/Plastic)	0 56	74	2.5 (2.2)
Low-e ,Triple-Glazed (D/M/D, Argon Filled)	0.61	69	0.84 (6.7)

There are potentially other types of low emissivity coatings. They include certain rare earth oxides, borides, transition metal nitrides, oxynitrides, carbides and oxycarbides. Very little is known about these materials except several exhibit metal-like (Drude) conduction. Some examples are shown in Fig. 8.1.3. A new conductive coating of ZnOxFy has been produced for a CVD float line process (Gordon, 1991). Furthermore, gradient index low-e coatings are yet to be developed. It is possible that some of the surface texturing studies performed on transparent semiconductors for photovoltaics may be useful for low-e applications coatings.

Mesh low-emissivity coatings are made from metals or highly doped transparent semiconductors. The mesh pattern allows higher transmission than continuous coatings. The mesh pattern is etched in the surface using photolithography. The theory of mesh low-e films has been developed. Also, several fabrications of experimental films been made (McPhedron and Maystre 1977; Maystre and Nevieve 1979; Pramanik, Sievers and Silsbee, 1979; Sievers 1980). One design involves chemical etching of the surface of an ITO film to form a regular grid pattern (Fan, Bachner and Murphy, 1976). The etched grid consists of square openings of d = 2.5 μm. For this grid, T_S increased from 0.8 to 0.9 while reflectance decreased from 0.91 to 0.83. The theoretical infrared reflectivity for grids has been determined from antenna theory (Kontorovitch et al., 1962). Metal grids can be used to make transparent low-e coatings too. The best modeled results for metallic grids were obtained for aluminum and magnesium where the line width would have to be about 0.1 μm to give $T_S = 0.90$ and $R = 0.90$ (Paramanik, Sievers, and Silsbee, 1979). Grid structures are generally more expensive compared to regular low-e films because of the lithography steps. If by some process, a molecular beam could be scanned over the surface forming the grid structure the cost could be reduced. A range of conductive grid structures on teflon FEP and Kapton films are being developed and evaluated under the SCATHA spacecraft materials development program by the U.S. Air Force (Wright Aeronautical Lab, Wright-Patterson AFB, OH). The primary application is to reduce static charging (Lehn, 1983).

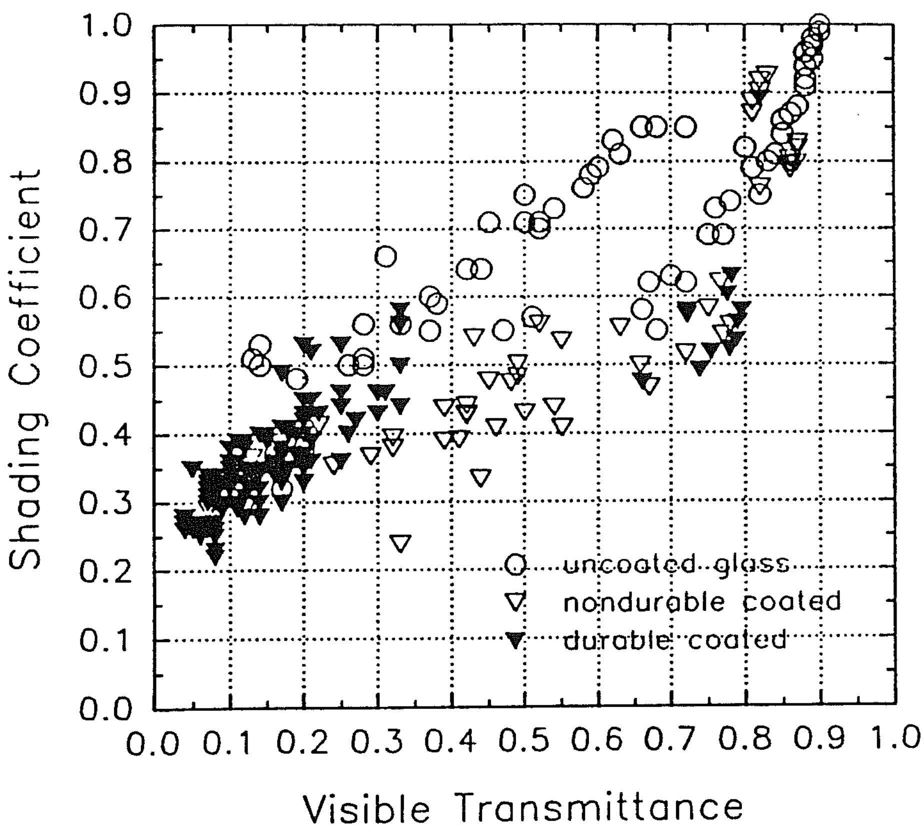

Fig. 8.1.1. Shading coefficient as a function of visible transmittance for uncoated glass, durable (pyrolytic tin oxide) coated low-e glazing and nondurable (D/M/D) coated low-e glazings (Rubin, 1990).

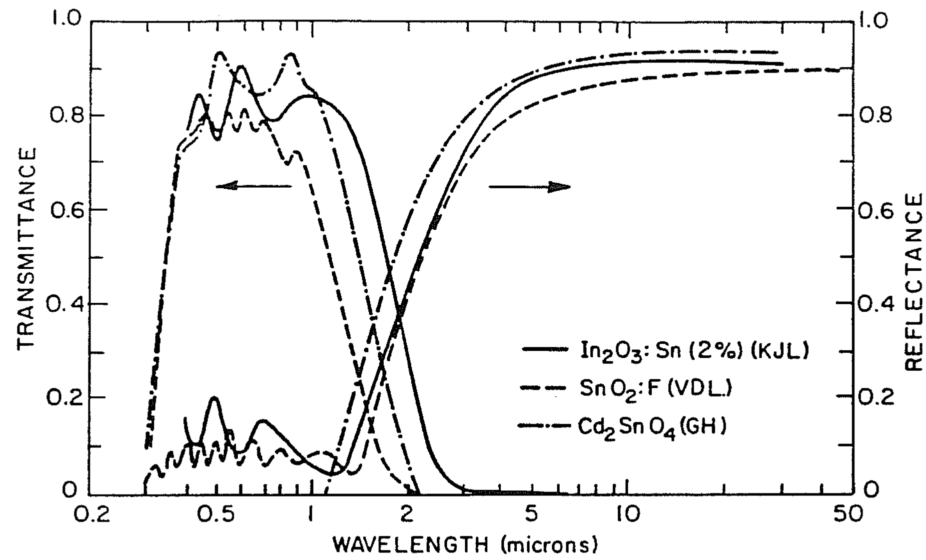

Fig. 8.1.2. Optical properties of the best research-grade highly doped transparent semiconductors.

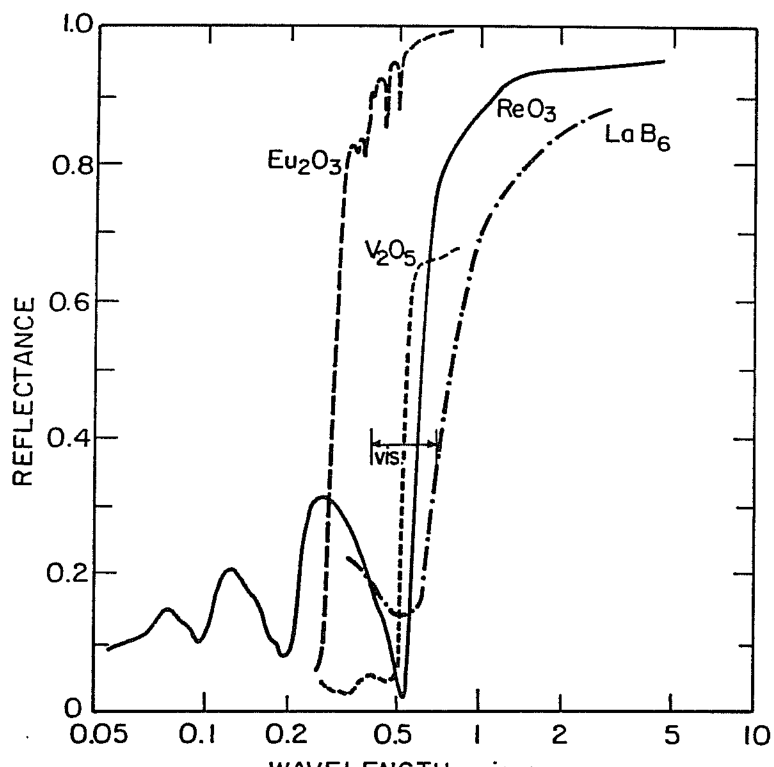

Fig. 8.1.3. Intrinsic selective materials (Lampert, 1982).

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8.2) Radiative Cooling Surfaces

Radiative cooling materials are selective infrared-emitting materials. The earth naturally cools itself by radiative transfer through high-transmission windows in the atmosphere to the cold troposphere. This effect is most noticeable on clear nights. A significant atmospheric window occurs from 8-13 μm wavelength. One can design an upward-facing surface that would emit over its wavelength range. To model radiative cooling, one must first consider the surface radiating towards the sky (Sakkal, Martin and Berdahl, 1979). A simplified radiation balance can be used to determine idealized radiative cooling power in the absence of convective and conductive heat-transfer effects. (Catalanotti, 1975). Conversely, coatings with high thermal infrared reflectance and high visible transmittance are used to reduce surface cooling by radiative processes. Tin oxide coatings are used to protect glazed surfaces from frost formation, experiments in Sweden (Volvo Motors) on automotive windows have verified this (Hamberg et al., 1987).

As a figure-of-merit the largest cooling temperature differential requires that E_{SC}/E_S , where E_S = average hemispherical emissivity of the cooling surface and E_{SC} = average hemispherical emissivity of the surface from 8-13 μm, be maximum and that the cooling power at near ambient is governed by E_{SC}. This implies that a material would have to have high reflectance for 0.3-50 μm, excluding the 8-13 μm region. In the 8-13 μm region the material would have to have a very low reflectance or high emissivity. It is theoretically possible for such a surface to reach 50 C below ambient. Experimentally obtained temperatures have been about 15 C below ambient. Temperatures below the dew point should be avoided, since the condensation of water on the surface will cause the emissivity to rise. The cooling power obtained by radiative cooling is less than the theoretical limit of 100 W/m^2, at near ambient.

Solid-state materials used for radiative cooling include SiO/Al, (Granqvist and Hjortsberg, 1981) Si_3N_4/Al (Eriksson and Granqvist, 1986) (see Fig. 8.3.1), and polymer-coated metals (Eriksson, 1984). Thin polymer films of polyvinyl chloride (PVC), polyvinyl fluoride (PVF, Tedlar), or poly-4-methylpentene (TPX) are used for covers. Also, a radiative cooling device can consist of two separate materials, a selective cover and an emitter. Infrared emitters are easier to design compared to the selective emitter, but the selective cover remains a challenge. Materials like polyethylene with coatings of tellurium or dispersions of TiO_2 have been experimented with. Materials need to be designed that not only satisfy the optical requirements but are also resistant to weathering and solar degradation. By using a selectivity infrared emitting gas as the emitter, the gas can serve as its own heat transfer medium. Gases such as ammonia, ethylene and ethylene oxide have been investigated (Lushiku and Granqvist, 1984). For the materials investigated thus far, the emissivity of the emitter needs to be optimized to take full advantage of the 8-13 μm window. Finally, methods of coupling these surfaces with heat-transfer media need to be devised.

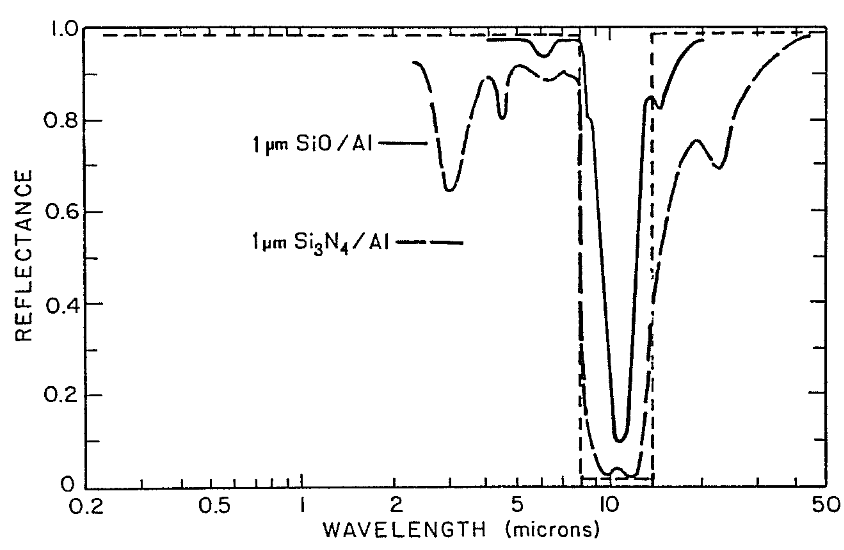

Fig. 8.3.1. Solar and infrared reflectance properties of two tandem radiative cooling surfaces. One coating is silicon monoxide on aluminum, the other is silicon nitride on aluminum.

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8.3) Spectral Splitting and Cold Mirrors

Spectral splitting coatings are used to divide the solar spectrum into different broadband regions. In this fashion various regions can be tailored to particular photovoltaic or photothermal needs. A liquid spectral filter has been developed for greenhouses, swimming pools and windows patented by Tel Aviv University in Israel. The undisclosed fluid separates the near-infrared from the visible portion of the solar spectrum (SEIR, 1990). Spectral splitting coatings allow for multiple photovoltaic and combined photovoltaic-photothermal systems (Bennett and Olsen, 1978; DeSande, 1985; Chendo, 1985, Osborn et al., 1986). By tailoring the solar energy to that of the photovoltaic response, the overall system efficiency increases. A cold mirror coating or a band pass filter could be used for this purpose. This array might consist of a series of cold mirrors, where the transition from high reflection to high transmission moves to longer wavelengths for each successive cell. The cold mirror coating has the opposite spectral response to that of the transparent low-e films. The cold mirror exhibits high reflectance in the visible region and transmits highly in the infrared. Cold mirrors are generally multilayer dielectric interference films. Multilayer film based on ZnS/MgF_2 and TiO_2/SiO_2 have been made (Winegarner, 1977). A simple design utilizing a conventional D/M/D low-e coating might be used to separate the visible and near-infrared portions of the solar spectrum. The visible portion could be used for photovoltaic conversion and the infrared portion could be used for photothermal conversion. Also, photovoltaics will operate more efficiently if infrared heating is eliminated. If transparent low-e coatings with different spectral characteristics were used, the solar spectrum could be partitioned from low to high energy as the low-e transition wavelength becomes shorter. Also, liquid crystals can be used as optical filters if they are aligned and solidified by polymerization. This processing can give preset optical properties. Broadband Lippmann Holograms have been used for spectral splitting (Jannson, Jannson and Yu, 1985). An example of the spectral response of a hologram designed for spectral splitting is shown in Fig. 8.4.1.

Another application for a spectral splitting cold mirror is for advanced greenhouse design (Levitt and Weber, 1984). Plants require a fairly narrow range of wavelengths (0.3-0.75 μm) for photosynthesis. The remainder of the solar spectrum is unused. This unused energy can be used as heat to warm the greenhouse indirectly.

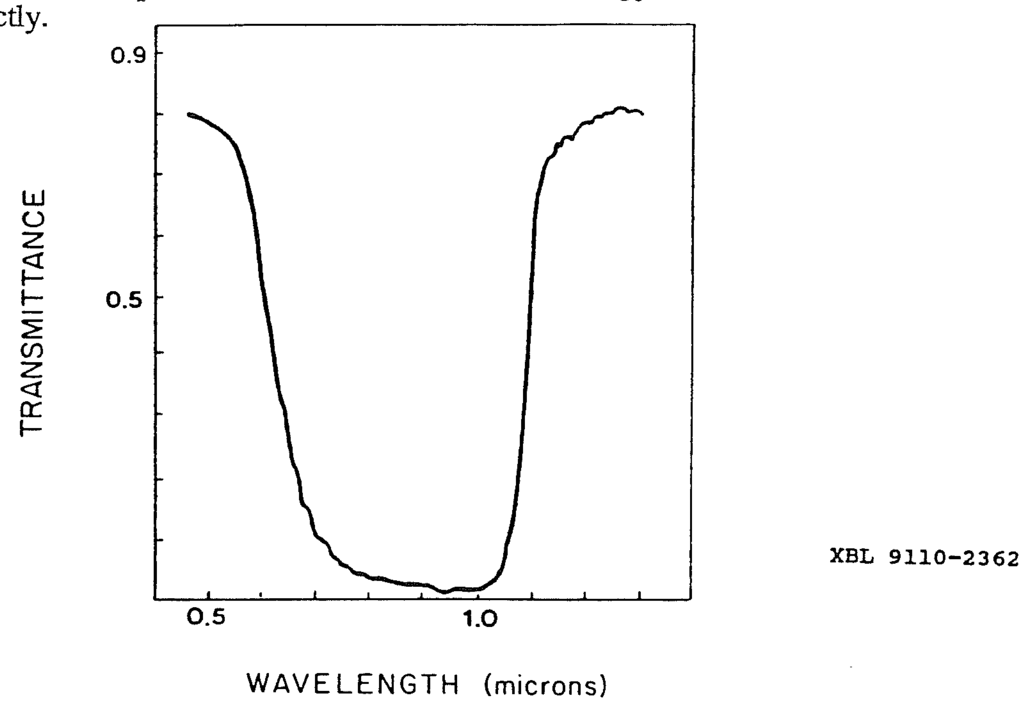

Fig. 8.4.1. Optical properties of a broadband Lipmann hologram designed as a visible transmission filter. This hologram exhibits a sharp change from transmissive to reflective at the edge of the visible spectrum, showing high visible selectivity.

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9. SUPER WINDOWS

A low-emissivity film alters only the radiative character of a window; the effects of convective and conductive heat losses must be taken into account, too. Convective and conductive heat transfer effects can be reduced by using a fill gas, weak vacuum or transparent insulation in the air gap of a multiple glazed window. The use of fill gases such as krypton, xenon, argon, sulfur dioxide, sulfur hexafluoride (SF_6), propyne (CH_3C:CH) and various freons can diminish the radiative heat transfer by as much as 70% for a 1 cm gas layer (Glaser, 1977; Eriksson and Granqvist, 1987; Reilly, Arasteh and Rubin, 1990). Also, SF_6 provides some additional acoustical insulation. Conductive heat transfer losses from the window frame can be reduced by use of composite polymers as the frame material. Window orientation, climate, and glazing type and application are important factors in choosing the exact combination of optical properties for the low-emissivity coating. A film with adjustable properties might be the best solution. By the combination of frame, fill gas and several low-e coatings a "Super Window" can be constructed (Gilmore, 1986). A range of designs has been studied (Arasteh, Wolfe and Selkowitz, 1987; Arasteh and Selkowitz, 1989). By use of a computer simulation program, Window 4.0, thermal conductance (U) values have been derived for various types of glazings shown in Fig. 9.1.1. Windows can be designed with center-of-glass U values of 0.56-0.71 W/m^{2}K (0.1-0.125 h ft^2 °F/Btu or R=8-10) using a 98% Krypton+2% Argon gas fill and low-e coated triple glazing (Arasteh, 1989). A new type of gas filled polymer insulation has been developed at LBL with U values as low as 0.157 W/m^{2}K/cm (0.07 h ft^2 °F/Btu/in or R=14/in). This insulation may be used in conjunction with super windows to make a super fenestration or building skin. (See Section 1.2 for more details). The Southwall Technologies Co.(Palo Alto, CA, USA) has introduced their "Superglass" window (as discussed in Section 8.1). It uses two low-e suspended polymer films inside a double glazing, with a krypton fill gas. This window has a center-of-glass U=0.71 W/m^{2}K (0.125 h ft^2 °F/Btu or R8 thermal resistance) rating, and with frame it is probably R4-R5. The filling cost for a typical window range from 0.25-1 US$. A non-glass insulated wall has thermal conductance values of U = 0.3-0.6 W/m^{2}K (0.053-0.11 h ft^2 °F/Btu) with corresponding thermal resistance of R19-R11. The largest challenge is to develop good seals that will hold in the gas over 10-30 years. Another type of superwindow is the aerogel window, discussed in Section 4.1.

Another important issue is frame design for advanced windows. Even as windows become more insulating, the net energy loss becomes significant because of losses by the frame. Because of this the performance of the overall window is degraded. With better windows have to come improved frames. The incorporation of low conductivity gas fill and low-e coating of a triple pane window can achieve a center of glass U value of less then 0.57 W/m^2 K (0.10 Btu/h ft^2 °F) (Arasteth, Selkowitz and Wolf, 1989) but this tempered by the property of the frame that can have thermal conductance of about U=1.42-3.4 W/m^2 K (0.25-0.6 Btu/h ft^2 °F). As a result the overall performance of the window is only U= 0.85-1.42 W/m^2 K (0.15-0.25 Btu/h ft^2 °F). Because of this problem new types of frames need to be developed. The thermal performance of frame design can be predicted by computer modelling. For certain conditions a conventional triple glazing with metal spacer can give U = 1.31W/m^2 K (0.23 Btu/h ft^2 °F). Now if an insulated spacer is used U falls to 0.96 W/m^2 K (0.17 Btu/h ft^2 F) and with an insulated vinyl or fiberglass laminated frame, with an insulating spacer U becomes only 0.74 W/m^2 K (0.13 Btu/h ft^2 °F) (Byars and Arasteh, 1991). Super windows will definitely have a role in future glazing.

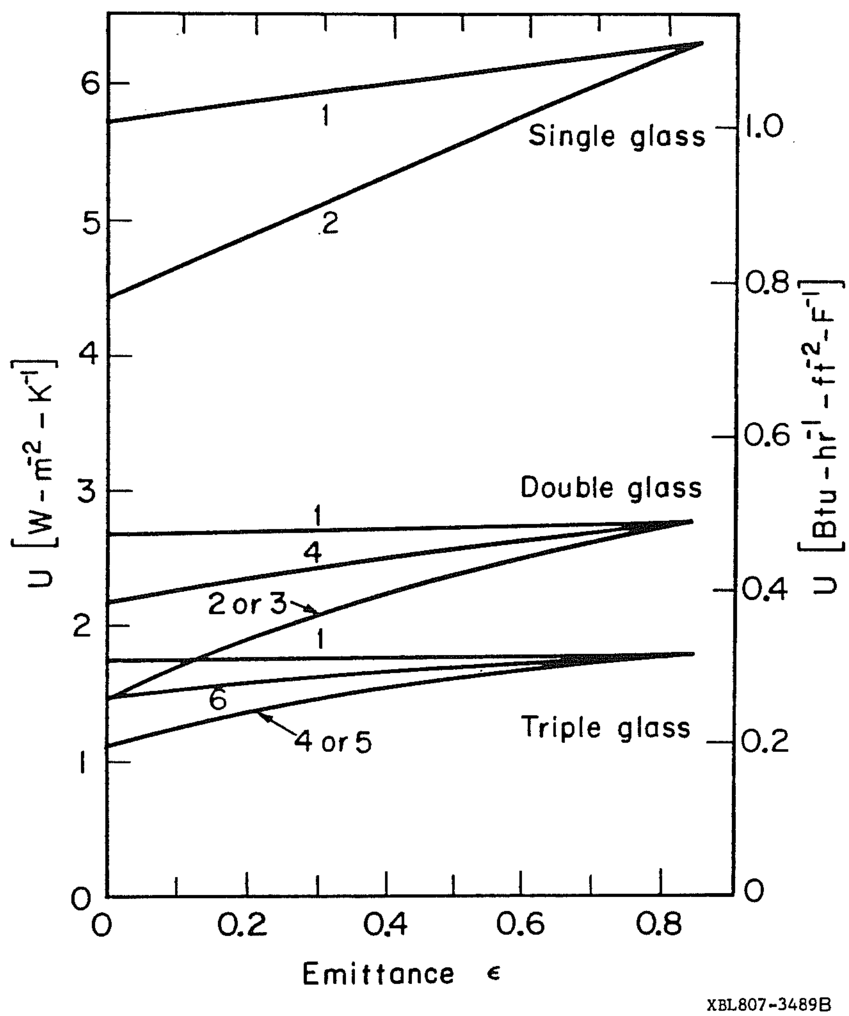

Fig 9.1.1. Thermal characteristic of different window designs using low-e coatings (Arasteh, Selkowitz and Hartmann, 1985).

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10) CONDUCTIVE POLYMERS

Conductive organic polymer metals belong into a new class of synthetic electronic conductors that include organic charge-transfer metals, the Krogmann salts (tetracyanoplatinates) and the transition element-macrocyclic ligand metals (Margolis, 1989). Organic polymer conductors can be used for a variety of applications including superconductors, electronics, waveguides, medical electrodes, light weight batteries, and energy conversion devices (Kuzmany, 1989). These materials also have future potential for optical applications in building, automotive and aerospace glazings. The development of polymer metals can have a major impact on optoelectronic devices, integrated circuits, photovoltaics, switchable windows, defrosting glazings, glazing security systems, RFI shielding of aircraft windows, lightweight conductors, flexible conductor systems, and conductive plastic surfaces.

Since the discovery of polyactetylene in the mid-1970s (Ito, 1974), there has been considerable interest in the development of synthetic electronic conductors. The conductivity and electroactivity of polyacetylene has been investigated (Chien, 1984). A number of other conjugated hydrocarbon and aromatic heterocyclic polymers, such as polypyrrole (Diaz et al., 1979), poly(p-phenylene) (Ivory et al., 1979), poly(p-phenylene sulfide) (Rabolt et al., (1980), poly(p-phenylene vinylene) (Wnek et al., 1979), and polythiophene (Tourillon and Garnier, 1982), have been found to be conductive. A few books review the properties of these unusual polymers (Blythe, 1981; Chien, 1984; Skotheim, 1986; Margolis, 1989; Kuzmany, 1989). The conductivity of these polymers is increased by doping with typically, Na, Li, I, and AsF_5 and resistivities as low as 10^{-2} ohm-cm have been obtained. Doping is easily performed because these polymers have an open fibril structure. They can be doped from the gas or liquid phase. Generally most organic conductors are not sufficiently transparent in their conductive (doped) condition for optical applications. Many are not stable in air and water. Polyacetylene is the most famous conductive polymer, it has conductivity of 10^{-5} S/cm. Conductivity can be increased to 10^{-3} S/cm by doping. Unfortunately the polymer is opaque, metal-like, and unstable in air, which restricts its applications. Certain polymers in the polymer families of polythiophenes $(C_4H_4S)_n$ and polyanilines $(C_6H_7N)_n$ show the most promise as transparent conductive polymers.

Current commercial transparent conductors are thin films of indium tin oxide (ITO), In_2O_3:Sn or doped tin oxide (SnO_2:F, Sb). Indium tin oxide is produced by vacuum evaporation and sputtering and tin oxide is produced by chemical vapor deposition onto a 400-600 C substrate. It is somewhat difficult to produce these coatings at low process temperatures. ITO is produced on polyester commercially with sheet resistance as low as 20-30 ohm/sq. Some producers are Courtalds Corp. (Canoga, Park, CA); Southwall (Palo Alto, CA); Deposition Technology (San Diego, CA) Teijin, (Tokyo, Japan); and Toray, (Tokyo, Japan). Getting to lower sheet resistance and maintaining high visible transmittance (above 70% is difficult). Unfortunately, doped tin oxide is not generally available on polyester, which is more chemically durable than ITO. The processing temperatures of the oxide transparent semiconductors limit their use in applications such as top electrical contacts for photovoltaics, integrated circuits, electrochromic switching devices, and electrooptic devices. These coatings can not be used due to subsequent damage to the underlying layers. Also, the cost of these coatings is fairly expensive. In other applications, partially transparent or antireflected thin metal films are used as conductors. These are produced by vacuum deposition processes. Potentially the most promising conductive polymers for optical applications are the polyanilines $(C_6H_7N)_n$. and polythiophenes $(C_4H_4S)_n$. The green form of a polyaniline dispersion is offered commercially for anti-static packaging and EMI shielding from Allied Signal (Morristown, NJ), Americhem (Cayahoga Falls, OH) and Zipperling Kessler (Ahrensburg, Germany). The conductivity of the commercial polyaniline blends can be as low as 20 S/cm A variant of polythiophene, polyisothianaphthene (PITN) is being studied, but it is subject to oxidative degradation (Wudl, et al., 1985). PITN has a band gap in the infrared region at about 1 eV (1.2 µm) and has been reported to become optically transparent in its doped state that is the reverse of most conductive polymers. A conductive polymer based on poly(3-methoxythieylene vinylene) has been patented by Allied-Signal Inc (Morris, NJ) for use as a selective coating to reduce solar heat gain in windows (Shacklette et al., 1990). The field of conductive polymers is still young and we still expect to see significant developments in the future. The use of conductive polymers for electronics will continue to increase for electronic applications. Conductive polymers are expected to be applied to optical applications in the future.

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11) MATERIALS WITH MODIFIED ANGULAR PROPERTIES

Angle selective materials and coating have the property of enhanced optical properties in selected directions, allowing light to be greatly transmitted at particular angles or ranges of angles. A schematic of angular selective structures is shown in Fig. 11.1. This area of research for glazings is fairly new. Work has begun under the Australian energy program on the deposition of oblique angle selective metal and cermet coatings on to glass for glazings. The deposition technique is magnetically filtered cathodic arc evaporation and oblique evaporation. The results of this work have shown films with good angle selectivity (Smith, 1989). This work studied metallic coatings. Angle selective metal films of Al, Cr and Ti have been studied at The University of Tanzania (Dar es Salam, Tanzania) (Kivaisi, 1982; Kivaisi, 1983) under a joint project with Chalmers University of Technology (Gothenberg, Sweden)(Mbise et al., 1989a; Mbise et al., 1989b). Oriented metal films of Al, Cr and Ta deposited using oblique angle evaporation have been developed with strong p-polarization selectivity (Smith, Ng and Ditchburn, 1990; Ditchburn and Smith, 1991). Recently, cermet films have been deposited using the filtered cathodic arc process (Smith, et al., 1990; Smith, et al., 1991a; Smith, et al., 1991b). The thermodynamic conditions to form this microstructural geometry has been explained by Thorton, 1974.

The largest commercial efforts in angle selective materials are in Japan at Nippon Sheet Glass and Sumitomo Chemical Company (NSG, 1986; Maeda et al., 1989; Ohno et al., 1989; Hozumi et al., 1989; Ishizuka et al., 1990). Nippon Sheet glass has introduced their "Angle 21" window glazing. The glazing consists of a polymer with an oriented column microstructure (Maeda et al., 1991). Depending on angle the material goes from diffuse scattering to specular transmitting. The optical properties of this film have been modeled (Tsujino et al., 1991). The angles are adjustable by the photo-polymerization processing conditions. Polymers in nature come in two general categories: one being the semicrystalline state and the other the amorphous state. In the semicrystalline state there is some regular ordering of the molecular chains. Generally films of this type scatter light and appear milky from the crystalline sperulitic structures. These films are regularly drawn and oriented under certain conditions to increase transparency. The increase is due to the formation of lamella structures with order over regions of dimensions greater than the wavelength of incident light. These structures are less optically heterogeneous than sperulitic structures (Neidlinger, 1986). It is also possible to orient polymer molecules in films in such away to give angular dependent crystal structure (Russo et al., 1986). This has been done for dispersed liquid crystal films. The result could lead to a switchable angle selective film. (Wu, West and Doane, 1987). Mixed refractive index polymer films have been developed for angle selective application (Kitayama, 1990). Other work on polymers includes the study of light scattering from rod-like polymer materials (Stein and Hashimoto, 1970). Texture formation in liquid crystal polymers and oriented polymer films has been investigated (Rojstaczer et al., 1988). A study of aggregation and angular dependence in PVB polymers was studied at IBM. At the University of Ultrect (NL) the angular dependence of polymer solutions has been studied. A color adjustable angular sheet for ornamental use has been patented in Germany by the Scholer Co. Dai Nippon printing (Japan) has patented a colored sheet for the selective transmission of light.

An architectural louvered glass was introduced by Corning in 1983. The product was known as Photolite or Louverre glass. This product gave a macro angle control and shading effects. Example tilts of the louvers are 0, 10, 20 degrees with 1 mm louvers separated by 3 mm spacing. This glass has effective transmittance ranging from 16-30% and reflectance of 17-23% with shading coefficient ranging from 0.4-0.5. Because of high manufacturing costs the product was never produced in large quantities. It was produced as a thin glass designed to be laminated to a thicker sheet glass. If this type of glass could be produced in the float process, then it might become cost effective. The louvers in the glass could be modified by processing to give a range of patterns on the glass. An advantage here is a wide range of products could be produced using the same glass formulation. A variant of this glazing would be to make the louver section variable by use of a chromogenic material.

There has been much research on angle-selective opaque surfaces. In particular the U.S. Air Force (Wright-Patterson Air Force Base, Dayton, OH) and Defense Advanced Research Projects Agency (DARPA) has had considerable effort in the modification of vehicle and aircraft surfaces to avoid or reduce detection by sensing beams. This work was coupled with coatings with radar absorption properties. Crystalline colloidal array filters have been studied for angle selectivity by the Air Force. The Christensen optical scattering effect on infrared properties of glazings was studied at Aberdeen Proving Ground Edgewood Arsenal (Aberdeen, MD). Coatings that increase high angle reflectivity have been studied at the Royal Signals and Radar Establishment (UK). The theory of angular light scattering from surfaces has been developed at The University of Arizona. There is work at the University College of Wales (UK) on angle selective absorption of certain photochromic molecules in PMMA (Jones et al., 1989). The National Technical Systems Corp. (NTS) has studied holographic films for angle selective applications. A joint project between VEGLA and the Volkswagen, Germany has resulted in the development of an angle selective glazing with forward visible transmittance greater than 75% and upward transmittance (towards the sky) of less than 40%. This is designed for the Futura (concept car) obliquely sloped windscreen. Sloped oblique transmittance of low-e coating has been done by Prof. Roos at the University of Uppsala in Sweden. The directional radiation properties of solar materials including fabrics have been studied by the Glavniiproekt Energy Institute in USSR.

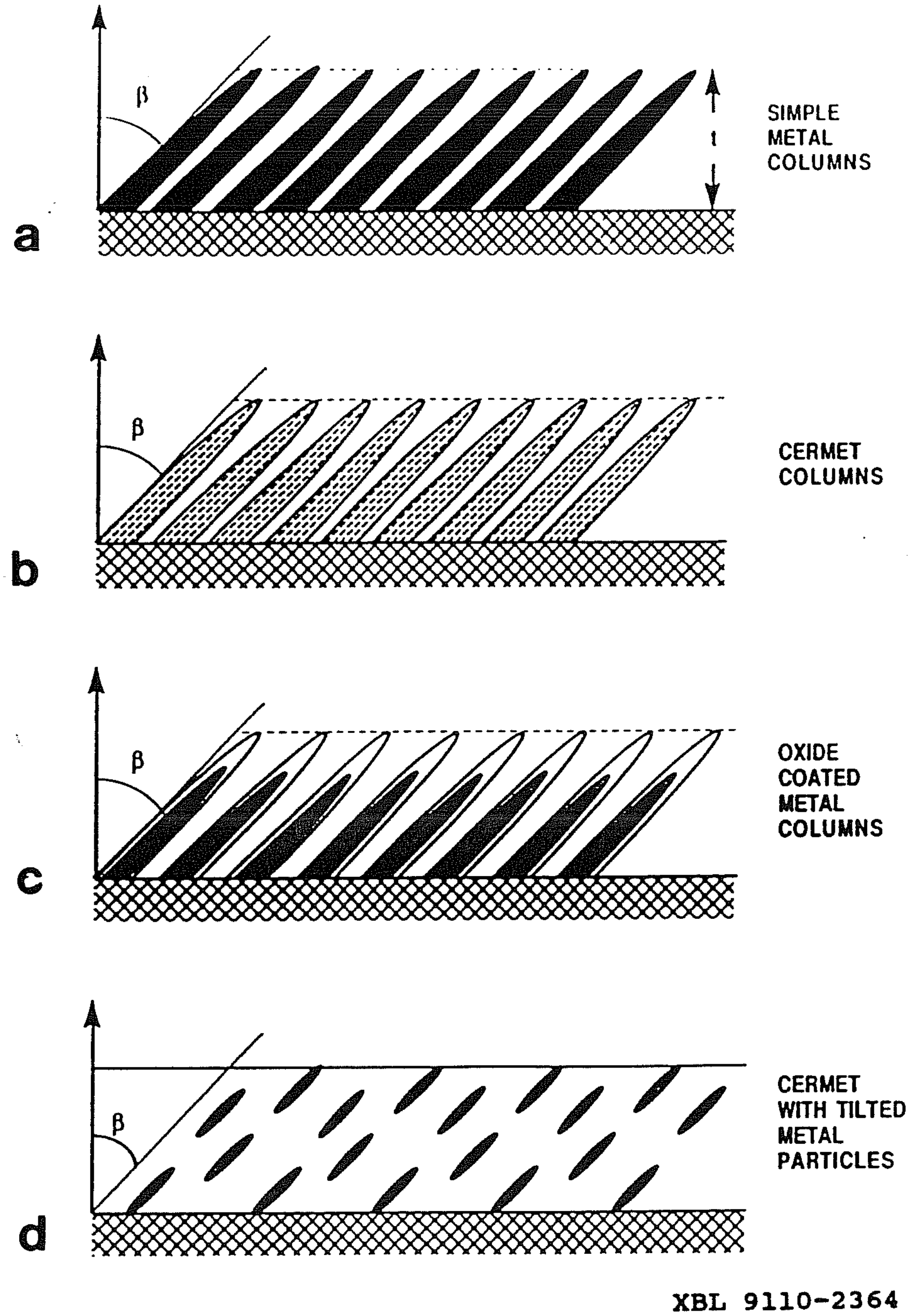

Fig 11.1. Schematics of different types of coating microstructures showing four types of angle selective structures (after Smith et al., 1991).

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12) ANTIREFLECTION COATINGS

Transparent covers and films used in glazings can have visible reflection losses reduced by antireflection treatments. For many years antireflection coatings have been devised, usually for existing optical products. Durability, wavelength response and cost-benefit trade-off are important issues for these coatings. Antireflection becomes especially important for glazing systems with transmission criteria, such as in auto glazing where visible transmittance, T_v > 70-75%. A complex coating such as electrochromic films may require antireflection coatings to increase the bleached transmittance. Reflection losses are caused by optical interference from the boundary formed between two media with different optical properties. As an electromagnetic wave propagates from one medium to another, there is a change in phase velocity, wavelength, and direction. Because of interference between the incident wave and the atoms of the new medium, a reflected wave is formed. When the incident medium is in a vacuum, the ratio of phase velocities (vacuum/medium) is the index of refraction, n. If the medium is energy absorbing, n can be a complex quantity. The refractive indices at 589 nm for typical media are: air, n = 1.000393; water, n = 1.3336; and crown glass, n = 1.523. Common solar glazing materials are soda-lime float and low-iron glasses (n = 1.51) and polymers like polymethyl methacrylate (PMMA), polyvinylfluoride (PVF), polyethylene terephthalate or polyester (PET), polycarbonate (n = 1.46 - 1.54). Common glare is caused by polarization on reflection and can be suppressed with polarizing filters. Several glass sheets or layers of optical thin films can also produce polarization. One glass plate removes about 8% of light polarized in one direction, and four plates remove about 67% of polarized light. Non-polarized reflectance is the average of two reflected components of light polarization, R_s perpendicular (s-wave) and R_p parallel (p-wave). The s-wave electric field oscillates in a plane spatially perpendicular to the plane of incidence. P-waves oscillate in a plane spatially parallel to the plane of incidence. The theoretical development of antireflection film is well established and follows the matrix method covered by Macleod, 1986.

The incident reflectance losses are about 3.5-4.5% per surface for most untreated polymers and glasses for glazing use, excluding low-index halocarbons. Examples for float glass are shown in Fig 12.1. By antireflecting the glazing surfaces the maximum increase in performance for each glazing would be about 7-9%. This gain in transmittance can be significant if multiple glazings are used. Certain antireflective coatings, if designed properly, can also serve as a durable overcoating material. Silica films deposited from sodium silicate or colloidal silica can be used for acrylic, polycarbonate, and several types of glasses. Popular protective materials are silicones, fluorocarbons, halocarbons, and acrylic resins. Inorganic thin films have been used for a wide range of single and multiple interference-coating applications. Compounds such as CeO_2, MgF_2, SiO, $SiO_{1.5-1.8}$, SiO_2, and TiO_2, are used for antireflection applications, with the silicon oxides also serving as durable barrier layers. A range of other less-common antireflection films for solar applications has been studied including, SiO_2-SiN_x, Al_2O_3-SiN_x, SiN_x-TiO_2, and Si_3N_4 (Sexton 1984). Silicon oxynitride films can be made with varying indices of silicon oxynitride (n = 1.46 to 3.4) depending on the substrate (Wilson, 1984). Metal oxyfluoride films have been used to antireflect low-e multilayers (Harding, 1985; Harding, Hamberg and Granqvist, 1985; Harding, 1986). Also antireflection coatings with color correction have been made for ITO low-e surfaces (Hamberg and Granqvist, 1983). A commercial product that uses a color correction layer is Pilkington K-Glass and LOF low-e glass. The effect of antireflection on reduction of light scattering has been studied (Amra, Albrand and Roche, 1986) (Certain low refractive index polymers can antireflect glass (n = 1.5) and other high-index plastics. Dispersions of fluorinated ethylene propylene (n = 1.34) can be used for this purpose (Lampert, 1983).

Many coatings are deposited by conventional physical vapor deposition techniques. A number of oxides can be deposited by the solgel deposition and drying process (Brinker, 1981; Pettit and Brinker, 1986). Also, solgel sources have been used to form uniform droplets for CVD deposition. Solgel coatings are formed by hydrolysis and polycondensation of metal alkoxides which react to form transition metal oxide coatings. Solgel coatings have been used to antireflect glass, changing transmittance from T_s = 0.91 to 0.96. Gradient-index coatings have been used for antireflection of glass and plastic surfaces (Lowdermilk, 1983). Gradient-index films present a versatile range of coatings having refractive indices that are not readily found in bulk materials. Also their wavelength response is generally broader than single index coating, which is very useful for solar glazing applications. Their properties have been explained by inhomogeneous-film theory (Jacobson, 1966; Minot, 1977). Also, angular reflection effects in gradient index films have been studied by Minot, 1977. Etched gradient surfaces can have superior mechanical properties to deposited films. Gradient index coatings have been developed in phase-separated glass by Corning Glass and Hoya Corp. A neutral solution for the processing of glass has been developed by Schott Glass for a wide range of glasses (Schroeder, 1974; Cook et al., 1982). Fluorosilicic acid can give a gradient-index, antireflective coating to glass. It primarily roughens the surface by etching out small pores, in non-silica regions (Pastirik and Keeling 1978). Selective leaching has been used to antireflect concentrating solar collector tubes and covers (Cathro et al., 1981; Miska, 1984).

Polymers have been antireflected by gas phase surface fluorination (Jorgensen and Schissel, 1985). Polyvinyl fluoride (n = 1.46) can be antireflected by dipping in acetophenon creating a gradient surface. Ion implantation can produce a microporous surface in plastic that gives an antireflection effect (Spiller et al, 1980). A treatment for polyethylene terephthalate and glass materials has been devised (Lee, 1980; Lampert, 1983). The coating is made from a steam-oxidized aluminum film; this processing causes a needle-like structure of aluminum hydroxide, $AlO(OH)_2$ to form (Lee and Debe, 1980). A polyester film treated in this fashion can serve in glazing applications where solar transmission must be optimum (T_p=95-98%). Both ICI America, Inc. (Wilmington, DE) and 3M Corp. have developed polymers by this technique.

The glazings of the future will certainly have antireflection coatings to optimize efficiency of the glazing. Probably the antireflection coating will be some combination of protective coating and color correction coating. The gradient index coating gives the broadest wavelength response, if it can satisfy the other requirements.

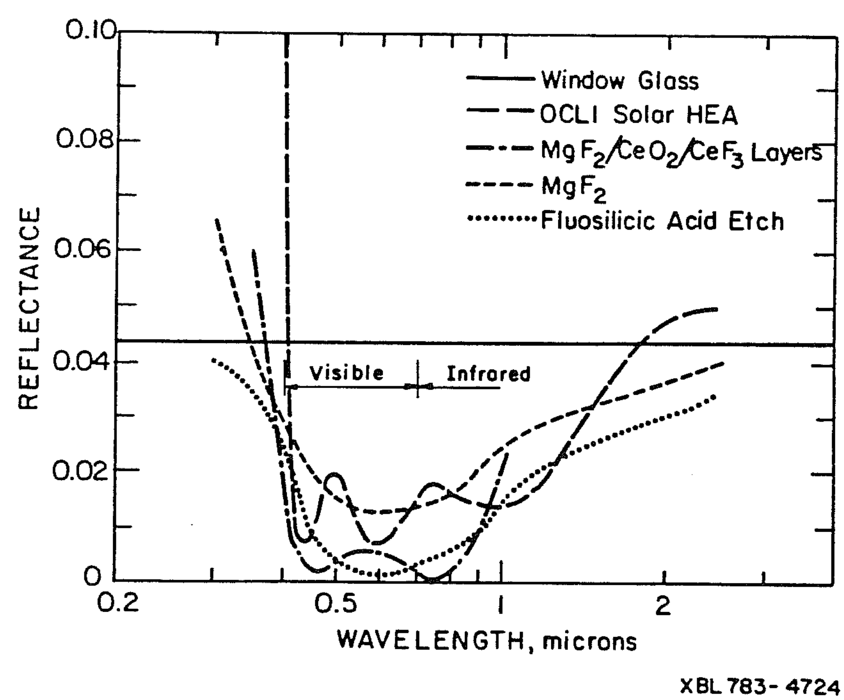

Fig. 12.1. Near-normal single surface reflectance properties of selected antireflection films on float glass compared to uncoated float glass.

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13) ANTISOILING COATINGS FOR GLASS AND PLASTIC

There is a strong demand for glass that has a self-cleaning feature or even glass that reduces the cleaning frequency. Currently, many building glazings are difficult and expensive to clean. All types of future glazing should reduce the need for cleaning. Several aspects of this problem have been studied for many years and still no clearly superior process for glass or plastic glazing has yet to be devised. In the solar field this problem is very serious for large-area collectors and photovoltaic arrays, especially ones using reflector surfaces. Considerable studies have been made to try to understand the nature of soiling and to provide insight into the problem (reviewed by Lind, 1980; Cuddihey and Willis, 1984). Surface soiling is a very complex problem, which is dependent on the nature of the surface, the particle type and size, and local environment (e.g., amount of rain, humidity, dew levels).

Another related area is the development of coatings that allow a water sheeting action during storms to increase visibility of glazings. This is a very important issue for all vehicle glazings, and has been studied by the military and aircraft industry extensively. No permanent treatment exists. Surface treatments to improve visibility of aircraft and marine glazings during rain storms have been researched for over 15 years at the U.S. Naval Research Labs (Washington, D.C.) and U.S. Ocean Systems Labs (San Diego, CA). Some of this technology may be available for commercial applications in the future. These surface treatments act to change the surface tension of the glazing so water totally wets the glazing rather then forming spots. Fluorocarbon coatings have been used to treat glass on buildings and ships. The fluorocarbon coatings tend to wear off with time and have to be replaced. Surface treatments of polymer glazings are common in greenhouses to prevent condensation and dripping of water onto plants. Also, a wide variety of surface treatment products to prevent soiling have been developed for polymer and natural fabrics and painted surfaces.

There are some antisoiling commercial products for glazings. The siloxane glass treatment, "Clear Shield" (Ritec International Ltd., London, UK) is an example of a temporary surface treatment for glass. By the amount of interest this coating has received it gives the appearance of the best on the market. The materials cost for this treatment ranges from about US $\$0.5\text{-}2.5/m^2$ depending on the condition of the glass. Also, Everest, Viracon and Musselman window manufacturers will produce a glazing product using the Clear Shield treatment or a similar one. Nippon Sheet Glass has also licensed this technology. PPG has introduced "Aquapel" a fluorinated siloxane coating for automotive windshieds. Nippon Sheet glass has filed a patent on Stay-Clean window glass based on a pyrolytic coating of TiO_2 with dopants of Pt, Rh or Pd (Kume and Nozu, 1986). UV light from the sun is absorbed on the surface of this coating, its action catalyzes surface organic compounds to become oxidized. Also, the water contact angle to glass is reduced promoting a sheeting action. Another coating has been developed by Asahi Glass that also provides antireflection for glass. This coating is based on polyfluorocarbosilane made by a dipping and drying technique (Masashi et al., 1986). Further work is being undertaken at LOF and Toyota Motors on slippery or hydrophobic glass coatings. Toyota has developed a silicone top layer coating to protect a solar load reduction multilayer coating (Shimizu and Tsutsuki, 1988). Also antifogging is a very important feature for cars from a safety viewpoint. Saint Gobain's bilaminate automotive windshield has an antifogging feature on its interior polyurethane layer.

This is a very important area for future improvement. It is hoped that suitable durable antisoiling coating can be developed for future glazings in the next 10-20 years, and can be used to coat existing glazings. The key to this technology is permanent chemical modification of the surface characteristics of the glazing.

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14) LIGHT COLLECTION AND TRANSPORT MATERIALS

Illumination for offices has become a major issue in office efficiency and comfort. Illumination is also important from an energy efficiency view point. Inefficient lighting can supply unwanted heating and consume expensive energy. The future home and office will certainly need more efficient and more effective lighting. Advanced illumination materials and optics have been the subject of a conference (Lampert and Holly, 1986) Solar optics using fresnel mirrors and heilostat systems have been evaluated by The Battelle-PNW Labs (Richland, WA) for commercial buildings (Eijadi, 1985; BSD, 1978).The development of more efficient light sources at the LBL Lighting group is providing more efficient electronic ballasts for fluorescent lighting and developing more efficient lighting sources (Berman, 1985). Studies to increase the efficiency of lamps include mechanisms for reducing ultraviolet self-absorption in gas-discharge lamps and excitation of the lamp plasma by radio frequency (RF) electromagnetic fields. The visual environment effects productivity in the automated workplace. The invention of a new high-frequency surface wave lamp is a significant development. It has 30% better efficiency than the common fluorescent lamp. A two-year test of solid-state ballasts in a large office building showed an electricity saving of 40%. Scaled to the entire country, this represents an annual saving of $5 billion. The energy-efficient surface wave lamp promises major reductions in energy use with considerably longer lamp life (Verderber, 1988).

Studies of office illumination need for current and future offices have been made by NEDO, (Tokyo, Japan), along with several businesses and technical societies (Takahashi, 1988). These studies have investigated versatile task oriented indirect lighting to reduce glare in offices with a number of video display terminals (VDT). Matsushita (Osaka, Japan) has developed a natural light collection and distribution system using optical ducts and fiber optics for high-rise office buildings (Yamashita et al., 1987). Centrally controlled lighting systems using advanced dimmers for fluorescent lights are being studied in the UK for future buildings (Dooley, 1989). Infrared controlled lighting has been studied by the UK Dept. of Energy. (UKDOE, 1986) Philips Corp. (NL) has developed a lighting integration function system (IFS) that controls lighting throughout the day with a central computer that adjusts for changes in daylighting levels and office space occupancy. Advanced lighting control systems are discussed under Smart Building Technology (Section 3).

Natural illumination is the most comfortable to the occupant and encourages greater worker productivity (McCluney, 1984). For many years there has been interest in the transport of daylight into buildings for indoor lighting. To do so, three elements must be developed: collection optics, concentration optics, and distribution system. Much of the tracking and collection optics and concentration optics depends on conventional geometrical optics design (Hecht, 1987). For the distribution system, solid glass and plastic light pipes, fluorescent concentrators, hollow metallized guides, and focusing optic guides have all been considered. Many of these suffer from cost or weight restrictions or optical lossses which make them impractical, although a variety of systems have been demonstrated. The fresnel lens can have its imaging performance improved by an order of magnitude. This is achieved by reduction in chromatic dispersion using a superimposed diffraction grating structure in its facets (Johnson, 1989). A new type of low-cost solar concentrator for large area solar thermal power generation may reduce the cost of collection optics for the collection of daylight. Currently stretched metallized polymer films are placed over a polyester/glass fiber composite that serves as the dish support structure. The parabolic shape on the metallized polymer is maintained by a vacuum. The current cost of this collection system is US$14.42/m^2 (1.34/ft^2) for the materials, but in production is expected to fall to US$ 11 m^2 (about 1/ft^2) including labor and materials (Alpert and Houser, 1989). If this technology can be successfully integrated and made cost effective it has potential for future buildings.

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14.1) Fibers and Hollow Light Pipes

Light transport systems using fibers and various types of light pipes have been studied. Only a few have been integrated into buildings to date. The large issues appear to be efficiency and cost. Future buildings may use these systems if they become more fully integrated with standard lighting and control systems in a cost effective manner. The design principles of a variety of reflective guides, prism light guides, dielectric light guides, fluid filled guides, lens guides and open light well guides have been studied (Johnson and Selkowitz, 1986). Recently, a new type of optical distribution guide has been developed called the prismatic light guide or Total Internal Reflection Film (TIRF) (Whitehead, Nodwell and Curzon; 1984; Hockey, 1985). The prismatic guide can be either a hollow cylindrical or rectangular tube shape. The guide material is smooth on the inside and corrugated on the outside. The corrugations are prism surfaces running the length of the guide. A schematic of this design is shown in Fig. 14.1.1 (Saxe and Wortman, 1987). This material transports light by total internal reflection down the guide. The reflectance (at 633 nm) of the internal surface range from 97.7% at g=0^{o} to 98.2% at g=65^{o}, where g is the vertical azimuth measured from the normal. The other angular parameter, Q, is the angle between the prism axis and the incident beam. A ray tracing system has been developed by Whitehead, 1982. The limits for total internal reflection of a flat film are Q= 27.6^{o} (acrylic), 29.5^{o} (polycarbonate) and g=4.35^{o} (acrylic), 9.38^{o} (polycarbonate). A commercial form of this material, called Scotchlamp is produced in sheet configuration by the 3M Corp. (St. Paul, MN) (Saxe, Whitehead and Cobb, 1986). This material is made of either acrylic or polycarbonate film. On one side of the film is formed 0.25-0.51 mm pitch linear prisms, the remaining film is nominally 0.51 mm thick. This material can be used for natural or artificial light distribution in buildings. There are several Israeli patents covering the use of the TIRF film light guide film used as an angle selective light transmitting panel for the roof or window application (see for example, Bar-Yonah, 1985). A typical light pipe made of polycarbonate, with a 10 cm diameter, transports 80% of the light 5 meters down the pipe while giving uniform illumination along the pipe. The illumination level can be increased by about 2.5x by using a mirror at the end of the pipe (Saxe and Wortman, 1987). This material is being used or specified in some commercial lighting systems in Canada (Hawley, 1987). We expect to see more examples of this technology used in buildings of the future.

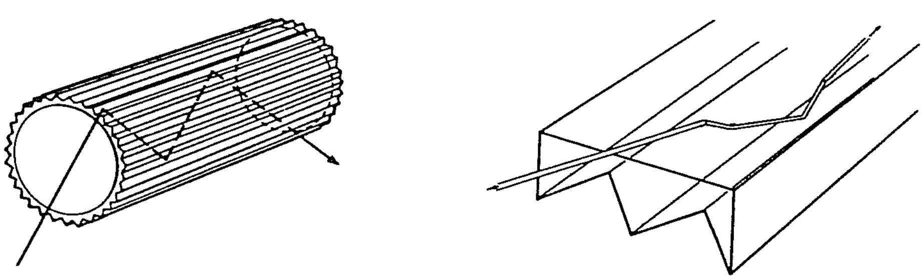

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Fig. 14.1.1. Schematic of the Total Internal Reflection Film (TIRF). The corrugations are prism surfaces running the length of the guide. A ray trace of the light trapping effect is shown.

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14.2) Fluorescent Concentrators

Fluorescent concentrators can play an important role in the concentration of light for lighting and solar conversion in buildings. They have the unique capability of being able to concentrate direct or diffuse light, unlike conventional concentrators. They can also be coupled with conventional lighting systems to give dramatic lighting effects. The greatest issues of this technology are stability of the dyes, conversion efficiency and wavelength response range. Fluorescent materials can be used to convert incident radiation of a shorter wavelength to longer wavelength, and to concentrate and guide it along the plane of the material. A fluorescent concentrator consists of a transparent plate made of either a polymer that has been doped with fluorescent dye molecules or rare-earth doped glass (Folcher et al., 1984; Neuroth and Haspel, 1987). The wavelength response of two coupled fluorescent dyes is shown in Fig. 14.2.1. Incident light corresponding to the fluorescent absorption of the dye will be captured and emitted isotropically. Because of the index of refraction difference between the plate and surrounding medium, a large portion of light will be trapped and guided to the edges of the plate by total internal reflection. One edge can be favored by silvering the other three edges. Optics can be placed at this favored edge for lighting. Concentration ratios for fluorescent concentrators can be fairly high (10-100x) (Goetzberger and Wittwer, 1981). By using three fluorescent covers selected portions of the solar spectrum can be separated and concentrated. The visible portions can be used for lighting while the near-infrared portion can be used for solar conversion. Each level of collector plate downward has a higher absorption energy, so that the innermost plate absorbs the highest energy. A mirror is used on the lowest level to reflect any uncaptured energy back to the upper lower-energy fluorescent plates.

Much of the research on solar fluorescent concentrators has favored polymethyl methacrylate (PMMA) and glass as host matrix materials. Their high optical transmission property is good to about 1 μm wavelength. For a variety of glazing applications there is a need to develop durable glazing materials that can maintain transparency further into the infrared. Generally, the fluorescent laser dyes used for solar and lighting experimentation with PMMA have not been specifically tailored for solar uses. Special dyes need to be developed with high quantum efficiency, separated emission spectra and low self-absorption. One of the most severe requirements for the dyes is they must be UV stable in the PMMA matrix. One method to improve the quantum yield and stability is by the addition of small silver particles to the dye (Wilson, 1987). It is possible that new materials such as ligands containing rare-earth ions and nonradiative coupled organic systems may offer greater stability. Furthermore, it may be possible to make a polymer-based fluorescent thin film that by index matching could couple energy into a substrate material. This design could minimize reabsorption by the dye. Emission-absorption coupled dyes may offer a wide variety of lighting, solar collection and energy redistribution possibilities. There have been several experiments in Germany in the use of fluorescence concentrators in buildings for lighting (Zastrow and Wittwer, 1986). Also these concentrators have been used for photovoltaic or photothermal energy conversion (Goetzberger and Greubal, 1977; Goetzberger and Wittwer, 1981; Stahl and Wittwer, 1983; Wittwer, 1984). Fluorescent concentrators have been used as wavelength shifters for windows in liquid junction photovoltaics (Skyllas-Kazacos et al., 1980) and photoelectrochemical cells (Muller and Manassen, 1983). A tubular luminescent photovoltaic light tube array is currently under investigation by the U.S. Air Force. With continued improvement in the lifetime and broadening of the frequency response fluorescent concentrator materials hold promise for future building lighting applications. Also, the direct coupling of fluorescent materials to light guide materials may make them more viable.

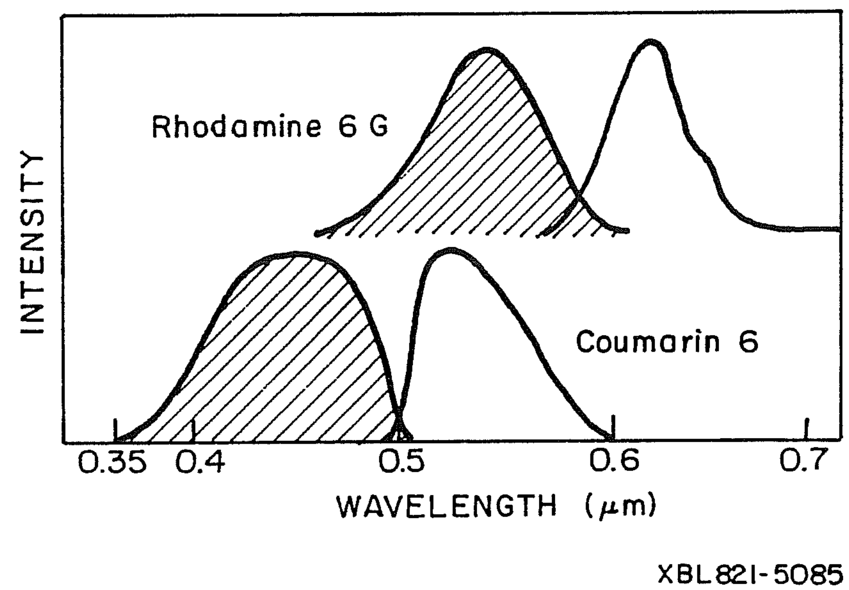

Fig. 14.2.1. The wavelength absorption and emission response of two coupled fluorescent dyes.

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14.3) Holographic Films

The use of holographic films in consumer goods and office machines has been growing rapidly for several years. The use of holographic technology for lighting and solar conversion has been hampered by several problems. These are the stability of the holographic recording material in exposed environments, chromatic dispersion and being able to accept a range of changing sun angles for natural lighting. The technology is possible for redirecting and the concentration of light for specific conditions. For tracking systems, the use of holographic concentrators has seen the most current applications. Overall, this field is young for building applications, but is expected to advance over the next 10-20 years. Holographic display systems are used in some automotive and aircraft applications. It is possible that holography as a communication medium (see Section 4) will find application in office or home information systems.

Holographic films have the potential to serve as concentrating elements, and selective filters for daylighting and solar energy applications. Holographic optical elements (HOE) are becoming used in a range of commercial applications. Transmission holograms can be designed to function similarly to conventional lenses and reflection holograms to conventional mirrors (Margarinos and Coleman, 1985). These holograms are further designated by thin or volume and absorption or phase type. Under a U.S. Dept. of Energy project holographic diffractive glazing is being studied for daylighting use. A range of holograms has been developed that can accept different sun angles and redirect neutal color light deeper into the building than conventional glazing can (Ian-Frese, 1985; Ian and King, 1987; Ian-Frese and King, 1988). Holographic lighting has been investigated for green houses (Bradbury, et al. 1986). It was shown that by redirecting the incident light from the sun in more favorable directions in the greenhouse, plant production increased. This is very significant in the winter season when the sun is at low angles to the greenhouse.

A set of stacked holographic films can be used to replicate the performance of a parabolic concentrating line-focus mirror (Hull, Lauer and Broadbent, 1986). The type of hologram used is a volume-phase reflection hologram. This type of hologram is governed by Bragg diffraction (Collier, Burckhardt and Lin, 1971; Solymar and Cooke, 1981). The efficiency and angular and spectral sensitivities of a hologram are predicted by coupled-wave or modal theory (Kogelnik, 1969; Graylord and Moharan, 1982). The reflection hologram typically has a bandwidth of 150 nm and at certain wavelengths diffraction efficiencies of greater than 90%. Since the solar spectrum is over 1500 nm wide, several holograms have to be used to cover that very large bandwidth. In a prototype experiment which has been conducted at Accurex (Mountain View, CA) three holograms were made, covering 450-1100 nm (Hull, Lauer and Broadbent, 1986). The overall reflection efficiency was 51%. If the stacking losses could be eliminated by more accurate design, then the ideal reflectance could be 69% An example of the wavelength response of the three hologram stack is shown in Fig. 14.3.1. (Hull, Lauer and Broadbent, 1986). It is expected with improvement of the holograms and by using a stack of five that 70% efficiency is possible. Even though holographic reflectors are not as efficient as metallic reflectors, nor have the bandwidth, their use in concentrating collectors will save on the weight and cost of the support structure. Fairly large holographic concentrators in excess of $1m^2$ have been fabricated in Germany (Tholl, and Stojanoff, 1988).

Selective band filters for window have been experimentally developed from transmission-phase Bragg-Lippman holograms. Holographic filters with sharp transmission cut-offs at the end of the visible have been fabricated. In the near-infrared (600-1100 nm) the reflection bandwidth was noted to be 500 nm (Jannson, Jannson, and Yu, 1985). This work is discussed in Section 8.3. Overall, holographic technology has promise for the future, but how quickly it will be integrated into building lighting design remains to be seen.

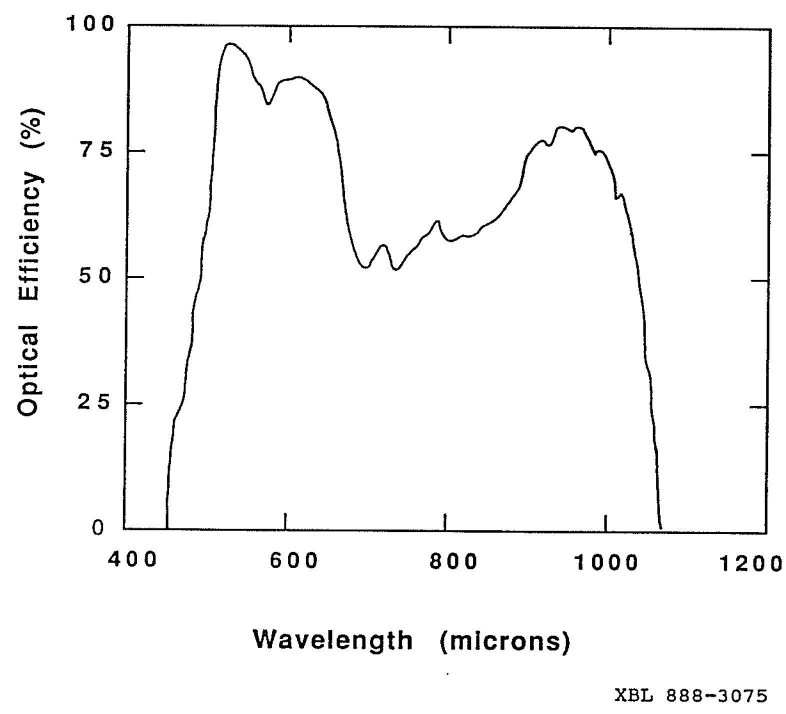

Fig. 14.3.1. An example of the wavelength response of a three hologram line focus concentrator stack (after Hull, Lauer and Broadbent, 1986).

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V. CONCLUSIONS

The future of glazing is both exciting and challenging. The excitement comes from the wonderful possible technologies, the challenge comes from the necessary upgrading and integration the fenestration industry must go through to make such advances in glazing possible. Substantial progress in glazing technology is seen today compared with ten years ago, with use of low-e coating and gas fill technology to improve the thermal properties of windows. The future will bring further improvements in the optical performance, selectivity and user defined properties of glazings. With changes in the industry, we will see integration of several technologies to make dynamic switching glazings and static glazings with tuned properties, optimized for their application or user preference. If the building and wall or cladding industry can effectively integrate, then highly efficient window-wall fenestration sections can be made. Advances in manufacturing technology will certainly allow this to happen, provided the industry will modernize. The cost of window and wall sections will also depend on the ability to produce the elements economically. There is much indication that international competition will push this technology forward, much as what happened in the automotive industry in the 1970s. In the area of computer based techniques we are seeing an explosion of technology with the increased development of the more powerful personal computers. Both design and energy analysis programs and architectural data bases are expected to be integrated in the future into expert systems. These expert systems will allow for more efficient design with a very high level of user friendliness. For glazings we expect to have glazings that are easier to clean and maintain, but may be more complex, performing multifunctions. Materials developed from other technologies can play a role in future glazing materials. Materials with angle selective properties can give further improvement to existing glazing. Antireflective coatings can provide a necessary improvement to glazed surfaces if they can be made durable enough. The field of communication will continue to influence glazings strongly with integrated communication and display glass used in office buildings. Some technology being developed in the automotive and aerospace sectors are expected to be transferred into building fenestration. A greater environment for security, safety and fire resistance is expected in the future because of improvements in fenestration. The use of smart windows, light collection and transport systems, along with smart control systems will increase the quality of lighting while enhancing efficiency. The arrival of smart office machines and residential smart appliances will help the development of smart building systems. It is expected that the use of natural daylighting for the work space will continue to grow in the future.

Summing up the future, we will see the integration of many technologies. We will see more intelligent use of energy, better comfort and improved interior regulation of office and residential environments. This will move forward at the rate at which the international fenestration industry can modernize to meet this challenge.

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