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# INFLUENCE OF WINDOWS ON BUILDING ENERGY USE

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## ABSTRACT

Window system design and operation have a major effect on energy use in buildings as well as on occupants' thermal and visual comfort. Window performance will be a function of optical and thermal properties, window management strategies, climate and orientation, and building type and occupancy. In residences, heat loss control is a primary concern, followed by sun control in more southerly climates. In commercial buildings, the daylight provided by windows may be the major energy benefit, but solar gain must be controlled so that increased cooling loads do not exceed daylighting savings. Reductions in peak elctrical demand and HVAC system size may also be possible in well-designed daylighted buildings. Improved analysis tools and more extensive experimental data on window performance in buildings are necessary to improve design decisions and guide new product development.

Key words: Fenestration, thermal performance, daylighting analysis tools, window test procedures

# INTRODUCTION

Windows play many important roles in the design of buildings and strongly affect their energy use. In order to develop effective energy-conserving uses for windows, first we must carefully define the nature and magnitude of their energy problems. Our perspective on the problem, and the context in which it must be solved, will influence the solution. Personal and professional perspectives vary: an architect will bring different insights than an engineer or a scientist. There is a national perspective: typical design practice, the cost of energy, and the overall importance of energy issues varies considerably from country to country. There is a technical component to the problem: the relative importance of heat loss, heat gain, daylight admittance, etc. Finally, there are many non-technical or non-energy aspects such as view, comfort, appearance, health and well-being, and design aesthetics. "Saving energy" is not a problem, it is a solution. If it was the problem, an easy solution would be to close all buildings, padlock the doors, and turn off the furnaces and electrical equipment. But the real problem is minimizing the consumption of nonrenewable energy resources consistent with the functional objectives of buildings. In houses these might include comfort and health; in offices they also include productivity.

A realistic set of solutions requires tradeoffs and compromises because the problem is complex and multi-dimensional. Much of this paper will focus on defining the nature of the energy problem associated with windows and the critical features that much be addressed to ensure maximum savings consistent with effective use. The examples are drawn primarily from experience in the United States, although much of what is covered will be broadly relevant to any country.

In the United States, about 5% of total national energy consumption can be attributed to windows; this is approximately evenly split between windows in houses and windows in nonresidential buildings. By providing daylight, windows can also influence 5% of the total national energy consumption attributable to electric lighting. Focusing on energy performance, we can define six primary factors:

1. Thermal transmission.
2. Light transmission.
3. Control of solar heat gain.
4. Infiltration.
5. Ventilation.
6. Condensation.

In addition to these primary energy performance issues are a host of other critical performance issues that influence decisions regarding window design. These include sound transmission, water penetration, resistance to wind loads and operating forces, view, appearance, durability, fire-safety, security, and costs. Most decisions regarding window design must account for these latter factors as well as the energy performance issues.

From an energy perspective, windows' net energy effect can balance thermal losses against useful winter solar gain and daylighting benefits. The response time to energy flows (solar gain and conductive gains or losses) is small compared to wall and roof elements. Windows are typically nonhomogeneous elements having joints and thermal bridges that influence performance. The influence of air films and air infiltrations is typically greater than for opaque building elements, and windows generally influence thermal comfort and satisfaction to a greater extent than do walls or roofs.

Windows are unique from the occupants' perspective because they provide light and view, functions not provided by other elements. From the designer's perspective they are unique because they represent a significant element in the vocabulary of architectural design. As such they are often used as formal elements of architectural expression in addition to the energy and non-energy performance requirements discussed previously.

The window is a dynamic element in the building envelope and must respond to continuously changing occupant needs as well as continuously changing environmental conditions. For example, at times a window must provide good optical clarity and view out, and at other times it must provide privacy for people indoors. We use windows to admit daylight but must counter that with glare control when the light source is too intense. In winter the sunlight through windows is often welcome, but at other times it may cause overheating. Thus a primary performance requirement for window systems is the ability to dynamically control heat flows and thermal fluxes.

Figure 1 indicates how the thermal properties of windows influence annual energy requirements. The thermal properties determine heat loss and heat gain, which in turn determine peak heating and cooling loads in a given climate. It is the dynamic response of the heating/cooling system to those loads which ultimately influences annual energy requirements. Window thermal properties also influence annual energy requirements indirectly because they affect occupant response to thermal comfort conditions, as shown in Fig. 2. Annual energy use for lighting in a daylighted building is influenced by window optical properties, which in turn may be influenced by dynamic fenestration controls to balance glare control and light admittance, as shown in Fig. 3. These effects are summarized in Fig. 4, which suggests that the thermal and daylighting performance of window systems results in a net energy performance only after the dynamic aspects of climate, building operation and control, and occupant requirements for thermal and visual comfort are satisfied throughout the year. In northern European countries, where the winters are long and cold, and the summers rather short and mild, window performance may be equated more narrowly with control of heat loss. But in much of the United States and elsewhere, the dynamic interplays of conflicting thermal forces throughout the year are the critical factors that influence overall performance and annual energy consumption.

Our perspectives on window energy performance have changed with time. In the early 1970s, just after the initial increase in oil prices, windows were seen primarily as an energy cost. Ten years later, a different perspective is emerging. This perspective acknowledges that losses can be minimized and that the useful winter solar heat gain and benefits from daylighting can turn windows into a net benefit rather than a net cost. In fact, we make the following claim: high-performance, managed window systems carefully installed in a well-designed, energy-efficient building will provide net energy benefits for any orientation in most parts of the United States. This means that window systems will outperform the best insulated wall or roof element. The systems that meet this claim may not be cost-effective in the narrow sense of that term, but we believe that some solutions can meet those requirements.

In the residential context we look primarily at tradeoffs between gathering useful solar gain and the conduction/convection/infiltration losses that form the negative side of the heat balance equation. Figure 5 schematically compares the heat gain and loss characteristics of several different envelope elements using transmittance as an approximate measure of solar heat gain, and U-value as an approximate measure of heat loss. Our ideal components would lie in the upper-left quadrant of the figure, displaying low heat loss rates and relatively high potential heat gain. Not all the available heat gain is useful, of course, which is why the dynamic controls discussed earlier are important. However, Fig. 6 shows a quantitative map of net useful energy flux through a south-facing window in Madison, Wisconsin, as a function of shading coefficient and U-value. One can immediately see the specific combinations of window properties which result in either a net heat loss, a zero energy balance (the dark diagonal line), or a net energy benefit for that building module. The following sections examine existing and new options for controlling heat loss, managing solar gain, and utilizing daylight.

## CONTROL OF HEAT LOSS

To better understand the performance of window systems that limit heat loss, we first must identify the heat loss mechanisms. Figure 7 illustrates the primary heat flows associated with double glazing and suggests the heat loss mechanisms that must be controlled to improve window performance. The primary mechanisms are: 1) radiation suppression, 2) convection suppression, 3) reduction of infiltration, and 4) movable insulating systems that completely cover the window.

The largest heat loss mechanism in a typical double-glazed window is radiative transfer. High-performance window systems can be made by introducing one or more low-emittance layers into multiglazed systems. An ideal low-emittance coating will be transparent in the solar spectrum and highly reflective to the long wavelength infrared energy that is a component of thermal losses. After years of experimental development, these coatings have appeared as commercial products applied to both glass and plastic substrates. Many new window products incorporating these coatings are emerging on the market. The U-value of conventional single-, double-, and triple-glazed systems as a function of emissivity and coating placement is shown in Fig. 8. At present, since most low-emittance coatings are not durable, they are enclosed in air spaces of double- and triple-glazed systems. Figure 8 illustrates that a double-glazed system with a coating of emittance 0.1 to 0.2, placed on the number 2 or number 3 surface (counting from the outside), will perform as well as or better than a conventional triple-glazed window. The first primary market penetration of these systems has been in this application where equivalent or improved performance is obtained with a window system that is simpler, lighter, and has room for additional thermal improvement, such as by adding low-conductance gases to the windows.

Additional research is in progress on low-emittance coatings to further raise their solar transmittance, lower their emittance, and improve their overall durability, particularly for exposed applications. Modern vacuum deposition processes have produced relatively inexpensive coatings on glass and plastic substrates, but work continues to produce even cheaper coatings using both vacuum and non-vacuum processes. Combinations of low-emittance coated substrates and low-conductance gases in a quadruple-glazed window make it possible to obtain K-values between 0.5 and 1 $W/m^2K$, with a solar transmittance of ~0.4 to 0.5.

Once a low-emittance coating is added to an air space, the use of a low-conductance gas such as argon, sulfur hexafluoride, or mixtures thereof will produce moderate additional reductions in heat loss rates. Many manufacturers have used such systems, although there appears to be some disagreement in the industry about how well these gases are retained in sealed-glass systems. One would expect future improvements in glass-sealing technology to further increase the opportunities for using low-conductance gases. Low-conductance spacer materials may also be required to reduce the edge losses that characterize sealed glass units with conventional aluminum spacers. In principle it is also possible to evacuate the air space completely and provide spacers to maintain glass-to-glass separation. This should result in K-values in the range of 0.5 $W/m^2K$ as long as a low-emittance coating is provided. Providing a long-term hermetic seal that is cost-effective is still the primary stumbling block for such a system. To obtain the appropriate reduction in conductance, the air gap must be evacuated to a very hard vacuum, which places severe requirements on the seal's integrity and durability.

A variety of movable insulating devices has been developed in the last decade for use with windows. Some are designed to be deployed on the exterior of the window, others on the inside, and still others between glass. The insulating properties claimed for these systems range from negligible improvements to K-values below 0.5 $W/m^2K$. The performance of many of these systems has been the subject of some controversy since most involve moving elements and edge seals that may deteriorate with time and use. In addition, their thermal advantages are realized only when occupants choose to close the device, an operation that can prove unreliable. The best results occur when the device provides privacy or comfort as well as thermal control since consistent operation is more likely to occur. Operable systems can be motorized but normally at substantial additional cost. Traditional systems in the European market, such as rolling shutters, have been redesigned to improve thermal performance, and are beginning to appear in the American market as both insulating and shading devices. The most successful movable insulating devices in the American market have been the simpler devices mounted on the interior of the window, which are sold primarily for their aesthetic value but which now have improved insulating performance. Interior devices that are highly insulating and fit tightly to the window are more expensive, are less widely used, and can create problems. In winter they increase the risk of condensation and glass breakage due to thermal shock when the devices are first opened and the glass panes are very cold relative to the indoor air temperatures. During other times of the year, the heat buildup between the window and a closed insulating device can reach temperatures high enough to damage the window and/or the insulating system.

Due to the difficulties of producing highly insulating movable devices, there is increased effort to produce a highly insulating glazing material. The multilayer windows described previously achieved the desired insulating values but have themselves become relatively complex because of the additional layers involved. Another approach is to use a glazing material that is intrinsically insulating. Silica aerogel is a microporous material that has excellent insulating properties, good optical clarity, and relatively high solar transmittance. The material consists of a network of small silica particles whose size is much less than a wavelength of light, thereby reducing scattering effects. The fine pore structure of the material results in a K-value lower than that of air. Figure 9 shows the K-value of an aerogel-filled window as a function of thickness. Since at present the aerogel material is relatively fragile, it too must be protected in a hermetically sealed double-glazed unit. With further research it may be possible to produce hard surfaces on each face of the aerogel, thus simplifying this packaging requirement. Initial experiments also suggest that the aerogel window could be evacuated, resulting either in further improvements to conductivity or equivalent low conductivity with a much thinner window, and therefore a higher solar transmittance. A significant feature of an evacuated aerogel window is that the improvement in thermal properties is reached with only a modest vacuum, requiring a much simpler sealing technology than the evacuated window described earlier. Furthermore, the aerogel acts as its own transparent spacer and has sufficient structural strength to withstand the applied pressure.

## CONTROL OF SOLAR GAIN

While heat loss has historically been the most important aspect of window energy use, the cooling loads resulting from uncontrolled solar gain are increasingly important. In the United States most commercial buildings, even in the northern part of the country, have central air-conditioning systems. During much of the year, heat gains from windows must be removed by these systems. Much of the new housing construction in the United States is located in the "Sun Belt", the southern one-third of the country where cooling loads are much higher than heating loads. Almost all new construction in this region is air-conditioned. Even in the northern half of the United States, a surprisingly large percentage of new housing is built with central air-conditioning. Cooling loads from windows not only add to annual energy costs, but also add first cost to the building due to the cost of the cooling system. Furthermore, although cooling loads may be smaller than heating loads, because the cost of electricity is normally much higher than the cost of furnace fuel, the annual cost for cooling is frequently larger than for heating. In nonresidential buildings the cooling issues are even more important because of the relatively high internal heat loads from office machines, lighting, and people. A traditional solution to reduce cooling loads in office buildings is to use low-transmittance glass. This results in the sleek reflective building skins that have characterized design in the last 20 years. However, these solutions minimize not only cooling loads but also available daylight, requiring that electric lights be on whenever the building is occupied. However, it is possible to provide sun control and still admit daylight using a number of design approaches, which are discussed below.

Fixed exterior shading devices such as overhangs, fins, or various types of shade screen materials are often employed. These typically shade the window from sun penetration but allow some view of the sky so that daylight can be admitted. In addition they often break up and diffuse the incident solar beam so that diffused and attenuated direct sunlight is also introduced. However, because they are fixed, these solutions invariably represent a compromise between the requirements of sun control, daylight admittance, and glare control. In principle, operable sun control systems should provide better performance than fixed systems. Operable systems include a variety of interior window treatments such as shades, blinds, and drapes. Exterior systems include movable awnings, operable fins and louvers, shade systems, and exterior venetian blinds. Either type of system can be manually or automatically controlled. Automatic controls with manual overrides would appear preferable, ensuring that the systems function properly at all times. Exterior operable sun control systems have been used successfully in Europe for some time, but are only recently attracting attention in the United States. They are relatively costly compared to interior treatments or reflective glass, but since they may allow reductions in cooling system sizing as well as permitting daylight utilization, they may be economically beneficial. Operable shading systems should also provide improved thermal and visual comfort relative to most fixed shading solutions. While it is difficult to estimate the economic benefits of comfort directly, the cost of unhappy and uncomfortable office occupants is clearly large.

Window shading controls can also be located between glass. In the case of exhaust air or air-flow windows, the ventilation air from the room is exhausted between the panes of a glazing system over a venetian blind and either exhausted to the outdoors or returned to a heating and cooling system. In the winter, this provides an interior glass surface temperature that closely matches the room air temperature, thus providing good thermal comfort. In the summer, the blinds, if adjusted properly, absorb the sun's energy; the resultant heat is then carried off in the moving air stream. On sunny days in the winter, the blind acts as a solar air collector and the heat collected may be used in other parts of the building. These systems have been rather extensively used in Europe and are only now beginning to be introduced into the United States.

Window systems of the future may use optical switching materials and coatings to provide much of the solar control that now requires mechanical devices. Ideally, one would like to control the intensity of the transmitted radiation, its spectral content, and perhaps its spatial distribution in the room. Since the sun's spectrum is approximately 50% visible energy and 50% near infrared, one could reject more than half the total energy content while having only a minor effect on light transmission. Blue-green glass and some metallic coatings have spectral sensitivity, allowing higher transmittance in the visible portion of the spectrum. Future improvements in coatings should further increase spectral control. It should also be possible to use the same coating technology to apply interference coatings to produce any desirable color or tint. An ideal reflectance curve for such a coating is shown in Fig. 10. Since the visible properties and the overall solar properties of such coatings may be different, it is important to specify each separately.

Most of the shading systems described previously somehow control the intensity of transmitted solar energy. It is possible to produce optical switching materials having transmittance properties that change from clear to reflective or absorptive as a function of exterior climate conditions such as sunlight intensity or temperature, or to use an electrical system that controls as a function of climate and building conditions. Examples of such materials are known to all of us: photochromic sunglasses switch with respect to light intensity; liquid crystal temperature indicators change optical properties in response to temperature changes, and many watch displays switch from transparent to reflective as each digit changes. However, it is difficult to scale these coating technologies up to window size and produce them at low cost in a form that will survive temperature extremes and solar exposure over many years. Research is in progress in a number of locations to produce such coatings. The most promising approach to providing active control of transmittance is based on electrochromic coatings. These multilayer coatings would be switched with a small applied current and could be continuously varied between high and low transmittance. Initial results in basic materials research look promising, but it will be some time before it is known whether this is a successful solution for building applications.

Another advanced coating application would be to produce window materials whose transmittance is a function of solar incidence angle. The coating might then perform like a series of fins or overhangs, rejecting light that arrives at greater than critical incident angles and admitting light otherwise. It may be possible to produce such effects using materials embedded within glazing substrates or with sputtered coatings or holographic films.

## DAYLIGHT UTILIZATION

In the United States half of all energy use in nonresidential buildings is attributable to lighting. There are many ways of saving lighting energy, but once again these solutions must be consistent with maintaining or improving productivity. Despite the high cost of energy, the value of human productivity is many times greater. In the United States, with our energy costs and wages, the annual cost of providing lighting energy for a small office occupied by a single occupant is approximately equal to that worker's salary for a single hour. Thus, if a poor lighting design costs the employer even one hour's worth of productivity in return for large annual lighting savings, the employer has lost money overall.

We can say that all buildings with windows or skylights are daylighted, but no electrical energy is saved unless the lights are dimmed or turned off. A proper discussion of daylighting in buildings would consider its impacts on the following issues: electric lighting integration, energy savings, peak load impacts, HVAC systems impacts, lighting quality, view, and glare. As an architectural design element, daylighting influences the built environment at many different scales: urban planning, building form, envelope design, fenestration design, and interior design.

There are significant differences between using the sun and sky as a source of light and using electric light sources. A primary difference is the inherent variability in daylight and its unpredictability. Standard clear and overcast skies have been defined and used for some time by the international lighting community. However, these standards were often created with minimum conditions in mind, in order to verify a minimum design standard. For the purposes of either estimating occupant satisfaction or calculating energy effects, these sky models must be expanded to include partly cloudy and direct sun effects and to account for the variability in daylight levels and sky luminance distribution over days, months, and the entire year. Research is under way in many locations worldwide to fill these gaps.

There are several dimensions to estimating the lighting energy savings in a daylighted building. The most important problems are to estimate the available daylight (Figure 11), to understand how the lighting control system responds to this available daylight (Figure 12), and then to estimate the overall energy impact including thermal effects. The cost implications of daylighting also should account for utility rate structures that may have additional costs for peak demand or may have time-of-day rates. We describe some insights on daylighting energy savings based on extensive use of a building simulation program, DOE-2.1B, which includes the effects of daylight in a typical office building. In these studies we determined that we can specify many daylighting effects using a new term, effective aperture, that includes the combined effects of window size and transmittance. The numerical value for effective aperture is simply the fraction of glass area in the wall (as a percent) times the visible transmittance of the glazing. Thus the value of effective aperture ranges from 0 to 1, although most practical values for typical wall facades and glazing types range between 0 and 0.4.

Figure 13 shows lighting energy consumption as a function of effective aperture for three cases: a nondaylighted office and two cases with daylighting, one with a dimming control, the second with on/off control. In both cases, the controls are set to provide 538 lux (50 footcandles). The dimming system shows the best performance for small apertures, but eventually the two curves cross, indicating that the on/off system performs better than the dimming system. This is because the dimming feature requires a minimum power of 10% even with no light output, whereas the on/off system is turned off and consumes no power above its setpoint. Different selections of these specific control algorithms would, of course, change these results slightly.

This annual perspective hides seasonal differences. Figure 14 shows lighting energy savings as a function of effective aperture for different seasons of the year. We see that the spring, summer, and fall curves are close together, but the winter curve shows significantly lower savings.

The selection of interior illuminance level as well as control type will also influence energy savings. Figure 15 shows the performance of an on/off system at three illuminance setpoints and one continuous dimming system at one setpoint. The selection of illuminance level has a major impact at small aperture areas, decreasing in importance as window size increases.

Figures 16 and 17 combine both daylighting and thermal effects in evaluating overall energy performance of an office building module as a function of effective aperture in two climates: Madison Wisconsin, a rather cold climate, and Lake Charles, Louisiana, a very hot climate. Each figure shows two families of curves at two different installed power densities and shows the dimming and on/off lighting control strategy as dotted curves and the nondaylighted building as a solid line. In all cases, daylighting provides significant energy savings compared to a nondaylighted building having identical glazing. In the case of a north zone in Madison, the daylighted building reaches an optimum with relatively large effective apertures. No daylighted case increases above the respective levels for insulated walls with no windows through the range of effective aperture considered here. However, for a south zone in Lake Charles, a cooling-dominated climate, the daylighting savings never reached the magnitude of the Madison case, and optimum values occur for moderately small apertures after which total energy consumption rises. The rising curves for both the daylighted and nondaylighted cases are driven by the impact of cooling loads; in both cases larger effective apertures make it possible to have daylighted buildings that show higher energy consumption than they would have with very small windows, or no windows at all.

This contrast between climate types and orientations suggests the difficulty of broad generalizations regarding fenestration properties and associated daylighting savings. Also in both cases the computer simulation assumes the use of simple interior blinds whenever the direct sunlight or glare from the window exceeds pre-set values.

Figure 18 examines the case of a skylighted building in El Paso, Texas, for three installed power densities. Here again we see substantial energy savings but note that the maximum daylight savings are reached at relatively small effective apertures, less than about 0.04.

Figure 19 examines the effect of daylighting and window management on annual electric consumption peak electrical demand and chiller size for an office building in Madison. The demand curves show the effects of both daylighting and "window management" (i.e., use of shades or blinds) on peak demand and suggest that using daylighting combined with window management to control solar gain is the best overall strategy for controlling peak electrical demand. In the bottom curves, which show chiller size as a function of effective aperture, the daylighted case without window management (c) requires a larger chiller than the nondaylighted case with window management (b) for apertures larger than 0.2. Chiller size affects the sizing of the whole heating and cooling systems and can represent a major cost in commercial buildings. This again suggests the importance of window management to control solar gains and cooling loads.

These and other simulation studies suggest that there are large potential savings in daylighted buildings but that fenestration systems must be carefully designed and controlled to produce optimum performance. Fenestration that is too large or poorly controlled may increase energy use due to increased cooling loads that exceed the daylighting savings. This will be increasingly true as electric lighting systems become more efficient. Daylighting and window management should be of interest to building owners because they represent a potential to reduce HVAC equipment size in the building and save first costs for the owners. They should also be of interest to utilities because they may reduce peak electrical demand and thus reduce requirements for new generating capacity. In the United States a number of utilities have recognized these potential benefits and have instituted programs to accelerate the use of daylight in nonresidential buildings. Despite the potentially large savings, most estimates are based on simulation results and there are few measured data in buildings to validate these conclusions.

The potential benefits of daylighting have increased interest in the use of traditional techniques to introduce daylight into large spaces and have generated new interest in the development of improved optical systems for daylighting in buildings. Large gallerias or covered malls are traditional elements of many older European cities. These glazed roofs and atria are becoming popular in large shopping centers in American cities as well as serving as elements within single large buildings. In most cases, pleasant spaces have been created; whether these are energy-savings strategies is still unknown. A related innovation is a large fabric roof structure to enclose buildings. Their traditional use has been in sports stadia, but in a few cases in the United States they have been used for retail stores, and there have been proposals to use these systems in office complexes. They offer some potential benefits, but heat losses and cooling loads must be better controlled if these are to be cost-effective solutions in most U.S. climates.

In more conventional buildings, glass block elements have been used for some time to redirect the light from a downward direction up to a ceiling. Research is under way on a variety of techniques using refractive and reflective optics as well as holographic elements to redirect daylight that is incident on vertical surfaces up towards ceilings. This should allow deeper penetration of sunlight into buildings in a way that does not contribute to glare or excessive thermal loads. Future techniques to provide deep sunlight penetration into the cores of buildings might involve the use of tracking mirrors, fiber optic or hollow light guides, and other optical techniques to collect, concentrate, transmit, and distribute light into buildings. Most of these systems utilize direct sunlight and would have limited use in climates having few sunshine hours. It is interesting to note that between 1890 and 1940 there were a large number of U.S. patents on optical devices for collecting and introducing sunlight and daylight into buildings. From the 1940s onward, as cheap fluorescent lights became available, interest in these optical systems decreased substantially. Now we find a new interest in advanced optical systems motivated by increased lighting energy costs. At the same time electric lighting hardware is being improved. It remains to be seen whether the next generation of advanced optical systems for collecting and distributing sunlight will compete cost-effectively with the coming generation of electrical systems. In either case a decision will not be made on energy issues alone. People may choose to pay for the color rendition and variability of daylight and sunlight even if the raw lumens introduced by these systems are not substantially greater than those from electric lighting.

Successful use of daylight in buildings requires additional effort in the design of the building envelope and in the integration of the daylighting system with the electric lighting system. The lack of simple-to-use design methods that help one make critical design decisions accurately and cost-effectively throughout the design process limits current daylighting design. One approach for designing daylighting spaces is to use architectural scale models. This approach is based on the fact that a scale model will have the same illuminance levels and distribution as the real space if all the critical architectural details are faithfully reproduced. It is thus possible to use photocells to measure the illuminance distribution directly for even the most complex building design if it can be reduced to a scale model. One of the difficulties with this approach is the ever-changing sky conditions that make it difficult to compare results on succeeding days. A solution to this is to bring the sky indoors. Several types of sky simulators have been built to reproduce one or more sky conditions in a facility in which models can be tested under repeatable sky conditions. A large hemispherical sky simulator is shown in Fig. 20. This simulator, recently constructed at Lawrence Berkeley Laboratory, can produce most of the standard CIE overcast, clear, and uniform sky distributions as well as direct sunlight. A computerized data-acquisition system collects photometric information from the model in seconds and can assist with the data analysis. This simulator has been used by several design firms for major new buildings in addition to being used as a research tool. Facilities of this type cannot readily be produced in many locations, but useful data can be collected from careful measurements made in somewhat simpler artificial skies.

Analytical models for calculating daylight factors or illuminance levels have long been used in daylight predictions. A major change during the past 10 years has been the shift from simple graphic and computational techniques to computerized techniques. Although computer programs allow more detailed and accurate calculations, their primary advantage will probably turn out to be their ability to present the resultant illuminance distribution data in a more graphic and understandable form than conventional numerical results. A sample isolux contour from one such model, SUPERLITE, is shown in Fig. 21. Computer users often get carried away with the apparent power and versatility of their models. In the future it will be important to be able to analyze luminance distribution and other aspects of lighting quality; these advanced computer models coupled with improved graphic output will provide new and more useful data to building designers. The computer also allows design solutions to be evaluated under a wide variety of conditions, which is important given that daylight changes by hour of the day and season. In the past the tediousness of these calculations meant that daylighting was typically evaluated under a minimum of circumstances. In the longer term, experimental and analytical models for determining daylighting performance of fenestration and solar gain effects will need to be integrated into the large hour-by-hour simulation models if the simulations are to accurately represent real building performance. Figure 22 shows a schematic diagram of how daylighting and solar gain algorithms for complicated fenestration systems are being developed for the next generation of the DOE-2 program. The primary purpose here is to provide substantial flexibility in modeling more sophisticated architectural solutions.

Examining a range of buildings that have been effectively daylighted in the past and some of the better designs emerging during the past few years indicates that fenestration systems can be designed to admit daylight in a way that provides effective lighting and reduces electric lighting energy requirements. It is equally clear that thermal gains and loss must be controlled in order to produce the most cost-beneficial solution. There are few data that relate thermal and daylighting aspects of a fenestration system with actual net energy requirements. To adequately account for occupant effects as well, it is important to make such measurements in occupied buildings. Energy performance data have been collected from a large number of houses and from a smaller number of nonresidential buildings over the past 5 or 10 years in many countries. However, in an occupied building it is difficult and in many cases impossible to accurately measure the effect of individual components such as windows. It is even more difficult to understand how small changes in window characteristics, which may affect heating, cooling, and daylighting, ultimately affect overall building performance. It is important to gather data at this level of detail since these are the design decisions that architects and engineers must make continually. We must close the design loop by providing architects and engineers with measured and analyzed data from real buildings and outdoor test facilities so that they can see the measured energy consequences of their design decisions.

In order to make detailed and accurate measurements of window system performance in a operating building, under realistic outdoor conditions, we have designed an outdoor test facility. Current performance estimates of annual energy consequences are based on laboratory tests of window characteristics, such as K-value and shading coefficient, coupled with computer models. To measure these effects directly under outdoor conditions would require the capabilities shown in Fig. 23. The Mobile Window Thermal Test Facility (MoWiTT), recently constructed at Lawrence Berkeley Laboratory, is designed to meet most of these operating requirements. It consists of two side-by-side guarded chambers, each of which will accept a window up to a size of about 2.5 $m^2$. The chambers will also accept skylights. In addition to the guard system to reduce losses on the non-glazed walls, we utilize novel large heat-flow sensors to determine the fate of solar radiation that enters each cell. A computer system that can measure up to 300 data points monitors and controls all aspects of the heating/cooling system in each chamber as well as collecting data from a local weather station and from sensors throughout each chamber. Data collected from this facility, which should be operational in late 1984, will be used to examine the relationship between traditionally measured or calculated window properties and the daily or seasonal consequences. By running tests extending over several days, in a variety of climates, the facility should collect a sufficient data base to allow us to evaluate the detailed window algorithms that form the heart of most state-of-the-art simulation codes. In addition, the identical side-by-side test cells allow for detailed comparisons between product performance or comparisons between the same product operating under different room conditions. The conductance, air leakage, thermal mass, and internal loads of each chamber can be controlled independently to simulate the effect of the window interacting with different building types. Figure 24 shows a schematic cross section of the trailer, and Fig. 25 is a photograph of the trailer undergoing calibration tests.

## CONCLUSIONS

We can summarize the details of this paper in a series of simple statements:

1. Window systems play a variety of roles in buildings, of which energy is only one. Since the primary purpose of most buildings is to provide habitation, or comfortable and productive workplaces, energy will never be more than one of the important factors that influence window design.

2. Whenever possible, one should attempt to couple improved energy performance with other desirable functions.

3. The annual energy performance of a window system involves complex tradeoffs between heating, cooling, and daylighting requirements. The relative importance of each of these will depend strongly on building type, climate, and patterns of occupancy.

4. It follows that no single simple window system will provide ideal performance under all conditions.

6. It further follows that dynamic control of window properties, either through the fenestration materials themselves or with the addition of interior and exterior control devices, will generally provide the most versatile and effective control.

7. In residences where heating is the primary energy factor, it should be possible to develop window systems that provide benefits on even the north side of a building.

8. In residences where cooling is the primary window design factor, it should be possible to combine static or operable shading systems to provide view and daylight while minimizing cooling load.

9. In nonresidential buildings characterized by a large lighting load, window and skylight systems can dramatically lower lighting energy consumption. However, care must be taken to

control solar gains so that increased cooling loads do not negate daylighting energy savings.

10. The full benefits of a daylighted building would include not only energy savings but also the value of reducing peak electrical demand and the possible value of reducing the size and costs of cooling systems.

11. New optical techniques are under development that could extend daylight utilization from the perimeter of the building to areas that are now out of reach.

12. Effective optimization of window properties requires design methods and design tools that are accurate and simple and can be used at different points in the design.

13. There are few data available to compare the relative value of different design tools or, in many cases, to evaluate the appropriate use of the tools.

14. In daylighting design the use of scale model studies, along with computational and graphic tools, adds a powerful design alternative.

15. In most cases once a designer has used a series of tools to make design decisions, there is no feedback loop to assess how well these solutions worked. Performance data from monitored buildings and field test facilities are important to provide this feedback. To be most useful, measured performance data must be of sufficient detail and accuracy to evaluate component performance in the building since this is the level at which most decisions are made.

16. It is possible to design fenestration systems that are consistent with the owner's requirements for comfort, health, and safety; the architect's concerns for functional integration and aesthetics; and the collective global concern to reduce the pressures on nonrenewable energy resources.

## ACKNOWLEDGEMENT

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

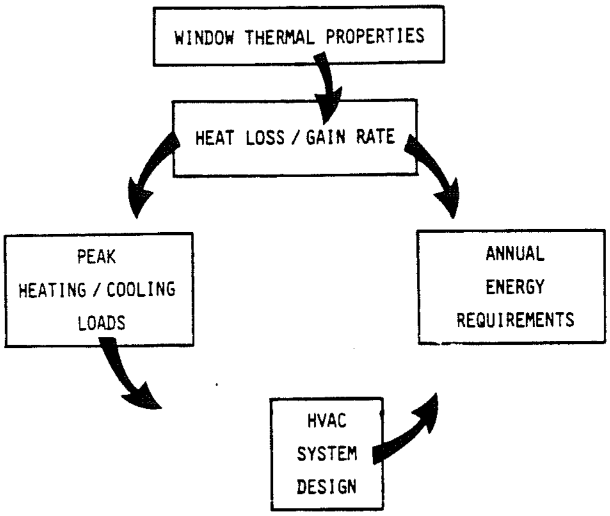


Figure 1. Factors that influence annual energy requirements of windows.

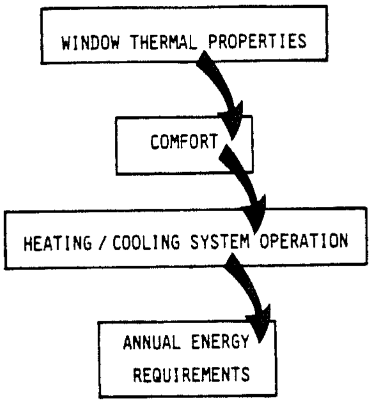


Figure 2. Influence of non-window factors on annual energy performance.

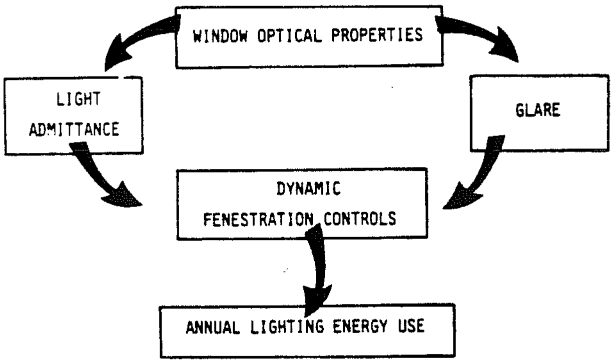


Figure 3. Dynamic fenestration controls, which optimize light admittance and glare control, influence annual lighting energy use.

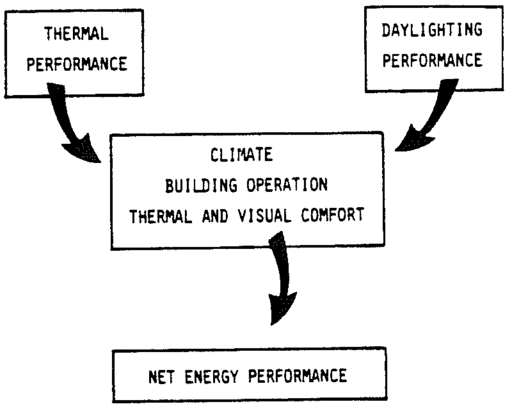


Figure 4. Determinants of net energy performance.

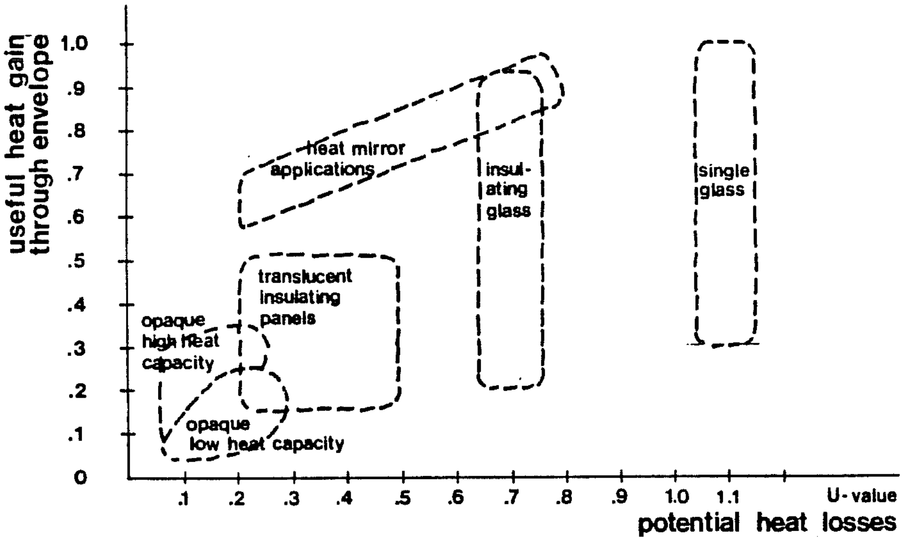
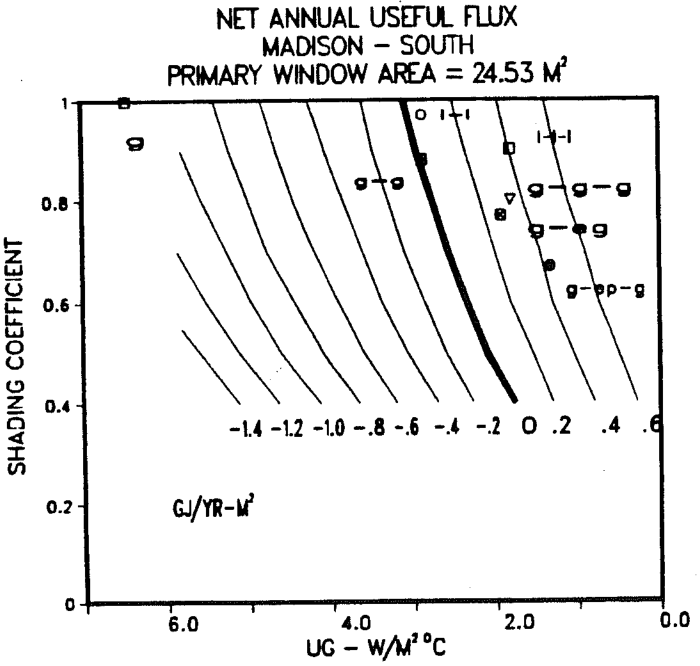


Figure 5. Solar gain and heat loss potentials of representative envelope elements.



| | U $(W/m^2{}^\circ C)$ | SC |
|---|---|---|
| g | 6.46 | 1.0 |
| g-g | 2.87 | 0.88 |
| g-g-g | 1.8 | 0.8 |
| g-eg | 1.92 | 0.77 |
| g-ep-g | 1.32 | 0.67 |
| l-l | 2.87 | 0.97 |
| l-l-l | 1.80 | 0.9 |

g: 1/8" DS float glass
l: 1/8" low-iron sheet glass
e: low-emittance coating, e=0.15
p: 4-mil polyester
All air gaps are 12.7 mm (1/2")
U-value: Standard ASHRAE winter conditions
SC: Standard ASHRAE summer conditions

Figure 6. Net annual useful flux in Madison, Wisconsin, for a primary window area of 24.53 $m^2$ for an orientation due south. The performance of typical glazing systems is indicated for glazing properties shown above.

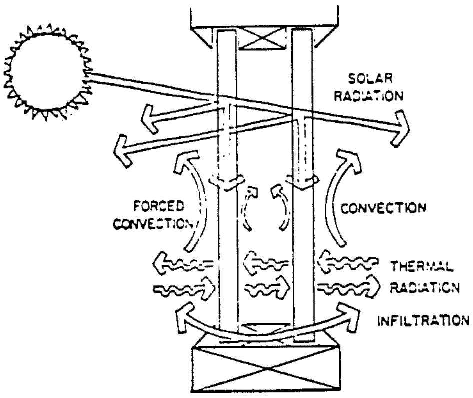


Figure 7. Major heat loss/heat gain mechanisms in windows.

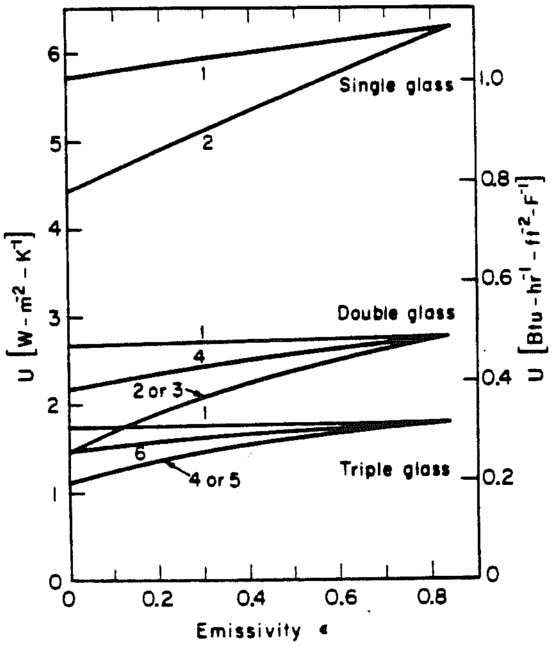


Figure 8. U-value of single, double, and triple glazing with a low-emittance coating vs. coating emittance and location. Surfaces on which the low-E coating appears are given on the curves, beginning with outermost glass surface (#1), inner surface of outer glazing (#2), etc. Calculated values for standard ASHRAE winter conditions.

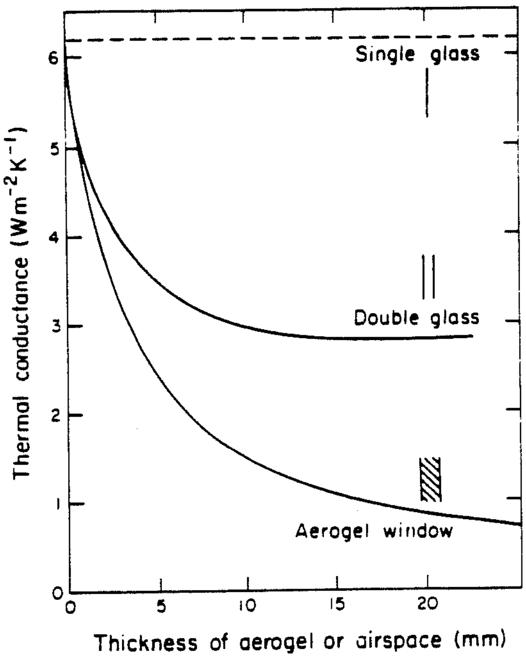


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Figure 9. Conductance of aerogel window and conventional double glazing vs. airspace or aerogel thickness.

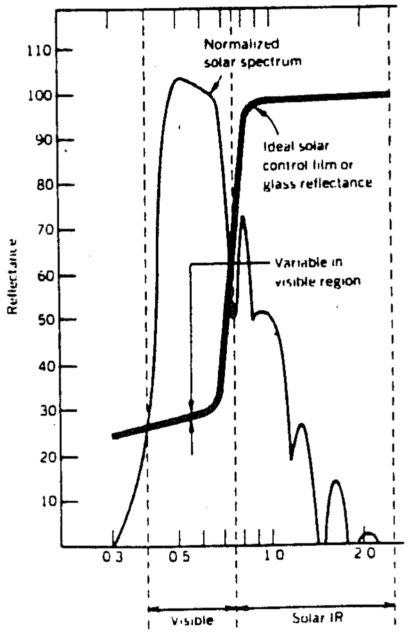

Figure 10. Solar spectrum showing ideal reflectance properties of a coating that maximizes daylight transmittance and minimizes near-infrared transmittance.

DAYLIGHT ILLUMINATION IN A ROOM ≡ AVAILABLE ILLUMINATION X SITE X FENESTRATION X ROOM

- Time of Day
- Season
- Cloud Cover
- Microclimate
- Air Pollution

- Latitude
- Orientation
- Landscape
- Obstructions

- Sun Control
- Framing/Wall
- Sash
- Transmission
- Maintenance
- Wall Location
- Size

- Geometry
- Surface Reflectance
- Maintenance
- Furniture
- Task Location

**Figure 11. Key variables and factors that influence calculation of interior illuminance from daylight.**

$$\text{ANNUAL LIGHTING ENERGY SAVED} = \sum_{\text{Day}}^{365} \sum_{\text{Time}}^{24} \sum_{\text{Zone}}^{N} \left(\text{Lighting Control System}\right) \times \left(\text{Daylight Illumination}\right)$$

- Sensor Location
- Time Response
- On-Off/Dimmable

- Light/Power Ratio
- Lighting System Type
- Automatic vs. manual
- User Response

**Figure 12. Key variables and factors that influence calculation of lighting energy savings.**

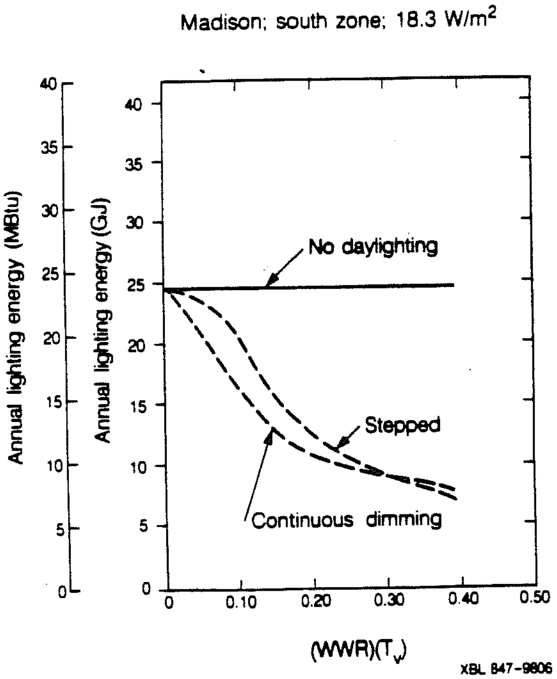

Figure 13. Annual lighting energy vs. effective aperture (window/wall ratio x visible transmittance) for a stepped switching and continuous dimming control in a south-facing office module in Madison, Wisconsin.

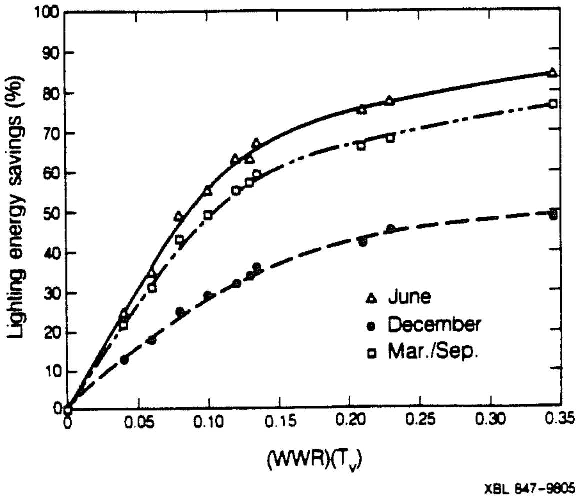

Figure 14. Seasonal variation in daylighting savings vs. effective aperture.

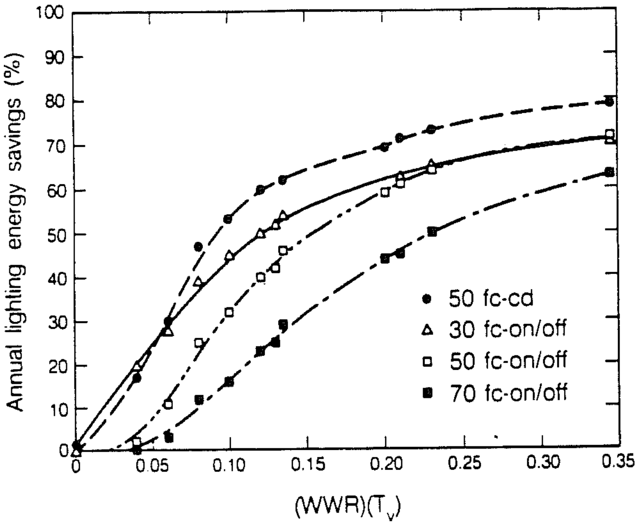

Figure 15. Daylighting savings vs. effective aperture for varying illuminance setpoints and lighting control types.

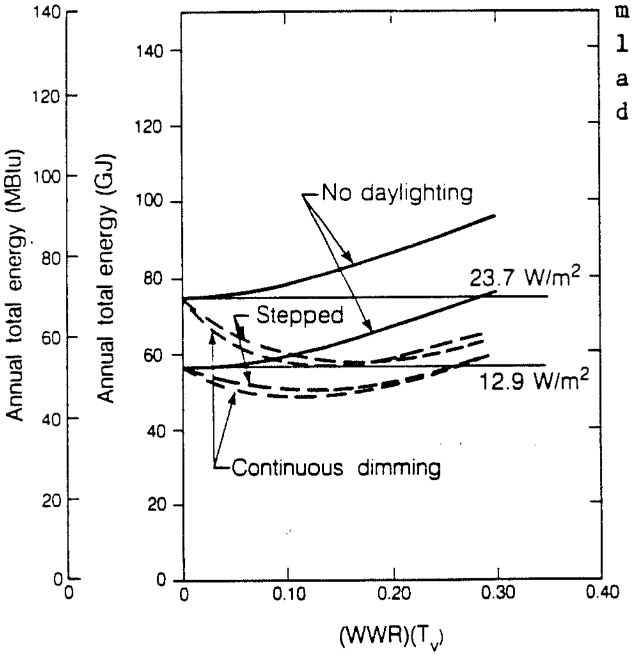

Figure 17. Total annual energy consumption vs. effective aperture in an office module in Lake Charles, Louisiana, for daylighted and nondaylighted cases at 12.9 and 23.7 W/m$^2$ installed lighting power density (south-facing office).

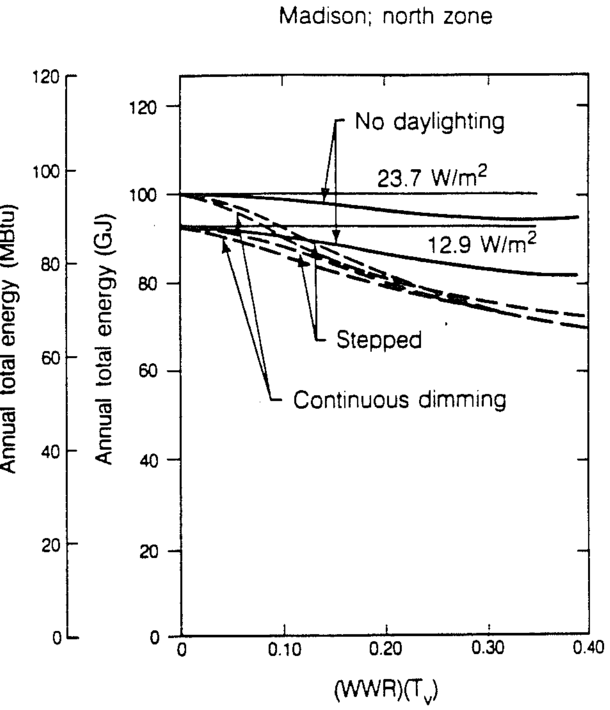

Figure 16. Total annual energy consumption vs. effective aperture in an office module in Madison, Wisconsin, for daylighted and nondaylighted cases at 12.9 and 23.7 W/m$^2$ installed lighting power density (north-facing office).

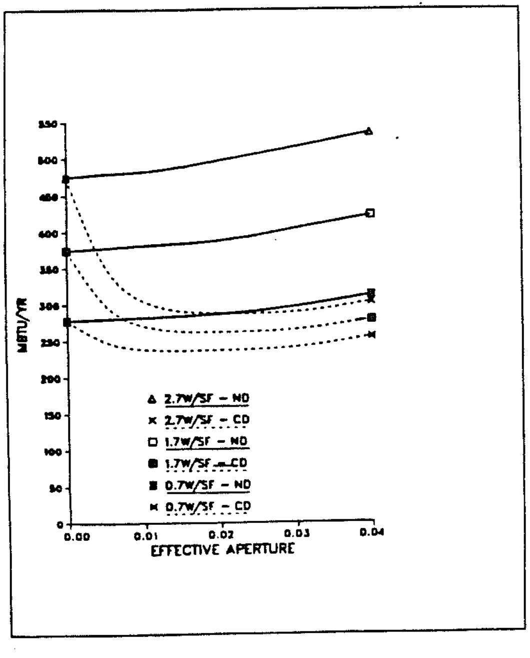

Figure 18. Annual energy consumption vs. effective aperture in a skylighted building in El Paso, Texas, comparing daylighted and nondaylighted cases for three levels of installed lighting power density (illuminance setpoint = 538 lux).

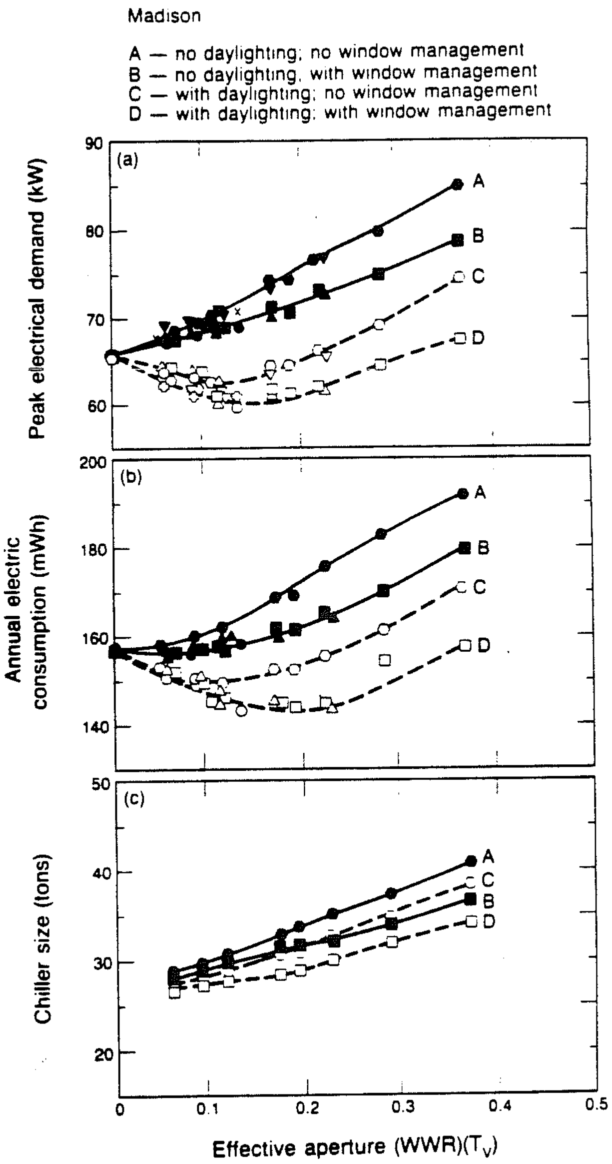

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Figure 19. Peak electrical demand and chiller size vs. effective aperture for an office module in Madison, showing effects of window management and daylighting strategies.

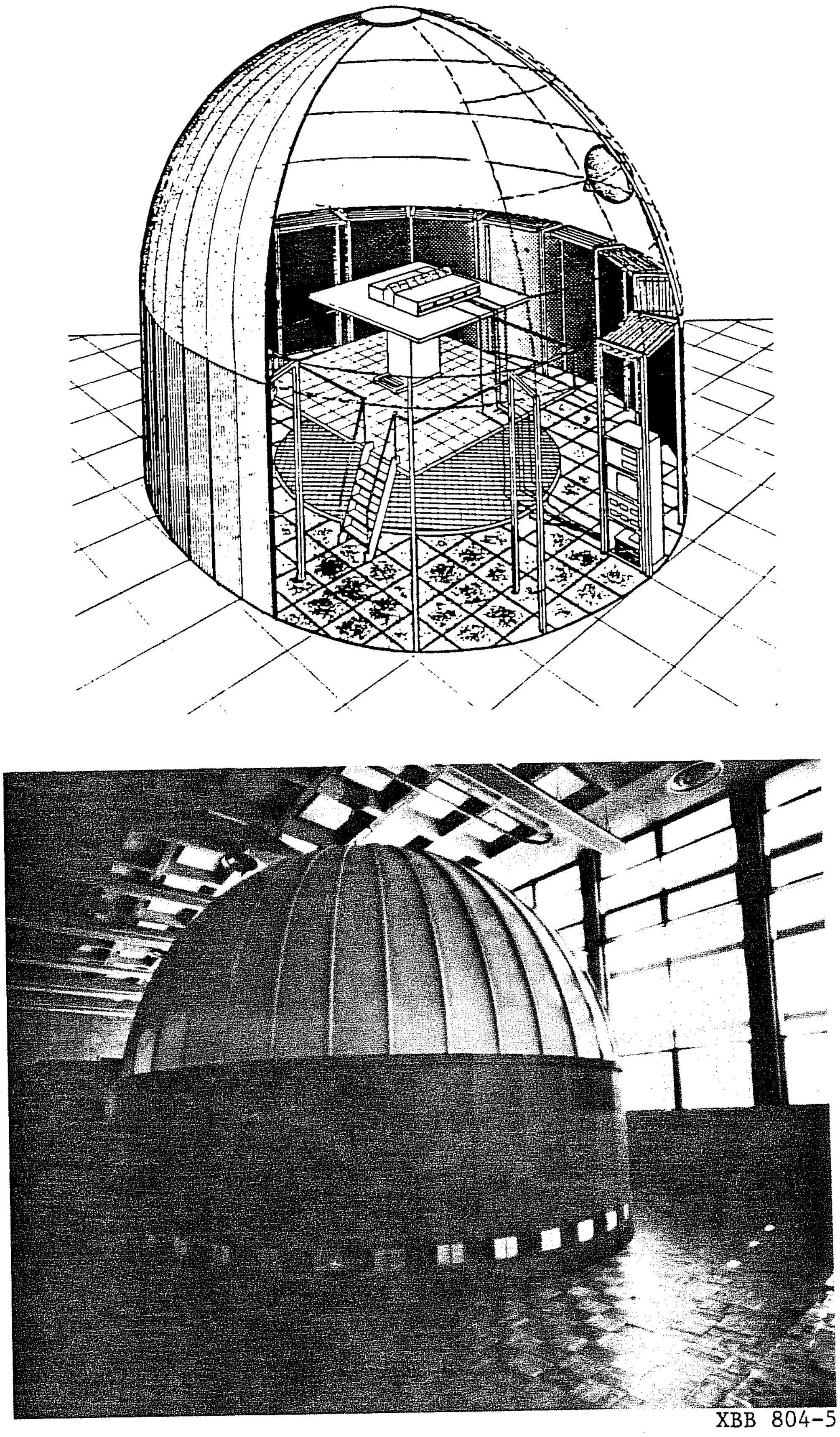

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Figure 20. Schematic and photograph of LBL's hemispherical sky simulator.

Sky is clear
Sun position: 40 off zenith
0° off S to E

Horizontal illumination
Direct sun: 0 fc
Sky: 2083 fc

| Contour Number | Illum. Level (Ft-candles) |
|---|---|
| 1 | 20.0 |
| 2 | 40.0 |
| 3 | 60.0 |
| 4 | 80.0 |
| 5 | 100.0 |
| 6 | 150.0 |
| 7 | 200.0 |
| 8 | 250.0 |
| 9 | 300.0 |
| 10 | 400.0 |
| 11 | 500.0 |
| 12 | 600.0 |
| 13 | 700.0 |
| 14 | 800.0 |
| 15 | 900.0 |
| 16 | 1000.0 |

Windows marked by •••••
Sunny areas are hatched

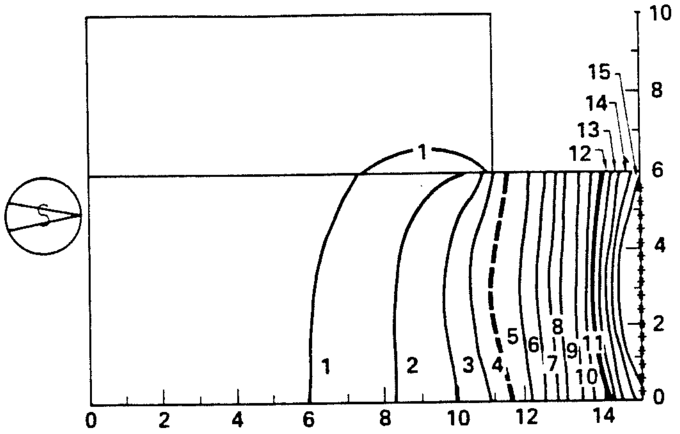

Figure 21. Sample isolux contours for a daylighted room using the SUPERLITE computer program.

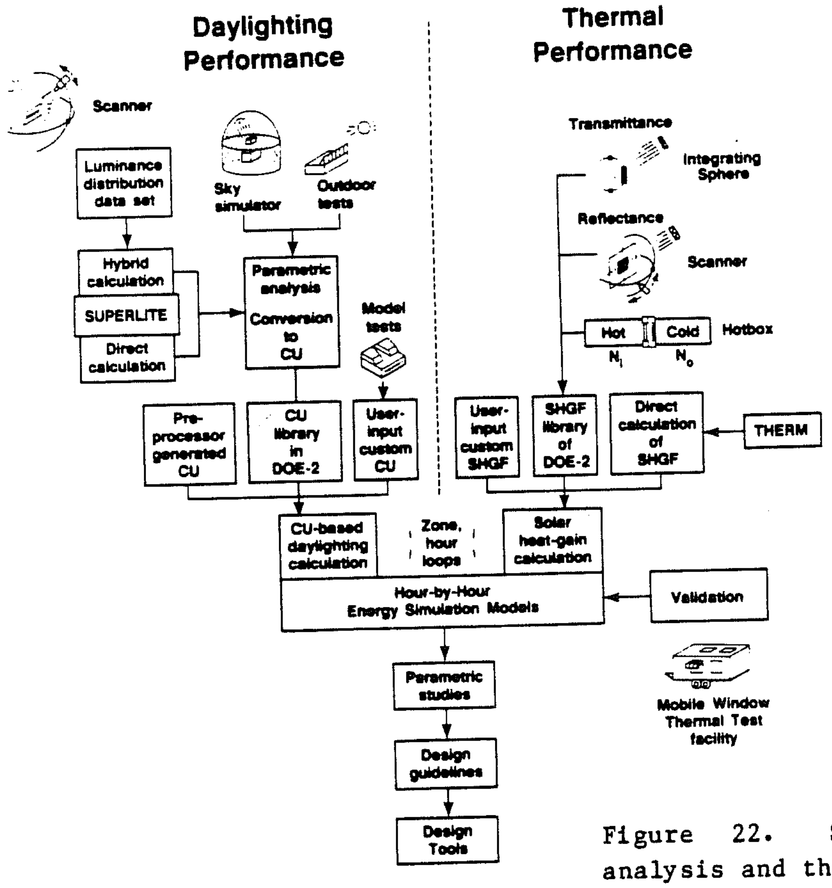

Figure 22. Schematic of daylighting analysis and thermal analysis capabilities under development for the DOE-2.1 program.

REQUIREMENTS FOR IDEAL DEVICE TO MEASURE

WINDOW AVERAGE PERFORMANCE

- REAL WEATHER
- WIDE RANGE OF CLIMATIC CONDITIONS
- GOOD RECORDING OF EXTERIOR CONDITIONS
- GOOD CONTROL FOR WEATHER VARIABILITY
- VARIABLE ORIENTATION
- WELL CONTROLLED INTERIOR ENVIRONMENT
- FULL-SIZE, ROOM-LIKE INTERIOR SPACE
- BUILDING OF VARIABLE CHARACTERISTICS
- CALORIMETRIC ACCURACY IN MEASURING HEAT FLOWS
- HIGHLY INSTRUMENTED

Figure 23. Ideal measurement capabilities for realistic testing of window performance.

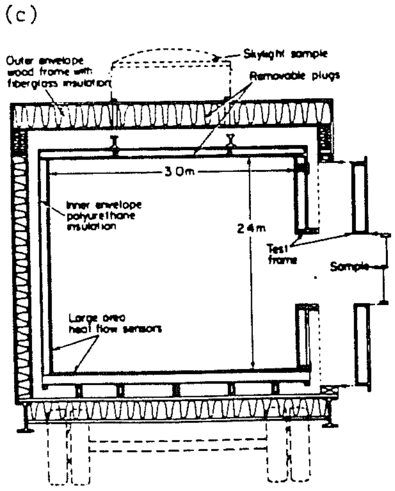

Figure 24. Cross section through window test chamber in the MoWiTT facility.

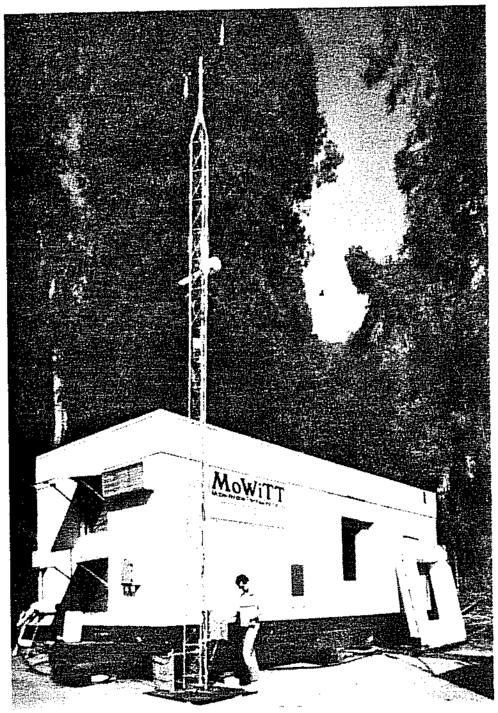

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Figure 25. Photograph of MoWiTT undergoing field calibration.