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Effective Daylighting in Buildings — Revisited

Contributions of daylight to lighting quality and energy savings

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STEPHEN E. SELKOWITZ & JAMES W. GRIFFITH

Introduction—a look backwards

Human beings developed with daylight as their primary source of light. Virtually all tasks that required higher levels of illumination for satisfactory performances were done between sunup and sundown until the first part of this century. When people first moved indoors into a controlled environment they took daylight into the space as the primary light source. As the visual complexity of indoor tasks increased, lighting requirements increased and as building designers created larger buildings with less access to windows and skylights, they had to add auxiliary light sources to maintain or increase productivity in those spaces. The incandescent lamp was a welcome replacement for gas flames, oil-fired lamps, or candles—but it was the fluorescent lamp and its great efficacy increase that first made it possible to compete with the sun and sky as a viable light source indoors. The trends toward larger buildings, high land costs, and dense urban environments and the availability and flexibility of the fluorescent lamp soon made people think of electric light as the primary and daylight as the auxiliary source.

Since daylight was free and electric light cost money to produce, in the post-war era it was still easy to justify daylight designs on a cost basis, even if the first cost of the fenestration system was accounted for and the energy cost was low ($.02/kWh).[1] This analysis was based on lighting costs alone and did not account for other positive or negative costs of the fenestration systems. In this time period, lighting systems were usually designed independently of other building systems and daylight was still used to provide light in many schools and offices.

This favorable situation for the use of daylight changed when air conditioning began to be more widely used. Daylight might be free, but the air conditioning system to remove cooling loads from windows was not. To reduce peak cooling loads, first costs, and operating costs, the HVAC designer had to reduce window size. Architectural preference kept window sizes large, but transmittance could be lowered to reduce solar heat gain (and available daylight). The resulting glass-skinned, low-transmittance building envelope is a familiar sight in most cities. In time, mechanical cooling, large windows, and higher light levels became the norm in buildings. Since electricity costs in real terms were falling, the economic penalty for these options was small. More significantly, view, thermal comfort, and pleasant working environments produced occupant satisfaction and owners/users were willing to pay for these amenities.

The oil embargo in 1973 and the subsequent large increases in energy prices forced every sector of the economy to reevaluate its energy use practices. In the very short term, large reductions in energy use were required and various curtailment and other drastic measures were enforced. Lighting was a major target of these actions because it was a large end use and, in part, because of its visibility and symbolism. It is possible to save a resource by not using it and many of the actions taken in the early days following the embargo were based upon this strategy. We turned lights off and we lowered our thermostats. "Freezing in the dark" was the patriotic message of the day. Fortunately, the embargo was lifted; but the price hikes remained. Therefore, there was both pressure and opportunity to respond more rationally and effectively to a changed perspective on lighting and building design. The country turned slowly to a strategy of conserving energy by a more efficient use of our resources rather than by not using them at all.

With energy no longer front page headlines, there is a temptation to dismiss the events of the early 1970s as history and to return to our old ways. This would be a serious mistake for the country and for the building design profession. Despite the pain and disruption that accompanied events of the last 13 years, we believe these events have created and nurtured new perceptions regarding lighting and daylighting in buildings and that to continue along this exploratory path will benefit all

Buildings—*Revisited*

concerned. More specifically, the "energy crisis" has triggered a critical evaluation of the building design process and overall building performance that now reaches far beyond the subject of energy use. These trends should help produce a new generation of buildings that not only use energy wisely, but that also better meet changing human needs.

First we examine some of the immediate energy and economic impacts. Most people are unaware that we have reduced energy consumption dramatically compared to 1973. If energy use per unit GNP in 1984 were the same as in 1973, we would have spent an additional 35 percent on our energy bills, or an extra $150 billion per year. This translates into a savings of 13 million barrels per day (oil equivalent)—several times our current import level. Gasoline prices are now low, but imagine our situation today if we still consumed energy as we did in 1973. OPEC would be strong, our supplies would be vulnerable, and prices would be high since the extra US demand would maintain pressure on the global oil market. This, in turn, would raise inflation, worsen our balance of payments, and divert scarce capital to the energy supply sector from other parts of our economy, thereby worsening the problems caused by our huge national deficits. Energy conservation activities have turned out to be smart economic policy as well. But we have achieved these savings so we can return to business as usual. Or can we?

We make decisions with energy consequences at many different levels, for example, buying a car or house or selecting a replacement lamp. The consequences of a purchase decision will depend, in part, on the service life of the item acquired. Lamps have very short lives—normally measured in a time frame of months to several years—relative to the life cycle of a building. Therefore, the natural replacement cycle for these lighting system components provides an opportunity for substituting more efficient products for less efficient items on a regular basis. Buildings have much longer effective use periods—typically, 50–100 years—although few will survive this lifetime without at least one major renovation. Therefore, it is particularly important to ask whether our buildings are designed with this longer view in mind. While we find the buildings of today are more efficient than their counterparts of ten years ago, we also find that they are still well below what is technically achievable in terms of current energy prices and existing technology. And there is still further room for improvement if we examine the ultimate technical potentials.

We believe that daylighting strategies could be employed as part of an overall integrated lighting and building design strategy to reduce building energy consumption 50 percent below the values that are achieved today. This may seem unrealistic to some in light of the battles that have waxed and waned over the last few years, but we speak as practitioners, educators, and members of IES and ASHRAE, as well as from the research perspective. We believe it is important to have a vision of where we ought to be in terms of building design and energy efficiency in the future, of how we ought to get there, and of the role of lighting and daylighting in achieving those objectives.

In 1978, one of us wrote an article entitled, "Effective Daylighting in Buildings" (*LD+A*, February, March 1979). This article was an attempt to define the critical daylighting performance issues, to review the state of the art in each area, and to speculate on future developments in research and practice. The author had recently joined the Lawrence Berkeley Laboratory to head the Windows and Daylighting Research Group. This group, funded largely by the US Department of Energy, was charged with developing a research program that would work cooperatively with industry and the design professions to identify and remove the obstacles to better daylight utilization. In reviewing that article today, seven years later, there is a feeling of both progress and *déjà vu*. On the one hand, little has changed. If the same article were published today with a few minor changes, many readers would probably accept it as a current survey. Most of the key issues identified in 1978 remain key issues today. Progress in changing the way the built environment is designed is notoriously slow (often for good reason).

In a few areas, primarily new technology, there have been several notable successes. For example, in the area of fluorescent ballast technology, a relatively small DOE investment in its Lighting Research Program has stimulated the development of a new industry selling electronic ballasts that provide not only improved efficiency, but also the dimming capability that is essential for many daylighted buildings. Modest DOE support in the Windows Research Program to develop new low-emittance (low-E) coatings to reduce window heat loss led to successful market introduction that is expected to capture 50 percent of the new window market for residences by 1990. New versions of these coatings with improved spectral control transmit daylight but reflect solar heat, thus raising the efficacy of transmitted daylight to greater than 200 lm/W. These technology advances are not only providing substantial energy savings, but they also provide additional options for designers and specifiers and they strengthen the competitive posture of US industry. By the turn of the century, the cumulative savings from these examples alone will run into billions of dollars. And these savings have been achieved with no sacrifice in amenity or comfort; in fact, in many applications, they will be improved.

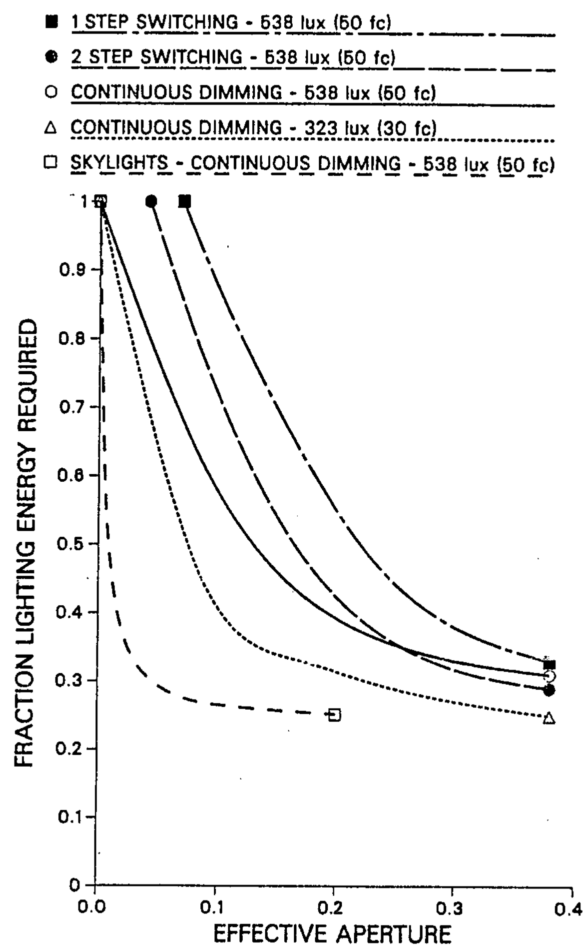
Another obvious area of change since 1978 has been the completion and occupancy of a number of new buildings that utilize daylighting strategies. A review of many of the award-winning buildings of the last few years will include many in which "daylight" plays a significant role. Here, the record is unclear regarding the real level of achievement. It is probable that among these building there are some notable successes, but it has been difficult to separate fact from fiction. The anecdotal information sources suggest that a number of problems have been encountered, some of which have been successfully resolved while others have not. It is common to read a story in the architectural press about a building that describes at length the daylighting intent in words, diagrams, and photos, but is totally lacking any critical performance evaluation. These comments, of course, are not unique to the field of daylighting or energy-efficient building design. Even without these performance data, some of these new buildings are clearly striking architectural achievements and have helped to maintain a high level of interest in daylighting.

In other areas, research progress has been substantial, but the resultant impact in the built environment is less obvious. We summarize several of these key points with the figures and discussions below. The results shown below are based largely on detailed building energy simulation studies using the DOE-2.1C computer program. This code has an integral daylighting prediction model that calculates interior daylight levels and a glare index on an hourly basis throughout the year for each zone in the building. It simulates responsive lighting controls, window management, impacts on heating and cooling loads, peak electric demand, and other building operating conditions.

Although it is used by us as a research tool, it is in widespread use by larger architectural and engineering firms and by consultants through the US and internationally. The interested reader is referred to additional references at the end of the article for a more detailed discussion of these results and the supporting studies.

1. Daylighting strategies can save a large fraction of typical lighting energy requirements. [1] shows the fractional lighting energy savings in a typical office with skylights and windows. "Effective aperture" is the product of glazing area (as a fraction of wall area) times the visible transmittance of the glazing. For the windowed office, we show the effect of different lighting control strategies and design illuminance levels. The selection of control strategy and design setpoint can have a large effect on savings if the fenestration is small; as the size increases, the savings increase, but the relative performance differences between alternatives

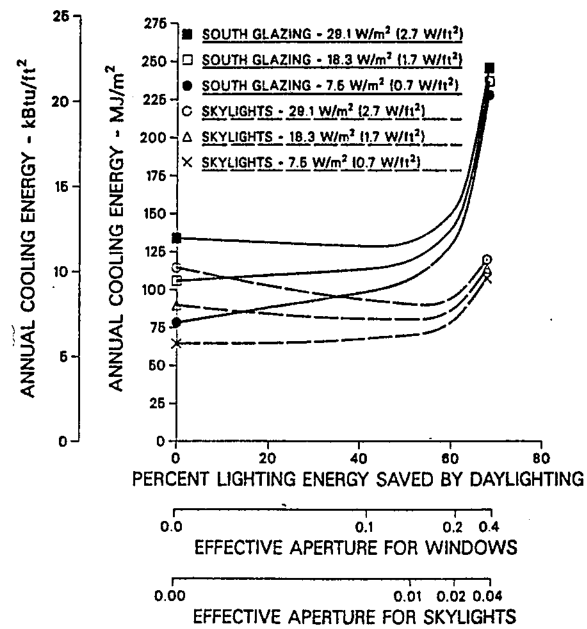
[1] Electric lighting requirements with daylighting in a south zone area as a function of effective aperture.



decrease. These curves also suggest that dimming systems have a clear performance advantage with smaller windows; for larger fenestration, switching and dimming will save similar amounts of energy. It is thus possible to save 60 to 75 percent of lighting energy consumption with modestly sized windows or skylights. Note that there are diminishing returns as effective aperture rises above .1 for skylights and .35 for windows. At those conditions, the midday lighting requirements have been met by daylight and additional glazing saves only a small increment during early morning and late afternoon.

2. Fenestration that provides daylight also admits solar gain that will contribute to cooling loads. But electric lighting also adds heat gain to an air conditioned space so we are interested in the relative contributions to cooling loads of daylight vs electric light. Firstly, we note that if we compare a daylighted space to a nondaylighted space with identical fenestration, the daylighted space will have lower cooling loads. However, it may not be reasonable to assume that the fenestration would be designed identically if daylight were not being utilized as an energy strategy. Secondly, there is a myth in the daylighting community that daylight reduces cooling loads any time it displaces electric light. This is based on the following argument: Sunlight and daylight have a luminous efficacy of 100–200 lm/W, while good fluorescent lighting systems have an efficacy of 70–90 lm/W. Therefore, replacing a lumen of electric light with a lumen of daylight will reduce cooling loads. But this simplistic argument is based on the dubious assumption that the "source efficacy" comparison is an accurate determinant of usable light in the space. In fact, this is not the case and we provide some illustrative data in [2]. On the horizontal axis, we show the percent of lighting energy saved by different sized skylights and windows (note that the lighting savings scale is linear, but the corresponding aperture scales below are not). On the vertical scale, we show the annual cooling required in an office building (16,000 ft^2) in Lake Charles, LA. The set of three solid curves shows results for windows, the dotted curves give the equivalent results for skylights. Each set of three curves covers a range of installed lighting power densities of .7, 1.7, and 2.7 W/ft^2, each providing a nominal design illuminance of 50 fc. For the case of the skylights, the two upper cooling curves (1.7 and 2.7 W/ft^2) fall first, then level out and rise at about 60-percent savings (.02 aperture). Therefore, daylighting does provide a reduction in cooling load for those specific cases. For the skylight with .7 W/ft^2, the cooling curve is flat, suggesting that the cooling impact of daylight from skylights is about equal to that installed electric lighting

[2] Annual cooling load as a function of electric lighting energy saved in a south zone with windows and in a skylighted zone.



power density. From this, we can estimate an "effective efficacy" of about 71 lm/W (50 fc/.7 W/ft^2).

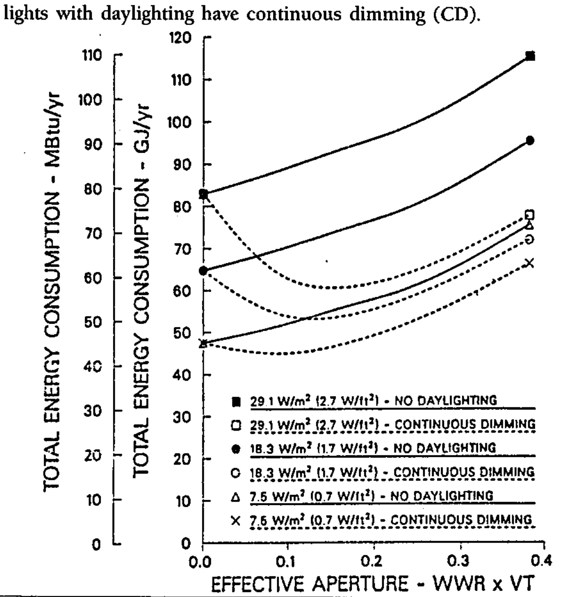
For the case with windows, the cooling curve rises for the two most efficient lighting designs and is flat for the case of 2.7 W/ft^2. The "effective efficacy" of these windows and the lighting system is about 18.5 lm/W. With more efficient lighting, cooling loads increase as daylight utilization increases, although there are still, of course, substantial lighting energy savings. These somewhat complex results are readily explained by examining the details of flux distribution in a top-lighted vs a side-lighted space, the relationship between the location of a lighting control sensor and the average illuminance level in the space, and other factors such as the time variability of daylight. In each case, an understanding of the cause of these effects has led to identification of improved design strategies or new technology to improve performance results. These results also point out the danger of oversimplifying the complex interactions between daylight, electric light, and building cooling loads.

3. The trends for total energy savings in a daylighted building are dictated by the conflict between lighting energy savings and cooling load costs. As aperture area increases, electric lighting energy consumption falls, reaching a typical minimum as illustrated in [1]. Cooling load may rise or fall initially, as discussed above, but eventually it will rise steadily if glazing area continues to increase. The trend for total energy

consumption is characterized by an initial sharp decrease in energy use (compared to an opaque wall), followed by a shallow minimum and then a linear increase dictated by cooling loads. In [3] we compare the daylighted and nondaylighted cases for three installed lighting power densities, as before in a 1500-ft² south zone. The trends are identical, although the specific magnitudes of savings will differ. Heating consumption may increase slightly in a daylighted building, but these are normally small effects. Note that there is a wide performance range over which a daylighted building will outperform an equivalent building without windows.

4., Peak electric demand and load management are increasingly important to utilities and to building owners. Daylighting can provide additional economic savings by reducing peak demand. In [4] we show a comparison of components of the peak electric demand for a daylighted and nondaylighted building. Note the large relative contribution of lighting to peak and the positive impact in the daylighted case. In [5] we show the peak electric demand for the 16,000-ft² building in Lake Charles for six combinations of 1) no window management, 2) interior shades, and 3) exterior shades, each with and without a continuous dimming daylighting system. Daylighting provides the greatest savings, but proper window management becomes increasingly important as window area increases. The electric lighting system is dimmed in response to

[3] Net annual energy consumption in south zone as a function of effective aperture with and without daylighting. No daylighting (ND) has no reduction in electric lighting in response to daylight. Electric lights with daylighting have continuous dimming (CD).

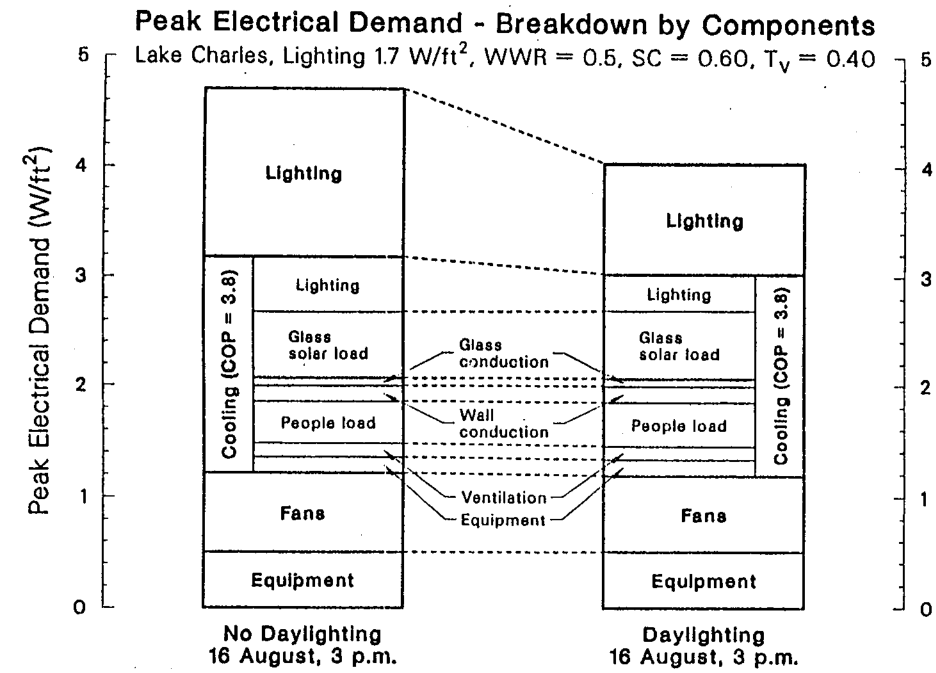


daylight only in the perimeter zone that comprises 38 percent of total floor area. Thus, in a building whose floor plan allowed more access to daylight, the savings would be expected to be even larger. In some portions of the country, building owners pay more for their electric demand charges than for electricity.

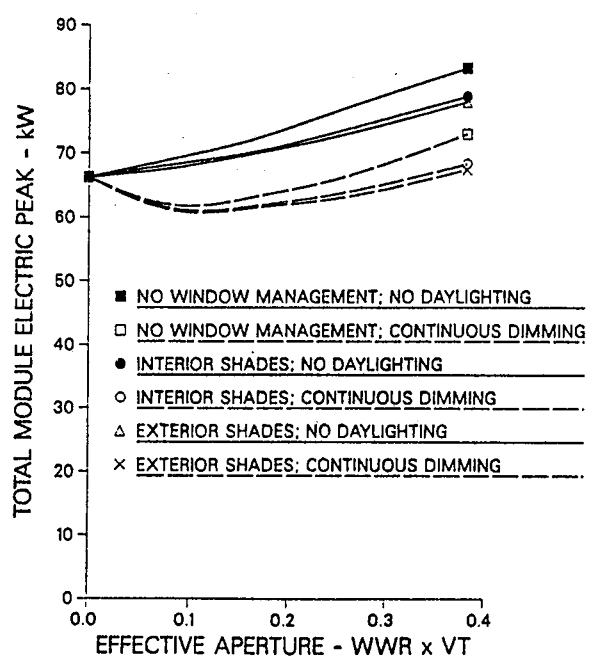
5. The total economic benefits from reduced energy consumption and peak demand can be substantial and are highly dependent on the utility rate structure. In [6] we show electric utility costs for two different utility rate structures for the three sets of installed lighting power densities. A new curve, representing the potential performance of new glazing technology, is now added to each set. These curves, which extend out to a larger aperture of .5, assume the use of an electronically controlled window whose transmittance would be continuously adjusted to maintain a maximum task illuminance of 50 fc under all sun and sky conditions. In addition, the glazing has improved spectral control so that it rejects more near-infrared energy from the sun while maintaining high visible transmittance when required. Research on advanced switchable coatings is now under way; similar control could be achieved using some types of operable mechanical window sun controls. Note that these devices radically change the shape of the performance curves, eliminating any penalty for window use (in fact, adding benefits) and allowing window area to be determined by factors other than energy. Economic savings are strongly dependent on the utility rates. Once one has an estimate of projected savings, it is possible to work the problem backwards to estimate the justifiable investment in new fenestration systems. The hourly performance of a switchable coating on a west office during a sunny July day is shown in [7]. Note that actively controlled glazing (AC) maintains an illuminance level of 50 fc throughout the day. Low transmission (LT) glass (T = .07) never provides adequate daylight. The passive response glass (PR, for example, photochromic) and the high transmission with and without shading (HTS, HT) allow excess light that may be desirable for lighting purposes but will increase cooling loads.

6. The daylighting costs and benefits to total building energy performance are complex because fenestration and lighting systems interact with most other major building systems. If one does not have analysis tools capable of probing these interactions for their subtleties and interdependencies, one risks coming up with the wrong answer and, perhaps, in some cases, with the wrong question. For practical and philosophical reasons, it is convenient to simplify complex problems. There is a great temptation to reduce daylighting design to rules of

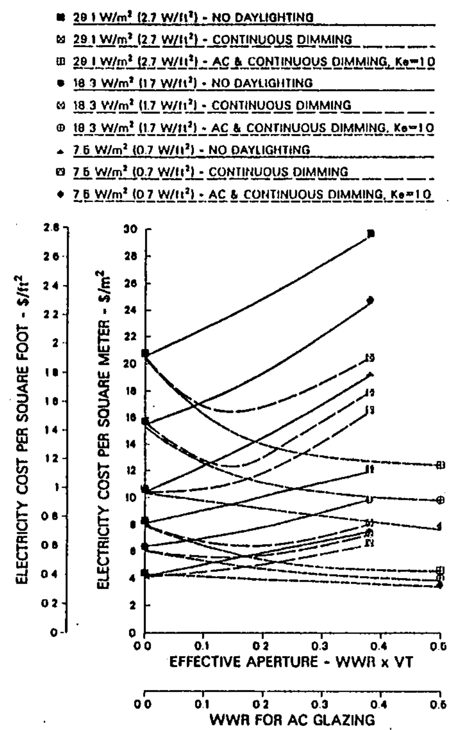
[4] A breakdown by components of the peak electrical demand in a 1600-ft² office in Lake Charles, LA. The installed lighting power density is 1.7 W/ft², window area = 50 percent of wall area and glazing visible transmittance = 40 percent.



[5] Peak electrical demand for the five-zone module as a function of effective aperture. Electric lighting power density is 1.7 W/ft² (18.3 W/m²). Electric lights are dimmed in response to daylight only in the perimeter zones which comprise 37.5% of total floor area.



[6] Annual electricity cost per square foot of daylighted perimeter zone space as a function of effective aperture for a high rate structure (New York City) and a low rate structure (Houston).

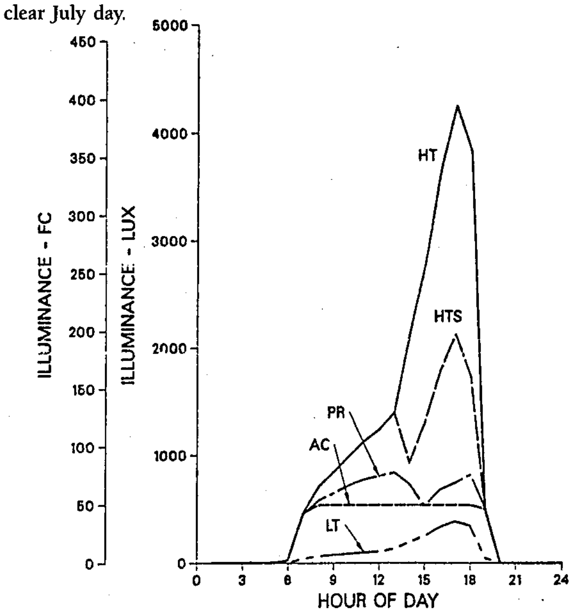


thumb. Admittedly, these are of value and, if properly formulated and applied, can be very helpful. But they will never substitute for the more formal and complex analysis required for most new large buildings today. The Department of Energy has supported development of new simulation models for building energy analysis (DOE 2), for predicting daylight illuminance (QUICKLITE, SUPERLITE), and for analyzing lighting controls (CONTROLITE). In addition, we have developed a new series of experimental facilities to characterize better the optical properties of glazing materials and entire fenestration systems. These include a large integrating sphere for measuring the hemispherical transmittance of fenestration [8], a luminance/radiance scanner to measure the bidirectional transmittance and reflectance properties of fenestration [9], a 24-ft diameter, hemispherical sky simulator for measuring interior illuminance distributions in scale models under controlled and reproducible sky and sun conditions [10a–d], and a large mobile field test facility for measuring the thermal behavior of windows and skylights, including daylighting interactions under outdoor weather conditions [11]. Together, these form the heart of a set of prediction capabilities that should allow us to analyze completely the relevant properties of glazing materials and fenestration systems. The individual elements are linked together to provide a complete performance description as shown in [12]. It is interesting to note that tools described above give us the ability to characterize the window as a light-admitting/emitting element in much the same way that a lighting designer characterizes a luminaire, using a candlepower distribution and total flux output from the lamps. Finally, we expect that some of these research tools will be directly usable by practitioners and that others will form the the technical basis for a new generation of design tools, not only with enhanced predictive powers, but with the ability to help the designer better formulate the problem definition as well as to help find a solution. We expect expert systems, advanced graphics capabilities, and new imaging technology to play an important role in this future work.

Building standards

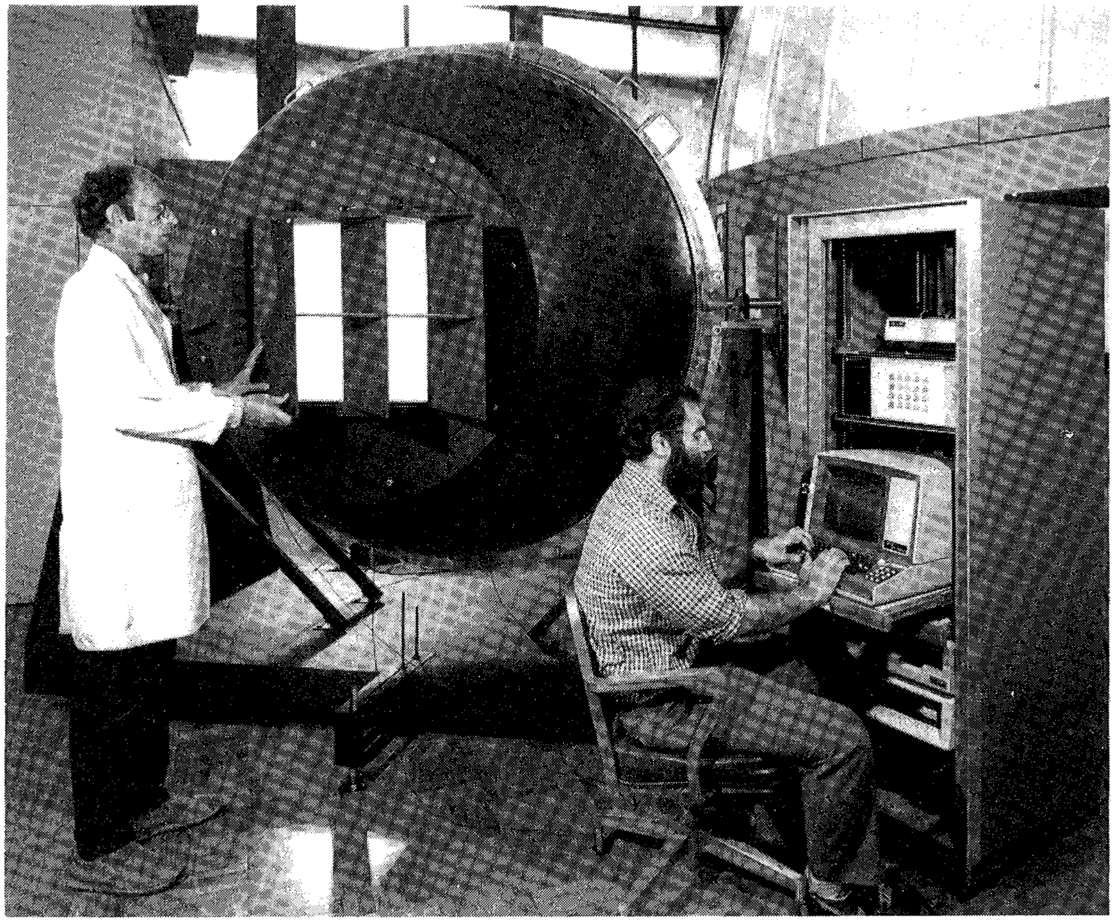
In addition to the daylighting research outlined above, the Department of Energy has been involved with the professional design community in the development of new building standards. There are direct links between these standards' activities and the types of simulation studies and measurement activities described above. The

[7] Hourly daylight illuminance level at the control point on a clear July day.



proposed standards have major new elements that give, for the first time, explicit credit for daylighting. The inclusion of those elements was based, in part, on results derived from the research studies described above. It would be difficult to discuss this subject further without acknowledging and commenting on the debate of the last three years regarding new building energy standards and efficient lighting design. How can we propose further substantial reductions in lighting energy requirements when the IES and ASHRAE have not yet fully resolved their differences over the last round of proposals? Each of us has been involved in different aspects of that debate and we may not agree on every detail. However, we do agree that performance improvements far in excess of the new standard are possible and, ultimately, desirable. The best designers can already meet and exceed the energy performance requirements of the standards that are still under debate. Formulating these standards into workable documents and procedures may be much more difficult than achieving them in practice in buildings.

It is important to build into the new standard links and tradeoffs between electric lighting design and daylighting. But since this will be new to many designers, it is certain to stir critical comment from potential users. Standards require a consensus among conflicting interests. This is essential for an implementable end product, but it almost inevitably works against achieving full potential. Standards try to prevent or reduce the likelihood of terrible performers



[8] Measurement of hemispherical transmittance of an exterior shading using the LBL integrating sphere.

and tend to point in the direction of better performance, but they rarely provide a framework for true optimization of a design. The IES and its membership should continue to participate actively in the development of new building energy standards, representing the true interest of the lighting design profession and the US as a whole. But we should not assume that participation in that activity alone will fulfill our obligation to help solve our national energy problems and provide well-lighted buildings.

True believers and the role of daylight—a recent history

In the view of its proponents, daylighting is *the* solution to the lighting energy problem. We believe this is far too simplistic an approach and we offer the caution that its proponents may not even agree on what they mean by the term "daylighting." We provide the following range of interpretations, each of which is equally valid:

Architectural definition—The interplay of natural light and building form to provide a visually stimulating, healthful, and productive interior environment.

Lighting energy savings definition—The replacement of indoor electric illumination needs by daylight, resulting in reduced annual electricity requirements for lighting.

Building energy consumption definition—The use of fenestration systems and responsive electric lighting controls to reduce overall building energy requirements (heating, cooling, and lighting).

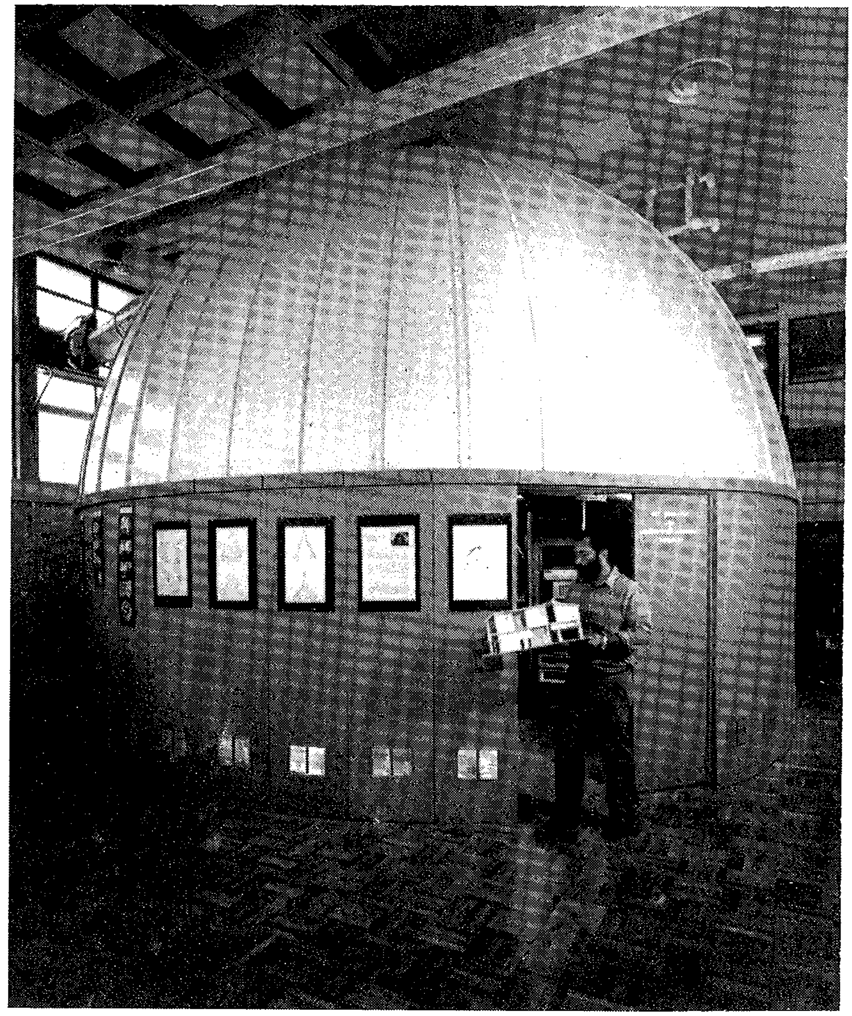
Load management definition—The dynamic control of fenestration and lighting systems to manage and control peak electric demand resulting from all building power requirements (*e.g.*, lighting, cooling).

Cost definition—The use of daylighting strategies (architectural design, fenestration design, lighting design) to minimize operating costs (fuel, electricity, demand charges), and maintenance costs and maximizing occupant productivity.

Pre-embargo

It is clear that our perspective has changed with time. In the decade prior to the embargo, there was little interest in the US in daylight as an engineered or

[9] View of the luminance scanner under construction.



[10a] Exterior view of sky simulator, Lawrence Berkeley Laboratory.

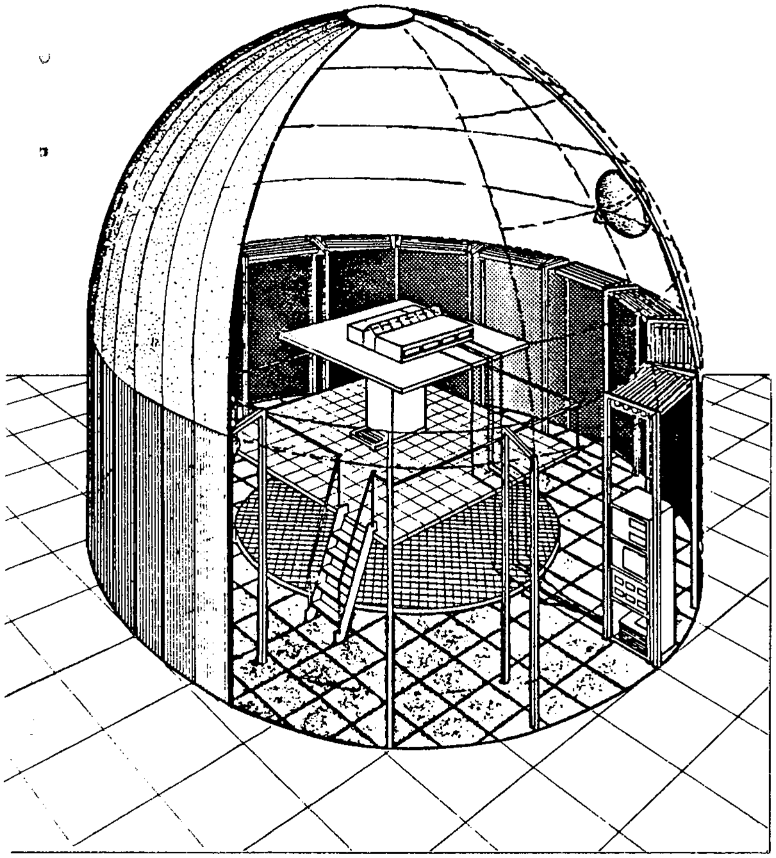
designed lighting source. There was certainly an artistic interest in manipulation of light for aesthetic purposes, but the published literature of the IES and ASHRAE suggests little activity and interest in those professional societies. In the five years after the embargo, daylight was rediscovered by researchers looking at old technical literature and new ideas and by a few architects who either remembered the earlier interest in the 1940s and 50s or who themselves were newly interested in this field. The focus of this interest was daylight as an energy-saving strategy, although the best of those involved understood the broader issues that were raised.

Post embargo—energy savings

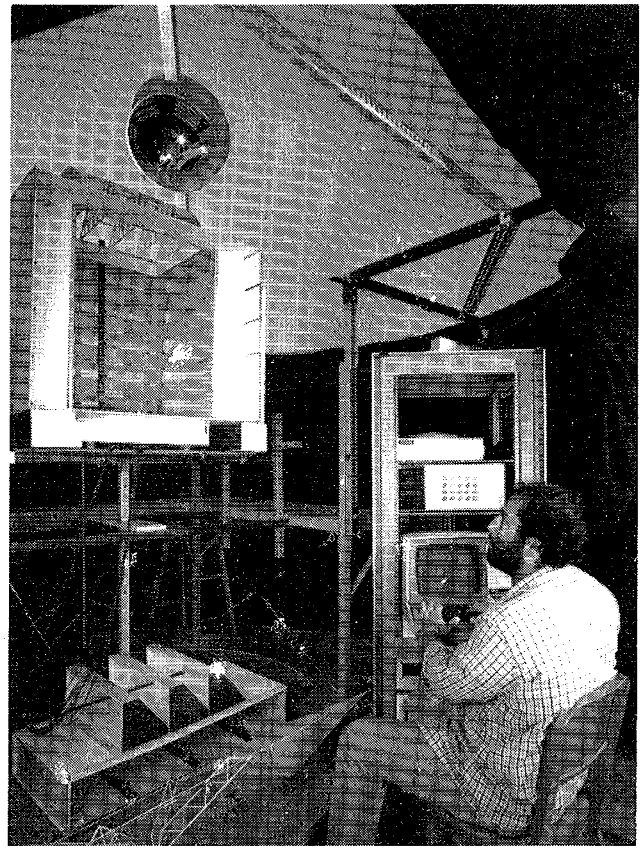
As the first collection of daylighted buildings was erected, it was apparent that, although many did an excellent job of admitting daylight, if the lighting controls were not adequately responsive, the predicted energy savings would never be realized. This immediately introduced not only the problem of hardware design, but the the issue of occupant response. Most of the photocell systems that respond to available daylight are responding to a specific illuminance or luminance level in the space. The relationship between that trigger level and overall occupant satisfaction was never well understood. When systems do not perform adequately due to design flaws or hardware failure, inventive occupants will almost always figure out a way to override the control system (black tape over the photocell is a simple favorite).

Integration—daylight and electric light

By 1980, recognition of these problems, which were viewed not simply as energy-saving strategy, but as integration of daylight and electric light, led to a different perspective on daylighting. This concept of variability which is intrinsic to daylight provided other benefits for the electric lighting industry which



[10b] Schematic view of the simulator.



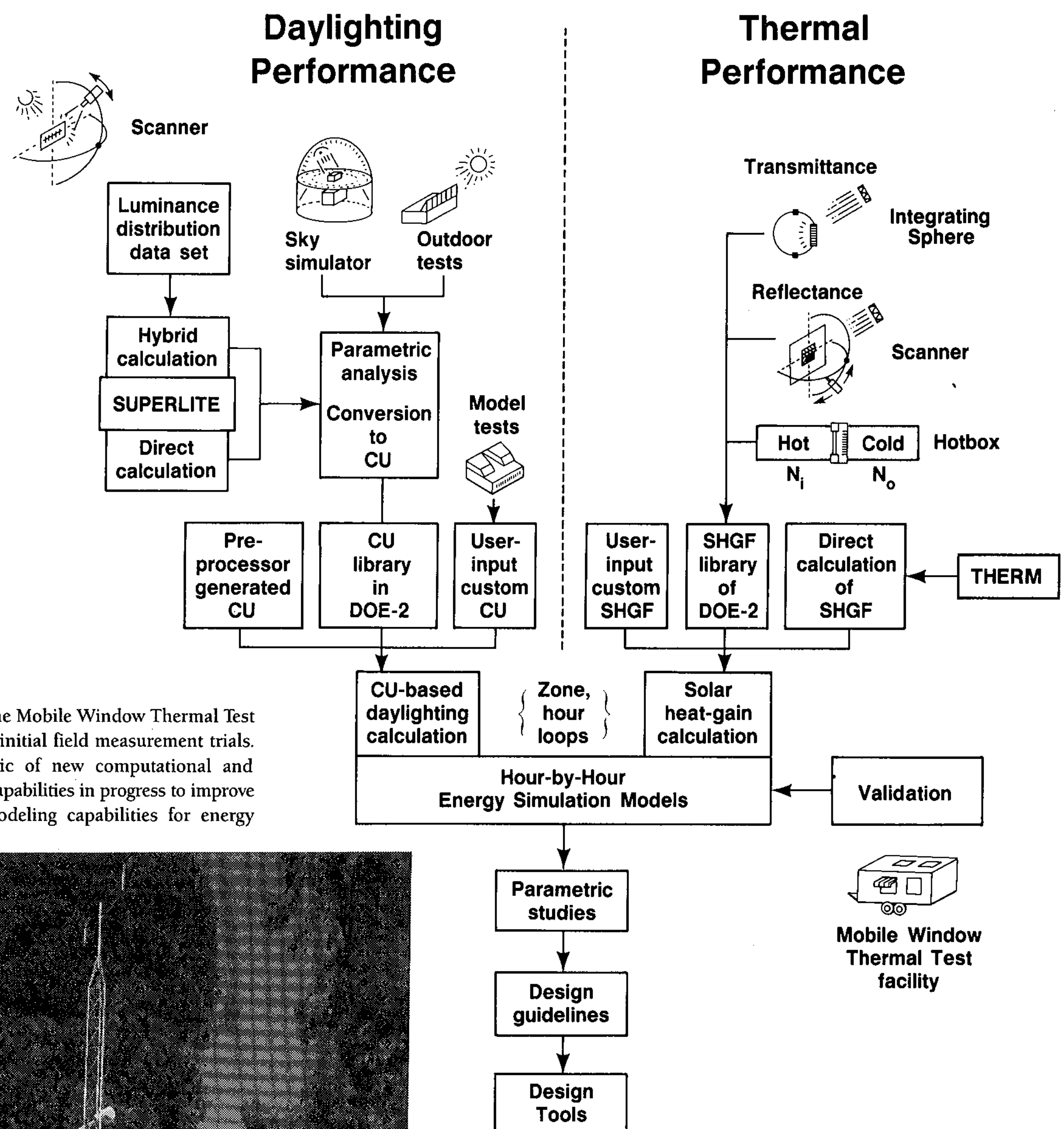
[10c] Interior view of sky simulator, showing atrium model being tested.

traditionally viewed lighting controls as circuit breakers with a simple on-off function for a large random slice of a floor. In fact, the movement away from the uniform illuminance levels based on worst-case design and the recognition that workspaces have variable occupancy patterns together with daylight control requirements all helped to build a lighting controls industry where none existed before.

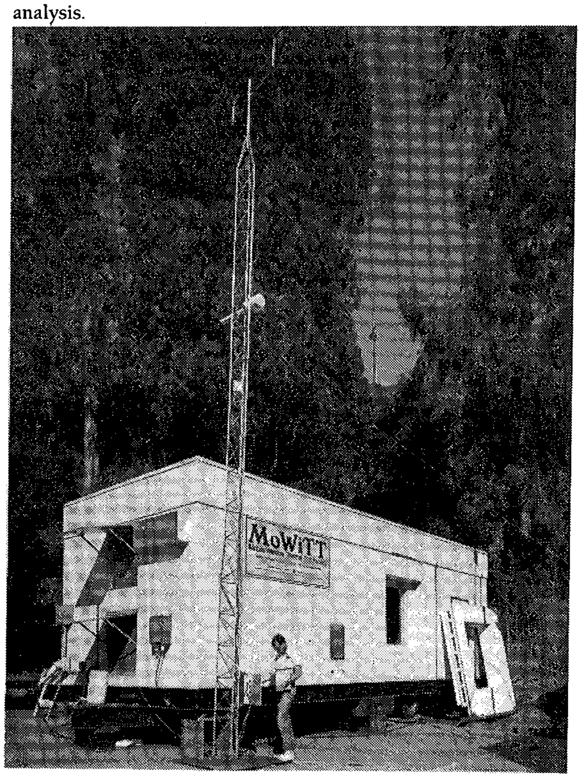
Daylight and lighting quality

While the potential savings from daylighting as an energy and load management strategy are increasingly being realized, the perspective that is more important in the mid 1980s is the relationship of lighting quality and daylighted buildings. The quality issue has both positive and negative connotations for daylight. Just as good electric lighting design is unlikely to emerge from focusing on measures of lighting quantity, it is clear that the quest for "daylight footcandles" must address the qualitative aspects of design. With daylight, there is the additional difficulty of managing a source of great variability in both intensity and direction. Poor design or improper window management will not only reduce occupant satisfaction but could result in increased energy use if occupants require additional electric light to balance excessive daylight-induced contrast differences. Given the fact that the lighting design community is still wrestling with the problem of developing a quantitative metric for lighting quality, it is not surprising that there are no simple techniques for assessing "daylight quality." In fact, we hope that when adequate "quality" models are developed they will be sufficiently robust to accommodate both electric lighting and daylighting designs.

Issues of lighting quality can also work in favor of daylight use. Daylight is flicker free, provides a full-spectrum (although variable) source, and has excellent (but variable) color rendition. If it is introduced with care it can provide both vertical and horizontal illuminance, can provide pleasant modeling effects, and can enhance task contrast. Daylight often brings with it visual information on the state of the world beyond the viewers' space—a highly valued amenity in almost all work environments. And, perhaps surprisingly, we note that daylight is a variable-intensity, "uninterruptible" light source—within the limits, of course, of daytime hours.



[11]↓ View of the Mobile Window Thermal Test Facility during initial field measurement trials.
[12]→ Schematic of new computational and measurement capabilities in progress to improve fenestration modeling capabilities for energy analysis.



Future perspectives

In the future, we expect that, while the interest in energy savings will be maintained or increased, there will be additional interest in the less easily quantifiable aesthetics and amenities associated with daylighted space. This will be driven by market interest, architectural interests, and the availability of new technology to serve the needs of innovative designers. In the latter category, we include the latest generation of selective coatings for glazing; coatings that will reduce heat loss, alter the spectral properties of transmitted light to reduce solar heat gain, and create a wide range of reflected appearances on the indoor and outdoor surfaces. Further in the future, we expect to see coatings that alter the distribution of transmitted light and can dynamically control intensity.

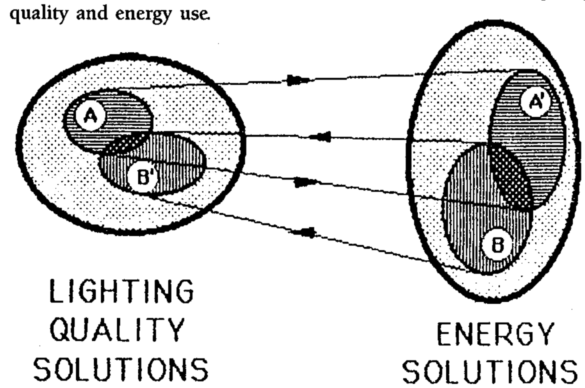
We can obtain a glimpse at the future directions of daylighted buildings by looking at the topics of current interest. Many new buildings contain glazed atrium spaces that provide a variety of amenities in addition to daylight illuminance. Atria are traditional forms that graced buildings in Europe past the turn of the last century. Their sudden ubiquitous presence in today's offices and retail complexes is connected to energy issues but is tied more profoundly to the economics of amenity and competitive rental rates. We have seen many atrium designs for which energy savings claims are made, but none in which such savings have been unambiguously demonstrated. Conversely, the success of a designer's intent to create lush, planted circulation and gathering spaces is quickly apparent—dying vegetation or empty spaces clearly signal a reality that fell short of the design intent. Many atria use more energy than a simpler, less appealing, unglazed interior space, but their importance to building owners is based upon the need to provide appropriate corporate imagery and to offer relevant amenity in the competitive real estate market. The importance of these issues is obvious if we note that when these needs conflict with increased energy use they will almost always take precedence. This suggests that the thrust of future studies might be to minimize unnecessary energy use in conjunction with attaining the aesthetic and functional goals for atria rather than viewing atria in a narrower sense, primarily as energy-saving features.

Daylight and total building performance

The example of atria brings us back to the observation that daylighting performance must be examined in the context of total building performance. The benefits of a building as well as the costs must be properly and carefully accounted for in order to properly evaluate daylighting or other environmental factors in the built environment. Energy will be one of these factors: however, it is not the only one and, often, not the most important one. Buildings are not built to save energy; they are built to convert energy and other physical resources to produce a useful output and to provide a pleasant and healthy environment for human activities. How do we determine if these goals are being achieved? It is possible to analyze performance to determine if the design criteria are being met. The real difficulty is developing the appropriate design criteria against which performance can be compared. To be effective and practical, these criteria must address both the technical aspects of performance, such as energy use and peak electric demand, as well as issues of comfort, amenity, *etc.*, that are traditionally less quantifiable.

We offer no simple solutions to this challenge, but we do suggest a framework in which solutions might eventually be developed. This framework is an attempt to relate the qualitative aspects of all lighting design solutions. We illustrate this schematically in [13]. Imagine that we have just been assigned the task of producing a high-quality lighting design that maximizes visual performance and minimizes energy consumption. On the left-hand side of the figure we show conceptually the range of all possible lighting quality solutions that meet the basic requirements for the lighting problem. Each point within the space represents a single lighting design solution. Within the range of all possible solutions, we show a smaller "design space" boundary, A, containing those solutions that meet minimum criteria for "good lighting quality."

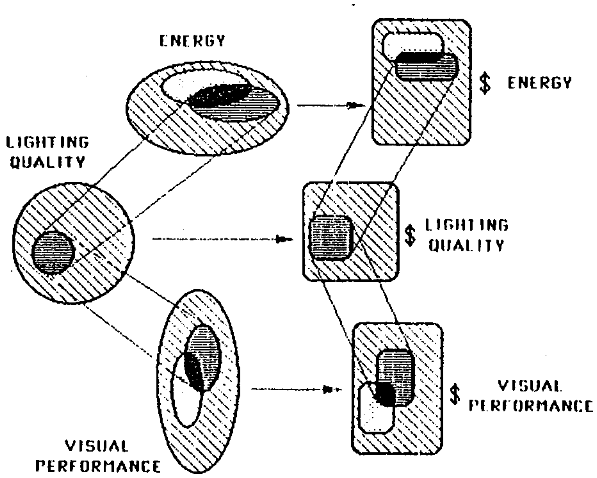
[13] Schematic representation of the relationship between lighting quality and energy use.



Each of our lighting design solutions has an annual energy use associated with it and each also provides differing levels of visual performance. On the right side of the figure, we show the solution space for energy performance. Each point in the lighting design solution space can be mapped into the energy space. Within the energy space, we also outline those solutions with the best energy performance, B. If we map all of the best visual quality solutions, A, to the energy space, A', we find that some also fall within the best energy performance boundary, B; while others lie outside. The same may be true in reverse. If we map the best energy solutions, B, into the visual quality space, B', some lie within the best visual quality space, A, and some do not. Much of the acrimonious debate over the last few years in the area of lighting energy standards can be interpreted as differing views as to the relationship between these two subsets of good lighting quality and good energy design.

How do we then decide between alternatives? Some form of explicit or implicit economic judgment is usually exercised. Annual energy and peak electric demand can usually be easily converted to economic costs. Unfortunately, much analysis stops at this point, assuming that the benefits or costs of lighting quality and visual performance are the same for each energy solution. But in many cases this will not be true and an extension of the analysis described above to include visual performance can be used to identify and quantify the tradeoffs [14]. Determining the value of increased or reduced visual quality or performance relative to some base case may be difficult, but it is quantifiable. For example, the value of the presence or absence of specific lighting quality features may be inferred from

[14] Schematic representation of the relationships between lighting quality, visual performance, and energy and the costs or benefits of each.



changes in rental value, vacancy rates, *etc.*, that result from the lighting quality feature. The scale of these terms varies considerably, as does our ability to quantify each of them. Lighting energy costs typically range from $.20 to $2.00/ft² per year, including demand charges. At the other extreme is the value of occupant productivity, which lies in the range of $100.00/ft²/yr to $1,000.00/ft²/yr. This is the total cost of the employee to the employer, only a portion of which will be sensitive to lighting factors. It is useful to note the difference in the magnitude of these numbers—one hour's worth of productivity is roughly equal to a year's worth of daylighting energy savings. Of course, we can rephrase these facts as follows: if the availability of daylight during a short power failure in a modern office building permits the occupant to continue productive work, the value of this increased productivity more than doubles the effective annual energy savings. A slightly longer blackout, for half of a day, might pay for the entire added first cost of a dimming lighting control system. (You may find it instructive to calculate the "value" of your productivity—multiply your annual salary by about 2.0 to account for benefits and your employer's overhead, then divide by the size of your office to get $/ft²/yr.

In the set of envelopes at the right of the figure we show the costs or benefits of energy, lighting quality, and visual performance translated into a consistent economic value that should allow tradeoffs to be made and solutions to be "optimized" within the constraints of the design criteria governing the solutions. We do not imply that this process is simple, but we do believe it is a worthwhile and achievable approach to ultimately reconciling apparently irreconcilable design factors.

Conclusions

Major advances in the efficiency of building design, construction, and operation over the past 13 years have produced significant reductions in US energy consumption and have saved consumers and building owners billions of dollars in unnecessary energy expenses. The planned use of daylight in buildings has emerged as one of the most commonly noted energy conservation strategies in new nonresidential buildings. We now look to daylight not only as a source of illumination and as an aesthetic element in building, but as a strategy for reducing electric energy consumption and peak electric loads. Daylighting may not be the dominant design feature in a building, but it is one of the most important energy-related design issues because it influences so many other building design decisions. It therefore requires the integrated efforts of all members of the design team to produce successful solutions.

Unlike some energy-saving strategies, daylighting represents a concept in which good architectural design, pleasant and productive work environments, and significant energy savings are mutually supportive and achievable goals. It is important to realize, however, that effective use of daylight as a lighting design strategy is not always synonymous with its best use as an energy conservation strategy. There is no inherent conflict, but success in one does not guarantee success in the other. Our experience with daylight as a light source is extensive; our experience using daylight to reduce energy consumption is very limited. However, since the energy concerns are more easily quantifiable, there is a danger that we will overlook lighting quality in our rush to squeeze the next kilowatt hour from the building energy budget. We must remember that we light the interior of buildings, not for the sake of the buildings, but for the needs of people. It is, thus, important to define carefully the design objectives in a daylighted building in order to evaluate properly our success or failure. Any proper accounting of the effectiveness of daylighting must assess the impact on human energy resources as well as on building energy consumption.

The lighting design community has a crucial role to play in this field. However, with a few exceptions, lighting designers seem to have conceded a pre-eminent role in daylighting to the architects and engineers who shape the envelope and interiors of buildings. Daylighting has been viewed as a threat by some lighting designers; it should be embraced as an opportunity and a challenge. All daylighted buildings require electric lighting systems; they also need better controls and more attention to master the design subtleties of a source whose properties vary over a wide range on a short time scale.

Buildings are becoming more complex and costly, and the design community desperately needs all the help it can get to address these problems. We need the vision to produce more innovative and effective daylighting design concepts and the skills and expertise to translate these concepts into reality. It seems reasonable to hope that the lighting design community would rise to this challenge and become interested and involved in this field. The challenges are great, but so are the potential rewards—for the individuals involved, for the building community, and for the country. ○

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