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Beam Daylighting: an Alternative Illumination Technique

ARTHUR H. ROSENFELD

Department of Physics and LBL, University of California, Berkeley, Calif. 94720 (U.S.A.)

STEPHEN E. SELKOWITZ*

California Institute of the Arts, Valencia, Calif. 91355 (U.S.A.)

This article is concerned with the energy savings and peak power reductions associated with the maximum utilization of natural light. The general characteristics of diffuse daylighting are discussed in terms of a standard office plan. An innovative technique of daylighting using direct beam radiation from the sun is treated in some detail. Beam daylighting, at 100 lm/W, is found to be more efficient than fluorescent fixtures and is capable of being directed up to 30 ft inward from the exterior facade by reflective louvers or blinds. The estimated cost of the system is calculated to be equivalent to the savings in electrical energy costs within a three-year period. It is also noted that relatively small savings in electrical consumption for air-conditioning are a by-product of the utilization of such a system.

INTRODUCTION

The power of sunlight as a source of heat and light is rarely appreciated. Consider the thermal balance across a one-foot wide section of a typical office curtain wall consisting of four square feet of glass and four square feet of insulated wall. On a clear winter day, sunlight provides in excess of 800 Btu/h to the space. A temperature differential of almost 140 °F is required (equivalent to an outside air temperature of −70 °F!) before the conduction and ventilation losses exceed the solar gains.

From a lighting perspective, sunlight acts as an intense collimated source with a color temperature pleasing to the human eye. If distributed uniformly, the lumens contained in a single square foot of sunlight could provide fifty footcandles (FC) of illumination over an area of 180 ft^2.

It is precisely because of the powerful nature of these heat and light sources that the sun is generally treated as a force to be excluded from a modern office environment. The designer has traditionally lacked both the economic incentive and conservation ethic necessary to attempt to control these sources effectively. Thus neglected, their power, variability and unpredictability overwhelm and dominate their potential usefulness. This article outlines a particular strategy to realize substantial energy savings by harnessing sunlight for illumination based on the use of an innovative, yet simple, control mechanism.

Any attempt to promote the widespread use of daylighting techniques to conserve energy must address the set of problems which has prevented its adoption and use. A glance at a modern building with its identical facades and permanent reflecting glass shows that it was not designed with the intent of using daylighting techniques for illumination. The remainder of this paper examines the limitations of existing daylighting techniques using diffuse solar radiation, and establishes the advantages, from a combined thermal/lighting energy perspective of using natural lighting. We then propose a novel daylighting system utilizing reflected *solar beam radiation* which appears to offer performance improvements over diffuse daylighting techniques.

LUMENS/WATT

Light from the sun is pleasant to us owing to its color temperature, and it is a comparatively efficient source of illumination,

*Now at Lawrence Berkeley Laboratory, Berkeley, Calif. 94720 (U.S.A.).

TABLE 1

Daylighting parameters: lumens/watt, solar heat grain, illuminance

	Direct beam sunlight	Skylight (incident) on vertical window)
1. Lumens/watt*		
(a) Measured, clear day	106 ± 2**	116 ± 7***
(b) Nominal values	100†	120†
2. Solar heat gain†† (Btu/ft^2 h)	300	35
3. Illuminance‡ (footcandles)	9000	1200

*Ross has found some mistakes in the Ross and Baruzzini report on Daylighting in Commercial Buildings [1]; this explains why lm/W tabulated here from those of Ross and Baruzzini, page III-25, eqns. 3 and 4, but agree with an Erratum to be issued by Ross.

**From I.E.S. Trans., (May) (1925), 493.

***From M. J. Blackwell, Meteorol. Res. Publ. No. 895, London, 1954.

†A 5800 °K black body provides 92 lm/W. Approximately 50% of the energy lies in the visible spectrum, 50% in the infrared. The atmosphere preferentially filters out the infrared, thus raising the lm/W (see Threlkeld, Thermal Environmental Engineering, 2nd edn., 1970, Fig. 13.12, p. 295). Diffuse sky radiation is the result of Rayleigh scattering, favoring visible over infrared diffuse sky radiation thus has higher lm/W than direct beam radiation and may be characterized as a 10 000 °K source.

††From ASHRAE Handbook of Fundamentals, 1974, Table 22.4, p. 390. Divide these values by 3.415 to obtain W/ft^2.

‡Can be obtained by multiplying the solar heat gain (in W/ft^2) by the lm/W.

producing 100 - 120 lm/W, as compared with nearly 70 lm/W for incandescent bulbs (see Table 1). There is a substantial variation in both the intensity and spectral composition of daylight owing to changing atmospheric and climatic conditions, and the diurnal and seasonal apparent movement of the sun across the sky. Average availability can be recorded or calculated but the daylight conditions at any given time are unpredictable.

DIFFUSE DAYLIGHTING

The daylighting of buildings has been extensively studied and is routinely practised. In predominantly overcast climates, diffuse radiation (sunlight scattered and reflected by the atmosphere and clouds) has been adopted as the standard design condition. Relatively large windows are then necessary to provide adequate illumination. These guidelines change, however, in climates characterized by clear sunny weather with blue skies of low brightness. Here, diffuse daylighting is based largely on sunlight reflected from adjacent structures, and smaller windows provide sufficient illumination. In neither case is beam radiation from the sun used directly to provide illumination.

Experience tells us that diffuse daylighting can almost always provide adequate illumination immediately adjacent to a window wall (see Fig. 1). It becomes considerably more difficult to provide good illumination as one moves towards the interior of an office space. Total available daylight declines exponentially as one moves away from the window. (Actual values depend on window size and location, room dimensions, *etc.*) The daylight reaching an interior position is the sum of (a) direct light from the sky, (b) light reflected from external objects, and (c) interreflected light which has been scattered from at least one internal surface. Far from the window, the internally reflected component replaces skylight as the dominant source of illumination and the reflectances of walls, ceilings and floor become important design considerations.

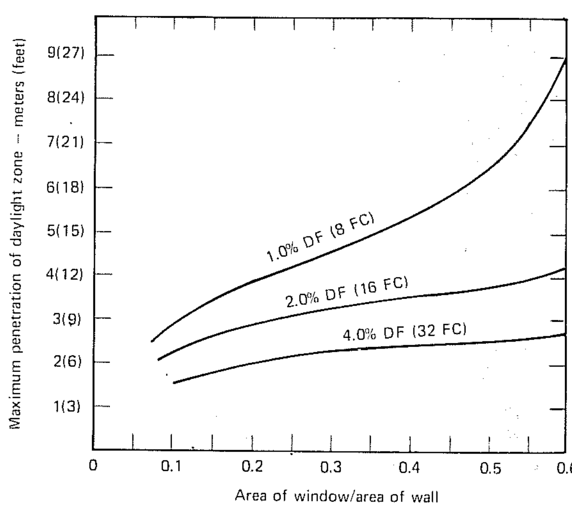


Fig. 1. Daylight penetration in side-lit rooms with window height of 1.8 m. Daylight factor (DF) is converted to illumination using weather-averaged value of 800 fL on north elevation during winter. Figure from N. O. Milbank, Energy Consumption in "Other" Buildings, British Building Research Establishment, BRE PD 136/1975.

Diffuse daylighting — north windows

Modern office building design has produced a variety of glass boxes with identical building elevations. Not only is the design of north and other elevations frequently identical, but the same solar control glazing is used, presumably for uniformity. Little summer sun is incident on a north wall, so the main effect of the reflective glazing is to reduce the daylighting potential. We suggest that there would be a market today for "facsimile" solar control glass for north windows. Its color would match that of the solar control glass on the other elevations, but it could have a much higher light transmission. In current energy conserving recommendations, the pendulum now swings the other way: codes to reduce heating and cooling loads now, under some conditions, suggest the elimination of all glazing on north-facing exposures, thus again removing the possibility of diffuse daylighting.

Diffuse daylighting — other elevations

For orientations other than north, diffuse daylighting is possible during certain hours of the day, but sun control must be provided to exclude the direct rays of the sun. Reflective and/or tinted glazing is now used extensively in new construction to turn back the sun's heat. This approach, however, reduces the available diffuse radiation that might be used for daylighting. For an unshaded building, diffuse radiation is the dominant available mode on a north elevation, but represents only 50% of available lighting hours on an east or west elevation and contributes little on a south elevation (see Fig. 2).

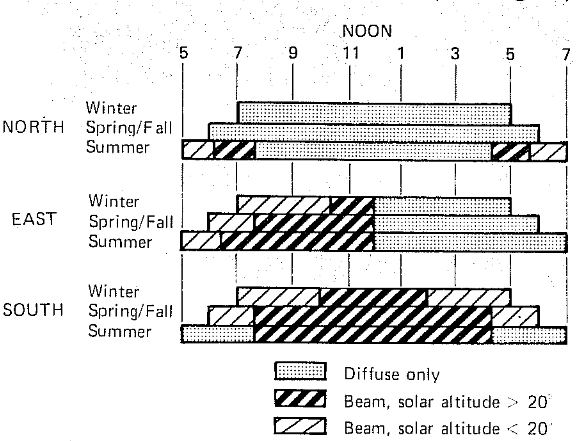


Fig. 2. Seasonal and hourly distribution of diffuse and beam daylighting opportunities for different building elevations at 40 °N.

With the introduction of overhangs and fins to exclude direct radiation, an increased proportion of natural light is available in diffuse mode. Any attempt to control direct radiation by the use of glazing with a fixed, low shading, coefficient will reduce the opportunities to utilize diffuse daylighting.

Other factors, such as the trend to lower ceiling heights, have reduced the daylighting potential in buildings. Perhaps the greatest impediment to the widespread utilization of daylighting techniques, has been the existence of a cheap and versatile substitute — an electric light. When used in a sensitive and intelligent manner, electric lighting produces comfortable and effective levels of task illumination. However, the power and versatility of electric lighting and an era of cheap and plentiful electricity have combined to promote the careless use of electric lighting and disinterest in daylighting possibilities. The energy crunch and rapidly rising energy costs are rekindling an interest in the potential of daylighting to reduce electrical energy consumption. Traditional methods of diffuse daylighting can and should be utilized wherever practical. They are subject, however, to the limitations described on the preceding pages. We now examine a novel daylighting design utilizing reflected beam radiation from the sun, which will extend daylight utilization to other building types and climates not suited to diffuse daylighting techniques.

BEAM DAYLIGHTING

Direct solar radiation from the sun on a clear day provides approximately 9000 FC (see Table 1). We propose to reflect beam radiation from the sun onto the white ceilings typical of most commercial buildings so as to penetrate up to 30 ft into the building, as shown in Fig. 3. A relatively small glazed area (approximately 2 ft high) near the ceiling of a standard window admits enough light throughout much of the year to provide desktop illumination levels in excess of 50 FC after reflection from the ceiling. Figure 4 shows the average lm/ft cast on a ceiling 30 ft deep from a south window at latitude 40 °N on an average clear day. With the exception of summer, illumination levels on the ceiling are consistently above 100 FC. Not all of this

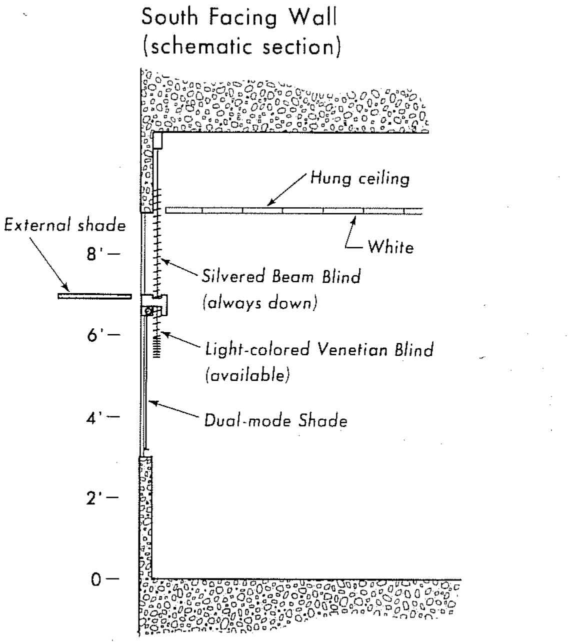


Fig. 3. Cross-section of typical office space (south perimeter location) showing location and schematic operation of beam daylighting apparatus.

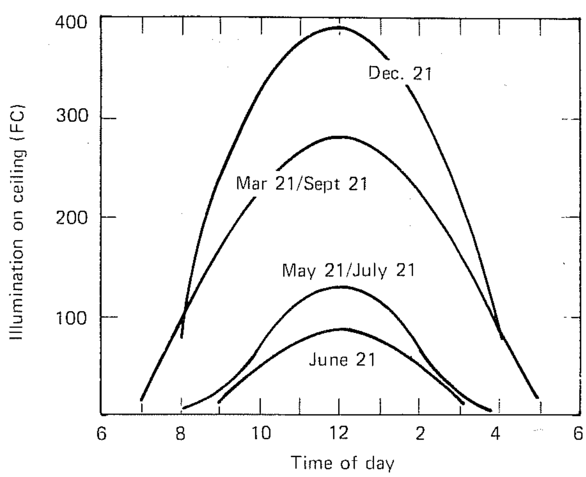
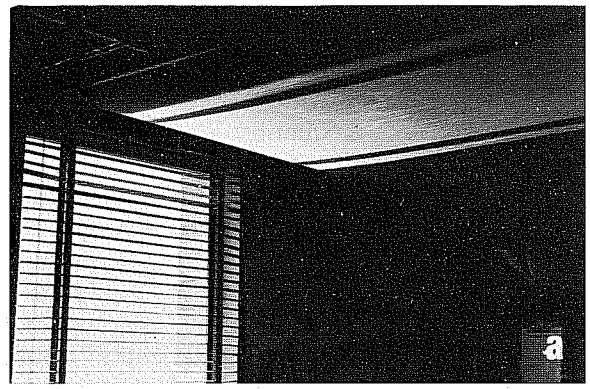
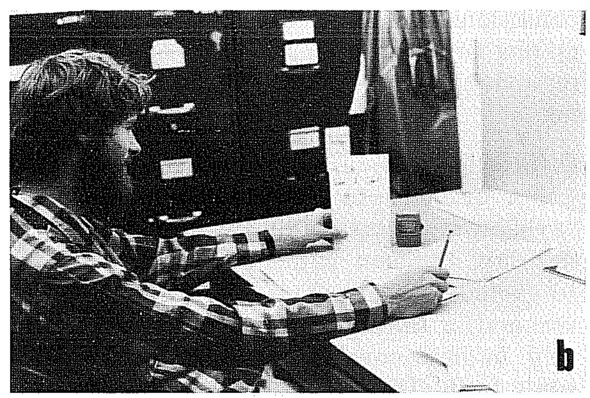


Fig. 4. Beam illumination on a 30 ft deep ceiling from two feet of south-facing clerestory window on clear days at 40 °N.

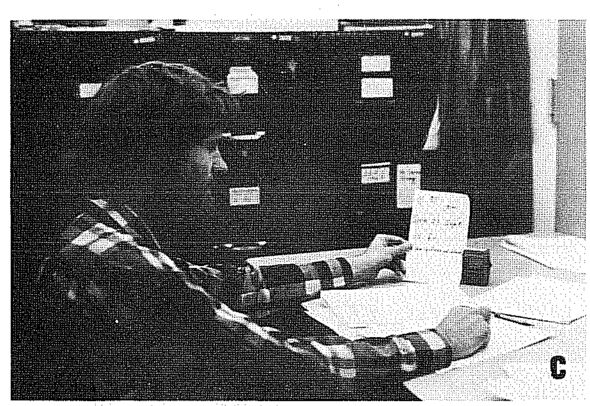
light reaches the work plane. Consider the illumination at noon at the equinox. In the center of a large room with a typical ceiling reflectance of 70% the work plane illumination will be approximately 210 FC when 300 lm/ft^2 strike the ceiling. Near the sides of the room the level would fall off to perhaps 175 FC owing to the proximity of walls of 50% reflectance. Figure 5 shows an LBL office, pleasantly daylighted by a single window of 4 ft width.



(a) Beam daylighting mock-up using 15 inverted venetian blind slats covered with metallic polyester film (chrome-colored). Light is spread over white screen at ceiling height.



(b) Lighting level at task surface in interior office with clerestory in separating partition, with treated blind slats.



(c) Lighting level under identical conditions with normal venetian blinds.

Fig. 5. (a) The single window with a blind whose top 15 slats are reflective, illuminates an inner office, (b). In (c) the reflecting films were removed; nothing else, including the exposure, was changed.

In a smaller office, these levels would be raised by a factor of two or three, providing illumination equivalent to that under an overcast sky, which would not be unpleasantly high. The height of the beam daylighting blinds could be reduced to one foot to drop the illumination level back to the level provided in the larger office.

Beam daylighting apparatus

The apparatus used to provide beam daylighting is illustrated in Fig. 6 as part of an overall optimized window design. Two different sorts of Venetian blinds, both mounted behind a clear window, provide visual and thermal control: a silvered "beam" blind mounted behind the upper window and a solar control (partially reflective) blind located behind the lower (Vision) window. (This latter blind is mentioned in an article by Silverstein contained in this report.)

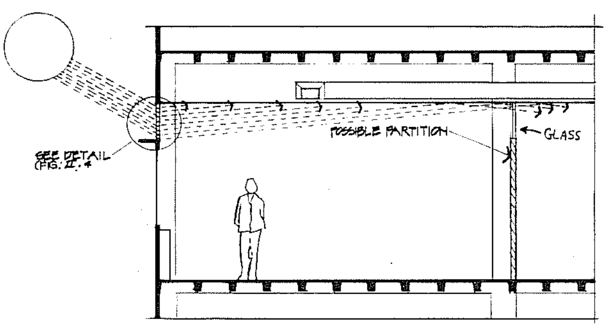


Fig. 6. Schematic section through southfacing wall. For the lower (view) part of the window, the solar control shade (*e.g.* Scotchtint) and the optional, light-colored, opaque Venetian blind, could be replaced by the dual mode shades discussed by Silverstein or the dual mode venetian blind discussed by Rosenfeld.

The beam daylighting blinds function independently of the solar control blinds. When there is no direct sun on a particular building elevation, the blinds would provide some diffuse daylighting. With direct sunlight, the slat tilt and spacing should be designed so as to prevent direct sunlight from traveling between slats and striking work areas. In addition, to provide optimum illumination at a constant depth in the room, the slat angle should be adjusted continuously to compensate for changing sun angles. In practice, only seasonal adjustment should suffice. Typical spacing and tilt conditions are shown in Fig. 7.

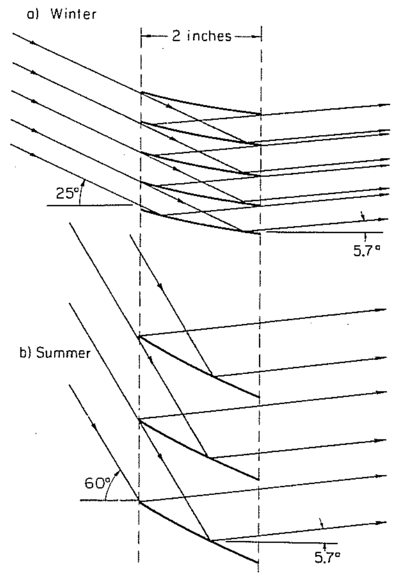


Fig. 7. Tilt and spacing for reflecting slats for typical winter and summer incident light conditions, for a 20 ft deep room at 40 °N.

Beam daylighting controls

We divide the discussion of controls into two cases: (a) a small, one-person perimeter office, and (b) a large, open-landscaped office.

(a) Perimeter office, one occupant

Here we see two options, the first of which is sketched in Fig. 6. In order to obtain the variation in both slat spacing and tilt angle, the conventional cloth straps have been replaced by elastic straps. The conventional tilt mechanism is unchanged. We then visualize that the occupant will occasionally adjust the blind tilt so that bands of light penetrate to the back of the office. The slat spacing can then be adjusted by means of a cord which runs over a pulley, shown recessed into the ceiling in Fig. 6. We can envisage no circumstances under which the occupant could not maintain conditions of visual comfort.

An alternative which we have not fully studied is to install "fixed" blinds (actually adjusted seasonally) which provide adequate, though not optimum, illumination. Preliminary studies indicate that illumination in excess of 45 FC can be provided for about 1000 clear-day hours per year from most window exposures. If some direct sunlight passes between the slats and enters the workspace in the one-man office with continously adjustable blinds, the occupant will readjust the blinds. In the large office with fixed blinds, precautions must be taken that a direct beam never gets below eye level. We are studying several solutions:

A second, fixed, Venetian blind, serving as a collimator which accepts only the shaded rays of light shown in Fig. 7.

An eggcrate grill mounted almost horizontally — actually sloping and grazing the bottom of the daylight beam — which stops a downward sloping direct beam but permits light scattered from the ceiling to travel downwards onto the task.

The only serious control problem we foresee in a small office is turning off the lights once sunlight becomes available. The cheapest solution seems to be that the light switch should have a built-in timer which could be controlled either centrally or by the occupant who could dial light for up to four hours. This would turn lights off at lunchtime and after a forgetful occupant has gone home. In addition, on days with highly variable daylight, some conservationists might wish to dial artificial light for brief periods, knowing that daylighting conditions would probably return. Is it irritating to have the lights turn off automatically at 5:30 PM when one is on the phone working late? We suspect not, because of the trend towards task lighting or multi-level lighting within a single office. However, a thoughtful timer could always signal shortly before the lights were to be turned off.

Independently of daylighting, timed light switches would amortize their additional cost quickly. A typical 150 ft^2 office, even with future lighting levels of 2 W/ft^2, consumes 0.3 kW, or about 5 kWh, for each night they are inadvertently left on (or 20 kWh per weekend). At 3¢/kWh, forgetfulness costs 15¢ per night or 60¢ per weekend. Our experience indicates that one light in five is often left on at the end of a work day. At that rate, savings amount to $12.00 per office per year, suggesting a payback period of about one year.*

(b) Large open landscaped office

In a large office, we anticipate using the beam daylighting apparatus to provide 50 FC illumination up to 30 ft from the windows.

*$12/office-year represents an annual savings of 400 kWh. At a heat rate of 13 000 Btu/kWh_e, or 0.1 gallon of oil/kWh_e, the savings are 40 gallons of oil per office per year.

Figure 4 shows that on a clear day sufficient lumens are available from a south-facing clerestory window of height two feet to provide more than 100 FC on the ceiling from 9 AM to 3 PM throughout most of the year, averaging about 6 h per day. Figure 8 shows the beam day lighting availability in hours per clear day for window orientations other than south. The relatively small differences in the annual averages over a wide range of orientations hide the large hourly and seasonal variations which occur.

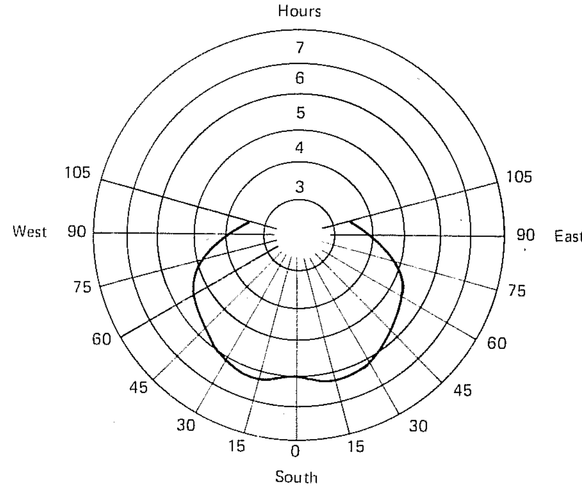


Fig. 8. Average hours per day during which illumination exceeds 100 FC on the ceiling from beam blinds as a function of window orientation. Results are based on optimal blind position on clear days at 40 °N, 2 ft clerestory, 90 blind reflectance and 30 ft deep office.

Translating available solar energy to useful illumination is a more demanding task in the large office than in the small office previously considered. Differing illumination requirements and the larger area to be lit make it more difficult to provide continuous illumination at the levels desired at any given location in the office. The larger space to be lit and greater potential savings will justify an increased investment in either a more sophisticated blind control mechanism and/or a "smarter" electric light controller (continuous dimming or multi-level control). Our studies indicate that a reliable and cheap photoelectric controller could be produced if ultimate demand justified the initial research and preproduction costs. A detailed study has not yet been made of the tradeoffs involved in increasing the complexity and cost of the beam control mechanism, thus permitting a "fixed" beam blind and more sophisticated electric lighting controls. In either case, a version of the timed light switch discussed in case (a) will still return excellent economic and energy savings.

THERMAL CONSIDERATIONS

North windows lose heat in winter and admit heat in summer. For a 5000 degree-day climate, small north windows daylight enough area to easily pay for their heat loss, but above 20% north glass area the increased cost of heating oil cancels electric savings. Natural gas is still cheaper, but in designing a new building one cannot plan on gas remaining cheaper than oil.

For non-north windows we shall now show that thermal considerations are not very important.

Winter

Windows which see direct sunlight in winter roughly break even (solar heat gain tends to cancel conduction loss), so any electricity saved by daylighting is simply a net gain.

Summer, case (a)

If an area is *already adequately daylit*, and is cooled with an air conditioner with a system COP of 2.5, then, of course, when 2 W/ft^2 are switched off, one saves nearly an additional watt per square foot of air conditioning demand. This is the case studied on page III-29 of Ross and Baruzzini [1] for a simulated 20-storey building, each floor with 15 000 ft^2. For St. Louis weather, switching off perimeter lights (when daylighting was adequate) saved 25% in lighting energy. In addition, their Table III-9, column 7 shows ΔkWh (cooling)/ΔkWh (lights) varying from 15% in Minneapolis to 26% in Los Angeles. (As for winter, heat requirements rose by only 5%.)

Summer, case (b)

More typically, and not studied by Ross and Baruzzini, daylighting will be achieved by designing *extra clerestory windows*, and we must compare the heat from the extra glass with the heat from fluorescent lamps. They roughly cancel; this can be seen as follows.

In Table 1 we saw that sunlight provides 100 - 120 lm/W; fluorescent luminaires are slightly hotter (50 - 70 lm/W). Diffuse daylighting is hard to control, however. Because of its exponential decay inwards it overlights and overheats near the window and probably averages 50 - 70 lm/W (*i.e.*, averaged over a whole office).

A 1 ft height of clerestory window is adequate for beam daylighting a one-person 150 ft^2 office with a 12 ft wide south exposure. Thermal input for this window is shown in Fig. 9. On a clear January day at noon, the office is brighter than necessary, but the heat and light are pleasant. During the cooling season, typified by the August curve, we note that the window is about as "hot" as the lights, even assuming future conservative lighting loads of only 2 W/ft^2.

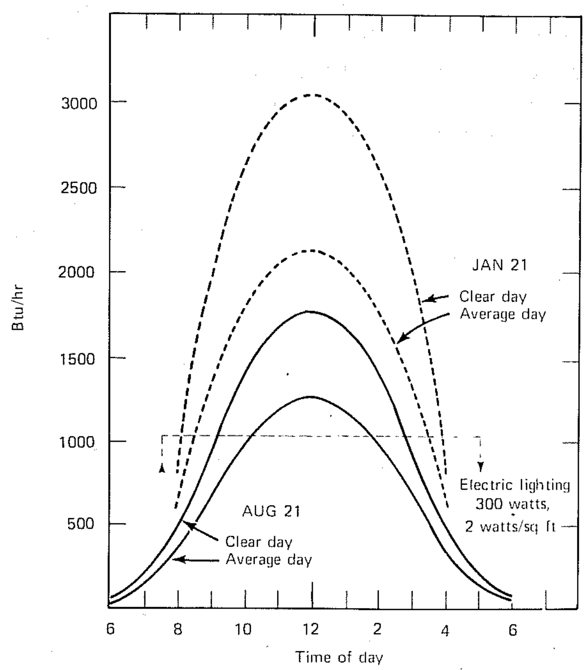


Fig. 9. Heat inputs to office space from beam daylighting clerestory window (12 ft^2) *vs.* electric lighting (2 W/ft^2), for a small office (150 ft^2) with a south exposure at 40 °N. Conductive gains and losses are not included.

We conclude that *extra* windows for diffuse daylight are about as hot as the luminaires they displace. Small clerestory windows for beam daylight are slightly cooler than artificial lights, but in general the side effects of reduced air conditioning are negligible.

There *are* significant thermal considerations for the "view" part of the window, but these are discussed elsewhere in this report by Silverstein and by Rosenfeld.

COST/BENEFIT

Small office

In the Introduction, the potential national energy and peak power savings were discussed. We now consider the potential cost/savings balance for the single-occupant office evaluated in a previous section. A 150 ft^2 office with a 12 wide south exposure would contain 12 ft^2 of beam daylighting blinds, assuming a 1 ft high clerestory window. This would provide a light intensity on the ceiling in excess of 100 lm/ft^2 for more than 8 h during an average clear day. Assume then that 80% of the occupied hours could utilize beam daylighting. Typical figures for sunshine availability are 65%. Thus, during approximately 50% (80% × 65%) of the 2000 annual working hours, beam daylighting is both available and feasible. The power and energy savings are summarized below.

Power: 2 $W/ft^2 \times 150\ ft^2 = 300$ W. Peak power charges are estimated (in a longer version of this paper, to appear in the FEA lighting symposium) to be about $4/year (see footnote on p. 44).

Energy: 50% × 2000 h × 300 W = 300 kWh/year. At 3 ¢/kWh, energy saved is $9/year.

Total savings (peak + energy charges): $13/year.

Costs: we assume timed light switches pay for themselves in a year or so by night-and-weekend savings, so the only cost is for the reflective blinds. Venetian blinds in the Sears and Wards catalogs cost $1/ft² and upwards. We assume the reflective ones will sell for $2/ft². Cost: 12 ft² × $2/ft² = $24. Maintenance: little is foreseen.

Payback period: $24 ÷ $13/year = 2 year payout.

Large office

Similar calculations were performed for one example of the large open landscaped office (south exposure, 120 ft × 30 ft deep). Instead of Venetian blinds adjusted by the occupant and yielding 1000 h of daylight annually, we assume seasonal adjustment and only 800 h annually. For peak power we assume that only 1 W/ft^2 can be saved.

Peak power savings, annually	$75
Energy savings, annually: 800 h × 2 W/ft² × 3600 ft² × 3 ¢/kWh	$173
Total annual savings	~$250
Costs: blinds, $2/ft² × 240 ft²	$480
Photocell control for lights	$320
Total costs	$800

Payback period: 3.2 years.

We conclude that the small office is the best target for beam daylighting, but that the large office is worthy of further R and D.

CONCLUSIONS

Increased use of daylighting is proposed in virtually every shopping list of energy conservation strategies published in the last few years. Traditional methods of diffuse daylighting do work in perimeter offices, although they have not been extensively used for a number of reasons that are reviewed in this paper.

We have proposed a new daylighting technique utilizing beam radiation from the sun which will substantially extend the applicability of daylighting. Reflecting Venetian blinds mounted behind a small clerestory window will reflect sufficient lumens off the ceiling to provide adequate illumination throughout much of the year. Further work is being performed to optimize the design of the blind mechanisms and their integration with the electric lighting controls. Substantial energy and peak power savings were shown to be possible in typical small and large offices. Energy savings should repay capital investment in the mechanisms and controls in two to three years. On a national scale, we estimate that 1/8 quad ($1/8 \times 10^{15}$ Btu) of resource energy might be saved each year and peak power demand reduced by 6 gigawatts if beam daylighting were installed in 20% of existing commercial floor space.

A longer version of this article, with details on peak power costs and a Table on optimal window size for diffuse daylighting appears in the Proceedings of the 1975 FEA Lighting Symposium published by the Federal Energy Agency, Washington, D.C. (April 1976).

REFERENCES

1 Ross and Baruzzini, Inc., Energy conservation applied to office lighting, FEA Rep. (Contract No. 14-01-0001-1845), April 1975.