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DAYLIGHTING DATA FOR ATRIUM DESIGN

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ABSTRACT

This paper focuses on atrium characteristics that influence the admittance and distribution of solar gain and daylight. We report on results of an extensive series of scale-model tests in a large sky simulator. Total visible transmittance of complex atrium glazing systems were measured using a large, newly developed integrating sphere. Performance results are described in terms of several generic geometric factors (cross section, length, width, height), orientation, interior surface treatments, and glazing systems for different sun and sky conditions. We describe how measured illuminance data in atria can be used to determine if an atrium design will admit adequate light for plant growth or provide adequate light for typical office tasks in spaces adjacent to the atrium.

INTRODUCTION

Atrium spaces are incorporated into new buildings with increasing frequency, often with the rationale of producing a more energy-efficient building design. A review of historical examples and modern case studies suggests that atria serve many functions in a variety of building types. In addition to aesthetic, social, and economic functions, a primary intent in many modern buildings is to use the atrium as a climate-modulating or thermal buffer zone to make "outdoor" space more comfortable and usable for more time during the year. A further extension of this concept is to provide partial or complete thermal space conditioning, which may increase heating and cooling loads relative to a "base case" building without the atrium. Although some designers claim atrium designs will reduce space conditioning loads, the anecdotal evidence seems to suggest the opposite. Daylighting design claims are only slightly less controversial. Daylighting will rarely increase lighting energy consumption--but the degree to which it will decrease consumption is not well known. One must distinguish between adequate daylight in the open areas under the roof glazing and daylight that penetrates horizontally from the atrium cavity to provide useful light in adjacent offices. Once again, anecdotal information suggests the visual environment (e.g., view) is greatly enhanced from adjacent offices but that the real energy impacts are minimal. We have also found examples of low-transmittance glazed roofs (required to control solar gain) that require extensive supplementary electric lighting to keep foliage healthy. There is little definitive experience and few measured data that can be readily analyzed to improve the daylighting contribution of subsequent designs. The success of daylighting strategies in atria depends on 1) a critical assessment of lighting design criteria that are appropriate to the functional and aesthetic program of the building, and 2) properly modulating the intensity and distribution of available daylight to meet those design criteria.

In the design of atria, good quality lighting and control of glare are expected. Commercial or public buildings are more demanding of this criteria, but the lighting criteria tend to be specific to the task rather than to the building type. For example, atria which serve as circulation spaces will normally have the same lighting criteria whether they are located in office buildings or hospitals. In some cases, minimum lighting design conditions may be dictated by the illuminance requirements of plants rather than by people who pass through. Atria are often viewed as light-admitting elements that transfer light flux to adjacent office spaces. While this objective may be readily achievable with atria in low-rise buildings it appears to be difficult to achieve in deep atrium designs and in most designs that block direct sun penetration.

In addition to their light-distribution functions, atria affect the overall thermal energy balance of buildings in many ways by virtue of their heat loss characteristics, their solar gain properties, and their natural and forced convection links to HVAC system. Proper selection of glazing types, shading devices (fixed and operable), fenestration orientation and geometry, and overall atrium size and shape will determine the overall energy costs and benefits for a specific building in a given climate zone.

The multiple functions served by atria increase their attractiveness to building owners but make the design analysis more complex. In this paper, we focus only on the daylighting and solar gain aspects of design, which are themselves very complex because of the variables involved. We have conducted extensive parametric measurements of illuminance distributions in atria as a function of fenestration, atrium geometry and reflectivity, and adjacent office conditions for different sun and sky conditions. The primary objective of this phase of our study is to identify the key design parameters and their relative impacts on interior illuminance, and to develop insights and design guidance regarding critical daylighting performance factors in atrium design. We examine only the case of a simple atrium of square cross section and variable depth with fenestration and interior surface conditions as the critical variables.

Conventional daylighting calculation techniques are inadequate to determine daylighting quality and quantity in any but the simplest atrium designs. We rely primarily on physical scale-model photometry using a large indoor sky simulator for our study [1]. We also examined different design options under outdoor sun and sky conditions. We used a newly developed integrating sphere to measure the total visible transmittance of entire atrium roof designs as a function of solar altitude and azimuth angle. [2] Although not covered in this paper, we use the computer program SUPERLITE to model illuminance distribution in atrium spaces and adjacent work areas.[3] We will extend this analysis in future studies to include an hour-by-hour assessment of lighting and thermal impacts using newly developed analysis capabilities in the computer program DOE 2.1C.

EXPERIMENTAL APPROACH

The daylight (and solar gain) that reaches task locations is influenced by several major design features, each of which can be controlled to some degree. The <u>fenestration system</u> will control the intensity and spatial distribution of light entering the atrium. The net transmittance of the fenestration will vary with glazing system geometry, glazing orientation and type, shading systems, and illuminance conditions (e.g., diffuse sky, direct sun). The atrium <u>light well</u> consists of all building surfaces facing the atrium space as well as interior obstructions (e.g., vegetation, stairwells), the length/height/width ratios, wall surface type and reflectivity. Wall glazing characteristics will also influence the flux distribution and intensity as a function of position in the atrium. These two clusters of parameters are useful for determining illuminance and luminance characteristics within the atrium space where the objective is to provide lighting for plant growth or for general circulation areas where visual performance requirements are minimal. When illuminance is to be provided in building spaces adjacent to the atrium, the optical characteristics of the glazing separating those spaces and the rooms themselves must be considered.

The primary objective of this study was to determine the relative importance of the key performance factors defined above. The study is limited to illuminance characteristics and does not directly address annual energy consumption. We also limit our evaluation to a single square atrium cross section, although the depth is varied. This phase of the study was intended to better understand atrium illuminance performance issues so that the following phases could focus on the most critical performance factors. We believe, however, that even these initial systematic results will be of some value to designers who must frequently make critical design decisions with a minimum of performance data.

A scale model (1/2" = 1) of a square atrium in a 10-story building was constructed so that walls, windows, atrium fenestration, and atrium height could be readily changed (Fig. 1). Several specialized photometric test facilities were used to measure atrium performance. The LBL sky simulator allowed us to test illuminance distributions in the model under a range of clear, overcast, and uniform sky conditions. High-intensity lamps were used to simulate sunlight penetration. A newly developed integrating sphere was used to measure total hemispherical transmittance as a function of angle of incidence. Limited measurements were also conducted outdoors for a range of sky conditions. High-quality photometric sensors with photopic and cosine correction were used. A multichannel data acquisition system linked to a microcomputer was used to collect, calibrate, and archive the photometric data. A typical test in the atrium model recorded photometric data at 40 locations.

We initially examined the optical properties of 14 atrium fenestration systems. These included 5 types of multiple roof monitors, a single-barrel vault, 3 A-frames, 3 pyramids, a flat clear glazing, and an open atrium; typical examples are shown in Fig. 2. Most of the designs included some obstructing structural elements. Clear, tinted, and diffusing glazing were studied in several cases. The hemispherical transmittance of each was measured as a function of incident angle and all were initially tested in the sky simulator under uniform diffuse skies. More detailed investigations were made on a limited number of systems.

The nominal atrium cross section dimensions were 48′ by 48′. Tests were conducted in atria with height varying from 2 to 10 stories with a floor-to-floor dimension of 13′. Wall reflectivity was varied at 3 values: 1.5%, 50% and 86%. Some tests were made with window cutouts in the atrium walls representing 4′-high continuous strip windows. A relocatable office zone bordering the atrium had a depth of 40 feet.

Most data are displayed as daylight factors, the ratio of illuminance at the location in question to the exterior horizontal illuminance.

RESULTS AND DISCUSSION

1. Fenestration System Effects

The fenestration or atrium system will have a major impact on interior illuminance levels and distribution. Figure 3 shows the variation in illuminance at the first floor level in a nine-story atrium with high reflectance (86%) interior walls under uniform sky conditions, with several systems tested under clear sky and direct sun conditions as well. The clear sky and sun conditions are for a single intermediate case, solar altitude = 50°, solar azimuth = 0°. Note that the ratio of clear sky daylight factor to direct sun daylight factor varies considerably depending on fenestration. This is readily understandable due to the directional properties of each fenestration system.

These properties are illustrated more clearly in Fig. 4, which shows the hemispherical transmittance as a function of solar altitude (0 azimuth) for seven fenestration systems (relative to an open atrium). The roof monitor systems (# 2, 3, 4, 5) show similar properties (i.e., reduced transmittance at high solar altitudes) while the pyramid, vault, and A-frame have much less angular selectivity. The transmittance vs. incident angle for azimuths of 90° and 180° differ from 0° azimuth as one would expect. The exterior reflectivity of the monitors has a modest effect on net transmittance. Note that the transmittance shown is relative to an open atrium; absolute transmittance will be lower, particularly at low solar altitudes.

The transmittance of each fenestration system in Fig. 4 and the illuminance results in Fig. 3 could be further reduced by using lower transmittance glazing or by reducing the effective glazing area (e.g., reducing glass area or increasing mullions and other structures.) The daylight factors in Fig. 3 would also be reduced if the atrium wall reflectivity was reduced: these values represent close to maximum achievable levels.

2. Atrium Wall Effects

Figure 5 shows the effects of a change in atrium wall reflectivity from 0.86 to 0.50 for five fenestration systems under several sun and sky conditions in a five-story atrium. The most striking effect is that the reduction in the direct sun component as the wall become darker is much greater than the reduction in diffuse sky component. The importance of wall reflectivity follows from the fact that the 50° altitude sun will first strike a vertical surface before being diffusely reflected in the atrium space. A component of sunlight striking the side walls may also be reflected specularly if the atrium walls are glazed.

Figure 6 shows the rapid drop-off in illuminance on a vertical atrium surface as a function of depth in a five-story atrium with an open roof for the high (0.86), modest (0.5), and low (0.015) reflectivity cases. The difference between the cases with wall reflectivity of 1.5% and the 50 and 86% reflectance walls indicate the relative importance of the interreflected component. If we compare the clear sky case to the uniform sky, the sky luminance distribution of the 50° clear sky allows more flux to reach the south-facing atrium wall. A vertical surface with an unobstructed view of the sky would have a daylight factor (relative to horizontal illuminance) of 0.5 to 0.9 depending on sky conditions. The vertical surface data shown in Fig. 6 illustrate the reductions relative to an unobstructed window as a function of depth in the atrium.

The illuminance at the floor of the atrium (or on vertical surfaces) can be used to estimate the adequacy of the lighting environment for plants. Many plants need between 1000 and 2000 lux for at least 12 hours per day [4]. Once daylight factors for various sun and sky conditions have been determined as a function of atrium design, it is possible to predict the hourly illuminance patterns using a computer model such as DOE 2.1B. A simpler presentation of average hourly/monthly data can be obtained using plots of exterior horizontal illuminance as a function of hour and month or probability distributions for available daylight.

There are several approaches for rapidly estimating the suitability of a design for plant growth. We illustrate a simple case. We wish to analyze the illuminance in a deep (9-story) atrium with a simple A-frame glazed roof (roof #7). The daylight factor at the center (under uniform sky conditions) is 8%, and falls off to 5% near the sides. For simplicity, we use the uniform sky data for all sun and sky conditions, rather than the specific overcast, clear sky, and sun data. (This simplifying assumption will be appropriate for an atrium roof with many structural members that reflect and diffuse incoming light, with shading elements designed to prevent direct sun penetration, or for diffusing glazing.) With a 5% daylight factor, we need 20,000 lux on an exterior horizontal surface to provide 1000 lux inside, and 40,000 lux outside to provide 2000 lux inside. Figure 7 shows a plot of average horizontal illuminance at the atrium floor as a function of hour and month based upon measured availability for San Francisco (Ref. [5]). One can readily see the hours per day throughout the year that specific illuminance levels are exceeded. Figure 8 shows the percentage of the annual daylight hours that values of 1000 and 2000 lux are exceeded for global and diffuse illuminance only. We see, for example, that illuminance in the atrium will exceed 2000 lux about 50% of the year using exterior global luminance. Figure 11 shows atrium illuminance levels for average clear (direct sun and diffuse sky) and overcast sky conditions as a function of solar altitude. We see, for example, that on typical overcast days interior illuminance will exceed 1000 lux only when the solar altitude is greater than 33°.

Use of heat-absorbing or reflective glass, or use of darker interior finishes would further reduce available daylight. We conclude that for this case (and for atria of this general cross section that are much deeper than 5 stories), it is difficult to maintain adequate illumination throughout the year for plants requiring 1000-2000 lux 12 hours per day. It is, of course, possible to find plants that will thrive in dimmer environments, or to supplement daylight with electric light.

Studies of atrium photometrics provide information that is useful in several ways. Once the specific illuminance requirements of plants are determined, one can assess what design changes might provide adequate daylight. Conversely, if the design is fixed, one can determine the indoor daylight levels and then specify plantings that will thrive in that environment.

3. Adjacent Spaces

Our measurements indicate that the daylight on a vertical atrium wall is normally less than 20% of the exterior horizontal value once one moves below 2 or 3 floors depth. Thus it would not be surprising to find that the task illuminance within an adjacent space is also low.

Analysis based on our measurements in adjacent spaces confirms that for many hours of the year (particularly winter months and overcast days) the interior daylight levels in adjacent spaces range from 50 - 500 lux and will not be adequate without supplementary light for many office designs. There is often sufficient flux available at the roof of the atrium, but the optical transfer process through the roof fenestration, the atrium light well, and into adjacent spaces is not efficient. Even though people are more mobile and tolerant of lower light levels than plants, these optical results suggest that the opportunity to provide "usable" daylight in spaces adjacent to atria is a function of many design parameters; it should not be assumed that the simple presence of an atrium provides adequate illuminance. More detailed quantitative data have been collected and will be analyzed in future studies.

CONCLUSIONS

The results of this study demonstrate the importance of each optical subelement of an atrium in a large building. The performance of different fenestration systems, the effects of atrium wall surface treatment, the orientation of the building with respect to sky conditions, and depth of the atrium are significant factors. Generalizations about daylighting effects in atria that are not specific with respect to these parameters should be used with caution. These results of systematic measurements can be used to predict illuminance levels inside the atrium if proper availability data are available. We caution the reader that the various daylight factors (for uniform, clear sky, etc.) are not interchangeable and must be used only with appropriate exterior illuminance data. We are using these data to validate a mainframe computer program (SUPERLITE) which will then become a new design and analysis tool for further detailed studies. Finally, the data obtained for this study will be part of a large data base that will be available to designers.

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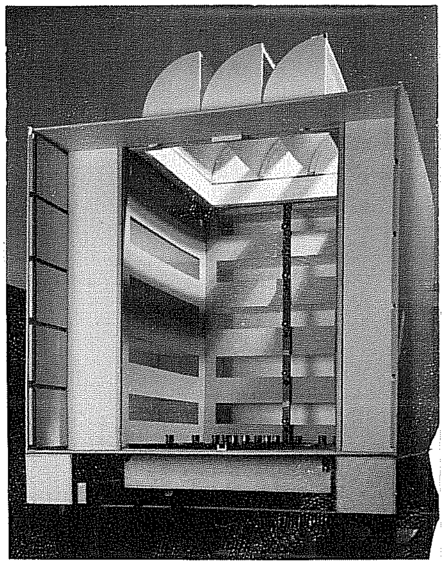
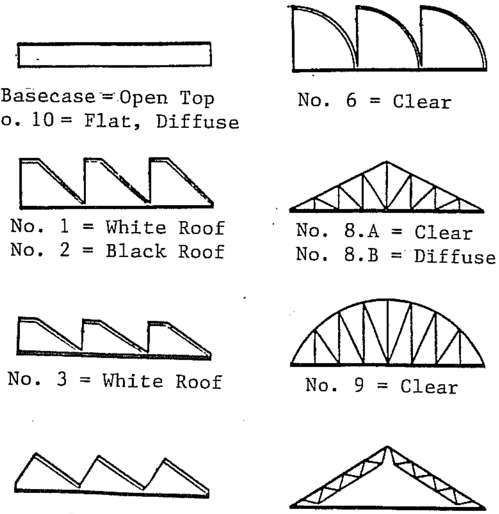


Figure 1. Atrium scale model with one side removed and one of 14 tops in place.



Basecase = Open Top
No. 10 = Flat, Diffuse

No. 6 = Clear

No. 1 = White Roof
No. 2 = Black Roof

No. 8.A = Clear
No. 8.B = Diffuse

No. 3 = White Roof

No. 9 = Clear

No. 5 = White Roof

No. 11 = Diffuse
No. 12 = Clear
No. 13 = Tinted

Figure 2. Schematics of most of the 14 atrium roofs tested.

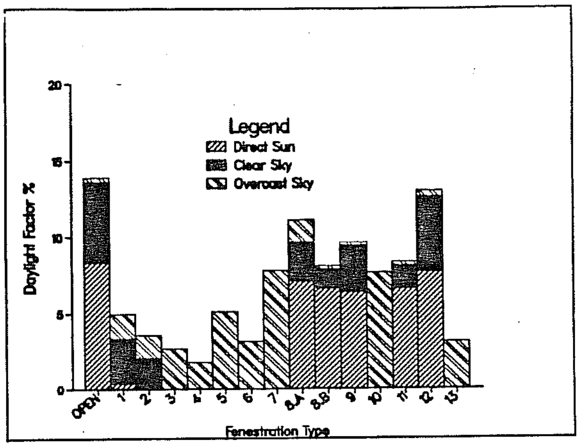


Figure 3. Illuminance (daylight factor) at center of 9-story deep atrium floor for 14 roof types under three sun/sky conditions.

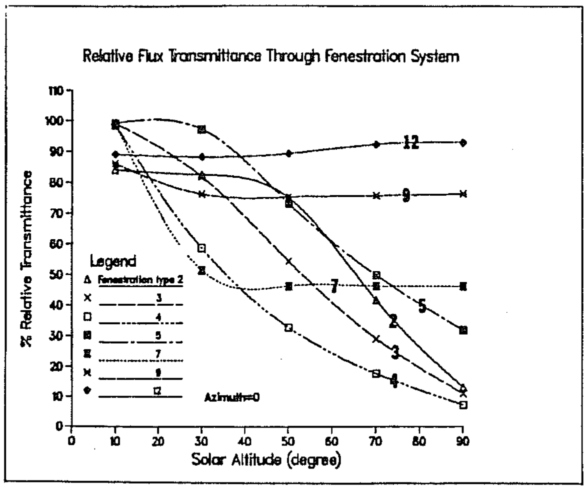


Figure 4. Relative flux transmittance through fenestration system as a function of solar altitude.

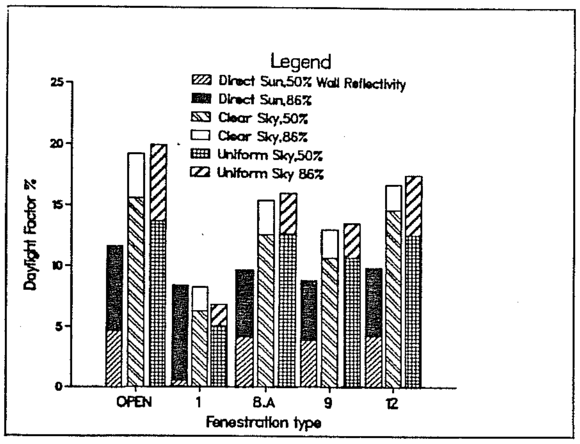


Figure 5. Horizontal illuminance (daylight factor) at center of floor of 5-story-deep atrium as a function of wall reflectivity. uniform, clear, direct sun at 50^o altitude.

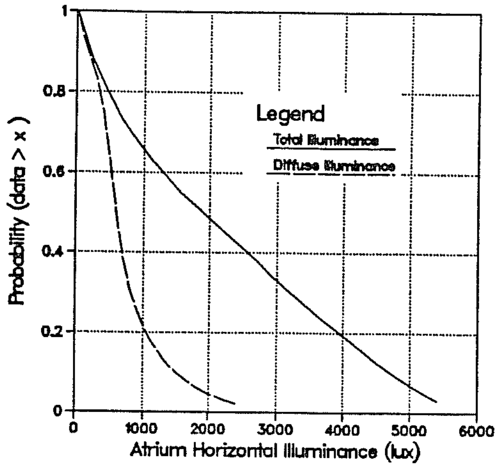


Figure 8. Probability distribution of total illuminance at atrium floor (diffusing atrium roof).

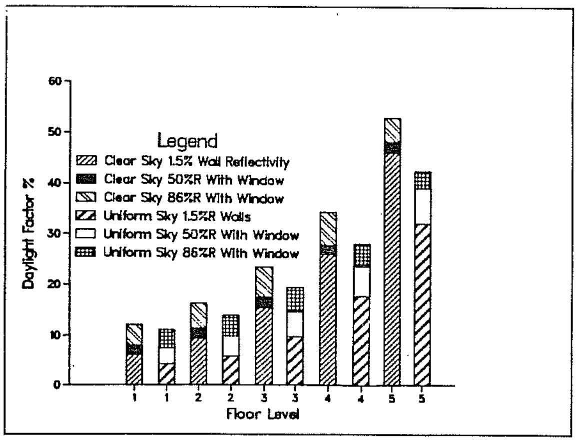


Figure 6. Vertical illuminance at window sill on south-facing wall as a function of floor level; uniform and clear sky conditions.

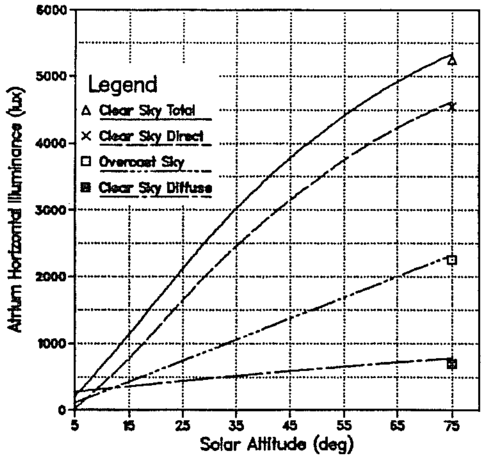


Figure 9. Atrium horizontal illuminance under overcast and clear sky conditions as a function of solar altitude. (Assumes a diffusing atrium roof.)

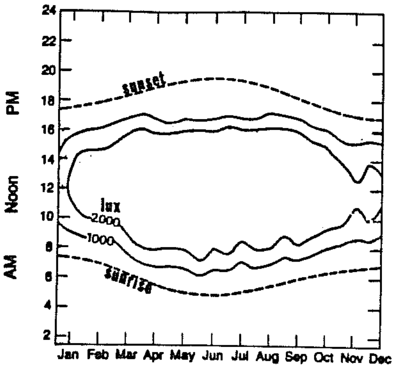


Figure 7. Average illuminance near edge of atrium as a function of hour and month for conditions described in text (San Francisco).