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The Role of Reflected Sunlight in Daylighted Office Environment

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Abstract

An increase in the design of commercial buildings with daylighting is beginning to receive more attention, claimed by some as a second revolution in architecture. The benefits of daylighting may vary significantly because a characteristic of daylight is the way in which it varies. Indirect sunlight, however, received in the interior of a building after reflection, can serve a useful purpose as the main source of illumination. In a cloudy climate it can serve as an occasional welcome addition to the available skylight. Also, site constraints or surrounding urban context may necessitate using reflected light sources, or such sources may be an integral part of the overall design objectives and aesthetics of the proposed projects.

When reflected sunlight is introduced into a space, its role in general illumination is what is of interest in this study. Results show that reflected sunlight may help the general illumination in almost same level of significance as daylight from diffuse sky. It is also summarized that the contribution of reflected sunlight to general illumination through the year round may be even and uniform regardless of the season. Consequently, introduction of reflected sunlight should be regarded as one of the successful means to enhance the visual environment in quantitative and qualitative way.

1. INTRODUCTION

Modern office buildings will make growing use of natural daylight illumination to improve lighting quality while reducing energy costs. A dramatic increase in the design of commercial buildings with daylighting manifests a renewed discovery of the architectural art of glazing as well as an energy-saving feature. Reintroduction of daylighting is beginning to receive more attention as we apply newer principles of intelligent building design, claimed by some as a second revolution in architecture (HartKopf, 1995). This building type is an excellent candidate for implementing daylighting techniques because of the relatively high electric lighting power densities and long daytime use pattern. To meet occupant satisfaction and work efficiency, thermal, acoustical, and visual comfort should also be considered. This, in combination with our increasing awareness and concern for the overall environmental quality of office interiors, creates the need for new directions in their design and management. From the viewpoint of lighting, it will become increasingly necessary to generate new concepts and improved data on the extent of the daylight potential and impacts on interior space planning and building form.

This paper aims to discover whether the existing design guidance in relation to daylit spaces is appropriate, and whether natural light is a preferable lighting source for perimeter spaces in offices in the presence of sunlight. In more detail, the main concern of this study is to examine the wide variations resulting from the combined effect of daylighting and reflected sunlight, orientation, and inter-reaction between these elements.

2. NATURAL LIGHTING IN OFFICE BUILDINGS

2.1 Preference of Natural Light

The visual effect of lighting is of importance as part of the total office environment. Even though every office buildings have different requirements, needs, and constraints depending on the task profiles, one or more compelling reason to use daylight as either a primary or a secondary light source may exist. Though it is becoming increasingly difficult to provide the light required for various office works by the use of daylight alone, the partial benefit of daylight in reduction of lighting and cooling loads, occupants' preference and visual relief, and pleasing effect of sunlight must be simultaneously taken into account. Office lighting affects the appearance of the space and its occupants, mood or affect, and productivity level. Over the past 20 years, a number of studies have documented the effect of light on all aspects of building and its occupants, such as physiology, mood, and behavior, which show convincingly the benefit of daylighting over electric lighting.

Several studies have been conducted that show occupants' preference of daylight with physiological, satisfaction and work efficiency in offices. At the same time, the emergence in new technologies, including the automated office with its problems as well as benefits, has altered the thinking of designers about lighting systems in relation to daylight level preferable to occupants.

Other studies presented levels of importance and satisfaction associated with lighting, daylighting, and controls with its problems as well as benefits, has altered the thinking of designers about lighting systems in relation to daylight level preferable to occupants (Hunt 1979). Consequently, lighting is considered one of the most important features affecting worker satisfaction with the office environment, and was a feature related satisfactory by most studies.

2.2 The Availability of Natural Light

There is increasing interest in using daylight to save lighting energy in buildings; however, it is possible that the benefits of daylighting may vary significantly because a characteristic of daylight is the way in which it varies from season to season, minute to minute, and region to region. The decision to use daylight and to select optimal daylighting systems in buildings must be first based on understanding daylighting availability of the site. The availability can affect the functional arrangement of spaces, aesthetic quality of each facade, and occupants' comfort.

The phrase "daylight availability" refers to the amount of light from the sun and the sky for a specific location, time, date and sky condition. The daily and seasonal movements of the sun with respect to a particular geographic location produce a predictable pattern of amount and direction of potentially available daylight. The impact of this variation on lighting energy use in daylighted spaces should be investigated in the preliminary design process of a building on the basis of meteorological data of the region. The traditional approach to analyzing the daylight resource has been to take detailed measurements for a given locale, and then use the measured data to establish a locale-specific illuminance model.

2.3 Reflected Sunlight in Daylighting Design

Apart from the orientation of buildings for penetration of sunlight for amenity such as atria, direct sunlight plays no part in the theory and practice of daylighting. Indirect sunlight, however, which is received in the interior of a building after reflection from the ground and or buildings outside, can serve a useful purpose as the main source of illumination in a sunny climate. In a cloudy climate it can serve as an occasional welcome addition to the available skylight. Also, site constraints or surrounding urban context may necessitate using reflected light sources, or such sources may be an integral part of the overall design objectives and aesthetics of the proposed projects. The illumination received from the sun in a sunny climate is of the order of 9,000-10,000 lm/ft^2. The ground, whose mean diffuse reflectance may be of the order of 10%, may therefore have a mean luminance of the order of 1,000 ft-L, i.e. of the same order as that of the blue sky (Hopkinson 1966). The ground illumination by sunlight can therefore serve as a useful source of interior lighting, in particular, when the sun is near the zenith. In any case, reflected sunlight sources need to be considered and provided for during site planning and analysis if they offer a potentially useful source of daylight to the building.

3. EXPERIMENTAL DESIGN

3.1 Model Construction

This study is based upon a systematic series of measurements within a sky simulator at Texas A&M University by using an indoor sun simulator and a heliodon, utilizing photometric sensors to read illumination levels. For this experiment, scale models of an interior layout module were constructed with different daylighting system. The open space has been established within a perimeter of an office interior measuring 70' (W)x 30' (D) as shown Fig.1. Two ceiling heights, that is, 10' and 12', were considered and a rectangular-shaped window on one wall measuring 68'(W) x 6.5'(H) with 10' high ceiling and 68'(W) x 8.5'(H) with 12' high ceiling were used as the sole source of daylighting.

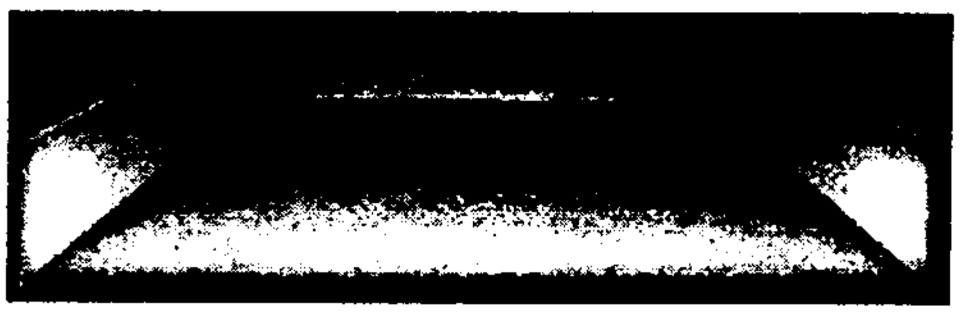

Fig. 1 A Model of Perimeter Interior Space

Also, to acquire the contribution of reflected sunlight only, two types of shading devices for full and partial shading were applied (Fig. 2).

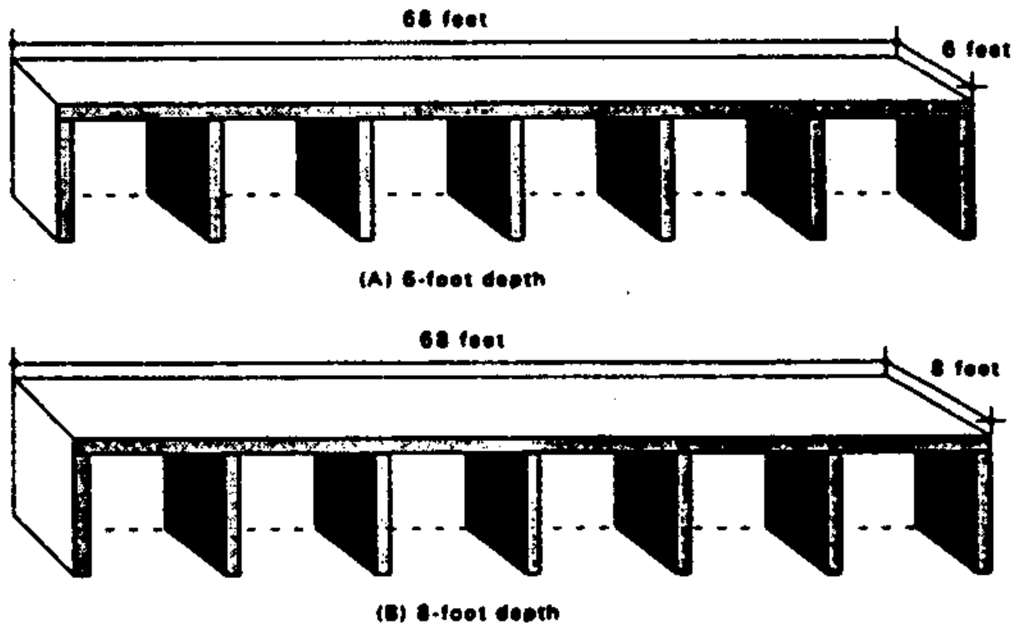

Fig. 2 Shading Devices

3.2 Instrumentation

The principal problem in the use of scale models is how to expose them to the desired sky conditions. Thus if it is desired to view a particular space under both overcast and clear sky conditions, and the latter for different seasons of the year, waiting for a real sky condition that corresponds to the one desired is obviously not a practical alternative. Fortunately, carefully designed and controlled artificial sky domes can duplicate overcast and clear sky conditions with a high degree of accuracy and thus are ideal for testing physical models. Simulated skies have the advantage of remaining essentially constant during model tests so that comparisons may be made easily. Each type of simulated sky, however, will have its own peculiar characteristics, and there must be an understanding of what these characteristics are and how they will affect comparisons of models to full-scale conditions. Generally, artificial skies attempt to simulate the dense, overcast sky with either a uniform luminance distribution or a distribution ratio of about 3:1, zenith to horizontal. The large sky simulator for daylighting research refurbished at Texas A&M University in 1985 allows adjustments to simulate conditions of an overcast sky, uniform sky and various clear sky luminance distributions. The size of the facility is a 28-foot (8.5m) diameter with a clear height of 12 feet (2.3m) so that all types of large-scale buildings which may be up to 5 feet (1.5m) can be placed. Horizontal illuminance on the model stand is about 750 fc (8100 lux) with all lamps on.

The heliodon, or tilt-table is a simple but very effective device that operates by rotating and tilting the building model with respect to the real sky until the desired solar altitude and azimuth is reached. Obviously, then, this technique is most effective with clear sky conditions to simulate the effect of direct sun. During reflected sunlight measurement, accordingly, the heliodon equipped at Texas A&M University is used to generate the desired geographical and chronological condition with an artificial sun.

3.3 Measurement Locations

As shown in Fig.3, three different locations - the front, mid, and the rear spaces - were separately considered because each depth of space from the window wall has different reflected sunlighting potentials.

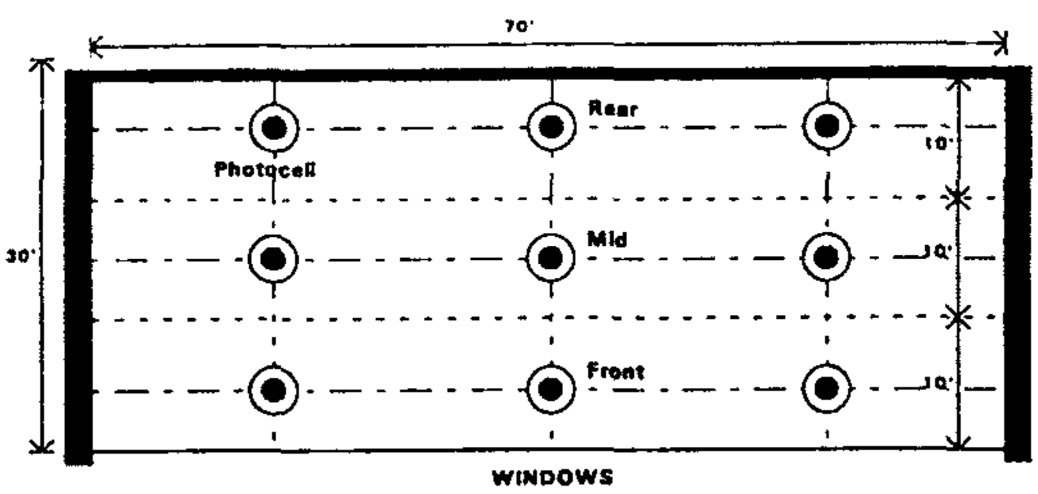

Fig. 3 Locations of Measurement

3.4 Data Acquisition

Daylight levels, the basic data for the evaluation of sunlighting performance, were determined from the measurements under diffuse sky conditions without sun. This measurement represented the performance results in terms of Daylight Factor (DF) defined as follows:

$$DF = \frac{\text{Indoor horizontal illuminance from daylight}}{\text{Exterior horizontal illuminance}} \times 100$$

A completely clear sky condition, which is an extreme case, contains a wide range of variation in the amount of direct solar insolation on the basis of the given time, location, and orientation, although the average amount can be calculated from the extreme sunlight availability data using the local sunshine probability. This has caused methodological difficulties in investigating the impact of the direct component of natural light. More laborious consideration is needed to deal with the directional ray of light in order to extract the generalized availability data of reflected sunlight illuminance levels, covering a full range of the involved variables. caused methodological difficulties in investigating the impact of the direct component of natural light. Most daylighting study techniques are based on the preassupmtion that no direct sunlight will penetrate the building fenestration, for the simple reason that direct sun on the interior is considered to produce undesirable seeing conditions, particularly if direct sun reaches visual tasks such as desks and chalkboards. Therefore, there are no calculation techniques available for predicting interior lighting levels when direct sunshine is present (Evans 1981).

The first phase in sunlight measurement is to select the sun's location which is to be involved as the most important factor. The position of the sun which is a function of site latitude, solar time and solar declination, is given in terms of solar altitude and solar azimuth. For the purpose of generalization mentioned above, solar azimuth angles and time of occupancy profile were considered year round for several building orientations. As representative dates, December 21, June 21, and September 21, are selected and the time when solar azimuth angle becomes 45°W or 45°E because the two cases produce representative average amount of reflected sunlight simultaneously for each orientation of the window wall, even if the altitudes are different. An exception to this would be the north facade.

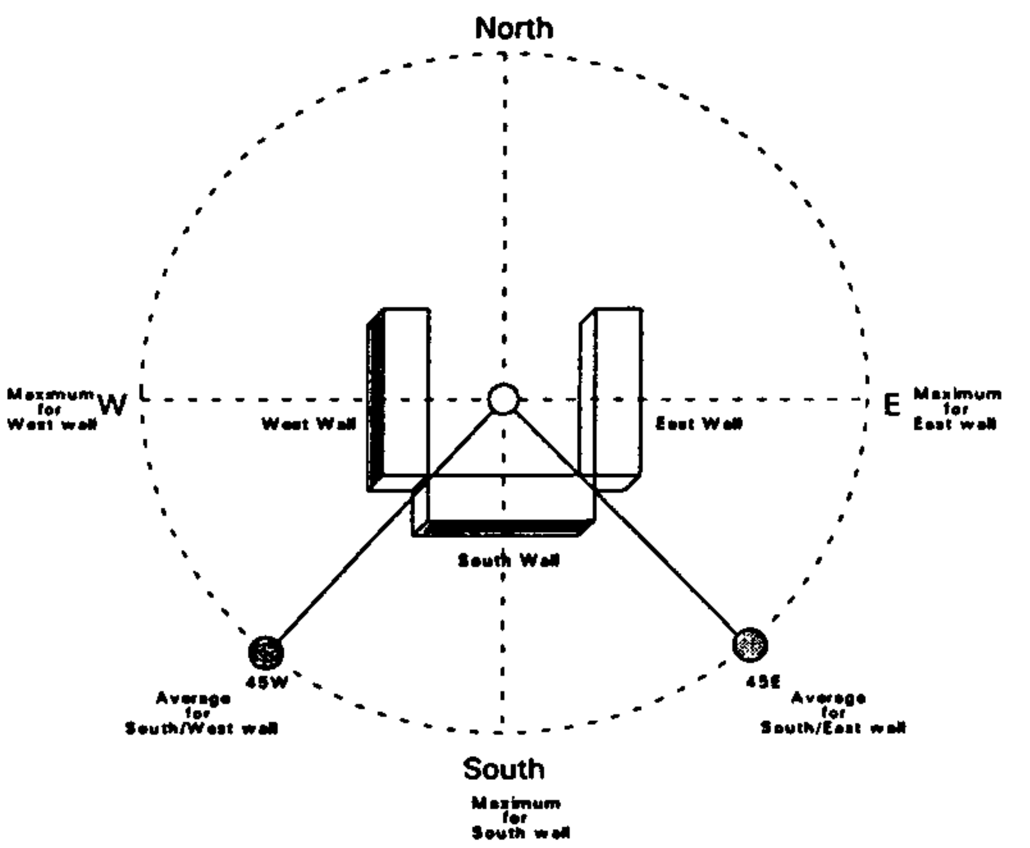

Fig. 4 Representative Azimuth Angle for Reflected Sunlight Measurements

Fig. 4 shows the concept of the generalization process for reflected sunlight measurements. The selected times and representative dates of year are graphically depicted in terms of solar azimuth angle and altitude. Fig. 5 shows the solar altitudes and azimuth angles for the selected times in San Antonio, Texas as a model site.

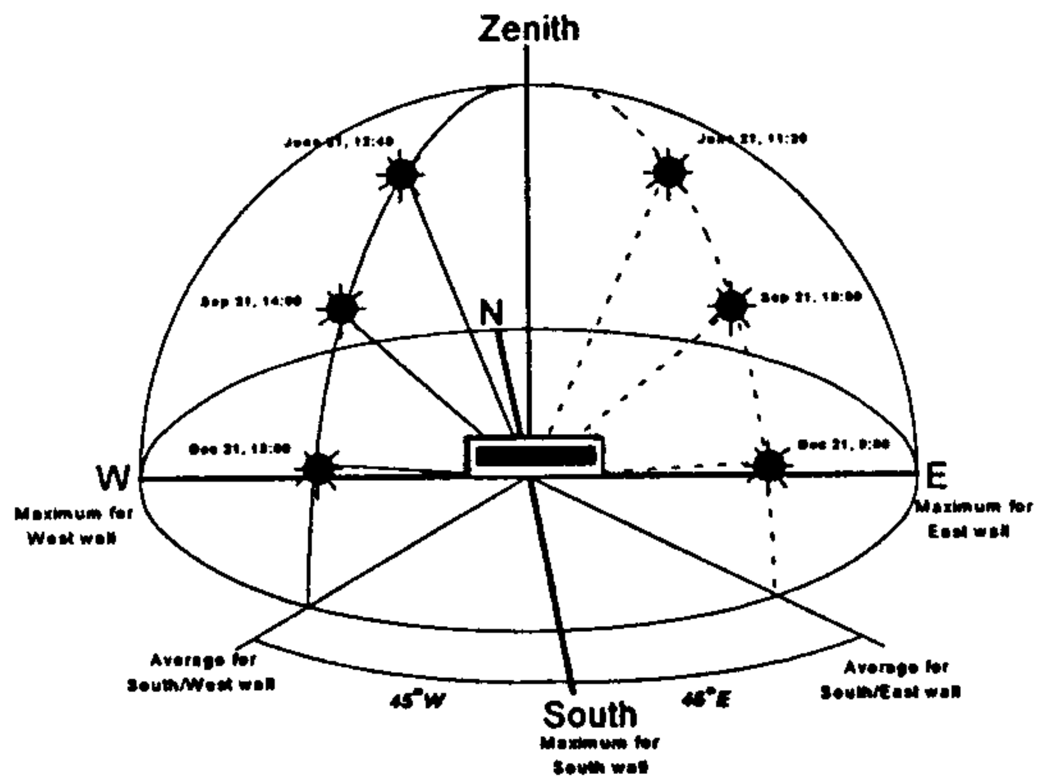

Fig. 5 Solar Altitudes and Azimuth Angles in San Antonio

In same way, the measurement results were represented in terms of Reflected Sunlight Illuminance Ratio (RSIR) defined as follows:

$$RSIR = \frac{\text{Interior horizontal illuminance from reflected sunlight}}{\text{external horizontal illuminance from direct sunlight only}} \times 100(\%)$$

4. ANALYSIS AND RESULTS

4.1 Reflected Sunlighting Performance

As described earlier, the measured reflected light levels in the totally-open plan were converted into RSIR and listed in Fig.6 for the latitude of 30°N. The three different depths of the space were again considered separately and shown with their reflected sunlighting possibilities. Also, two different reflectances of ground produced two series of RSIR data. At a glance the RSIR is noted to have the same range of values as the Daylight Factors measured under diffuse sky condition. It might be because the reflected component of direct sun is another form of diffuse light. However, it must be stressed that the real illuminance value that the RSIR represents would need to be much higher to get the required light level for general illumination.

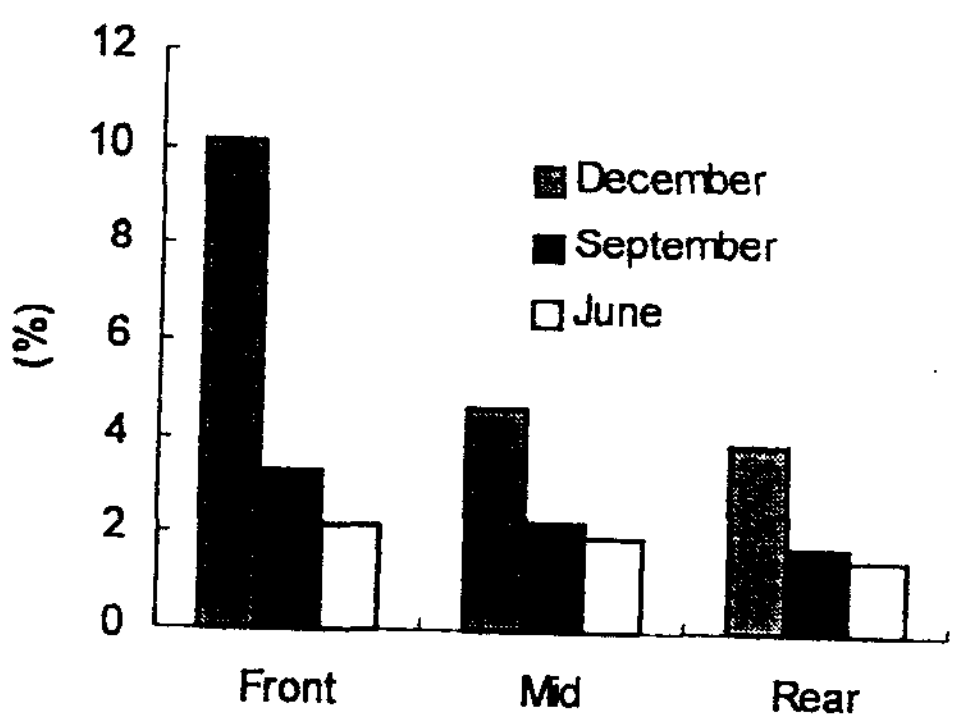

Fig. 6 Seasonal RSIR for South Orientation

The measured RSIR values in winter are higher than other seasons because the solar altitude is lower. More reflected component of direct sun can bounce into the interior space. In fact, the real impact of reflected sunlight in winter time would be lower than that in summer because the intensity of direct sun in winter is much less than summer. Ground reflectance is generating approximately a change of 2 or 3 percent in RSIR and its contribution is useful for the deep space in which daylight availability is relatively lower. The different orientations of the space do not make a significant variation in the deep space for the same reason.

As Daylight Factor, the calculated RSIR can be applied to any location in order to estimate approximately its reflected sunlight availability although the RSIR values of the site should be measured with appropriate sun ◎ geometry and accurate configuration of building facade. In utilizing the measured RSIR, the first phase is to apply RSIR to the real sunlight availability data. Although basically the measured amount of direct solar insolation is the essential data, sunlight probability data of the site is the most important factor in estimating the reflected sunlighting potentials because RSIR deals with extreme condition, completely clear sky. Accordingly, when the SIR and sun probability data are considered in one expression, new term Reflected Sunlight Coefficient of Utilization (*ReSCU*) which is described in following relationship.

ReSCU = RSIR * Sun Probability [%]

E_{ReCue} = ReSCU * Horizontal Direct Solar [lux or fc]

where, E_{ReCue} is interior illumination level due to reflected sunlight only

The usefulness of ReSCU is mainly stemmed from the fact that ReSCU represents the actual potentials of reflected sunlighting in a designated site with a handy fraction and can be also used to calculate directly the real reflected sunlight level inside buildings using the given relationship previously. Together with RSIR, ReSCU is used as a important index to describe reflected sunlight availability.

San Antonio has about 50 percent of the possible sunshine during the winter months and more than 70 percent during the summer. Skies are clear to partly cloudy more than 60 percent of the time and cloudy less than 40 percent. The net amount of direct solar can be acquired by subtracting the diffuse sky from the clear global illumination value.

Table 1 ReSCU in San Antonio, TX [%]

DF	G. Ref.		20%			40%	
	Loca	Front	Mid	Rear	Front	Mid	Rear
	Dec.	5.15	2.38	1.97	7.80	2.71	2.01
South	Sep.	2.64	1.80	1.44	4.48	2.27	1.77
	Jun.	1.84	1.68	1.34	2.70	1.68	1.34
	Dec.	6.32	3.64	2.14	6.78	4.13	2.29
East	Sep.	3.35	2.32	1.65	3.72	2.71	1.92
	Jun.	2.72	1.93	1.56	2.89	2.06	1.61
	Dec.	8.06	4.64	2.73	8.65	5.27	2.92
West	Sep.	3.35	2.32	1.65	3.72	2.71	1.92
	Jun.	2.65	1.88	1.52	2.82	2.01	1.57

To acquire the actual possibility of reflected sunlighting which can be described as ReSCU, local sun probability data in San Antonio was applied to the RSIR. Table 1 illustrated the seasonal average values of ReSCU in the consideration of different orientation, depth of the space, and ground reflectance, yielding a more practical view of reflected sunlighting availability. The different sun probability in the morning and afternoon creates the difference in ReSCU between East and West orientation.

4.2 Accumulated Performance of Natural Lighting

In the final process to estimate the practical availability of natural light, reflected sunlight and daylight should be considered simultaneously, which accounts for the accumulated effects of natural lighting. To evaluate this combined effect of two natural light sources, daylighting performance data under overcast diffuse sky condition and reflected sunlighting performance were totalled. As before, San Antonio's climatic data were used.

Illumination levels which can be achieved by daylight from diffuse sky were calculated on the basis of daylight factor measured and the global overcast illumination data. Unlike reflected sunlight, these light levels represent minimal and worst possibility. When daylight and reflected sunlight are combined, the interior light levels will be more than doubled. Briefly, the interior illuminance throughout the whole perimeter space is sufficient enough to attain desired light levels (550 lux) from natural resources.

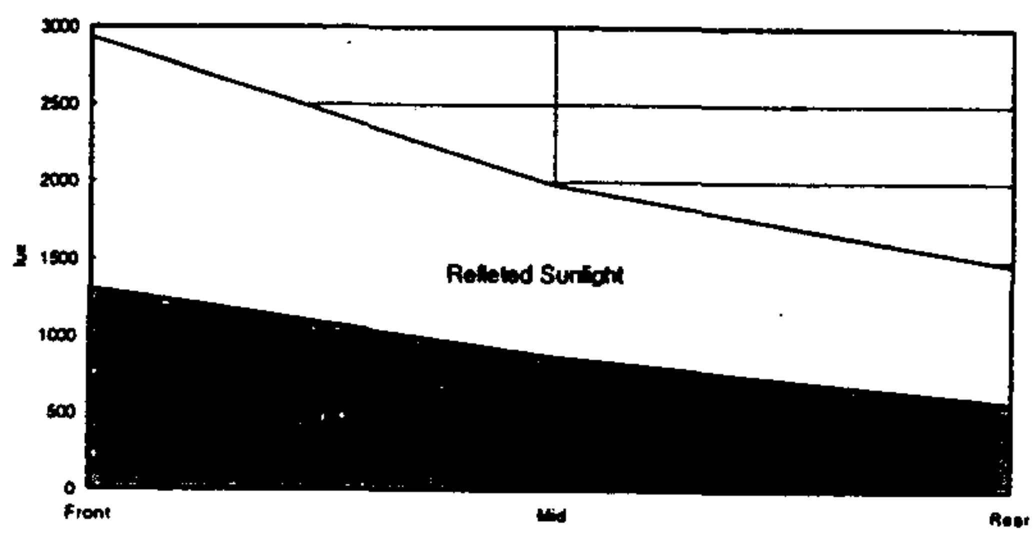

Fig. 7 Reflected Sun and Daylight in September

In addition, the distribution of the natural light for the whole year becomes more even than in the case of using only one of the natural resources. Although higher ground reflectance can contribute on the illuminance for deeper space, it should be remembered that it may also cause uneven distribution of natural light. To illustrate the accumulated effectiveness of two natural light sources in the open plan, Fig. 7 illustrates the amount of light due to each light source with south window in a fall month in San Antonio, Texas.

5. CONCLUSIONS

Reflected sunlight may help the general illumination in almost same level of significance as daylight from diffuse sky. It is also summarized that the contribution of reflected sunlight to general illumination through the year round may be even and uniform regardless of the season. Consequently, introduction of reflected sunlight should be regarded as one of the successful means to enhance the visual environment in quantitative and qualitative way. As shown in Fig. 8, RSIR becomes higher in winter due to lower sun, and the largest reduction in light level caused by the partition is experienced during winter for the same reason. More seasonal variation in RSIR is measured in West and East orientation since the sun's altitude varies widely for the orientations.

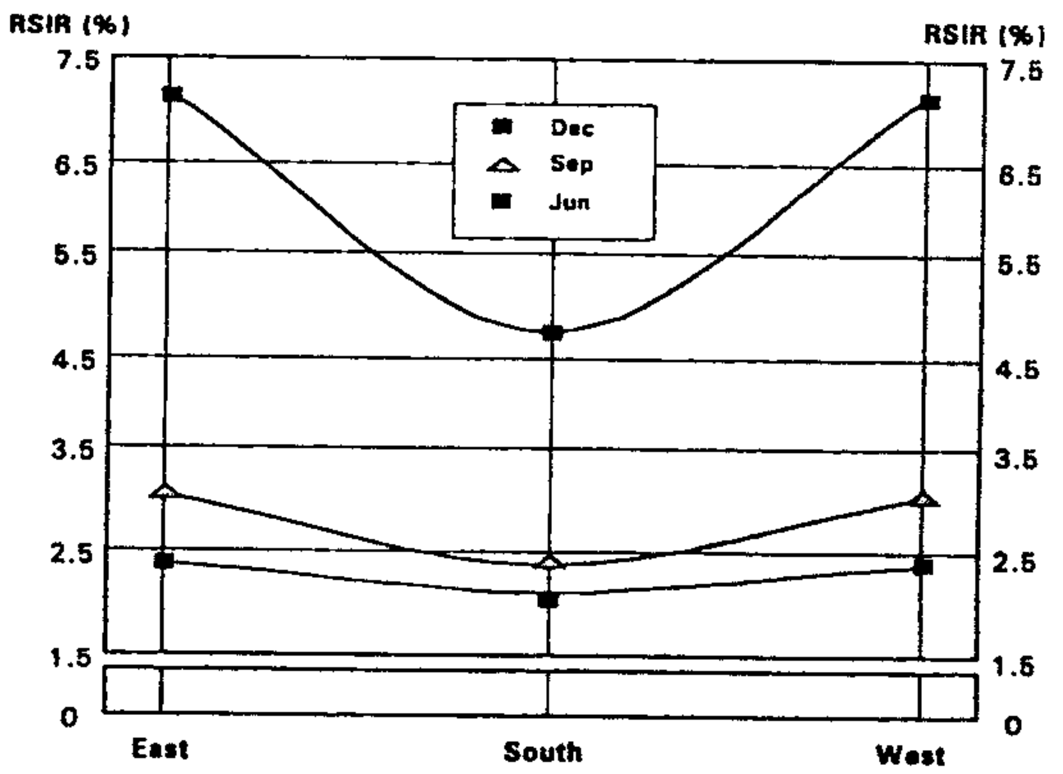

Fig. 8 Reflected Sunlight Performance in Mid Space

In San Antonio, Texas, it is concluded that reflected sunlight may quantitatively help the general illumination in almost same amount as daylight from diffuse sky. It is also observed that the contribution of reflected sunlight to general lighting through the year may be more uniform regardless of the season. For example, the higher RSIR in winter may represent almost the same amount of light as the lower RSIR in summer because the sun's intensity is much higher in summer. The variation in the amount of light with different orientation is moderate.

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