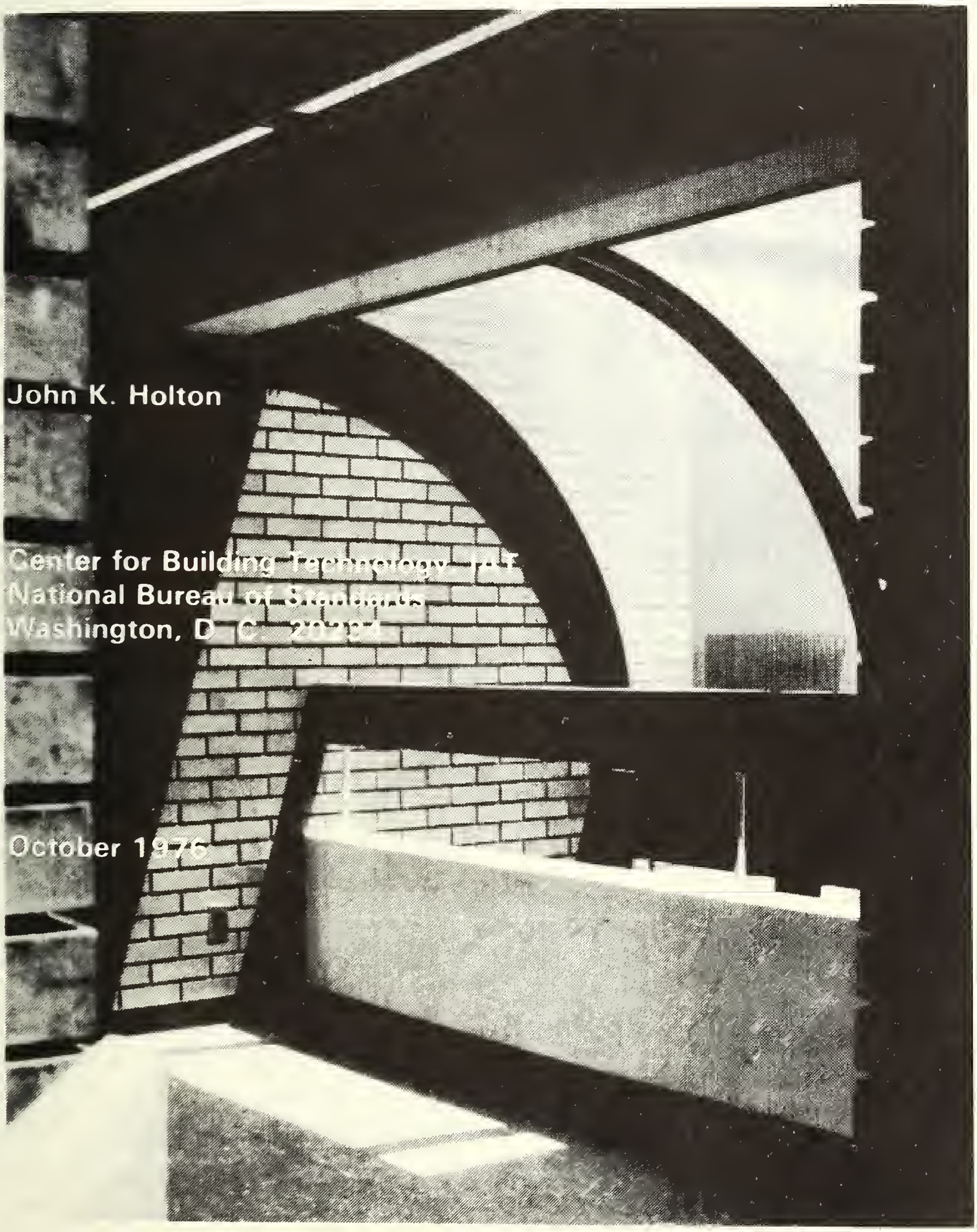
NBSIR 76-1098

DAYLIGHTING OF BUILDINGS
A Compendium and Study of its Introduction and Control



John K. Holton

Center for Building Technology, IAT
National Bureau of Standards
Washington, D.C. 20234

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U. S. DEPARTMENT OF COMMERCE

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U.S. DEPARTMENT OF COMMERCE, Elliot L. Richardson, ***Secretary***

Edward O. Vetter, ***Under Secretary***

Dr. Betsy Ancker-Johnson, ***Assistant Secretary for Science and Technology***

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Acting Director***

ABSTRACT

We can no longer ignore daylight as a valuable natural resource for building illumination. Significant reductions in the energy consumption of buildings are possible by decreasing the dependence on artificial illumination and decreasing air conditioning loads by employing methods which bring in cool light. In order to design buildings utilizing daylight effectively there must be an understanding of the design principles of daylighting. This requires a knowledge of illumination to meet the needs of the building users, an understanding of characteristics of daylight at the location of the building, and imagination in developing ways to introduce and control daylight. This paper is directed toward the identification of innovative techniques for the introduction and control of daylight. It is arranged in three sections: a Compendium, a Study section, and a Reference section. The Compendium presents a number of state-of-the-art methods to assist the designer in successfully employing daylight more extensively. The Study section provides more detailed information on these methods so an increased understanding can be developed of those which appear to have suitability in a given situation. Finally, the References provide background for further investigation.

The Study organizes daylighting methods as they relate to three zones of a building, the perimeter, the intermediate and the deep zone. Each has different characteristics and is suited to daylighting by different methods.

Key Words: Daylight gathering; daylighting of buildings; energy conservation; lenses; light conduits; light control; reflectors; skylights; windows.

ACKNOWLEDGMENTS

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SI CONVERSION UNITS

In view of the present accepted practice in this country for building technology, common U.S. units of measurement have been used throughout this document. In recognition of the position of the United States as a signatory to the General Conference on Weights and Measures, which gave official status to the metric SI system of units in 1960, assistance is given to the reader interested in making use of the coherent system of SI units by giving conversion factors applicable to U.S. used in this document.

Length

1 in = 0.0254* meter

1 ft = 0.3048* meter

Area

1 in^2 = 6.4516* x 10^{-4} $meter^2$

1 ft^2 = 0.09290 $meter^2$

Volume

1 in^3 = 1.638 x 10^{-5} $meter^3$

1 gal (U.S. liquid) = 3.785 x 10^{-3} $meter^3$

1 liter = 1.000* x 10^{-3} $meter^3$

Mass

1 ounce-mass (avoirdupois) = 2.834 x 10^{-2} kilogram

1 pound-mass (avoirdupois) = 0.4535 kilogram

Pressure or Stress (Force/Area)

1 inch of mercury (60°F) = 3.376 x 10^3 pascal

1 pound-force/$inch^3$ (psi) = 6,894 x 10^3 pascal

Energy

1 foot-pound-force (ft-lbf) = 1.355 joule

1 Btu (International Table) = 1.055 x 10^3 joule

Power

1 watt = 1.000* x 10^7 erg/second

1 Btu/hr = 0.2930 watt

Temperature

$t_{°C} = 5/9\ (t_{°F} - 32)$

Illumination

1 ft candle = 10.6 lux

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*Exactly

CONTENTS Page

PREFACE

Daylight is a natural resource that is readily available to provide illumination for the interior of buildings and has been used in this manner for centuries. As buildings have grown larger in size, the ability to constructively employ daylight has suffered from the problems of drawing it deep into the interior. Furthermore, in an economy of inexpensive electric energy, artificial illumination has often been less costly than equivalent daylighting. More recently, the ever-increasing demand for environmental control has brought a lessened use of daylight because of the seeming difficulty in its control and the heat gain and loss through large glazed areas.

We can no longer ignore daylight as a valuable natural resource for building illumination. Significant reductions in the energy consumption of buildings are possible by decreasing the dependence on artificial illumination and decreasing air conditioning loads by employing methods which bring in cool light. In order to design buildings utilizing daylight effectively there must be an understanding of the design principles of daylighting. This requires a knowledge of illumination to meet the needs of the building users, an understanding of characteristics of daylight at the location of the building, and imagination in developing ways to introduce and control daylight. This paper is directed toward the identification of innovative techniques for the introduction and control of daylight. It is arranged in three sections: a Compendium, a Study section, and a Reference section. The Compendium presents a number of state-of-the-art methods to assist the designer in successfully employing daylight more extensively. The Study section provides more detailed information on these methods so an increased understanding can be developed of those which appear to have suitability in a given situation. Finally, the References provide background for further investigation.

This paper is concerned with the introduction and control of daylight. In many cases the apertures used for this purpose would also normally be used to provide a view. Though no consideration of the requirements for view have been included here, they will of course modify the design as developed for daylighting. Also, since the purpose is to introduce concepts and reference sources of detailed information, no attempt is made to provide quantitative data on daylight availability, requirements for task lighting, or computational methods.

A word should be added about the nature of daylight. There are two types, the direct rays of sunlight and diffused sky light (from either a clear or cloudy sky). The type of light influences the effectiveness of the various methods of introduction and control. All methods will work with sunlight but some are not particularly effective with diffused light (notably polished reflectors and lenses). Where a system is not well suited to diffused light, it is so noted.

COMPENDIUM OF METHODS

1. Perimeter Zone
   - The zone where direct daylight penetration is effective.

2. Intermediate Zone
   - The zone beyond the perimeter where daylight can be directed utilizing simple, stationary, non-concentrating means.

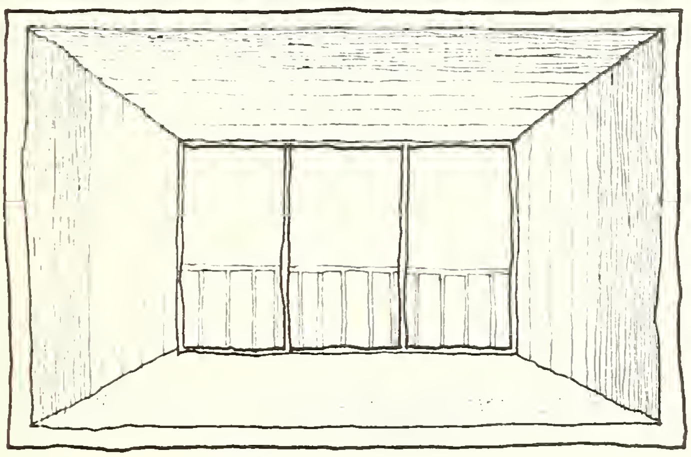
3. Deep Zone
   - The core area or areas where daylight is diminished by distance or obstructed by partitions or floors. Concentrating and beaming methods are required in this zone.

1.0 PERIMETER ZONE

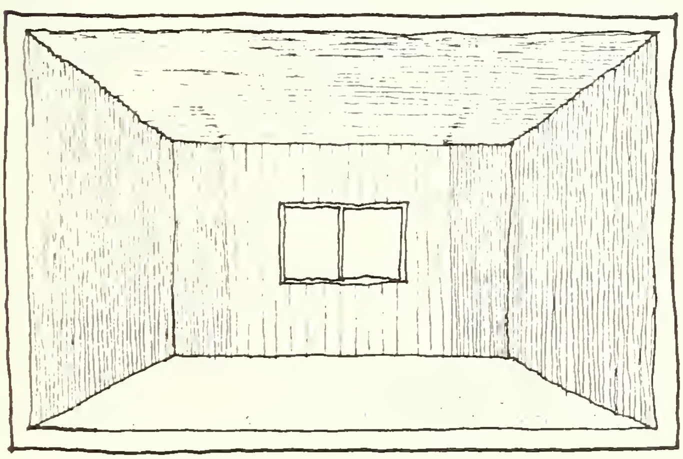
1.1 Windows

Windows are the commonest of all introductory methods. There are several characteristics that are of significance from a daylighting standpoint:

1. The proportion of the wall area that is opened up influences the sheer volume of light admitted.



100% maximum

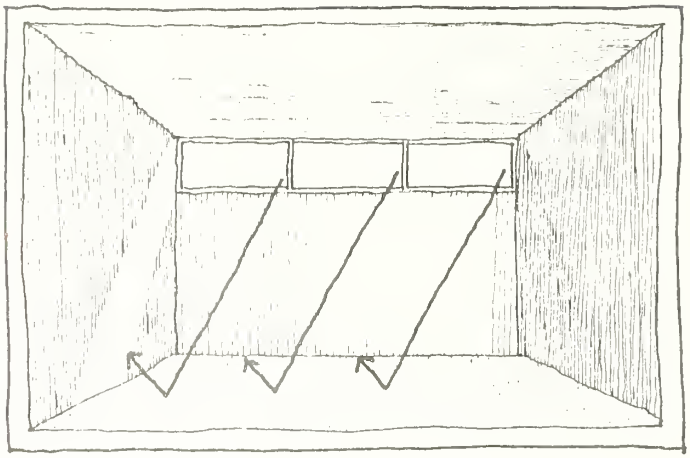


20% minimum (suggested by studies)

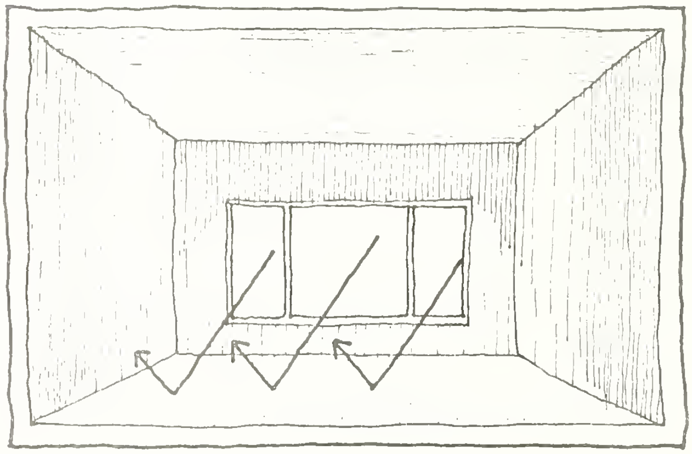
(Note: In current codes, minimums are often expressed as a % of the room floor area.)

1.1 Windows continued

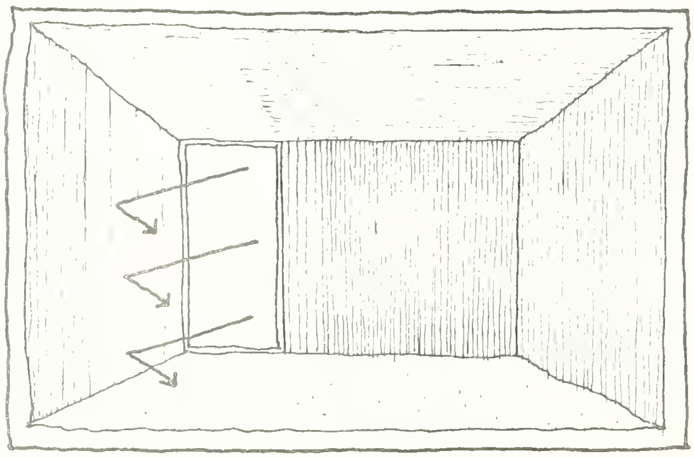
2. The position of the window relative to the internal room surfaces influences internal light distribution.



- high window allows deep penetration



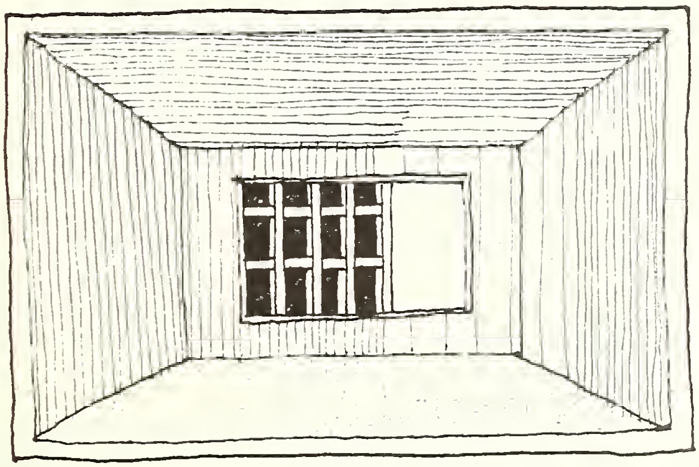
- low sill can allow floor reflected light to help balance near ceiling and wall areas



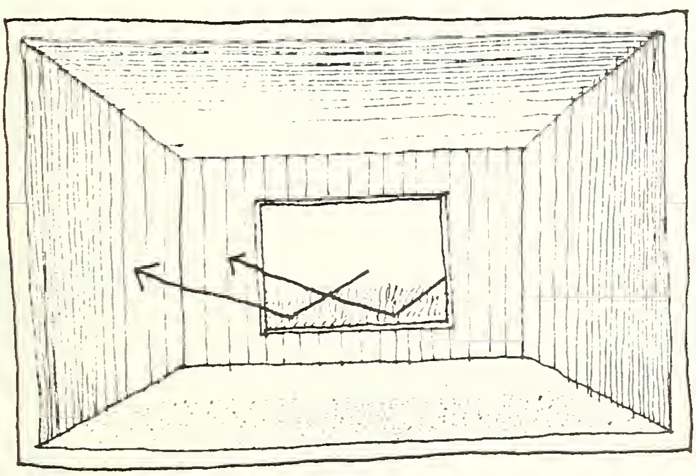
- near wall emphasizes side reflected light

1.1 Windows continued

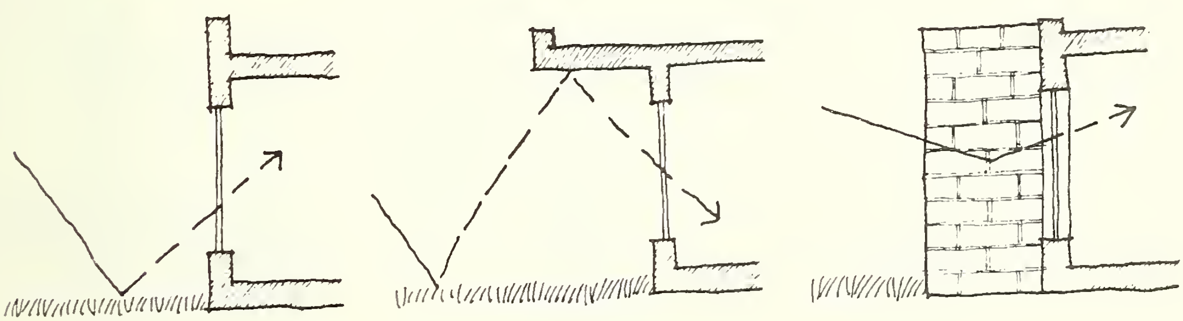
3. The position of the window relative to external surfaces influences the ammount of light that can be admitted by the window.



- adjacent surfaces can obstruct portions of the sky and reduce the amount of daylight



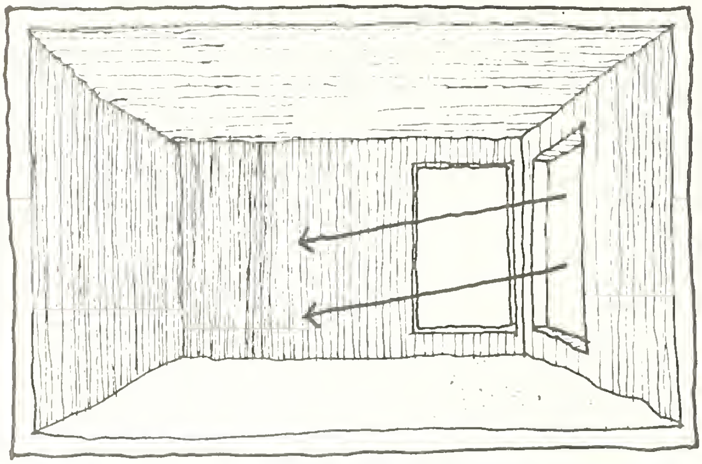
- adjacent surface can reflect light into windows and increase the amount of daylight



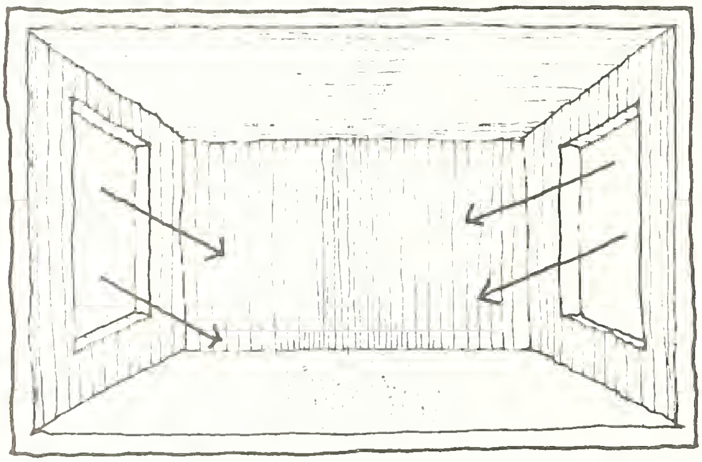
- some examples of adjacent surface reflective action

1.1 Windows continued

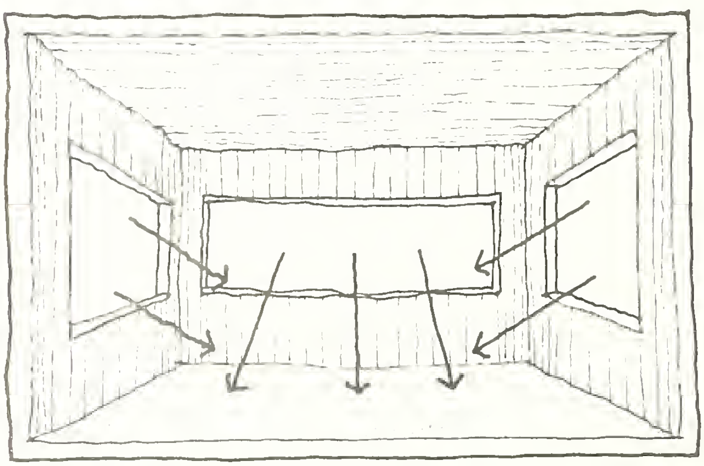
4. The number of room surfaces that contain windows will affect the ability to provide more than mono-directional light. (True only for diffused sky light).



- windows on adjacent walls will light their adjacent walls

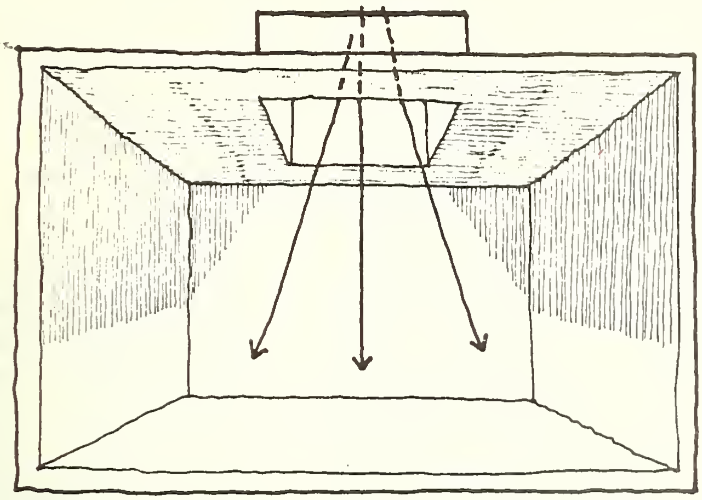


- windows on opposite walls give good bi-lateral light and can light their adjacent walls

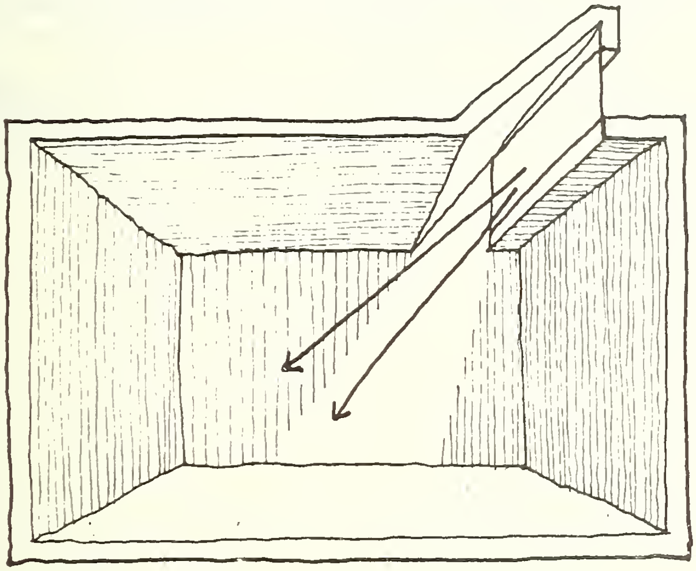


- windows on multiple surfaces provide opportunity to reflect light in several directions

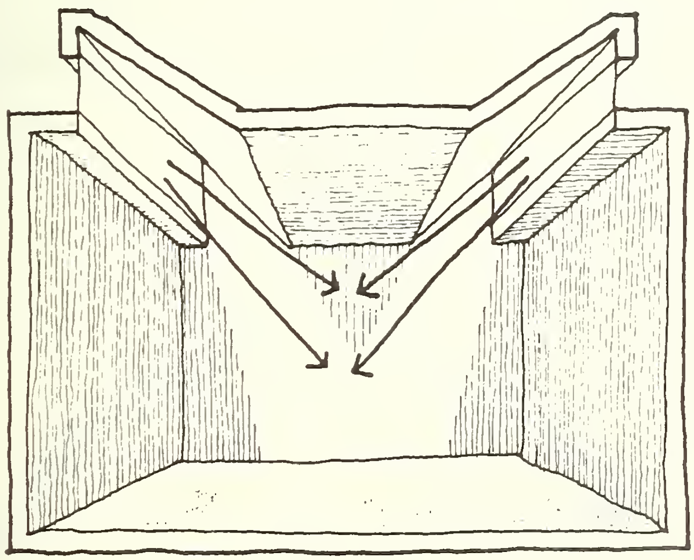
1.2 Direct Skylights and Clerestories (non-reflective)



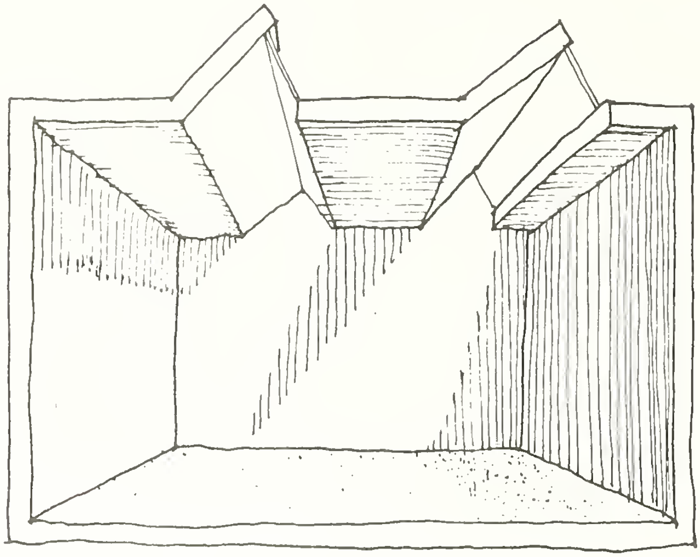
- direct downlight skylights depend on reflectivity of room surfaces (particularly floor) for dispersion



- single side skylights or clerestories give mono-directional light unless room surfaces reflect well



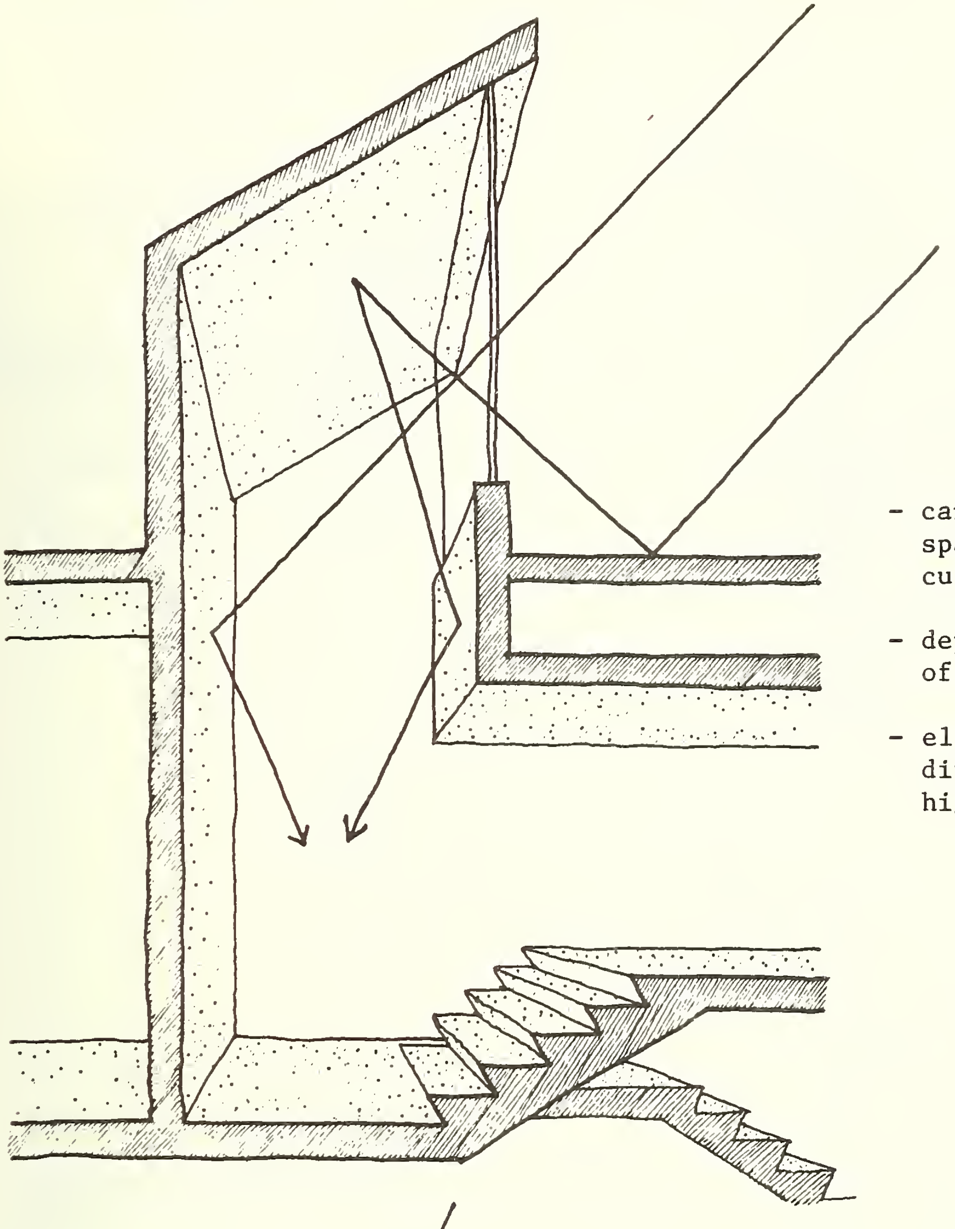
- opposite side skylight or clerestories give two-directional light (with diffused skylight)
- light can be more uniform than with single side installation



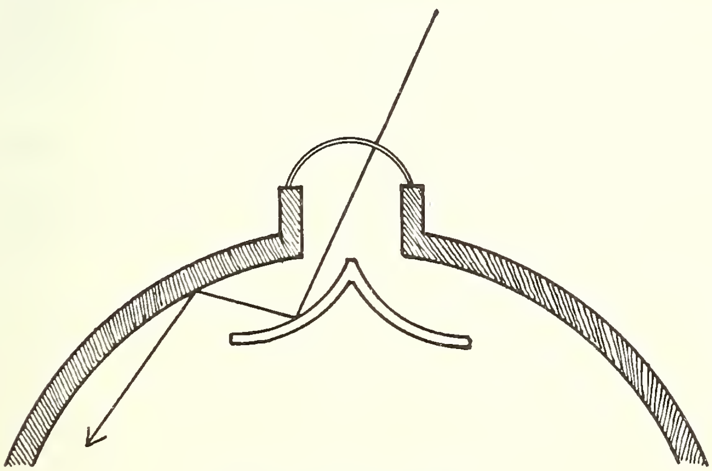
- saw tooth skylights or clerestories give mono-directional light unless room surfaces reflect well

- light can be more uniform than with single unit installations

1.3 Reflective Skylights, Monitors, Clerestories



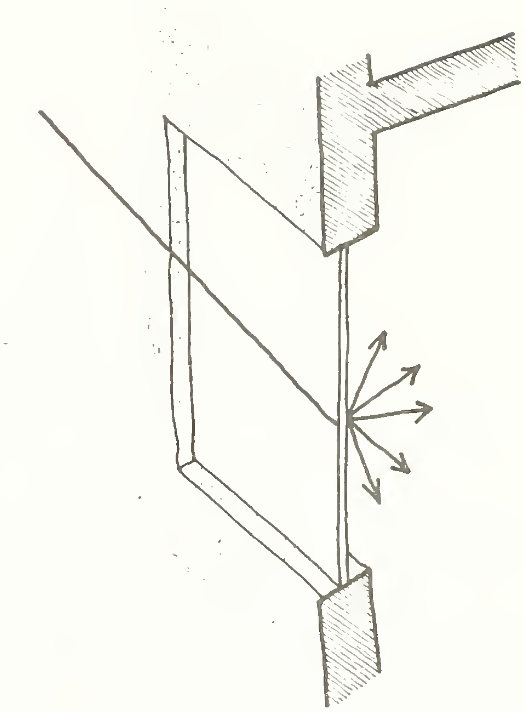
- can gather light into spaces otherwise difficult to illuminate
- depends on reflectivity of surface
- eliminates problems of direct sunlight if not highly reflective



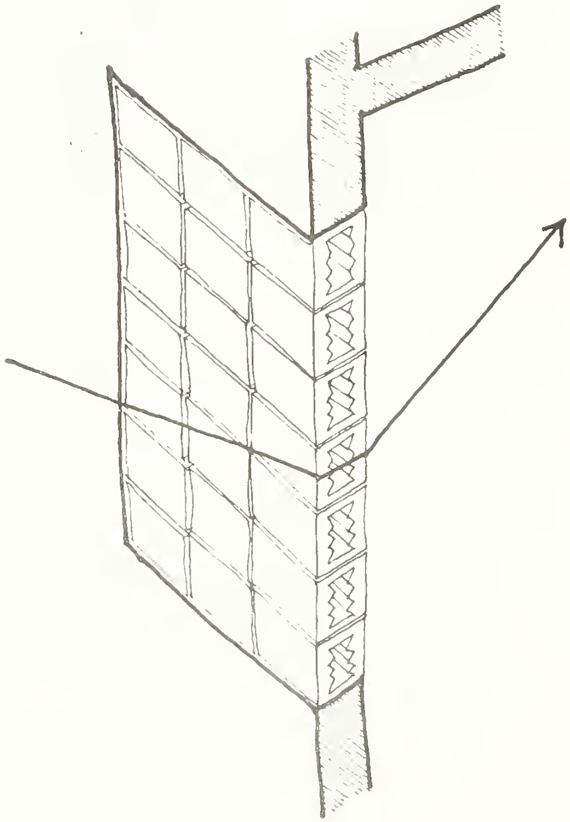
curved shape engineered for uniform vault illumination

Kimball Art Museum

1.4 Diffusing Panels



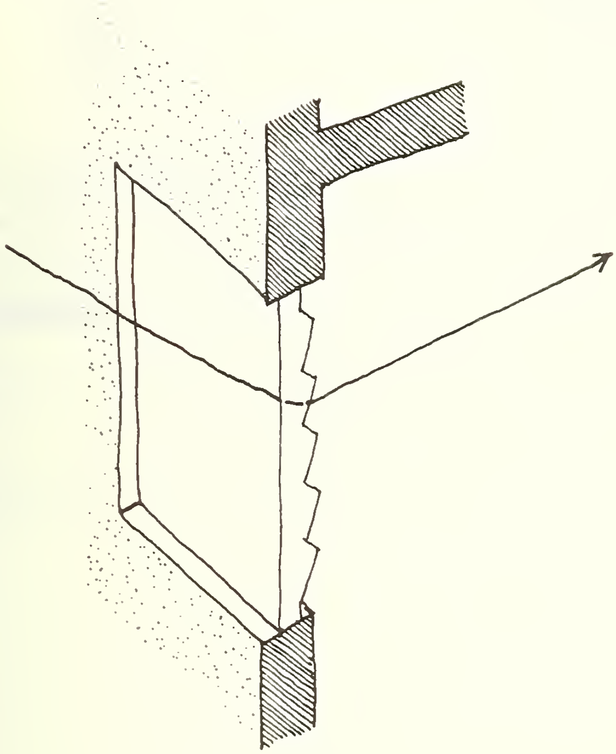
- panels of diffusing glass or plastic give diffused light on inside
- may be single or double layer and can provide thermal insulation
- glare must be controlled
- may be used on wall or roof



- prismatic glass block can re-direct light
- also can accept light from selected directions thereby cutting out light at undesired times
- can be used on wall or roof
- most effective with sunlight

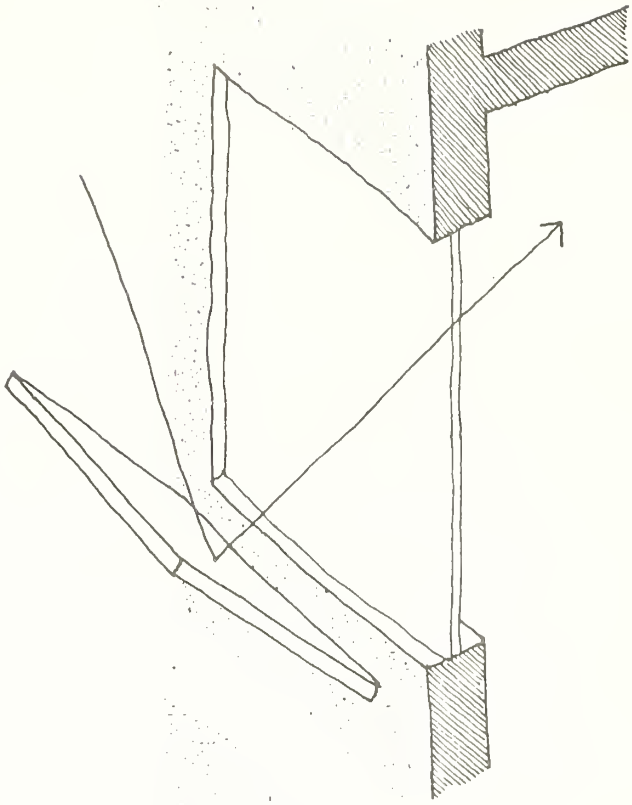
2.0 INTERMEDIATE ZONE

2.1 Linear Lenses

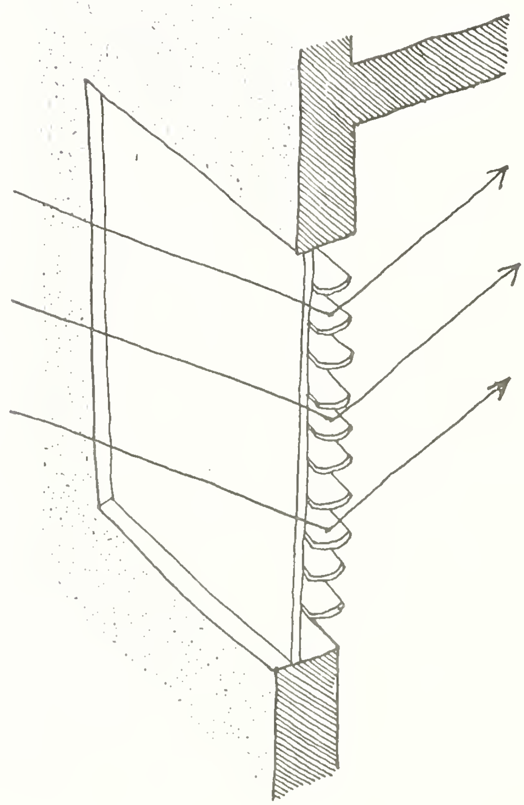


- lenses similar to those employed in lighting fixtures can angle daylight upward and thus deeper into buildings than normal ray pattern would allow
- most effective with sunlight

2.2 Reflectors



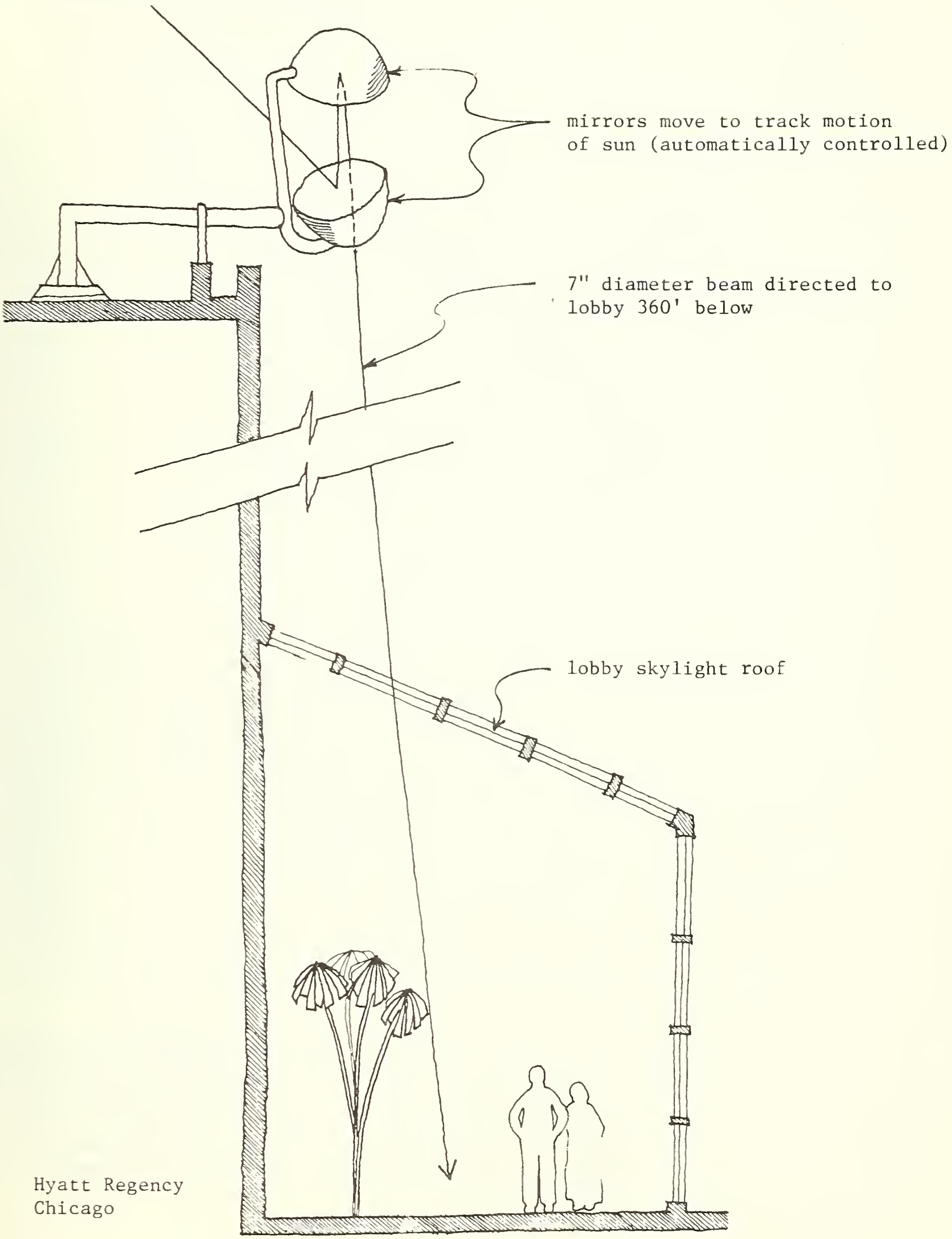
- reflecting surfaces can direct daylight into the upper levels of a room and thus to greater depths
- may be fixed or movable
- may reduce portions of window view
- most effective with sunlight



- multiple reflector surfaces can be movable like blinds to allow adjustment to track the sun or control the amount of daylight entering
- may reduce portions of window view
- most effective with sunlight

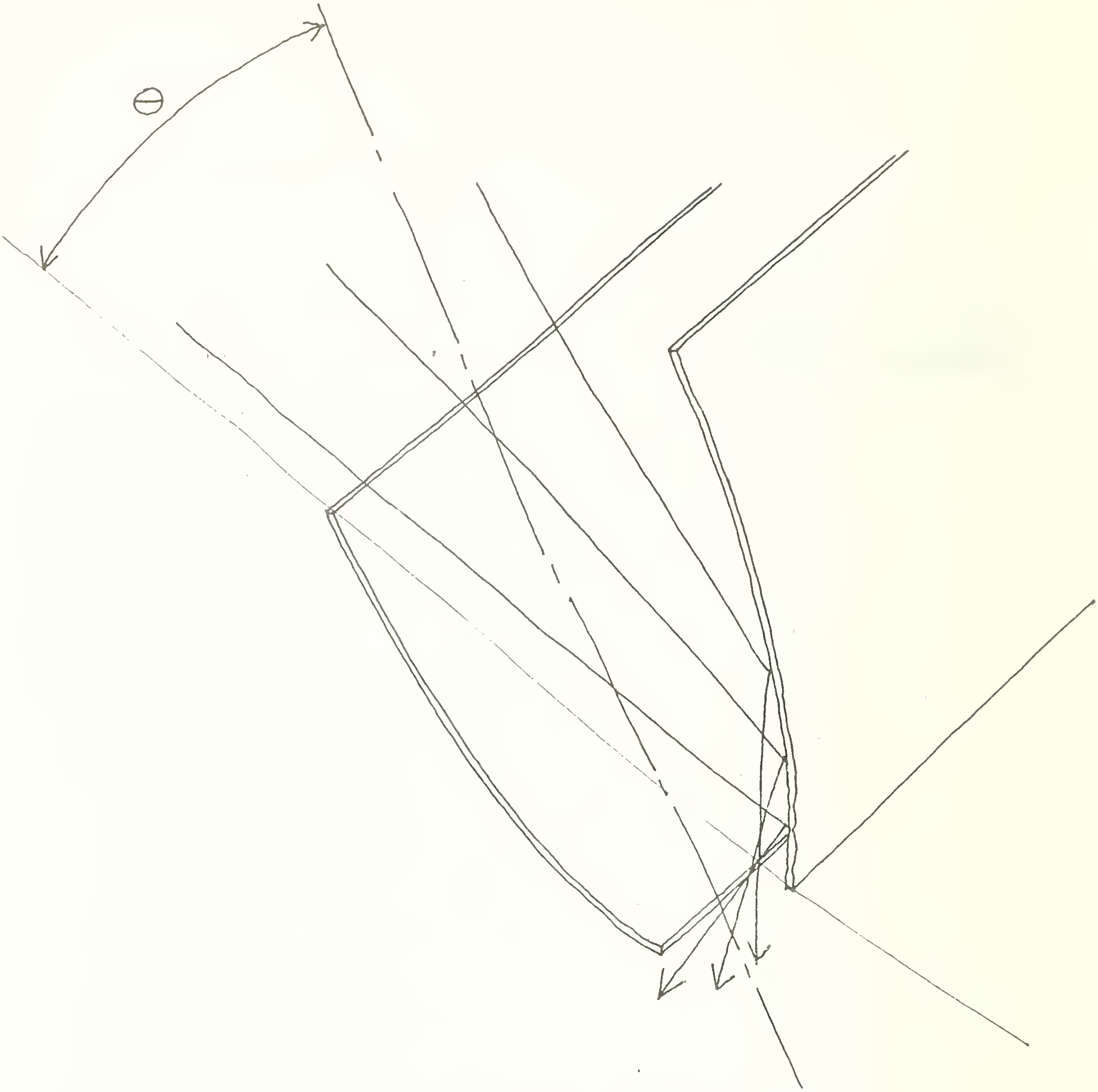
3.0 DEEP ZONE

3.1 Tracking Reflectors (Heliostat)
Useful only with sunlight



Hyatt Regency
Chicago

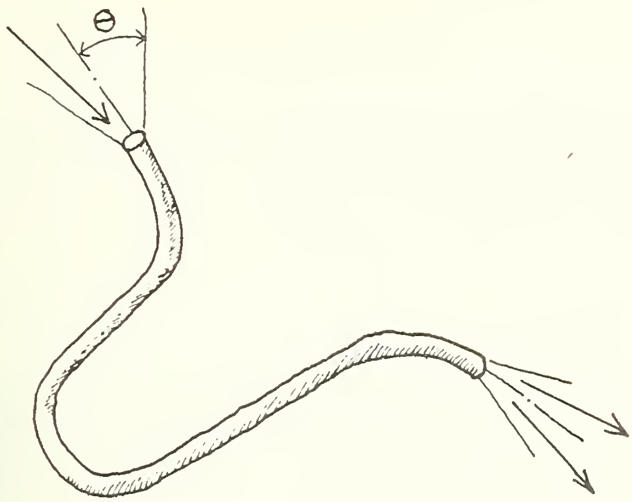
3.2 Concentrating Reflectors
Most effective with sunlight



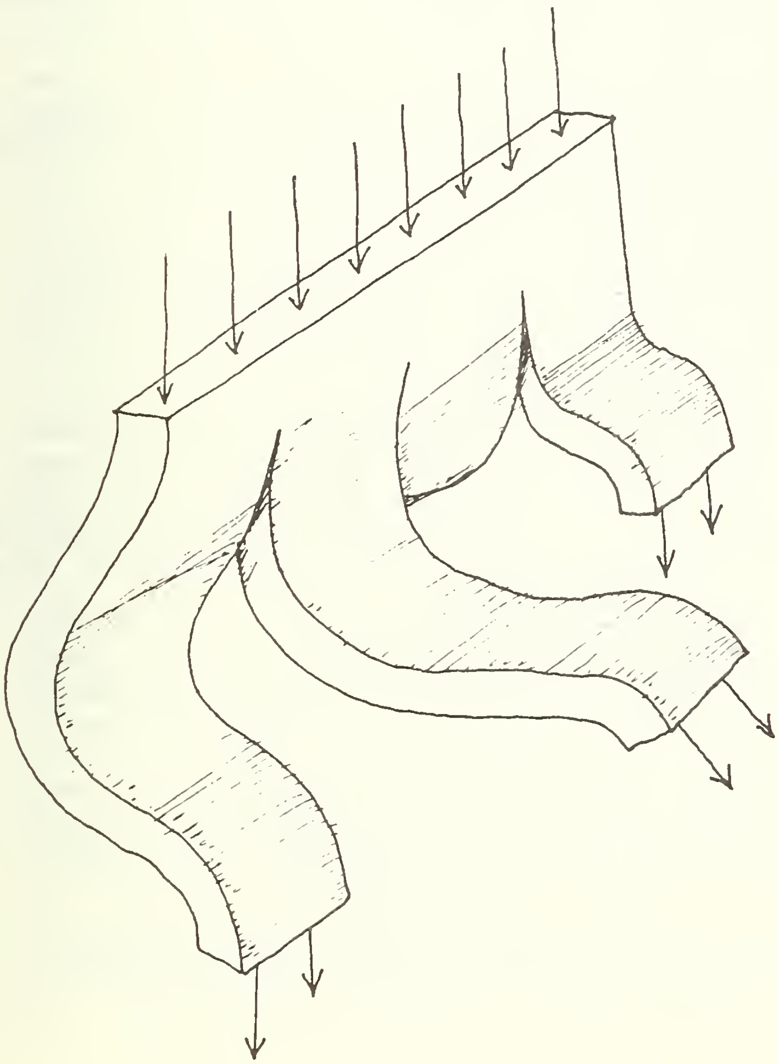
Compound Parabolic Concentrator (CPC)

The CPC is a reflector composed of parabolic elements which can concentrate sunlight severalfold. To do this, the sun's rays must strike it directly or within an angular range (θ°) to either side. Because of this angular acceptance, it can operate through much of the range of the sun's daily movement. The sunlight, concentrated by reflection within the parabolic surfaces, may be introduced into a light pipe or fibre optics bundle for transmission into the building.

3.3 Light Conduits



fibre optic filaments and bundles of glass or plastic accept light through an angle of approximately 39°. High transmission losses are the main drawback to their use. New development may reduce this loss but currently they are not effective for daylighting use.



Light pipes of acrylic plastic can conduct light in many directions. They can be larger than fibre optics. High transmission losses are the main drawback to use. Currently they are not well suited to daylighting use.

STUDY OF METHODS

Problem

To utilize daylight effectively for building illumination purposes the designer must understand interior illumination requirements, the characteristics of daylight, and how daylight can be introduced and controlled. This study section examines in greater detail the methods by which daylight may be introduced and controlled to provide the designer with an understanding of the performance of these methods.

Preface

The study of daylight introduction and control has been organized into building zones (perimeter, intermediate and deep) because each presents a different set of basic geometric and spatial daylighting design conditions. The perimeter zone, where direct daylight penetration is effective, allows the greatest freedom because the resource can be used in its raw state. Its very abundance, however, may introduce other problems such as glare, brightness and thermal control.

The intermediate zone cannot be served by direct daylight and requires some means of manipulation of the light for reasonable effectiveness as illumination. However, simple, stationary, non-concentrating methods may be employed. Consequently diffused light as well as sunlight may be utilized.

In the deep zone the problems are more severe. It is so removed from the perimeter by distance or obstructions (by floors or partitions) that only concentrating and beaming methods are effective. Here the principal issue is simply introducing sufficient natural light to be effective.

As previously noted, daylight is composed of sunlight and diffused light. The two are quite different in their behavior and hence in effective methods for introduction and control. Sunlight is collimated light with essentially parallel rays. It can therefore be manipulated by optical means. With diffused light, on the other hand, the light rays that may be coming from any direction, cannot be as effectively manipulated by optical means such as lenses and mirrors. When considering the use of a method for introduction or control it is important to determine what type of light is to be dealt with. It is also worth noting that diffused light is present along with sunlight on clear days and is also present on overcast days when sunlight is not. Therefore, methods which are useful for both types of light offer more flexibility.

Orientation is another factor to be considered as any methods depending on sunlight alone will be most effective with a maximum exposure to the sun's path during the day. Sunlight availability should be keyed to space use recognizing the sun's morning, noon and afternoon positions. The vertical position of the sun also varies over the year and must be considered in the design since at certain times it may be desirable to encourage deep penetration by the sun while at other times this may be undesirable.

1.0 PERIMETER ZONE

1.1 Windows

Extensive research has been conducted on the introduction of daylight through windows. Some very good work was done early in the century in relation to industrial applications where light was needed for critical tasks inside factory buildings [1.1-8]. Daylight was a normal design requirement in most buildings prior to the introduction of fluorescent lighting in the late 30's and 40's. Thereafter it became less and less critical as the provision of high level artificial illumination became more "practical". Nevertheless, studies and analysis continued on daylighting, particularly in relation to school classrooms -- probably because their moderate room sizes and predominant occupancy during daylight hours continued to make it practical to consider the use of daylight [1.1 - 10, 11, 12]. After the 50's, however, most daylight research took place in England and Europe and it is from these sources that much of our current research information is obtained [1.1 - 1.3, 4, 5, 7, 16]. A few sources from the U.S. are also useful [1.1 - 6, 15, 2.].

In order to evaluate the usefulness of windows as a light source, a number of factors must be considered. The proportion of the wall area that is occupied by windows will influence the volume of light that it is possible to introduce. The upper limit, of course, is the complete window wall. This will provide maximum light volume in a given situation but may well create other problems such as over-illumination, over-heating and psychological problems such as exposure and insecurity [1.1 - 14]. At the other end of the range are the suggested minimum window areas. Building standards and codes such as the FHA Minimum Property Standards will set limits such as 10% of the room floor area which give a simple recognition of the need for daylight as a function of the area of the room. Other minimum standards have been suggested [1.1 - 9] such as 20% of the wall area based on the psychological value of a view. Light related and view related standards are probably both useful minima, as window performance relates to both requirements.

The position of the window in the exterior wall will clearly have an effect on the nature of penetration of sunlight and to a lesser extent, diffused daylight as well. A window located high on the wall will allow the deepest penetration of sunlight. A low sill height allows the floor surface to play an important role in light reflection. A window located adjacent to a side wall improves illumination by reflection from the adjacent wall [1.1 - 1]. Therefore, window position and related interior surface characteristics can influence the design of windows where daylighting is an important criteria.

Conditions outside the window have received considerable attention in the development of methods to predict daylight illumination of buildings [1.1 - 1, 3, 15, 16]. Methods to calculate the effect of light blockage by adjacent buildings or landscape features can be used to determine the conditions at a specific window [1.1 - 3]. The light reflected from light colored ground surfaces, roof or soffit elements or adjacent walls, can appreciably increase the amount of daylight that enters windows [1.1 - 15]. Both the decrease of light by blockage and the increase of light by reflection can be caused by forms located beyond as well as within the site. The effectiveness of these elements is influenced by their orientation which can be designed to maximize the light directed into the window.

In a given room, the number of walls in which it is possible to provide windows will determine the nature of the light admitted. With windows in only one wall the light will be mono-directional, and task layout in the room must be based on this condition. If it is possible to provide windows on two opposing walls bi-directional light will be provided, task layout will have more flexibility, and a space twice as wide can be illuminated [1.1 - 15]. (Note that sunlight, if it enters, will be mono-directional.) Windows on several sides of a room can accommodate the movement of the sun and allow good illumination over a large portion of the day.

1.2 Direct Skylights and Clerestories (Non-reflective)

Direct downlight skylights are quite efficient for introducing diffused light which is incident from all directions of the sky. With sunlight they are subject to angular cut-off problems similar to windows, but because roof construction is frequently thick, the cut-off may be more severe. Calculation methods for determining the amount of daylight introduced by these skylights are well developed [1.2 - 1, 2].

Single and double side skylights and clerestories are treated more like windows located at an elevated position as they are frequently subject to obstruction of some portions of the sky which illuminate them [1.2 - 1, 2]. Opposite side skylights or clerestories, when oriented to east and west, allow the introduction of sunlight (at varying levels) through almost the entire day or a balanced bi-directional diffused light which gives greater uniformity of room illumination.

Studies also have been made which assess the potential for energy saving through the use of skylights for daylight introduction and control [1.2 - 3, 4, 5].

1.3 Reflective Skylights, Monitors, Clerestories

Reflective skylights, monitors and clerestories offer added degrees of light control. By their configuration they can introduce light into spaces that might otherwise be difficult to illuminate with daylight. Shape design can give selective admission or cut-off of sunlight. Color treatment of the reflective surfaces can change the nature of the reflected light, cooling or warming it as desired. Added screens and louvers can provide very precise control as in the Kimball Art Museum installation where a reflector of mathematically calculated shape made of perforated reflective metal produces almost totally uniform illumination of the curved vault [1.3 - 1, 2].

1.4 Diffusing Panels

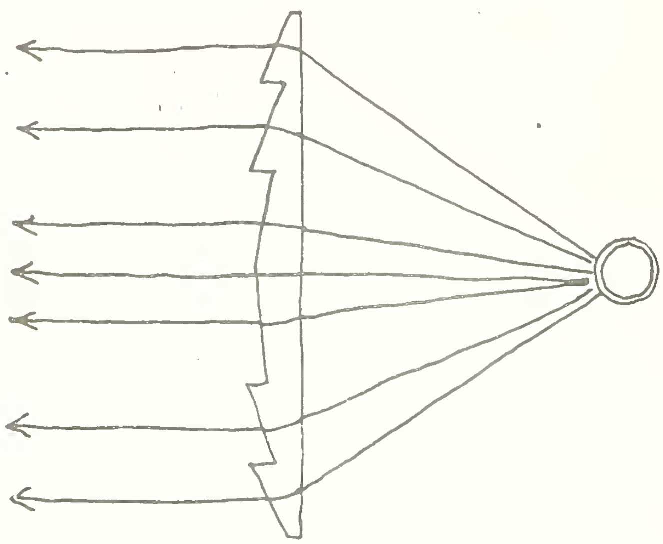
Diffusing panels offer a range of light manipulation capabilities. In a very fine grained diffusing panel such as transluscent plexiglass, light which enters the panel will be diffused over a wide area. This will convert incident sunlight to a distribution similar to diffused light, thus providing a more uniform distribution throughout the day. Because they distort visible rays, such panels offer increased privacy and visual screening. Glare can be a problem with these materials, particularly under sunlight conditions when they can become very bright; thus, the design of their installation must be carefully considered. Design data for these materials is generally available from plastic, glass, and assembly (such as transluscent insulating panel) manufacturers.

Installation of prismatic glass block can provide unusual properties. Constructed with rows of louvers cast into the two internal faces of the block, sunlight can be selectively introduced into the room. In one installation [1.4 - 1] roof mounted block were designed to transmit the low angle winter sun, block summer sun above 45°, and admit all north light. These directional properties are most effective with sunlight, as diffused light can only be partially directed by the louvers. Since the internal surfaces consist of continuous small ridges (louvers), these units will obscure vision and are useful in providing visual privacy.

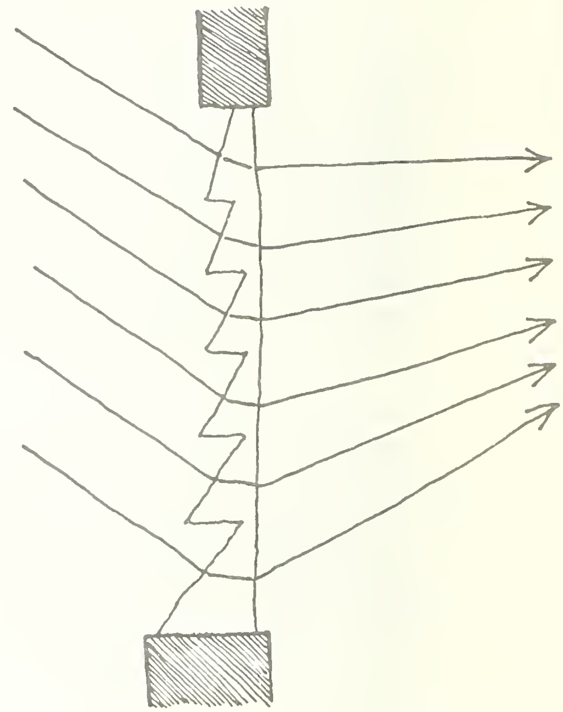
2.0 INTERMEDIATE ZONE

2.1 Linear Lenses

Linear lenses are generally long rectangular lenses based on the Fresnel principle which accept light from a point source and form it into a beam of essentially parallel rays [2.1 - 1] (Fig. 1). By reversing this and using sunlight as the essentially parallel ray light, a converging pattern of light may be projected into a room (Fig. 2).



Lighting Application
Fig. 1



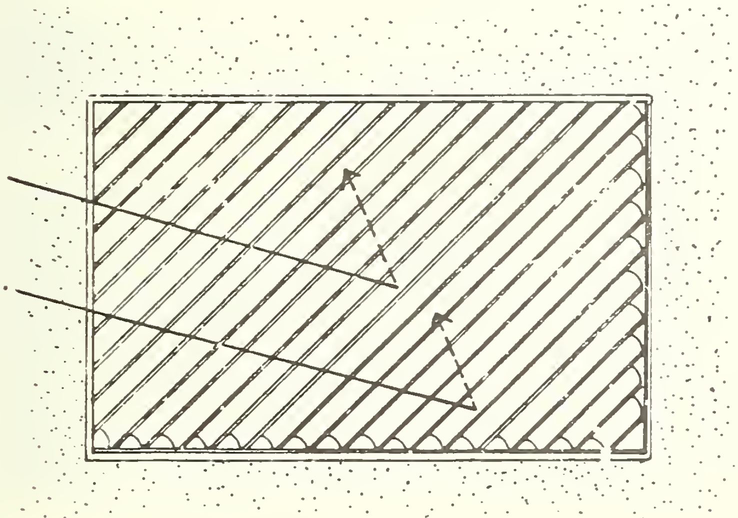
Daylighting Application
Fig. 2

Current applications employ a long lens, usually in a fluorescent trough light, with a fluorescent tube mounted either in the center or to one side to provide wall wash light [2.1 - 2, 3]. Using this principle, incident sunlight coming from an angle above the lens could be directed deeper into a room to provide illumination on a wall or ceiling. These lenses are normally of glass or plastic.

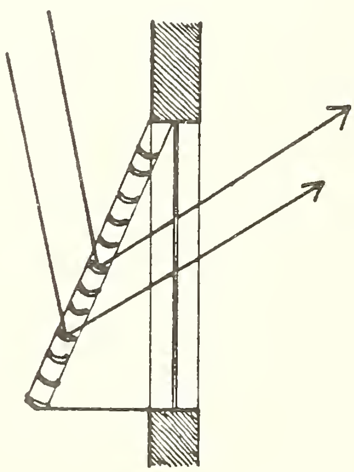
2.2 Reflectors

The use of reflective surfaces to direct daylight through windows is a very straightforward approach to increasing the amount of light gathered and the depth of its penetration into a room. Specular reflective surfaces can direct a very controlled beam into the room. They are effective with sunlight which is collimated and work well with diffused light also. Light matte surfaces are less effective but will provide a diffused reflected light from incident sunlight or diffused light. Simply providing light colored surfaces on those building elements viewed by a window will increase the level of reflective light but specifically designed reflectors are more effective as they can be formed to direct light where it is desired in the interior [2.2 - 1]. Keeping the reflectors clean is imperative if they are to be effective. Design provisions must be made for easy cleaning or self cleaning by rainfall.

An interesting variation on reflected sunlight is being researched by a group at the University of California, Lawrence Radiation Laboratory [2.2 - 2]. In this system narrow reflecting blinds are located at the window to direct light deep into the room. These are adjustable and can be set to give maximum light penetration for a given angle of sunlight. Further, they can be moved to follow the motion of the sun, direct light to various portions of the room or control the amount of light entering. The blinds are often used in conjunction with a highly reflective ceiling surface to extend the depth of light penetration by additional reflection. The reflecting blinds may be used on east, south, or west walls but different configurations provide optimum performance in each case. For east or west walls the louver system is rotated up to 45° in the plane of the window (Fig. 3).



east or west
Fig. 3



south
Fig. 4

2.2 Reflectors continued

On the south wall light can be collected through a much longer portion of the day if the louver/window system is tilted out at its base up to 20° to intercept more vertical sun's rays (Fig. 4). This is because, as the sun reaches higher noon positions in the summer months the amount of sunlight which is incident on a vertical window is reduced. If the louver/window system is tilted outward at the base it can intercept an appreciably larger portion of this incident light and reflect it back into the room. Such a configuration introduces numerous practical design and maintenance problems.

3.0 DEEP ZONE

3.1 Tracking Reflectors (Heliostat)

The heliostat is a reflecting device which has mirrors mounted on a polar axis mount similar to that of a telescope that can be moved to track the motion of the sun. In this way a constant beam of light can be directed into the building from a suitable location on the building roof or face. The installation at the Hyatt Regency Chicago [3.1 - 1, 2] uses 4' diameter mirrors which provide a 7' diameter pool of light in the lobby, 360' below the roof line. On clear days (illuminance of 10,000 ft. candles [100,000 lux]), the illuminance of the light pool will be 1,000 - 2,000 ft. candles (10,000 - 20,000 lux).

The heliostat is motor driven and automatically controlled through a photoelectric guider to track the sun each day at its correct position and to return to the sunrise position in the morning. A Xenon spotlight projects onto the mirror system at night or on cloudy days and will provide a 14' diameter pool of light of 300 ft. candles (3,000 lux).

In this installation four heliostats have been mounted on the roof and illuminate garden areas in the hotel lobby by beaming down through the glass roof. The intensity of light is affected by cloud cover, air haziness and elevation of the sun. The beam is brightest when the sun is directly overhead and drops off as it lowers in the sky. According to the operating engineers, the intensity is quite affected by haziness and air pollution as the blurred (partially diffused) light source does not form as sharp and intense an image. Intensity of light at the lobby floor is also affected by cleanliness of the roof skylight through which it beams.

The light beam can be directed to different locations at the lobby level by moving the upper mirror and predetermined target locations have been included in the automatic guidance program.

3.2 Concentrating Reflectors

The Compound Parabolic Concentrator (CPC) is a shape originally designed for high energy physics to receive faint nuclear particles coming from widely divergent angles. Its suitability for use as a solar collector was developed at Argonne National Laboratories [3.2 - 1, 2, 3] in pursuit of a solar collector for heating water that could concentrate sunlight and reduce the need for tracking movement (figure 5). This ability also appears to make it attractive for use with light conduits to gather and transmit daylight into a building.

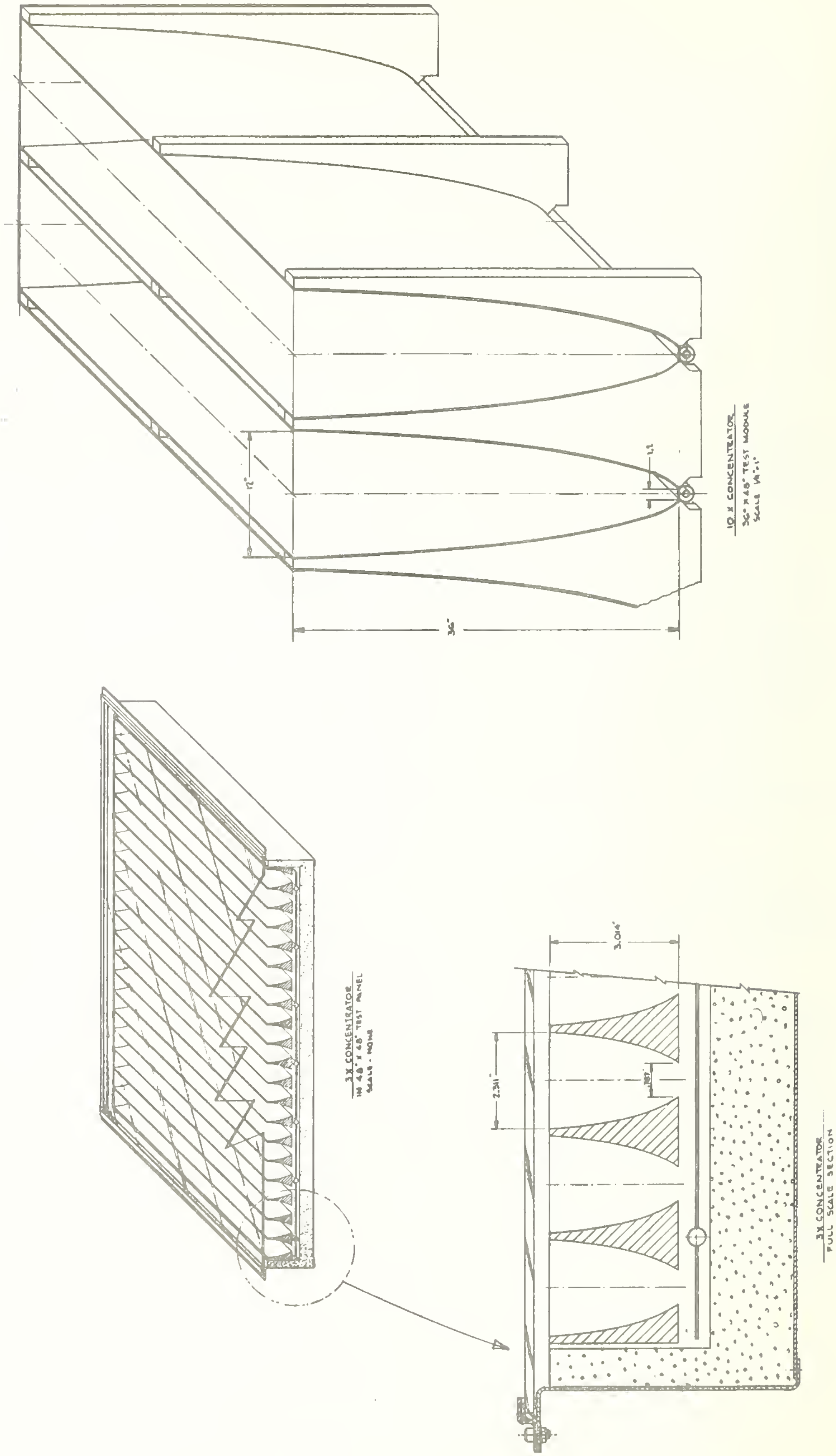

10 X CONCENTRATOR
36"
12"
3X CONCENTRATOR
3X CONCENTRATOR
FULL SCALE SECTION
3.014"
2.311"

Fig. 5 [ref. 3.2-1]

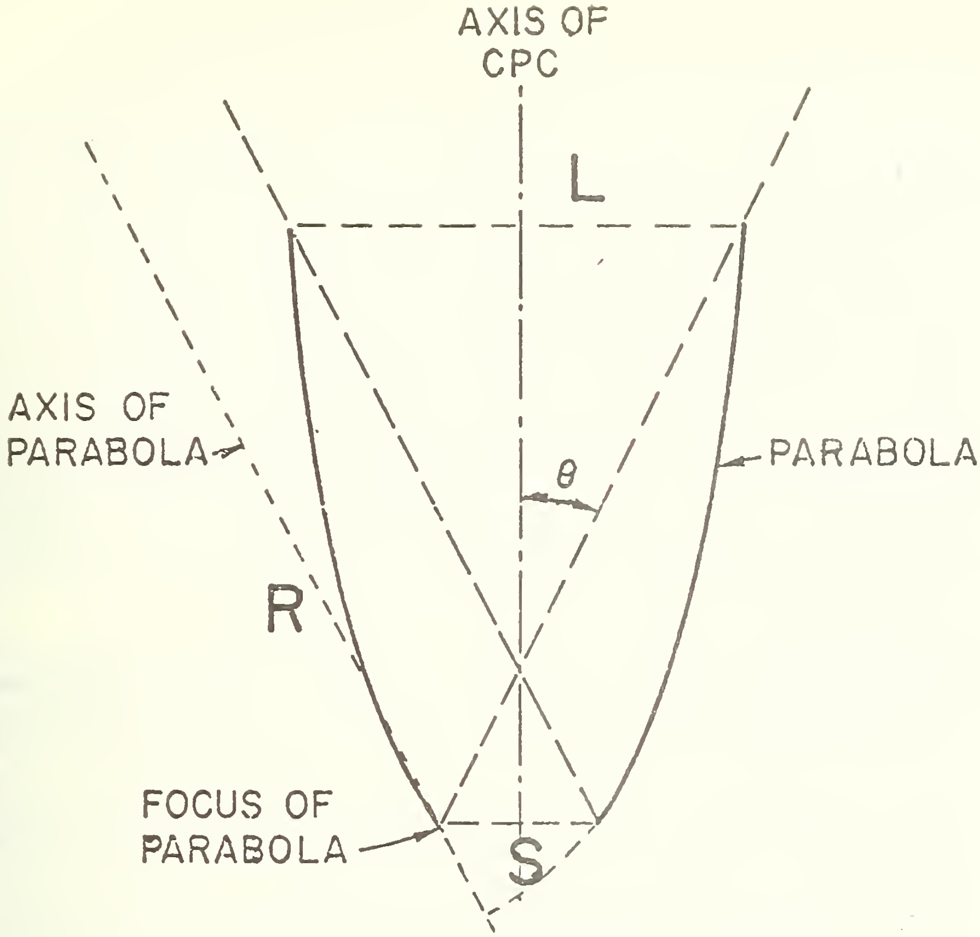


Fig. 6 Cross Section of CPC [ref. 3.2-3]

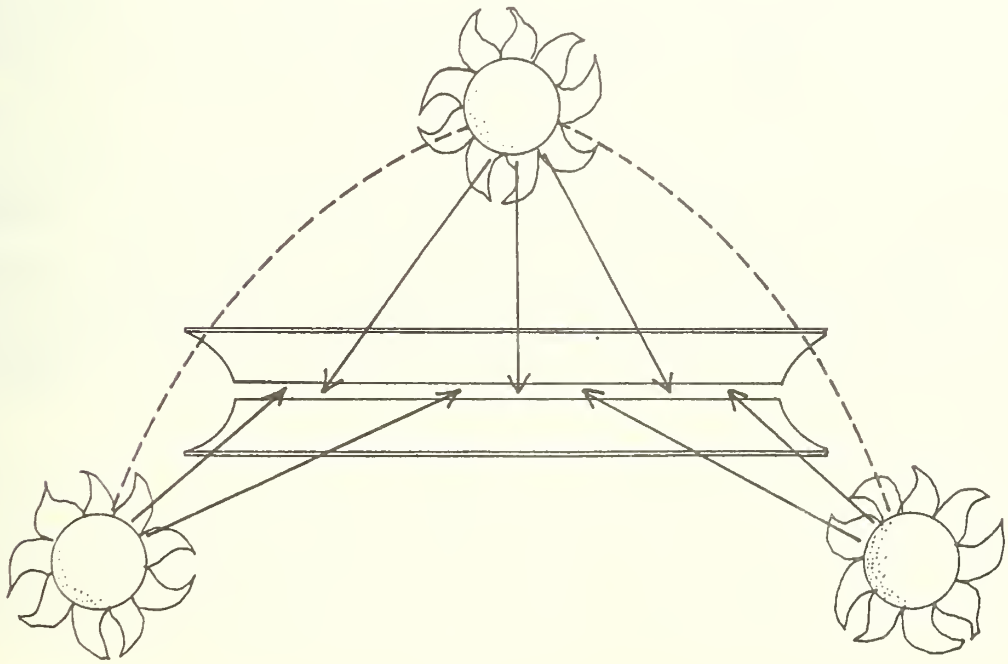


Fig. 7

3.2 Concentrating Reflectors continued

The geometry of the CPC (figure 6) is such that the higher the concentration factor the narrower the acceptance angle for light. This trade-off is illustrated as follows:

θ max (1/2 total angle)	Concentration
19.5°	3
11.5°	5
5.7°	10

Also, the wider the acceptance angle the less the CPC will need to be moved to track the path of the sun. Thus, with an angle (θ) of 7°, sunlight can be collected for 7.4 hours without movement. With wider angles this can be increased to take care of some seasonal movement of the sun as well.

In order to use the capability of the CPC to accept sunlight over a considerable angle while itself remaining stationary it is desirable that it be designed as long trough so that the ends do not interfere at the lower portion of the range (figure 7).

The concentrating ability is an advantage in stepping up the intensity of the light that is fed into the end of the light conduit, but it also increases the heat. In a lighting application (as contrasted to solar heating) this must be dissipated to a certain degree. Approaches to this so far have centered on radiation by the metallic surface of the CPC itself or the passage of air through the CPC trough. In either case the heat could possibly be extracted for useful purposes.

One of the reasons that keying the CPC to fiber optics and light pipes is attractive is that much of the light that departs from the base of the CPC is at an angle that an optical fiber can accept. The acceptance angles for these range from 32° to 42° (from vertical) for plastics and 39° for glass.

Research is currently being conducted at Argonne National Laboratories on the CPC and its application for solar heating and cooling. Investigations have been conducted by the author on its usefulness for daylight introduction when combined with light conduits. These have not yet reached a definitive stage and some questions still need to be answered, such as: heat build-up and dissipation; losses in the light conduit; optimal balance of concentration vs. acceptance angle; and most effective CPC geometry.

3.3 Light Conduits

Light conduits are of three basic types: (1) glass fibers, (2) plastic fibers and, (3) plastic shapes. Glass and plastic fiber optics are are very small strands usually gathered together to form a bundle. Currently the maximum diameter of such bundles is 1". Light shining down the fiber is reflected back and forth off its internal surfaces and stays completely within the fiber as long as it does not hit the sides at too steep an angle (called the critical angle). Reflective losses at the ends and losses in the fiber itself reduce the total possible transmission. These materials have approximate properties as tabulated below.

Material	Transmission loss (Visible light)	Acceptance Angle (1/2) (critical angle)
glass-normal (fib opt)	50%	39°
glass-medium loss (fib opt)	4%	
glass-loss (fib opt)	less than 1%	8°
plastic-Crofon (fib opt)	80%	32°
plastic-acrylic (light guide)	70%	50°

[Ref. 3.3 - 1, 2, 3, 4, 5, 6, 7, 12, 13]

The acceptance angle influences the care with which the incoming light must be collimated and aligned with the end of the fiber. These ends must also be carefully finished to avoid high reflective losses. The fiber bundles may be curved and bent to almost any shape as long as the radius of curvature is not too small.

Installations at a scale similar to room illumination have been demonstrated in expressway signage illumination [3.3 - 13].

Plastic light guides are generally made of acrylic plastic and perform in the same manner as fiber optics but are usually of larger dimension. Their minimum radius of curvature is greater than that of fiber optics because the light channel is normally much larger.

For both plastic fiber optics and light guides of plastic there are significant limits to the temperature of operation. This means that if concentrating reflectors provide the light source cooling may be necessary.

For any of the light conduit materials there is a trade-off between directionality of the entering beam and transmission loss. These must be selected and balanced for a given application. The low and medium loss glass materials are just being developed for the market. They are currently limited to communications applications. Their use for building lighting has not been evaluated but it may hold promise if the balance of properties can be keyed to effective collection methods.

Conclusions and Recommendations

In the perimeter zone there are many methods available for daylight introduction and control. Because daylight is so readily available this is the zone where its usefulness can be extended through more hours of the day and into more variable conditions. For example, color control is a very interesting area of study, for frequently interior lighting is used simply to combat the gloom of daylight on a gray day and an ability to modify this (commonly defined) coldness could greatly extend the use of daylight. Though many types of architectural light control are provided by the methods noted in the study, there are numerous others that are considered to be in the area of furnishings and interior work. Methods such as curtains, shutters, shades, and screens all are potentially very effective methods of modulation and control. The question of light balance is also important as daylight levels vary greatly and light levels at the rear of a room require a balancing of daylight and artificial sources.

In the intermediate zone the major problem is to extend the usefulness of daylight deeper into the building. Sunlight is more usable than diffused light in this zone because it can be manipulated by optical methods. The challenge is to simplify the devices used and to make them effective over the longest portion of daylight hours.

In the deep zone the transmission losses of light through various devices appears to be the primary problem to overcome. Introducing sufficient light to be useful is by no means an easy task as current installations demonstrate. Distribution from gathering points to dispersed use points is also a problem involving control and losses.

In all methods of introduction and control maintenance is a critical issue. The methods depend on reflection from light colored surfaces or transmission through clear or translucent panels. Cleanliness, scratches, denting and warping are all types of degradation that can have serious effect on the usefulness of these methods. Designs must consider this fully.

When diffused light and sunlight are introduced at a single point in a room, they have directional characteristics. Even though the diffused light radiates in many directions, it still displays a principal directionality. In these cases the planning and arrangement of functions in the interior spaces so illuminated must take this directionality into consideration. In many instances this will represent a strong planning constraint.

Based on this investigation, a number of recommended study areas may be suggested:

1) A study of the methods for daylight color control.

2) Studies of daylight control including curtains, shutters, shades, and screens.

3) A study of the role of the human occupant of the room as a part of the complete light control circuit.

4) A study of light modulating glass and plastics. Chemical additives and coatings may offer unusual means for varying light transmission and reflection properties.

5) A study of construction methods as related to the various light introduction methods. Many offer some unique opportunities for integrating structural and window components with the light introduction components.

6) A study of the probable costs and the cost effectiveness of the various methods.

7) A study of the combined energy costs of the various introduction methods. This would include manufacture and installation as well as long term operation and maintenance.

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We can no longer ignore daylight as a valuable natural resource for building illumination. Significant reductions in the energy consumption of buildings are possible by decreasing the dependence on artificial illumination and decreasing air conditioning loads by employing methods which bring in cool light. In order to design buildings utilizing daylight effectively there must by an understanding of the design principles of daylighting. This requires a knowledge of illumination to meet the needs of the building users, an understanding of characteristics of daylight at the location of the building, and imagination in developing ways to introduce and control daylight. This paper is directed toward the identification of innovative techniques for the intro duction and control of daylight. It is arranged in three sections: a Compendium, a Study section, and a Reference section. The Compendium presents a number of state-of-the-art methods to assist the designer in successfully employing daylight more extensively. The Study section provides more detailed information on these methods so an increased understanding can be developed of those which appear to have suitabilit in a given situation. Finally, the References provide background for further investigation.

The Study organizes daylighting methods as they relate to three zones of a building, the perimeter, the intermediate and the deep zone. Each has different characteristics and is suited to daylighting by different methods.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Daylight gathering; Daylighting of buildings; Energy conservation; Lenses; Light conduits; Light control; Reflectors; Skylights; Windows.

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