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ENERGY & ENVIRONMENT DIVISION

Technology Reviews: Daylighting Optical Systems

J. Schuman, F. Rubinstein, K. Papamichael, L. Beltrán, E.S. Lee,
and S. Selkowitz

September 1992

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TECHNOLOGY REVIEWS
DAYLIGHTING OPTICAL SYSTEMS

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TECHNOLOGY REVIEWS : DAYLIGHTING OPTICAL SYSTEMS

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Executive Summary

We present a representative review of existing, emerging, and future technology options in each of five hardware and systems areas in envelope and lighting technologies: lighting systems, glazing systems, shading systems, daylighting optical systems, and dynamic curtain wall systems. The term *technology* is used here to describe any design choice for energy efficiency, ranging from individual components to more complex systems to general design strategies.

The purpose of this task is to characterize the state of the art in envelope and lighting technologies in order to identify those with promise for advanced integrated systems, with an emphasis on California commercial buildings. For each technology category, the following activities have been attempted to the extent possible:

- Identify key performance characteristics and criteria for each technology.
- Determine the performance range of available technologies.
- Identify the most promising technologies and promising trends in technology advances.
- Examine market forces and market trends.
- Develop a continuously growing in-house database to be used throughout the project.

A variety of information sources have been used in these technology characterizations, including miscellaneous periodicals, manufacturer catalogs and cut sheets, other research documents, and data from previous computer simulations. We include these different sources in order to best show the type and variety of data available, however publication here does not imply our guarantee of these data. Within each category, several broad classes are identified, and within each class we examine the generic individual technologies that fall into that class. Each technology section has the following format:

I. TITLE PAGE & CONTENTS

II. SUMMARIES

- Summary descriptions for each technology.
- Summary table(s) showing comparative performance characteristics or other comparative information.
- Brief discussion/summary of the most promising technologies and trends in this category. Emphasis is on electricity peak reduction and on potential for integration with other systems or technologies.
- List of product brand names for each sub-category.

III. DATA ENTRY FOR EACH TECHNOLOGY

Each sample technology is characterized through one or more of the following. Sections may deviate as required:

- Description
- Sources
- Status of availability
- Pros and con
- Energy performance
- Comfort performance
- Impact on building design
- Cost, per unit basis
- Life cycle cost economics
- Market share, expected trends
- Case study installations

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DAYLIGHTING OPTICAL SYSTEMS: SUMMARIES

OVERVIEW

Conventional daylighting design components (i.e. fenestration systems) can normally provide adequate daylight in the perimeter of buildings, i.e. within 15 feet of windows or skylights. To provide daylight in a larger fraction of the building area requires one of two approaches. One option is to increase the fraction of the floor area that is adjacent to fenestration using architectural design strategies to alter floor plans from rectangular to reentrant forms, use of atria, stepping back upper stories of the building, etc. The second option is to use daylighting optical systems to deliver light to building locations beyond the perimeter zone. In this section, we present several technical approaches for introducing daylight and sunlight deeper within buildings. We consider situations where light transmission is desired over longer distances (15' - 100') and where it may be desirable to penetrate either horizontally or vertically through the core of a building. These includes daylighting techniques based on the use of light shelves, wide window sills, special reflectors, louvers, baffles, reflective blinds, and other ways to direct light deep into the building's plan. These methods are intended to avoid the glare and the strong modulation (intense light near the window, rapidly falling off with increasing depth) of direct-beam daylighting.

Such optical systems require three major elements. First, a collection system is required to gather and redirect the available light flux and, in many cases, to concentrate it. Second, the light flux must be transmitted through a transmission system to the point of use in a building. Third, the light flux must be distributed in a way consistent with the end use of the lighting. In some systems several of these functions may be combined.

Through the combination and integration of one or more daylighting systems the amount of light in deep spaces can be increased. The most promising technologies are the ones that can easily be incorporated into buildings, at reasonable costs, and that can provide the maximum benefits in terms of reduced energy consumption and user satisfaction. Designers plan buildings following certain standards to achieve a luminous level inside usable spaces. The most common building type used in commercial buildings is an open plan building with sidelight windows.

The objectives of promising technologies include:

- simple design with few or no moving parts
- responsive to most building types
- easily adapted to existing buildings
- uniform year-round performance
- low building cost
- simple construction
- high optical efficiency
- deep light penetration

CAPSULE SUMMARIES

1. LIGHT COLLECTION SYSTEMS

The collection system may consist of reflective or refractive devices that can be passive or active. The tracking or active daylighting system is costly but highly efficient. The non-tracking daylighting system is lower cost but generally will have lower efficiency. There has always been some debate as to the acceptance of an active component versus a passive system for daylighting applications. The active system requires maintenance over its lifetime to perform properly. Active tracking systems can readily include concentrating elements so that the transmission component can have a smaller cross section than the collection element.

1.1 PASSIVE COLLECTORS

Passive optical collectors use fixed reflective and/or refractive elements to collect sunlight and redirect it to a transport or guide system. In some cases the "guide system" is simply a large building volume such as an atrium. The systems lack the control and efficiency inherent in a tracking system but in principle are lower costs and require less maintenance.

1.2 TRACKING COLLECTORS

1.2.1 Daylight Heliostats

Daylight heliostats are devices which are used to direct sunlight to a stationary target by mechanically compensating for the earth's rotation. They consist of either a primary reflector that directly illuminates the interior of the building, or a combination of a primary reflector that tracks the sun in some fashion, and a fixed secondary reflector that reflects the sunlight into the building. Tracking heliostats can provide light to a specific location in a building, e.g. atrium, or can be the collection element of a light guide system.

2. LIGHT TRANSPORT SYSTEMS

The following are the most common types of light guides with good transmission characteristics:

- Prismatic light guide
- Reflective guides
- Lens guides
- Fiber optics
- Acrylic rod
- Fluid filled tubes

The most basic form of light pipe is simply an empty shaft along which a collimated beam of light can travel. Except for lenses and reflective guides, the other guides mentioned use the principle of total internal reflection. Thin fiber optic cables are efficient but require a concentrating system for the input. Solid guides of large cross section, either of glass, plastic or even liquid-filled, seem impractical due to the weight and massive amount of material involved. The expense of acrylic rods and the weight and unacceptable blue color emitted from water tubes narrows the option of using light guides to lenses and prismatic or reflective tubes.

In this report, we emphasize four types of light guides with the most promises. Table 1 presents a comparative summary of each technology.

2.1 PRISMATIC LIGHT GUIDES

The prism light guide is a hollow light guide structure wherein light is channelled by means of total internal reflections from a prismatic dielectric surface. Light ray must lie within 26° of the central axis of the guide in order to be propagated by total internal reflections. The guide can be constructed with any cross section although square, rectangular and circular are most common. The prism light guide can be used to transport light to a core region in a building and to evenly, efficiently distribute it along the surface of the guide.

2.2 REFLECTIVE MIRROR GUIDES

Mirror light guides utilize multiple specular reflection at the reflective inner wall surface to transport the light entering the input aperture to the output aperture. The overall transmission is a function of the surface reflectance and the input angle(s) of the incident light. Using modern highly reflective silvered polyester (r=0.96) semicollimated light can be transmitted over 100 feet with only small losses. These systems can transmit diffuse light but at lower efficiency.

2.3 LENS GUIDES

The lens guide is an arrangement of lenses in which each individual lens transmits an image of the preceding lens to the one following. A physical guide is not necessary between lenses. The spacing of lenses is a function of the degree of collimation of the light source. Large lenses can be expensive, unless a Fresnel lenses or annular lens is used.

2.4 FIBER OPTICS

Fiber optic cables transmit light through a thin solid fiber with high efficiency by total internal reflections. The best known commercially available system using fiber optic guides is the Himawari, manufactured by La Foret Engineering in Japan. The Himawari system consists of a hexagon-shaped honeycomb-patterned Fresnel lenses collector (concentrating, altitude/azimuth tracking) that filters and focuses light to fiber-optic transport cable. The quartz based fiber optic cables transmit light to specialty lighting applications that benefit from filtered light with good color rendition. The systems are very expensive.

Table 1: SUMMARY OF LIGHT TRANSPORT OPTICAL SYSTEMS

	Impact on Building Design	Average Duct Size	Duct Shape	Average Distance of Transmission (ft.)	PROS	CONS
FIBER OPTICS	No	in^2	N.A.	< 300	Easy installation in small spaces. No extra hardware at bend. Long distance transmission.	Extremely expensive. Requires expensive tracking collector/concentrator.
PRISMATIC GUIDES	Yes	ft^2	○ □	<100	Can act as distribution as well as transport.	Requires light input within +/- 26°of axis.
REFLECTIVE MIRROR GUIDES	Yes	ft^2	△ ○ □	< 100	Simple non tracking collectors may work, will work with non collimated and diffuse light. Simple construction. Can act as distribution as well as transport.	Need coatings that maintain very high values of reflectance.
LENS GUIDES	Yes	ft^2	N.A.	< 100	Potentially simple system if input is well collimated.	Cleaning of optical surfaces, may be difficult.

Note: All systems can be provided with filters to reject near-IR and thus reduce air conditioning impact.

3. LIGHT COLLECTING SYSTEMS

These are simpler systems which represent a reduction both in scale and in complexity compared with larger light collection and transport systems. In place of large collecting devices to serve a whole building, smaller reflective surfaces for each window are used. Instead of complicated distribution systems, the surfaces of the room and of other devices are used to spread and diffuse light deep in the space. Table 2 presents a comparative summary of each promising system.

3.1 LIGHT SHELF, FIXED AND OPERABLE

Light shelf is a horizontal or near horizontal baffle positioned (usually above eye level) to reflect light onto the ceiling off its top surface, and to shield direct glare from the sky. Much of the interest in light shelves springs from their assumed ability to project daylight deep into the building core, beyond the normal daylighting perimeter of the building and beyond the normal penetration from the shelfless apertures. In addition light shelves can reduce cooling loads caused by solar gains and can improve visual comfort in a space.

3.2 REFLECTIVE LOUVERS, SILLS AND SCOOPS

Reflective louvers are used to redirect light onto the ceiling towards the middle and rear of the room. The aim is to improve penetration of light deeper within the space. Louvers can be of two types: fixed and moveable. Fixed louvers works optimally for only a limited range of solar altitude. For this reason moveable reflectors are usually recommended, although motorized systems tend to be costly compared with the simple reflective louvers. Reflective sills and scoops can be viewed as a simple fixed louver system.

3.3 PRISMATIC PANELS

Prismatic panels are made of optical prisms and insulating glass. The prismatic panels work on the principles of both reflection and refraction to enable the use of daylight inside buildings in a more controlled manner. The system reflects light coming from a certain angle and transmit the light coming from any other angle. In other words, they have a cut-off range and a transmission range. The cut-off range prevents the transmission of direct sunlight into the interior, thus providing the sunshielding effect. In the transmission range, the optical refraction of the prism changes the direction and intensity of the transmitted zenith light. At the same time, this light becomes controllable. The daylight entering through a window can be directed up towards the ceiling in the interior. As a sunshield direct sunlight is kept out and only vertical light from the sky is admitted into the room

3.4 REFRACTIVE DAYLIGHTING DEVICE

This daylighting device could be permanently mounted in a window to redirect sunlight deep into a room irrespective of the elevation of the sun. The basic component of the current prototype device is a single solid section of dielectric material with a sloping curved base and a v-shaped trough as the top surface. The individual sections stack together to from the module, creating an enclosed air gap between each section. The angles are such that light entering a section passes through it by total internal reflection, remaining always within the dielectric until

emerging generally in an upward direction. Prototypes have been built and tested; this is not yet commercially available.

3.5 LIGHT CONTROL PANELS

A laser cut light deflecting panel consist of a window panel which deflects incident daylight deep over the ceiling of the room while maintaining reasonable viewing transparency. The window panel may be fixed vertically or may be tilted to deflect light deeply into the room for a wider range of incident sun angles. As the laser cuts the acrylic material by melting, the internal surfaces formed are highly reflecting ensuring efficient light control by total internal reflection. The panels may be produced in standard thickness, 3 mm., 6 mm, etc. The precision and flexibility of programmable laser cutters allows production of deflecting panels with the same thickness as conventional glass window glazing and in any size or shape. Prototypes have been built and tested; this is not yet commercially available.

3.6 HOLOGRAPHIC GLAZINGS (For other glazing systems that redirect light see Glazing Systems Technology Review.)

Holography offers a new approach to collecting and redirecting daylight. A microns-thin, transparent, holographic pattern is fabricated on a glazing (layer using silver-halide emulsion, photopolymers, embossed thermoplastic, etc.). The hologram can redirect incident light towards the ceiling in the back of the room, from which it is diffusely reflected. There are tradeoffs in the design of holograms between optical efficiency, angular response and spectral response. A hologram designed to redirect incident light from a particular range of input angles to a specified output angle would be specific to the latitude and azimuth of installation and to the angle of the glass if not vertical. Researchers estimated the mass-production cost of embossed holograms at ~ $1.50/sq. ft., corresponding to retail costs of about $5/sq.ft. but these figures are still speculative.

Experimental holograms have been fabricated that transmit 85-90% of visible light through a 47° range of altitude and 100° of azimuth. These holograms redirect daylight into a bright white area fringed with colors. A prototype design for controlling color shifts and fringing has been tested; remixing of rainbow colors largely eliminated colors, though slight blue or pink casts remained in some spots. Alternatively a matrix of different holographic glazing can be designed, with overlapping diffractive patterns to provide better performance at different incident angles. This has the effect of reducing the overall efficiency of the systems. This technology is still in a research and development stage.

Table 2: SUMMARY OF LIGHT COLLECTING OPTICAL SYSTEMS

	Impact on Building Design	Average Distance of Transmission (ft.)	PROS	CONS
LIGHT SHELVES (fixed)	Yes	< 20	Shading: reduce cooling loads. Improve visual comfort in space.	Requires high ceilings. Maintenance problems with exterior reflective light shelves.
VALRA	Yes	30	Deep penetration of light. Good performance year-round.	Requires tracking system. Projects from building envelope.
REFLECTIVE DEVICES Louvers, Sills, Scoops	No	< 20	Redirect sunlight into the room to form a large diffuse light source on the ceiling.	Glare becomes a major difficulty. Sunlight can reflect straight into the eyes of occupants. Louvers block view out. Maintenance problems.
PANELS Prismatic	No	< 25	Avoid glare from sunlight and sky. Reduce luminance of windows to values prevailing in interiors. Rejects solar heat gains.	Rainbow reflections Products not available in U.S.
Refractive Device	No	30	Reduce glare problems. Redirects high sun angles. Easy cleaning.	Under development.
Light Control Panels	No	30	Maintain viewing transparency. Increase deep illumination.	Under development.

PASSIVE COLLECTORS

DESCRIPTION
The passive collectors require a relatively large collection area and may consume considerable floor area for the transport component if the light is not concentrated. The specifics depend upon the relationship between the collector area and the floor area to be lighted.

Other passive options can be designed with monthly or seasonal manual adjustment to maintain proper operation. These include: operable through collector with sophisticated volutes, adjustable reflective tilted mirrored surfaces, or Fresnel lenses with secondary reflectors (Ref. 11).

An advantage of the non-tracking systems is that they usually require fewer moving parts. Costs should be lower with passive collectors than with tracking systems, but efficiency should be higher with trackers. The resultant benefit/cost ratio may thus vary widely.

The following are the most common elements used as concentrators:

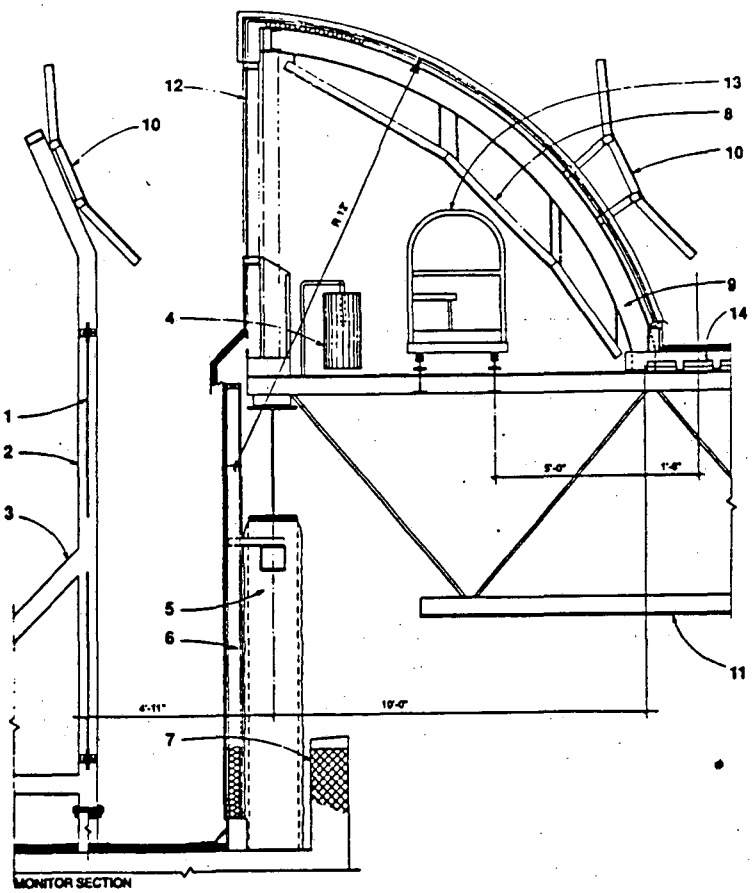
- Parabolic mirror (concentrating, reflective)
- Flat mirrors (non concentrating, reflective)
- Fresnel lens (concentrating, refractive)

CASE STUDY INSTALLATIONS

3M HEADQUARTERS, AUSTIN TX

CRSS Architects, Inc. was responsible for the architectural design of this 3M headquarters facility. The solution incorporated an enclosed 65-foot-tall atrium between five-story office buildings. The objective was to develop an atrium glazing system to redirect light to the bottom of the atrium space. Fresnel reflective panels were used to make the primary and secondary collectors (see Figure 1). The surface of each reflector is a wafer-thin, extruded-solar-lens reflecting film developed for the project by 3M scientists. The geometry of the system is designed to collect direct sunlight from all solar altitudes and redirect and diffuse the light vertically downward to illuminate the paseo and bridge walkways below. The film itself resembles corduroy, with parallel ribs that scatter reflected light +/- 5 degrees. The 3M daylighting film was laminated to 3.8 cm. thick polystyrene panels having an acrylic exterior surface. Three similar panels were fabricated for the secondary reflector. The Fresnel grooves of the 3M daylighting film run horizontally on the primary collectors and vertically on the secondary reflective panels. This serves to spread the direct sunlight +/- 5° in the north-south as well as the east-west direction. The finished panels are mounted in a metal frame which, in turn, are fastened to the adjacent roof structure or dormer. The exterior collectors and the windows are easily accessible on the roof. The system is designed to compensate for the varying amount of available sunlight between summer and winter months. Benefits include the reduction of air conditioning loads and the reduced need for electric lighting.

Total atrium glazed area (which is north facing and vertical) is 28% of the total floor space of the atrium. Preliminary light level measurements in August 1990 indicate peak light levels in the range of 9,500 lux on the fifth floor, and as high as 4,000 lux on the second floor at noon. Original estimates were for maximum light levels to be in the range of 1,500 to 2,000 lux on the second floor. Light levels were higher than anticipated for this month. Detailed measurements of light levels for different seasons and sky conditions are not yet available.



1 Cross-Bracing
2 Free-Standing Lens Support
3 Free-Standing Lens Support Bracing Member
4 Light Fixture
5 Steel Column Beyond
6 Steel Stud Wall Construction

7 CMU Construction
8 Secondary Reflector
9 Steel Beam
10 Primary Concentrator
11 Steel Truss
12 Insulated Glass
13 Window Washing Equipment
14 Roof Deck

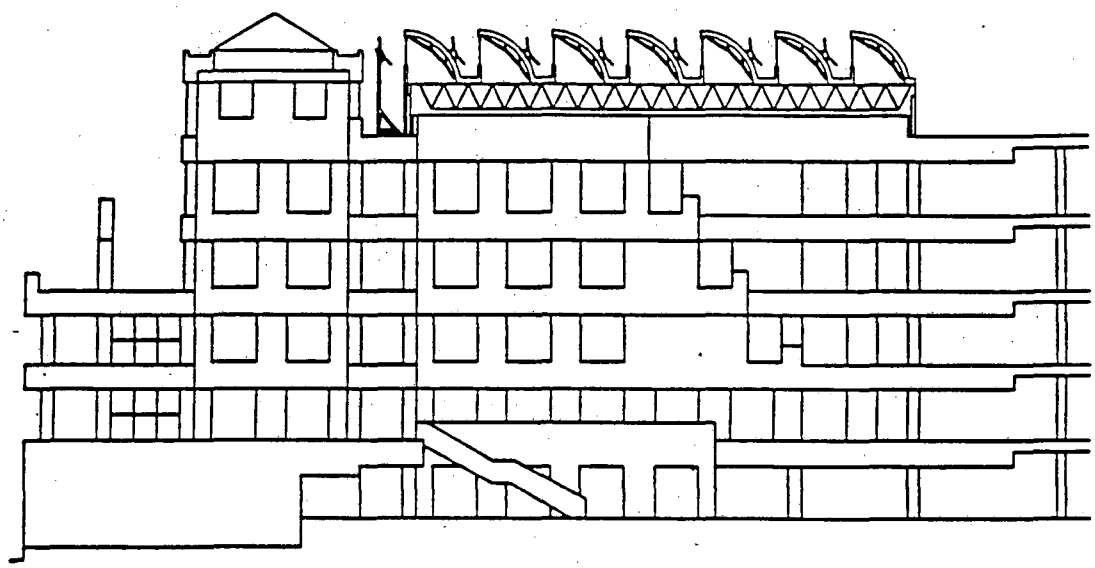


Figure 1. Section of the 3M Headquarters Building, and an enlarged view of the daylighting system on the roof of the building (Ref. 17).

THRESHER BUILDING, MINNEAPOLIS, MINNESOTA

The Thresher Building is a historic warehouse that was renovated and converted to an office building. The design goal was to develop a way to transform the dark interior floor area at the center of the building into a viable office space. The building renovation was completed in 1985 by BRW Architects, Inc. The designers used an optically beamed sunlight system, to project daylight into deep interior spaces. A double curved, roof mounted reflector system admits daylight into the building. The reflecting surfaces have Fresnel grooves to uniformly spread the reflected sunlight within a ten degree angle. This proved to have three advantages. First, the intensity of the concentrated sunlight was too low to start fires. Second, the reflected light took on a soft, pleasant appearance. Third, the efficiency of a light spreading Fresnel is considerable higher than using light diffusing techniques. The collector is a fixed light scoop at the roof which beams light vertically in a light well through five stories (Figure 2). Light into adjacent rooms is simply borrowed from the light well. The passive collectors that are used in this building require a relatively large collection (sun scoop) and consumes considerable floor area for the transport component (light well).

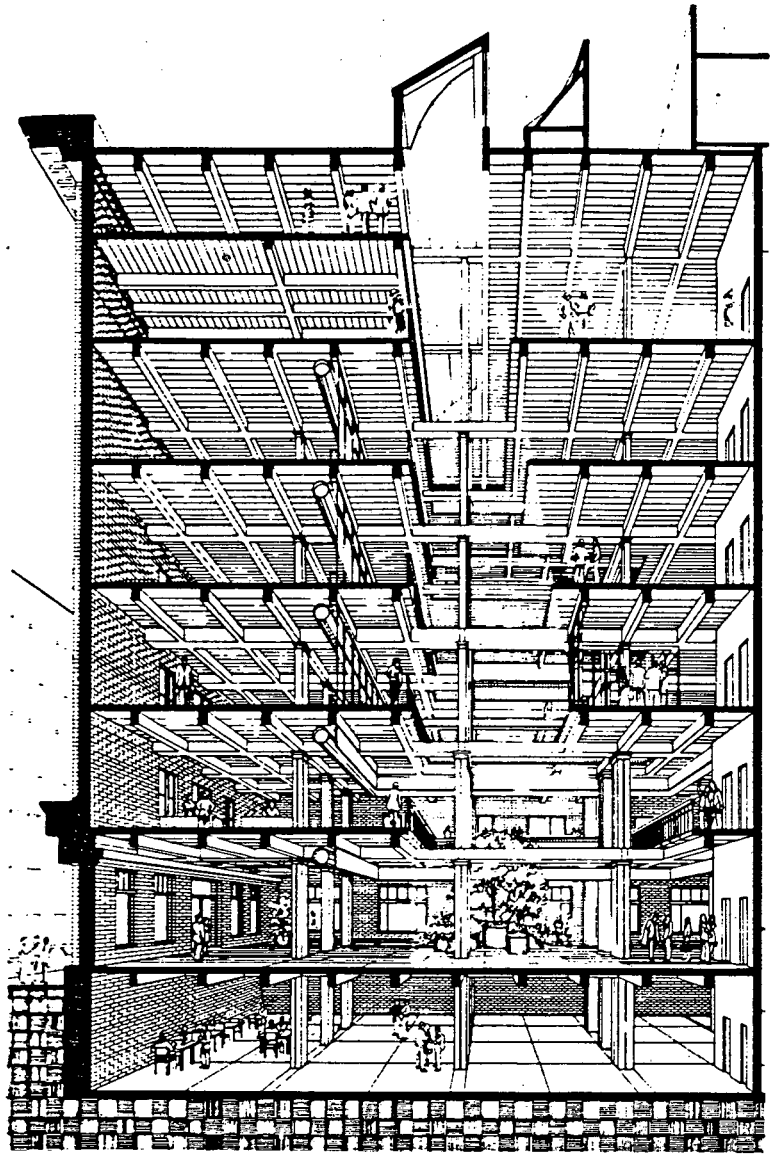


Figure 2. Thresher Building partial section looking west (Ref. 3).

TRACKING COLLECTORS (active system)

The advantage of active systems is the potential to collect and deliver a relative large flux of sunlight to a smaller transport network throughout the day all year. A tracking system may be operated by a computer program for that particular region to predict the location of the sun or the sun motion can be actively tracked by sensors. Collectors can include plane mirrors, curved mirrors or lenses. Depending on the collector assembly, there are several different approaches to tracking: altitude tracking, azimuth tracking, altitude/azimuth tracking and polar axis/azimuth tracking. Concentrators can be added to most of these systems to reduce the cross sectional area of the transport system.

DAYLIGHT HELIOSTATS

A heliostat is a device which directs sunlight to a stationary target by mechanically compensating for the earth's rotation.

Daylighting heliostats consist of (a) primary reflector that directly illuminates the interior of the building, or (b) a combination of a primary reflector that tracks the sun in some fashion, and a fixed secondary reflector that reflects the sunlight into the building. Although a number of different heliostat systems can be used for solar thermal applications, only three have been developed that use a primary/secondary reflector system for daylighting purposes. These are:

- Azimuth-tracking, fixed-altitude systems
- Altitude-tracking, fixed-azimuth systems
- Altitude/azimuth-tracking systems

In azimuth-tracking, fixed-altitude heliostat systems, the primary reflector continuosly tracks the solar azimuth while the slope of the reflector remains fixed at a specified angle (usually equal to the latitude) and cannot track the change in solar altitude. In the altitude-tracking, fixed-azimuth systems, the primary reflector continuosly tracks the solar altitude but is fixed to a specific solar azimuth -usually due south. In altitude/azimuth tracking systems, the primary reflector continuosly tracks both solar altitude and azimuth. In all of these systems, the secondary reflector is fixed in position. Further, in order to be able to track altitude and/or azimuth continuosly, the heliostat must have an automatic control system; it cannot be manually driven.

CASE STUDY INSTALLATIONS

HONG KONG BANK

This 51-story building designed by Foster Associates has a gross area exceeding one million sq. ft. It encompasses 130 ft. high, 11-story central atrium, capped by 30 floors of office space. An altitude tracking collector at the south elevation beams light horizontally to reflecting mirrors at the top of the atrium which directs the light vertically twelve stories down (Figure 3).

The sunscoop system is like a periscope, offsetting and redirecting the rays of the sun so that they strike the interior of the atrium. The primary steps of this process are:

1. Outer mirror bank: The bank is optically a flat mirror positioned so that it reflects that portion of the sky through which the sun travels in a given day through the upper part of the level 11/12 space to the inner mirrors. To allow rotation to be about a true north/south axis to utilize normal technology, the mirror actually consists of 480 mirrored louvers arrayed in 20 banks of 24 each on the outer mirror structure.

2. Inner mirror bank: This is essentially a static convex mirror which redirects the beam downward and spreads the parallel beam coming from the outer bank. It is fabricated as seven cylindrical mirrors.

3. Blinds: These open and close sequentially to provide an aperture for light from the outer mirror to strike the inner mirror. Light from the outer mirror which, because of the east-west movement of the sun, misses the inner mirror is prevented from entering the building to eliminate glare and heat load. The entire wall of blinds closes on extremely cloudy, bright days when the image of nadir-sky would be glaring to occupants of level 11.

The computer controlled mirror system resulted in a general natural illumination in the atrium of 150 lux at the edges with a central maximum of 1,500 lux on a sunny day. A small computer was used to monitor the position of the louvers in each bank of 24 mirrors and to keep them within the required operating tolerances. Data for the desired position at any date or time is stored in the computer memory.

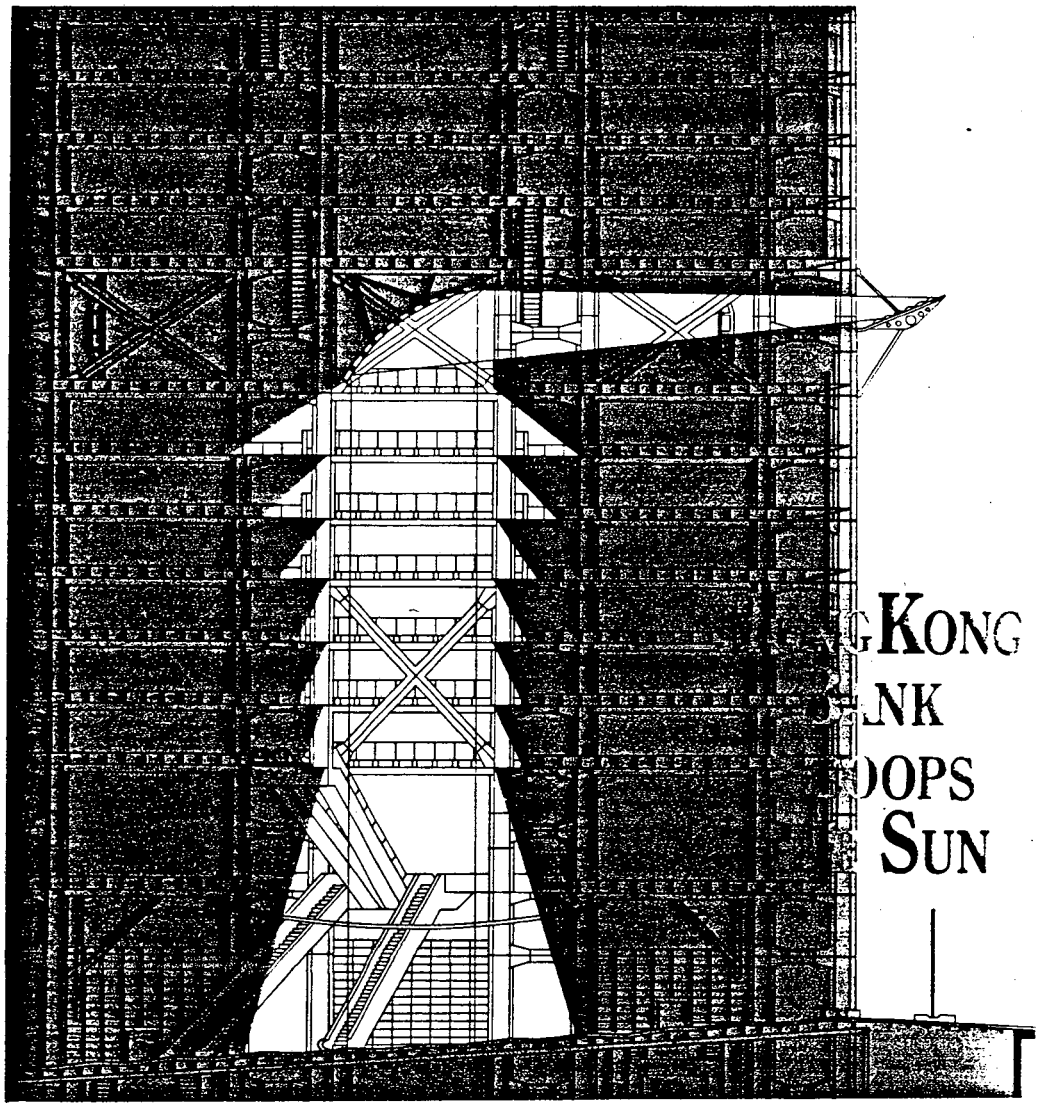


Figure 3. Section of the Hong Kong Bank showing the location of the sunscoop system (Ref. 8).

LIGHT TRANSPORT SYSTEMS

DESCRIPTION

Light pipe systems generally consist of three components: an outside heliostat, usually on the roof, to collect sunlight; the light pipe itself; and an emitter or luminaire which releases light into the interior space. There is strong relationship between the guide selection and collection/concentration optics. In this section we focus on the light pipes.

The most basic form of light transport is simply an empty shaft along which a collimated beam of light can travel. Light can be transported horizontally and vertically. In order for light that is not perfectly collimated to be transported efficiently over long distances, it must be guided without excessive optical losses.

The following are the most common used or proposed types of light guides because of good transmission characteristics (Figure 4):

- Prismatic tube or film (refractive ducts)
- Fiber optics
- Lens guides or collimating guides
- Reflective metal tubes or mirror ducts
- Acrylic rod
- Fluid filled tubes

The most basic form of light pipe is simply an empty shaft along which a collimated beam of light can travel. Except for lenses and reflective tubes, the other guides mentioned use the principle of total internal reflection. Solid guides of very large cross section, either of glass, plastic or even liquid-filled, seem impractical due to the weight and massive amount of material involved. The expense of fiber optics and acrylic rods and the unacceptable blue color emitted from water tubes narrows the option of using light guides to lenses, prismatic tubes, or reflective film.

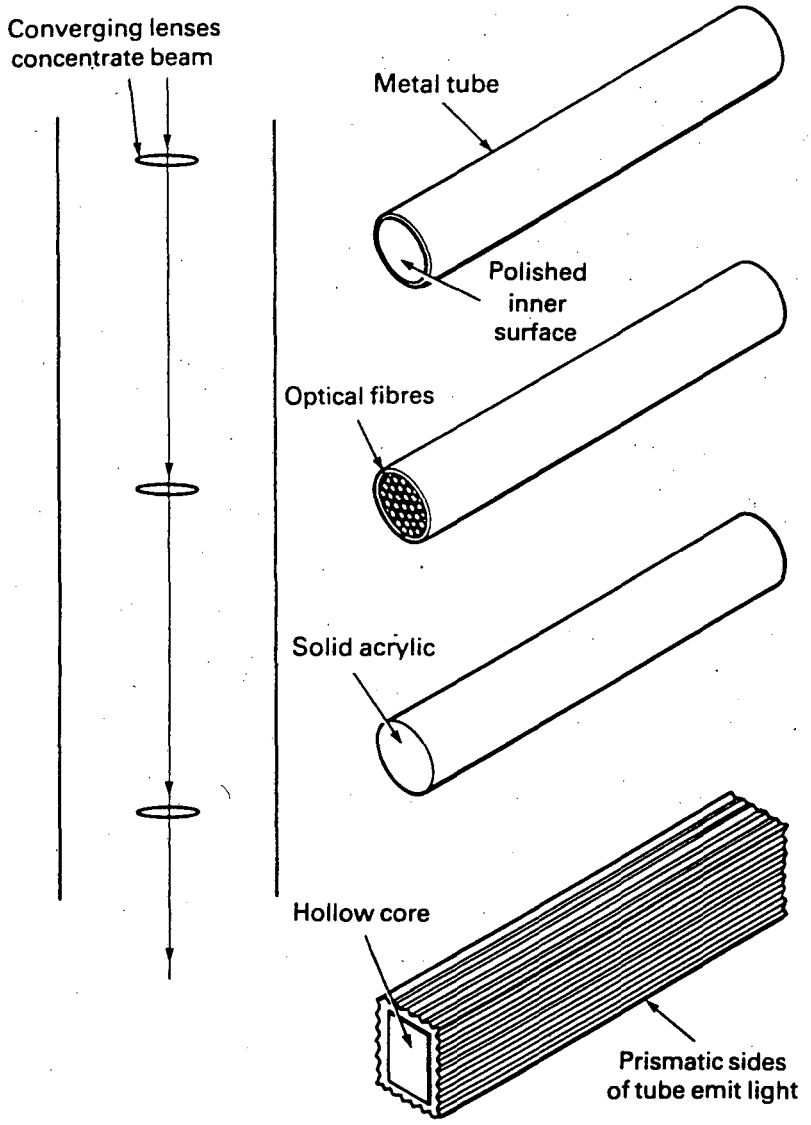


Figure 4. Various types of light pipes. On the left is a lens guide. On the right, from top: a reflective metal tube; a fiber optic bundle; an acrylic rod; and a prism light guide. (Ref. 9)

PRISMATIC LIGHT GUIDES

DESCRIPTION
Prism light guides are sealed, empty square or rounded-section ducts made of clear acrylic. Their inner surface contains precisely shaped prismatic grooves which cause total internal reflection, confining the light to the central airspace. Ideally all light is reflected but impurities in the acrylic scatter enough light to make the tube glow like a fluorescent lamp. In order for light to be transmitted by total internal reflections it must be introduced with a cone whose half angle is less than 26°.

There is currently only one product available in this category. The following pages discuss this one product.

PRODUCT PROFILE: TIR LIGHT PIPE

TIR Systems is the inventor and main distributor of prismatic light pipes which are commonly used for electric lighting. 3M extrudes the prismatic panel and the guide is fabricated under license from TIR.

STATUS OF AVAILABILITY
3M and TIR offer light guide elements as well as other optical components to allow the guide system to turn corners, extent light, etc. Although there are a number of standard components, most systems are custom designed at this time.

PROS AND CONS
Approximately half of the sun's heat can be removed by selective filters, resulting in a 'cool' light that does not add appreciably to air conditioning bills. The environmental conditions in remote or underground spaces may be improved by having natural ('full spectrum') light. The guide acts as both a conduit to transport light as well as a diffusing system.

COMFORT PERFORMANCE
With filters minimum cooling loads are added to the building, compared to conventional lights.

IMPACT ON BUILDING DESIGN
TIR Systems believe that the system is possible to be installed virtually anywhere, free of the requirements of a complex building structure to house it, electrical power to operate it, or highly skilled technicians to install it.

The system requires the following main components whose locations need to be planned in the building:
• Collectors: Sun tracking reflectors, concentrating mirrors and rooftop apertures.
Sun tracking mirrors are designed to move in the correct way so as to always reflect the sun's rays into a fixed direction toward the concave mirrors which concentrate and direct the sunlight into the vertical guides. An important design consideration is the extent to which the sun tracking mirrors should be protected from the weather.
• Vertical light conduits: These ducts sections use prism light guide wall material
• 90° Transition Units and Supplemental Metal Halide Lamps
• Horizontal distribution guides: The vertical depth of these depends on the architectural constraints of the building.

COST, PER UNIT BASIS
Very expensive at the present time, since each system is a custom prototype.

LIFE CYCLE COST ECONOMICS
There are three separate categories of potential savings. The first is direct savings in the energy costs of lighting, the energy costs for air conditioning and the maintenance costs for the electrical equipment associated with the lighting and air conditioning. Regarding to electric power billings, these savings will take the form of direct reduction in energy consumption, as well as reduction in peak load billing which results from the fact that the solar lighting is available during periods of peak heat load corresponding to solar loading during sunny conditions. Another operating savings lies in the ability of the owner of the building to charge more rent, charge a higher price in selling the building, or save in salaries due to the enhanced attraction of working in the building. These "human benefits" result from the perceived desirability of "natural lighting", and the psychological contact with the outdoors due to the variations in brightness and color of the outdoor light during the day.

Table 3 represents an analysis prepared by TIR based on the factors described above. The analysis represents a hypothetical building, about ten years from now (assuming volume manufacturing), in a region with substantial air conditioning requirements, and high solar availability. Other assumptions are that the solar light systems is operational 1500 hours per year, that a conservative electrical energy billing rate is $0.16 per kilowatt hour off-peak and $0.21 per kilowatt hour peak, with this peak period representing 50% of the time the solar system is operational, and additionally that there is $11 per month per kilowatt peak load billing. Regarding the "human benefits", there is an assumption that the billable rate for the rental space with the benefits of solar lighting is increased by 5%. The ratio of annual savings to net investment is 20%, without taking human productivity issues into account, and is 57% when the personnel and human factors in this example are taken into account.

TABLE 3
Economic Analysis for 1 kW Unit of Solar Lighting For a Potential Future Application (1990 US $)

Cost of collection optics	$2,500
Cost of vertical distribution optics	$1,250
Reduced capital cost A/C	$ (680)
Net capital cost	$3,070
Electricity savings	$ 363/yr.
Electrical peak load billing savings	$ 166/yr.
Maintenance savings	$ 92/yr.
Total "hard savings"	$ 621/yr. = 20% of net investment
Power outage labour savings	$ 380/yr.
"Human factors" savings	$ 760/yr.
Total savings	$1,767/yr. = 57% of net investment

MARKET SHARE, EXPECTED TRENDS

One can expect some reductions in component costs and large reductions in total system costs. However the overall complexity of the systems suggests that it will always be in the premium cost range.

The horizontal light distribution guides are a standard commercially available product, which is generally used in commercial or industrial settings with electric light systems.

CASE STUDY INSTALLATIONS

VICTORIA PARK PLACE, TORONTO

The system demonstrates sunlight collection, transmission, distribution and capability of integration with the artificial illumination system. Eight identical altitude/azimuth tracking heliostats form a collection array of flat 47 x 72 inch primary mirrors. Parabolic focusing stationary secondary mirrors concentrate focused sunlight through each 60 square inch glazed roof aperture. The entire collection network is sealed in a solarium isolating it from the environment and office spaces. The vertical transmission guide carries light from the solarium to the office one level below where prismatic light tubes serving both as a horizontal transport and light emitter. The light guides distribute light to 1,900 square feet. Four-hundred-watt metal-halide bulbs beam light into the light pipes when sunlight is inadequate. The $200,000 demonstration project was partly sponsored by the Canadian Department of Energy, Mines, and Resources. Mirrors beam the light into light pipes, which distribute it to offices. Each collector of approximately 4 ft. in diameter can illuminate 253 sq.ft. of office space well in excess of 1,280 lux.

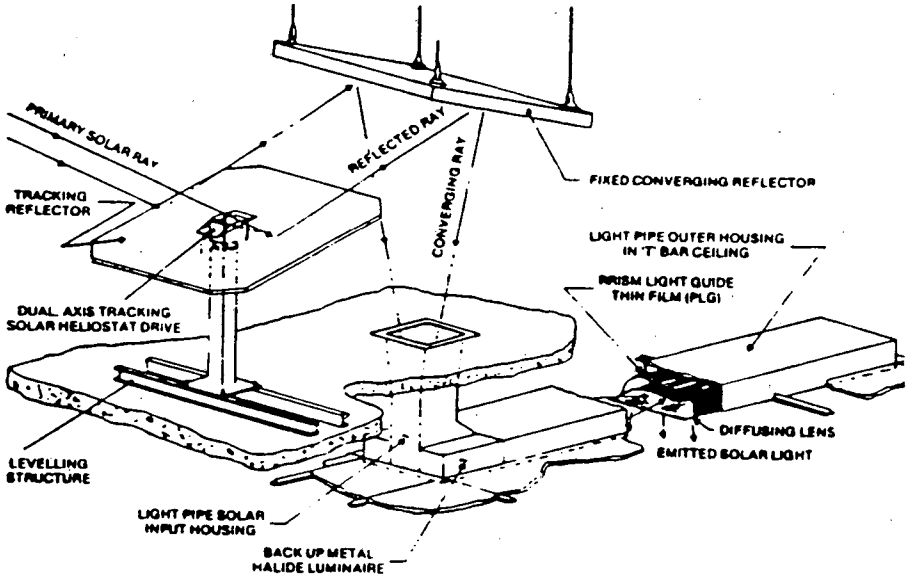
The building has been successfully operating for four years. The high precision mirror orientation devices required skilled personnel for installation. The cost of this experimental project should not be considered representative. The backup to each heliostat/light distribution system is by two 400-W metal-halide lamps controlled by photosensors. The illuminance averages 88 fc. at night and "well in excess" of 120 fc. in full sunlight.

MARKET LANE ELEMENTARY SCHOOL, TORONTO

A new project still under development by TIR is a four-story building which includes a school and a shopping center (see Figure 5). The goal is to provide solar light and backup electrical light in the lunchroom. This 1,035 sq. ft. area is located four stories below the roof of the building, and has very limited direct light access to natural light. Most of the students remain indoors during their lunch break during the cold winter months.

The rooftop collection system consists of four 22 sq.ft.heliostats which direct light onto four 18 sq. ft. concentrating mirrors which further direct concentrated light into the rooftop input aperture of four 41 ft. high, 2 ft. diameter vertical light conduits. Laboratory tests of the optical components demonstrate that the efficiency of this system will be 20.1%, that is, 20.1% of the visible light which was initially incident upon the heliostats is actually emitted by the horizontal guide structures. The horizontal distribution guides are also illuminated with backup metal halide light sources. Because these sources are located closer to the point of utilization, more of their light (45.1%) is utilized when solar light is not available.

Under full sunlight conditions, the expected illumination in the lunchroom will be 750 lux, and with no sunlight and all metal halide lamps on, the illumination will be 720 lux.



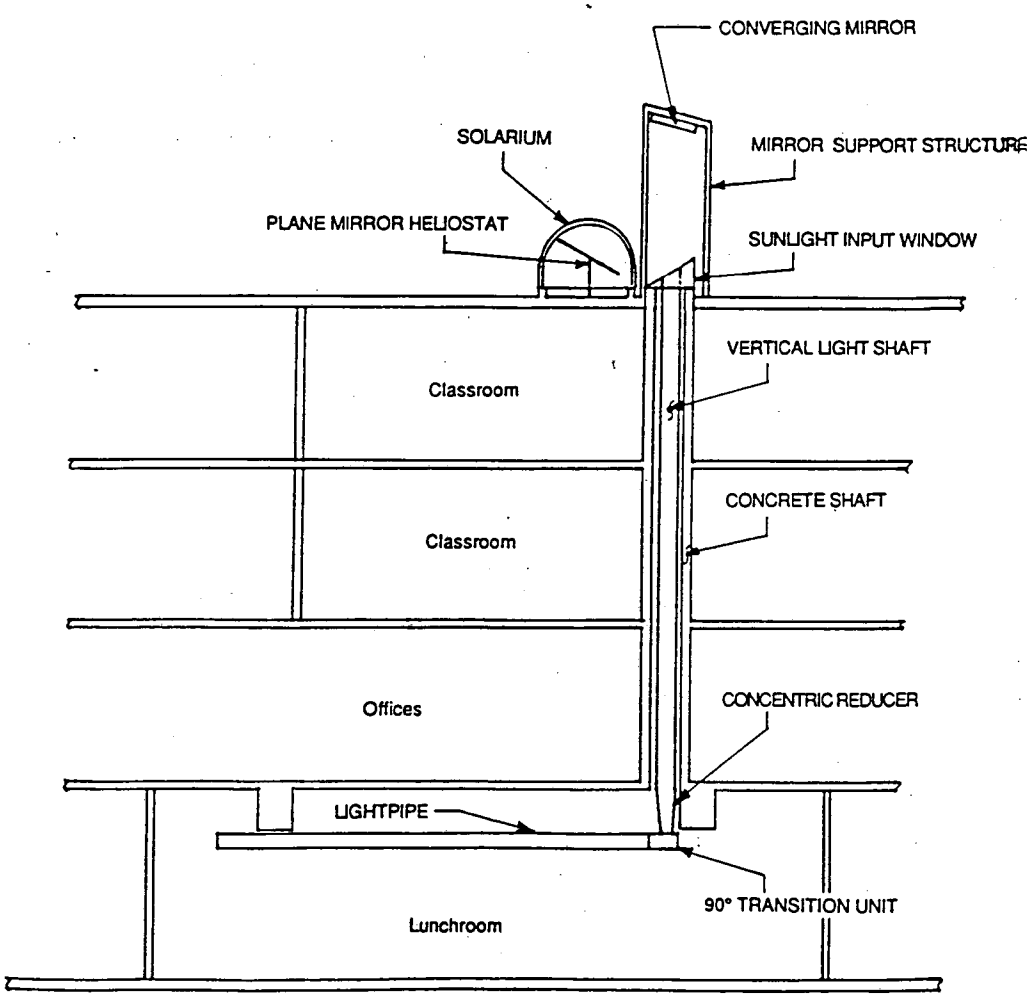


Figure 5. Diagram showing the heliostat and prism light guide system (top). System overview for the Market Lane Elementary School (bottom). (Ref. 13 and 15)

MIRROR LIGHT GUIDES

DESCRIPTION

Mirror light guides are devices that utilizes multiple specular reflection at the inner side of their walls in order to guide the light entering the input aperture to the output aperture. If the path the light has to travel is long compared to the diameter of the pipe, the number of reflections necessary is high, and therefore the losses depend strongly on the reflection coefficient of the material used, at least for light entering the pipe under high angles relative to the pipe's axis.

The efficiency of a light pipe thus depends strongly on the ratio of length to effective diameter, which is the projection of the average distance between two successive reflection points onto a plane perpendicular to the light pipe's axis. This ratio depends not only on the input area of the pipe but also on the geometrical form of the cross-section and, for certain geometries, also on the input coordinates of the light rays considered.

CASE STUDY INSTALLATIONS

STUDENTS' LIVING QUARTER STUTTGART-HOHENHEIM, GERMANY

This complex is a demonstration daylighting system that comprises six buildings, 2 to 4 stories high (Figure 6). The northern rooms have little daylight, the only light sources being light transmitted through the glass roof over the staircase, through the glass doors of the students' rooms (if not darkened by shutters or curtains) and through the entrance door. After several discussions, it was proposed to build a system which would collect the light near the glass cover of the staircase and then reflect it into the darkest kitchen, about 20 feet below the roof.

The mirror light guide installed is of equilateral triangular cross-section (with side length about 2'4") made from Alucobond material (aluminium laminated onto plastic) which is covered with 3M Silver-lux (R=95%) film on the inner surface. The system has light transmission efficiency of .23 (measured) for diffuse light. The output mirror has a special shape in order to reflect as much light as possible into the kitchen to be illuminated. The total output of the light guide depends on the weather conditions. For direct radiation, the efficiency also depends on the position of the sun but will be relatively high. A large fraction of the light leaving the pipe is lost at the walls of the staircase, and in addition, at one of the pillars bearing the staircase, which is located just in front of the output aperture (this problem would not exist, if the original plan to build the light pipes directly above the kitchen tables had been carried out). Each pipe provides electricity savings of 400 kWh/y compare to incandescent lamps and 50-100 kWh/y compare to fluorescent tubes.

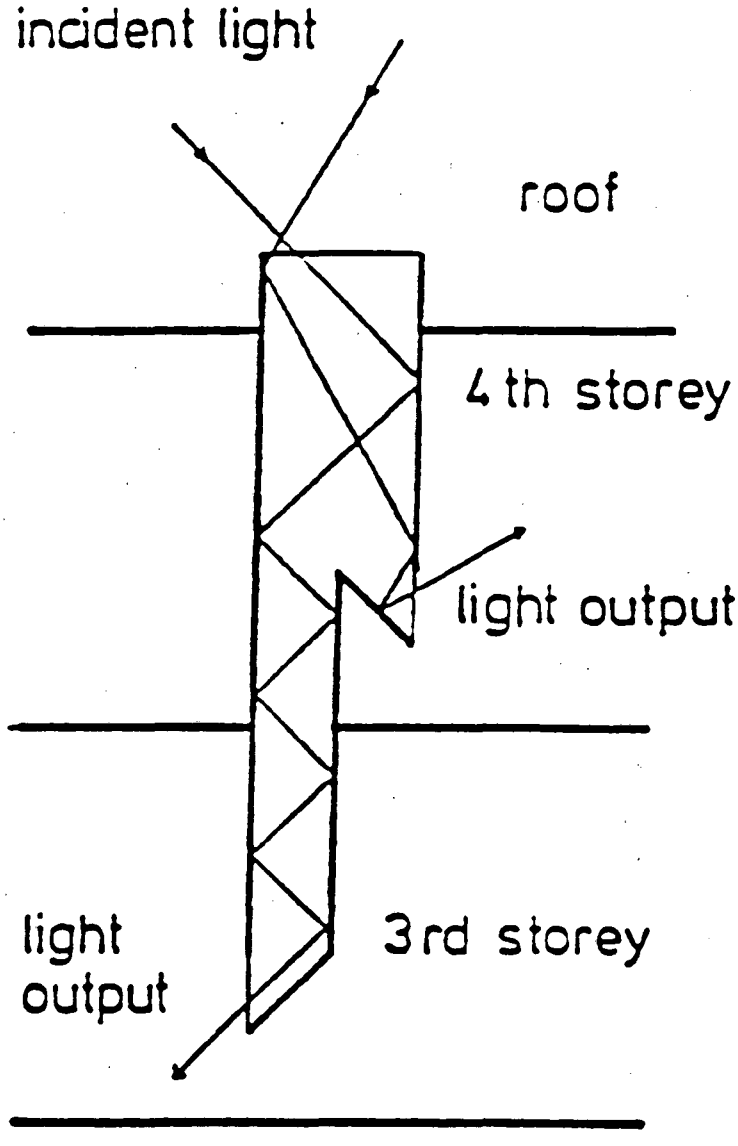


Figure 6. Daylighting systems on the basis of mirror light pipes. (Ref. 16)

LENS LIGHT GUIDES

DESCRIPTION

The lens light guide is an arrangement of lenses in which each individual lens projects an image from the preceding lens to the following one. By using the lenses to keep the light source moving from source to target, a walled guide structure is needed. The details of the optical design of the lens system would vary with many design parameters.

CASE STUDY INSTALLATIONS

CIVIL MINERAL ENGINEERING BUILDING, MINNESOTA

BRW Architects, Inc. an architectural firm based in Minneapolis, Minnesota had responsibility for the architectural design. Working with Dr. Duguay, the design team applied the principles of the lens guide system he was using to transmit remote images to interior spaces. Sunlight is caught by a heliostat on the roof and beamed through lenses to a working space 110 ft. (35.5 m.) below the ground. The environment on the underground space is improved by having natural, full spectrum lighting, it is claimed.

This building illustrated the concept of beaming and guiding light through a restrictive shaft. Sunlight is collected, then concentrated, and directed it through a shaft in the building via an assembly of lenses and mirrors (Figure 7). The final product includes a glass cupola which protects two heliostats from the elements thus enabling the production of a low cost heliostat operated by a Hewlett-Packard 41 CV calculator. Each 6 sq.ft. heliostat, costing approximately $6,000 and drawing 1.5 W of power, delivers approximately 10,000 lumens to a public receiving area. This was accomplished through the use of existing vertical shaft space in the building. The system fulfills its mandate as a public demonstration by relocating the sun deep in interior spaces and as a functional amenity by providing psychological relief to people physically isolated from the sun. The system is not, however, a cost effective energy saving strategy.

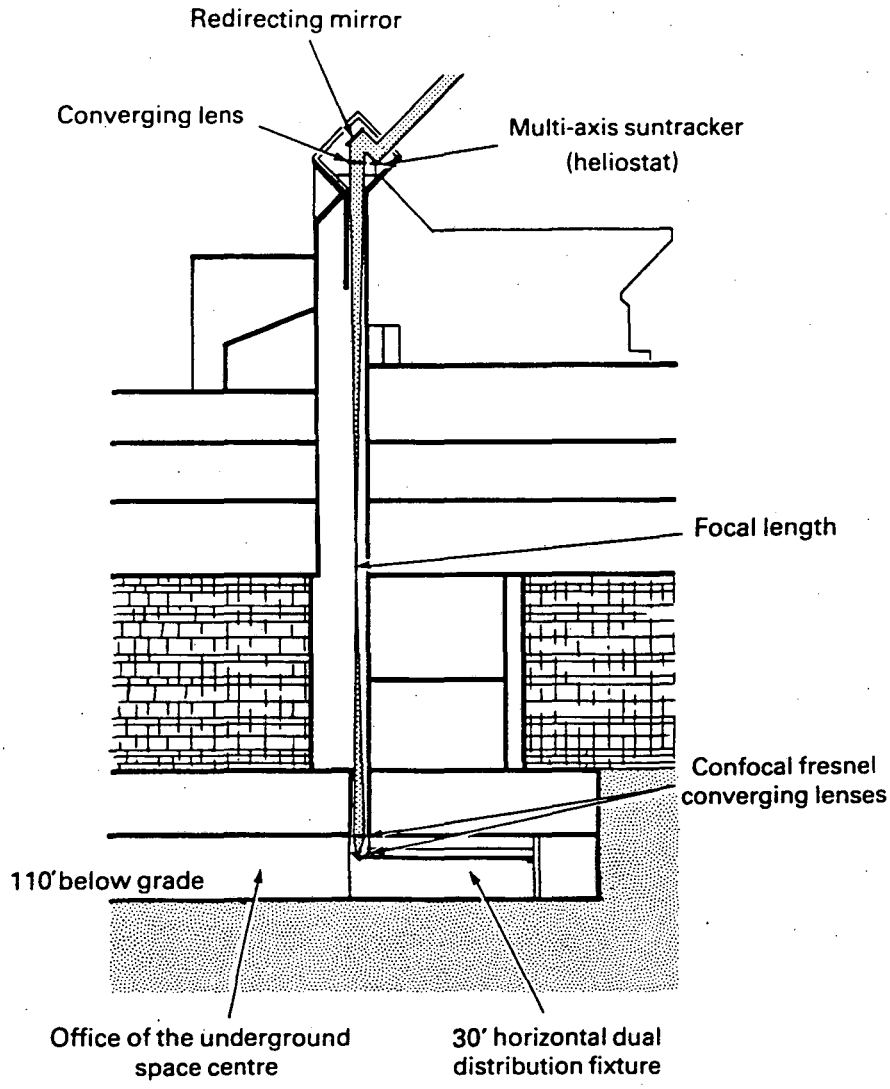


Figure 7. Lens light guide system at the University of Minnesota. Tracking mirrors on the roof direct sunlight below ground to illuminate an underground space. (Ref. 9)

FIBER OPTICAL DISTRIBUTION

Fiber optic cables transmit light through a thin solid fiber with high efficiency by total internal reflections. There is currently only one known commercially available system, made in Japan by La Foret Engineering. It consists of a hexagon-shaped honeycomb-patterned Fresnel lenses collector (concentrating, altitude/azimuth tracking) that filters and focuses light to fiber-optic transport cable. The quartz based fiber optic cables transmit light to specialty lighting applications that benefit from filtered light with good color rendition. The systems are very expensive.

PRODUCT PROFILE: HIMAWARI ("Sunflower")

La Foret Engineering Inc.(Tokyo, Japan) has developed a unique system that collects solar radiation using tracking Fresnel lenses and transmits the collected rays over a fiber cable to any desired place. The system is known as *Himawari*, which means "sunflower" in Japanese. Light enters the collection system through a protective transparent acrylic sphere. Inside the sphere, hexagon-shaped, honey-comb-patterned Fresnel lenses focus incoming light rays onto the highly polished input ends of fiber optic cables. These pick up the concentrated sunlight and deliver it to the rooms below (Figure 8.) The Fresnel lens concentrates light by a factor of 10,000.

Each Fresnel lens focuses light to a 4-milimeter cable coupled to the lens. Each fiber-optic cable consists of bundles of 19 to 37 fibers, depending on the size of the system, each fiber being 0.5 mm in diameter. The light-conducting fiber optic cable is similar to a telecommunications cable in that the core of the cable consists of quartz glass fibers, but the quality and composition of the cable differs. A wide variety of light output fixtures are available according to the interior location and type of task.

A microprocessor-controlled tracking system keeps the lenses trained on the sun throughout the day and returns the sunflower to face the sunrise after sunset. The sensor sends information to a small internal computer, which directs the movements of the lens array inside the capsule. Tracking is accomplished by pulse motors that move the lenses in azimuthal and horizontal directions. When the sun is too obscured for the sensor to register its light, a backup clock-controlled mechanism engages, and the Himawari estimates the position of the sun and tracks it accordingly. When the sun reappears, the Himawari is trained on it, or near enough to allow the sensor to make the final adjustment.

STATUS OF AVAILABILITY
Currently the Himawari is produced in Japan by La Foret Engineering Inc. Sumitomo Corporation of America at Los Angeles is the U.S. distributor of the Himawari.

PROS AND CONS
Fiber optics' advantage over light pipes is its easy installation in ducts and absence of mirrors at bends. Fiber optics bundles can have very good transmission characteristics but tend to be extremely expensive. The cables can be wired like common electrical outlet wiring so that fixtures can be plugged into lighting outlets.

Himawari provides effective and safe lighting facilities in places where explosives are present, or in other special applications where nearly full spectrum light is needed.

The Himawari is not intended as a primary lighting system, but is best used for supplemental or specialized illumination. As an ambient lighting supplement to electrical lighting, this system is extremely expensive. Its use is mainly in accent, specialty lighting.

ENERGY PERFORMANCE
The tracking system and associated hardware will require maintenance. The system requires energy to track the sun. The ratio of energy input to energy output improves as lenses are added to the system.

Number of lenses	Tracking Power	Light Equivalent
Single lens	60 watts or less	100 watts
Seven-lens array	150 watts (max.)	700 watts
19-lens array	180 watts (max.)	1900 watts

Actual energy output and luminous intensity will vary greatly depending on location, time of day, and the distance that light must travel through fiber optic cables. According to these numbers the system provides more energy than it consumes. Light collected by one lens and transmitted through 130 feet of cable is equivalent to that produced by a 100-watt quartz-halogen bulb.

Light Utilization Efficiency of Himawari:
120 ft. over 30%
300 ft. over 20%

However, if a better quality (but more expensive) fiber cable whose transmission loss is 15 dBm/km is used, the transmission distance can be extended beyond 1 kilometer.

COMFORT PERFORMANCE
Most of the sun's ultraviolet and infrared radiation is filtered out by the acrylic bubble and by the focusing characteristics of the Fresnel lenses.

IMPACT ON BUILDING DESIGN
The system is quite "visible" as the size vary from 1.70 ft. dome diameter to 5.35 ft. diameter with a weight of 28 to 1,322 pounds respectively. This variation depends on the number of lenses ranging from 18 to 196. Himawaris need to be carried to and installed on roof, balcony, or any other suitable space exposed to direct sunlight year-round. Fiber optic cables require a minimum duct area compare to other systems, only 0.011 sq. ft. or 1.5 sq. in. which can be easily routed within conventional walls and ceilings.

COST, PER UNIT BASIS
The Himawari system is costly. A home-size system (with one collector of 18 small lenses) sells for about $10,000 in Japan A full-size system (with a 196-lens collector) costs around $200,000. Prices in U.S. are about 30% over Japanese prices.

LIFE CYCLE COST ECONOMICS
The Himawari system currently suffers the fate of other new technologies: high production costs and low marketplace competition. The cost of the fiber optic cabling itself can account for as much as half the cost of the system -or more, depending on how much cabling is required. There would appear to be little hope of lowering the cost to the point where it would compete for general lighting.

MARKET SHARE, EXPECTED TRENDS
As the costs for the system are intrinsically high its promising market will be a niche market where premium costs can be justified for an unusual effect.

CASE STUDY INSTALLATIONS

Currently, nearly 100 Himawari systems are in use in private homes, museums, office buildings, hospitals, schools, resorts, and nursing homes, all of them in Japan. Some of these examples are: Kofu Station Building at Kofu City, Tsukuba Expo '85, Ark Mori Building at Minato-ku. Sumitomo Corporation of America have installed two Himawaris in U.S.: one in the Environmental Research Laboratory at the University of Arizona at Tucson, and the other one to Boeing Aeronautics. Both are used for demonstration purposes only.

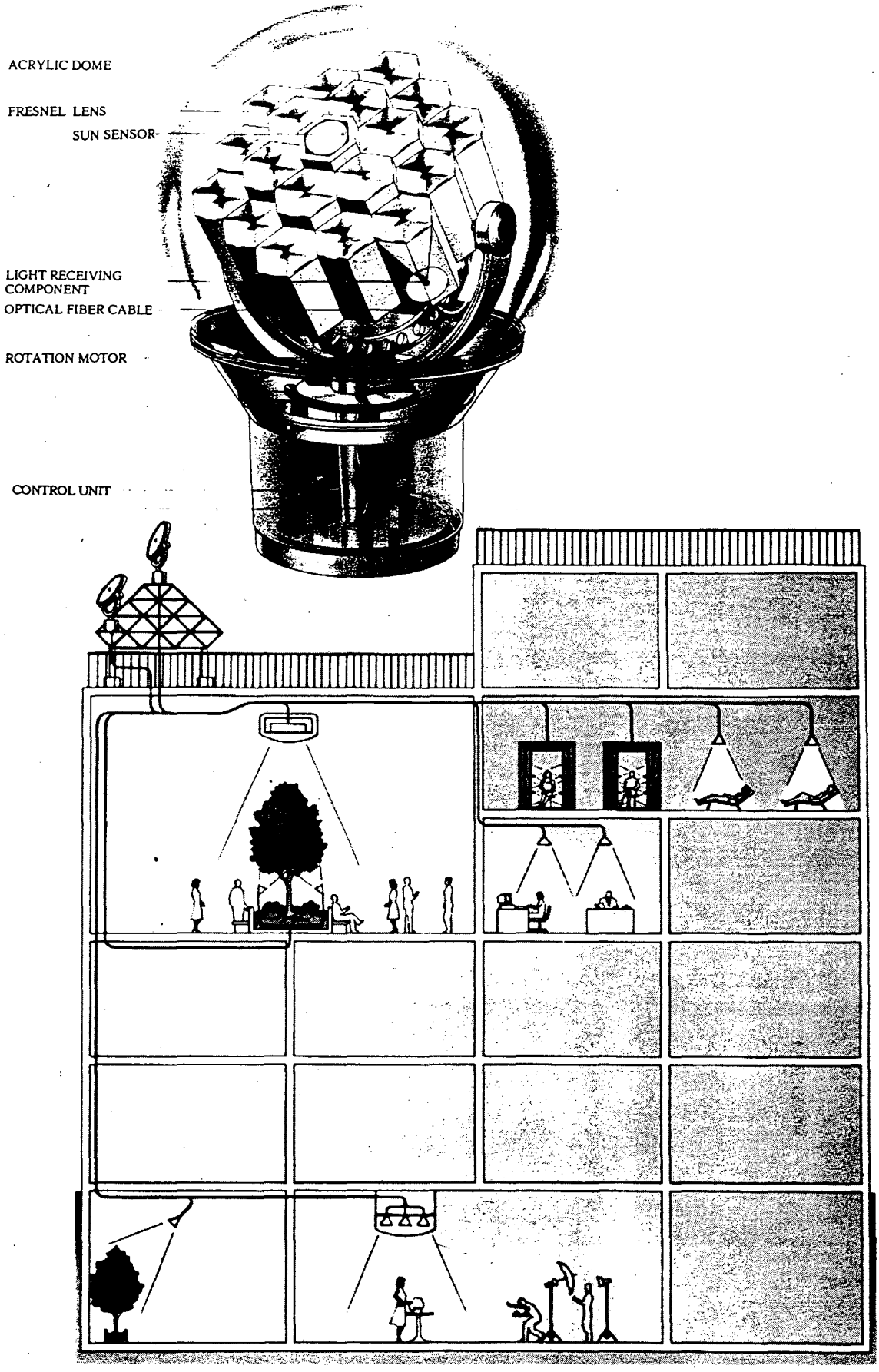


Figure 8. Himawari light collection unit (top). The Himawari's fiber cables can transmit the light of the sun anywhere it is necessary (bottom). (Ref. 6)

LIGHT SHELVES

DESCRIPTION

A light shelf is a horizontal or near horizontal baffle positioned (usually above eye level) to reflect light onto the ceiling off its top surface, and to shield direct glare from the sky. Much of the interest in light shelves springs from their assumed ability to project daylight deep into the building core, beyond the normal daylighting perimeter of the building and beyond the normal penetration from the shelfless apertures. In addition light shelves can reduce cooling loads caused by solar gains and can improve visual comfort in a space.

Geometry

Light shelf configurations can generally be classified as interior, exterior, or combined. An interior light shelf extends from the plane of the aperture into the space. An exterior light shelf extends from the plane of the aperture away from the space and projects outside the building although it may be enclosed. A combined light shelf is an exterior and interior light shelf, in one unit.

Light shelves can be horizontal, and tilted outwards or inwards. An outwards tilted light shelf will improve shading, but less light will be reflected onto the ceiling, while an inwards will increase daylight penetration, but give poorer glare control.

Optically-treated light shelves

The performance of a light shelf varies with the reflectivity of the shelf's upper and lower surfaces, and with the glazing type used. Specular reflectors are often used on the upper surface of the light shelf; however, a specular surface can be a source of glare, as can the bright band of light it reflects into the space. In most instances, specular surfaces that are in the field of view or that reflect a band of light into the field of view should be avoided. Modified specular surfaces, e.g., brushed aluminum, produce some diffusion of the reflected light. White diffuse surfaces will provide light in the proximity of the shelf but will not push light deeper into the space. Recent advances in coupling a refractive plastic surface texture to a specular coating result in a material with a good compromise between the specular and diffuse extreme cases. 3M produces several types of reflective films suitable for light shelves. Some of them reflect light specular similar to mirrors, while others have some dispersion. The 3M reflective daylight film with linear grooves spreads light within 10°-12° angle.

Tracking systems for light shelves

Moveable light shelves can be designed to be adjusted seasonally for low and high sun angles or even on hourly basis.

SOURCES

Light shelves are not standard architectural products. They are typically designed and built as part of the building facade. Surface treatments can be purchased commercially as noted below.

PROS AND CONS

Studies in scale models have shown that daylight factors throughout a space with light shelves were less than for an unshaded window of equivalent height. But with the light shelf the available daylight was more uniformly spread, improving the visual conditions in spaces, especially near the window. Claims of producing high illuminance levels deep in a space have been generally unfounded.

An exterior light shelf will shade the outside of the window, reducing solar gain to the room, and collect more high altitude summer sun. An interior shelf provides better visual protection from sun glare at intermediate depths within the room. Comparing a diffuse to a specular surface in a light shelf, the latter one improves daylight penetration deeper into the space.

Specular surfaces need to be cleaned more often in order to maintain their reflective properties. Maintenance in general can be a problem with light shelves. An internal shelf acts as a dust trap, while an external shelf can collect dirt, or become a nesting place for birds or insects. The deeper the light shelf the more difficult cleaning will be.

Shallow light shelves, allow low altitude winter sunlight to pass straight through. This may cause glare problems for people at the rear of a large room, in which case additional shading will be required, i.e. baffles.

One of the major problems with light shelves is that they require a high ceiling in order to work effectively in moving light deep within a space.

IMPACT ON BUILDING DESIGN
Light shelves should be above eye level to avoid reflected glare, and should be designed to block direct sun coming through the clerestory window at all times. A light shelf of practical dimensions would allow sunlight to pass directly over it in winter. The deeper the light shelf the less of a problem this will be, but deep light shelves allow less daylight through into the interior at other sun angles.

COST, PER UNIT BASIS
Highly variable.

PRODUCT PROFILE: VARIABLE AREA LIGHTING REFLECTING ASSEMBLY (V.A.L.R.A.)

DESCRIPTION
VALRA is a tracking light shelf system that reflects light into a building at the south elevation or the roof with open air space as its transport. The system utilizes both direct and diffuse sunlight contributing to the building's primary lighting. The system uses a reflective plastic film surface as a collector over a tracking roller assembly within a fixed light shelf (at elevation) or fixed scoop (at roof). Glazing at the exterior and interior sides of the collector provides environmental and thermal isolation and helps keep the surfaces clean. Light beamed from the collector is reflected off of the ceiling at a low angle to illuminate the room. This operable system extends the projection capabilities of a typical fixed light shelf or sunscoop so that it operates more efficiently under all incident sun angles. The nature of collection and mounting limits the effective beam transmission to a length of about 30 feet. See Figure 9.

Although, prototypes have been built this system has not been installed to date. A simple payback period for the VALRA based purely on energy economics, is said to vary between about 3 years and about 20 years, depending on the climate, the ratio of collection aperture to floor area being illuminated, the enhancements employed, the building type, and the utility rate structure.

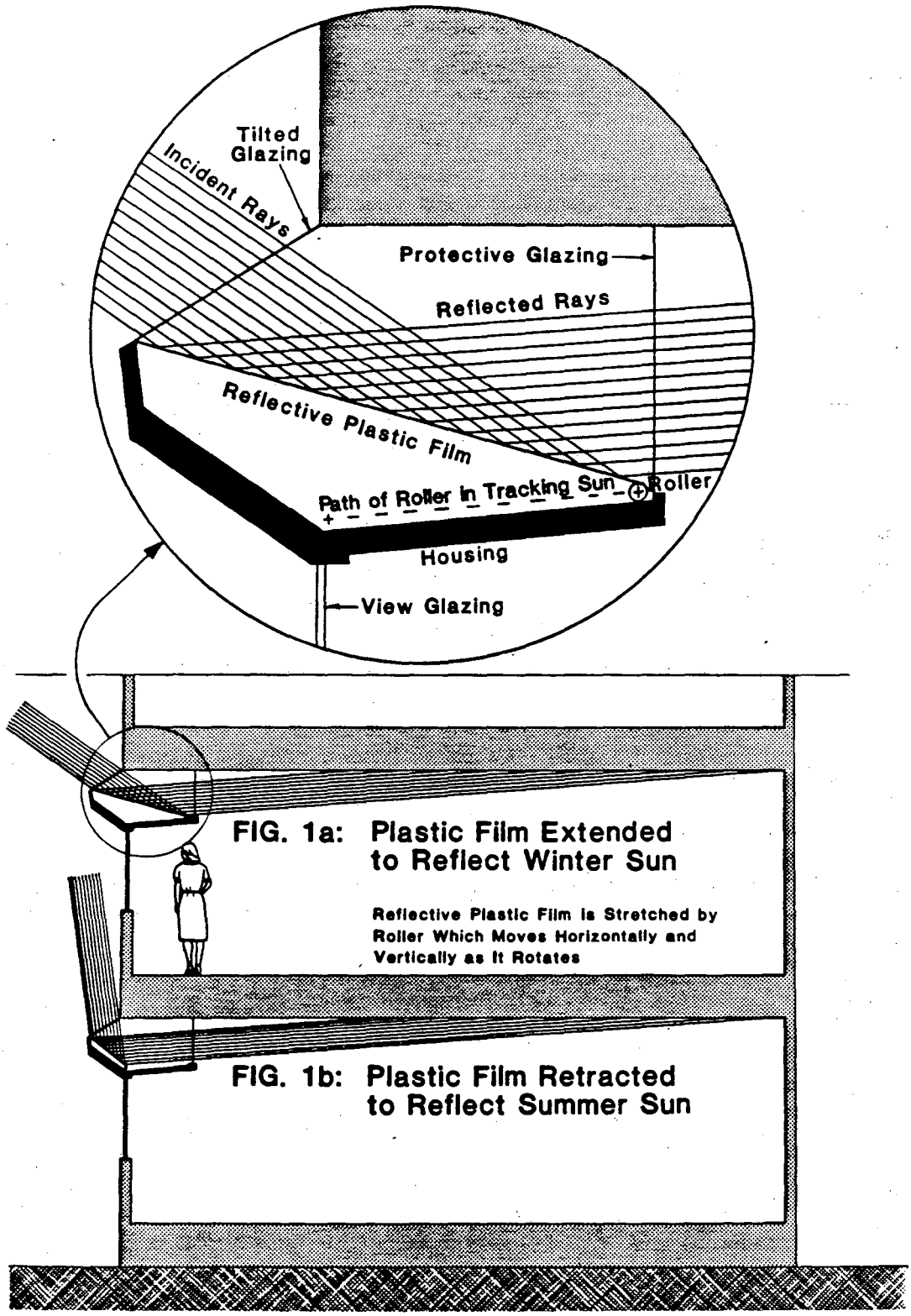


Figure 9. Winter and summer operation of the V.A.L.R.A. (Ref. 7)

REFLECTIVE LOUVERS - Fixed and moveable systems

DESCRIPTION
Reflective louvers stop direct sunlight from entering a space and striking the occupants and instead redirect it onto the ceiling of the room. The geometry and surface reflectance properties of the louvers will influence the distribution and intensity of the reflected light on the ceiling. The aim is to improve penetration of light deeper within the space. Horizontal louvers are best suited to south facing windows. There are trade-offs between the simplicity and lower cost of fixed systems vs. the improved performance of operable systems.

PROS AND CONS
Louvers tend to block the view out, so they are often installed only on the top part of the glazing. The other problem is maintenance, especially where highly reflective or silvered surfaces are used, or where automated systems are used. In this respect, internal louvers are better than external, but have less ability to catch sunlight as they are partially shaded by the window reveal. Louvers can be viewed as sun control blinds that have been modified to admit more daylight.

Studies of venetian blind usage suggest that people do not consistently adjust conventional shading devices. A daylighting system needs either to be fixed (in which case the previous guideline may be hard to achieve), automatically controlled, or adjusted by maintenance staff at a few critical times a year.

SOURCES
Pella had developed prototype systems in the mid 1970's but felt that the paybacks at that time for automated systems would not justify the investments.

Synertech Systems Corporation (Syracuse, NY) developed a prototype louvered window screens designed to reflect light into the building. The fixed micro-louver is constructed of reflective aluminum and is installed on the interior of a window, or between two layers of glass for ease of maintenance and assurance of cleanliness. Because of its small size and scale, views to the outside are still possible, but glare is said to be controlled. As a device, it offers little chance of user error, has no moving parts to break down, but will operate most effectively over a limited range of sun angles.

STATUS OF AVAILABILITY
Some reflective-blind installations have been noted in Europe. In U.S. most of prototypes mentioned above are still seeking a manufacturing/marketing partner to bring their products to market.

FIXED LOUVERS
The main problem with fixed louvers is that they only work optimally for a limited range of solar altitudes. At higher solar altitudes not all the light will be reflected directly onto the ceiling, but onto the louver above where it is either absorbed or reflected downwards forming a potential glare source. Worse still is the problem at low solar altitudes when stripes of sunlight penetrate the louver screen with unpleasant visual consequences.

MOVEABLE LOUVERS
A simple pivoting louver system can prevent sun penetration but cannot be optimized for light transmission at extremes of solar altitude. For example, at high sun angles louvers are wider than needed so that a lot of internal reflection occurs between them, wasting the available

sunlight and creating reflective glare. Motorized systems tend to be costly compared with the simple reflective blind.

IMPACT ON BUILDING DESIGN
Most of the sidelighting systems work by using the ceiling as a secondary diffuser of light. Thus, the ceiling needs to be a light colored as possible. Almost all sidelighting systems require a fairly high ceiling for deeper penetration of light into the space.

REFLECTIVE SILLS AND SCOOPS

DESCRIPTION
A reflective window sill is another inexpensive system where sunlight striking the sill is bounced onto the ceiling to be reflected onto working areas. This is a potentially very low cost item if the sill was already intended to be part of the architectural design. They will generally not provide deep light penetration.

Glare becomes a major difficulty here, because at certain circumstances sunlight can reflect straight into the eyes of occupants. Low sun angles could reflect glare into the space (early morning and late afternoon). Sills will brighten the window surround, which reduces the contrast between window and adjacent wall.

PRISMATIC PANELS

DESCRIPTION
The prismatic panels work on the principles of both reflection and refraction to enable the use of daylight inside buildings in a more controlled manner. The system can be designed to reflect light coming from a certain angle and transmit the light coming from other angles. In other words, they have a cut-off range and a transmission range. The cut-off range prevents the transmission of direct sunlight into the interior, thus providing some sunshielding effect. In the transmission range, the optical refraction of the prism changes the direction and intensity of the transmitted light. At the same time, this light becomes controllable and can be directed up towards the ceiling in the interior. As a sunshield direct sunlight is kept out and only vertical light from the sky is admitted into the room.

These daylighting systems are being promoted as a means of improving visual comfort while reducing electric lighting and cooling loads in perimeter zones. In concept, these panels are configured to reject sunlight and solar heat gain while selectively directing cooler zenith skylight toward remote interior surfaces, usually via a highly-reflective configured ceiling system.

PRODUCT PROFILE: SIEMENS PANELS
Siemens (Germany) produces several types of prismatic panels for sidelight or roof windows. See Figure 10.

AVAILABILITY
Siemens is not distributing its products any more in the U.S. since 1989. The product is being sold in Europe.

The design of the prismatic panels varies depending on the application and particular position on the building. They can be used for:
- sun-screening and/or optical control
- moveable or fixed
- sidelight or overhead light

PROS AND CONS
They can utilize skylight as well as direct sunlight. They avoid disturbing glare from direct sunlight and the sky. However the panels themselves can become a glare source. They can reduce the luminance of windows to values prevailing in the interior and acceptable at VDU workstations. The panels require coordination with the facade design but can also be fitted on existing buildings.

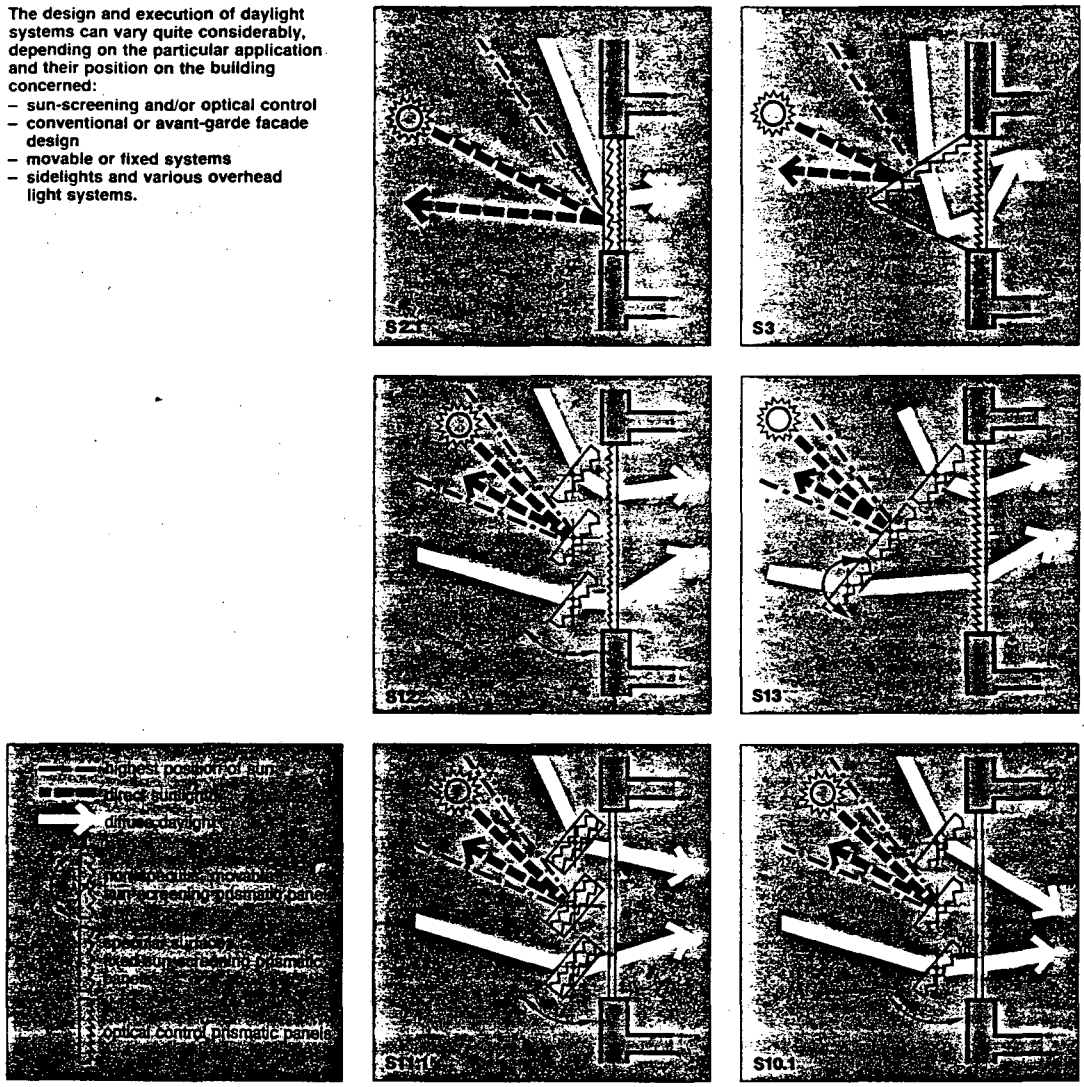
Allow lower room temperatures to be maintained in summer and/or reduce air-conditioning costs due to the lower solar heat gain.

Window prism panels may project "rainbow" reflections, under direct sunlight, onto side walls as well as reflective ceiling surfaces. These may be annoying in some situations.

ENERGY PERFORMANCE
The manufacture claims comparative studies between a room with clear glass and a fixed prismatic panels have shown an improvement of 30% more daylight in a room under an average sky and a 135% more daylight during clear days. They distribute natural daylight more evenly throughout a room, during overcast and clear sky conditions. Energy costs for lighting are reduced in about 30% considering a maximum operating time of 2500 hours/year.

The design and execution of daylight systems can vary quite considerably, depending on the particular application and their position on the building concerned:

- sun-screening and/or optical control
- conventional or avant-garde facade design
- movable or fixed systems
- sidelights and various overhead light systems.



Glazing and clear glass windows are not shown

Figure 10. Siemens' Sidelight Prismatic Panels (Ref. 12).

COST, PER UNIT BASIS

The cost of the Siemens system is considerably higher than more conventional systems. However, some of this cost may be offset by savings in the cost of the building air-conditioning system, and also from the potential energy savings from both air-conditioning, and lighting running costs. As a standard product made from a thinner laminated plastic the costs could potentially be much lower.

CASE STUDY INSTALLATIONS

Several buildings have been built in Europe using these prismatic panels (made of acrylic plastic) manufactured by Siemens AG, but limited evaluation studies have been performed.

THREE BANK OFFICE BUILDINGS, GERMANY

In each of these buildings prismatic panels were located in the upper window areas while leaving lower areas clear for view. The intention of the panels in each case was to reject direct sunlight and solar heat gain while admitting and directing zenith luminance toward highly reflective interior ceiling surfaces. Each system included two prism panels. The exterior panel was either fixed, or moveable, permitting adjustment to the current position of the sun, while the interior panel was always fixed.

The project concluded that further study is needed to verify the benefits of this system as claimed by the manufacturer. The prism panel/vision panel concept needs to be carefully designed and applied in order to benefit visual comfort while reducing the need for electric lighting in office workplaces. Local lighting conditions may actually exaggerate and thereby complicate interior luminances provided by this system, such as in the west sides of buildings. If the prisms are shaded from skylight, there will be negligible daylight to be distributed onto remote ceiling surfaces. Window prism panels may project "rainbow" reflections, under direct sunlight, onto side walls as well as reflective ceiling surfaces. These may be seen as pleasing or annoying, such as in the reflected view of VDU tasks. Field studies of existing prism panel installations are recommended before considering them for use elsewhere. Window prism panels should be tested in full-scale before final design decisions are made.

REFRACTIVE DAYLIGHTING DEVICE

DESCRIPTION
Researchers at the Queensland University of Technology in Australia are developing a new design for a daylighting device that could be permanently mounted in a window to redirect sunlight towards the ceiling in a room over a wide range of sun elevations. The basic component of the device is a single solid section of dielectric material with a sloping curved base and a v-shaped trough as the top surface. See Figure 11. The individual sections stack together to form the module, creating an enclosed air gap between each section. The angles are such that light entering a section is redirected by total internal reflection, remaining always within the dielectric until emerging generally in an upward direction.

PERFORMANCE
Some scale model and full size room tests have been conducted. Model results show typical light enhancement factors of 4 to 6 times for all angles of incidence through the back half of the room, with some values approaching 10 times in rooms of about 30 feet deep. Light levels were measured over 40 fc. all through the room indicating that under these conditions little or no artificial lighting should be required in the room for many general office tasks.

STATUS OF AVAILABILITY
This device is still under development and could be available in the market probably in about a year.

PROS AND CONS
At most incident angles sunlight striking the window is redirected as required into the room without the panel needing to be tilted or adjusted in any way. A small fraction of the light escapes downward, creating potential glare conditions.

The device is preferably placed in the top part of the window for two reasons. Firstly, the majority of redirected light would stay above head height for people in the room, thus reducing the possibility of glare. Also, by the nature of its action the daylighting device is not uniformly transparent and will severely distort the view through it. Secondly all downward and horizontal vision out through the conventional window would be retained, with some upward vision through the refractive device still possible from points near the window.

The device has a simple external profile similar to a pane of glass. With no external dust collecting crevices it could be easily cleaned. Also, the device can be butted against an existing pane of glass or sandwiched between two glasses surfaces for protection and extra thermal insulator if required.

COSTS
In commercial use it is anticipated that the modules would be 3/8" to 5/8" thick. An estimated cost of the modules is $6 to $7 per sq. ft without frame. Assuming energy savings from lighting alone of only 30%, calculations indicate a payback period of the order of 2 years for commercial applications.

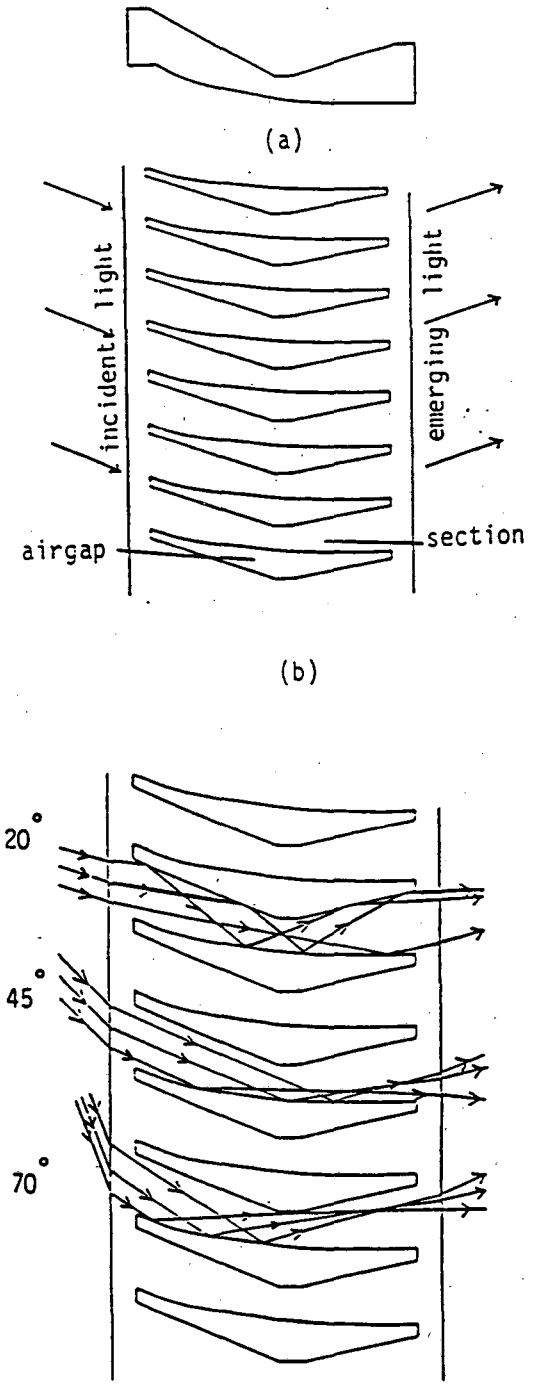


Figure 11. Top: Profile of the daylighting device showing (a) a single section and (b) the resulting module. Bottom: The path of rays through the device for sun elevation angles of 20°, 45°, and 70°. (Ref. 4)

LIGHT CONTROL PANELS

DESCRIPTION
A laser cut light deflecting panel is under development at Queensland University of Technology in Australia. This product consists of a rotatable acrylic panel which can either reject light in one position or deflect incident daylight to the ceiling of the room while maintaining viewing transparency. The window panel may be fixed vertically or maybe tilted to deflect light deeply into the room. The laser cutting of acrylic plastic provides a precisely formed light deflecting slat. As the laser cuts by melting, the internal surfaces formed are very smooth ensuring efficient light reflection by total internal reflection. The precision and flexibility of programmable laser cutters allows production of deflecting panels with the same thickness as conventional glass window glazing and in any size or shape. See Figure 12.

At near normal incidence the rectangular geometry and fine laser cuts (< 2 mm) provide transparency similar to a venetian blind maintaining adequate contact with the outside. Some possible applications are:

- Adjustable louvered or hung windows
- Skylights and atria
- Windows that face tall buildings in close proximity, thereby blocking the lower part of the sky.

A fixed vertical panel can provide approximately twice the illumination deep in a room as a conventional plane window. The view through a vertical panel is adequate to maintain visual contact and glare is similar to that from a conventional window. The greatly improved illumination achieved with tilting panels provides energy savings only if controlled adjustment of the panel is combined with controlled dimming of electric lights. An effective application is as a hung or louvered window panel tilted so as to direct sunlight towards the ceiling. By tilting to near horizontal the additional control function of rejecting sunlight may also be achieved by the same system. In the absence of direct sunlight the system can also be used to add skylight to the room.

STATUS OF AVAILABILITY
The device is currently under development and test.

COST, PER UNIT BASIS
With automated equipment, manufacturing costs for the panels should be low ($2-3/sq.ft.). Complete system costs would depend upon the mounting and installation details.

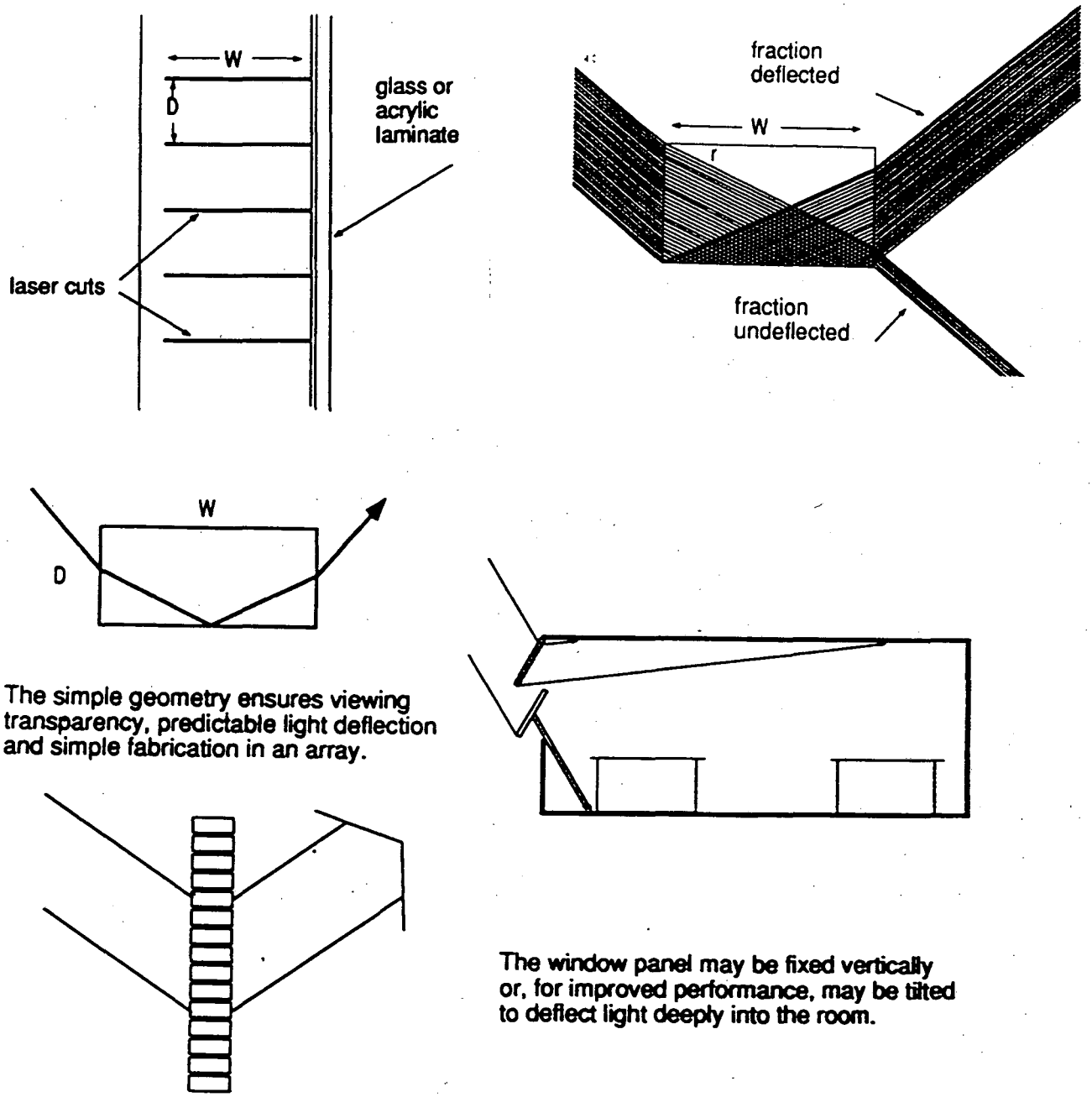


Figure 12. Light Control Panels (Ref. 5).

DIRECTORY OF MANUFACTURERS / VENDORS / R&D FIRMS BY TECHNOLOGY CATEGORY

Inclusion in this list does not imply applicability or endorsement. Additional companies may also manufacture these products.

HOLOGRAPHIC GLAZING

ADVANCED ENVIRONMENTAL RESEARCH GROUP
Attn. Richard Ian-Frese
Rt. 2, Box 2948
Davis, CA 95616
Tel. (916) 757-2567

HELIOSTATS

ALTERNATE ENERGY INSTITUTE
Attn. Dr. Martin Learn
5333 Mission Center Rd. N° 351
San Diego, CA 92108
Tel. (619) 692-2015

SO-LUMINAIRE CORPORATION or
DAYLIGHTING SYSTEMS
Attn. Bill Lindaer, marketing
2301 West Dunlap, Suite 108
Phoenix, AZ 85021
(602) 395-0156

FIBER OPTICS

SUMITOMO CORPORATION
Attn. Mr. Koichi Andoh
444 South Flower St.
Los Angeles, CA 90071-2975
Tel. (213) 489-0371
Fax (213) 489-0300

LIGHT GUIDES

TIR SYSTEMS
Attn. Chris Pekar
3935 2nd Ave.
Burnaby BC Canada V5C 3W9
Tel. (604) 294-8477
Fax (604) 294-3733

3M (Scotch Optical Lighting Film)

Attn. Paul Jaster
3M Center Bldg. 225-2N-06
St. Paul, MN 55144-1000
Tel. (612) 733-1898
Fax (612) 736-3893
X/TRA LIGHT - Costa Mesa
1 (800) 443-0219

LGM & Associates
Attn. Greg Miller
P.O. Box 2613
North Brook, IL 60062
Tel. (708) 272-6977

BOMIN SOLAR
Lightron System
Lorrach, Germany
Tel. (49) 7621-5093
Fax (49) 7621-54368

REFLECTIVE BLINDS OR LOUVERS

Synertech Systems Corporation: Daylighting Micro-Louvers
Attn. Peter J. Arsenault, Laurence F. Kinney
472 South Salina St. Suite 800
Syracuse, NY 13202
(315) 422-3828

SEA CORPORATION
2010 Fortune Drive, Suite 102
San Jose, CA 95131
Tel. (408) 954-1250
Fax (408) 954-1254

PRISMATIC PANELS

SIEMENS AG.
Lighting Division
Ohmstrabe 50
DW - 8225 Traunreut
Federal Republic of Germany

Yazaki Co. Ltd.
1370 Koyasu-cho
Hamamatsu-shi
Shizuoka 435
Japan
0534-61-7111

REFRACTIVE DAYLIGHTING DEVICES

DEPARTMENT OF PHYSICS
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Brisbane Q 4001, AUSTRALIA

LIGHT CONTROL PANELS

SCHOOL OF PHYSICS
Attn. Ian Edmonds
Queensland University of Technology
2 George Street
GPO Box 2434
Brisbane Q 4001, AUSTRALIA

SPECULAR CEILING REFLECTORS

SIEMENS AG.
Lighting Division
Ohmstrabe 50
DW - 8225 Traunreut
Federal Republic of Germany

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