EXPERIMENTAL EVALUATION OF INNOVATIVE WALL DAYLIGHTING SYSTEMS [1]

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ABSTRACT

Daylighting offers the potential to save electrical energy and reduce peak demand for lighting, the major consumer of energy in a variety of buildings. However, widespread adoption of daylighting techniques is hampered by the lack of both daylight resource information and simple, reliable methods of testing daylighting designs.

To surmount these obstacles, facilities for collecting illuminance data and for testing small-scale and full-size models have been established. These are (1) an extensively instrumented resource measurement station, (2) a sun angle simulator for exploring the geometries of the sun and the building during the early stages of design, (3) a heliodon to allow detailed illuminance and luminance distribution measurements in scale models, and (4) a rotating test building for quantitative and qualitative assessments of full-scale components.

The current research efforts have been using these facilities to seek ways of projecting light admitted through walls deep into interior spaces. Sidelighting systems are of interest because the wall is the only available source of daylight in many commercial buildings.

Innovative static and dynamic reflector assemblies have been examined and proven effective. Compared with typical sidelighting designs, the systems examined in this study project light deeper and produce more uniform illuminance across the space.

BACKGROUND

More than five percent of the nation's primary energy is consumed providing illumination in commercial and industrial buildings (1.). Another several percent is consumed for cooling these buildings. Furthermore, commercial buildings account for a substantial fraction of the peak electricity demand on United States utilities. Providing illumination in buildings using sunlight as a substitute for electric light is attractive for several reasons:

1. The solar illumination resource is substantial; during most working hours, the solar illumination on a building is several times greater than that required to illuminate the interior, indicating that it should be possible to design solar apertures that provide enough illumination to offset most of the daytime lighting electricity consumption.
2. The luminous efficacy of sunlight is generally superior to that of commercially available electric lamps, which means that sunlight has the potential for reducing building cooling loads by replacing electric light of higher heat content.
3. Sunlight is plentiful during the hot, clear, summer periods when many utilities experience their peak demand, suggesting that there is a potential for reducing demand for both lighting and cooling electricity, with consequent demand-charge savings for the building owners, and reduced capacity requirements for the utility.

Using detailed building energy analysis, Lawrence Berkeley Laboratory (LBL) has shown that if both beam sunlight and diffuse skylight are effectively used, substantial reductions in lighting electricity consumption can be achieved through very modest glazing areas (2% to 3% of the building floor area) (2.). Furthermore, reductions in cooling electricity consumption and peak electricity demand can be achieved with such a daylighting system. For the office building studied, the energy cost saving associated with introducing the daylighting system was about \$0.40 per square foot of building floor area per year. When one extrapolates this savings to the entire national commercial building stock of 10 billion square feet of floor area, the energy cost savings would be \$4 billion per year.

Furthermore, the results of the LBL study indicate that the energy cost savings per unit of collection aperture can be very high. For the energy cost savings of \$0.40 per square foot of floor area per year, the ratio of the floor area to the glazing area was approximately 20 to 1, indicating the annual energy cost savings can be on the order of \$8 per square foot of glazing area per year. In other words, a well designed device should have a high benefit-to-cost ratio, and consequently a high potential for penetrating the market.

While the opportunity is large, the problems in achieving these savings are also large. To begin, we must understand that using simple windows is not an effective enough approach to take significant advantage of the opportunity. Simple windows are generally not very effective in providing illumination inside a building for the following reasons:

1. For all orientations except north, windows admit beam sunlight which can cause severe glare problems.
2. Windows do not necessarily provide significant amounts of daylight in the interior spaces of the building. (As a rule of thumb, a simple window can illuminate a distance into the space that is about 1.5 times as great as the distance from the top of the window to the task surface being illuminated. For example, if the top of the window is 6.5 feet above the floor and the task surface is 2.5 feet above the floor, then the daylighting will be effective a distance of only 1.5 [6.5 ft - 2.5 ft] = 6 feet into the building.)

Identifying good daylighting solutions is a very complex process. The number of elements in the system is large and the potential roles of the elements are highly varied and often subtle. Figure 1 shows diagramatically the various elements in the system.

The "givens" of the problem are outlined in heavy lines. These include direct beam sunlight, diffuse skylight, ground reflected sunlight, and the human user, with all the inherent complexity of the human visual, psychological, and thermal responses, along with the specific issues associated with each of the visual tasks being performed. Outlined in dashed lines are all of the things over which we have a large degree of control in the design process. They include: the overall geometry of the building; the location, area, tilt, orientation, and transmission of the aperture glazing; the various static and dynamic aperture controls that can be located either inside or outside of the aperture; the interior design elements such as ceiling surfaces, wall

1 Funding for the facility and the research described in this paper has been provided by the North Carolina Alternative Energy Corporation.

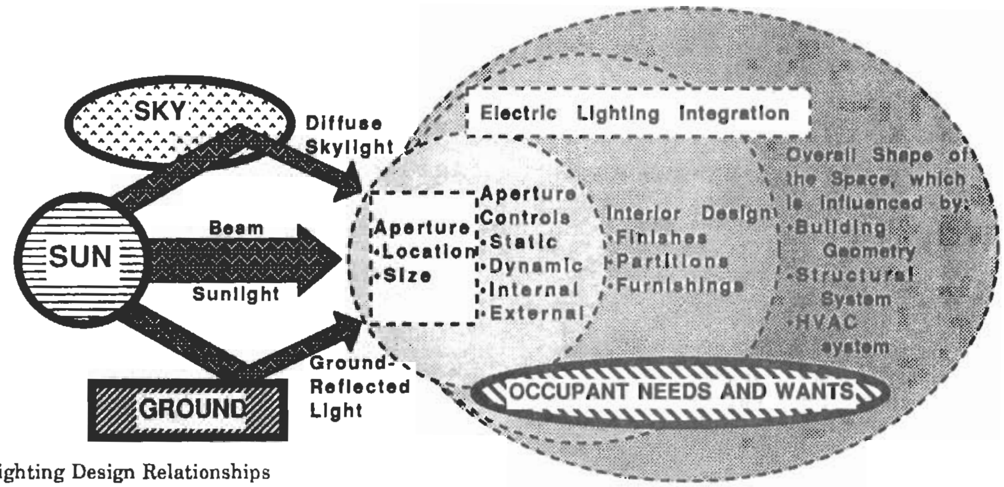

Fig. 1 Daylighting Design Relationships

surfaces, and interior partitions; and the electric lighting system that must be designed to work with the variable daylighting resource.

The relationship between all of these elements is so complex that substantial research must be done to grasp the nature of these relationships and then reduce that knowledge to simple principles that can be applied in a normal design process.

The work described in this paper is part of a larger research effort directed at characterizing the solar resource and generating and evaluating daylighting design concepts. The concepts addressed in this paper deal specifically with wall-based daylighting schemes for providing daylight deep inside multistory buildings. Future papers will address roofing systems.

THE RESEARCH APPROACH

In planning the daylighting research program at North Carolina State University, we considered who the users of the information would be, what kind of information they would need, and how that information could most effectively be generated and transferred.

We began by making a list of research tools and generating a matrix indicating what issues these tools were most useful in addressing (see Figure 2). In the process, we also considered what was being done at other institutions that could be transferred to our program. In this manner, we could avoid duplicating work that was already well advanced elsewhere and focus our efforts on the things that were not getting adequate attention. For example, we decided to use capabilities at other institutions to perform the detailed energy analyses.

DAYLIGHTING ISSUES	TOOLS OF EVALUATION AND EXPLORATION: RESOURCE MEASUREMENTS	OPTICAL ANALYSIS	SCALE-MODEL STUDIES	FULL-SCALE STUDIES	ENERGY SIMULATORS
LIGHT QUANTITY	✓✓✓	✓	✓✓	✓✓	
LIGHT QUALITY			✓	✓✓✓	
THERMAL IMPACTS				✓✓	✓✓✓
PSYCH. IMPACTS				✓✓✓	
SYSTEMS INTEGR.				✓✓✓	

✓ Tool can help, but is not adequate by itself.
✓✓ Tool is adequate by itself, but there are other tools that work also.
✓✓✓ Tool is essential to properly exploring the issue.

Fig. 2 Assessment of Research Tools

In addition, we have identified our primary users for the research products as the design students at NCSU and design practitioners in the state of North Carolina. Both these groups are highly visually oriented, so we want to use tools of exploration that will be consistent with the need for visual information. This suggested that scale-models and full-scale test structures would be important elements in our program. Models are highly consistent with the traditional modes of operation of the primary user groups and full-scale test structures are extremely important for exploring light quality and aesthetics issues. Full-scale structures are valuable for both research and demonstration activities.

Figure 3 shows the activities being pursued in the daylighting research program at NCSU. The emphasis is on generating and evaluating daylighting concepts that can be applied in a wide range of climates to a variety of building types. The focus in these efforts is on roof aperture systems and deep-penetration, wall-based daylighting systems.

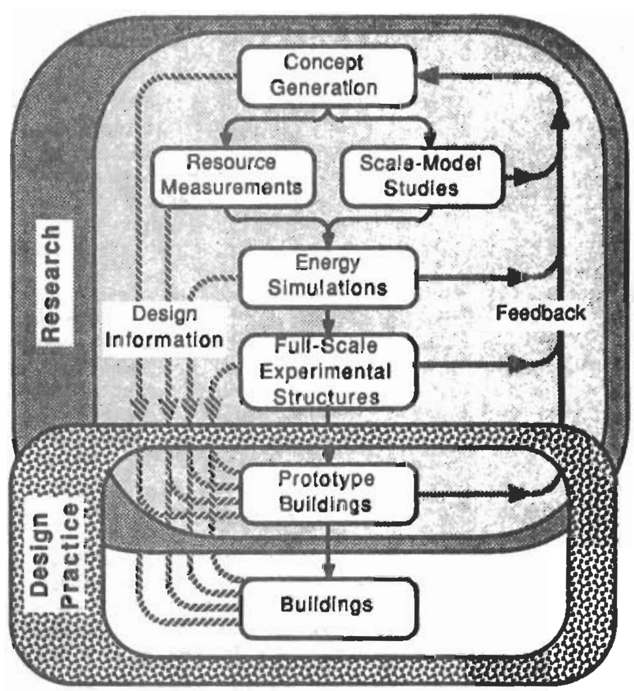

Fig. 3 Research and Development Process

As we generate daylighting system concepts, we evaluate the resource measurements in terms of their adequacy in providing information necessary to properly assess those concepts. As an example, a daylighting system that relies on beam sunlight cannot be accurately assessed using values of beam sunlight intensity that are averaged over time periods that are long compared to typical fluctuation periods associated with intermittent cloud cover in partly cloudy situations. In other words, the time scale for resource measurements is sensitive to the daylighting systems being assessed. Similarly, the performance of some daylighting systems is extremely sensitive to the direction of incident daylight. As always, there are cost-limitations on the frequency and type of measurements, so we are constantly pondering what kind of data and how much data we actually need.

Scale-model studies are performed on each daylighting concept. This approach allows rapid generation of information on illuminance levels, luminance distributions, spacial aesthetics, and visual comfort. (The issue of visual comfort is addressed only in a preliminary way using scale models, since the human eye cannot respond to the "spacial surround" of a scale model in the same way that it could for a person operating in a full-scale space. The larger the model, the better the preliminary assessment -- particularly if the model is large enough for the observer to comfortably put his head inside it.) Illumination information generated from the scale models can be used as design information by itself or can be used as input to building energy simulations. Daylighting concepts that look particularly promising based on model studies and energy simulations will next be mocked-up at full scale. These studies are conducted at the NCSU research facility and are still in the nature of controlled, laboratory-grade experiments. Concepts surviving that test will then be incorporated into "prototype" buildings. These buildings are built and occupied by real users and therefore must satisfy some of the criteria of economic forces and market-place evaluation. If the concepts survive this test, then they can be expected to become assimilated into the mainstream of building construction process, without significant further intervention by the inventors or researchers.

There are, of course, many feedback loops in the process described above. At almost any point, significant changes might be introduced in the concept that will require beginning the process anew at some point further upstream in the process. Also, design information can be generated at the completion of almost any stage in this process. The nature of the design information will depend on how many stages of the process have been completed, who the users are, and how the information is to be used. For example, other researchers may have more use for the resource measurements, but design practitioners might be more interested in the documentation from the prototype buildings.

DESCRIPTION OF THE EXPERIMENTAL FACILITIES

Figure 4 is the site plan for the Daylight Measurement Facility, showing

1. the heliodon staging area where scale models are tested under full solar conditions,
2. the rotating test building for evaluating deep-penetration, wall-based daylighting systems for multistory buildings,

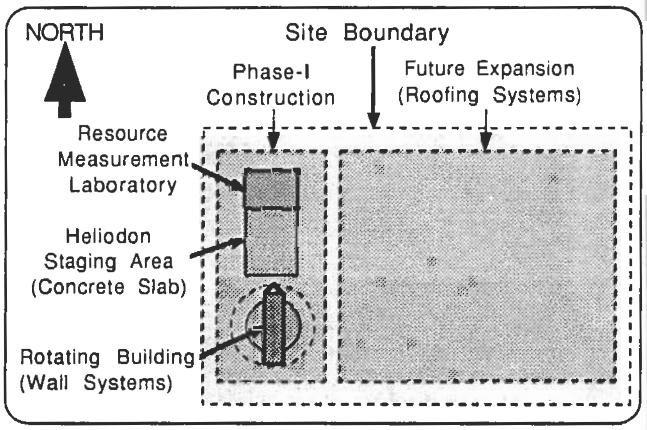

Fig. 4 Site Plan of Facility

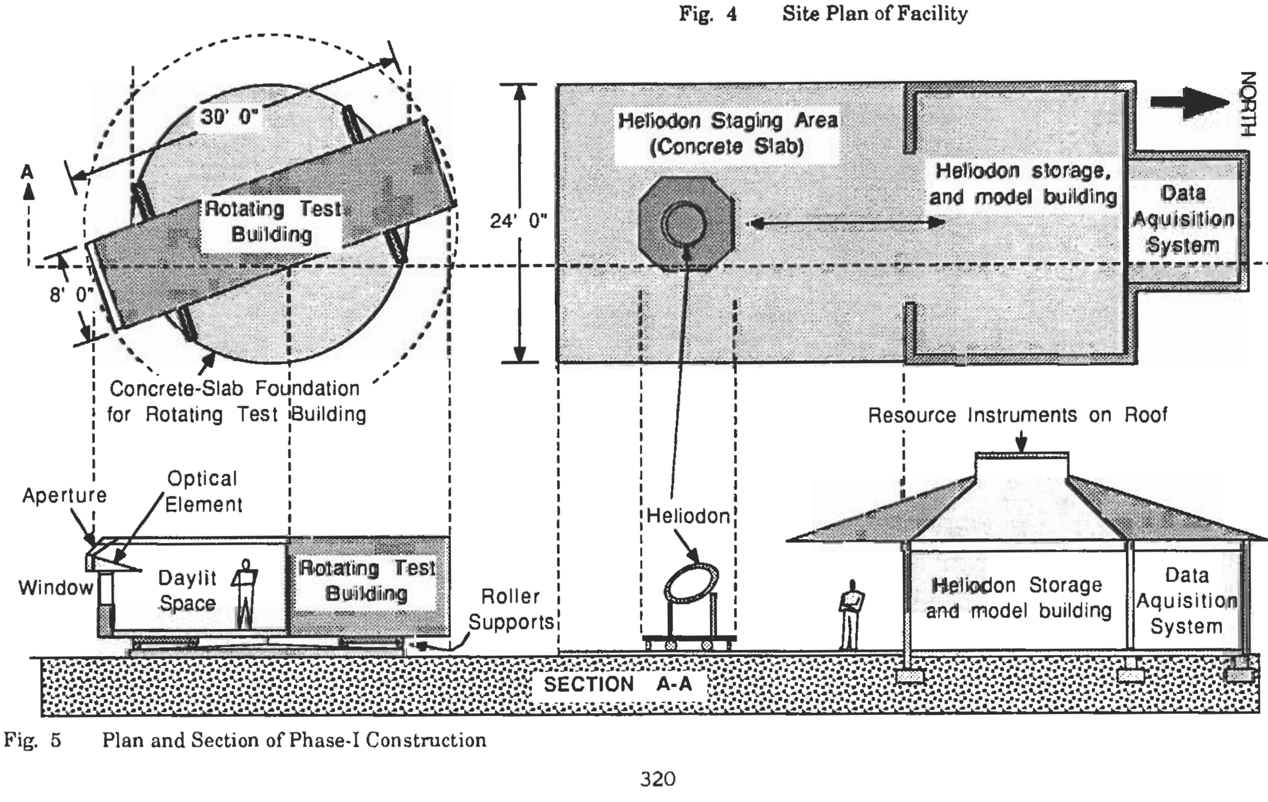

Fig. 5 Plan and Section of Phase-I Construction

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3. the two-story building with the resource measurement equipment on the roof, the computerized data acquisition system on the second floor, and the model fabrication and storage space on the first floor, and
4. the location of future expansion for the roofing system test buildings.

Figure 5 is a blow-up of the existing facilities (the first three elements listed above).

Figure 6 is a photograph of the existing facilities.

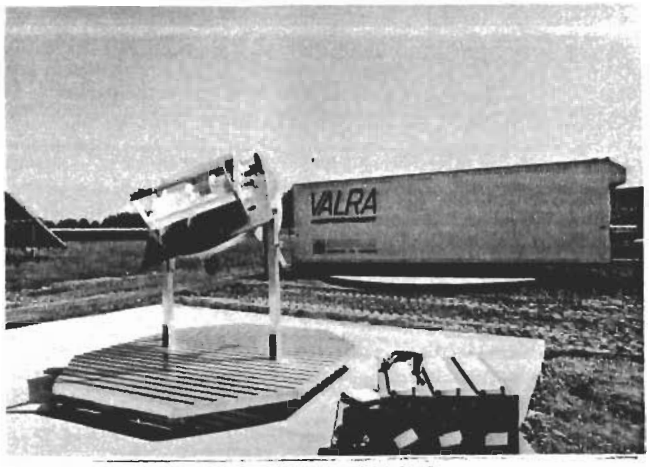


Fig. 6 Rotating Test Building and Heliodon

Shown are the heliodon in use with the rotating test building in the background. The Resource Measurement Laboratory is currently being constructed.

Figure 7 shows the sensor arrangement for the resource measurement station and the rotating building. The data loggers used in conjunction with the heliodon are similar to those being used inside the rotating test building.

DESCRIPTION OF THE DAYLIGHTING SYSTEMS BEING INVESTIGATED

Several approaches have been proposed to enhance the illumination benefits from glazing in walls. The simplest is to design the building structure so that the opaque spandrel that normally occurs above the window can be replaced by additional glazing, thereby allowing the top of the window to be located higher in the wall (see Figures 8a and 8b). This design allows greater penetration of light into the building but still has the problem of glare from beam sunlight penetrating into the space.

To help alleviate the problem of glare, an interior "light shelf" can be added (see Figure 8c). The light shelf intercepts some of the sunlight that would have penetrated the space and reflects it up to the ceiling, thereby providing a more diffuse, less disturbing illumination.

The addition of the interior light shelf effectively creates two distinct glazings systems, the upper glazing being the primary provider of illumination and the lower glazing being the primary provider of view. With this division of functions established, the design can be refined by differentiating the properties of the two kinds of glazings. For example, we can use

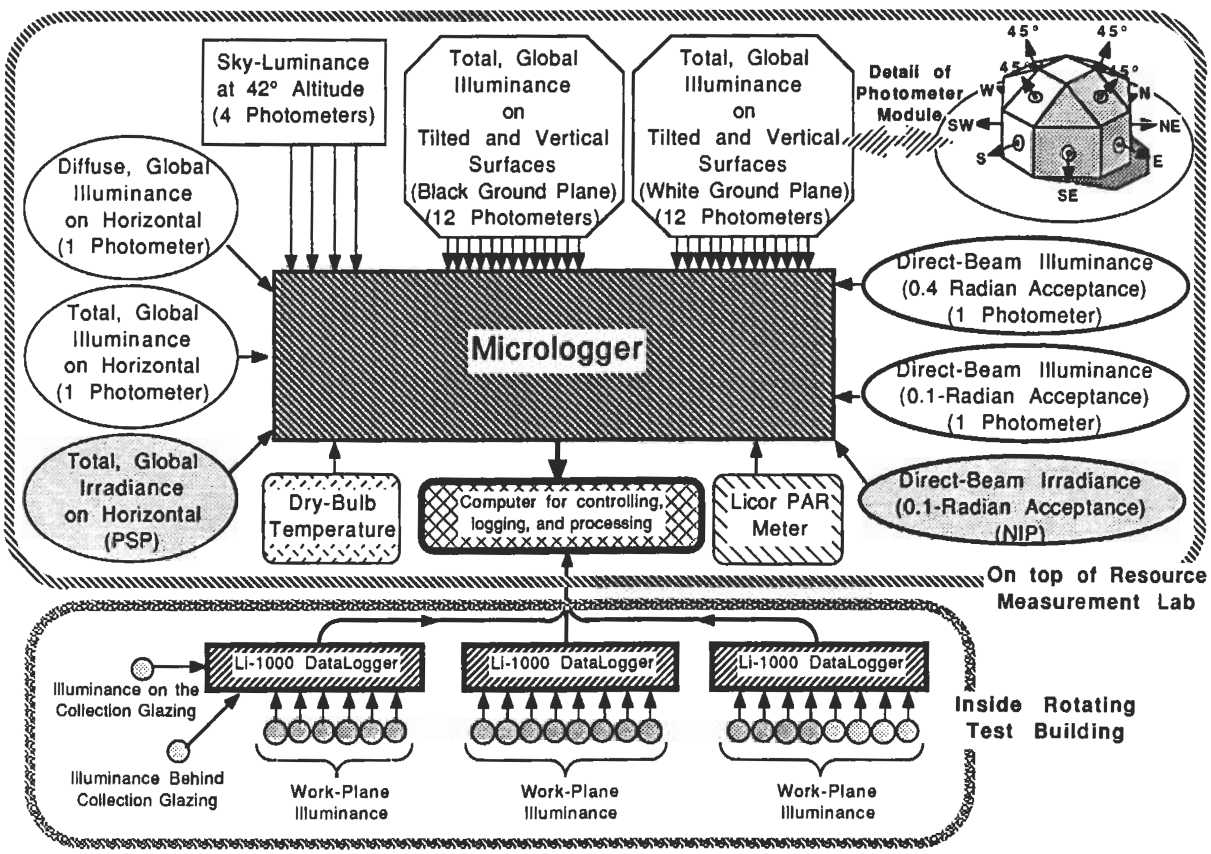
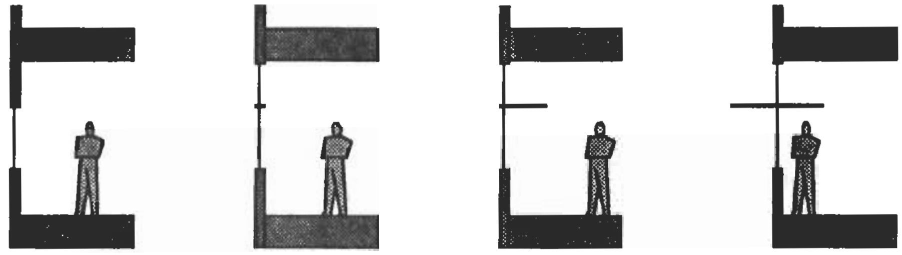


Fig. 7 Instrumentation and Data Acquisition System



(a) View Glazing with opaque spandrel

(b) Glazing to the ceiling

(c) Glazing to the ceiling with inside light shelf

(d) Glazing to the ceiling with inside and outside light shelf

Fig. 8 Common Configurations for Walls Receiving Beam Sunlight

high transmission glazing above the light shelf, to admit as much useful light as possible, while using low-transmission glazing below the light shelf to reduce the potential of glare from bright objects outside, and to reduce solar gains that can aggravate the cooling electricity consumption.

The light shelf concept can be further refined by adding an exterior element that intercepts some of the sunlight that would otherwise penetrate the view glazing and reflects it through the illumination glazing (see Figure 8d). This reduces the glare and excess solar gains associated with the view glazing and enhances the illumination contribution from the glazing above the light shelf.

Studies of conventional light shelves have demonstrated clear advantages in terms of providing higher quality illumination (3., 4.). However, those studies also indicate that the light shelves make no significant contribution to increasing light levels deep in the building. In other words, they improve the quality of the light in the zone that would normally have been illuminated by the high glazing, but do not increase the light level or extend the zone of effective illumination levels.

In order to address the problem of getting daylight deeper into the building, various optical devices have been proposed (5.-7.). All of the effective devices have involved tracking mechanisms, and some of them have required focusing optics and exotic light guides.

One of the most promising of these devices was invented by one of the authors, T. C. Howard (see Figure 9). That device, called a Variable-Area, Light-Reflecting Assembly (VALRA) has been under development for several years (5.). In scale-model studies, it has been demonstrated to illuminate up to 100 feet into a building under full sunlight at solar noon. Since most buildings must operate under a range of solar conditions, for all hours of the day, a more practical design would attempt to illuminate only 40 or 50 feet into the building. A full-scale, functioning prototype of the VALRA has been built and demonstrated to achieve good daylighting 40 feet into the building. This prototype has been installed in a rotating test building and will be the subject of extensive testing to be outlined later in this paper.

The VALRA is a tracking device. In order to reduce the initial cost and maintenance costs, Wayne Place and T. C. Howard invented a static optical system which has most of the performance attributes of the VALRA, without the requirement for moving parts. The greater simplicity of manufacture and operation should make the static system more attractive economically.

The primary goals of the static daylighting device are as follows:

1. To take sunlight incident on glazing set high in a wall and deliver it to the task surfaces deep within the building and

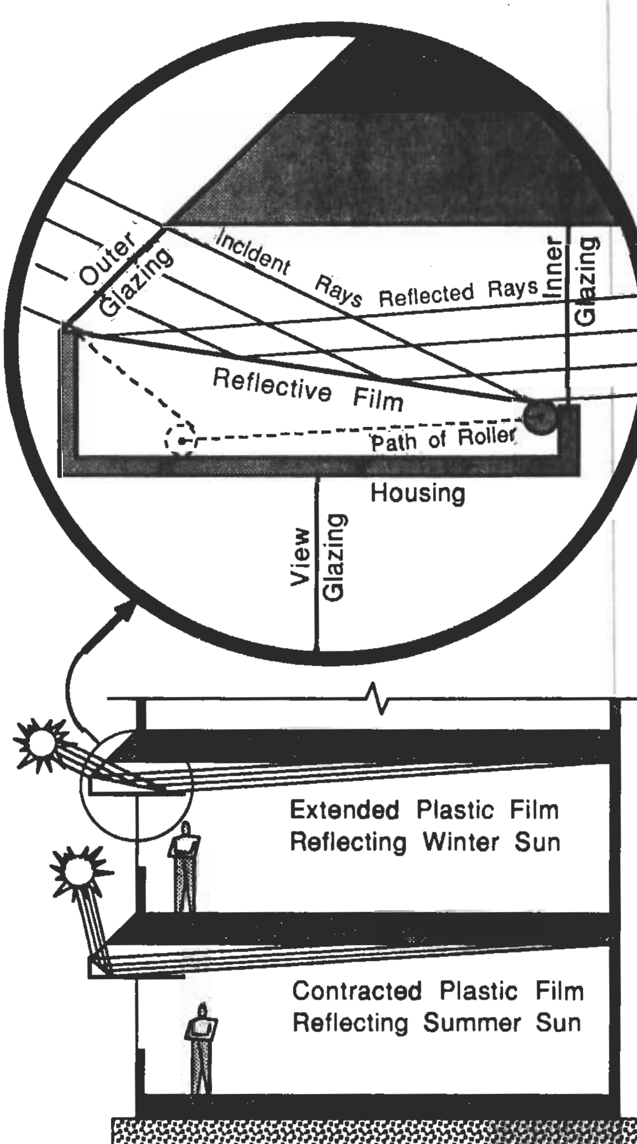


Fig. 9 A Wall-Mounted Version of the VALRA

2. to distribute the light as uniformly as possible over the task surfaces, so that the electric lighting system being used to supplement the daylight can be as simple as possible.

The second of these goals relates to the issue of spacial uniformity and not to uniformity as a function of time. The solar resource varies between about 100,000 lux under peak conditions to essentially zero at night, so there are bound to be changes in the daylighting levels as a function of time, and we must have an electric lighting system that is able to compensate for these temporal variations. The question is: How elaborate does the electric lighting system have to be? Or more specifically, how many sensors and control circuits do we need to compensate for changes in the daylighting levels in the various parts of the occupied space? The more spacially uniform (or at least consistent) the daylighting levels, the fewer sensors will be required.

These two design goals present an interesting design dilemma. Illuminating deep within the building using a limited amount of glazing necessitates heavy reliance on beam sunlight since diffuse skylight is not a strong enough source. Beam sunlight is constantly changing in direction over a large range of angles.

On the other hand, to achieve uniformity of the illumination levels within the space, the direction of the daylight that enters the space should not change as a function of incident sun angles. The optical dilemma is to take light incident on the collection glazing from many directions and always project it in the same direction inside the building.

One method of resolving the dilemma is to use a highly diffusing collection glazing that will scatter the entering sunlight uniformly in all directions as it enters the space, regardless of the direction of the beam sunlight incident on the outside of the glazing.

Of course, this is not exactly optimal, since much of the light admitted by the glazing will be moving downward toward the portions of the work plane close to the wall. Since there is already more light in that area than is needed, it would be preferable to direct almost all of the light deeper into the space. A curved, mirrored surface placed below the collection glazing can intercept the light headed downward and project it toward the back of the space (see Figure 10).

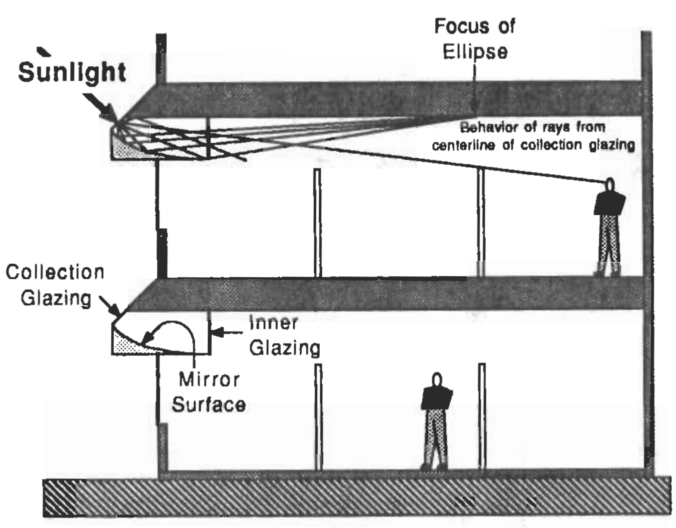


Fig. 10 Daylight Projector with Diffusing Glazing and Curved Mirror

The extremely intense nature of beam sunlight is the savior in such an approach. The intensity of beam sunlight allows the use of a fairly narrow strip of collection glazing. For the projection process to be effective, the mirror must be substantially larger than the light source, i.e., the mirror must be substantially larger than the collection glazing. The narrowness of the glazing means that a modest sized mirror can be fairly effective in projecting the light in the desired direction.

The most appropriate shape for the mirror depends on the size and shape of the space being serviced and on the lighting objectives defined for the space. The issue of the shape of the mirror is still under intensive investigation.

For example, suppose we have a large space that is divided into three smaller spaces by partitions. The space closest to the window will tend to get a fair amount of daylight from the window. So, we want to deliver most of the light from the projecting mirror to the two inner spaces. One way of doing this without causing glare to the occupants is to project the light on the area of ceiling over the two spaces and allow the ceiling to serve as a secondary source of light for the task surfaces in the spaces. The difficulty is that there are a large number of possible distributions of light on the ceiling that might produce satisfactory distributions of light on the task surface. Also, we have a distributed light source of significant dimension that will not allow us to put all of the daylight exactly where we want it.

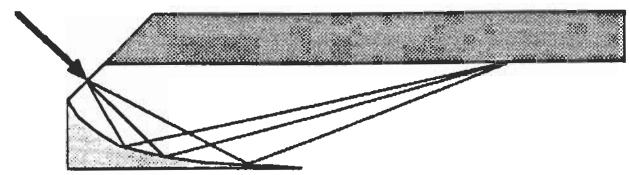
One way to simplify the problem is to imagine the long, narrow, diffusing glazing strip as a linear source of multidirectional light localized along the horizontal line at the center of the glazing. Next, the image of the line source might be focused over the partition between the two interior spaces. In this manner, the light bouncing off the ceiling can be shared between those two spaces (see Figure 10).

To achieve this optical behavior, the appropriate cross-sectional shape for the projecting mirror would be an ellipse with one of its foci at the line source (i.e., at the center of the glazing) and one of its foci at the line image (on the ceiling over the two partitions). Of course, we do not actually end up with a line image on the ceiling, because we do not actually have a line source of light. The glazing is a distributed source that produces a distributed image on the ceiling. Whether this distributed image produces the most desirable pattern of light in the space is the subject of ongoing research. However, the ellipse was the point of departure for this investigation.

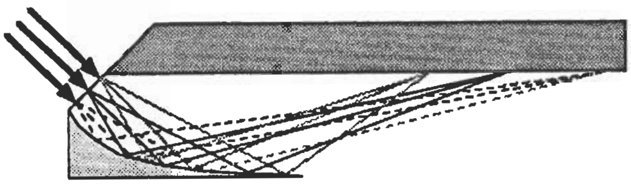
Once we settle on the ellipse, the shape of the mirror cross-section is set, but its overall size is not. The distance that the projecting mirror extends into the space depends on a variety of factors. The desire to move more daylight to the back spaces would prompt one to make the mirror large, while the cost of the mirror and the desire not to rob the front space of too much light and its sense of spaciousness would encourage limiting the size of the mirror. The conflict between these two desires produces a design optimization issue that needs to be resolved.

In the discussion above, we have addressed the horizontal "line of light" at the centerline of the aperture. Obviously, the aperture is not a single line of light but is a distributed source. Light from each part of the glazing gets sent to a different part of the ceiling by the curved mirror. Figure 11a shows the focusing process for light from the centerline of the glazing. Figure 11b shows the way in which light from different parts of the glazing gets distributed about the space.

The basic concept of the sloping collection glazing with the curved mirror we call the Daylight Projector. The basic device can be enhanced by a number of other elements, including ceiling baffles, mirrors along the sides of the space to direct off-axis light back into the work space, and, of course, the electric lighting system with appropriate controls to respond to changes in the daylighting level. The combination of the device and these other elements we refer to as the Daylight Projector System.



(A) Showing rays from the centerline of the glazing



(B) Showing rays from three parts of the glazing

Fig. 11 Optical Behavior of Elliptical Mirror

STATUS OF THE RESEARCH

RESOURCE MEASUREMENTS

Resource measurements have not been initiated at the time of this writing. The sensors and control computer have been purchased. Some software modules have been purchased and other parts of the software are being written. Specifications for the data logger have been written and candidate units have been identified.

SCALE MODEL TESTING

A mock-up of the Daylight Projector has been built and incorporated into a model of a prototype office space (See Figure 12).

The space shown is 10 feet high, 30 feet wide, and 30 feet deep. Partitions have been included to simulate a realistic office environment. Photometers in the work plane of the model indicate that the light level in the back two thirds of the space is extremely uniform for a wide range of exterior sun angles, and that the illuminance on the work plane in those two spaces under the influence of bright sunlight can be as high as 1100 lux, or twice the normal level prescribed for office environments. Comparisons with the full light shelf indicate that the light levels provided by the Daylight Projector are more than twice the levels provided by the full light shelf.

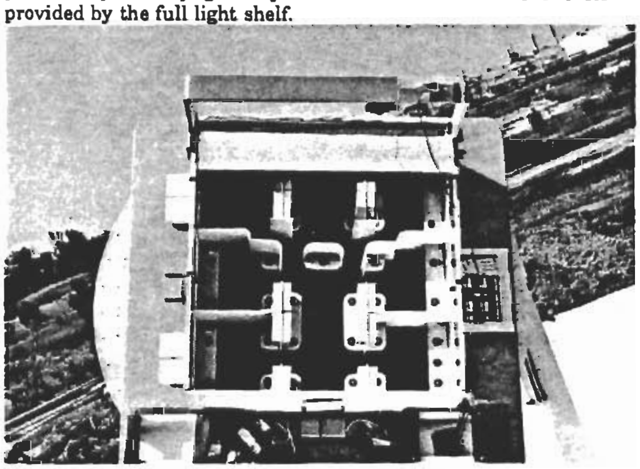


Fig. 12 Photograph of Prototype Office Model

Initial scale-model studies of the Daylight Projector have indicated a problem with excessive luminance of the collection glazing relative to the luminance of the task surfaces in the back spaces, where occupants have a view of the collection glazing (see Figure 10). As measured in the scale model, the ratio of the luminance of the aperture to the luminance of the task surface is on the order of 80. This glare problem has been addressed using suspended baffles that block the view of the collection glazing (see Figure 13).

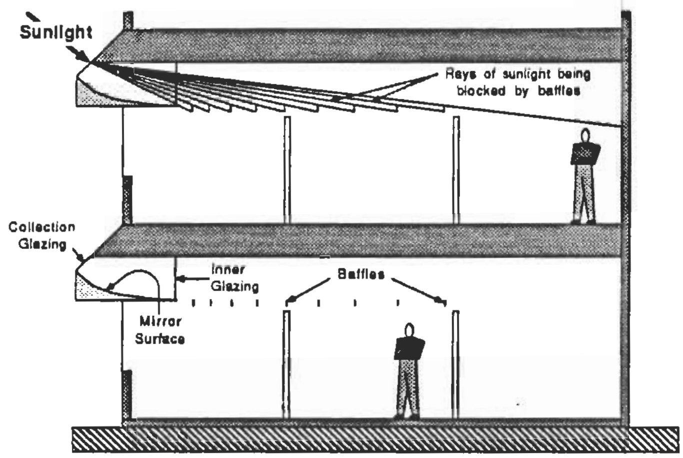


Fig. 13 Daylight Projector with Ceiling Baffles to Block View of Luminous Glazing.

These baffles should be spaced closely enough to block the view of all of the collection glazing from any perspective in the space, but no closer than that. Keeping the baffles as far apart as possible is advantageous in making the occupied space seem larger and in allowing light from the ceiling to move to the work plane with minimal obstruction. The spacing of these baffles can become larger with distance from the Daylight Projector. Slightly beyond halfway into the space, no baffles are needed, since the light that gets beyond that point is too high to hit anyone in the eyes.

Details of the model studies will be the subject of another paper to be issued in draft form within the near future. Those studies have assessed the importance of: the tilt, area, transmissivity, and diffusivity of the collection glazing; the shape and size of the curved mirror; the size, spacing, and optical properties of the ceiling baffles; the impact of various floor plans and room shapes; the impact of various partition designs; and the impact of mirrors on the side and back walls of the space being illuminated. In evaluating these issues, measurements have been made of task surface illuminance throughout the space and of luminances of various surfaces in the space.

Extensive scale-model studies of the VALRA have already been conducted and reported in the literature (5.). These studies have addressed the same design issues outlined above for the Daylight Projector. The studies suggest that the VALRA is very effective in illuminating up to 50 feet deep into the building. The VALRA has the disadvantage that the light is not as uniform as the light provided by the Daylight Projector. This results in a more complicated electric lighting control system. Several methods of making the illumination more uniform are currently being explored, including rotating louvres behind the collection glazing and static beam splitters mounted inside the VALRA housing.

ESTIMATING THE POTENTIAL ENERGY IMPACTS

The illumination information acquired from the model testing is used in estimating the electric lighting energy reduction attainable by use of the various daylighting concepts. It can also be used on the front end of a detailed building energy analysis tool, such as BLAST or DOE-2, to assess the thermal tradeoffs associated with admitting the sunlight and reducing the energy input to the electric lights. Extensive energy analyses have already been performed on the VALRA (5.). These involved the use of BLAST to determine the impact of the device on a prototype office building. Energy factors evaluated were: lighting electricity consumption, cooling electricity consumption, heating fuel consumption, peak electric demand, and the total cost of energy, accounting for local fuel costs and local utility rates for consumption and peak demand.

Detailed energy analyses on the Daylight Projector have not been performed. Based on the VALRA studies, we expect that the lighting electricity reductions will be overwhelmingly the most significant energy impact of the Daylight Projector, with the impacts on heating energy consumption, cooling energy consumption, and peak electric demand being secondary. This results from the fact that, for practical configurations, the sunlight is projected far enough into the building and spread far enough over the task area that it does not cause significant overheating. Typically, the solar heat admitted to the space comes very close, under most operating conditions, to offsetting the reductions in heat generated by the electric lights.

(The critical system parameter related to this issue is the ratio of task area being illuminated to the glazing area for collecting sunlight. If this ratio is on the order of 20, the solar gains approximately balance the reduction in heat generated by the electric lights. For larger ratios, the cooling electricity consumption and peak electric demand tend to go down. For smaller ratios they tend to go up. Since the practical range of application for this device will probably be ratios from 15 to 30, and since heating energy consumption, cooling electricity consumption and peak demand are relatively insensitive to that ratio over that range, the impact on these energy issues is going to be relatively smaller than the impact on the lighting electricity consumption. Therefore, the primary emphasis in the near term will be on generating good estimates of lighting electricity consumption, while using simple techniques and previous simulations [5.] to estimate the thermal and peak-demand impacts.)

FULL-SCALE EXPERIMENTS IN THE ROTATING BUILDING

A VALRA mock-up has been generated and all the mechanisms and the computer controls for the device have been tested and are fully operational. Test-cell studies will be initiated in the very near future to examine the device from two points of view:

1. measuring illuminance levels as a function of a range of sun angles, to determine the effectiveness of the rotating louvres behind the collection glazing [Because of scaling problems, this component of the device could never be tested at small scale.],
2. using test subjects to evaluate light quality, psychological response, and the effectiveness of the visual environment for occupants involved in a variety of tasks, including: reading, writing with a pencil, and using a video display terminal.

Designs for the full-scale version of the Daylight Projector are currently being assessed, based on the information that has been gathered in the scale-model studies. After the initial experiments on the VALRA device have been completed, it will be replaced with a mock-up of the Daylight Projector.

PROTOTYPE BUILDINGS

A prototype building has been designated, and a version of the VALRA or the Daylight Projector will be installed within the year. None of these concepts has yet reached the phase that market forces would be likely to propel it into wide spread use.

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