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L.O. Beltrán, E.S. Lee, K.M. Papamichael, S.E. Selkowitz

Building Technologies Program
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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L.O. Beltrán, E.S. Lee, K.M. Papamichael, S.E. Selkowitz
Building Technologies Program
Energy and Environment Division
Lawrence Berkeley Laboratory
Mailstop 90-3111
Berkeley, CA 94720

ABSTRACT

We present results from the design and evaluation of three advanced daylighting systems: a light shelf, a light pipe, and a skylight. These systems use optical films and an optimized geometry to passively intercept and redirect sunlight further into the building. The objectives of these designs are to increase daylighting illuminance levels at distances of 4.6-9.1 m (15-30 ft) from the window, and to improve the uniformity of the daylight distribution and the luminance gradient across the room under variable sun and sky conditions throughout the year. The designs were developed through a series of computer-assisted ray-tracing studies, photometric measurements, and observations using physical scale models. Comprehensive sets of laboratory measurements in combination with analytical routines were then used to simulate daylight performance for any solar position. Results show increased daylight levels and an improved luminance gradient throughout the year – indicating that lighting energy consumption and cooling energy due to lighting can be substantially reduced with improvements to visual comfort. Future development of the designs may further improve the daylighting performance of these systems.

1. INTRODUCTION

Substantial savings in energy consumption and peak demand can be obtained with the use of daylighting controls that dim electric lighting in response to available daylight. For a prototypical commercial office building in Los Angeles, DOE-2.1D energy performance simulations indicate that annual whole building electricity consumption savings of 14% and peak demand savings of 16% can be achieved over a non-daylit building if daylighting controls are used within a 4.6 m (15 ft) deep perimeter zone [1].

If daylight is used to offset lighting energy requirements over a larger floor area, additional energy savings can be obtained. However, the use of larger windows and higher transmittance glazings to provide sufficient levels of daylight at distances further from the window has proven to be inefficient. Daylight levels decrease asymptotically with distance from the window, so that a disproportionate amount of daylight/ solar radiation must be introduced into the front of the room for small gains in daylight levels at the back of the room. While this can increase lighting energy savings over a larger floor area, the corresponding increase in cooling due to solar heat gains can offset these savings and greatly exacerbate peak load conditions. The non-uniform workplane illuminance distribution and luminance gradient within the space can also result in an uncomfortable lighting environment.

In this report, we present three advanced daylighting systems – light shelves, light pipes, and skylights – that have been designed to ameliorate these conditions. All three systems are presented in detail, along with the methods used for their design and evaluation. Finally, daylight performance results are presented and discussed, along with recommendations for further research and development.

2. PROTOTYPE DESIGNS

The advanced daylighting systems were developed with the following concepts: By reflecting sunlight to the ceiling plane, daylight can be delivered to the workplane at depths greater than conventional windows or skylights, without significant increases in daylight levels near the window. This redirection serves to improve visual comfort by increasing the uniformity of wall and ceiling luminance levels across the depth of the room. By using a relatively small inlet glazing area and efficiently transporting the daylight, lighting energy savings can be attained without severe cooling load penalties due to solar radiation. By carefully designing the system to block direct sun, direct source glare and thermal discomfort due to radiant asymmetry can be diminished. The challenge of the design stems from the large variation in solar position and daylight availability throughout the day and year.

The initial designs of the prototypes were completed using computer-assisted ray-tracing calculations to determine the geometry of various light-redirecting optical elements. The designs were tailored to utilize direct sunlight because diffuse daylight from the sky and surroundings contributes insignificant daylight illuminance due to its lower intensity; the intensity of direct sunlight is four to seven times greater than diffuse skylight [2]. Rays were traced back from the target, located 4.6-9.1 m (15-30 ft) from the window at the ceiling, back to the reflector for sun rays incident over the full range of solar altitude angles. Based on the two required angles of incoming solar rays and outgoing rays from the reflector, the optimum angle of the reflector was determined. Hourly sun rays were then traced to verify that no outgoing rays were directed downwards into the space which may create sources of direct glare. All prototypes were designed for latitude 34°N (Los Angeles and Palm Springs). Slight alterations would be necessary to tailor the design for a different latitude.

For all designs, efforts were focused on determining the optimum aperture size and reflector size and shape, to take advantage of the optical properties of the daylighting films, and to accommodate the sun path viewed by the window for a specific orientation and building latitude. The light shelves and light pipes were designed to supplement the daylight provided by a lower vision window and to be the primary source of daylight at 4.6-9.1 m (15-30 ft) from the window wall. The lower window employs a spectrally selective glazing with an operable shading device to accommodate the requirements of the occupant adjacent to the window, such as the desire for view, privacy, etc.

2.1 Light Shelves

Two light shelf designs were developed to fit within 0.6-1.5 m (2-5 ft) deep articulated building facade (Figure 1). One for south-facing orientations which can receive direct sun throughout the day. The other for east or west-facing orientations that receives direct sun only during morning or afternoon hours, respectively, and diffuse skylight during all other hours. The main reflector consists of a curved segmented surface to better redirect sunlight with changing solar altitudes. The surface of the reflector is a special, highly reflective film (88%) that has a compound reflection with a specular and narrow spread. This film has linear grooves that spread outgoing rays within a 12°-15° angle. A secondary reflector with a highly reflective specular film (95%) is placed above the main reflector at the ceiling plane near the window, to intercept incoming low winter sun angles penetrating the space, and to redirect these rays onto the main reflector. The outside aperture of the light shelf is small (0.2 m (0.6 ft) in section) and uses a spectrally selective glazing so that solar heat gains are minimized. The light shelf has been designed to be completely sealed from the interior and exterior environment to maintain the high reflectivity of the films by preventing dirt depreciation and occupant interference.

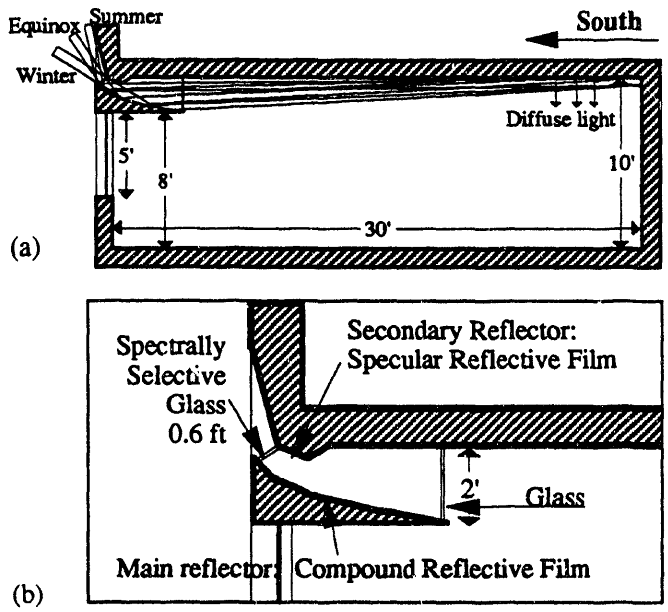

Figure 1. South facing light shelf: (a) Section along centerline of room, and (b) Detail of light shelf reflectors.

2.2 Light Pipes

The light pipe was designed to fit within the ceiling plenum, with its daylight receiving aperture flush against the glazed spandrel of the building, so that it can be used with flush as well as articulated building facades. The light pipe was also designed to be used in combination with a lower vision window (Figure 2).

A total of ten light pipe options were iteratively designed and evaluated. Additional design parameters were considered: The light pipe needed to be small enough to fit with other building subsystems (mechanical ducts, lighting, structure, etc.) within the ceiling plenum. We varied the cross section of the light pipe, studying the changes in illumination efficiency and distribution. The reflector system ideally needed to redirect incoming sunlight to minimize interreflections within the transport section of the light pipe in order to maximize the efficiency of the system. We altered the shape of the light pipe transport cross section and investigated various reflector options to redirect daylight to the workplane.

The final light pipe design couples a reflector similar to the light shelf to a 9.1 m (30 ft) long transport/ distribution pipe. To maximize efficiency along the full length of the light pipe and to improve overall daylight distribution within the space, no daylight is distributed by the light pipe for the first 4.6 m (15 ft) from the window. This transport section is designed with a tapering 0.6 by 0.61 m (2 by 2 ft) square cross section and lined on all interior surfaces with a highly specular film (95%). The distribution section of the light pipe, 4.6-9.1 m (15-30 ft) from the window wall, consists of a 4.6 m (15 ft) long diffuser with a 50-88% transmittance located at the ceiling plane.

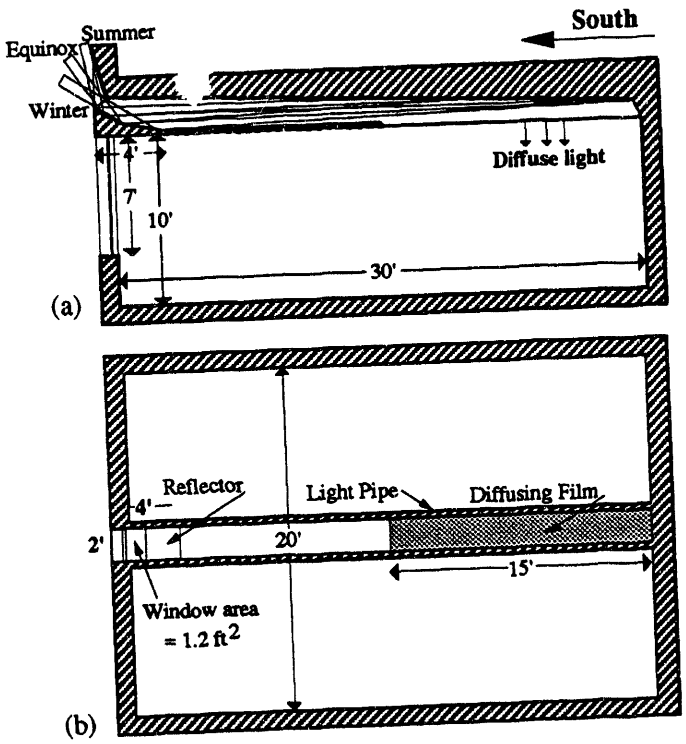

Figure 2. South facing light pipe: (a) Section along centerline of room, and (b) View plan of light pipe.

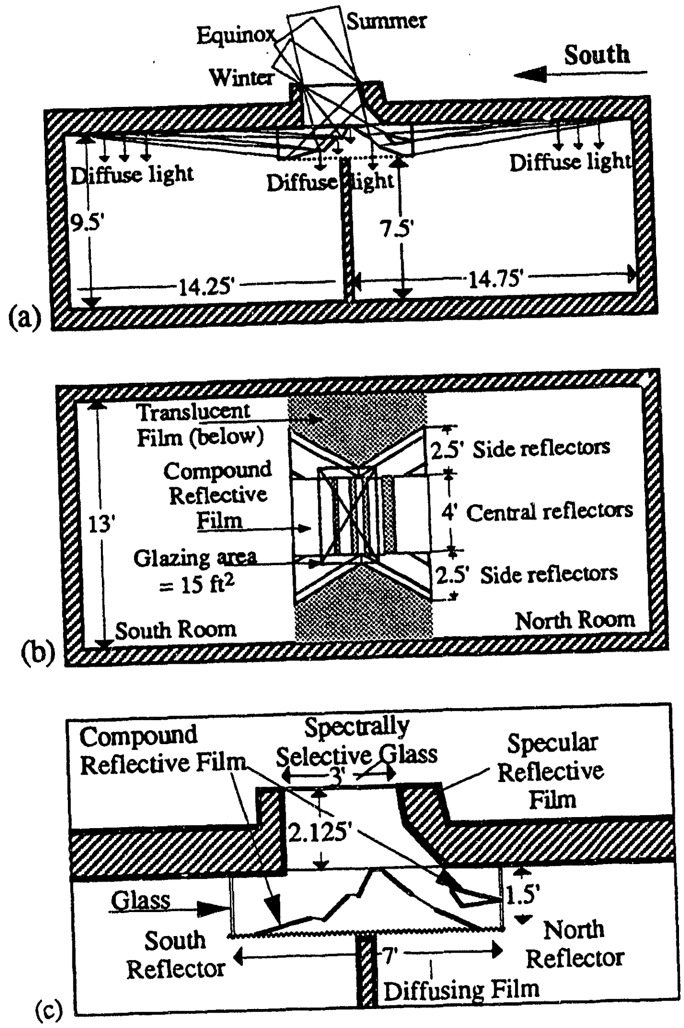

Figure 3. Skylight prototype: (a) Section along centerline of room, (b) View plan of skylight reflectors, and (c) Detail of reflectors.

2.3 Skylights

The skylight was designed to be the primary source of daylight for two single story windowless offices in the Palm Springs Chamber of Commerce (Figure 3). This Southern California Edison showcase demonstration gave us an opportunity to test and refine our concepts in a real-world building application. Several new constraints were imposed on the design: specific building code requirements, existing building subsystems such as mechanical ducts and equipment, architectural aesthetics, issues of construction detailing and fabrication, etc. We developed the skylight with the same design objectives as the light pipe and light shelf, paying close attention to minimize the size of the skylight opening. Palm Springs has a fairly hot climate (summer temperatures range 19-46°C (67-115°F)) with high sunlight availability. The focus of our efforts was to avoid greatly exceeding the design lighting levels, to improve uniformity, and to minimize solar heat gains.

The skylight was designed to split incoming daylight from a single aperture between two separate of about 4.6 m (15 ft) deep rooms. The skylight design improved upon the first two prototypes by adding two side reflectors to increase light redirection by oblique surface-solar azimuth* angles. The skylight reflector is composed of two halves, north and south, to redirect sunlight to the two rooms. Each half consists of a main central reflector and two side reflectors (Figure 3b). The central reflector is similar to the light shelf reflector (optical film and geometry), and is designed to redirect sunlight onto the ceiling at the back of the space for surface-solar azimuth angles, $\gamma \leq \pm 30°$. A secondary upper central reflector at the north end is also used to redirect sunlight, reducing the overall length of the reflector. The side reflectors were rotated 60° inwards to the central reflector, to face the sun during morning or afternoon hours and to redirect sunlight to the center back of the room for $\pm 30° < \gamma \leq \pm 90°$. The 0.9 by 1.5 m (3 by 5 ft) skylight opening was centered over the entire skylight reflector. The light well was covered with a highly specular reflective film (95%) to redirect low sun angles (e.g., during the winter) down to the south reflector, and from there up to the ceiling of the south room. A diffusing film was placed underneath the skylight reflector to illuminate the area below the skylight (Figure 3c). Sunlight can pass through small gaps between individual sections of the central reflector. Glass with a partial diffusing frit pattern was used to seal the skylight from the interior environment and to control the direct glare from the reflectors.

* Surface-solar azimuth angle is the angle between outward normal of the window and the solar azimuth angle, where negative angles are towards the east, and positive angles towards the west.

3. EVALUATION

We started with rough, approximate evaluation methods to gain insight into general daylight performance, then progressed to more accurate evaluation methods to refine the design. Lasers and smoke chamber photography were used to visualize light redirection and degree of spread resulting from the complex designs. Scale models of all prototypes were built to resolve and evaluate critical daylighting, sun penetration and glare issues. A series of experimental outdoor tests were conducted to evaluate the qualitative and quantitative daylight performance of each prototype, allowing progress toward more refined designs. Finally, experimental measurements under laboratory conditions were carried out to obtain a more accurate daylighting performance evaluation for all daylight hours throughout the year.

3.1 Outdoor Physical Model Tests

Initial designs of the prototypes were mocked up with physical scale models, then measured and photographed outdoors under clear sky conditions and representative times of the year. These tests enabled us to obtain an immediate evaluation of the efficiency of the system, to visualize the amount of daylight redirection, to observe how direct sun penetrates the interior space, and to detect the presence of specular reflections or bright areas due to the optical films.

The scale models for the light shelf and light pipe were constructed at a scale of 1:12 (1 in = 1 ft), to model a real scale office space with dimensions of 6.1 m (20 ft) wide, 9.1 m (30 ft) deep, and 3.1 m (10 ft) ceiling height. The interior surface reflectances were 0.76 for the ceiling, 0.44 for the walls, and 0.21 for the floor. Only the upper daylighting aperture was modeled to isolate the daylight contribution from the prototype design. Workplane illuminance measurements were taken at 18 interior reference points. The scale model for the skylight prototype was built at a scale of 1:6 (2 in = 1 ft), to model a prototype office of 3.6 m (12 ft) wide, 4.6 m (15 ft) deep, and 2.9 m (9.5 ft) ceiling height. The interior surface reflectances were the same as the light shelf/ pipe scale model, and workplane illuminance measurements were taken at 16 interior reference points per room. Measurements were taken for the 34°N latitude at 9:00 AM, 12:00 PM, and 3 PM on the winter and summer solstice (June 21 and December 21) and the equinox (March 21 and September 21).

3.2 The IDC Method

The simulation of the annual daylight performance of these optically complex systems was accomplished using the IDC (Integration of Directional Coefficients) method, which combines scale model photometric measurements with analytical computer-based routines to determine daylight factors and daylight illuminance under any sun, sky, and ground conditions [3]. Using the LBL Scanning Radiometer, workplane illuminance measurements were taken inside a 1:24 (0.5 in = 1 ft) scale model of a space similar to that used for the light shelf and light pipe outdoor tests. Measurements were taken at the same interior reference points as the outdoor tests. A total of 121 incoming directions of solar radiation at 15° increments, covering the whole hemisphere seen by the window, were used to create a comprehensive set of directional illuminance coefficients for each interior reference point. These coefficients were then used in analytical, computer-based routines, to simulate the daylight performance of the modeled space for 168 sun positions under CIE clear sky luminance distributions, with a uniform ground reflectance of 0.20. The light shelf and light pipe prototypes were modeled for Los Angeles outdoor sunlight conditions [4]. The resulting workplane illuminance levels due to the sun component were plotted over a sun angle chart for latitude 34°N [5] for a comprehensive analysis of the luminous performance throughout the year of each prototype designed (Figures 4a and 5a). No IDC tests were performed for the skylight design.

4. RESULTS

4.1 Light Shelf Results

Results from the IDC method indicate that for an inlet aperture area of 1.1 m^2 (12 ft^2) the south facing light shelf prototype can achieve workplane illuminance levels of over 300 lux (28 fc) throughout the year for surface-solar azimuth angles, $\gamma < \pm 45°$ (10 AM to 2 PM year-round) and can achieve over 50 lux (4.6 fc) for $\pm 45° \leq \gamma \leq \pm 90°$ at a distance of 8.4 m (27.5 ft) from the window wall (Figure 4a). These daylight levels are given for the direct sun contribution only, since the clear sky contribution was relatively small: less than 25 lux (2.3 fc) throughout the year. For the east/west facing light shelf, the workplane illuminance level is over 300 lux (28 fc) throughout the year for $0° \leq \gamma \leq \pm 15°$, and can achieve over 50 lux (4.6 fc) for $\pm 15° < \gamma \leq \pm 90°$. The distribution of workplane illuminance along the centerline of the space, at distances of 4.6-9.1 m (15-30 ft) from the window wall is fairly uniform under clear sky conditions, varying ±6-8% for all solar altitudes throughout the year for $\gamma = 0°$ (Figure 4b). Less uniformity occurs for sun angles that are not directly in front of the window since redirected daylight falls on the upper opposite sidewall surfaces for very oblique sun angles. In open plan offices where there are no sidewalls to obstruct redirected daylight, the distribution may be more uniform for oblique sun angles.

4.2 Light Pipe Results

The light pipe prototypes performed less consistently throughout the year than the light shelf designs, primarily due to the smaller inlet aperture area (0.1 m^2 (1.2 ft^2)). For the south facing light pipe, the workplane illuminance level at a distance of 8.4 m (27.5 ft) from the window wall is over 200 lux (18.6 fc) throughout the year for $\gamma < \pm 30°$, and over 100 lux (9.3 fc) for $\gamma \leq \pm 50°$ (Figure 5a). These data were determined using the IDC method. For $\gamma > \pm 60°$, the illuminance contribution from the light pipes was insignificant. The contribution of the clear sky component was less than 25 lux (2.3 fc) throughout the

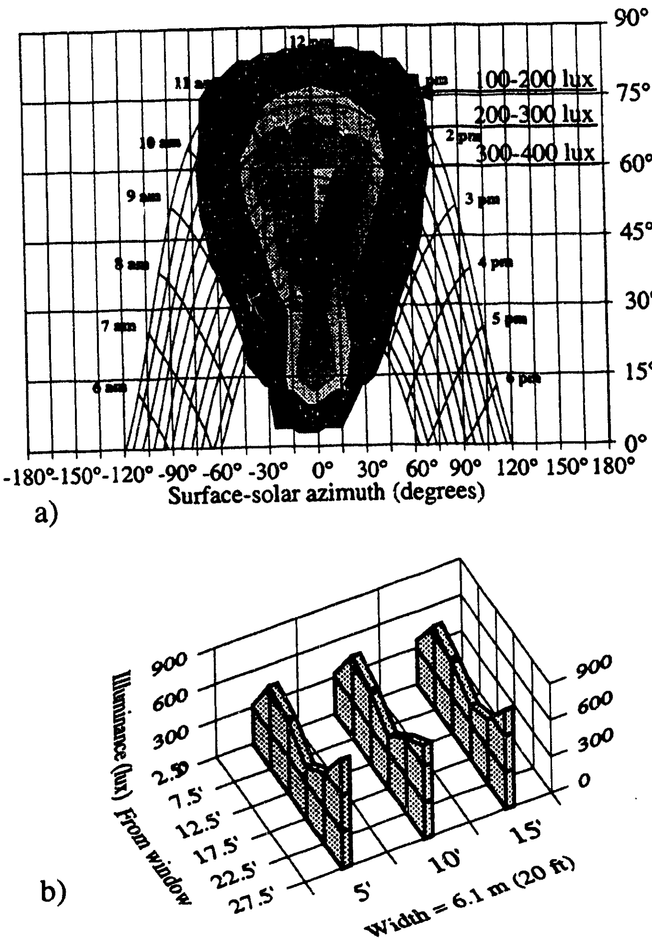

Figure 4. Workplane illuminance of south facing light shelf, modeled with the IDC method for latitude 34°N: (a) due to direct sun contribution only at 8.38 m (27.5 ft) vs. solar-surface azimuth angle, and (b) on September 21 at 12:00 PM. Total horizontal exterior illuminance is 88,750 lux (8245 fc).

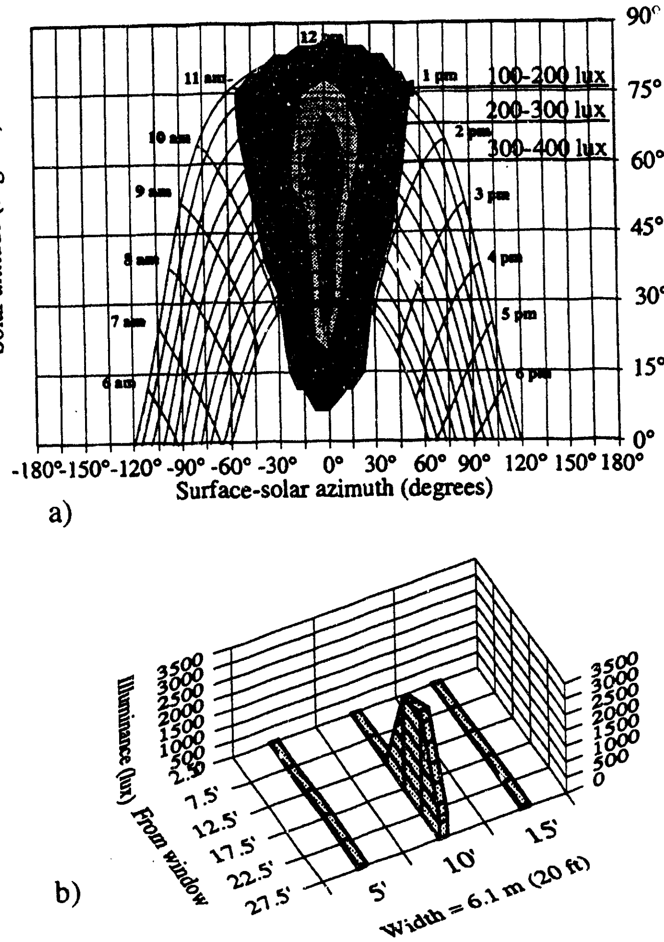

Figure 5. Workplane illuminance of south facing light pipe, modeled with the IDC method for latitude 34°N: (a) due to direct sun contribution only at 8.38 m (27.5 ft) vs. solar-surface azimuth angle, and (b) on September 21 at 12:00 PM. Total horizontal exterior illuminance is 88,750 lux (8245 fc).

year at the back of the room. Workplane illuminance levels can reach up to 3,300 lux (306 fc) at the back of the room; for example, when sunlight illuminates the 0.3 m^2 (3.2 ft^2) segment of the inlet reflector for the noon equinox hour.

With a single light pipe running along the centerline of the room, the distribution of workplane illuminance along the centerline of the space, at distances of 4.6-9.1 m (15-30 ft) from the window wall is not uniform under clear sky conditions, varying ±19-29% for all solar altitudes throughout the year for γ=0°. Over the entire 6.1 m (20 ft) wide space, work-plane illuminance levels drop as low as 50 lux (4.6 fc) throughout the year for γ=0° (Figure 5b). In the zone nearest the window (0-4.6 m (0-15 ft)), these levels will be supplemented by daylight from the lower view window. However, daylight levels and distribution can be improved if the input aperture area is enlarged, if side reflectors are used to redirect oblique sun angles, or if more than one light pipe is used in the space.

4.3 Skylight Results

Results from outdoor tests show that the skylight prototype distributes daylight more evenly throughout the space (including ceiling and wall surfaces) than the diffusing base case skylight (a skylight with the same aperture and light well shape as the prototype). The base case contrast gradient (maximum/minimum) is greater than the prototype for all nine times throughout the year; on the order of five times that of the prototype during summer noon hours (prototype contrast gradient = 9, base case = 46 in the room). Workplane illuminance levels of the skylight at the back of the space (3.66 m (12 ft)) are higher than the base case for both the south and north rooms (Figure 6). Because the prototype redirects light to the ceiling plane, partitions and furnishings are less likely to affect daylight illuminance levels. The skylight prototype may perform well in even deeper spaces, since we designed the reflectors for a short target distance for this particular building application.

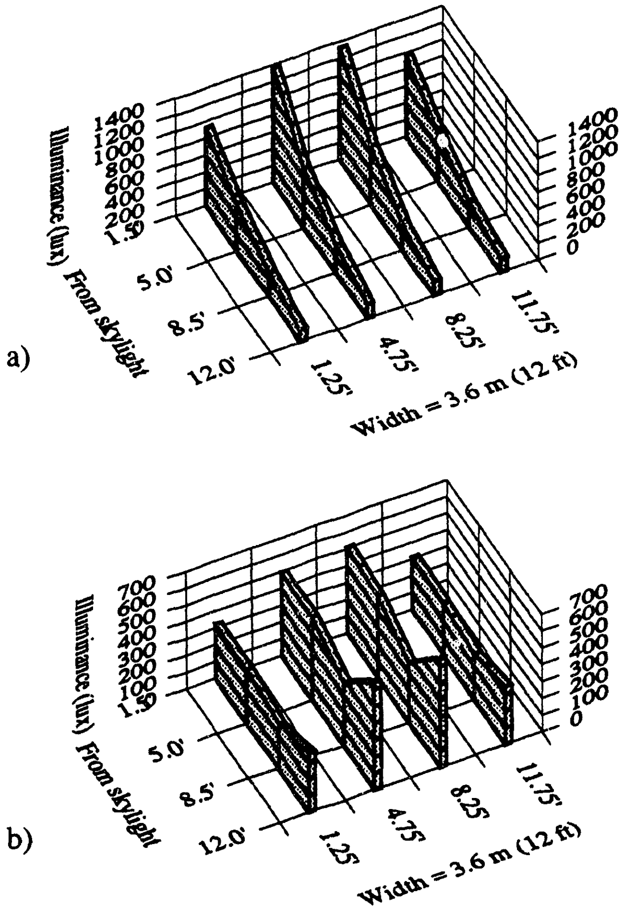

Figure 6. Workplane illuminance in the south room for the (a) Base case skylight and (b) Skylight prototype on December 21 at 12:00 PM, during outdoor tests. Total horizontal exterior illuminance is 55,350 lux (5142 fc).

5. CONCLUSIONS AND RECOMMENDATIONS

Results indicate that these passive light shelf and light pipe designs can introduce adequate ambient daylight for office tasks in a 4.6-9.1 m (15-30 ft) zone of a deep perimeter space under most sunny conditions with a relatively small inlet area. Sunlight is efficiently redirected towards the back of space when the sun is in front of the window within a 30° surface-solar azimuth, achieving workplane illuminances consistently above 200 lux (18.6 fc) for the light shelf and light pipe throughout the year. Lower but still useful levels of daylight are provided for a greater range of sun angles.

A visual inspection of the physical scale model has shown that under sunny conditions, the light shelf and skylight designs redirect virtually all of the sunlight towards the ceiling plane, thus lighting the room depth with a significantly improved uniformity. The light pipe also provides generally higher wall surface brightness at the back of the room, which can help to improve visual comfort. Direct glare from low incoming solar angles has been controlled in all designs by interception and redirection of the sunlight towards the ceiling.

Several refinements to these daylighting designs are under development to improve the daylight performance for a wider range of surface-solar azimuth angles. We are currently working to adapt these prototypes to several new and retrofit commercial buildings.

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