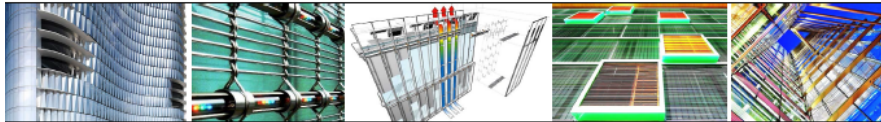


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Using Sunlight as a Light Source in Building Cores

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This paper presents the lighting performance of a passive horizontal solar light pipe designed for deep floor plan buildings with open-plan configuration. The light pipe system was designed to deliver natural light at the back of deep-plan buildings (5-10 m from window wall) using an optimized geometry and high reflective materials. The current light pipe system was developed for latitude 30.6°N in a predominantly sunny and clear sky location. A 360° rotating experimental room was built to test the light pipe performance at different orientations. The experimental room represents a section of a deep open plan office space of 3.6 m high, 6.1 m wide, 9.1 m long, with an area of 56 m².

Preliminary results of photometric measurements in a South-facing orientation have shown that on clear and partly cloudy days (global horizontal illuminance GH, ranging 20,000-120,000 lux), the light pipe can provide at 8 m from the perimeter, between 300 to 2,500 lux for about nine hours (9:00 am-6:00 pm). The highest illuminance values (above 1,000 lux) are achieved consistently between 10:30 am and 4:30 pm under clear sky conditions. Natural light is evenly distributed over the workplane; the sidelight window illuminates the front of the room and the light pipe system the back.

Keywords: daylighting; solar technologies; core sunlighting; light pipe; passive design

Introduction

Researchers around the world had demonstrated that daylighting is an effective strategy to offset electric lighting, reduce cooling and heating loads (Heschong 2003a); as well as to increase human comfort and productivity (Heschong, 2003b; Foster, 2011; Veitch & Galasiu, 2012). This paper is presenting a passive core sunlighting technology that introduces adequate daylight levels in building cores without glare and solar heat gains.

We live and work in buildings that are often isolated from natural light and where electric light is often around 200 lux and seldom exceeds 500 lux (Foster, 2011) in order to save energy. In recent years light pipes have been explored because of their potential to introduce daylight further into the building core. One of the first developments of a passive horizontal light pipe suitable for deep plan office buildings was developed by LBNL (Beltrán, Lee, Papamichael & Selkowitz, 1994; Beltrán, Lee & Selkowitz, 1997). The characteristics of the light pipe presented in this paper are based on the preliminary design concepts developed by the author at LBNL. Other researchers adapted this passive horizontal light pipe design to locations at low latitudes, 3°N and 14°N (Chirattananon, Chedsiri, & Renshen, 2000; Garcia & Edmonds, 2003). In these locations the light pipes were oriented to face the sun, East or West, limiting the light pipes' daylight performance. An anidolic (non-imaging) ceiling was also developed to collect light rays from the sky and redirect them to the back of a small room (6 m). This system is suitable for locations with predominantly overcast skies (Courret, Scartezzini, Franzoli & Meyer, 1998). Recent developments to redirect sunlight include active light guiding systems that integrate electric lighting, as backup

lighting, along with heliostats and tracking mirrors (Rosemann, Cox, Upward, Friedel, Mossman & Whitehead, 2007). Some researchers consider that these systems are not economically viable for general-purpose lighting due to the expense and maintenance of the active collectors (Leslie, 2003). However, new technologies continue being developed to introduce natural light at further distances from building facades. This paper presents the long term assessment of a core sunlighting technology.

Description

The light pipe system is designed to introduce daylight passively in any floor of deep-plan multi-story buildings (9 m-12 m) (Beltrán et al., 1997). The system was designed for latitude 30.6°N in a predominantly sunny and clear sky location (College Station, Texas) with an annual 81% of clear and partly cloudy days. The light pipe prototype uses a relatively small inlet glazing area, 0.3 m by 1.5 m, to efficiently redirect sunlight at distances up to 12 m from the window wall. The challenge of the design stems from the large variation in solar position and daylight availability throughout the day and year. Several reflectors are used to collimate incoming sunlight to minimize inter-reflections within the transport section of the light pipe, and to maximize the efficiency of the system (Beltrán & Martins, 2007; Beltrán & Uppadhyaya, 2008). The pipe is coated with a 99.3% specular highly reflective film. At the end of the light pipe a 4.6 m long diffusing radial film with 68-88% visible transmittance (T_{vis}) has been incorporated to distribute light into the space. The window wall ratio (WWR) and window floor ratio (WFR) of the light pipe are 2.5% and 0.8%, while the sidelight window has a WWR of 45% and a WFR of 7.5%.

Methodology

Experimental Facility

The experimental facility consists of a 360° rotating room that represents a section of a deep open plan office space of 2.5 m high, 6 m wide and 9.1 m long. This study presents results of the light pipe in a south-facing orientation. The space includes two sidelight windows of 2.7 m wide by 1.5 m high with T_{vis} of 51%. The windows have external moveable blinds with a reflectance of 0.8 (Figure 1). The interior surface reflectances are 0.81 for the ceiling, 0.88 for the walls, and 0.15 for the floor.



Figure 1. Exterior view of testing facility

Quantitative and Qualitative Assessment

Interior illuminance measurements were taken at twenty five reference points at workplane height, 0.76 m (Figure 2). Twenty five cosine- and color corrected LI-COR photometric sensors (LI-210SA) were placed over the workplane at equal distances, 1.5 m to 7.6 m from the window wall, at centerline. Outside the test room, two sensors were placed on the roof and façade to take global horizontal illuminance (GH) and global vertical illuminance (GV). Data was collected every 30 seconds. The analysis of illuminance levels are based on 10 hours, 8:00 am to 6:00 pm true local time (TLT), which is a typical office building schedule.

High Dynamic Range (HDR) images were created using the programs HDRcapOSX and Evalglare to assess the visual comfort in the testing room. HDR images were created from thirteen bracketed exposures to cover luminance ranges from 1-20,000 cd/m². False-color images were created from the HDR images to visualize the spatial luminance distribution, and measure the luminance variability across the space. Two glare indices Daylight Glare Probability (DGP) and Daylight Glare Index (DGI) were used to assess glare probability in the space (Jakubiec & Reinhart, 2012). A Canon EOS 60D camera with a fish-eye lens was used to capture a wide view of the interior lighting conditions.

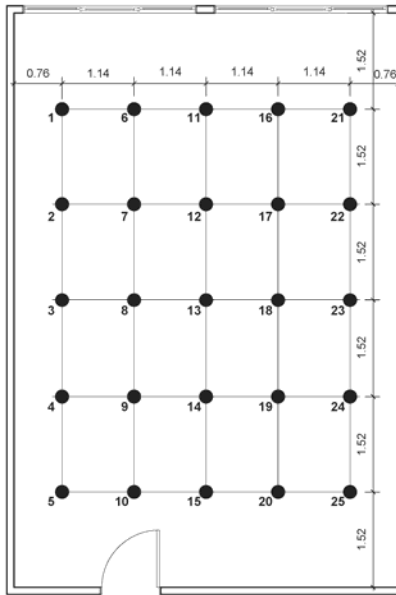


Figure 2. Photometric sensor location

Results

The light pipe and sidelight window provide natural light evenly distributed over the workplane and throughout the space (Figure 3). The space shows an overall uniform daylight distribution, the sidelight window illuminates the front of the room and the light pipe illuminates the back. Illuminance values at 4.5 m to 8.5 m from the window wall are higher than at 3.6 m. The high illuminance levels introduced by the light pipe at the back of the space demonstrates the efficiency of the light pipe design, which with an opening of 1/18th of the sidelight window area provides 5-6 times higher illuminance levels than those provided by the sidelight window at the back of the space. Figure 4 compares the illuminance distribution throughout the space with and without the light

pipe on April 23 at around solar noon. It is worth mentioning that a single light pipe is able to introduce adequate illuminance levels across a 6 m wide space. Long-term illuminance measurements confirmed that the light pipe provides similar lighting levels at the back of the room as in areas adjacent to the windows (Figure 4); for example, at 1.5 m from the window, light levels reach over 2,500 lux while at the back of the space (beyond 6 m) light levels reach over 2,000 lux. Daylight delivered by the light pipe at the back of the space allows having high light levels in interior office cubicles throughout the day.

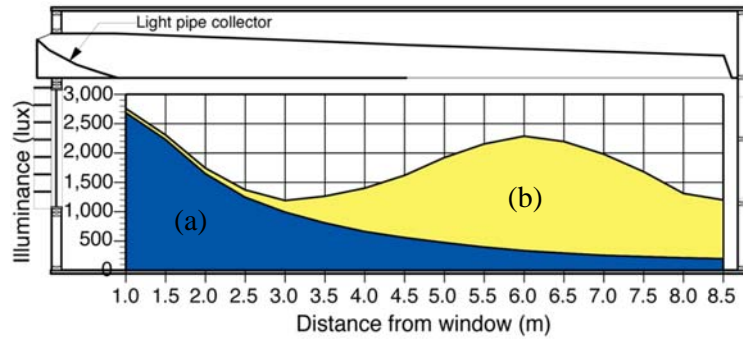


Figure 3. Illuminance distribution along centerline, (a) window and (b) light pipe, clear sky, 1:00PM, April 11

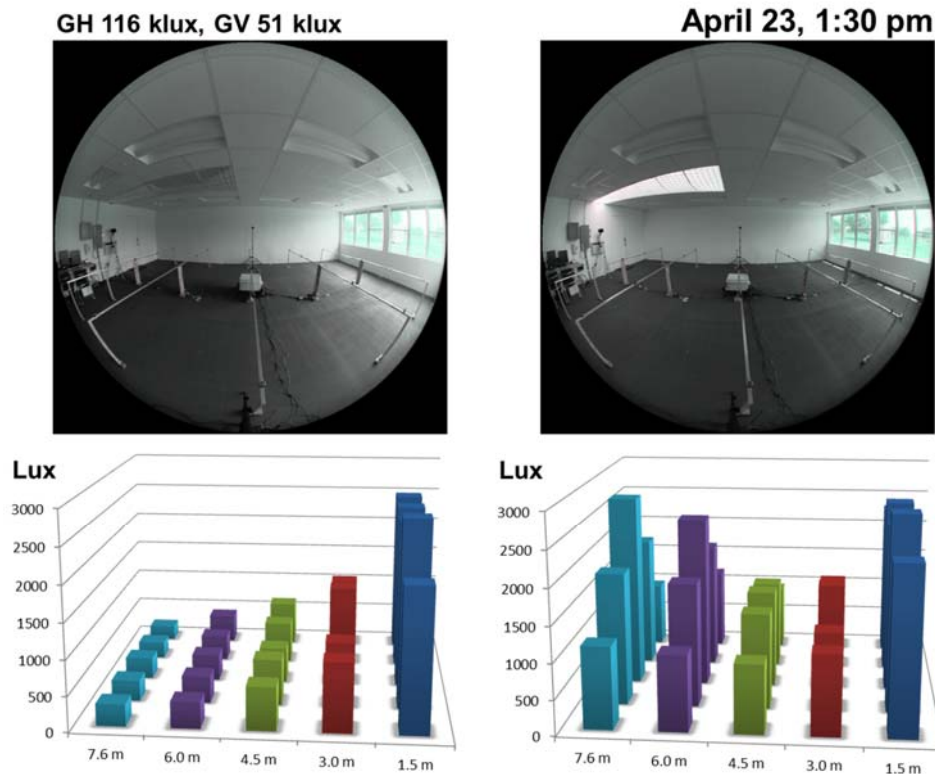


Figure 4. Daylight distribution in the room without (left) and with (right) the light pipe

The diversity of illuminance (DI) was calculated to measure the uniformity of light in the experimental room. DI is expressed as the ratio of the maximum illuminance to the minimum illuminance at any point, and must not exceed 5:1 (CIBSE, 1994). On April 23, the DI at the back (4.6 m-9.2 m) of the room did not exceed 5:1; it ranged

from 2.4:1 to 4:1 at all hours. The lowest DI at the back of the space is achieved at 12:25 pm, and the highest at 12:32 pm. Long-term measurements shows that the light pipe contributes to achieve a uniform illuminance distribution throughout the whole space during daytime hours.

Figure 5 depicts plots of the GH and GV with workplane illuminance at 7.6 m and 6.1 m from the window wall during three days around the winter solstice week (December 24-30). During this week, 5.5 days were clear and partly cloudy, and 1.5 days were overcast. These skies are representative of the local sky conditions in College Station, TX. Under clear skies (Figure 5a), the light pipe provided more than 300 lux for about nine hours at the back of the space (7.6 m). Higher illuminance levels (over 1,000 lux) are achieved between 10:00 am and 3:00 pm under clear sky conditions. Even during partly cloudy sky conditions with highly variable sky conditions (Figure 5b), the light pipe provided illumination of more than 300 lux for more than 7 hours, and over 1,000 lux for about 5 hours. Under overcast conditions (Figure 5c) the light pipe introduced at the back of the space more than 300 lux (>4 hours) when GH is over 15 klux. It is worth noting that this light pipe design could provide more than 300 lux in locations with predominantly overcast conditions. Even when GH and GV falls below 15-18 klux, the light pipe provides useful light levels (100-150 lux) at the back of the space which can be supplemented with electric lighting to reach to the desired 300-500 lux. A prototype, under development, will integrate LED lighting (within the distribution section of the light pipe) to provide supplementary lighting when illuminance levels fall below 300 lux.

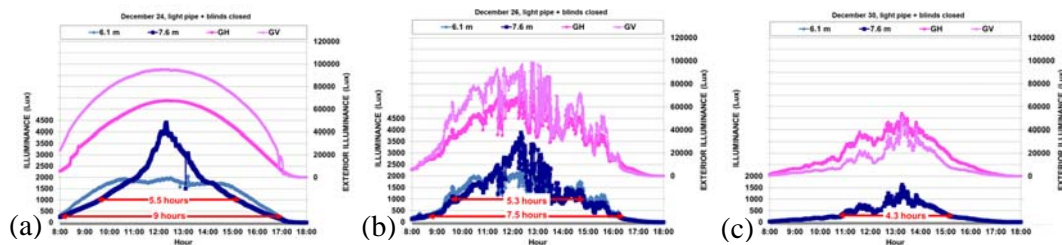


Figure 5. Hourly workplane illuminance at the back of the space with light pipe and blinds closed under (a) clear sky, (b) partly cloudy, and (c) overcast skies, around winter solstice

Figures 6a-f depicts clear and partly cloudy days from January to July between 8:00 am and 6:00 pm (typical office space schedule). The light pipe provides high illuminance levels around noon hours during winter solstice when the sun is low in the sky during short winter days (Figures 5a and 6a). Around spring equinox and summer solstice, light levels above 300 lux are achieved during more than 9 hours due to longer summer days. The overall annual performance consistently demonstrates the efficient sunlight redirection of the light pipe design. Figure 7 shows the sun positions (in solar time) of the measurements taken from January to July (Figure 6) when illuminance levels were above 300 lux and 1,000 lux. It is noticeable that when the sun is not facing the light pipe opening and it is at oblique incident angles, $>90^\circ$, (early in the morning and late afternoon between equinox and summer solstice), the light pipe introduces more than 300 lux. Ambient light of 300 lux throughout deep floor plan spaces is important for saving energy during daytime hours because it reduces the use of electricity for lighting.

The light pipe introduces more than 600 lux at the back of the space for more than 7 hours from January to July, as shown in Figure 6. Therefore, during these hours

illuminance levels throughout the space exceed current illuminance recommendations for reading and writing in spaces where at least half of the occupants are over 65 years old (DiLaura, Houser, Mistrick, & Steffy, 2012). This is particularly important due to an increased ageing population (65 years or older) with needs for higher illuminance levels because less light reaches the retina of an aging eye than it does in a younger eye.

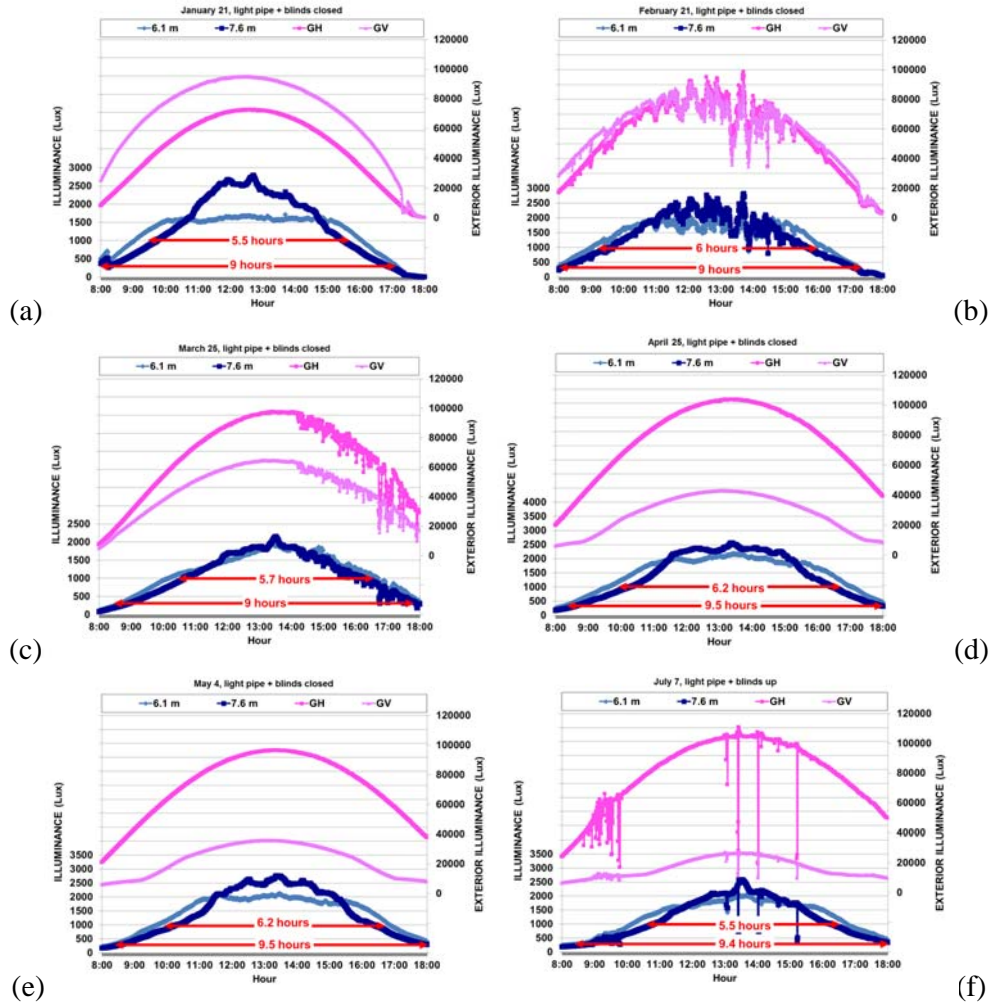


Fig. 6 Hourly workplane illuminance at the back of the space from (a) January to (f) July, under predominantly clear and partly cloudy skies

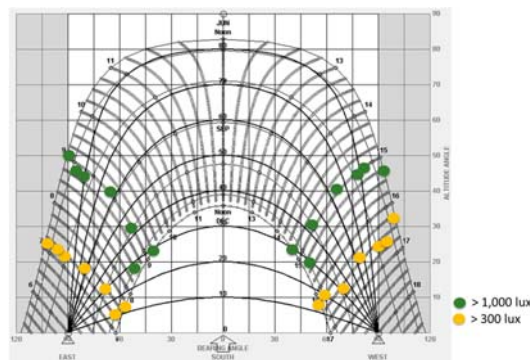


Figure 7. Sun positions when more than 300 lux and 1,000 lux are introduced at 7.6 m from window wall (May 3).

Moreover, the light pipe is able to provide bright light (more than 1,000 lux) for more than 5.5 hours (55% of the time) mainly in building cores (Figure 6) where sidelight windows are not able to introduce more than 150-200 lux. In recent field studies, researchers have demonstrated the benefits of bright light in building occupant's well-being. Subjects exposed to bright light showed reduced sleepiness, shortened reaction times on psychomotor vigilance task, increased alertness and vitality (Iskra-Golec & Smith, 2008; Smolders, de Kort & Cluitmans, 2012; Phipps-Nelson, Redman, Dijk & Rajaratman, 2003). The benefits of having bright light in building cores become extremely important for occupants that spend most of their time indoors. The fact that the light pipe system introduces more than 1,000 lux of full spectrum light for more than 5.5 hours throughout the year, means that this passive daylighting technology is beneficial for occupants' health, especially to those that spend most daytime hours indoors, e.g. offices, schools, nursing homes, hospitals, etc.

The amount of daylight that is transmitted by (9.1 m long) this South-facing horizontal light pipe varied from 0.02 to 0.3. Transmission was calculated as the ratio of the measured luminous flux passing out the light pipe over the measured luminous flux falling on the light pipe opening. Measurements were taken 9 m from the light pipe opening, under its diffuser. The transmittance is not a fixed value and it changes according to the amount of outdoor illuminance. For about 53% of a typical partly cloudy summer day (August 15) the transmittance ranged between 0.05 and 0.3, with the highest values between 11:30 am and 3:30 pm TLT. The mean value was 0.07 and standard deviation of 0.04.

Figs. 8 and 9 show a sequence of HDR and false-color images taken from 7:00 am to 6:00 pm on May 3. In the false-color images, green and blue tones represent the lowest luminance values ($< 20 \text{ cd/m}^2$), and yellow tones represent the highest values in the space. The luminance distribution over the floor and East sidewall demonstrates the uniform light over horizontal and vertical planes surrounding the light pipe distribution area. The luminance values over the floor, underneath the light pipe and areas adjacent to the sidelight window are similar between 11:00 am and 4:00 pm. During these hours, the brightest area in the space is the sidelight windows with blinds up. This area has an average of 35% of luminance values exceeding $2,000 \text{ cd/m}^2$ with a mean luminance value of $1,950 \text{ cd/m}^2$. The brightness of the windows is usually controlled by occupants by opening or closing the interior or exterior blinds. The second brightness area in the space is the light pipe diffuser. This area has an average of 20% of luminance values exceeding $2,000 \text{ cd/m}^2$ and lower mean values than the sidelight window ($1,650 \text{ cd/m}^2$). In order to control the brightness of the light pipe distribution area, miniature louvers and electrochromic glass could be integrated to the light pipe opening. This will give occupants the option to have control of the illuminance levels and brightness of the space.

Preliminary assessment of the visual comfort in the space using the discomfort glare indices (DGP and DGI) had shown that glare is imperceptible most hours of a typical clear day (May 3). Table 1 presents DGP and DGI values throughout the day at a location in the middle of the room next to the West wall. The shaded cells in Table 1 indicate hours when vertical illuminance levels at the photo camera were below 380 lux, and evalglare may have underestimated glare sources. Further analysis of glare probability will be evaluated in the space at different locations in the room, and with interior cubicles with typical office furniture.

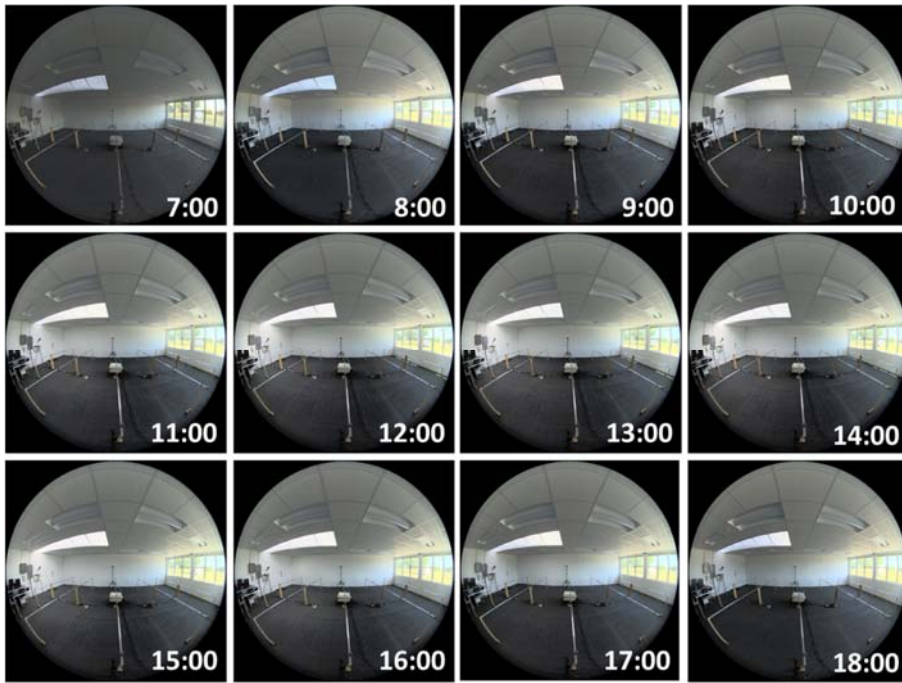


Figure 8. Time-lapse of HDRs on May 3

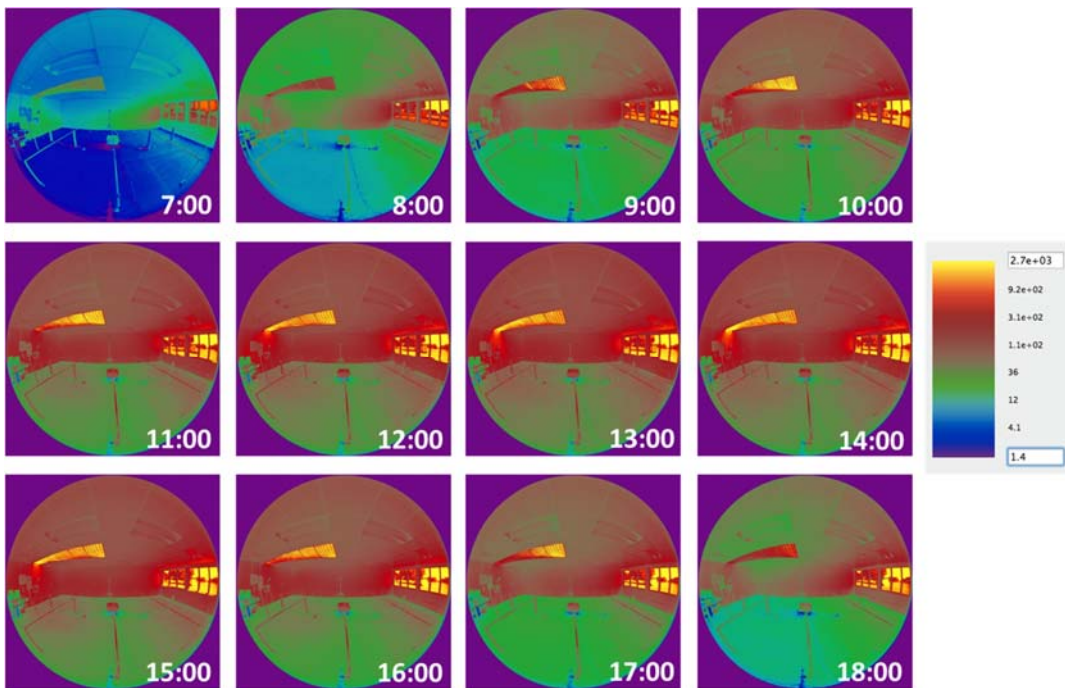


Figure 9. Time-lapse of False Color images on May 3

Table 1. DGP and DGI values, on May 3

| Time | DGP | DGI |
|----------|------|-------|
| 8:00 AM | 0.09 | 11.32 |
| 9:00 AM | 0.20 | 14.57 |
| 10:00 AM | 0.22 | 16.42 |
| 11:00 AM | 0.21 | 15.46 |
| 12:00 PM | 0.21 | 14.49 |
| 1:00 PM | 0.22 | 14.72 |
| 2:00 PM | 0.21 | 14.33 |
| 3:00 PM | 0.21 | 14.63 |
| 4:00 PM | 0.21 | 14.94 |
| 5:00 PM | 0.21 | 15.71 |
| 6:00 PM | 0.18 | 13.27 |

Conclusions

The passive core sunlighting system presented in this paper is an effective daylighting system that can provide healthy full-spectrum lighting in deep floor plan spaces for 9 hours under clear and partly cloudy sky conditions, which is the annual predominant sky condition in the central southern part of US. The light pipe introduces consistently throughout the year illuminance levels between 300-2,500 lux at 9 m from the window wall. Exposing building occupants to bright light (>1,000 lux) will help them regulate the timing of their circadian rhythms, which also has a direct effect on alertness and performance (Foster, 2011).

The lighting levels provided by the light pipe at the back of the space are similar to the ones provided by the sidelight window at the front of the space, even though the light pipe's glass area is only 5% of the sidelight window area. Therefore, cooling loads generated by the light pipe will be insignificant compared to the ones generated by the sidelight window, and to the cooling loads generated by the electric lighting it offsets. Light levels are distributed uniformly throughout the space creating a visually comfortable space for occupants of deep floor plan buildings.

The light pipe is a sustainable technology that can change the way buildings will be designed in the future. It may not be necessary to have large expanses of glass to introduce more daylight to the core of buildings and deal with the effects of increased cooling loads. Several building types (e.g. offices, schools, nursing homes, hospitals, housing for the elderly and visual impaired people) can benefit from this technology, which utilizes direct solar energy with no operational costs, and provides high illuminance levels of full-spectrum light.

Currently, we are monitoring the light pipe performance for other orientations, e.g. East, West, SE, SW, and its interactions with lighting controls and automated shading devices. We are also developing light pipe systems for other locations, integrating them with electric lighting and HVAC, improving its efficiency, and simplifying its construction for mass production.

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