Paper No: 199 Displacing Electric Lighting with Optical Daylighting Systems

Liliana O. Beltrán, Ph.D.[1]*, Kapil Uppadhyaya[2]

College of Architecture, Texas A&M University, College Station, TX, USA[1]*
LOBeltran@archmail.tamu.edu

Abstract

This paper presents the findings of a study that evaluates the overall daylight performance of two optical daylighting systems in two large physical scale models representing a multi-story deep office building (30ft) with open-plan configuration. These two optical systems are: a passive optical light shelf, and a light pipe. The systems were designed to introduce daylight at the back of deep-plan spaces (15-30ft) using optimized geometries and highly reflective materials. The systems were designed for a south-facing façade located in a hot climate with predominantly sunny and clear sky conditions at latitude 30°N. The main objectives of this experimental work are: to compare these daylighting systems with a reference case (typical office layout with partitions, blinds and shading devices); to take illuminance measurements and collecting detailed data under different sky conditions for extended periods of time; to analyze these data using the following metrics: Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), Illuminance Contrast Gradient (ICG), High Dynamic Range (HDR) photographic evaluation, Unified Glare Rating (UGR) Coefficient of Variation (CV) of luminance, and Luminance Ratios (LR). Results have shown that both daylighting systems achieved a higher daylight performance than the reference case in terms of adequate light levels for office tasks, uniform light distribution throughout the room, and a visually comfortable space for occupants. The light pipe system had demonstrated to be an effective system that provides high illuminance levels, 300-1,500lux at the back of the space (15-30ft) for more than 7 hours (between 8:30am to 4:30pm) under clear skies. The light shelf increases the illuminance level along the space by about 190lux, as well as the uniformity across the space. The combined workplane illuminance values measured on clear days (>500lux) are satisfactory without the need to turn on the electric lights, for more than 6 hours between 9:00am and 4:00pm. When the two daylighting systems are integrated in the space, their lighting performance is extremely well mostly under sunny skies; and under overcast skies they provide useful illuminance levels, 1% of EXHG (exterior horizontal global illuminance) at the back of the space. As for light uniformity and visual comfort, the two integrated systems demonstrated to have lower ICG, LR, and lower CV than the reference case, and with UGR values within the recommended lighting standards.

Keywords: daylighting, light pipes, light shelves, visual comfort

1. Introduction

The use of daylighting in commercial office buildings is an effective strategy to offset artificial illumination and to reduce cooling, and heating loads; as well as to increase human comfort and performance [1]. However, commercial buildings are frequently designed with deep floor plans (a hundred feet or more), resulting in building cores with limited access to daylight and windows that provide high light levels to the first 15ft from the window plane. As a result the interior spaces have uneven illumination, with extremely high illuminance levels near the window and low light levels at the back of the space. Therefore, the core of these buildings depends exclusively on electrical lighting for obtaining adequate illumination, leading to the subsequent increase in energy consumption.

This paper shows that two passive optical systems: a horizontal optically-treated light pipe and a light shelf can be able to provide adequate light levels at the back of a deep space and displace the need for electric lighting without introducing additional solar heat gains to the building.

The characteristics of the light pipe and light shelf of this study are based on the daylighting systems developed by LBNL [2]. A first light pipe prototype was built and monitored throughout a year [3]. Results showed that the light pipe could provide illuminance levels of more than 300lx at the back of a deep plan space (15ft to 35ft) for more than six hours under clear sky conditions. The present research has focused on the optimization of the light pipe geometry and integration with light shelves and shading devices (external and internal.)

2. Daylighting Systems

Two south-facing deep open plan office spaces of 10ft high, 20ft wide and 30ft long were represented in two models (scale 1:4) [3]. Both models included identical exterior horizontal shading devices and interior blinds in a semi-open position (inwards 45º) to intercept winter low sun angles (Fig.1.) The objective was to represent an office envelope that minimizes solar heat gains and maintain views to outside. The Reference Model (RM) is illuminated thru a sidelight window only, while the Test Model (TM) includes also a light pipe and a light shelf. The light pipe is placed at the center of the space within the ceiling plenum, and the light shelf runs across the space below the light pipe. Some tests were done with a removable partition (5ft high) placed at 15ft from the window wall, across the width of the space.

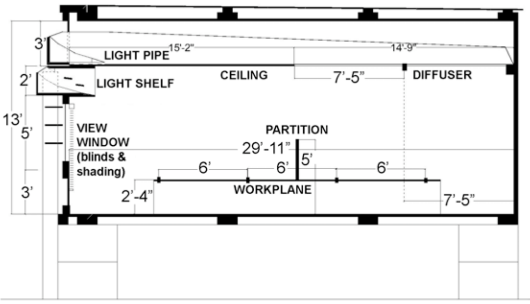


Fig 1 Cross-section of models showing the light pipe and light shelf

2.1 Location

Both models were placed side-by-side on the roof of the College of Architecture at the Texas A&M campus in College Station, Texas (latitude 30.6ºN, longitude -96.3ºW.) The site has minimum obstructions, with limited sun access before 8:00am and after 4:00pm year-round, which provides about 8 hours of direct sunlight in winter and 6 hours in summer over the south-facing façade (Fig.2.) The percentage of annual clear and partly clear days is higher than 81% [4].

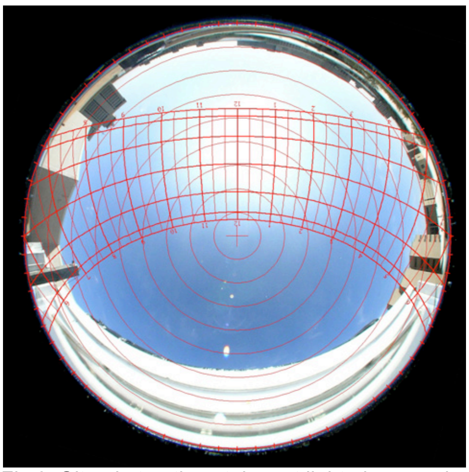


Fig 2. Site obstructions taken at light pipe opening

2.2 Light Pipe

The light pipe was designed to capture, transport and distribute daylight over the last 15ft of the room. It consists of three distinct parts: collector, transport section and diffuser (Fig.3.) Previously to this study a light pipe prototype (Fig.5a) was built with similar characteristics as the one developed by LBNL [2]. The results showed that this prototype has a good daylight performance, it can introduce more than 300lx for more than six hours under clear sky conditions [3]. The next challenge was to optimize this prototype to increase the daylight output at early morning and late afternoon hours.

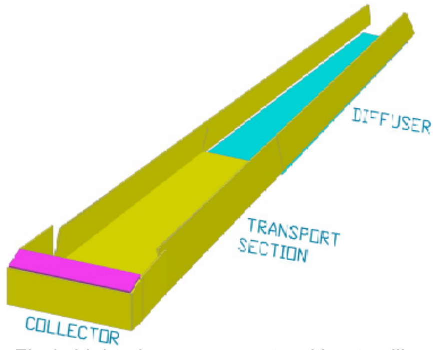


Fig 3. Light pipe components without ceiling

The present study focused on the optimization of the light pipe geometry and interior reflectors without increasing the glazing area. The glass area is 5.5ft^2, the window floor ratio (WFR) and window wall ratio (WWR) are 0.9% and 2.1%, respectively. The ray-tracing program TracePro (Fig.4) was used to evaluate the light flux output at extreme sun positions (solstices and equinox) of six different light pipe designs (Fig.5a-e.) The light pipe with the highest light output at low sun angles and the lowest overall volume was selected. The objective was to increase the amount of light transported at oblique sun angles during early morning and late afternoon hours.

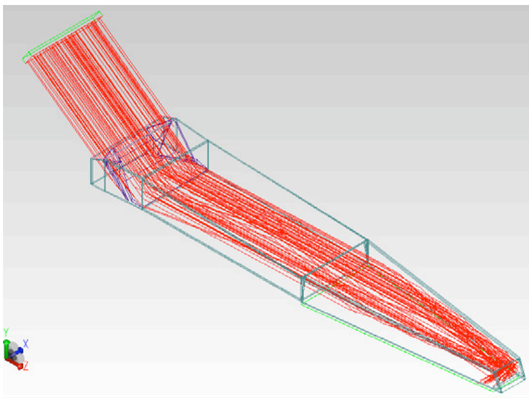


Fig 4. Ray-tracing analysis of optimized light pipe for June 21, 12:00pm.

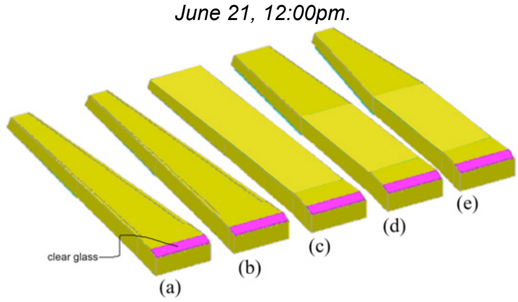


Fig 5. Light pipe prototypes tested, (a) original design [2], (b)-(d) design variation, (e) final optimized design.

2.3 Light Shelf

A light shelf adapted from LBNL's original design [2] to latitude 30.6ºN was constructed to provide higher workplane illuminance levels deeper into the space and to increase light uniformity across the space. The light shelf has three primary reflectors that respond to daily and seasonal range of sun positions, and two secondary reflectors to intercept and redirect low winter sun angles. Each reflector was designed to block direct sun, control direct glare and thermal discomfort. The glazing area of the light shelf is 14.7ft^2 (2.7 times the light pipe glass area,) WFR and WWR are 2.5% and 5.6%, respectively.

3. Methodology

3.1 Photometric Assessment

Interior illuminance measurements were taken at twelve reference points at workplane height (28") in each model. TM had three additional sensors over the back and sidewalls at seating eye level (47"), and one sensor on the ceiling facing down (Fig.6.) The twelve sensors over the workplane were placed at equal distances (6ft to 24ft) from the window wall, at the centerline, and 5ft on either side of the centerline. Outside the models, four sensors were placed in pairs to take global and diffuse of horizontal and vertical illuminance. Light levels were recorded every minute by a CR23X datalogger. The measured illuminance data was used to calculate metrics such as: Daylight Autonomy (DA) [base 300-500lx], Useful Daylight Illuminance (UDI) and Illuminance Contrast Gradient (ICG) [5]. To evaluate the light contribution of the light pipe and light shelf by themselves, the lower window of the TM was covered with a black cloth. To observe the variations of sun penetration throughout the day of the light pipe and light shelf, time-lapse sequences were recorded.

3.2 HDR Photography

High Dynamic Range (HDR) images were created using the program Photolux 2.1 to assess the visual comfort in the models. HDR images were created from nine bracketed exposures to cover from 1-20,000 cd/m^2. A Nikon Coolpix 5400 camera with a fish-eye lens was installed on one of the side openings of the models. From the HDR images were calculated the UGR, LR and CV of luminance.

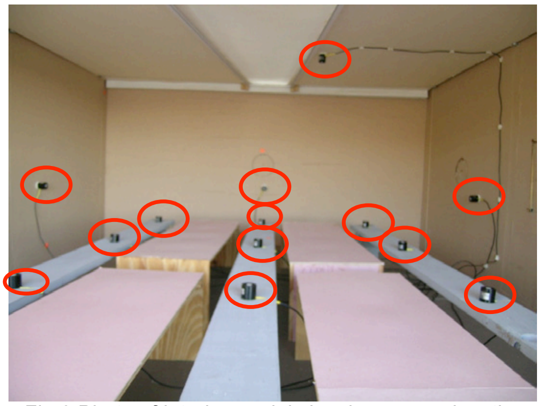


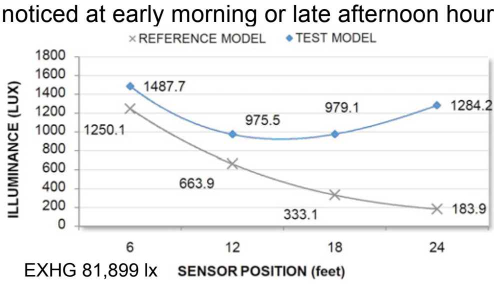
Fig 6.Photo of interior model showing sensor location

4. Results

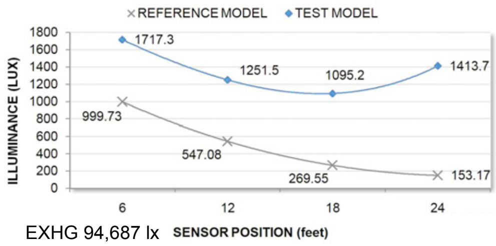
4.1 Lighting Performance

Illuminance levels of the RM and TM were compared. Fig.7 shows the workplane illuminance distribution in the RM and TM at 1:00pm under clear sky conditions on two different days. On Feb. 7, the TM was evaluated with light pipe only (Fig.8a); the light pipe introduced, at the back of the space, 3 to 7 times the illuminance introduced by the sidelight window of the RM, while on Mar. 5 when the TM was evaluated with light pipe and light shelf (Fig.8b) introduced 4 to 9 times the illuminance levels of the RM. The interior illuminance levels in the RM are lower on Mar. 7 than on Feb. 5 because the sun is 10º higher (52.3º and 42.6º respectively.) In addition, Fig.8 depicts that the light pipe introduces about 6-8 times more daylight than the light shelf at the back of the space. The light shelf introduces more daylight at the front of the space about twice the amount reaches the back.

On a clear day (maximum EXGH 80,000lx), the light pipe can provide more than 300lx for about eight hours at the back of the space, while the RM introduce less than 200lx throughout the day (Fig.8.) With the light shelf, the illuminance levels in the TM are increased (1,000-2,800lx) between 11:00am and 1:00pm, but no major contribution is noticed at early morning or late afternoon hours.



(a)



(b)

Fig 7. Workplane illuminance distribution in RM and TM at 1:00pm, (a) with light pipe, Feb. 7, (b) with light pipe and light shelf, Mar. 5

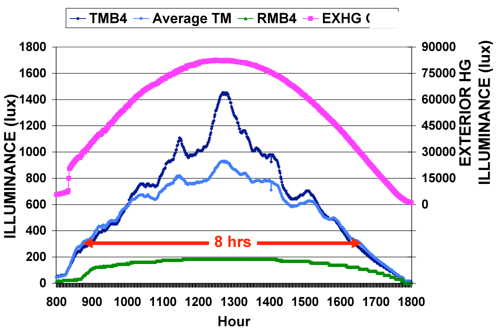


Fig 8. Workplane illuminance in back zone, TM with light pipe, Feb. 7

Under overcast conditions (EXHG<20klux), at 24ft, the TM with light pipe introduces two times the illuminance level in the RM (Fig.9.) Under similar conditions, light levels can reach ~200lx when the light shelf is added to the TM with light pipe.

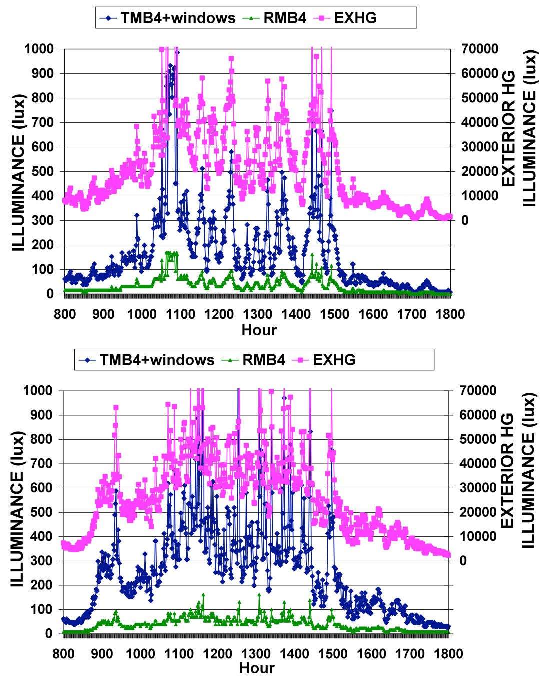


Fig 9. Comparison of RM and TM under cloudy sky conditions at 24ft, (top) Mar. 2, light pipe, (bottom) Mar. 17, light pipe and light shelf

The original light pipe design (Fig.5a) introduced more daylight near window (~2,000lx) and lower values at 24ft (~650lx). This occurred because the TM of the original light pipe design did not have any exterior shading device and have interior blinds in closed position to intercept sunlight. With the new light pipe and light shelf, light levels have decreased near the window and have increased at the back of the space (1,000-1,529lx) as shown in Fig.10.

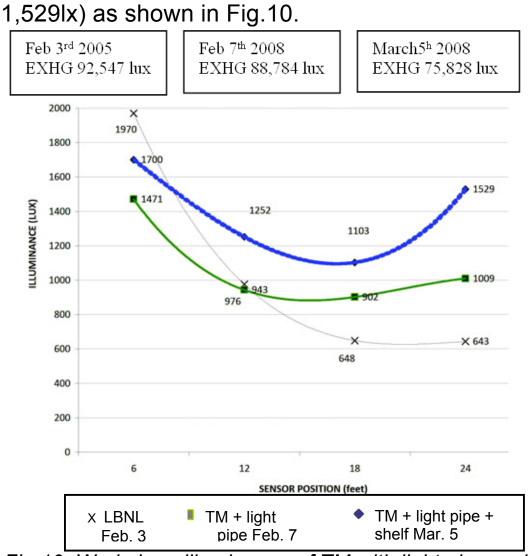


Fig 10. Workplane illuminance of TM with light pipe and light shelf with the original light pipe, 12:00pm

Table 1 shows that the average DA factor at the back of the space with light pipe only, under partly clear (Jun. 10) and clear sky (Feb. 7) conditions based on a 10-hour space occupancy between 8:00am-6:00pm is 67 and 77, respectively. This means that occupants can work between 7 to 8 hours with daylight alone.

Considering that the annual percentage of partly clear and clear days is more than 81%, the annual DA (based on 300lx) can be estimated as higher than 62.

The average annual UDI [100-2,000] at the back of the space varies from 74 to 79 under clear and partly clear sky conditions, which represents useful daylight between 9 to 10 hours more than 81% year-round.

Table 1: DA and UDI under clear sky conditions, average at the back of the space (15-30ft zone) based on 10 hours (8:00am-6:00pm) with light pipe

		DA >500	DA >400	DA >300	UDI [100-2000]	UDI [<100]
Feb 7	%	59	70	77	91	9
	hrs	6	7	8	9	1
June 10	%	48	59	67	98	2
	hrs	5	6	7	10	0.3

4.2 Visual Comfort Assessment

Visual inspection inside the models using HDR photography showed (Fig.11) that the TM with light pipe introduces a large amount of daylight at the back of the space (over workplane and center back wall) compare to the RM. When the light shelf is used in combination with the light pipe the illumination over the back wall and ceiling is higher, given the appearance of a much brighter space.

(a) *(b)* *(c)*

Fig 11. HDR images at 12:00pm, (a) RM on Feb. 6, (b) TM with light pipe on Feb. 7, (c) TM with light pipe and light shelf on Mar. 5

The illuminance contrast gradient (ICG), an indicator of lighting distribution uniformity in a space [4], is 2.5 times lower in the TM with the light pipe and light shelf than in the RM. Figs.12 and 13 demonstrate that the ICG values in the RM remains almost constant throughout the day, around 3.75, which means that the front of the space is almost four times brighter than the back with or without the 5ft partition. The overall ICG in the TM with light pipe and light shelf remains around 1.5 for most part of the day (10am-3:30pm) and increases up to 2.5-3.0 around 5pm. The partition affects slightly the uniformity in the TM showing variations of ICG between 1.5-2.0. This is mainly due to the window being blocked by the partition, which affects mainly the third row of sensors.

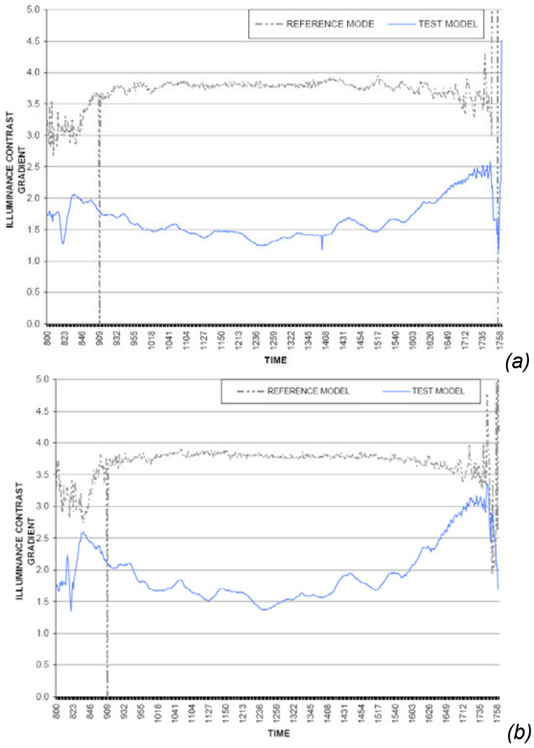


Fig 12. ICG, TM with light pipe (a) without partition, Feb. 7, and (b) with partition, Feb. 8

The CV of luminance was used to compare the variation of luminance on surfaces over time. On the back task plane, the lowest CV and ICG without partition were found in the TM with light pipe and light shelf (Fig.14a,) and the lowest CV with partition was found at RM, which shows also the lowest illuminance levels (>200lx.)

On the West wall the lowest CV was with the TM with light pipe and light shelf after 12:00pm while the CV on the TM with the light pipe only remained low and constant throughout the day.

On the back wall the CV was the highest in the TM with light pipe and light shelf (Fig.14b,) this occurs because the light shelf redirects sunlight towards the back wall mostly around noon hours. The partition did not affect luminance uniformity over sidewalls or back walls.

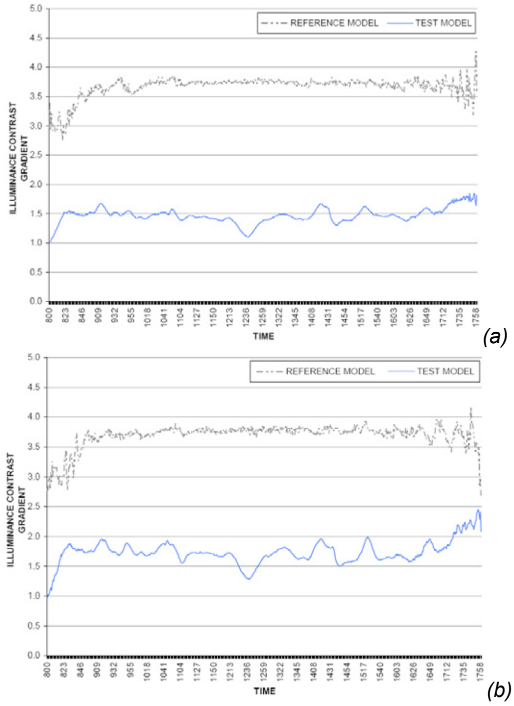


Fig 13. ICG, TM with light pipe and light shelf, (a) without partition, Mar. 5, and (b) with partition, Mar. 4

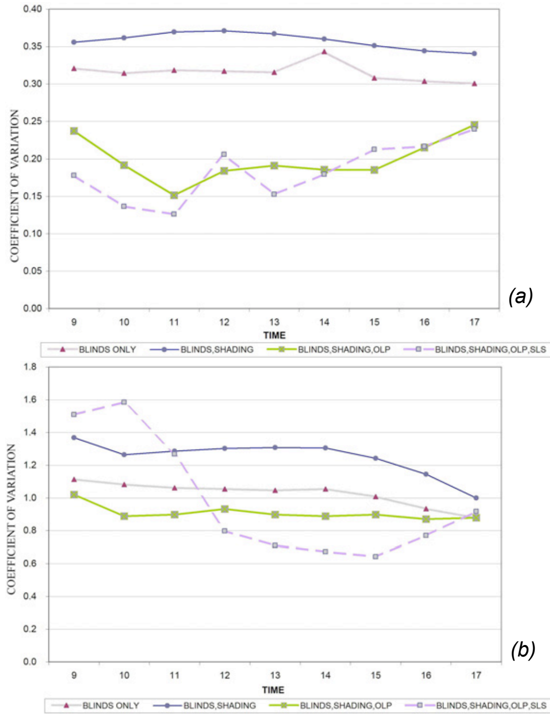


Fig 14. CV without partition (a) at back task plane, and (b) West wall

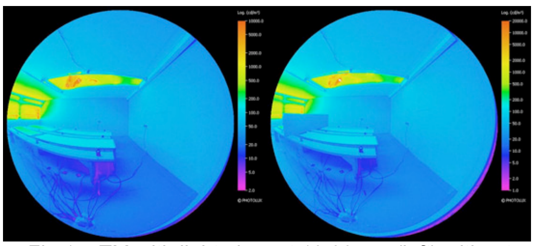


Fig 15. TM with light pipe, at 10:00am: (left) without partition, Feb. 7, (right) with partition, Feb. 8

The UGR was used to determine the possibility of glare. It was measured at the back of the space (24ft) on the East wall in both models. The overall UGR values in RM and TM were under the maximum recommended limit of 20 for office spaces [5]. With the partition the UGR in the RM were reduced because of a partly blocked view of the window, while UGR in the TM with light pipe and light shelf is increased with peaks between 12:00-1:00pm (Fig.16.) The UGR values of TM with light pipe only are high (15-17) between 10:00am-4:00pm.

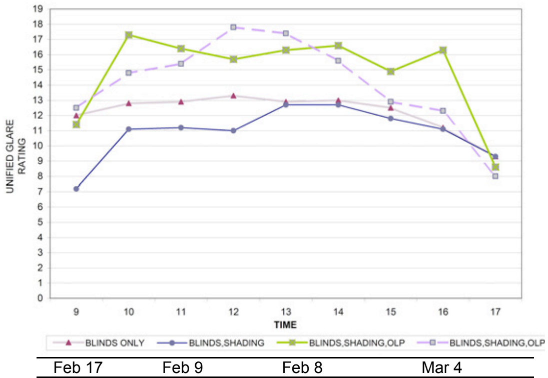


Fig 16. UGR variation throughout a day from a location at 24ft over East wall, with partition

LR between a VDT and the maximum luminance over the West wall in the TM with light pipe remained within the recommended levels, <10 [5]; while the TM with light pipe and light shelf had LR values over 10 before 1:00pm without partition, and before 12:00pm with partition (Fig.17.) This indicates that there is some probability of glare during these hours in areas adjacent to the light shelf. During afternoon hours, the East wall shows a similar pattern.

LR between VDT and maximum luminance of back wall remained less than 3 for TM with light pipe with or without partition. With the addition of the light shelf the LR increased to about 6 indicating that possibility of glare for workstations facing towards the window otherwise, the back will be illuminated by light reflected from this wall.

5. Conclusion

The optimized light pipe design presented in this study have demonstrated its potential to be an effective daylighting system than can displace the use of electric lighting in multi-story deep plan spaces for more than 7 to 8 hours under clear and partly clear sky conditions, which is the annual predominant sky conditions in the central southern part of US. The light pipe can introduce consistently illuminance levels between 300-1,500lx at 24ft from window wall. Under overcast skies [20-40klux] the light pipe can introduce 1% of the EXHG at the back of the space. The light shelf introduces lower light levels over the back task plane (average 190lx along centerline) than the light pipe, but it distributes daylight over back wall and ceiling given the appearance of a brighter and more uniform lighted space. Both the light pipe and light shelf do not increase additional solar heat gains to the building thermal loads due to their relatively small total glazing area (>3.5% WFR, >7.7% WWR.) The overall illuminance levels and distribution in deep plan spaces is improved with the light pipe and light shelf, along with the shading devices and blinds.

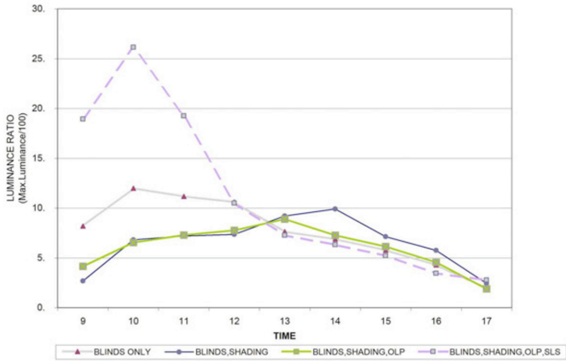


Fig 17. LR between VDT (100cd/m^2) and maximum luminance in TM with light pipe and partition

Currently the daylighting systems in the two models are being measured to assess their annual lighting performance. The next stage, which is in progress, is the integration of an energy efficient electric light source within the light pipe to maintain light levels in the space within 300-500lx during the 10-hour occupancy schedule to reduce the LPD (0.9W/ft^2) in office buildings.

6. Acknowledgements

The authors would like to thank the College of Architecture at Texas A&M University for funding this research and to Ms. Betina Martins-Mogo (M.Sc. Arch 2005) for the design and construction of the physical scale models and equipment setup.

7. References

1. Heschong, L., and D. Mahone, (2003). Windows and Offices: a Study of Office Worker Performance and Indoor Environment, California Energy Commission, San Francisco, CA.
2. L. Beltrán, E. Lee and S. Selkowitz, (1997). Advanced optical daylighting systems: light shelves and light pipes. *Journal of the Illuminating Engineering Society*, 26(2):p. 91-106.
3. Beltrán L. and B. Martins-Mogo, (2007). PLEA 2007, Development of Optical Light Pipes for Office Spaces. In *PLEA 2007 Conference*, Singapore, Nov. 22-24.
4. Martins-Mogo, B. and L. Beltrán, (2006). Evaluation of the Daylight Performance of Advanced Optical Light Pipes Using an Innovative Experimental Setup. In *EuroSun 2006 Conference*. Glasgow, UK, June 27-30.
5. Illuminating Engineering Society of North America IESNA, (2000). Lighting Handbook 9th ed. New York.