Nomination for the Far East Economic Review Asian Innovation Awards 2003 in association with Global Entrepolis @ Singapore

FAR EASTERN ECONOMIC REVIEW

Global Entrepolis @ Singapore

Light Pipes: An Innovative Design Device for Bringing Natural Daylight and Illumination into Buildings with Deep Floor Plan (Patent Applied)

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1 Innovation

The innovative device is the “light-pipe” as a passive low-energy device for transmitting natural daylight into buildings with deep plans.

The light pipe is a device that brings daylight into the inner parts of buildings (c. 12 meters) without the use of any electrical or other sources of energy. The extraction and emission of daylight is transmitted horizontally and vertically using internal mirrored surfaced within a box-tube structure (hence the term “pipe”) coupled with laser-cut panels at the outer edge of the pipe as collectors.

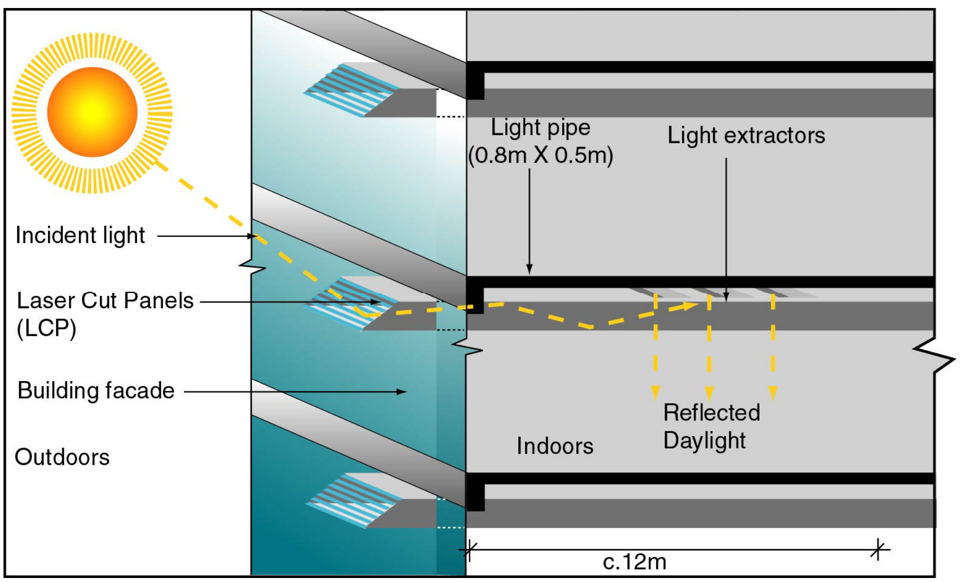


Figure 1: Diagram of light pipe.

2 Rationale for the Design

Buildings with deep-plans have become a common practice as they offer maximum financial returns from high urban land prices by achieving maximum plot to gross floor areas ratios (Yeang, 1999), and more space for tenants’ businesses to be

contained within the one floor. A consequence of this design is the tendency to locate service cores at one side of the building and increase the depth of the floor plate.
With such deeper floor plans (>10 m from windows), the usual natural illumination from daylight from side windows becomes impossible.

Previous research has shown that light transport systems represent a solution to naturally illuminate deep-plan buildings (Aizenburg, 1997, Whitehead el at., 1984), and provide increased energy efficiency; and physiological benefits in humans (ie regulation or circadian rhythms; Baker and Steemers, 2002). Previous studies (Garcia Hansen et.al, 2001) have shown the potential of mirrored light-pipes in deep-plan buildings, but that light distribution and extraction along the pipe was not optimal.

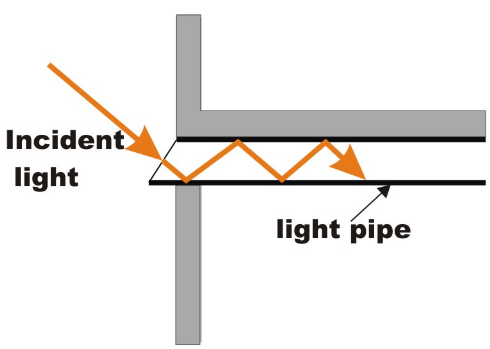
Consequently, in this invention we have developed a way to achieve light extraction ratified by theoretical calculations and scale-model measurements to optimise light distribution from horizontal and vertical mirrored pipes. Two case studies are considered here.

3 Description of the Light Pipe

There are 2 type of light-pipes developed here – the horizontal light-pipe and the vertical light-pipe.

The horizontal light pipe comprises of a box (ie. Like a duct that has highly reflective interior mirrored surfaces and an arrangement of laser cut light deflecting panels (LCP) at the outside edge as sub-light collectors and extractors that redirect light along the pipe to the interior spaces as required and with light emitters to spread the light uniformly around the space. The light pipe dimension is 2m wide and 0.8m high and 12 meters long.

The light deflecting panel at the aperture of the light pipes enhances the performance by redirecting sunlight more directly along the axis of the light pipes (figures 1a and d 1b).



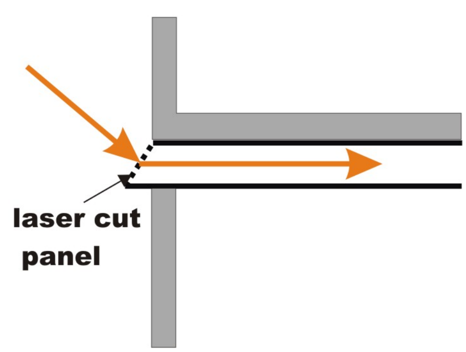


Figure 1a: Light pipe with clear glazing. Light at any high angle coming into the pipe will be lost due to multiple reflections.

Figure 1b: Light pipe with LCP. LCP redirects the light along the pipe reducing the number of reflections and therefore loss of intensity.

The light pipe takes light incident on the Western façade through the plenum area above the utilities zone and distributes light into the inner zone of the building. The performance of the long light pipes (24 metres long and 4 per floor) is enhanced with: 1) a laser cut panel light deflector at the input aperture to deflect high elevation light more directly along the axis of the pipe, 2) a light extraction system to extract the required proportion of piped light into the inner zone and 3) a light spreading system (shown in Fig 2a and Fig 2b) to distribute the light away from the area directly below the light pipe and more evenly over the zone.

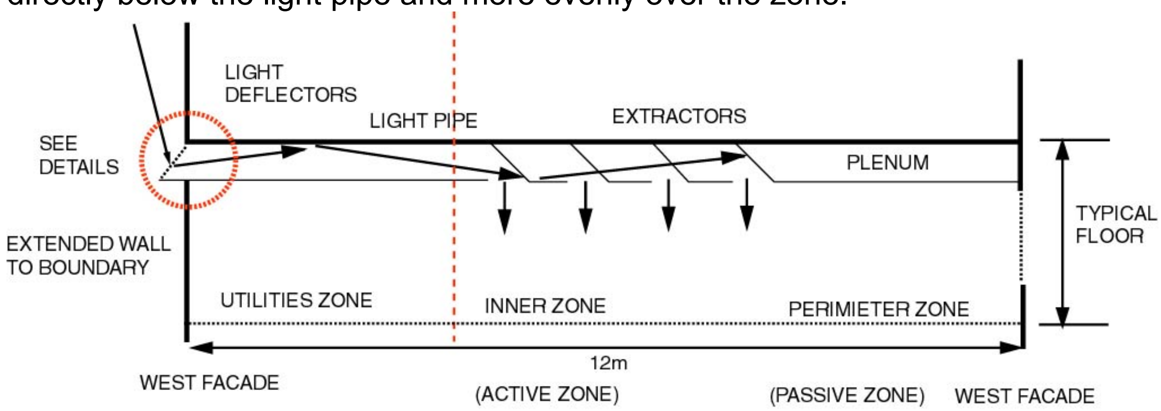


Figure 2a: Light Pipe Cross-section

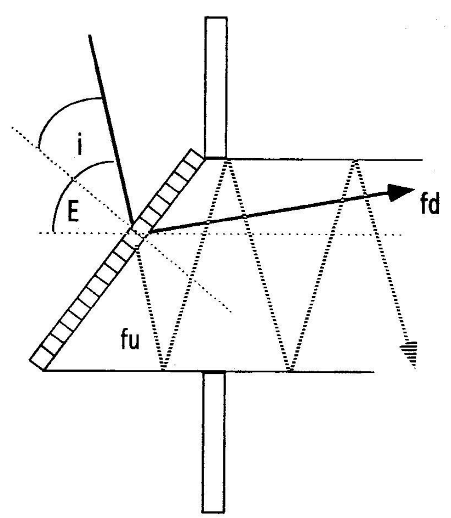


Figure 2b: Detail of the laser cut panels as light collector, and deflection of incident sunlight in to the light pipe

Laser cut panel (Edmonds, 1993) is produced by making parallel laser cuts in transparent acrylic panel- each cut becoming a thin mirror, which provides powerful deflection of off-normal light as illustrated in Fig 7. The fraction of light deflected, fd, depends on the angle of incidence, I, and the cut spacing to cut depth ratio, D/W, as shown in Fig 3a and 3b for three nominal D/W ratios.

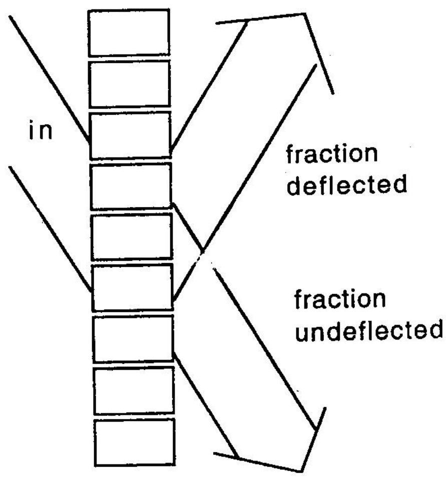


Figure 3a: Laser cut panel section. Incoming light deflected and transmited.

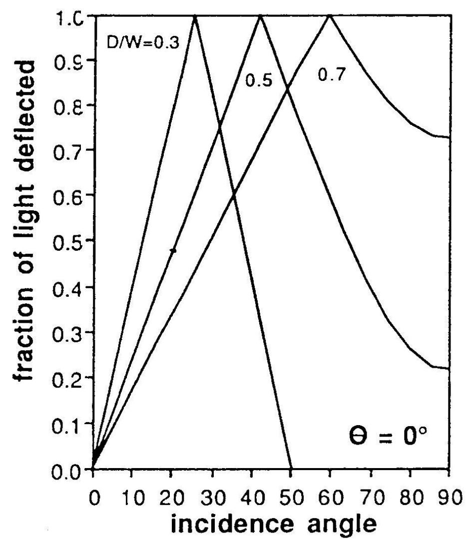


Figure 3b: Fraction of incident light deflected for different spacing to depth ratios, D/W.

For effective light collection and deflection of incident sunlight into the light pipe the laser cut panel is placed at an angle to the input aperture as shown in Figure 9. Incident sunlight is split into a deflected beam, (fd), and an undeflected beam, (fu=1-fd). High elevation sunlight is deflected more axially down the pipe and therefore makes fewer reflections in traversing the pipe than the undeflected beam. The transmission of light through the pipe is given by $T=r^N$, where r is the reflectance of the pipe surface and N is the number of reflections along the pipe which bring the light to the point of interest. In the model used in this work the reflectance of the pipe material (aluminium) was 0.85. For example, if the defected beam makes two reflections before reaching an output aperture, the transmission is $T=0.85^2 = 0.72$, while for the undeflected beam, for example, making 12 reflections before reaching an output aperture, the transmission is $T=0.85^{12} = 0.14$.

Both solutions or horizontal and vertical light pipes for the deep plan buildings comprise a highly reflective mirrored light pipe, and an arrangement of laser cut light deflecting panels (LCP) as sub light collectors, extractors along the pipe to redirect light to the space as required, and light emitters to spread the light uniformly around the space.

Horizontal light pipes

The main façade of the high-rise office building in Malaysia is southeast-oriented, and building utilities are located on the west façade (ie. As a thermal buffer). With this design setting in mind, the objective was to increase daylight in the core of the building, during afternoon hours when the utilities zone blocked natural light along the west façade. The design used four horizontal light pipes per floor, oriented west-east, with LCP used as light collectors on the west façade. The pipes were 20 m long, 2m wide and 0.80m high, formed from 85% reflectance material. Each pipe is to illuminate an area of 12m x 12m. LCP as collectors are inclined at an angle of 550, which is the optimum angle for a fixed system (in Kuala Lumpur) to redirect sunrays more axially along the pipe, and reduce the number of reflections (Figure 5). Five transparent panels are inserted at a fixed spacing (2m) along each pipe with sufficient reflectance material to extract approximately one-fifth of the light at each aperture (Edmonds et. Al. 1997). A triangular arrangement of LCP is then used to redirect the extracted light sideways to achieve a better and more uniform light distribution in the floor space.

Collection systems, laser cut panel coupled with horizontal and vertical light pipes, and deflected (fd) and undeflected (fu) beams of incident light (i) angle of incidence, (E) sun altitude angle.

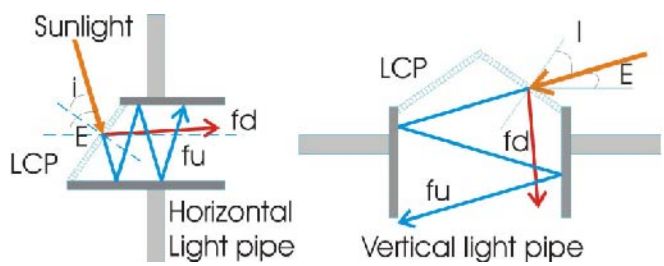


Figure 4: Collection system, laser cut panel coupled with horizontal and vertical light pipes, and deflected (fd) and undeflected (fu) beans of incident light (i) angle of incidence, sun altitude angle

The device was tested for an office building in Kuala Lumpur (latitude 2.9^0) with the objective to increase daylight in the core of the building, during afternoon hours when the utilities zone blocked natural light along the west façade. The design used four horizontal light pipes per floor, orientated west-east, with LCP used as light collectors on the west façade. The pipes were 20m long, 2 m wide and 0.80m high, formed from 85% reflectance material, LCP as collectors are inclined at an angle of 55^0 , which is the optimum angle for a fixed system (in Kuala Lumpur) to redirect sunrays more axially along the pipe, and reduce the number of reflections. Five transparent panels are inserted at a fixed spacing (2.0m) along each pipe with sufficient reflectance material to extract approximately one-fifth of the light at each aperture (Edmonds et/ al., 1997). A triangular arrangement of LCP is then used to redirect the extracted light sideways to achieve a better and more uniform light distribution in the floor space (Fig 3.) The result is a ambient level of lighting of 160 lux to 240 lux throw 12 meters into the wiring depths of the building.

Vertical light pipes

The design of the vertical light pipes (Figure 5) comprised of a pyramid form LCP collector to improve the redirection of low and middle-high sun angles more axially (Figure 5) into a 2m diameter, 18.4 m long vertical light pipe (Aspect ratio: 9.1).

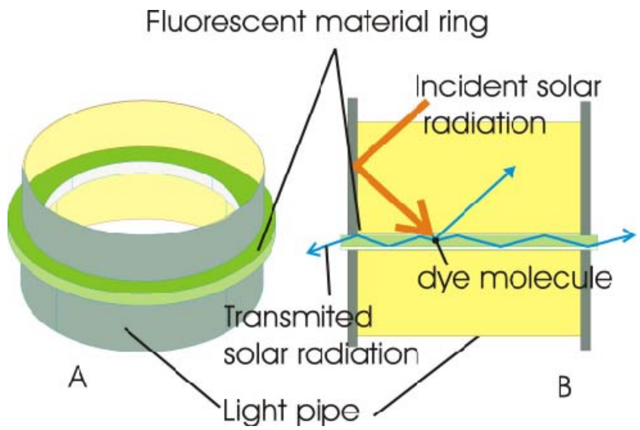


Figure 5: Fluorescent rings as light pipe extractors.
A axonometric view of light pipe section, B-transversal section of the light pipe.

The pipe was extraction apertures at each floor. Two strategies have been tested: 1) A combination of extraction and distribution systems comprised of cone-shaped reflective extractors inclined at 37.5^0 placed within the pipe at apertures to redirect the light into the space and illuminate an area of 12 x 12m, with a diffusing shelf surrounding each aperture to spread the light upwards and avoid direct view of the aperture by the occupants (Figure 5) ring shape PMMA (polymethyi methacrylate) fluorescent collectors with green fluorescent dyes placed at 1.2m from the ceiling at each floor (Figure 6). The dye molecules in the panel absorb part of the solar radiation incident on the plate and re-emit fluorescent radiation that it is transported to the edges of the plate by total internal reflection.

A vertical version has also been developed comprising of a pyramid form LCP collector to improve the redirection of low and middle-high sun angles more axially into 2m diameter, 18.4 m long vertical light pipe. The pipe has extraction apertures at each floor. Cone-shaped reflective extractors inclined at 37.50 are placed within the pipe at apertures to redirect the light into the space and illuminate an area of 12 x 12m. A diffusing shelf surrounds each aperture to spread the light upwards and avoid direct view of the aperture by the occupants (Figure 6 below).

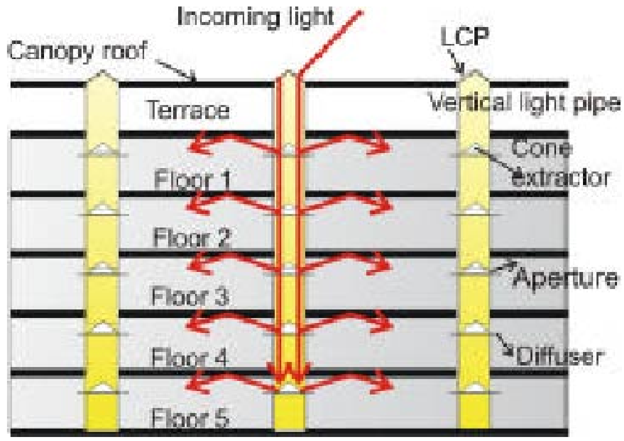


Figure 6: Vertical light-pipe

4 Theory

The theory of direct sunlight transmission through light pipes after redirection by LCP (Edmonds et.al, 1995) was modified for on-dimensional propagation in rectangular light pipes, which is reasonable approximation for a horizontal east-west oriented pipe in an equatorial building. If the transmission of the pipe between one extractor and the next is t, then to achieve equal outputs the fractions f^j deflected at sequential extractors are given by (Edmonds et at., 1997) :

$$F_j = t\, f_{j+1} / (1 + t\, f_{j+1})$$

Having found the lumen output at each extractor, the average workplace illuminance, in the present work, was approximated by dividing the lumen output from each aperture by the area of workplace associated with each aperture.

5 Background

Numerous daylight systems have been developed to improve natural illumination in the deep core of buildings. Innovative daylight systems can be generally divided in two groups: 1) light guiding systems, which redirect natural light (direct and diffuse) to the core of the building up to 8 to 10 metres, by means of reflection, refraction or deflection (e.g. light shelves, louvers), or 2) light transport systems, which can reach further distances than light guiding systems by means of channelling sunlight (generally the direct component of subight) through guides from the building exterior where it is collected, to the interior to be distributed (e.g. light pipes). Benefits of light transport systems include: 1) the potential of integrating artificial and natural light into one system: 2) providing a centralized lighting system in the building that pipes light to distribution system in the building that pipes light to distribution devices, thereby replacing many electrical fixtures and cabling (Whitehead et.al., 1984): 3) eliminating infrared and ultraviolet radiation from sunlight: and 4) reducing hear in air conditioning areas.

Light transport systems consist of three major components: 1) light collection (a device to capture sunlight), 2) light transport (guiding material), and 3) light distribution (extraction and distribution within the space) Current research on light transport technologies is focussed on improving each of the light pipe components. The general classification of light transport systems depends on the material used to transport the light. Current light transport technologies include the following.

1-Fibre optics are highly efficient systems that transport light by total internal reflection. They are usually made of silicate glass or plastic. Its use has been constrained to decorative applications and artificial light due to cost. Light need to be highly concentrated before entering the fibre, as the fibre acceptance aperture is very small. Therefore, when used for day-lighting applications, the optical fibre systems need complicated heliostats to concentrate daylight.

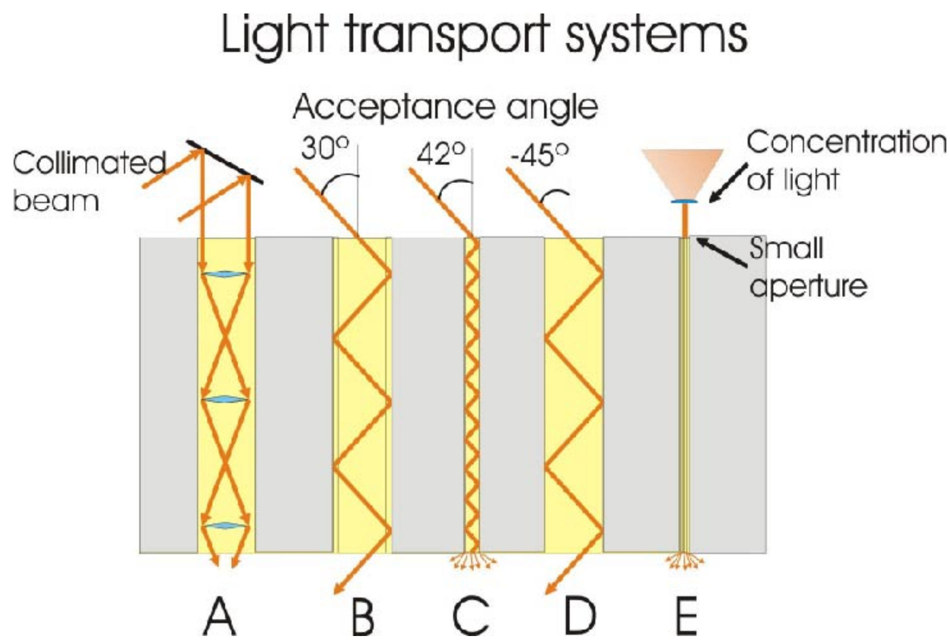


Figure 7: Different light pipe technologies.
A: Lenses, B: Hollow Prismatic Pipes, C: light rods, D: Mirrored light pipes and E: Fibre optics.

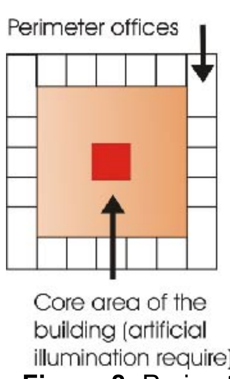
The efficiency of the system depends on the length of the fibre and not the width. The attenuation values are from 0.1 dB m to 0.6 dB m, which means light traverses for 18 to 30m before loosing half of the intensity. Fibres are only 6mm wide and can be 40m in length (Ayers and Carter, 1995). Recent studies are exploring the use of luminescent solar concentrators to absorb the natural light emitted as fluorescent light and then transport the fluorescent light through flexible light guides made from low cost material as a more economical alternative to fibre optics.

2- PMMA Transparent guides: polymethyle methacrylate or PMMA is a transparent acrylic material that has been used for its transmittance properties and relatively low cost. Light is transported by total internal reflection. The guides can be light rods or hollow cylindrical pipes. As a light road, the system can have an efficiency of 50% for a pipe of an aspect ratio (length: 1200mm to width: 50mm) or 24 (Callow and Shao, 2002), but it has only been tested for small scale buildings.

3- An arrangement of lenses and mirrors are also used to transport light. Lenses have good transmission characteristics and they are capable of maintaining a concentrated beam of light. This system does not need a guide. The high cost for lens-systems, however, is a problem, in addition to complications in lens mounting due to the precision required in the system. Lenses have a 92% transmittance and the spacing of lenses depends on the lens focal length. Studies have shown efficiency for the system after passing through 13 lenses of 28% (Bennett and Eijadi, 1980).

4-Prismatic pipes are hollow structures with transparent acrylic walls containing precise right angles that transport the light by total internal reflection. Currently, prismatic pipes are made out of a new thin transparent film from 3M, making the system more efficient. Conversely, the device required complicated daylight collection systems due to the range of the input angles ($-28^0/30^0$) needed for the light to be guided through the pipe. Research has shown efficiencies on the order of 20% for pipes of aspect ratios of 30 when used as a daylight solution (Whitehead et.al., 1984, Aizenburg, 1997).

5-Hollow mirrored pipes, which transport the light by multiple specular reflections, relatively cheaper than other light transport systems and potentially have a wide application in building design. Efficiency depends on areas and geometric form of the pipe, reflectively of the material (85%, 95%, 98%), and directional properties of the light source. Well collimated sunlight could produce an efficiency of 50% (Ayers and Carter, 1995). Mirrored pipes have been coupled with different light system collections (i.e anidolic systems, laser cut panels). Anidolic ceilings are devices that integrate compound parabolic collectors with a highly reflective guide to redirect light deeper into a room; they have been designed to improve illumination in buildings occurring in regions with predominately cloudy conditions (Courret et.al., 1998). Previous work has suggested that laser cut panels (LCP) coupled with mirrored pipes could be a simpler, more cost-effective daylight solution for sunny climates. Overall performance of a mirrored light pipe coupled with LCP of an aspect ratio of 30 is 20% (Edmonds et.al., 1995, Garcia Hansen et. al. 2001). This paper explores the benefits and limitations of mirrored light pipes (horizontal and vertical) coupled with laser cut panels as a simple solution for the enhancement of natural illumination of deep plan buildings.



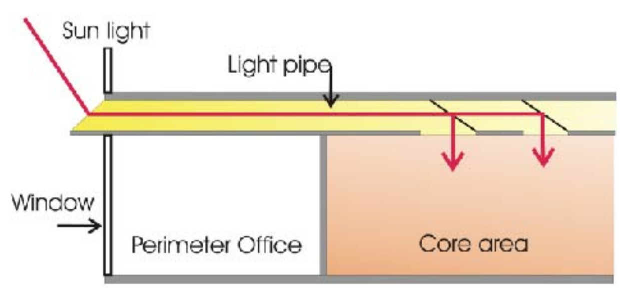


Figure 8: Perimeter offices blocking natural light to the core area of the building (left). Possible application of light pipe technology to enhance natural illumination in

The core of the office building (right).

The light pipes are designed to channel sunlight into the deep zone of the office plan as sunlight falls on the façade of the building.

The light deflecting panel at the aperture of the light pipes enhances the performance by redirecting sunlight more directly along the axis of the light pipes

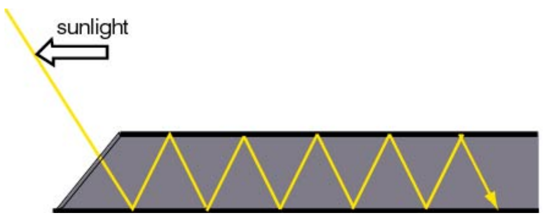


Figure 9 Light pipe with clear glazing . Light at any high angle coming into the pipe will be lost due to multiple reflections.

Figure 10 Light pipe with LCP. LCP redirects the light along the pipe reducing the number of reflections and therefore loss of intensity.

The performance of the long light pipes (24 metres long and 4 per floor) is enhanced with: 1) a laser cut panel light deflector at the input aperture to deflect high elevation light more directly along the axis of the pipe, 2) a light extraction system to extract the required proportion of piped light into the inner zone and 3) a light spreading system (shown in Fig 13 and Fig 14) to distribute the light away from the area directly below the light pipe and more evenly over the zone. The cross section of the light pipes:

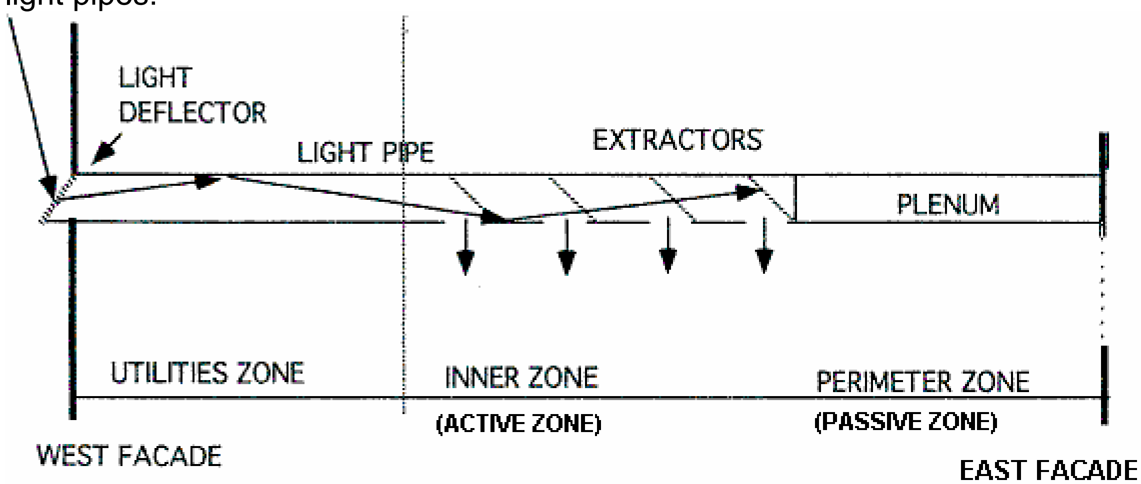


Figure 11: Section through the light-pipes

The pipe input apertures for building near the Equator (c. lot 0^0) should be on the Western and Eastern façade and sunlight enters the apertures from 12 noon through the afternoon as illustrated in Fig 14. It is evident from this illustration that the amount of light incident on the apertures and transmission of this light through the pipes depends in a fairly complicated way on the sun elevation angle and, therefore, on time of day.

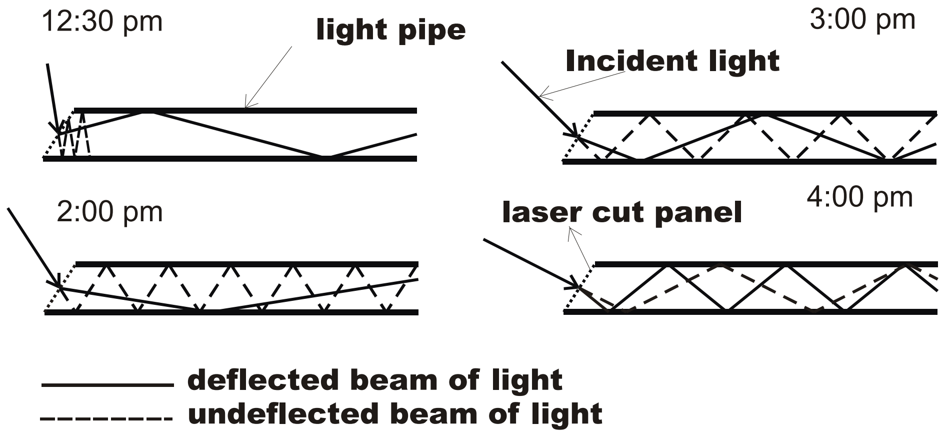


Figure 12: Transmission of the light through the pipes for the deflected and underflected beam of light at different times of the day.

As the light traverses the pipe specified proportions of the light must be extracted at intervals along the light pipe to provide the desired light distribution (usually uniform distribution) below the light pipe. The principle of a light extraction system is illustrated in Figure 13. In this example the same amount of light is extracted at each aperture. To achieve this the first extractor panel is made sufficiently reflecting to deflect ¼ of the light. The second reflects 1/3 of the remaining light, the third ½ and the final extractor refracts all of the remaining light. More complicated ratios may be derived to account for transmission loss in the pipe which occurs between each extractor (Edmonds et.al. 1997). As is evident in Figure 14 the transmission loss will vary with incidence angle of the light and hence with time of day. Therefore it is expected that the distribution of light from the light pipe will also vary with time of day.

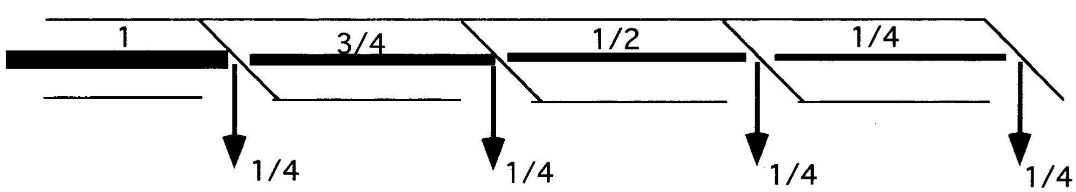


Figure 13: light extraction in the light pipes

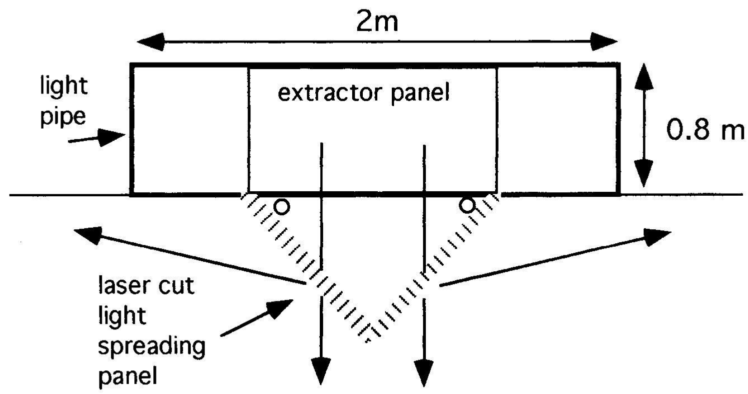


Figure 14: Laser cut light spreading panel.

As the light is directed near axially and is extracted by reflection off plant extractors it follows that the extracted light is emitted into the room as an approximately vertical and fairly well collimated beam. In this case, only the area directly below the apertures is well illuminated. To distribute the light more widely a light spreading system comprising a triangular arrangement of laser cut panels was used. Figure 14 shows a cross sectional view of the light pipe and light spreading arrangement. A high proportion of downwardly directed light is deflected by the panels over the ceiling to either side of the light pipe thereby improving the distribution of light in the room. The effect is illustrated in Figure 15 and 16.

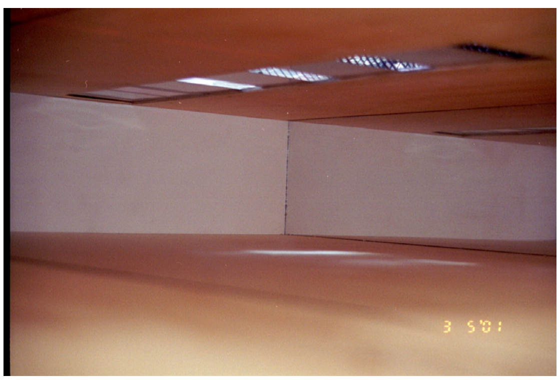


Figure 15: Distribution of the light without emitters.

Figure 16: Light redirected to the ceiling by LCP emitters.

6 Scale Modelling of the Light Piping System

A 1/20th scale model of the system was fabricated, Figure 17, and measurements made under direct sunlight conditions. While only one light pipe was modelled the effect of multiple light pipes was simulated by making the vertical sidewalls of the model reflecting. The grid of measurement points within the model interior is shown relative to the light pipe in Figure 18.

Figure 17: scale model testing

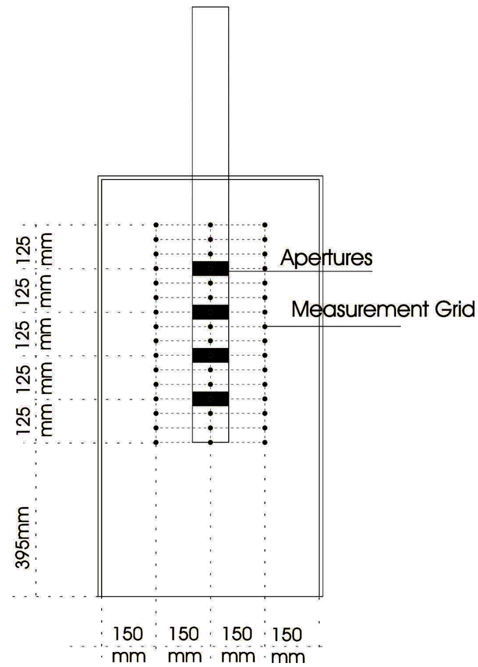


Figure 18: Measurement grid

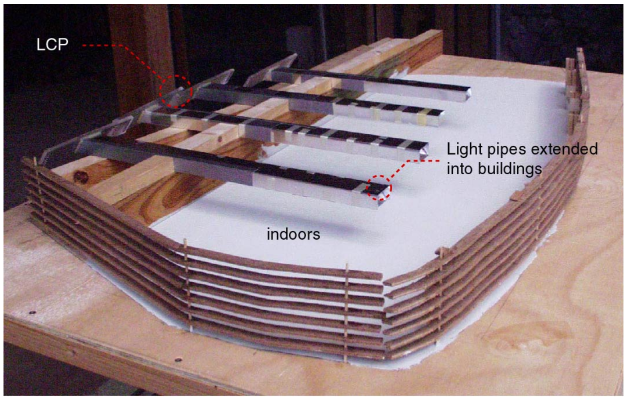


Figure 19: Another example of a testing model

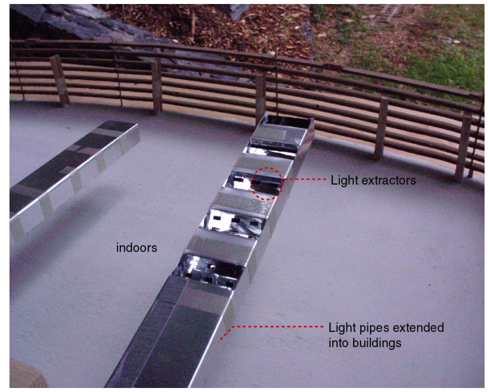


Figure 20: Details of the light-pipes and extractor

Figure 21: Integration of the light-pipes in buildings tested by model

Measurements of workplace illuminance made at various sun elevations are shown in Figures 22 to 25. It is evident that the amount of light delivered, ranging between about 200 and 300 lux over the time period from 12 noon to 4pm contributes significantly to the illuminance level (design level 300 lux) required in the building. That the area directly below the light pipe receives up to 3 times as much light as areas to the side is due to a less than optimal design of the light spreading system. This will be improved by using laser cut panels with cut spacing to provide maximum deflection of light to the side. The emitted light shows a moderate reduction in strength with distance along the light pipes. This is due, primarily to the fact to the proportions of light extracted by the extractor panels cannot be varied to adjust for varying transmission in the light pipe as the sun elevation and time of day change. However the reduction is moderate and it is expected to be compensated by a fall off in illumination from the window walls on the Eastern façade of the building.

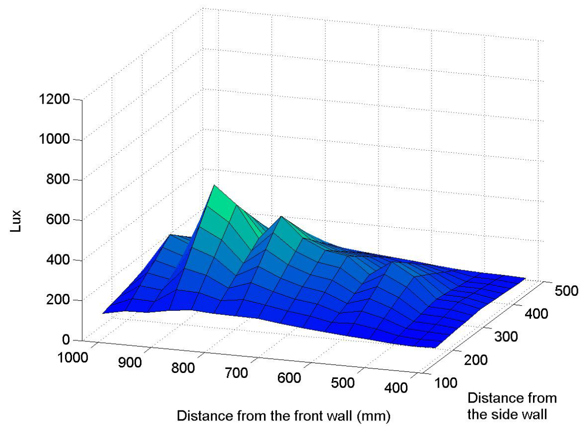


Figure 22: measured values for 81° sun elevation

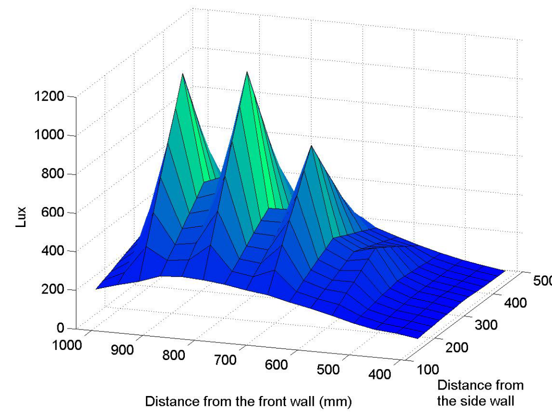


Figure 23: measured values for 57° sun elevation

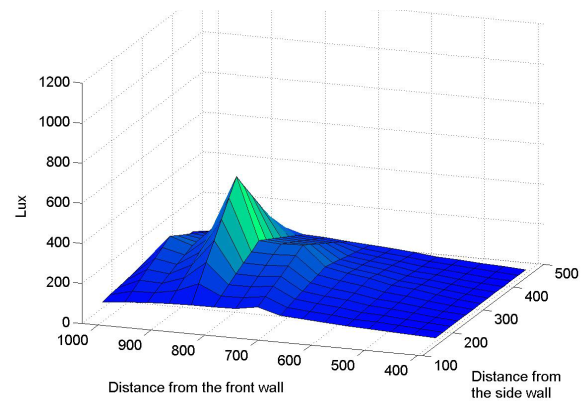


Figure 24: measured values for 45° sun elevation

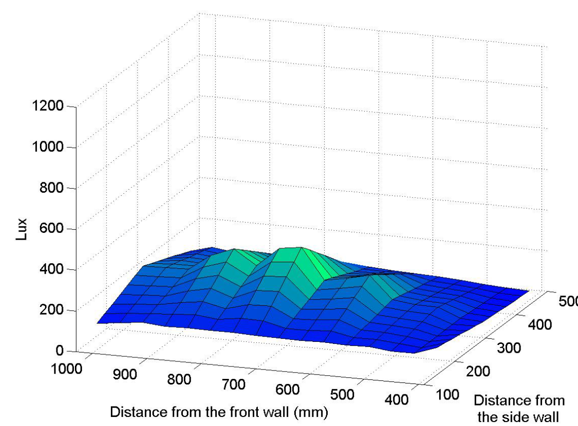


Figure 25: measured values for 27° sun elevation

The elementary theory of light pipe performance outlined above may be summarised as follows. calculate :

1) the number of lumens incident on the input aperture
2) the fraction of incident light deflected and undeflected
3) the transmission of both components to each of the four light pipe apertures
4) the average workplace illuminance by dividing the lumen output from each aperture by the area of workplace associated with each aperture, 30 sq.m

The calculations are compared with the average measured values in Figure 26 for the four different solar elevations for which measurements were made. Given the simplified theory used the fair agreement between theory and measurement is encouraging.

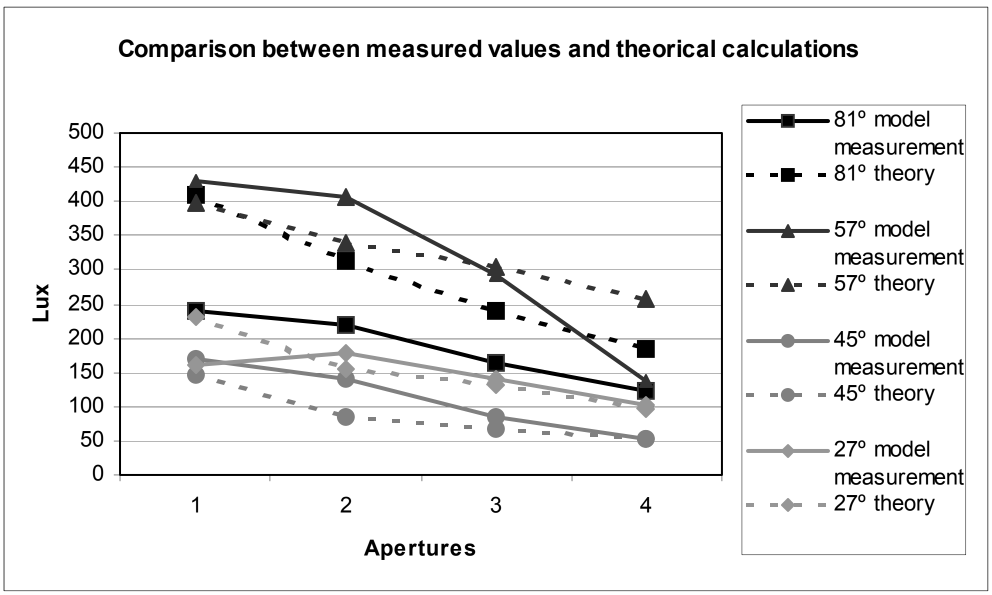


Figure 26: Comparison between measured value and theoretical calculations

Two scale models representing portions of the Kuala Lumpur high-rise building and the middle-high Library building were built for testing under sunny sky conditions and artificial sky (figure 27-28).
Horizontal light pipe scale model. A scaled 1:20 model representing a section (12 x 20m) of one floor of the high-rise office building was constructed for testing (figure 27). Mirrors were placed on the sidewalls of the model to reflect the remaining space of the plane floor (figure 28).
Vertical light pipe scale model. Figure shows the scale model built of a section of the Millennium Library building that represents the area of influence of one vertical light pipe (12 x 12 m) throughout five floors. Mirrors were placed in the surrounding walls of the model to reflect the remaining space of the plane floor.

Reflective cones, for the extraction of the light were constructed of transparent acrylic with reflectance material figure 27. The fluorescent rings were made out of a commercially available fluorescent sheet with green dyes. To obtain neutral light a combination of three coloured (ref, blue and green) fluorescent sheets are needed (Smith and Franklin, 2000), however as the aim in this study is to assess the feasibility of the material as an extractor strategy, and light distribution within the space, only the green dyed sheet was used.

Figure 27: Horizontal light pipe scale model under sunny sky conditions

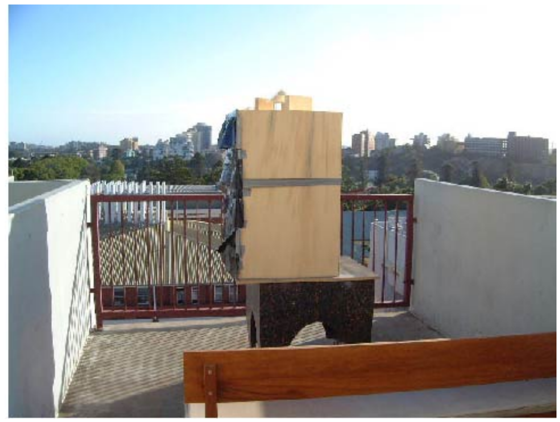


Figure 28: Vertical light pipe scale model under sunny sky conditions

Experimental testing under sunny conditions

For the Horizontal light pipe model, testing was performed under sunny sky conditions for a wide range of sun angles (20^0 to 79^0). Figure 29 shows model interior where the LCP triangular distribution arrangement can be observed.

Figure 29: Interior of horizontal pipe model tested under sunny sky conditions

Figure 30: Interior of the vertical light pipe model testing under sunny sky conditions (11am, summer)

Testing of the Vertical light pipe model was carried out under sunny sky conditions for a range of different sun altitude angles (9^0 to 72^0) for a 45^0 and 35^0 LCP collector, and with the cone extractor strategy as in Figure 30. Observations during testing indicated that at early hours of the morning when the sun is low, light distribution in the space was homogenous, however as the day advances and the sun angle is higher, sunny patches are reflected on the ceiling. As a result, further studies of light extraction and distributions were then tested under the artificial sky.

<u>Experimental testing under artificial sky</u>

The artificial sky simulator at the School of Design and Built Environment of Queensland University of Technology is of a mirror type (Figure 32). The diffuse ceiling is formed by fluorescent tubes and a diffuser fabric, and wall mirrors, inter-reflections between the mirrors form an image of an infinite diffuse sky, which due to absorption in the mirror diminishes its brightness as the virtual horizon is reached. The mirror box has a square base, and the mirrors are 1180x2400mm. To allow for entrance into the mirror box is lifted 900mm above the floor.

Studies have been done to test the distribution of the light in the artificial sky , and the results have shown average illuminance of nearly 7900 lux and the distribution approximates the CIE standard overcast sky conditions.

The artificial sky was mainly used to test the performance of the pipes under overcast conditions as well as the assessment of different extraction and distribution devices for the vertical light pipes. Figures 31 shows the interior of the vertical light pipe model with fluorescent ring concentrators as extractors, and Figure 33 shows the interior of the same model with cone reflective extractors. The pictures reveal the light distribution in the space. In the first example the fluorescent light is more diffuse, whereas in the second case, cones and shelves redirect light to the ceiling.

Figure 31: Experimental testing of the vertical light pipe in the artificial sky

Figure 32: Interior of vertical light pipe model with fluorescent ring extractors, tested in artificial sky

Figure 33: Interior vertical light pipe model with reflective cones for light extraction. Testing under artificial sky

Comparison on Experimental Results and Theory
Horizontal light pipe

Figure 34 shows the measured average illuminance level obtained from testing under sunny sky conditions over the floor space at 2m intervals along the pipe. Figure 35 shows the corresponding calculated values.
Note that the distribution is adequately uniform along the light pipe in both cases. However, theoretical calculations revealed greater lux values for higher sun angles and inferior lux values for lower sun angles. The measured and theoretical values show a similar trend of average illuminance versus sun angle (figure 36).

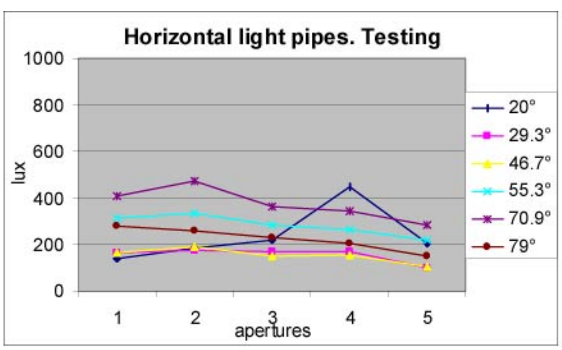


Figure 34: Interior average illuminance levels obtained from testing HLP under sunny sky conditions.

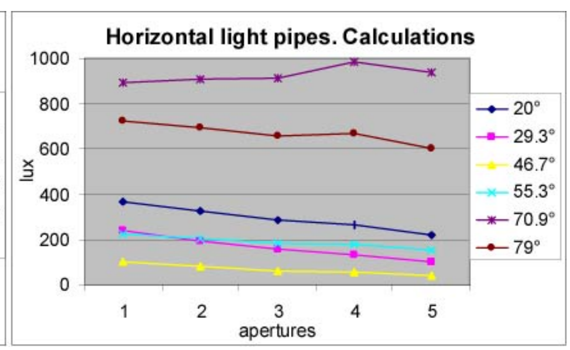


Figure 35: Interior average illuminance levels obtained from calculations for HLP

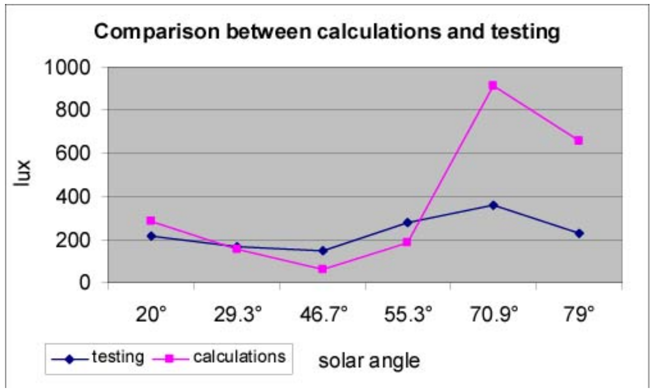


Figure 36: comparison between calculation and testing under sunny sky conditions

The more extreme values obtained in the calculated model may be a consequence of neglecting the roughness in the cut surface of the LCP, which diffuses the deflected light with an angle spread of +/- 8^0. The variation in illuminance values throughout the day (100 to 400 lux) corresponds to varying light transmission along the pipe for different sun angles. At lower and higher sun angles, a higher amount of undeflected or deflected light respectively, travels axially along the pipe.

However, at sun angles between $40\text{-}55^0$, the LCP has little effect. The light passes through undeflected, and then undergoes multiple reflections along the light pipe. Daylight factor values obtained under overcast conditions (artificial sky) ranged from 0.18 to 0.52.

<u>Vertical light pipe (VLP)</u>

Figure 37 shows measured average illuminance levels at each floor during testing under sunny sky conditions with a 45^0 pyramid LCP collector. Figure 37 shows the calculated values for a similar range of sun-angles. A reasonable distribution along the pipe is achieved. By using the 45^0 LCP collectors, a relatively modest variation of illuminance level with sun elevation was achieved (50 to 200 lux). For a 35^0 LCP (Figure 34), the variation was higher (50 to 400 lux). Testing under artificial sky showed daylight factor values ranging from 0.12 to 0.20 for light pipes with 35^0 LCP collectors, 0.1 to 0.17 for the 45^0 collector, and 0.13 to 0.24 for no collector.

Figure 39 shows comparative daylight factor values obtained from the two light extracting strategies in the vertical light pipes. The measurements were taken along three points in a straight line from the pipe to the wall. The fluorescent panels showed decreasing values towards the wall while the cones had higher values in the middle of the space due to the light redirected to the ceiling.

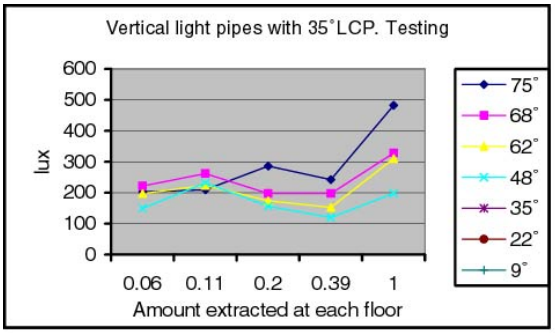


Figure 37: Interior average illuminance levels for testing of VLP with 35 degree LCP under sunny conditions

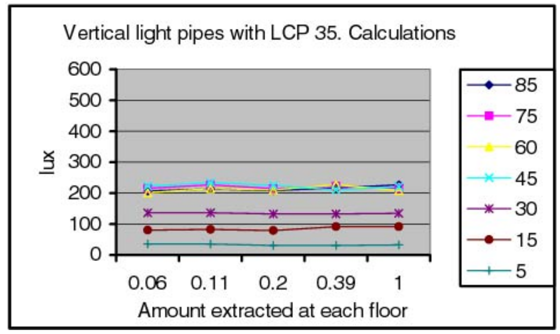


Figure 38: Interior average illuminance levels obtained from calculations

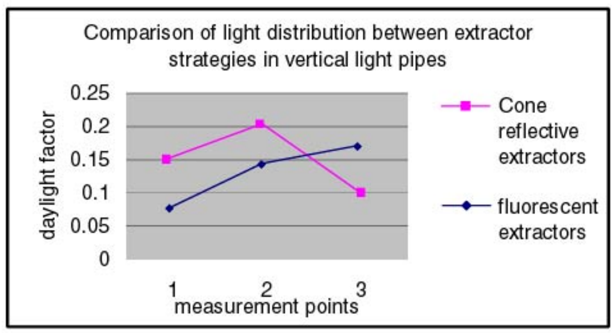


Figure 39: Comparison of light distribution strategies measured under artificial sky

7 Building Integration

Below are images of how the light pipes can be integrated with the façade of the building.

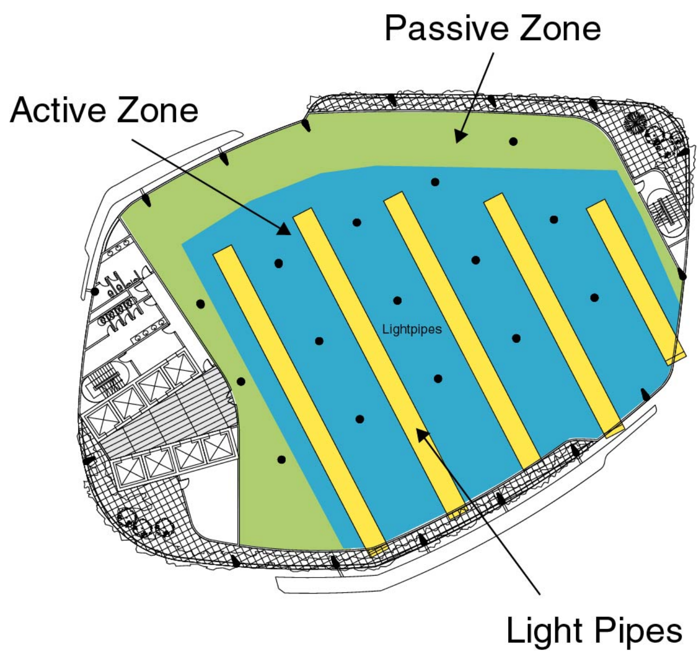


Figure 40: Light pipes in plan (yellow), aligned to come through the westerly core, (source Grey Evant). Passive zone spaces located on the perimeter that can benefit from the ambient environment (daylight, solar gain, ventilation, (view). It is normally twice the floor to ceiling height (Baker and Steemers, 2000).

Figure 41 : Light Pipes integrated into building façade design and becomes a building design feature (Yee Nan Tower, © Ken Yeang 2003)

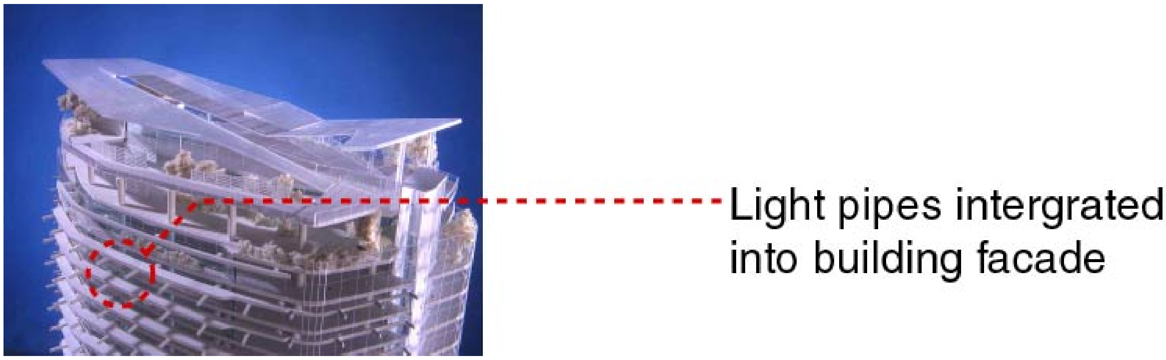


Figure 42: An example of details of light pipe design and building façade

8 Discussion

This submission has shown that horizontal or vertically orientated mirrored light pipe systems coupled with LCP (Laser Cut Panels) collectors provide a potential solution for the natural illumination of deep-plan office buildings, achieving an adequate spatial light distribution along the pipe. Illuminance values range from 100 to 400 lux for the horizontal light pipes over a period from noon to 4pm; 50 to 200 lux for the vertical pipes with LCP at a 45^0 angle; and 50 to 400 lux for vertical pipes with a 35^0 angle LCP during the day. Thus, whereas a near constant light distribution along the pipe can be achieved, it may necessary to use an adjustable light deflector system at the input of the light pipe to reduce variation with time.

The device shows the potential to daylight the inner parts of building and the theoretical calculations show that we are able to reduce 160 to 240 lux level without the use of any electrical energy source. If one corridor that for most office building the expected level of illuminance is 300 lux that achieve 240 lux is considered a major achievement.

In time where energy costs become exceeding high, then buildings will become more and more dependant all passive (non use of renewable sources of energy). The light pipe will lower energy consumption, improve the quality of light in the inner parts of building up to depths of 2 meters (or more) and also enable office buildings to have deeper floor depths.

For example office building in Germany have a maximum glass-to-glass distance of 15 to 16 units because no desk is permitted to be more than 7.5 meters from a window to received daylight. The light pipe will permitted office building with deeper flow plates.

For alternative to the light pipe is the use of holographic glass which is too expensive to be viable.

9 References

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10 Credits

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