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Methods for the illumination of multilevel buildings with vertical light pipes

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Abstract

This paper examines the feasibility of using vertical light pipes to naturally illuminate the central core of a multilevel building not reached by window light. The challenges addressed were finding a method to extract and distribute equal amounts of light at each level and designing collectors to improve the effectiveness of vertical light pipes in delivering low elevation sunlight to the interior. Extraction was achieved by inserting partially reflecting cones within transparent sections of the pipes at each floor level. Theory was formulated to estimate the partial reflectance necessary to provide equal light extraction at each level. Designs for daylight collectors formed from laser cut panels tilted above the light pipe were developed and the benefits and limitations of static collectors as opposed to collectors that follow the sun azimuth investigated. Performance was assessed with both basic and detailed mathematical simulation and by observations made with a five level model building under clear sky conditions.

Keywords: multilevel daylighting, light pipes, extractors, laser cut panels, daylight collectors

1. Introduction

The need for energy efficient buildings and an appreciation of the physiological and psychological benefits of natural light for building occupants has encouraged the development of innovative daylighting technologies. These technologies – defined here as Daylight Guidance Systems (DGS) (CIE, 2006)- can increase daylighting levels and illuminate much deeper areas within buildings than is usually achieved by windows alone, reducing the need for electrical lighting, and consequent cooling load of a building. Thus, DGS potentially reduce overall building energy consumption and provide healthier environments for building occupants. Examples include mirrored or prismatic light pipes, fibre optics, lenses, etc. DGS usually comprise a light collection system (that captures daylight), a transport/guidance section (that transports the light over long distances into the building) and a system to distribute light and illuminate the space (Garcia-Hansen, 2006) .

These new technologies have received a great deal of interest from researchers, designers, product developers and building industry (developers/builders/etc.). Their application in buildings ranges from the technically unsophisticated DGS in user-owned domestic buildings, to DGS in office, educational, industrial and health-care facilities (Al Marwaee and Carter, 2006), to avant-garde architectural DGS installations. Examples of the latter are Toyo Ito's Sendai Mediateque, Carpenter-Norris' light pipe in Morgan Lewis offices in Washington, and Peter Cook's light nozzles of Kunsthaus building in Graz, Austria.

Current research on DGS includes the following areas: new designs (Garcia-Hansen 2006, Rosemann et al. 2008, Baroncini et al., 2010) and design optimization (Garcia-Hansen, 2006, Garcia-Hansen et al., 2009, Robertson et al., 2010, Nair et al., 2014); performance monitoring (Paoncini et al. 2007), prediction models (CIE, 2006, Lo Verso et al., 2011), simulation (Duttonad shao, 2007, Kwok and Chun, 2008, Kocifaj, 2009) and comparative studies (Oh et al., 2013); monitoring of real building applications and glare analysis (Al Marwaee and Carter, 2006, Isoardi et al., 2012); user attitudes and user perception (Garcia-Hansen et al., 2010, Carter and Al Marwaee, 2009); integration with electrical lighting (hybrid systems) (Mayhoub and Carter, 2010); and finally, cost and life cycle analysis (Carter, 2008, Mayhoub and Carter, 2011).

Mirrored light pipes are the most popular of the DGS, as they are less complicated to build than other DGS (e.g. prismatic pipes, lenses) are currently cheaper than fibre optics, and potentially have a wide application in building design (Garcia-Hansen et al. 2001, Garcia-Hansen and Edmonds, 2003). Mirrored light pipes transport light by multiple specular reflections, and as a result their performance is affected by 1) light collection (amount of light at the input aperture), and 2) the dependence of luminous power transmission on solar elevation; both aspects can be improved by efficient daylight collectors. Performance monitoring of a simple light pipe over a year demonstrated the variation of performance throughout the day and the year and the need of improved simple daylight collectors (Paroncini et al., 2007). Latest examples to improved designs for daylight collectors for light pipes include shaped rods and Fresnel lenses (Ferron et al., 2011, Nair et al., 2014).

The methods for daylighting multilevel buildings described in this paper are based on a case study of using vertical light pipes to naturally illuminate five floors of a library building in sub tropical Brisbane, latitude – 27^{o}, (Garcia-Hansen, 2006). There are significant technical challenges in daylighting a deep plan, multi level building. These include adequate collection of ambient light, transmission of the light and distribution of the light to each level of the interior. An outline of, and the basic approach taken to meet each of these challenges is given in section 2. Sections 3 outlines the performance of vertical light pipes at different latitudes. Section 4 and 5 describe the design and performance of extractors in a model multilevel building. Section 6 outlines the design and performance of collectors for use with light pipes. Section 7 presents observations of the performance of a combined DGS in a model multilevel building. Section 8 draws some conclusions on feasibility of the proposed design.

2. Basic approaches to multilevel natural lighting via vertical light pipes.

In a case study of a five level, 100 m x 60 m floor plan building the shortest distance to capture and pipe natural light to the inner (80 m x 40 m) zone was from the roof. It was proposed that the inner zone, which would normally depend entirely on electrical light for illumination, be illuminated by natural light piped from the roof via 32 light pipes, Garcia-Hansen (2006). The question posed by the case study was whether there is enough light available to adequately illuminate a multilevel building via vertical light pipes and whether the light pipes occupy a reasonable fraction of the floor area. Figure 1 is a simplified schematic of the proposed lighting system. Light pipes collect ambient light at the roof and transmit the light to the various levels of the building where the light is extracted to illuminate each floor level. The required illuminance of an interior is, typically, 500 lux. The interior illuminance on the floor in lux, E_{INT}, can be estimated if the light output to the interior in lumens, Lo, is known.

$$E_{INT} = L_o/[A_F(1 - R^2)] \tag{1}$$

where A_F is the area of the floor and R is the average reflectance of the ceiling and floor. Here it is assumed that the interior zone is sufficiently wide plan that the walls can be neglected. Equation 1 is based on a well known relationship concerning radiant heat transfer between two parallel planes, Holman (1992). Equation 1 applies reasonably well to the illumination of rooms provided R is not close to 1. In office buildings typical values of R range between 0.3 and 0.5. For a room illuminated via light pipes and assuming no losses, $L_o = E_H.A_P$ where E_H is the external horizontal illuminance and A_P is the total cross sectional area of the pipes. Equation 1 becomes $E_{INT} = E_H A_P/[A_F(1 - R^2)]$ and the relation can be expressed in terms of the daylight factor $DF = E_{INT}/E_H = (A_P/A_F)/(1 - R^2)$. We note that, more accurately, the term $(A_F - A_p)$ would replace A_F in this relation because the interior floor area to be illuminated is the building floor area reduced by the cross section area of the light pipes. In practical cases $A_P << A_F$ and equation 2 is a good approximation. When M levels are equally illuminated

$$DF = (A_P/MA_F)/(1 - R^2) \tag{2}$$

For R = 0.5, $1/(1 - R^2) = 4/3$ and $DF = (4/3)(A_P/MA_F)$. Ideally an interior workplace requires E_{INT} = 500 lux. For clear skies at noon $E_H \sim$ 100,000 lux and therefore the required daylight factor is 0.005. For M = 5 floor levels the ratio $A_P/A_F = 0.018$. Thus, in the ideal case, the total area of the pipes is only 1.8% of the floor area and the lighting system occupies only a small fraction of the building. At equatorial locations, under clear skies, E_H, at four hours before and four hours after noon, is reduced by the factor cos(60) = 0.5 and has fallen to about 50,000 lux. The total area of pipes required to provide 500 lux is now 3.6% of the floor area. For overcast skies $E_H \sim 25{,}000$ lux at noon and the light pipes required would occupy 7.2% of the floor area, a substantial fraction. However, in traditional building practice, the provision of natural lighting by windows to a five level wide plan building would involve designs with substantial atria or alcoves which would intrude very substantially on the useable building floor area. Further, multiple light pipes would distribute natural light more evenly to a wide plan area than windows in atria and alcoves. So, delegating ~ 7% of the floor area to light pipes may be a practical natural lighting solution. However, the practicality relies on the light transport system being ideal, i.e. transmitting sunlight to the interior with an efficiency close to 1.

From the discussion above the percentage of floor area required for light pipes to deliver 500 lux for 8 hours per day under clear sky conditions is 3.6%. To assess the size of pipe required we note that if 32 pipes illuminate 5 levels of an 80m x 40 m inner zone the required cross sectional area of each pipe is 3.6% of 100 m^2 i.e. 3.6 m^2, the pipe diameter is 2 m and the length of pipe to the lowest level is about 12 m assuming the floor to floor spacing is 3 m.

It is interesting to consider briefly the use of a photovoltaic system to supply the same interior illumination. The light in lumens provided by a square metre of photovoltaic panel, E_{PV}, available from a photovoltaic powered electric light system when the illuminance on the panel is E_H is given by

$$E_{PV} = (E_H/C_D)e_{PV}C_S \tag{3}$$

where C_D is the efficacy of direct sunlight, ~ 100 lumens/W, e_{PV} is the energy conversion efficiency of the photovoltaic panel, ~ 0.1, and C_S is the efficacy of converting electrical power to light, ~ 80 lumens/W for fluorescent lamps. When E_H = 50,000 lux, E_{PV} = 4000 lux. Thus, comparing an ideal light pipe system, transmission = 1, with a photovoltaic lighting system the area of photovoltaic panel required is about 50000/4000 = 12.5 times the area of light pipe required. In the ideal case outlined above where the light pipe system occupies 3.6% of the roof area this rough calculation indicates equivalent lighting could be obtained by a photovoltaic system covering 12.5 x .036 = 0.45 times or approximately half of the 3,200 m^2 roof area.

It is also interesting to consider the prospect of the natural lighting system having the additional function of providing artificial lighting to the building, (Mayhoub and Carter, 2010). A typical, 2000W, narrow angle (25^o), floodlight for stadium lighting provides 160,000 lumens through an output face 0.5 m wide. Earlier in this section we found that a light pipe 2.0 m wide would be suitable to illuminate an area of 100 m^2 at each of five levels of a building. Thus the total area to be illuminated is 500 m^2. A single floodlight, occupying a fraction $(0.5/2.0)^2$ = 0.06 or 6% of the pipe aperture at the roof of a building could provide illumination of 160,000/500 = 320 lux to the interior space via the light pipe. There may be some advantages in having the electrical lighting for the building provided via the natural lighting system and serviceable at the roof level of the building.

3. The performance of vertical light pipes as a function of latitude.

Vertical light pipes have been used for a long time in domestic and commercial buildings (Al Marwaee and Carter 2006, CIE, 2006). However, a major problem with vertical light pipes is that the projected input area of a pipe falls, with light elevation ε, as $\sin(\varepsilon)$ and a vertical pipe is a poor collector of low elevation light. Long light pipes have a further problem in that the collected low elevation light is reflected to the pipe output by a large number, N, of reflections. Reflection loss varies as ρ^N, where ρ is the pipe reflectance. In the simplest case of a two dimensional pipe of width A and vertical length L the number of reflections, $N = (L/A)/\tan(\varepsilon)$, can be very large at low light elevation. To illustrate the joint effect of diminished projected area and reflection loss we calculate the transmission through a square pipe with side A = 1 m, L = 10 m and $\rho = 0.9$ under a clear sky. Usually, finding the transmission of direct sunlight through a light pipe involves a three dimensional calculation which can be complicated (Kocifaj, 2009 Edmonds, 2010). However, the points we wish to illustrate here, and in later sections, can be made adequately by using the much simpler two dimensional calculation appropriate for sun movement in the vertical plane of symmetry over the light pipe when the simple equation $N = (L/A)/\tan(\varepsilon_S)$ applies. Here, ε_S is the elevation angle of the sun. Diffuse skylight from a clear sky, which is significant at low sun elevations, can be included by using an approximate relation for diffuse illuminance, E_D, under a clear sky, $E_D = 800 + 15{,}500\sin(\varepsilon_S)$ to calculate the diffuse illuminance at the input of the pipe, (I.E.S., 1984). Finding the transmission of diffuse skylight through a square pipe requires an integration over the dome of the sky of the expression for the average number of reflections, in a square pipe, $N = 1.273(L/A)/\tan(\varepsilon)$, (Edmonds, 2010). Figure 2A compares the total (direct plus diffuse) illuminance at the input and at the output of a long pipe, of aspect ratio $L/A = 10$ under a clear sky. The diffuse input and output are shown separately. We note that the variation of illuminance at the pipe input reflects the $\sin(\varepsilon_S)$ dependence of the illuminance due direct sunlight and that the difference between illuminance at the input and the output reflects the effect of losses at multiple reflections in the pipe. There are several features of Figure 2A that are critical to the utilisation of long pipes: the illuminance at the pipe output peaks sharply at high sun elevations and the pipe output illuminance is negligible at sun elevations below 20^o. The practical ramifications of the results in Figure 2A for the use of light pipes at different locations around the world can be assessed by using sun maps for various locations to estimate sun elevations at different times of the day and year. However, simply calculating sun elevation versus time of day at midsummer, equinox and midwinter for equatorial, mid latitude and polar latitudes, Figure 2B, provides useful general information. At equatorial latitudes the sun rises, near linearly with time, from the east to overhead at noon then falls, near linearly with time, to set, at 6 pm, in the west. Evidently the sun path corresponds closely to the two dimensional sun - pipe model on which Figure 2A is based and, as there is a linear relation between sun elevation and time, the results in Figure 2A are fairly accurate indication of the variation of light pipe performance with time between sunrise and noon at equatorial locations. We note that for about half of the day the sun elevation is below 40^o and a long light pipe is ineffective i.e. < 25% transmission. At polar latitudes the sun – pipe geometry is again simple with sun elevation always $< 23^o$. Conventional vertical light pipes are, evidently, useless at high latitudes. However, we show later that sun tracking collectors transform this situation. At mid latitudes the sun elevation is below 45^o for the winter half of the year when, according to Figure 2A, the transmission of the long light pipe is less than 33%. For a relatively short time in summer the sun elevation is above 60^o when the transmission is above 50%. The integrals of the curves in Figure 2A provide approximate information about the accumulated lighting energy input when using light pipes for natural lighting. This is because there is an approximately linear relationship between sun elevation and time for equatorial to mid latitude locations.

The above analysis indicates that, for much of the day, in all locations, the use of long light pipes for natural illumination is problematic. The next sections consider how light can be more effectively collected and redirected down a light pipe and how the collected light can be extracted from the light pipe and delivered to the interior of a multi level building.

4. Extraction and distribution from light pipes in multi level buildings.

Figure 3A outlines the extraction – distribution arrangement adopted at each floor of a five level building. Figure 3B shows the dimensions, in cm, of the scale model building used to test system performance. The floor dimensions of the building are 60 cm x 60 cm. A cylindrical light pipe extends from the roof to the lower level. Transparent plastic cones with base angle = 37.5^o are mounted in the pipe at each level. A fraction of each cone is covered with high reflectance material that reflects light out through a transparent section of the cylindrical light pipe onto the surrounding ceiling. A light shelf around the lower edge of the transparent section, (not shown in Figure 3), reflects any low elevation light to the ceiling. Equal light output at each of the five levels is achieved by varying the fraction of the transparent cone covered with high reflectance material. The theory of light extraction (Edmonds et. al. 1997) is based on the energy balance between two sequential extractors, Figure 4. The general extraction case is shown in Figure 4A. When there are no losses in the system other than the fractions extracted equal outputs are achieved when $f_1 = t_1.f_2 = (1-f_1)f_2$. This relation can be rearranged to $f_1 = f_2/(1 + f_2)$ and generalised for n extractors to

$$f_n = f_{n+1}/(1 + f_{n+1}) \tag{4}$$

At the last output all of the remaining light is extracted so, for a five level system f5 = 1 and the fractions extracted at the preceding levels are 1/2, 1/3, 1/4 and 1/5 and the five outputs are each 1/5 of the input. In the present case the light pipe used is highly reflecting with $\rho = 0.95$ and, in order to simplify the analysis, we assume that one of the collectors described later has directed most of the sunlight near axially down the pipe. We also assume that any light that falls directly onto the vertical window is reflected with high reflectance i.e. the transparent pipe window is highly reflecting to near axial light. Thus sunlight passes directly down the pipe and there are no losses other than the amounts of light extracted. The amounts extracted depend on the fraction, fa, of the area of the cones covered with high reflectance material. The fraction of incident light reflected off the high reflectance area is fa as the reflectance of the coating material is taken, again for simplicity, as 1. The fraction of incident light reflected off the remainder of the cone is r(1 – fa) where r, ~ 0.15, is the reflectance of the transparent part of the cone. The energy balance equation for this case is shown in Figure 4B. The two outputs can be equated and solved to give fa_1 as a function of fa_2 and expressed, generally, as fa_n as a function of fa_{n+1}. With $fa_5 = 1$ the preceding fractional areas can then be calculated. However, in practice it is simpler to solve the equality f1 = t1.f2 numerically rather than derive an analytical solution of the balance equation, which can be complicated. By numerical solution the results for the fractions, fa_n, of the cones covered with reflecting material are 1, 0.42, 0.22, 0.12 and 0.06. With these values for fa_n the outputs, as expected, are all 20% of the input to the pipe as can be verified by substitution in the output expressions in Figure 4B. The reflected light from the cone passes through a transparent window with a transmission of 0.9 and is reflected off the ceiling with reflectance 0.7 to the interior floors. Taking these loss factors into account the outputs to the interior would each be 20x0.9x0.7 = 12.6% of the input to the pipe. The previous analysis is quite complex. However, it is actually a simplification that ignores other factors relevant when the light input to the pipe is not axial. These factors include light exiting through the transparent windows in the pipe that is not reflected at the extracting cones and light absorbed during reflection from the pipe walls. The operation of the extractors in the model building is illustrated in Figure 6A.

To assess if the extractor system delivers equal outputs to each level a light source was mounted above the input to the light pipe of the model and the daylight factor was measured at an equivalent point on the floor of each level, Figure 5. Figure 5 shows that for the vertical beam input, i.e. the design condition, the illumination is fairly constant at each floor level. When a 20^{o} off vertical beam or when a 40^{o} half angle cone of light from an approximately point light source is applied to the input the variation at each floor level is larger with more light extracted to the higher floors and less to the lower floors. Two effects seem to be in play, (1), some non axial light will be emitted directly through the pipe windows in the upper floors leaving less for extraction at lower levels and (2), losses, in particular reflection losses in the pipe, are increased for non axial light. This is evidenced by the fact that the average daylight factors over all five floors are: vertical beam, 0.0024, 20^{o} off vertical beam, 0.0019 i.e. a 21% loss in the off axis outputs. The photograph of the interior of the scale model, Figure 6A, shows that the light from the top level extractor forms a uniform concentric pattern on the ceiling. This occurs because the top extractor in the model is a smooth transparent cone with only a small fraction of the cone, 6%, covered in reflective material. The lower extractors have higher fractions of reflective material and these are formed by small pieces of flat reflecting material. In consequence, as shown in Figure 6A, the ceiling distribution becomes progressively less uniform towards lower levels as more of the smooth cone is covered with flat reflectors. It is clearly desirable, for cosmetic reasons, to use a smooth film of reflecting material.

5. Performance of the model building under natural light.

5.1 Predicted performance

If we include the transmission of the pipe window, t_w, and the reflectance of the ceiling, r_c equation 3 becomes

$$DF = E_{INT}/E_H = t_w r_c(A_P/MA_F)/(1 - R^2) \quad (5)$$

This relation is accurate only for axial light. However, we use it here to provide a first estimate of extractor performance. Figure 3B gives the dimensions of the model building in centimetres. A room 60x60x18 is repeated at five levels. Pipe sections 13 cm high with extractor sections 6 cm high are centred in the building. There is a pipe section 6 cm high at the roof level. The interior walls are mirrored to give the optical effect of a very wide plan building intersected by many light pipes. The reflectance of the walls is high, > 0.95, and the effect of the walls is ignored in estimating the average reflectance of the interior. The reflectance of the ceiling is about 0.7 and the reflectance of the floor is about 0.3 giving an average interior reflectance, R = 0.5. The interior floor area, $A_F = 0.6x0.6 = 0.36\ m^2$, the pipe area, $A_P = 0.0078\ m^2$ and the number of levels M = 5. Substituting these values in equation 5, in the ideal case, DF = 0.0036 in the interior. To put this in context, early in the morning when the sun elevation is ~ 10^o, E_H is ~ 10,000 lux, Figure 2A, and the predicted E_{INT} = 36 lux. At noon, when the sun elevation is about 65^o, E_H = 100,000 lux and the predicted interior illuminance E_{INT} = 360 lux.

5.2 Measured performance of the model building lighting system.

Figure 7 shows the floor illuminance versus sun elevation angle when the model was tested at 6, 7, 8, 9, 10, 10:30 and 11 am on a clear day in summer, January 13, in Brisbane. It is evident that the illuminance varies more strongly at the lower levels than at the higher levels of the building. However, as expected, the average floor illuminance at low sun elevation, < 50 lux at 10^o, is much less than the average illuminance at high sun elevation, ~ 300 lux at 70^o, and there is clearly a case for considering some means of collecting more sunlight into the system at low sun elevation.

6. Light collectors for vertical light pipes.

A collector has two functions. (1) To present a higher projected area to incident light than the aperture of the light pipe and, therefore, collect more light. (2) To deflect a significant fraction of collected light more directly along the pipe so as to reduce reflection loss in the pipe. For light pipes designed to transfer light horizontally from the walls of a building the collector is designed to enhance the collection of high elevation light e.g. anidolic daylighting systems, Scartezzini et. al. (2002). The present work is concerned with light pipes transferring light from the roof of a building and the collectors are designed to enhance the collection of low elevation light. Here we consider three forms of light collector formed from laser cut panel, (LCP): the panel, the gable and the pyramid forms. These forms are most appropriate for a square pipe but can also be mounted above a cylindrical light pipe. As an example, a small gable collector, used commercially on 400 mm light pipes in residential buildings, is shown in Figure 6B. For the purposes of this paper a panel collector is a single rectangle of LCP tilted at a base angle, typically, 35^o, above the pipe aperture. The gable collector is two rectangular LCP, each half the size of a panel collector, tilted towards each other at 35^o, forming a gable. A pyramid collector is four triangles of LCP tilted at 35^o to form a pyramid above the pipe aperture. When aligned to face the sun direction a panel collector is two times as effective as gable collector and four times as effective as a pyramid collector in collecting low elevation light. Each of the collectors has a third useful function, in lower latitude locations, of rejecting high elevation sunlight. The fixed gable collector is suited to near equatorial latitudes between $+/-30^o$ and its performance can be assessed quite accurately in the sun – pipe geometry where the sun moves at a constant angular rate directly over the light pipe, c.f. Figure 2B. The panel collector can be analysed as a simple extension of the gable form. The pyramid form, with four faces, is much more difficult to analyse and, as mentioned above, is less effective as a collector of low elevation sunlight than the panel or gable forms. For this reason we analyse only the gable form of collector, Figure 8, and only for light incident in the plane of the diagram in Figure 8, i.e. we do not consider light at oblique incidence.

6.1 The gable form of fixed light collector

LCP are made by laser cutting an array of cuts through or partly through a thin panel of clear acrylic plastic. If the cuts are made perpendicular to the acrylic panel a fraction, fd, of light incident at angle i is deflected through an angle 2i on transmission through the panel.

The optical properties of a LCP are defined by the ratio D/W where D is the cut spacing and W is the cut depth. When the cuts are made normal to the panel the incident angle at which all light is deflected is given by $i0 = \sin^{-1}[1.5\sin(\tan^{-1}(D/W))]$. When $i < i0$, the fraction of light deflected $fd = (W/D)\tan(r)$; when $i > i0$, $fd = 2 - (W/D)\tan(r)$, where r is the angle of refraction at the first face of the panel. The fraction undeflected, $fu = 1 - fd$, (Edmonds, 1993). Referring to Figure 8, a fraction, fu1, of sunlight at elevation εs, incident at angle i1 on point Y of side 1 of the LCP gable, passes through the gable undeflected. A fraction fd1 is deflected through angle 2i to pass into the light pipe at elevation angle εd1. The fraction of undeflected light from side 1 accepted into the light pipe is given by the ratio fua1 = XY/XZ. The geometric relations involved in finding i1, εd1 and fau1 are $i1 = 90 - \beta - \varepsilon_S$, $\varepsilon d1 = 180 - 2\beta - \varepsilon_S$ and $fua1 = 2\sin(\varepsilon_S)\cos(\beta)/\sin(\beta + \varepsilon_S)$. For the geometry of Figure 8, the fraction of deflected light from side 1 that is accepted, fda1 = 1. When $\varepsilon < \beta$ sunlight is incident only on side 1 and the radiant power incident on side 1 of the gable is Pin1

$= I_N A^2 \cos(i1)/ (2\cos(\beta))$, where I_N is the intensity of sunlight. In this work the intensity of sunlight I_N = 1368Tatmos Wm^{-2} where Tatmos = [e(-0.65m) + e(-0.095m)]/2 (Kreith and Kreider, 1978) and m, the optical depth of the atmosphere, is given by $m = [1229 + (614\sin(\varepsilon_S))^2]^{0.5} - 614\sin(\varepsilon_S)$, (Pirsel, 1991). Finally the number of reflections in the pipe for the undeflected light $Nu1 = L/(A\tan(\varepsilon_S))$ and the transmission of undeflected sunlight through the pipe is given by $tu1 = \rho^{Nu1}$. There are similar expressions for fad1 and td1 corresponding to deflected light. Finally the radiant power output at the bottom of the pipe from side 1 is given by Pout1 = Pin1(fd1.fad1.td1 + fu1.fau1.tu1). The radiant power input to the pipe without the gable collector is Pinopen = $I_N A^2 \sin(\varepsilon_S)$ and the power output at the bottom of the pipe without gable collector is Poutopen = Pinopen.tu1.

When $\varepsilon s > \beta$ sunlight is incident on both side 1 and side 2 and there are four different sunlight components that must be followed through the system. Similar expressions as above arise for sunlight incident on side 2 and the radiant power output for sunlight incident on side 2 is given by Pout2 = Pin2(fd2.fad2.td2 + fu2.fau2.tu2).

Figure 9 shows the radiant power output for sunlight incident on side1 of the gable and on side 2 of the gable. Also shown, dotted line, is the power output when the pipe is a conventional open pipe with no gable collector. Clearly the effect of the gable collector is a large enhancement in power output for low sun elevations and a large decrease in power output at high sun elevations relative to the power output of a pipe without collector. Note that there are several inflection points in the curve in Figure 9. Considerable care is necessary to follow sign changes in fd and εd at these inflection points when programming the equations outlined above.

Figure 10 shows the total radiant power at the pipe output versus sun elevation for various values of the cut spacing to cut depth ratio, D/W, of the LCP. The ratio D/W is simple to vary. For example if the laser cuts were made right through a 10 mm panel D/W = 0.5 would be obtained by spacing the cuts in the panel by 5 mm. It is evident from Figure 10 that there is considerable scope to tailor the performance of a gable collector. For example, in hot equatorial locations where it is desirable to minimise radiant heat input at noon a ratio D/W = 0.45 might be preferred. A fixed gable collector is suited to application where the sun path is predominantly in the east, west, zenith plane. This path corresponds reasonably closely to sun paths at locations in the latitude range +/- 30^{o}. When the azimuth direction varies significantly from east or west the fixed gable collector and the panel collector become ineffective at boosting low elevation sunlight.

Successful application of fixed collectors depends on how these collectors perform when sunlight falls obliquely on the collector. Figure 11 shows the results of a simple experiment where a single LCP, tilted at 45^{o}, above a vertical light pipe could be rotated in the beam of a spotlight, the elevation of which could be varied between 0 and 90^{o}. The output of the light pipe was transmitted via a diffuser into a light box and the light input to the box was measured with a photometer. Calibration of the light box was made by removing the light pipe and comparing illuminance on the diffuser with illuminance in the light box. Figure 11 shows the light box input versus azimuth angle of the beam for various elevation angles of the beam. For low elevation light the pipe output falls rapidly as the oblique angle of the light varies from 0 to 50^{o}. Conversely for higher elevation light the pipe output is relatively much more constant with oblique angle. The reasons for this are intuitively obvious. Light at zero elevation and zero azimuth is defected directly down the light pipe by a 45^o LCP and the output is high. However, as the azimuth angle increases low elevation light is deflected more obliquely into the pipe and reflection losses in the pipe account for the decreasing pipe output. At light elevations near the tilt of the panel, 45^o, light deflection is minimal and the LCP has little effect. At high light elevations most light is deflected near horizontally by the LCP, does not enter the light pipe and the output is reduced. We conclude from this experiment that any LCP collector – light pipe system provides enhancement of low elevation light at azimuths perpendicular to the faces, almost no enhancement at azimuths diagonal to the faces and significant reduction for high elevation light at all azimuths.

6.2 Tracking light collectors for light pipes.

Tracking of collectors by rotation about a vertical axis to follow the sun azimuth direction is necessary at mid to low latitude locations. At mid to equatorial locations adequate tracking is accomplished by simply flipping the collector from east facing to west facing at noon. We consider here two types of tracking collector (1), a single panel LCP and (2), a single panel LCP – mirror combination. Both collectors would track the sun azimuth by rotating about the axis of the vertical light pipe. The performance of the two types of collector are very similar in practice so we consider only the LCP – mirror combination, Figure 12, as its performance is exactly twice the performance of the first face of the gable collector. Thus the theory is essentially the same, apart for a factor of 2, as the theory for the gable collector analysed in the previous section. Figure 12 is a schematic of an LCP and a flat vertical mirror (M) combination that rotates about the axis of a light pipe of length L and aperture width

A, here considered to be a square pipe. The mirror acts to produce a virtual image of the system. Sunlight passing through the LCP and incident on the mirror follows an actual path which is the mirror image of the virtual path in a gable system with two times the actual pipe aperture. Thus multiplying the radiant power output from side 1, Pout1, in Figure 9 by two we obtain the output of a tracked LCP – mirror system as a function of sun elevation angle, Figure 13A. The output of the open pipe i.e. pipe with no collector system, remains the same as indicated in Figure 9. The performance of this collector is twice that of a gable collector. If we consider direct sunlight only the pipe output at 20^{o} sun elevation is about forty times more than for the pipe without collector. However, in practice the diffuse light from a clear sky reduces this ratio considerably because the diffuse input approaches a non zero value as sun elevation tends to zero. The effect of diffuse light can be accounted for very approximately as follows. Practical experience with light collecting systems of the sort discussed here indicates that the effect of the collector on light from a uniform diffuse sky is minimal. Although not shown theoretically, it appears that the gains from low elevation diffuse light are compensated by losses of high elevation diffuse light when these systems are operated under uniform or near uniform diffuse skies. Thus, as a first approximation, the output of a pipe without collector under a uniform diffuse sky, Figure 2A, can be added to the output due to direct sunlight to find the total output, direct plus diffuse. The pipe outputs in Figure 2A are in lumens per square metre. However, the value can be converted to radiant power output in Watts per square metre by dividing by the efficacy of diffuse skylight. This varies somewhat with sun elevation in the range 100 to 120 lumens/Watt, (Pohlen et al 1996). Here we use 100 lumens/Watt. The diffuse component output in Figure 2A is, after conversion to radiant power, also shown in Figure 13A. When the diffuse component is added to the two direct components and the ratio, total output collector to total output open, is taken the result in Figure 13B is obtained. We note that the enhancement obtained at 20^{o} when $\rho = 0.9$ is now reduced to about 17 and, when $\rho = 0.95$, to about 7. The enhancement due to a collector increases as the pipe reflectance decreases, an effect illustrated by including results for $\rho = 0.95$, 0.9, and 0.8 in Figure 13B.

6.3 Different tracking options for collectors.

Ideally a collector is tracked to face the sun azimuth direction in order to maximise system output at low sun elevation. Tracking usually requires a sensor and electronic control of the movement of the collector. Also, in cloudy or overcast conditions sensor controlled tracking can be erratic. Here we consider a simple alternative where the collector is rotated about the system axis at 15^{o} per hour making one full rotation every 24 hours as in a 24 hour clock.

Figure 14 shows the difference between the sun azimuth direction and the clock angle direction for locations at latitudes -45^{o} and -60^{o}. It is evident that at mid latitude to polar locations the difference is $<20^{o}$ for most of the time. In winter the difference is $< 10^{o}$. Thus, for these locations 24 hour clock rotation is a simple and effective means of tracking the sun. At lower latitudes and particularly during summer, the angle difference can be greater than 20^{o} for much of the time. As Figure 11 shows, and as discussed earlier, when sunlight falls on an LCP collector at oblique angles the collection efficiency for low elevation sunlight falls rapidly. For oblique angles of 20^{o} or greater the efficiency is less than 50% of the collection efficiency at normal incidence.

At high latitudes the sun is always at low elevation and a 24 hour clock rotation follows the sun closely. Therefore, from the technical point of view, an ideal natural lighting strategy for buildings at high latitudes is minimal wall windows and a clock driven LCP – mirror collector coupled to a vertical light pipe delivering sunlight to the building core, (Edmonds, 1997).

To test the performance of some of the previously described systems under natural sunlight a pyramid collector, and a sun azimuth tracking collector were used with the light pipe and light integrating box system described in section 6.1. Results obtained for a clear day near mid summer, December 1, at Brisbane are shown in Figure 15. The results are much as expected. In the early morning and late afternoon when the sun elevation is low, ~ 20^o, there is weak enhancement relative to the open pipe, < 2, by the fixed pyramid collector while the tracked panel collector provides enhancement of about 5. When the sun elevation is high both collectors are effective in reducing the radiant input and output, Figure 15.

In summary: Fixed east - west oriented gable collectors are effective at latitudes < 30^o. Pyramid collectors are less effective in improving low elevation sunlight collection but as effective in rejecting high elevation sunlight. Collectors comprising a tilted panel LCP are effective in enhancing output of low elevation sunlight but must be reversed at noon at low latitude locations or must track sun azimuth at mid to high latitude locations. Tracking with a 24 hour clock mechanism is effective at mid to high latitude locations.

7.0 Observed multilevel lighting performance with a tracking collector.

7.1 Observations

The model building was set up in an open location with a view to the horizon in most directions. The objective was to measure interior illuminance with and without the collector, in this case a 35^{o} panel – vertical mirror manually tracked collector of the configuration in Figure 12. The collector had vertical side mirrors as well as the back mirror and was rotated manually about the pipe opening to track the sun azimuth angle. It is difficult, during summer, the wet season in Brisbane, to obtain days with continuously clear skies. However, on March 3, 2015 clear skies enabled observations from 6:15 am to 8:30 am of interior illuminance for the pipe with collector and the open pipe at all five levels, Figure 16 A. Also shown in Figure 16A is the exterior horizontal illuminance in klux. The observed enhancements at all five levels are shown in Figure 16B. It is evident, from Figure 16B, that the time interval of observations covered the time when the tracked collector significantly enhanced the interior illuminance for low sun elevation angles. The enhancements observed are, as expected, higher for the lower levels of the building where the pipe is longer. The average interior illuminance over all five levels at 20^{o} sun elevation is 70 lux. This indicates that a larger pipe area, in the model only 2% of the floor area, would be desirable. The lighting system is complex and the interior illumination is expected to increase more than proportionally with pipe area so it is difficult to specify exactly how much larger the pipe area should be to achieve some nominated level of average interior illuminance. On the basis of simple proportionality of output with pipe area increasing the pipe area to 10% of the floor area would provide interior illuminance approaching 400 lux at low sun elevation angles. The illumination at high sun elevation angles might then be excessive without the reduction in output due to the collector, Figure 10 and Figure 13A.

A further set of observations were made in the sun elevation range between 23^o and 27^o of the interior illuminance at the third level as the collector was progressively deviated away from the sun azimuth direction. For deviations 0^o, 10^o, 20^{o}and 30^o the average relative readings were, 1.00, 0.93, 0.81, and 0.78, indicating that the collection of low elevation sunlight was not strongly dependent on the deviation of the collector from true sun azimuth for this range of deviation. Comparison with the results of Figure 12 for a 45^o panel collector without side or back mirrors indicates that the back and side mirrors are useful in maintaining collection at deviations away from sun azimuth.

7.2 Predicting system performance.

In the ideal case when all light passes axially through the pipe and the light is extracted and distributed to each level equally we can use equation 5, DF = $E_{int}/E_H = t_w r_c(A_p/MA_f)/(1 - R^2)$, to predict the daylight factor, DF, or if external horizontal illuminance is known, to predict the interior floor illuminance, E_{int} at any level. With a 35^o panel collector the deflected sunlight passes directly down the pipe at sun elevation 20^o. The LCP used in the collector had a cut depth, W, of 6 mm (the panel thickness was 6 mm and the cuts were made right through the panel) and the cut spacing, D, was 4 mm. So from the relation fd = (W/D)tan(r) the fraction of incident sunlight deflected axially down the pipe was 0.62 or 62%. We note from Figure 16B, that, for the lower three levels, the enhancements have broad peaks centred, approximately, on 20^o. In section 5.1 substitution of the parameters of the model building ($t_w = 0.9$, $r_c = 0.7$, $A_P = 0.0078$ m^2, $A_F = 0.36$ m^2, $R = 0.5$ and $M = 5$) in equation 5 predicted a daylight factor of 0.0036. So, in the ideal case, the daylight factor at each level would be 0.0036. From the observations in Figure 16A the observed daylight factor can be found from the ratio of the observed interior illuminance, E_{INT}, to the observed horizontal exterior illuminance, E_H. At sun elevation of 20^o, the sun elevation angle expected to provide maximum axial sunlight, the observed interior illuminance at the lower three levels is close to 50 lux and the observed exterior horizontal illuminance is close to 15,000 lux. Thus the observed daylight factor at the lower three levels is 0.0033 and is close to the value, 0.0036, predicted by equation 5. At the top two levels the observed daylight factor at sun elevation = 20^o is significantly higher than predicted by equation 5. At level 1, DF = 0.0086 and at level 2, DF = 0.0057. It is likely that much of the 38% of undeflected sunlight that enters the pipe at elevation angle 20^o is exiting the pipe directly through the pipe windows at the upper levels and bypassing the extraction process at the extractors. However, equation 5, despite its simplicity, provides a good estimate of the illumination of the lower levels of the building in the specific case of near axial deflection of sunlight by the collector.

In summary, the simple relation developed in section 5, $DF = t_w r_c(A_p/MA_f)/(1 - R^2)$, is adequate to predict illumination from a multilevel daylighting system for sun elevations when the collector provides near axial sunlight to the system. At other sun elevations the more detailed collector – light pipe relations developed in section 6 can provide a only a rough indication of how interior illumination varies with sun elevation due to the neglect, in the theory, of some effects relevant to the more complex form of light pipe with extractors.

8. Conclusions.

This paper is a comprehensive examination of the prospect of using vertical light pipes to naturally illuminate the central core of a multilevel building. The challenges addressed were finding a method to extract and distribute equal amounts of light at each level and designing collectors to improve the effectiveness of vertical light pipes in delivering low elevation sunlight to the interior. A further challenge was finding analytical means of predicting the performance of a complex optical system. Theory developed for the collector design indicated the tilt angle and cut spacing to depth ratio required for the laser cut panel in order to optimise low elevation and/or high elevation performance. A complete natural lighting system with tracked collector and extractors was tested in a five level model building with each level fitted with mirror walls to simulate a wide plan building core area illuminated by an array of light pipes. The light pipe in the model occupied about 2% of the floor area. Use of the tracked collector increased the illumination at the lower levels of the building by a factor of about seven for low sun elevations. This resulted in an average illumination, over all five levels of the building, of 70 lux at low sun elevation, indicating that a higher pipe area occupying up to 10 % of floor area would be necessary to achieve average interior illuminance of 500 lux for low sun elevations.

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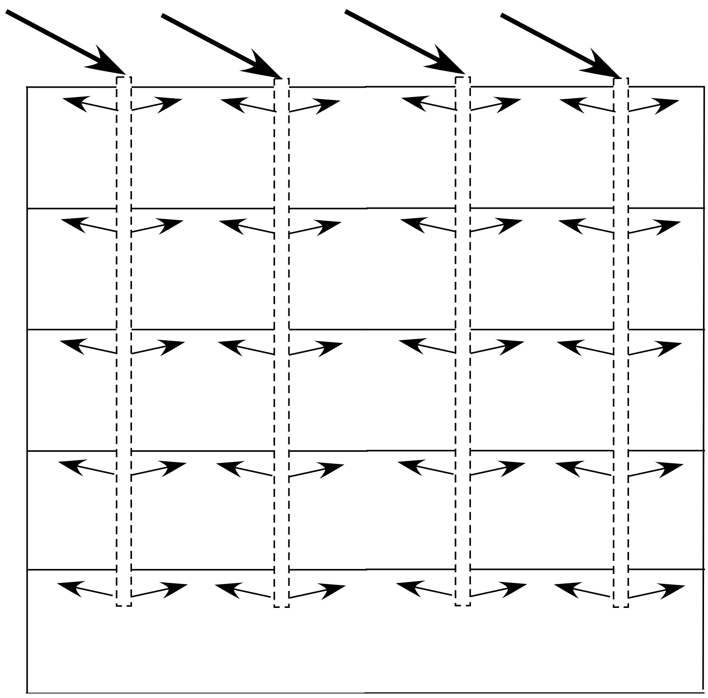

Figure 1. Basic concept of a system to deliver natural light via light pipes to a five level building.

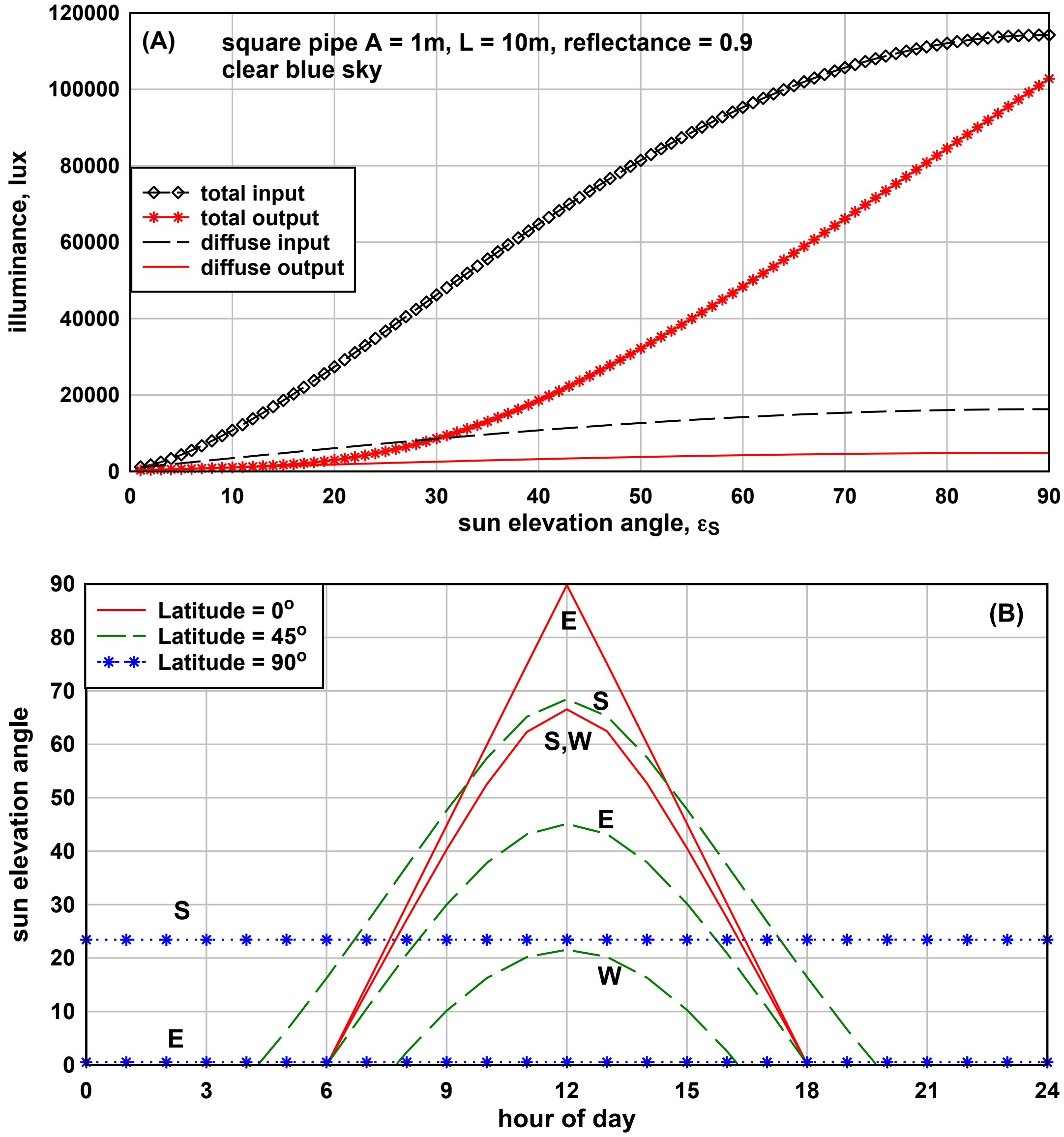

Figure 2. (A) The theoretical pipe input and pipe output illuminance for a square section light pipe under a clear sunny sky. (B) The sun elevation angle versus hour of day for mid summer, S, mid winter, W, and equinox, E, at various latitudes.

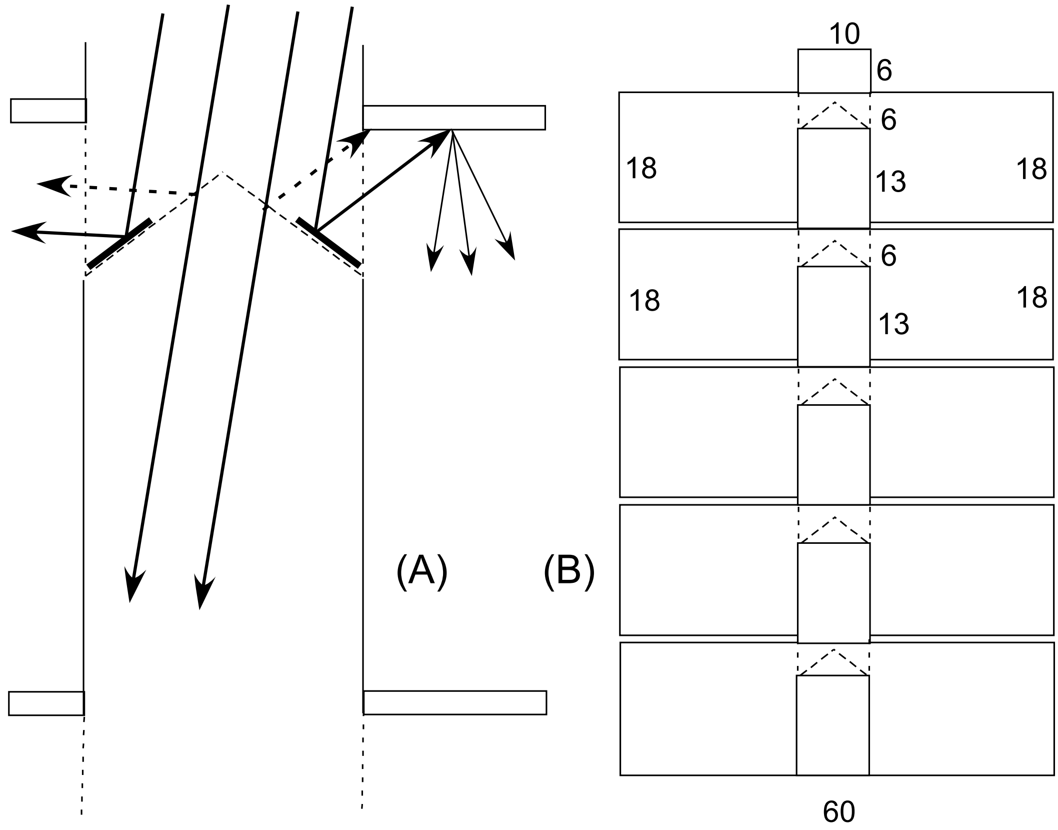

Figure 3. (A) The arrangement for extracting light by reflection off a cone set in a windowed section of a light pipe. (B) The dimensions in cm of the five level model building used in this study. The floor dimension of the building is 60 x 60 cm.

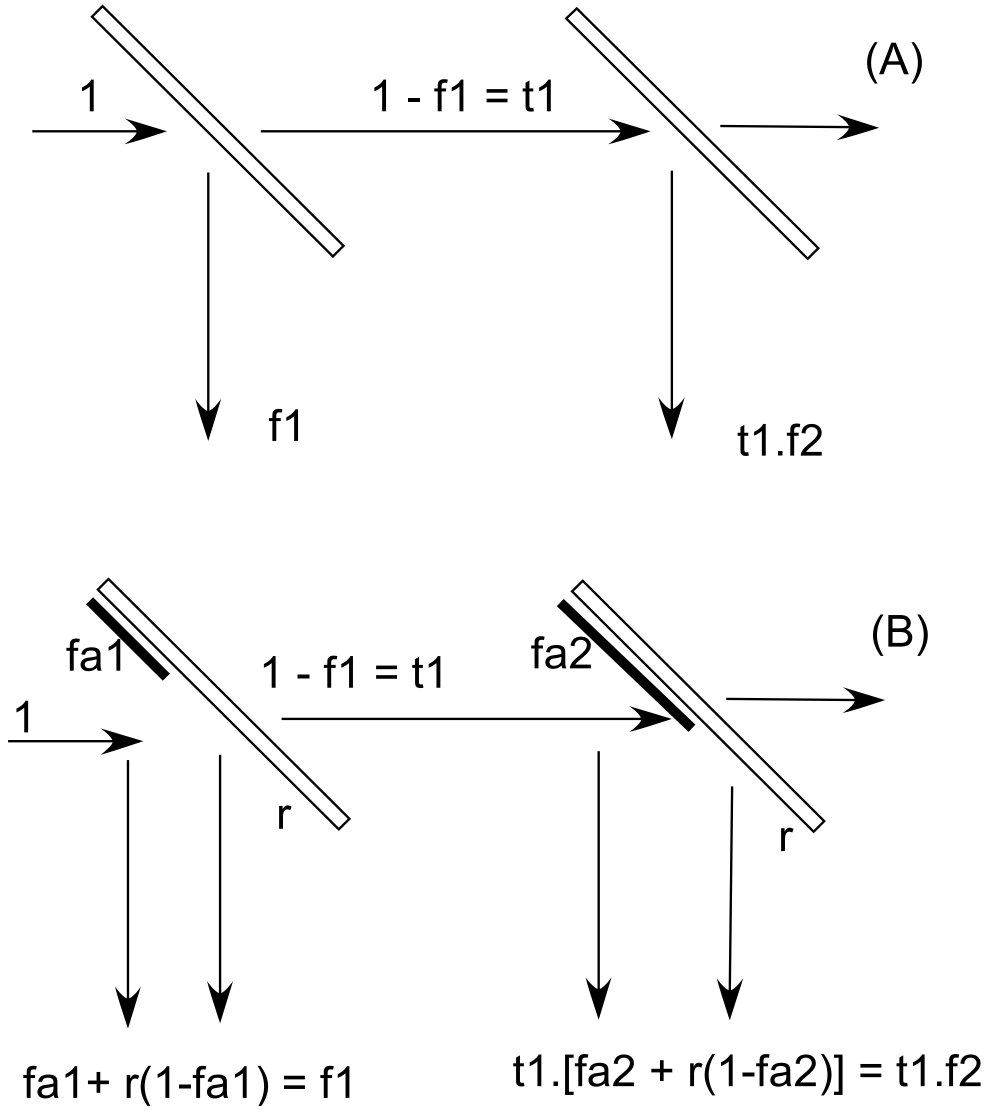

Figure 4. (A) Basic energy balance diagram relating to two extractors in a sequence of extractors. (B) The energy balance diagram for extractors where a fraction, fa, of light is extracted by reflection off reflective material of reflectance 1 and transparent material of reflectance r.

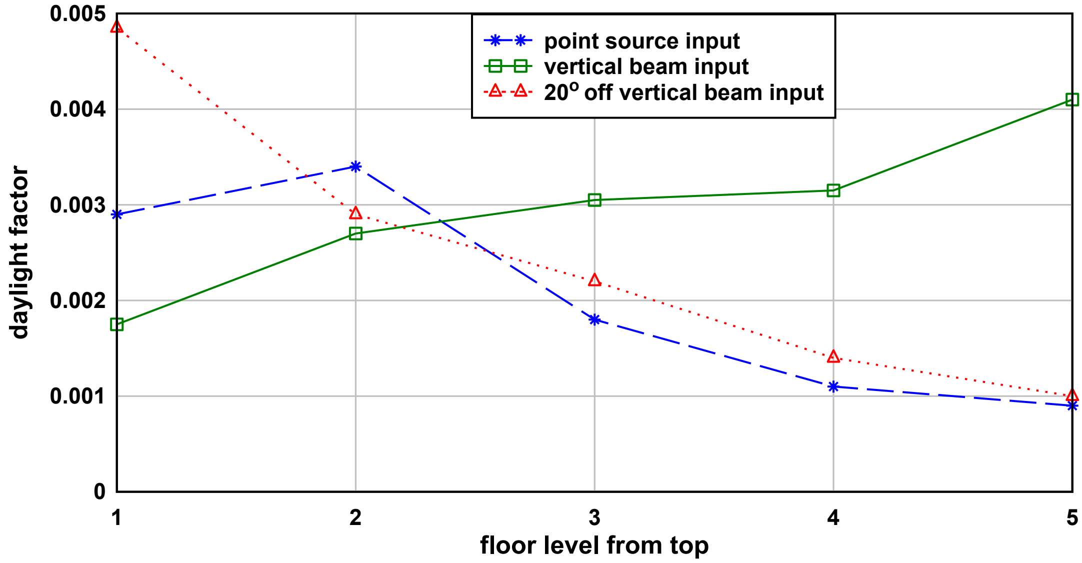

Figure 5. The daylight factor measured at each level of the model building for various forms of input light.

 (A) (B) 

Figure 6. (A) A view of the interior of the five level model building. Mirrored walls simulate multiple light pipes illuminating a wide plan interior. A mirrored access door opens to the right. (B) A gable collector that sits under the dome (not shown) of a 400 mm diameter light pipe for residential application.

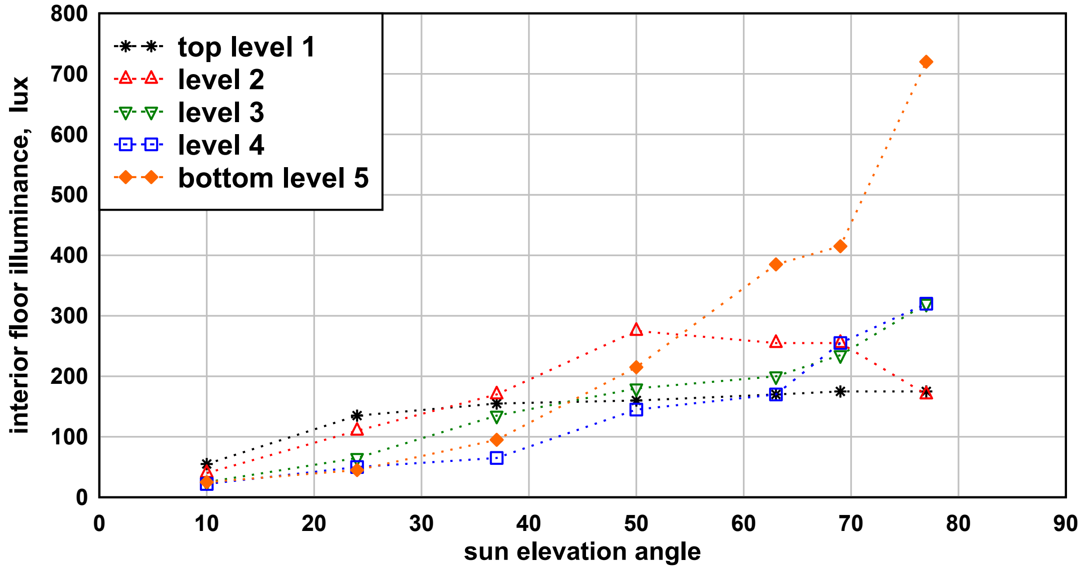

Figure 7. Observed interior illuminance in a five level model building with no collector on the light pipe delivery system.

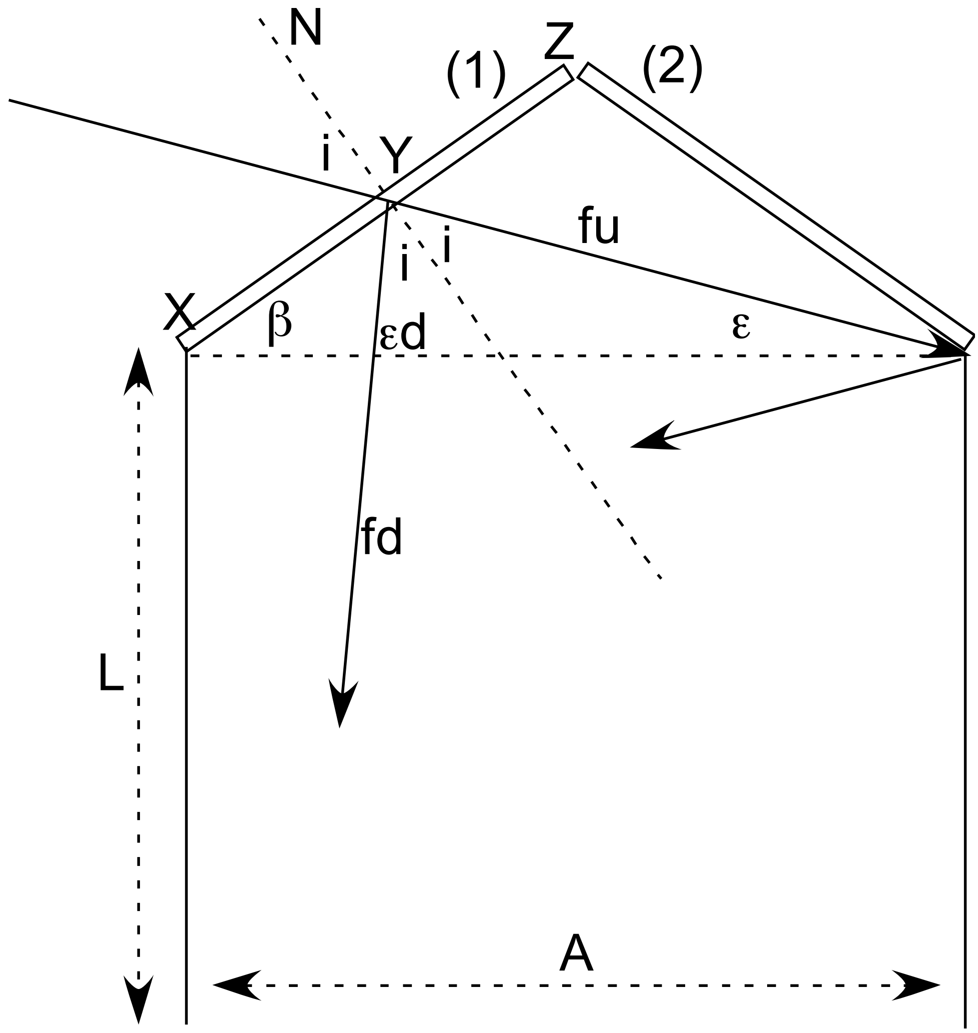

Figure 8. Geometry of a gable collector formed from two laser cut panels tilted at angle, β, above a light pipe of aperture, A, and length, L.

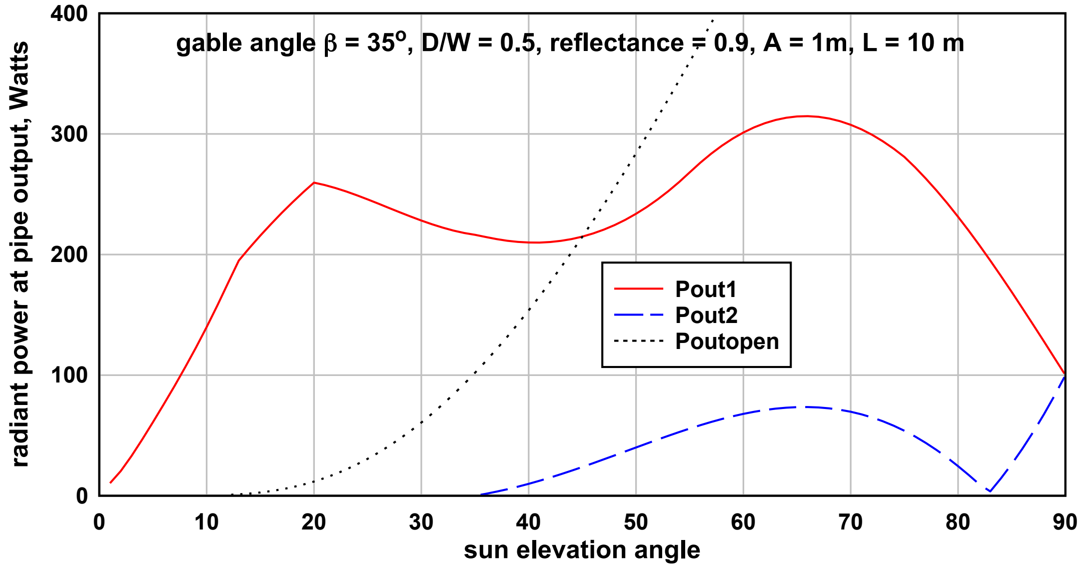

Figure 9. The radiant power output from a gable collector - square pipe system of side 1 m and length 10 m versus sun elevation angle. Outputs for sunlight incident on side 1 of the collector, on side 2 of the collector and for an open pipe, i.e. no collector, are shown separately.

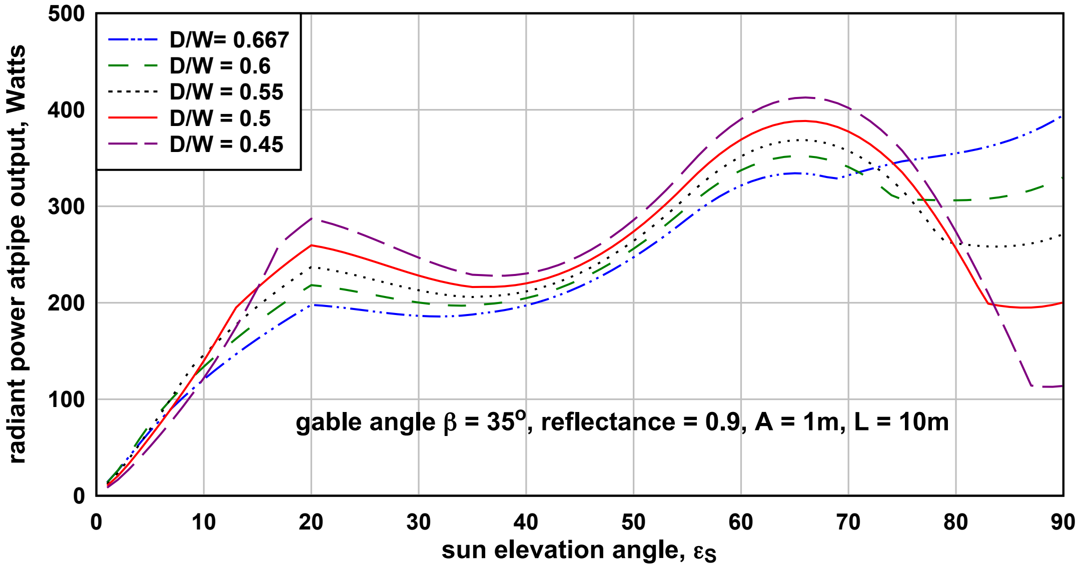

Figure 10. The radiant power output for a gable collector – square pipe system for varying cut spacing to cut depth ratio, D/W, of the laser cut panel.

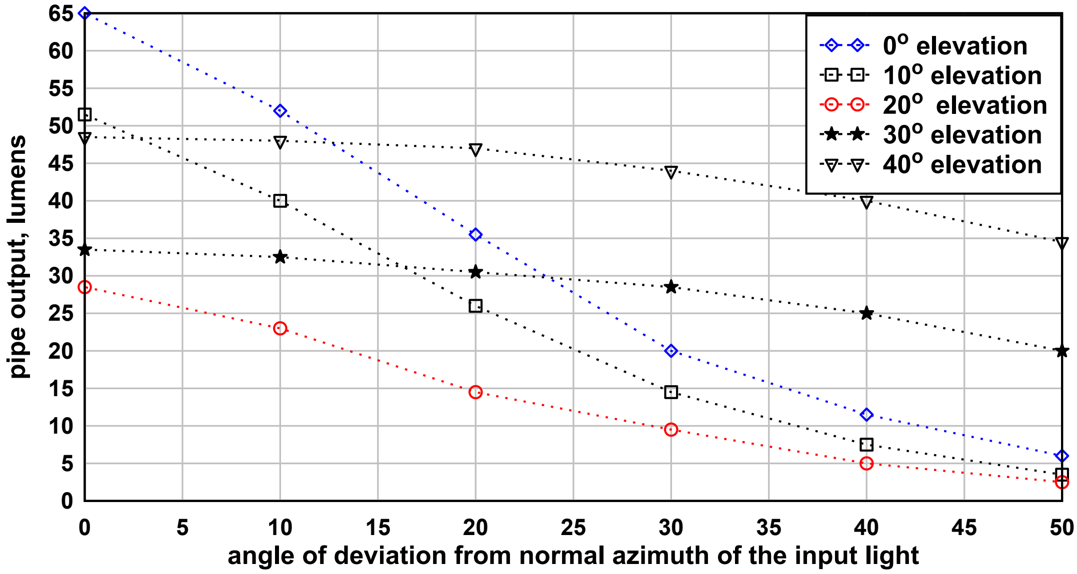

Figure 11. The pipe output in lumens for a 45° panel collector – cylindrical light pipe system illuminated by a beam spotlight, the elevation angle of which could be varied. The system was rotated about a vertical axis to obtain outputs as the azimuth of the beam deviated from the normal azimuth to the collector.

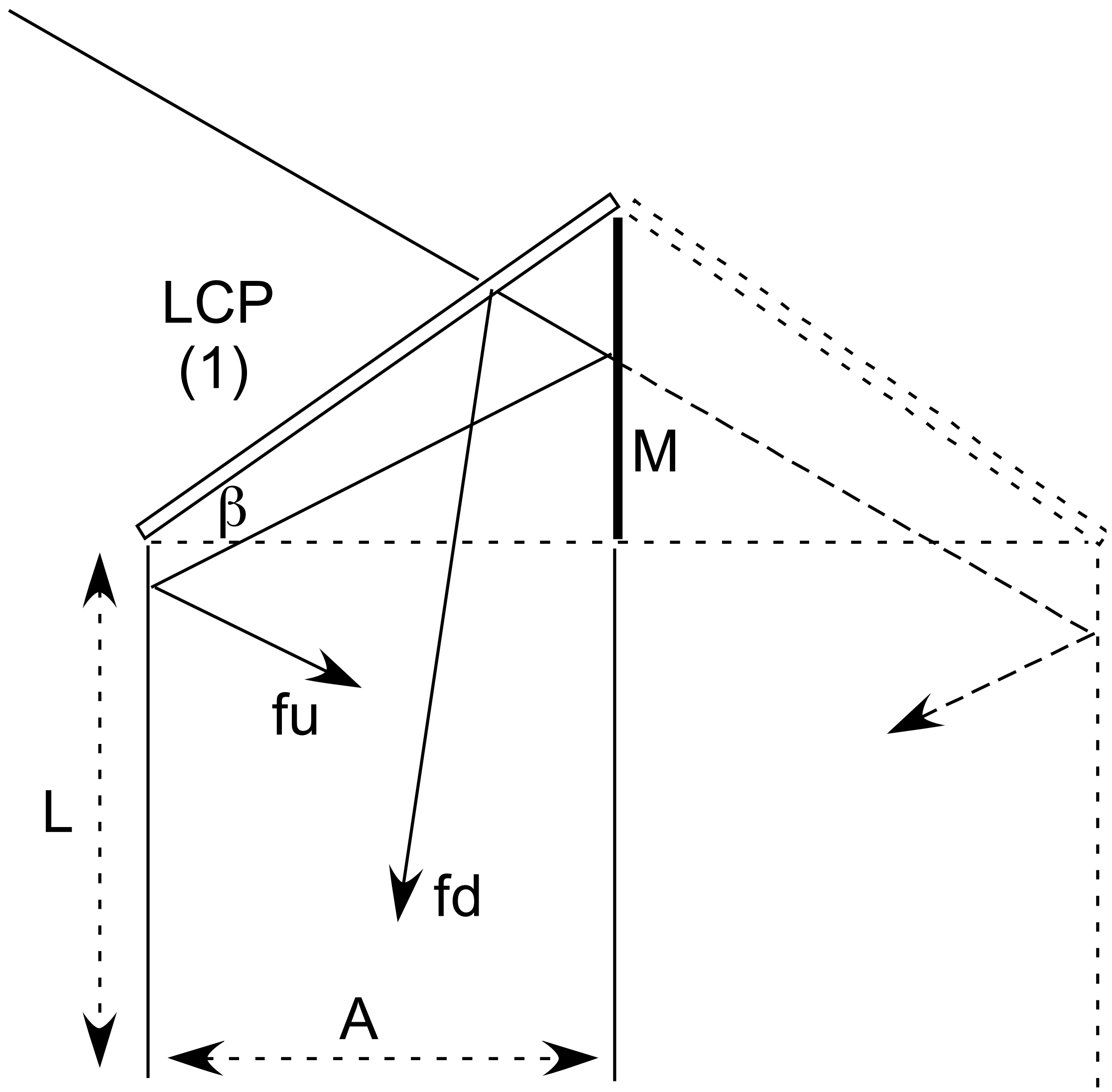

Figure 12. A panel collector, LCP(1), combined with a vertical mirror, M, above a pipe of aperture, A, performs essentially the same as a gable collector operating into a light pipe of aperture 2A, provided input only to LCP(1) is considered. Therefore the output of a panel – mirror collector is twice the output of side 1 of a gable collector.

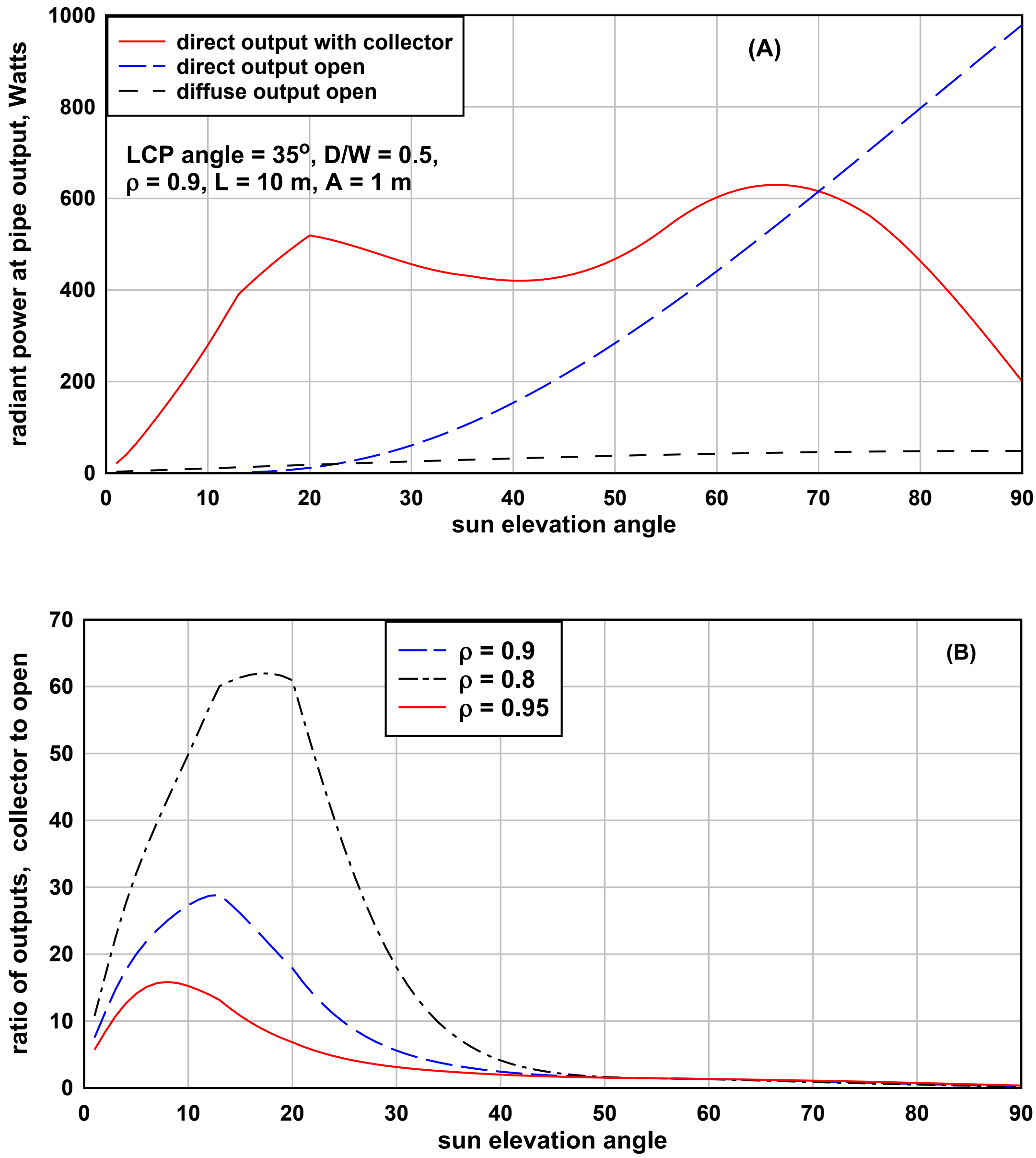

Figure 13. (A) The radiant power output versus sun elevation of a panel – mirror collector light pipe combination for direct sunlight illumination. Also shown the output of an open pipe for direct sunlight and for diffuse blue sky illumination. (B) The enhancement due to the collector when total output (direct plus diffuse) with collector is compared with total output (direct plus diffuse) for an open pipe.

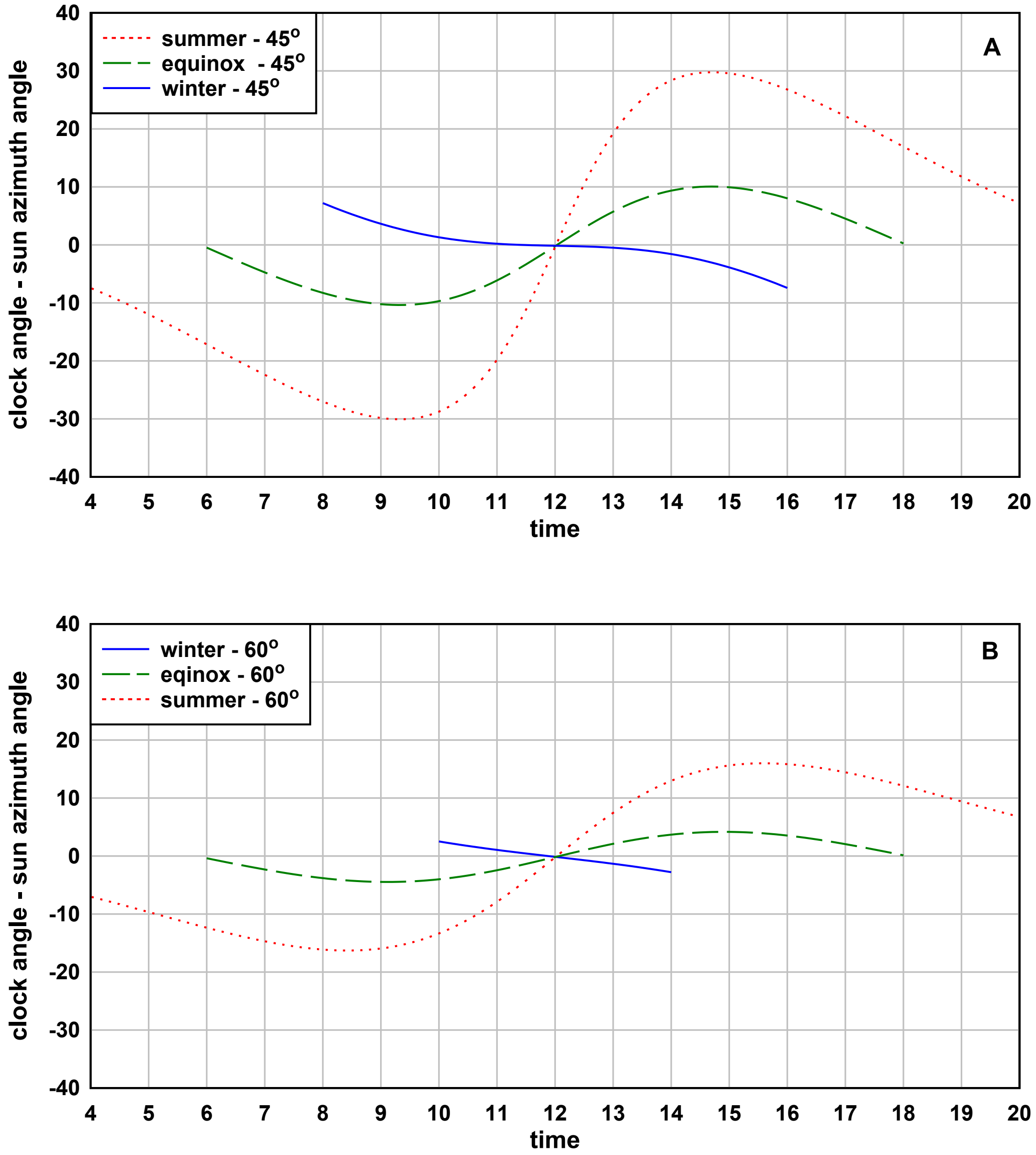

Figure 14. The time variation of the deviation of the 24 hour clock angle from the sun azimuth angle at midwinter, equinox and midsummer for latitudes (A), -45^{o} and (B), -60^{o}.

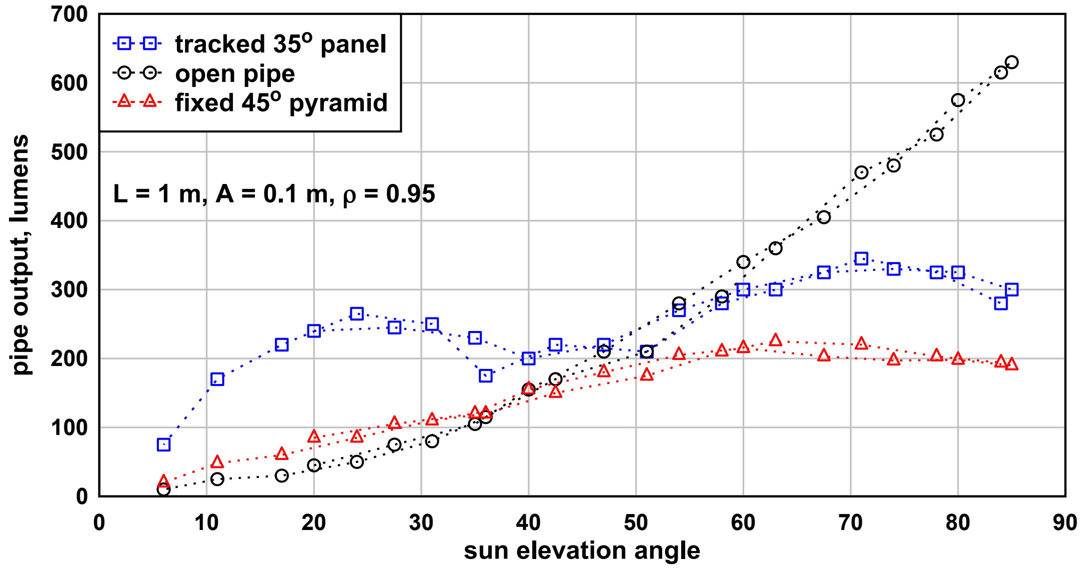

Figure 15. The pipe output in lumens versus sun elevation for an open light pipe, aspect ratio 10, and for the same pipe with a fixed 45^{o} pyramid collector and with a solar azimuth tracked 35^{o} panel collector. The overlapping graphs correspond to overlapping morning and afternoon observations.

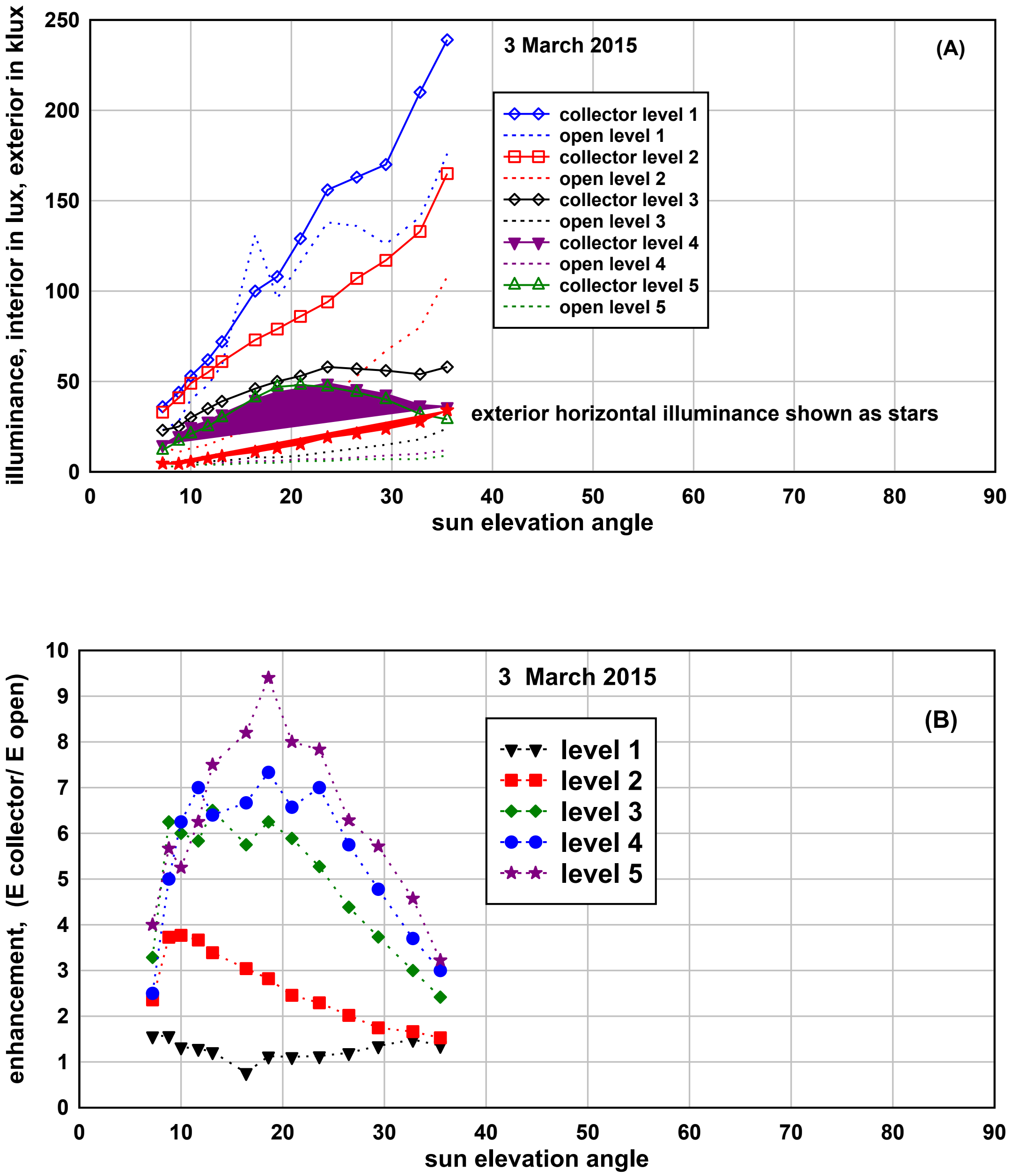

Figure 16. (A) Observed interior illuminance, with collector and without collector, on the five floor levels of the model building versus sun elevation on the morning of a clear day, March 3, in Brisbane. (B) The enhancement due to the sun tracked panel – mirror collector at the five levels of the model building.