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# HARNESSING DAYLIGHT POTENTIALS AS A TOOL FOR VISUAL AND THERMAL COMFORT IN RESIDENTIAL BUILDINGS

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**ABSTRACT**

Architects have a responsibility to understand clearly, and sensibly plan housing units and ultimately the cities so as to achieve a sustainable whole. By so doing, these professionals cannot afford to neglect any aspect of the housing envelope, nor consider it in part or as a whole as un-important. It is for this purpose, that we look at the aspects of harnessing daylight through a variety of systems and methods so as to make best use of this free and in-exhaustible commodity for both visual and thermal comfort.

The major question which this thesis attempted to answer was to find a means of improving visual and thermal comfort in our homes while at the same time reducing our fossil fuel emissions. It was to this end that attention was turned towards the earth's major source of energy and to see how best to harness this resource and put it to passive use in the best possible non-intrusive manner. This thesis as a whole, attempted to evaluate existing lighting and thermal devices with an aim to enhancing them as well as suggesting novel devices to replace the existing ones.

This thesis reviewed and tested the performance of solar evacuators, optical rods known to have high transmittance, as well as light pipes to see their applicability in residential dwellings in terms of the provision and lighting and heating within the residential buildings. Studies were also done to determine the effect of the combination of two technologies on the same platform i.e. light-pipes combined with light rod, as well as light rods combined with solar evacuators to ascertain and enhance their viability. These tests were carried out in three ways, viz; laboratory tests, outdoor tests as well as field tests on existing real life applications on the singular technology in use as a base-line for assessing the new technologies.

Further studies were also carried out with the introduction of nano-technology, i.e. aerogel, so as to test its suitability as an insulator of heat and to examine its economic viability and use in residential buildings. Aerogel was also tested as filler in double-paned glass window to determine its transmittability whilst still maintaining its properties of being a good insulator. Consequently, suggestions were made into the application of the investigated devices, and how best they can be used in new buildings and retro-fitted in existing ones.

# DEDICATION

This thesis is dedicated to all the mothers who have striven to achieve their dreams despite the numerous hurdles in difficult terrains such as ours.

**ACKNOWLEDGEMENT**

This may be the longest acknowledgement yet, but then only those who know how long and difficult this entire process has been will understand, as several people have been instrumental in the completion of this project.

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Thank you my amazing sister, Didi, words cannot express how grateful I am to you for your unwavering support, duas and love – even when I felt I had run out of steam, you kept encouraging me – you were there every step of the way. May your children Abba and Iman (who are more like mine) continue to be a source of joy to you and us.

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With great sincerity and love, my heartfelt appreciation and gratitude goes to my husband Baba Tee who made the most difficult of all sacrifices. Your continued encouragement and wonderful spousal support made the separation more bearable. I can never thank you enough, but I pray Allah will reward you with a house in Jannah.

Finally, to friendships forged.

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# 1. CHAPTER 1 INTRODUCTION

## 1.1. Background

It is important for architects to appreciate the manner in which energy is used in buildings as well as the fuel type employed for its generation. This is particularly important because it will help in identifying ways in which we could attempt to reduce our dependency on fossil-fuel, and thus consider new forms of renewable technologies.

Various studies agree that lighting is a major factor in determining the way in which people experience the internal environment, how they experience buildings, as well as how they are able to respond to certain tasks. These studies further show that daylighting has an important role in health and mental development.

The source of daylighting as well as the management of it in both residential and public buildings is a major consideration especially in the area of building sustainable cities. The primary aim of providing buildings with continuous natural light is also reinforced by the need to improve thermal comfort. There is the need therefore, to convert this light source into various other forms such as air conditioning/heating, so as to minimise the use of fossil fuel generated energy for associated heating and cooling thus, reducing $CO_2$ emissions and ultimately global warming and its adverse effects.

The excessive use of electric lighting in buildings can lead to undesired effects on the occupants and is discouraged by energy conservationists (Heschong, Mahone Group, 1999). The energy consumed on electric lighting for domestic buildings rose from 7% in 1970 to as high as 13% in the year 2000 (DTI, 2000). Jenkins and Muneer (2003) therefore opined that whilst electric lighting is obviously necessary during evening hours, very often, energy is wasted on lighting in the day time due to poor building design and/or lack of windows.

This research explores the various means of using daylighting with a view to reduce the consumption of fossil-fuels which give off emissions that contribute to global warming (Shao, 2003). This is especially useful in developing countries where there are frequent power outages as well as lack of energy services. Of all the available systems, light pipes and fibre optics have the greatest capacity to allow light to penetrate a considerable distance into the building envelope (Shao, 2003).

The primary requirement of the building envelope is to provide adequate light and thermal comfort, so as to ease communication. The use of daylight for indoor task illumination has been widely advocated so it's a task for the architect, to balance the different environmental parameters with the design variables.

Previous and numerous researchers (Tragenza P. & Wilson, M. 2011; Reinhart, C. 2006 and Leslie, R. P. 2003) carried out show that lighting is a major factor in determining the way in which people experience the internal environment, how they experience buildings, as well as how they are able to respond to certain tasks. Indeed, studies in Sweden and Canada show that daylighting has an important role in health and mental development. Other researchers (Sanchez-Lorenzo et al 2010) have also observed that climate change may bring more sunshine hours, more intense radiation and temperatures. The onus therefore lies on all professionals in the building industry - architects, engineers - to design buildings that will have a significant impact on the thermal and lighting performance of buildings which may have resulted in overheating by highly glazed and un-shaded facades which also increase glare. It is therefore important for architects to design buildings that have a low energy form.

Roaf et al (2004) observed that the climate change may bring more sunshine hours, more intense radiation and temperatures. As such, there will be a significant impact on the thermal and lighting performance of buildings which may result in over-heating of the highly glazed and unshaded, as well as increased glare. It is therefore important to design buildings that have a low energy form.

Further still in this research, optical rods known to have high transmittance along with evacuated solar tubes are employed so as to test their applicability in residential buildings. The optical rod is be subjected to further testing as it is found to transport light with high efficiency over a distance of up to 1.5metres. New applications to enhance the viability of the light pipes and light rods were explored and thus tested.

### 1.2. Aims and Objectives

The main aims of this study is to

- ✓ Look at innovative daylighting methods, technologies and devices for building integration with a view to combine solar lighting, solar heating on the same platform without compromising the purpose of either of the two.
- ✓ Investigate the aspects of solar tracking for high-rise buildings with the application and incorporation of various forms of optical instruments such as optical light rods (due to its high total internal reflection capabilities), light pipes as well as a combination of the two.

- ✓ Another aim, is to work with technology while incorporating aspects of light transmission components with the architectural aesthetics component, thereby creating a fusion of both art and science.
- ✓ Incorporation of nano-technology such as aerogel to test its viability in the area of insulation and light tramsnittance
- ✓ Integration of lighting with every day building materials as bricks, blocks concrete and mortar.

Some of the objectives include:

- ✓ Continuously provide buildings with natural light and further still, to turn this light source into various other forms such as air-conditioning for cooling and heating, so as to reduce over dependence on fossil fuel and reduce our carbon foot-prints.
- ✓ Determine the types of technology to use as well as application of the various materials to be experimented with, i.e. transparent concrete (see Figure 1-1), optical rods, light pipes and aerogels. Further investigate the possibility to share the light between different rooms (and rooms with corridor). During day, the inside and outside of a room could share sunlight and at night they share artificial light thereby saving energy (Saffa, 2010). Figure 1-1 shows devices such as light rods which can be used to share light from one room to another room whilst utilizing the same source. This figure also shows the use of transparent concrete both as roof lighting and as light sharing.

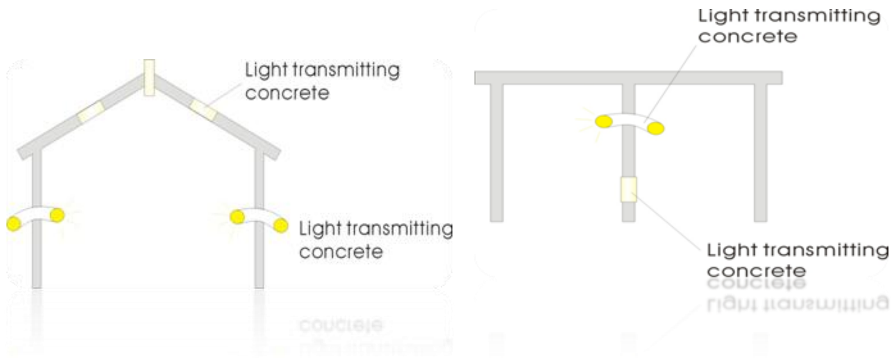



**Figure 1-1 Light Transmitting Concrete: Showing Light-Sharing**

- ✓ To determine the easiest ways to harness natural light and apply it to everyday use while incorporating aesthetics in the best architectural form.
- ✓ To convert the temperature (realised from the process of harnessing the light) into a source of power for heating/cooling as the case may be.

## 1.3. Relevance of the Study

With the main aim of this study being to look at innovative daylighting methods, technologies and devices for building integration with a view to combining solar lighting and solar heating the researcher looks at this with the view to pulling this off both as an architectural as well as an engineering feat. This can be done in a systematic manner that functionality will be of the utmost importance, whilst giving attention to aesthetics.

The relevance of this study cannot be over emphasised especially with the rapid rate of global warming. $CO_2$ is one of the main gases that contributes to global warming, which is now scientifically recognised as a real threat to today's climate. This does not just mean warmer summers and milder winters: global climate change is responsible for there being more floods, storms and droughts around the world than ever before (Mirza, 2002)

This study also took into account tropical regions such as Nigeria - as some of these devices will be subsequently tested there - where there is an abundance in sunlight with massive untapped potential. As Nigeria is struggling to grabble with developmental issues such as incessant power outages, this project will go a long way in proffering a sustainable and healthy solution to that problem.

Both Britain and Nigeria have made and are still making an unacceptable contribution to the world's $CO_2$ emissions. In light of that, the world as a whole and indeed both Britain and Nigeria have a role to play in finding ways to reduce their carbon foot prints by reducing to the least possible amount their $CO_2$ emissions. Britain especially has also a huge role to play because as of today they contribute a whopping 2% of the total world $CO_2$ emissions.

### 1.4. Research Methods and Methodology

The research methods are based on

- The review of relevant data and existing literature in terms of daylighting devices.
- Modelling through the use of a recognised and appropriate software e.g. RADIANCE®.

- Experiments are carried out using some of the various devices earlier mentioned as well simulations of real – life, real – time weather conditions. The experiments were laboratory-based as well as outdoor testing. Furthermore, monitoring was done on such existing devices in a couple of residential buildings.

### 1.5. Novelty of the Research and its Benefits

Extensive research have been done in the aspects of daylighting, yet still there are several missing gaps, some of which the content of this research has attempted to fill. By no means however are the solutions and suggestions documented in this research exhausted and perfect. This research can be clearly looked at in terms of two parameters – visual effects of natural daylighting as well as the thermal component.

Firstly, a novel system of incorporating lighting and thermal comforts on the same platform was investigated into, through the novel use of insertion of light rods into evacuated solar tubes so as to utilize the daylight resource while the system runs simultaneously so as to achieve light and thermal comfort concurrently.

Secondly, in terms of visual comfort, this research looked at using existing daylighting devices and testing methods of enhancing two existing technologies so as to further improve their performance, results which have shown an efficiency of 77% in the new dual technology device incorporating light rod and light pipe.

Thirdly, introduction of nano-technology was investigated upon so as to investigate the application of aerogel as an insulator whilst using light pipes for lighting the interior, as well as the introduction of aerogel filled double –glazed window to test its viability for transmission of light without the heat loss/gain into the interior of building from the exterior irradiation of the sun. This is especially desirable where illumination is required without visual contact between two spaces and heat loss/heat gain is kept to a minimum.

The benefits of this research are based solidly on the ethos that we can make more useful use of daylight as a resource in a passive manner such that we reduce our dependence and indeed over dependence on fossil fuel. The solutions are simply in the technologies; however their application is of high rating which go a long way in reducing the rate of pollution in our environment. It is sacrosanct to state here that this will by no means go a long way in improving quality of the air we breathe and consequently increasing our life expectancy. It is also expected that with the technology created, the simple yet novel devices can easily be replicated in any country in the world, and just as easily installed to cut down our carbon footprints.

## 1.6. RADIANCE® Software

The RADIANCE® Software was used to model the devices prior to the commencement of the laboratory testing. The results of the modelling when placed alongside that of the experiments was the benchmark used in the validation of the tests/experiments carried out. It is a software package for architectural lighting simulation developed by the Lawrence Berkeley National Laboratory.

RADIANCE® is a suite of programs for the analysis and visualization of lighting in design.

Input files specify the scene geometry, materials, luminaires, time, date and sky conditions (for daylight calculations). Calculated values include spectral radiance (i.e.

luminance + colour), irradiance (illuminance + colour) and glare indices. Simulation results may be displayed as colour images, numerical values and contour plots. RADIANCE® is used by architects and engineers to predict illumination, visual quality and appearance of innovative design spaces, and by researchers to evaluate new lighting and daylighting technologies (http://www.radiance-online.org/).

## 1.7. Thesis Layout

Chapter 1 looks at the structure of the entire thesis along with the aims and objectives as well as the methodology applied to achieve the set goals. This chapter also states the novelty of the research undertaken as well as its benefit to mankind. Here also, there was a brief description of the RADIANCE® software used to model some sections of the experimental aspect of the thesis prior to commencement of laboratory work. The results of the modelling was employed to and used as a benchmark to determine the tests/experiments to be undertaken and gave the validity for which the thesis is hinged upon.

Chapter 2 covers the literature search into the existing daylight systems/devices and their applications in everyday living. These existing daylight systems studied include light pipes, (optical) light rods, (optical) light fibre, light shelves, louvers, and laser cut panels, prismatic panels, light guiding shades and holographic optical elements. Works that have been done similar to those carried out in this thesis report were also examined and a link between the previous works done and those under taken in this report was established in this chapter.

Chapter 3 saw the work moved from an indoor laboratory setting to an outdoor set up in the aspect of the use of the light rods. The test carried out included investigation of existing light harnessing systems of acrylic light rods on their own as one system, and light pipes on their own as another separate system. Unlike chapter five that were basically wall-based systems, tests in this chapter were roof-based.

Furthermore, innovative tests were carried out for a combination of these two systems to run on a singular platform to test its viability to harness more daylight within the same given spatial set-up. Comparative analysis was run to assess the efficiency of the new system against the two existing systems of individual light pipes and individual light rods.

Chapter 4 highlights the computer modelling and software modelling carried out prior to the laboratory tests. These simulations were validated through the documentation of tests carried out on existing life cases in currently occupied residential dwellings to give a true picture of the working of a light pipe in real life condition.

Chapter 5 is the first in this report, to report the extensive laboratory work carried out. The work undertaken in this chapter deals mostly in terms of heat collection through a solar thermal system by the use of dark coated Solar Evacuated Tubes (STC). It also looks into the novel method of heat collection using simple Solar Thermal Collectors and incorporating aluminium foil sheets as a catalyst to further elevate the temperature.

This chapter also explored the novel idea of incorporating thermal and lighting considerations on the same platform, with one complementing the other. This innovative new system shows the insertion of optical light rods into the thermal collector so as to harness both light and heat.

Chapter 6 is also laboratory based, but of purely architectural context. It was geared towards the aesthetics aspects and application of light rod on facades of buildings. This was done by replacing the conventional glazed window with short light pipes so as to transport light into the building with little or no heat gain/loss.

Chapter 7 is in two parts: Part 1 investigates the use of aerogel fibre sheets as a nano-insulator in wall cavity so as to stop heat movement from one medium to another. In these tests, two conditions were simulated, one was that of the temperate climate, and the other was that of the tropical climate. Subsequently, the wall was punctured to accept the same size of light rods as the one used in the tests in chapter 5. These light rods were used to transport light whilst the aerogel was used in the cavity to minimise the heat gain/loss, through the poor insulation of the wall material. The second part of this chapter looked into the introduction of aerogel gel into the cavity of a double glazed test window so as to test it for transmittance and used as substitute for the windows filled with inert gases such as Argon. For both aspects above, the tests were wall-based systems.

Chapter 8 caps all the work done, and covers a general analysis and conclusions. It also identifies the weak areas and the aspects that need to be further studied by researchers along a similar line of thought.

# 2. CHAPTER 2 LITERATURE REVIEW

## 2.1. Introduction

Vast literature exists on the use of daylight through the employment of various daylight devices and the benefits to the use of this infinite resource, as well as looking into the problems associated with resource. This chapter thus documents work done in this aspect and analyses some of the existing literature.

Over time scientists over the world have pondered over the manner in which light travels and subsequently manifests.

In the year 1666, Isaac Newton discovered that white light actually consisted of a spectrum of seven colours i.e. red, orange, yellow, green, blue, indigo and violet, very often abbreviated as ROYGBIV. (Tragenza and Wilson, 2011). The source of daylighting is the sun. The sun is a huge nuclear reactor that has been continuously emitting solar radiation for about 4.5 billion years (Zhang 2002).

## 2.1 What is Daylighting

Daylighting can be defined as that visible light which is emitted via the electromagnetic radiation from the sun (Yohannes, 2001). Daylighting is preferred to artificial lighting as it boosts productivity (EREC, 2001). Lack of daylight exposure for a long period of time is found to cause mood swings and depression (Tregenza and Loe, 1998; Cakir and Cakir, 2000).

Daylight itself has a continuous spectrum with apparent difference in brightness.

Human eye's sensitivity to spectral colour varies from violet to red, which is corresponding to the solar radiation spectrum of 0.39 to 0.78μm for visible light. Although daylight covers only a narrow band of the whole solar radiation spectrum, it has a fundamental and significant bearing on human being's life on the earth (Zhang, 2002). Figures 2-1 and 2-2 show the spectrum for light

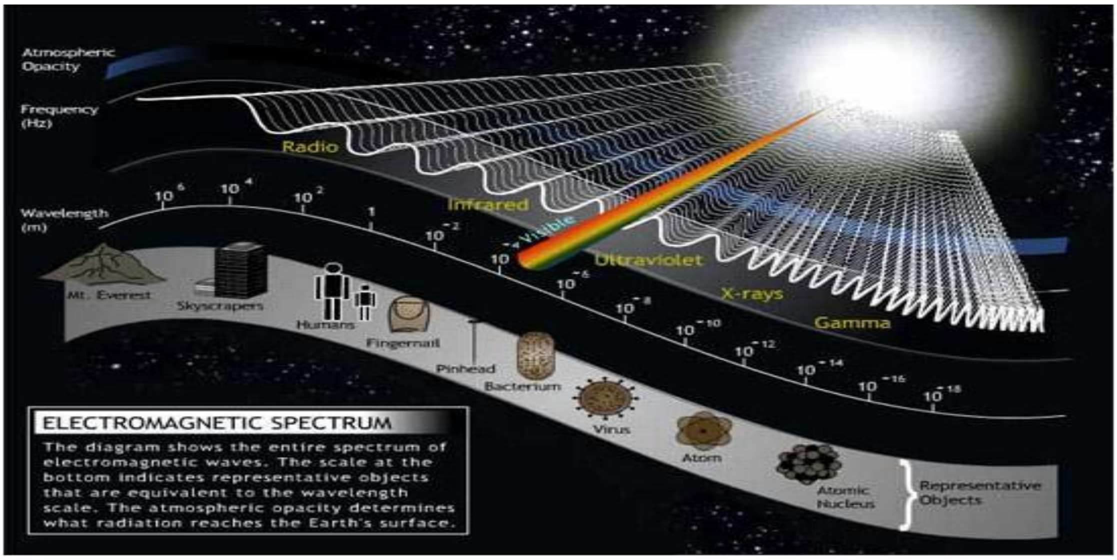



**Figure 2-1: Electromagnetic Spectrum showing the visible spectrum (Source: NASA)**

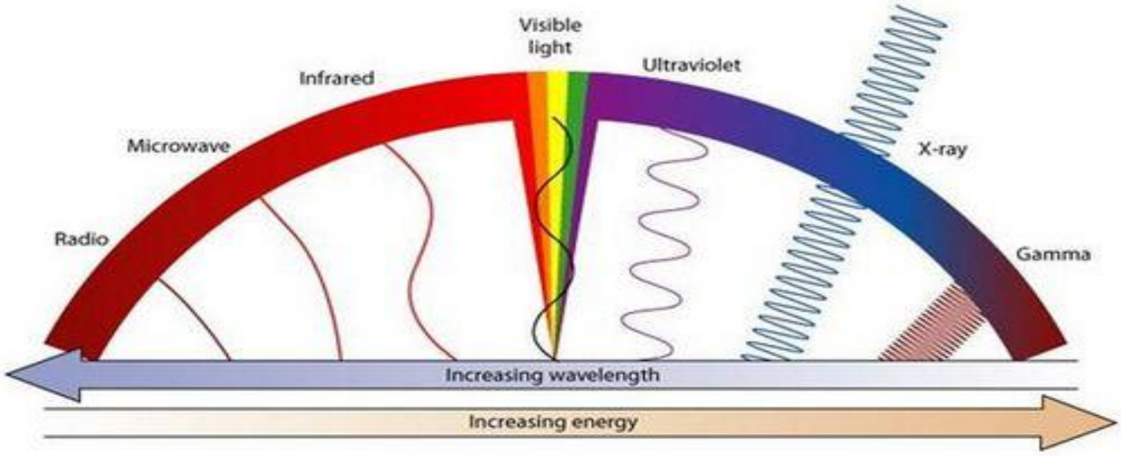



**Figure 2-2: Electromagnetic Spectrum showing the wavelength pattern (Source: Science Learning Hub, New Zealand)**

## 2.2. Daylighting in Residential Buildings

Using fossil fuel for lighting, cooling and heating buildings produces $CO_2$ which consequently causes environmental degradation. It is also known that buildings consume a large amount of energy for lighting and subsequently space cooling/heating (Tragenza and Loe, 1998). Roaf et al in 2004 opine that lighting cannot just be measured in "amount" alone, and that indicators of good lighting should include:

i. Visual comfort

ii. Visual delight

iii. Average illumunance in the working plane

iv. Uniformity of illumunance in the working plane

v. Luminance ratios within the space

vi. Glare levels in the space

vii. Direction of light and the effect of shadows

viii. Colour temperature of light

ix. Colour rendering of light

As with most natural phenomena, there are problems associated with using excessive daylighting in hot climate regions, these include heat gain, glare and direct light inside a building (Edmonds, 2002). As such, care must be taken in the employment of daylight and its application and the excess solar power to be converted to other sources of usable power.

In terms of daylighting energy savings and durability, it worthy to note that saving electric energy is an important means to reduce $CO_2$ emissions. Even though daylighting is freely available and renewable, the main drawbacks are the thermal load that may come from windows and (in most cases) the unpredictability of the daylight intensity. Other drawbacks are the initial costs of the acquisition of the daylight harnessing devices as well as probable ownership and maintenance costs. On the flip side, it is important to note here that the acceptance of the system by the user(s) is perhaps the most important indirect economical aspect. (IEA, 2001)

### 2.3. What Does the Code for Sustainable Homes Mean?

The Code for Sustainable Homes (the Code) was introduced in England in April 2007 following extensive consultation with environmental groups and the home building and wider construction industries. It has since been adopted by Wales and Northern Ireland, though it is yet to be operational in Scotland (Code for Sustainable Homes, 2006)

The code currently requires that at least 30% of internal light fittings are dedicated energy efficient fittings and further states that the internal lighting awards either greater than 40% or greater than 70% of dedicated, fixed internal energy efficient light fittings. The Code also proposes that 75% of fittings are either dedicated fittings or standard fittings supplied with low energy lamps with integrated control gear. It also allows the benefits of Low Energy Lighting to be recognised in the Daily Energy Requirement (DER) calculation.

The Code for Sustainable Homes (CfSH) was developed by the UK Government and Local Communities, in order to support the reduction of energy consumption in the domestic sector. They define this project as "…a standard for key elements of design and construction which affect the sustainability of a new home. This code will in time become the single national standard for sustainable homes, used by home designers and builders as a guide to development, and by home-buyers to assist in their choice of home" (Government, C.a.L., 2006 Pp 2).

The CfSH is a point based system that evaluates the dwellings in the UK by the impact of them on their environment. There are nine items, and when each requirement is achieved, a credit is awarded. Therefore, to achieve level 4, of the CfSH, a reduction in dwelling emission rate between 44% and 99% over target emission rate, has to be achieved. While, to achieve level 6, a 100% reduction is required, in addition to lifetime home requirements.

"Lifetime Homes are ordinary homes incorporating 16 design criteria that can be universally applied to new homes at minimal cost. Each design feature adds to the comfort and convenience of the home and supports the changing needs of individuals and families at different stages of life." (The Foundation for Lifetime Homes and Neighbourhoods, 2005)

The main differences, in design, between Tarmac Home 10 (Level 6) and Tarmac home 12 (Level 4) are: the fenestrations, the sunspace, the envelopes and the technology. These differences have two main consequences over the dwellings: the level of the CfSH achieved, and that Level 6 Visual Comfort may have been compromised, in order to meet thermal comfort requirements. This issue was the main drive of this work:

Is there a need to compromise Visual Comfort, In Tarmac Home 10, in order to reduce energy used for space heating? (Communities and Local Government Publications, 2006)

### 2.3.1. Benefits of the Building Code for the Environment

- Reduced greenhouse gas emissions: With minimum standards for energy efficiency at each level of the Code, there will be a reduction in greenhouse gas emissions to the environment. This will enable us to reduce the threat from climate change.

- Better adaptation to climate change: The Building Regulations (Approved Document L – 2006) already limit the effects of solar gains in summer. With minimum standards for water efficiency at each level of the Code, and other measures in the Code, including better management of surface water run-off, our future housing stock will be better adapted to cope with the impacts of climate change which are already inevitable.

- Reduced impact on the environment overall: Inclusion of measures which, for example, promote the use of less polluting materials, and encourage household recycling, will ensure that our future housing stock has fewer negative impacts overall on the environment.

(Communities and Local Government Publications: www.communities.gov.uk, Product Code 06 BD 04224; December 2006).

Various researches have been done into energy use in modern residential buildings as seen in figure 2-4 below. It is important however, to note that even though lighting quota is only 9%, the importance of lighting as a form of illumunance cannot be over emphasized, as illumination is required for a very large number of day to day tasks undertaken by occupants.

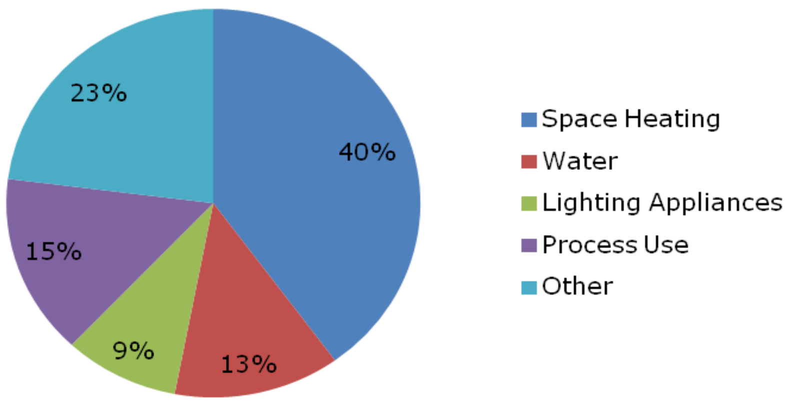



**Figure 2-3 Energy Consumption in Domestic Sector by Use in the UK (Department of Trade and Industry)**

As part of the aim of this research is to express and justify what constitutes comfort, effort was made to look at this comfort and categorise it thus in terms of either quantitative parameters or qualitative parameters. For the purpose of this study however, the research was more concerned with the quantitative aspects which is further broken into visual comfort and thermal comfort, as seen in figure 2-4 below, and these are the parameters and context to which this thesis is hinged.

It is difficult to define visual comfort as it varies from person to person. As such, it can be defined by its degree of discomfort bordering on glare and inability to see things clearly and in true colour. Thermal comfort can be defined as the ambience that affects the morale of occupants, their wellbeing and productivity.

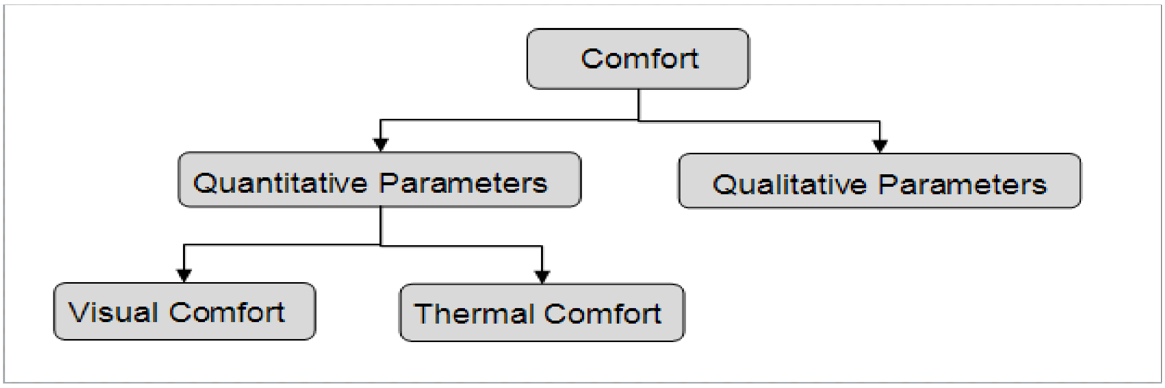



**Figure 2-4: Comfort Components Analysed (Vergara Salvat, 2011)**

Table 2-1 gives a guideline to the estimated illuminance required for day-to-day tasks in offices.

**Table 2-1: Level of Illuminance required in Day-to-day tasks (Vergara-Salvat, 2011)**

| Class of Visual Task | Typical Examples | Recommended Horizontal Illuminance |
|---|---|---|
| Difficult | Colour matching, Inspection of fine work (e.g. precision instruments) | 800 lux |
| Moderately Difficult | Office work with poor contrast: Drawing offices | 600 lux |
| | Routine Office Work: typing, filing, reading, writing | 400 lux |
| Simple | Waiting rooms, social activities | 200 lux |
| Orientation | Corridors, Stairs, Restrooms | 100 lux |

## 2.4. Architecture and Daylighting

Depending on the climate, Daylight is dynamic, constantly changing in terms of intensity, direction and colour properties, and is in some cases unpredictable and unreliable (Boubekri, 2008). Because we are dependent on light for perception, it is natural that we should be psychologically affected by it. (Boubekri, 2008). Numerous studies over the world have shown that daylight is important in buildings, and daylight may have positive impact on view, visual comfort, psychological comfort, health and workplace productivity (Boyce P. et al, 2003).

Studies have gone further to show that utilization of daylight as a renewable energy resource may reduce electricity consumption for lighting and heating energy (Boyce P. et al, 2003). Studies by Heschong (2002) show that daylight is intrinsically more efficient than any electric source because it provides more lumens per unit of heat content. Thus Heschong (2002) goes on to opine that if appropriate daylighting techniques are used to displace electric illumination, the savings for lighting and cooling can be dramatic.

## 2.5. Daylighting Technology Tools and Devices

The obvious question is then: Why is daylight not always being a primary consideration in building design? Throughout the world, there seems to be a number of barriers that hinder appropriate integration of daylighting aspects in the building design. Roaf et al (2008) however, have identified some of the barriers to overcome, these three easily recognized major barriers are:

i. Lack of knowledge and information on new fenestration technologies and lighting control systems and the ability of such systems to enhance daylight utilization

ii. Lack of convincing evidence that daylighting can substantially improve energy efficiency and visual quality in buildings

iii. Lack of appropriate and user friendly daylighting design tools including models for innovative daylighting systems and controls

Literature search has been carried out however, to identify the daylighting designs available in the today, as documented by many researchers which include Freewan (2007), Jeong & Kim (2009), Oakley (2000), Edmond & Pearce (1999) and Greenup & Edmonds (2004).

### 2.5.1. Light Pipes

This is an advanced daylighting technology which is used to bring light to a space with no direct contact with the outside (Freewan, 2007). They are used for transporting or distributing natural or artificial light (see figs 2-6, 2-7 & 2-8 and table 2). In applications for daylighting, they are also often called sun pipes, solar pipes, solar light pipes, daylight pipes, tubular skylight, sun scoop or simply tubular daylighting device. In comparison to conventional skylights and windows, a light pipe offers better heat insulation properties and more flexibility for use within buildings, however with little visual contact with external environment (Jeong, Kim – 2009). The SUNPIPE® natural daylight systems seen in figures 2-9 and 2-10 consist of silverised mirror-finish aluminium tubes that carry daylight down into the room below. The SUNPIPE natural daylight system terminates in the patented Diamond dome, which seals the pipe against the ingress of rain, dust or insects, the ceiling diffuser seals the SUNPIPE natural daylight system at ceiling level. With this arrangement there is virtually no heat loss in winter months and solar gain is minimised during summer months. SUNPIPES are ideal for providing daylight into areas in the home where windows cannot reach (Monodraught, 2012).

The effect of the pipe's length, bend and diameter on its performance was investigated on by Oakley et al (2000), who have shown pipes are proficient devices for introducing daylight into buildings, with the most effective light pipes being straight and short with low aspect ratios. Further tests carried out by Oakley et al (2000) also showed that light pipes with a large diameter will probably be more effective.

**Figure 2-5 A Typical light pipe (Source Kim J.T., Kim, G. 2009)**

Kim, J. T amd Kim G. carried out research into ways to further enhance a typical lightpipe to improve its performance. They developed a new light pipe system using acrylic, with 99% transmittance. The system uses an optical device mounted inside a dome facing south to capture and redirect the daylight into the tube. The size of the optical device can be changed depending on site conditions. As with typical light pipe, the tube is made of aluminium film, as is coated with a thin prismatic material which transports daylight from the dome to the diffuser through multiple specular reflections. An acrylic is attached to the internal end. Figure 2-6 illustrates the installation procedure of the light pipe system. Figure 2-8 shows the mock-up room in which the light pipe was installed for testing (Kim, J.T and Kim G., 2000).

**Figure 2-6 Light pipe system installed in a mock up room (Source Kim J.T., Kim, G. 2009)**

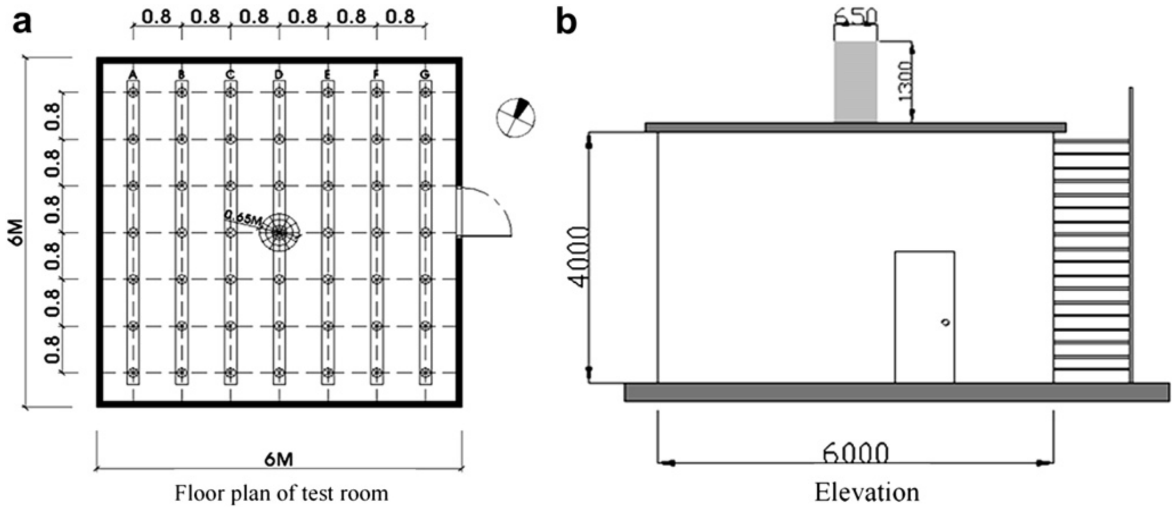



**Figure 2-7 Mock up model configuration. (a) floor plan of test room, (b) Elevation (Source Kim J.T., Kim, G. 2009)**

The tests were carried out in a room with given dimensions as in Figure 2-7. When the tests were carried out in overcast and clear sky conditions for Korea (East Asia), the average outdoor illuminances were 34,779 lux and 79,247 lux respectively. The corresponding average illuminances obtained were 238 lux in overcast conditions and 510 lux in clear skies, with recordings of up to 1,548 lux at the peak at 1pm. The results obtained indicated that going by the Korean standard of illumination, the light obtained from the light pipe for both sky conditions produced sufficient light for ambient conditions in residential buildings.

Furthermore, research has shown that various light pipes systems have been used successfully in several buildings, as seen in Table 2-2.

**Table 2-2: Application of Manufactured Light Pipe System. (source Kim, J. K. and Kim G. 2009)**

| Manufactured system | | Location | Building Type | Technical details | Image: Outdoor | Image: Indoor |
|---|---|---|---|---|---|---|
| Mono draught | Sun pipe | Sutton Arena Surrey, UK | Arena | · 14 Sunpipe (750mm ) +8 Windcatcher(1m)<br>· No artificial light is needed in the daytime |  |  |
| | Sun catcher | The Priory Neighbourhood Centre, Hastings, UK | Public center | · suncatcher (1200mm ) +Sunpipe (750mm)<br>· Installed in IT center and cafeteria<br>· Improved ventilation and daylight performance |  |  |
| | Sun catcher | BMW head office, Oxford, UK | Office | · 26 Windcatcher and Suncatcher is installed in $3000m^2$ space<br>· Company's logo was applied in diffuser |  |  |
| Sola tube | Sola tube 21-O | Federated Logistics and Operations, CA, USA | Factory | · 800 Solatube (530mm)<br>· Prisnaic diffuser<br>· 604, 408kWh electricity was saved |  |  |
| | Sola tube 21-C | Community Collegeof Southern Nevada NV, USA | Education | · 530mm tube with optical diffuser<br>· 75% of daylight in inner space |  |  |
| Velux Company | TCR 022 | Customer Service Center, Greenwood, SC, USA | Office | · Rigid suntunnel system<br>· Work plane illuminance of 50fc was achieved |  |  |
| Doel | Sola spot | Kumho Company, Korea | Factory | · 100 Solaspot (650mm) with Prismatic diffuser |  |  |

The Monodraught SUNPIPE® is the technology used in both the David Wilson House and the Tarmac House in the University of Nottingham, UK. The technology is as described below and relates only to the square type for the case studies undertaken.

Figure 2-8 shows a round installed Monodraught Sunpipe, Figure 2-9 shows a security guard for the corresponding round sunpipe, and Figure 2-10 sows the square sunppipe.

**Figure 2-8: Round Monodraught Sunpipes mounted on roofs (Monodraught, 2012)**

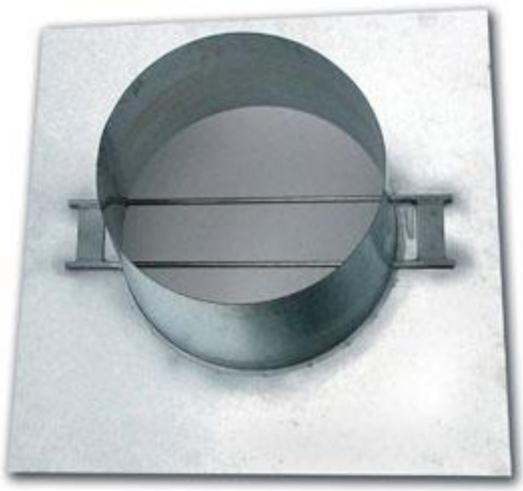


**Figure 2-9 Round Monodraught Sunpipes Security Guard (Monodraught, 2012)**

**Figure 2-10 Square Monodraught Sunpipe (Monodraught, 2012)**

The Square SUNPIPE® natural daylight system as seen in figure 2-10 is ideally suited to a room with a flat ceiling, as opposed to a typical loft conversion. The system has been specifically developed to provide an unobtrusive termination for any roof finish. (http://www.monodraught.com/daylight_products.html retrieved)

### 2.5.2. Light Rods

Light rods are a fairly new daylight system made from polymethyl methacrylate (PMMA) material (see Fig 2-11 and Fig 2-12), a transparent thermo plastic. It is used to transport light over a long distance, depending on the total internal reflections (Freewan, 2007). Light rods can either have their ends polished as seen in figure 2-11 or unpolished (figure 2-12). The purpose for polishing the ends is to remove the undesirable "ring" effect under direct sun, caused by the circularity of the end of the rod, as documented by Callow (2003). Callow further opines that though there is a loss of transmission in the polished rod, it improved the overall visual ringless output of the illuminance under direct sun.

**Figure 2-11 Side emission of light by rod with ground length (Callow, 2003)**

**Figure 2-12 Three light rods with bends of 40°, 60º and 90° produced using IR heating and found during measurement to have less than 20% loss of transmittance (Shao 2000)**

Figure 2-12 shows rods of various bends which can be used to transport light through challenging or restrictive spaces such as between roofing members. Callow's (2003) testing shows that's there was very little significant loss in illuminance in the use of bent rods over the straight rods. It can thus be deduced that the carriage and transmittance of light to otherwise unlit spaces by far overweighs the insignificant loss due to bending of the rod.

The advantages of using light rods range from its workability to its aesthetic properties. Other advantages include:

- Has a high optical finish, with high tramittance level of up to 93%.
- Can be extruded to different shapes, lengths and diameters (up to 200mm diameter for cast acrylic rods).
- Has great impact strength yet is relatively light in weight (about half the weight of glass), and does not scratch easily (and when scratched, it can easily be buffed with a special polish).
- High longevity and not easily affected by sunlight and fluorescent light.
- Can be made in a variety of colours
- It can easily be cut, drilled, sawed, decorated, etched upon and silkscreened.
- Easily commercially available.

Though it has a many advantages as mentioned above, it has disadvantages which incude

- Toxicity in the manufacture process, as it releases dangerous fumes during the polymerisation process.
- It is not easily recyclable.
- It is relatively expensive.

.

### 2.5.3. Lightshelves

A light shelf as seen in Figure 2-13, is a horizontal or an inclined plane projected over a view window. It may be external or internal or both, with a considerable reflective upper surface. As a shading device, it blocks the direct sunlight from entering the room, thus reducing heat gain and glare. As a daylighting system, it is used to improve uniformity and reflect light deep into the interior of a room (Freewan et al, 2007). Applications include tall conventional windows and clerestory windows. Light shelves operate most effectively in sunlight. In this context ceilings are designed to be higher

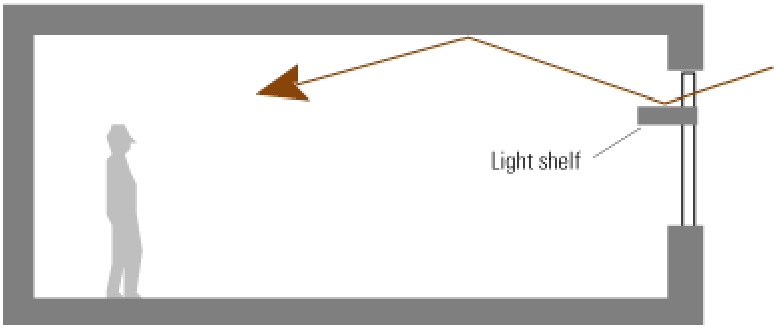



**Figure 2-13: Figure 2-14 Light Shelve (Wordpress, 2012)**

than normal for best operation. Dust can settle on a light shelf to degrade illumination; therefore, light shelves need to be cleaned on a regular basis. Also, proper installation during construction is needed to ensure no thermal breaks are created. The width of the daylighting zone along the exterior wall extends into the space 10 to 20 feet, which translates to electricity savings of 10 to 40 watts per foot along the wall. The heat energy added to the space is not much different from what would be added by an equivalent amount of electric lighting. Light shelves can yield to a reduction in monthly demand charges due to reduced lighting energy during peak hours (High Performance Technology Template, 2013).

### 2.5.4. Louvers

These comprise of multiple horizontal, vertical or sloping slats with different shapes and surface finishes, examples of which can be seen in Figure 2-15. Louvers or blinds as they are interchangeably called may be internal or external, and they obstruct partially or completely, the sun's rays and views, and they can be used in different directions and latitudes (Freewan et al, 2007). The general purpose for louvers is to prevent direct undesirable sunlight from penetrating into the room. Louvres can be fixed or rotatable either manually or automatically so as to eliminate glare.

**Figure 2-15: Horizontal & Vertical Louvers** (Raven Industries, 2003 and Vollay Systems, 2013 respectively).

### 2.5.5. Laser Cut Panels (LCP)

This is an innovative daylighting system used to redirect high angle light upwards towards ceilings by total interior reflections and redirecting low angle light or diffusing light downwards by internal refractions, thus it is used to reflect light into deep rooms. LCP is an optical material produced by making fine parallel laser cuts in a sheet of thin panel of clear acrylic material Edmonds, 1993; Reppel and Edmonds, 1998; Edmonds and Pearce, 1999) – see Figure 2-16. These laser cuts work by deflecting a fraction of the incoming light through total internal reflection at the surface of the cuts, whilst the remaining light passes through the panel undeflected (Hirning et al 2010).

Hirning et al (2010) further opine that LCP's perform better in climates with clear sky conditions, deflecting direct sunlight into the ceiling avoiding direct sunlight on the workplane. Advantages of LCPs include the fact that little maintenance is required and they can increase the natural illumination in the deep space of a room (Hirning et al 2010).

**Figure 2-16:** A typical Laser Cut Panel System. (Source: Hirning et al)

The laser-cutting divides the panel into an array of rectangular elements. Each cut surface then becomes a small internal mirror that deflects light passing through the panel. An advantage of the panel is that in between the cuts, a view to outside of the window is maintained, although it is somewhat distorted. (ECBCS, 2010)

### 2.5.6. Prismatic Panels

These are thin planar saw tooth devices made of clear acrylic that are used in temperate climates to redirect or refract daylight. These can both be used as daylighting and as shading devices, as they can refract direct sunlight while transmitting diffuse skylight and redirecting the light to the rear part as seen in Figure 2-18. Prismatic panels can improve the illumunance level in the rear of a space by redirecting the light to the rear part (Freewan et al, 2007). Prismatic panel are suited to all climates, and can be attached to vertical windows and sky lights, thereby giving protection against glare (Kischkoweit-Lopin 2002).

The The Trutec Tower as seen in Figure 2-17 & 2-18, was designed by Barkow Leibinger and completed in 2006. In this building, the architect designed an admittedly self referential building - The modulated array of prismatic glass panels creates a pixelated image of the building’s surroundings, allowing the facade to reflect and distort whatever context may eventually arise. The interior also benefits from the effect, casting interesting shadows and unconventionally frames views of the exterior (Subtilitas, 2009).

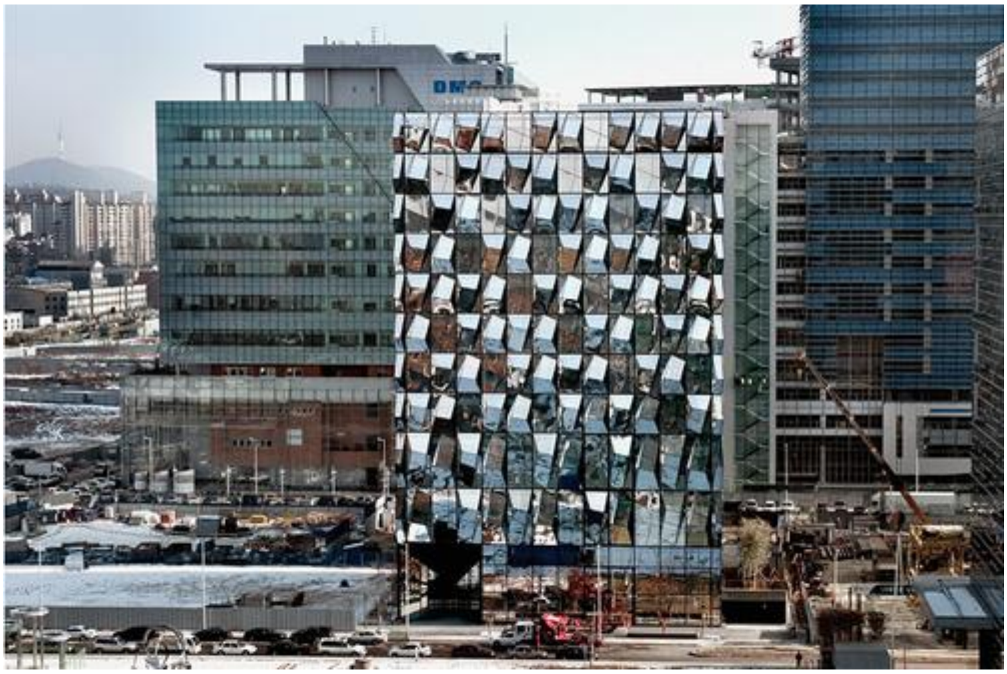
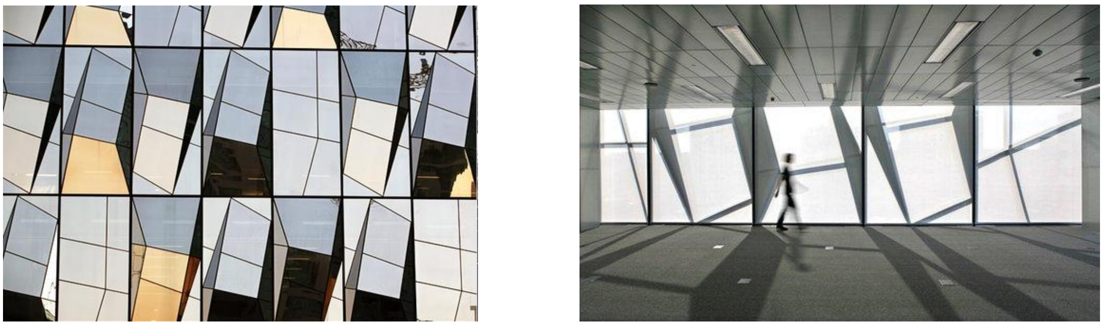


**Figure 2-17: Prismatic Panels on Building Exterior**
(Subtilitas, 2009)



**(a) The Exterior** **(b) The Interior**
**Figure 2-18 Prismatic Panels on The Trutec Building**

### 2.5.7. Light-guiding Shade (LGS)

This is an external shading system that redirects sun-light and skylight onto the ceiling. According to Greenup and Edmonds, the device was created in response to the need for daylighting technologies that can utilize direct sunlight while maintaining visual and thermal comfort in sub-tropical buildings. Greenup and Edmonds (2004) further investigated the ability of the micro guide shading system to achieve the objectives of the innovative daylighting systems. As a result, they found that a micro LGS is an effective daylighting device that acts dually as window shading and as a light redirecting device, with an efficiency of about 50% (Freewan et al, 2007). The concept of the LGS arose from the need to shade windows without reducing natural lighting in sub-tropical buildings as seen in figure 2-19.

**Figure 2-19: Residential application of LGS**

### 2.5.8. Holographic Optical Elements (HOE)

Mohan et al (2006) opines that Holographic Optical Elements are diffractive structures that are constructed holographically by interference of two beams of light. Freewan (2007) goes on further to state that these are transparent shading systems and directional selective shading systems that reject incident light from a smaller angular area of the sky vault. Thus, the system can redirect or reflect incident beam sunlight, while transmitting diffuse light from other directions. This selective shading provides daylight to building interiors without seriously altering the view from the windows (IEA – Task- 21, 1999). It can transmit the diffuse light and reject or redirect the direct light, thus it can be used for both shading and daylighting in hot climates to utilize the daylight, while excluding direct light to reduce heat gain (Freewan, 2007). Figure 2-20 shows a schematic representation of a HOE

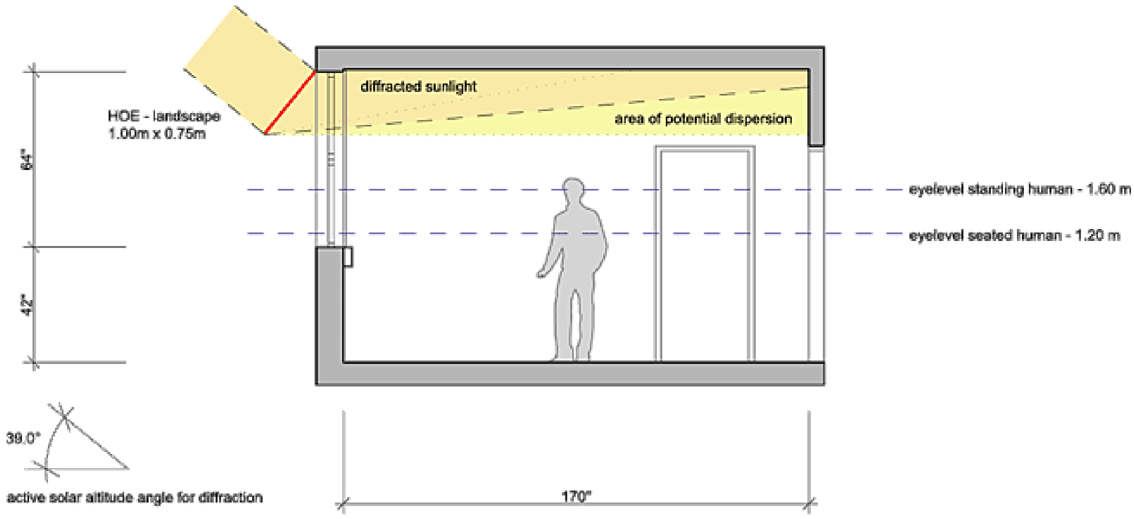



**Figure 2-20 Schematic representation of the function of a building integrated light directing Holographic Optical Element.**
(University of Southhampton Sustainable Energy Reseach Group)

## 2.6. Heating, Lighting And Thermal Comfort In Residential Building.

The importance of heating in the temperate climates cannot be over emphasised and vice versa as is the case for cooling in the tropics. Thermal comfort for human beings, is one of the indices used to judge the suitability or otherwise of the building envelope.

Thermal comfort is defined as the state of mind that expresses satisfaction with the surrounding environment, as such maintaining thermal comfort for occupants of buildings or other enclosures is one of the important goals of HVAC (Heating Ventilation Air Conditioning) design engineers.

Windows and daylighting systems influence the distribution of daylight and the thermal load of a building. A suitable daylighting system can help to reduce the heat gains in the building due to the favourable lumen per watt ratio of daylight, and save on energy for cooling. Daylight responsive control of lighting is often combined with thermal control. In the tropics when no occupants are present, thermal control will reduce heat gains in the summer (which last for approximately 8 months in the year) by closing the shades during the night to cool by radiation. In the temperate climates during the winter, this should be reversed. (IEA Task 21)

As with lighting, thermal comfort affects ones performance and productivity and thus thermal discomfort has been known to lead to Sick Building Syndrome (Roaf et al, 2000)

### 2.7. Definition of Sustainable Buildings and Examples from around the World

In 1987, the world Commission on Environment and Development sought to address the concern about the accelerating deterioration of the human environment and natural resources and the consequences of that deterioration for economic and social development (Pomeroy, 2011) and published its findings in “Our Common Future”. It is from this report that the phrase sustainable development was first used (ibid).

However, sustainable buildings are a broad multi criteria subject related to three basic interlinked parameters: economics, environmental issues and social parameters (Dimitris et al, 2009). Having said that, modern buildings and Heating, Ventilating and Airconditioning (HVAC) systems are nowadays required not only to be more energy efficient while adhering to an ever-increasing demand for better performance in terms of comfort, but equally in respect to financial and environmental issues (Korolijaa et al, 2011 and Neto, A. H. & Fiorelli, F. A. S., 2008).

The Carbon Trust and the World Resource Institute define the Carbon footprint of a typical person with regards to lifestyle as the amount of $CO_2$ produced as seen in Figure 2-21. They are most commonly described as direct emissions which result from combustion of fuels which produce $CO_2$ emissions (Patel, 2006), such as the gas used to provide hot water or space heating, and electricity used for equipments and lighting (Mempouo, 2011).

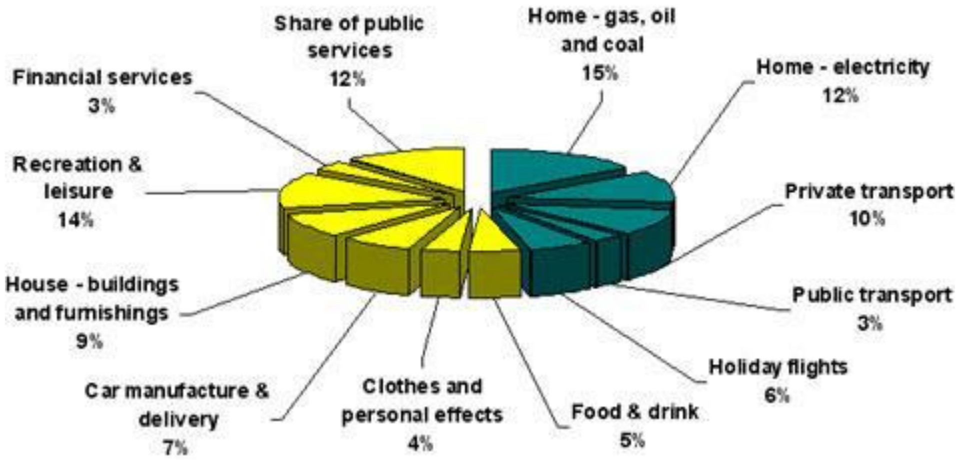



**Figure 2-21 Main Elements of a Typical Person's Carbon Footprint in the Developed World (Home Of Carbon Management, 2011).**

Varied and different and forms of renewable energy sources are available to us today, as is shown in Figure 2-22, as well as the projections in 2013. The variables range from the high and wide availability of solar power and wind power, to a host of other combined non-renewable energy sources.

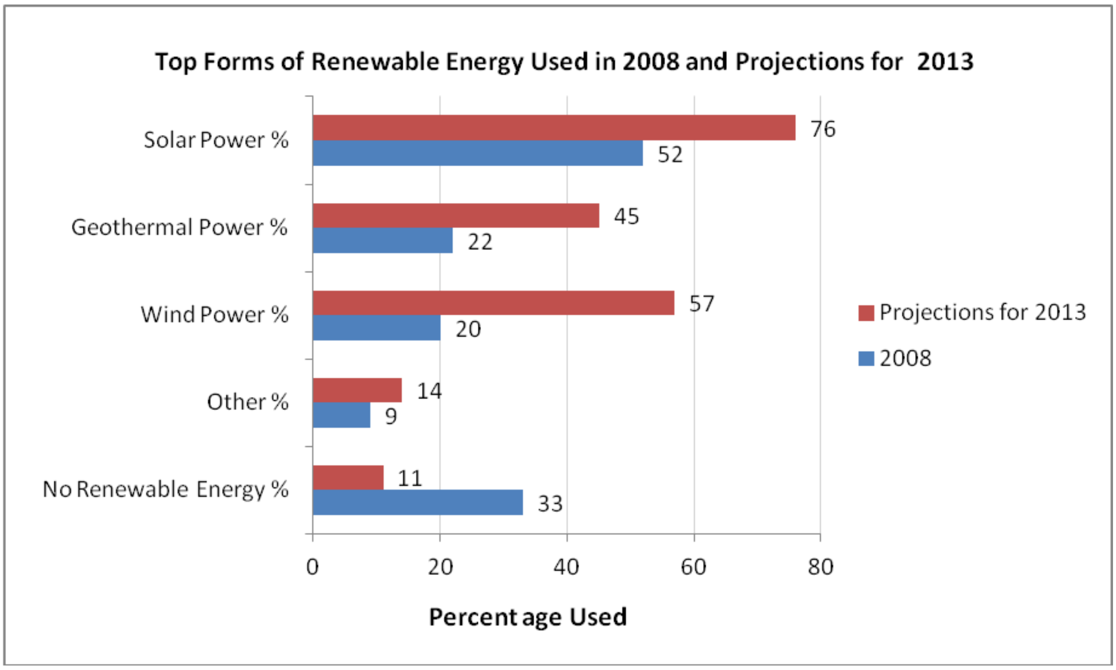



**Figure 2-22: Top Forms of Renewable Energy Used - 2008 and 2013**
(Source: Global Green Trends Smart Market Report, McGraw Hill, 2008)

There have been many agitations and reasons as to why the globally green buildings have still not got the popularity required for it to be seen as standard method for construction of all buildings now and in the future. These reasons range from high initial cost of construction, to lack of political will, as well as poverty and extreme harsh weather conditions. This variability is demonstrated in Figure 2-23.

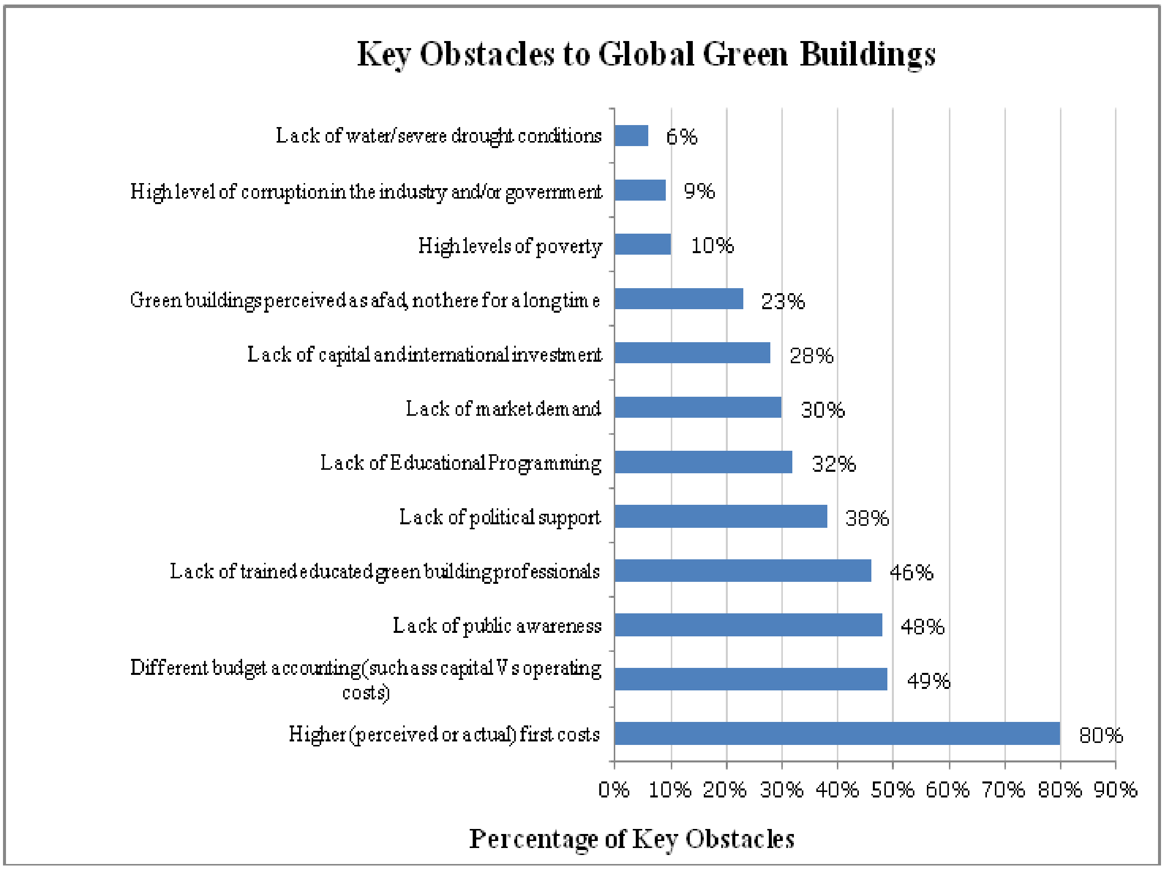



**Figure 2-23: Key Obstacles to Global green Buildings**
(Source: Global Green Trends Smart Market Report, McGraw Hill, 2008)

Further, statistics from Global Green trends Smart Market Report (McGraw Hill, 2008) seen in Figure 2-24, shows that great efforts have been made around the world to attain the goal of sustainability and the involvement of industry has also helped in bringing to the fore, buildings that that have achieved various levels of sustainability.

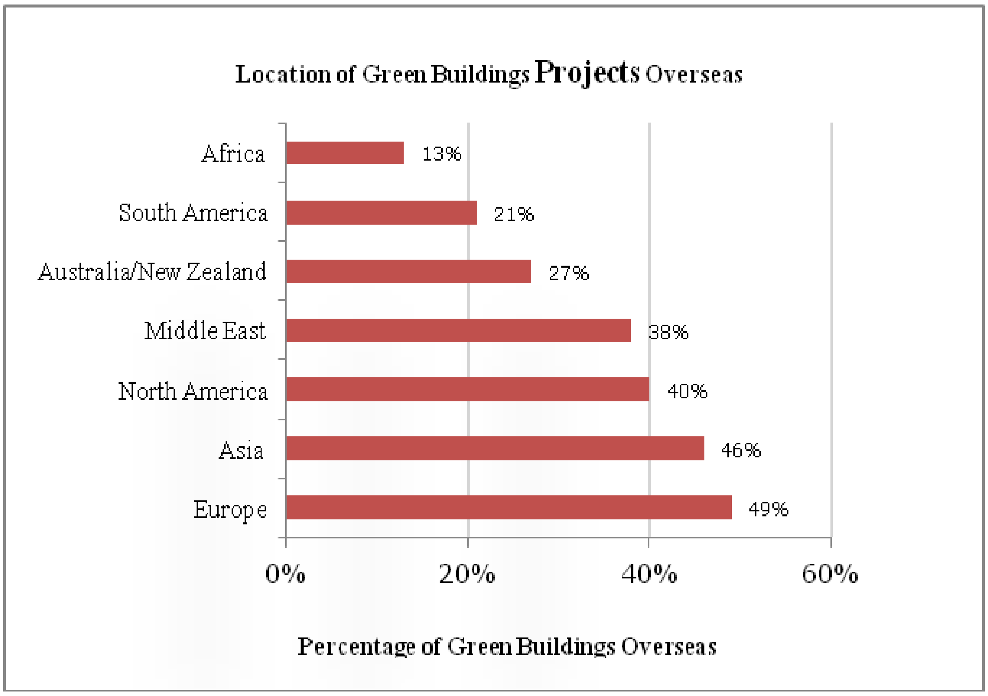



**Figure 2-24: Location of Green Buildings Overseas**
(Source: Global Green Trends Smart Market Report, McGraw Hill, 2008)

## 2.8. Examples of Sustainable Buildings from Around the World

This section aims to look at a few examples of buildings that have met the sustainability requirement around the world. Examples are drawn from Europe and South East Asia.

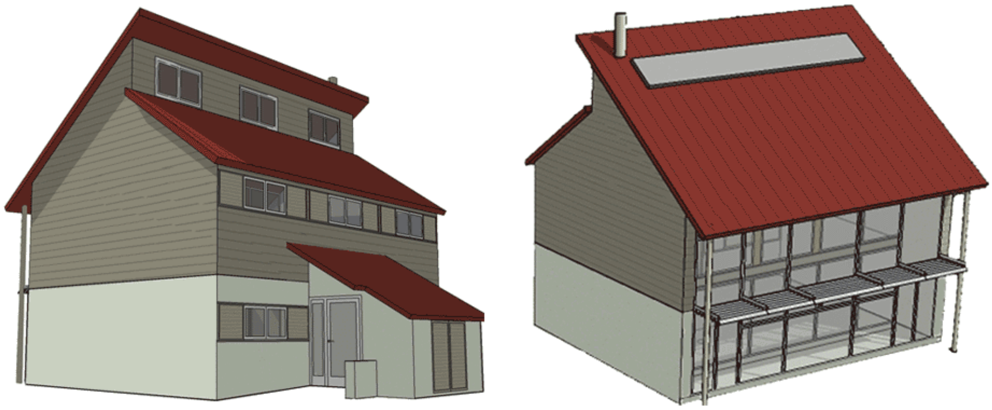
### 2.8.1. BASF House University of Nottingham, UK

The BASF House, University of Nottingham UK as seen in (Figures 2-25 a - d) was a house built to demonstrate how BASF raw materials can be used to create an energy efficient and affordable home. The house is part of the Creative Energy Homes Project a showcase of energy efficient homes of the future built at the University of Nottingham, University Park Campus Site. (Creative Energy Homes, University of Nottingham)

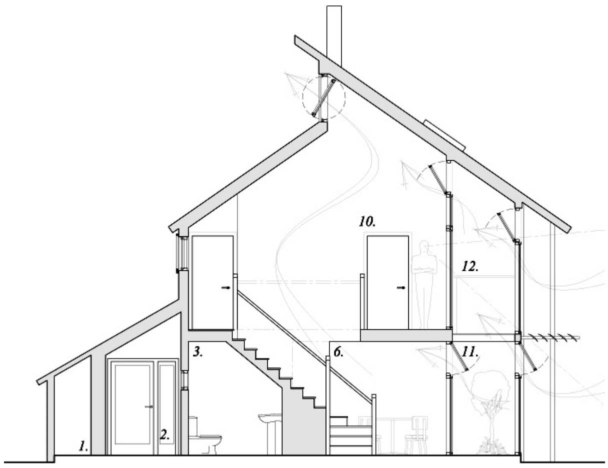
In a document on “Sustainable Housing in the East Midlands” by Prof Saffa Riffat (Riffat, 2008), had this to say:

> “This BASF house was designed to function as a conventional dwelling, and the house demonstrates how BASF raw materials can be used to create an energy efficient and affordable home.
>
> The two most significant aspects of our brief make the house different in appearance from more conventional housing. Firstly, the house is intended to be extremely energy efficient and to have as near as possible zero carbon emissions. Secondly, the house is intended to be extremely economical and affordable. The key effect of these two important briefing considerations is that the house has a compact floor area and relies as much as possible on passive solar design. In essence the design is extremely simple.
>
> It has highly insulated north, east and west walls with the minimum number of openings compatible with acceptable daylighting standards. The southern elevation consists of a fully glazed two-layer sunspace. This space is adjustable. A number of different opening apertures of various configurations ensure that both of the glazed screens to the sunspace can be opened or closed to facilitate heating or cooling. The space will contribute to heating by the admittance of solar gain in the summer and for air pumped into the building from below ground in the winter to pre-heat the space. The sunspace will contribute to cooling by the admittance of pre-cooled air in the summer from below ground and by minimising the effects of solar gain through enhanced natural ventilation utilising a stack effect induced by creating a low-pressure zone above the mechanically opening vents below ridge level.”

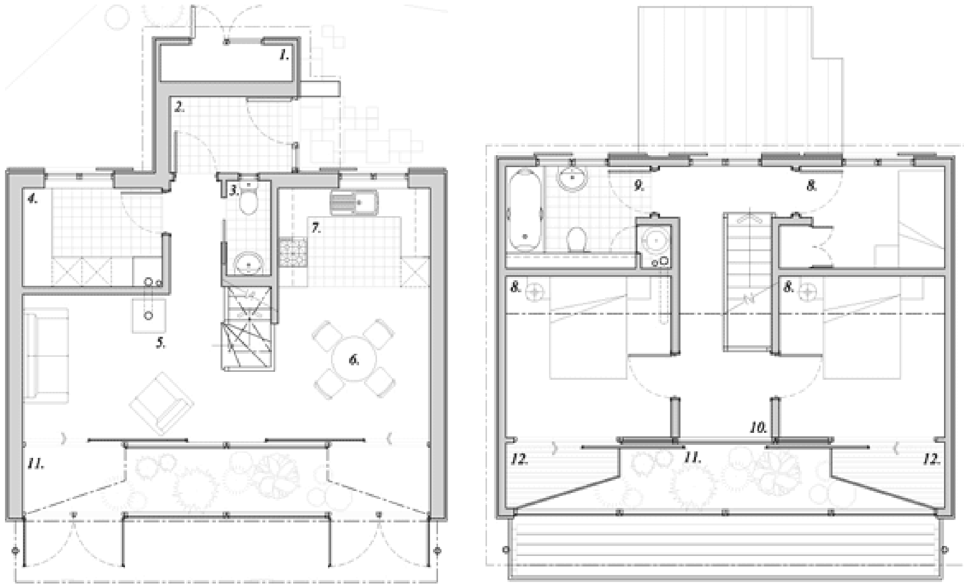
**Figure 2-25: a – d BASF House**



(a) Front and Rear Views




(b) Section




(c) Ground floor (d) First floor

1. Pellet/Bicycle store; 2. Porch (draught lobby); 3. WC; 4. Utility (optional GF bedroom); 5. Living; 6. Dining; 7. Kitchen; 8. Bedroom; 9. Bathroom; 10. Study landing; 11. Sunspace; 12. Balcony.

### 2.8.2. Idea House, Malaysia

The Idea house (Figures 2-26 and 2-27) is the first zero-carbon residence South-East Asia, located in Shah Alam, Malaysia, modelled under the concept of the *"Malay Kampung"* house. This house was conceived with the intention to serve as a test bed, as well as to provide an insight into tropical living in terms of modern terms of sustainability.

**Figure 2-26: Idea House, Malaysia (Pomeroy, 2011)**

**Figure 2-27: Idea House, Malaysia (Pomeroy, 2011)**

In terms of daylighting, due to the careful orientation of the Idea House, with the shorter faces to the east and the west, there was a minimization of solar heat gain as well as that of glare through low angle sun path (Pomeroy, 2011). This was further complimented by deep overhangs so as to provide shading from the sun and torrential rain

The narrow plan form aided in the optimisation of daylight penetration which provided illumination exceeding 150 lux (beyond Malaysian Building Standards of 100-300lux for habitable areas). Daylight factors on ground and first floor respectively were 4.16% and 2.90%. Thus, it can be concluded that there are good levels of natural daylight in these rooms (ibid).

With respect to harnessing the sun's rays as renewable energy source, a 90panel photovoltaic (PV) array was incorporated on the roof to provide an estimated 17,008kWh/year. With the estimated annual consumption (based on a household of 5) being 16,271kWh/year, there is an expected excess of 4.33% which can be fed back into the grid (ibid).

In terms of materials used in construction, timber flooring was used for living areas, ceramic floor and wall tiles for wet areas e.g. kitchen and bathrooms. Windows were 8mm double glazed, double layer of plaster board on steel studs with glass studs with glass wool acoustic/thermal insulation was used for internal partitions. For the ceilings, Medium Density Fibreboard (MDF) tile, mineral wool based tile and wood wool based tile were considered but rejected due to heavy weight of the former and high cost of the latter. As such the consensus was to use suspended plasterboard ceiling. "Grey water" captured from sanitary fittings is passed through a filtration process, and the water recycled to flush the WCs.

## 2.9. Summary

As UK's 21million homes are responsible for 27% of emissions (Haoyang, 2012) it was critical to look at the challenges that are posed by the housing units. This chapter thus covered the literature search carried out on existing daylight devices available in the market today as well as their applications. This is with an aim to enhancing the devices so as to make them more efficient. Daylighting was also defined in terms of visual comfort, visual delight, and illuminance on working plane, glare, shadow effects and colour rendering.

With regards to the daylight enhancing devices discussed, the light pipe has proven to be the most popular. This is as a result of its simplicity in installation and retrofitting into existing building, as well as its cost efficiency. The PMMA acrylic light rod light rods have also recently gained popularity due to their strength, light weight and workability. The louvres have been popular in all climates and date back a long time, its functionality has been downplayed because of its aesthetic compromise, however, its simplicity and efficiency has made a choice to be considered. The less popular options of laser cut panels, prismatic panels, light guiding shades and holographic optical elements are still very viable options as daylight optimisers and may probably gain more popularity when its becomes easier to obtain at competitive costs.

# 3. CHAPTER 3: NOVEL HARNESSING OF DAYLIGHT THROUGH THE COMBINED EMPLOYMENT OF LIGHT PIPES AND LIGHT RODS

## 3.1. Introduction

Much research has been done in the aspect of looking into the advantages of natural illumination over artificial lighting for both the domestic and the industrial sectors (Jenkins, Muneer, 2003), and recent scientific interests in new technologies focussed on energy efficiency and sustainable development is enormous (Darula et al, 3013). This is mostly backed by the European Parliamentary directive no. 2002/91/EC (2002) which gives guide lines for energy savings in buildings and design for indoor comfort in various climates (Darula et al, 2013). These energy savings aim to proffering sustainable and relatively inexpensive options which at the same time reduce pollution (Fell H.J., 2006; Lund, H., 2007 and Perez-Lombard et al, 2008).

For this purpose we are looking into the application of light pipes into new buildings or retrofitted into existing buildings. The use of light pipes in buildings has been on for over 30 years (Mankova et al, 2009). Novel daylighting systems tend to follow trends in energy efficiency by transmitting daylight into windowless spaces in building cores or even underground spaces and into deep offices and halls (Darula S. et al, 2010)

The UK government's Climate Change Bill pledges that the UK will make cuts in emissions of greenhouse gases of 80% by 2050 (Monahan, J. and Powell J. C., 2011). Currently, domestic energy consumption for space and water heating, cooking, lighting and appliances in the UK is responsible for approximately 30% of total energy consumption and 26% of total carbon dioxide emissions (DECC, 2009a). To meet the government's long term carbon targets household energy consumption will need to reduce by 29% based on 2008 levels by 2020 (DECC, 2009b).

The UK government has identified the house building industry as a key sector for delivering carbon reduction and, consequently, the sector has been subject of numerous reports, initiatives and regulatory changes in recent years culminating in the aspiration to achieve a zero carbon standard by 2016. This aspiration, which will be delivered by a progressive and incremental tightening of energy standards in the building regulations, will instigate something of a revolution in the way new homes will be designed and constructed, and the ways in which energy, and the services that it provides, will be delivered. In conjunction with this, there is a significant push for a new programme of housing construction that could see an addition of 3million new homes added to the total UK housing stock by 2020 (current economic climate not withstanding) (DCLG, 2007).

Several homes on the University Park Campus have been designed and constructed to various degrees of innovation and flexibility to allow the testing of different aspects of Modern Methods of Construction (MMC), energy efficient design and renewable energy systems. The projects aim to stimulate sustainable design ideas and promote new ways of providing affordable, environmentally sustainable housing that are innovative in their design (Creative Energy Homes, University of Nottingham, 2013)

It is as a result of the above that Architects have striven to find workable and lasting solutions to reduce carbon emissions in buildings. The focus of this study is to evaluate the rewards of incorporating light pipes in residential buildings, so as to maximise the daylight hours abundant especially in the summer period. Tubular light pipes represent a convenient concept of illumination of windowless parts of buildings by natural light (Darula et al, 2013). Light pipes are also an effective way of doing this, with the added benefit that they can be retrofitted into a building with little difficulty whilst reducing the problem of heat/loss and excessive glare (Jenkins, D. and Muneer, T. 2003).

Two buildings were evaluated to establish the reliability and viability of the use of light pipes in existing buildings. The buildings thus evaluated are The Tarmac House and the David Wilson (Ecohouse), both located in the University Park Campus of the University of Nottingham, UK.

## 3.2. Field Studies

Field studies were carried out on two existing residential building so as to investigate the application of the sun pipe (light pipe) day light system in the passive process of harnessing daylight, and thus, bring the aspects of the building code into play. The two buildings studied are the Tarmac House and the David Wilson home, both located on the University Park Campus of the University of Nottingham, UK.

The Tarmac Houses are two semidetached properties. The concept was to provide practical answers to some of the questions which surround the Code for Sustainable Homes (CfSH). Another important factor was to make the homes visually appealing to the majority of potential home owners and create and build a home that is both affordable and easy to maintain.

The homes have been designed by architect Bill Dunsters of Zed factory Ltd. One property has been built to level 4 CfSH and the other to level 6 CfSH. They are both 3 bedroom, 5 person properties. The homes aim to demonstrate that the highest levels of the Code for Sustainable Homes are achievable now by using existing traditional and readily available masonry products and techniques (Creative Energy Homes, University of Nottingham, 2013).

The traditional masonry materials used throughout the build have a number of benefits over other modern methods of construction which include (Creative Energy Homes, University of Nottingham, 2013).

- their high thermal mass helps counteract summer overheating
- traditional risk free build techniques and skills can be utilised
- they are fire resistant
- they offer a high level of security
- they can use locally sourced materials
- history shows they have a long in-service life

### 3.2.1. Field Study 1: The Tarmac House (Code 4), University of Nottingham, UK

The Tarmac house (seen in Figures 3-1 to 3-3 and 3-6) are a building comprising of two semi-detached one storey residential units built to meet the minimum requirements for the Code for Sustainable Homes (CfHS) Levels 4 and 6. The Code for Sustainable Homes (CfHS) is a national standard for the design of sustainable buildings to be used for residential purposes. This is a standard set up by the government of the United Kingdom for the development of new homes from the 1st of May, 2008 (Haoyang, 2012).

The Tarmac house was designed primarily with the aim to meet energy efficiency standards, and it is a masonry building that was designed to be easily mass-produced, affordable, with good aesthetics quality so as to appeal to a large number of potential home owners (Haoyang, 2012).

**Figure 3-1: The Tarmac house Front View**

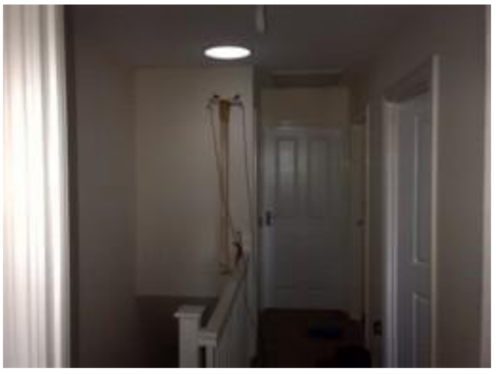
**Figure 3-2: The Tarmac house Front View**


**Figure 3-3: The Tarmac House Rear View**

3.2.1.1 The Set-up and the Experiment:

A wooden pole of length 1.2 was anchored above the staircase railing on the landing and two (2) Skye® Lux sensors were placed on it 300mm below the end of the diffuser of the Sunpipe. The tests to determine the illumination in the Tarmac House using the above setup were performed for six (6) consecutive days and nights as seen in Figure 3-4 (a – h) and Figure 3-7.

**Figure 3-4 (a-h)** **Interior Pictures of the Tarmac House showing experiment rig set-up.**

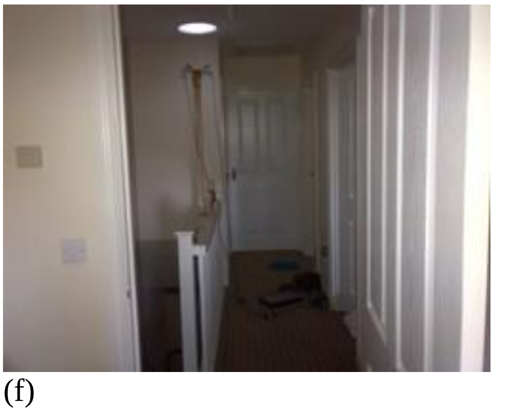

(a)


(b)


(c)


(d)


(e)


(f)

During that time, for approximately 3 days, the Sunpipe diffuser was covered was a black plastic material as seen in 3.4 g & h below, so as to ascertain the quantity of light that will pass through the diffuser.


(g)


(h)

**Figure 3-5 (a-h) Interior Pictures of the Tarmac House showing experiment rig set-up.**

The Tarmac house studied is as seen in Figure 3-6 and 3-7 below. Figure 3-6 shows the ground floor plan (courtesy of Zed Industries, and Figure 3-7 is the first floor plan showing the area under study where the light pipe is and where readings were taken, with perspective view and section drawings..

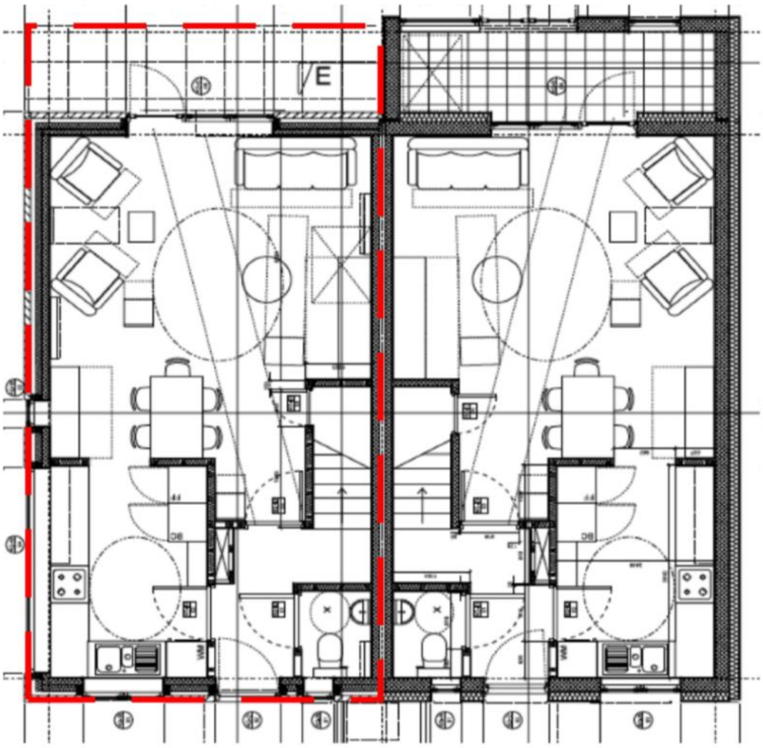


**Figure 3-6: Tarmac House Studied (Left Wing in Red)**

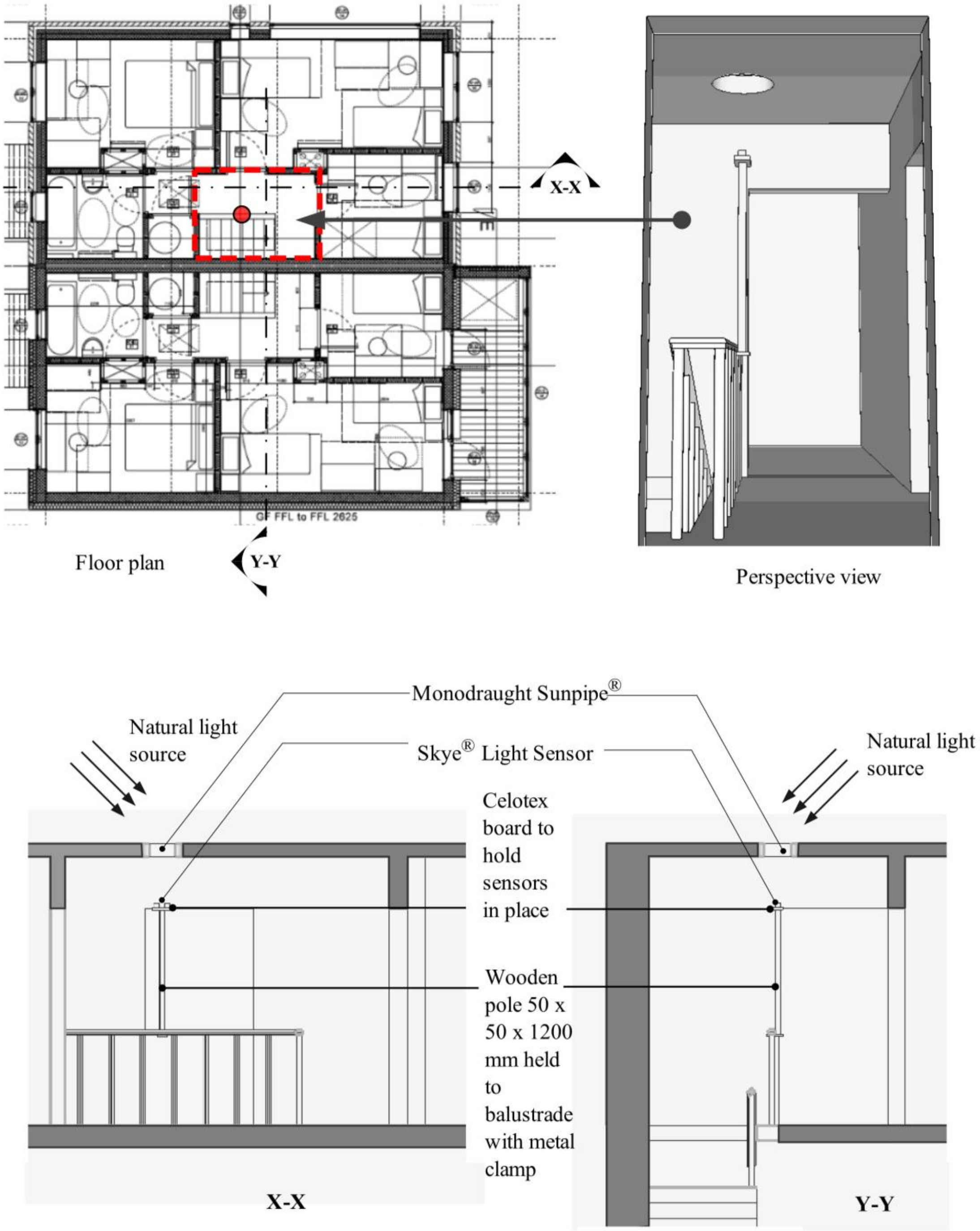



**Figure 3-7: Tarmac House Second Floor Plan, Perspective View of Corridor where Lightpipe is Positioned and Section of the Corridor**

#### 3.2.1.1. Analysis of Tests Carried out on the Tarmac House

Data collected was analysed and the result represented in the graphs to follow.

Figure 3-8 shows that the hours between 7 a.m. and 7p.m. (16-05-2012) recorded the most illuminance ranging from 200 lux to 340 lux. From 8.30pm to 5.30 a.m. there is little or no light recorded, and subsequently, there is a gradual rise until 7a.m.

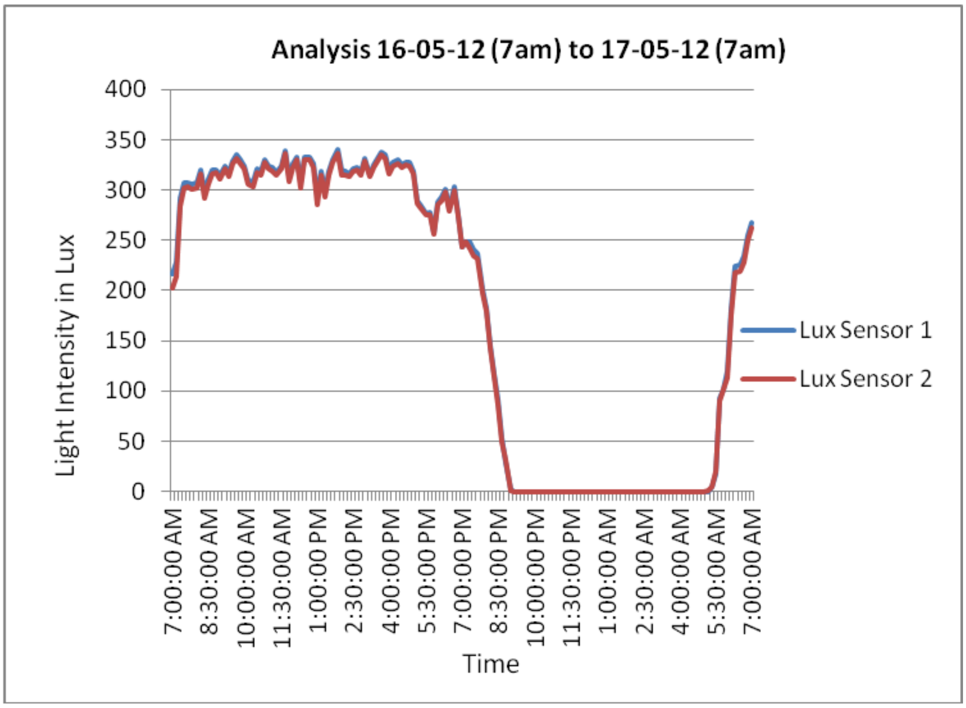



**Figure 3-8: Analysis of Light During the hours of 16-05-12 (7am) to 17-05-12 (7am)**

Data recorded on17-05-2012 as seen in Figure 3-9 shows a similar pattern to that of 16-05-2012.

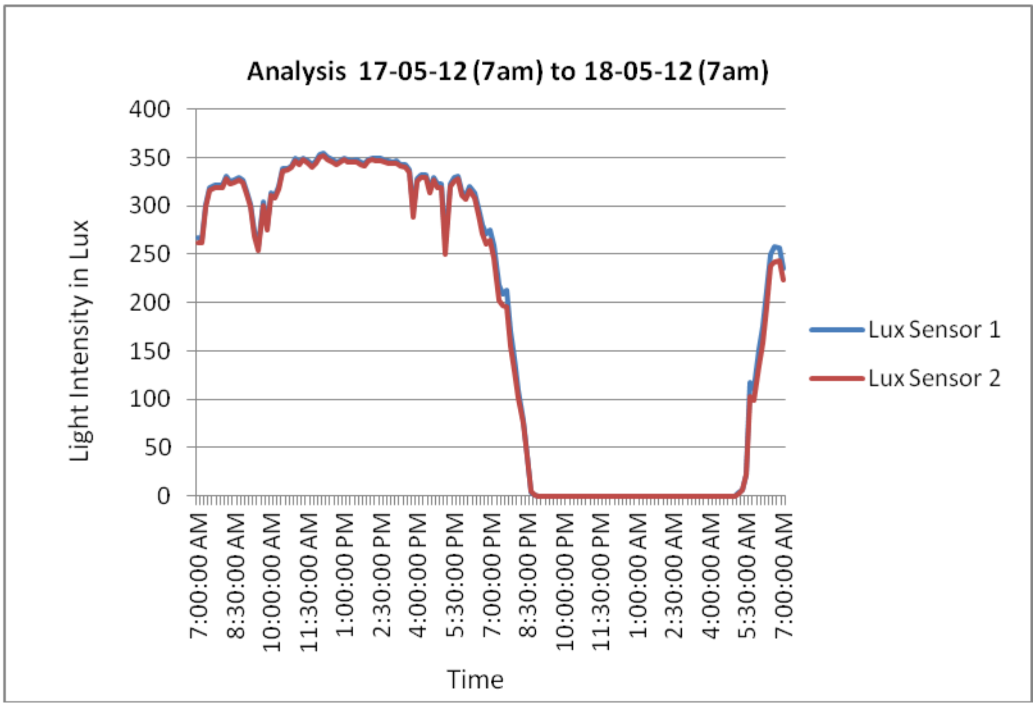



**Figure 3-9:** **Analysis of Light During the hours of 17-05-12 (7am) to 18-05-12 (7am)**

This pattern continues on 18-05-2012 as seen in Figure 3-10 below.

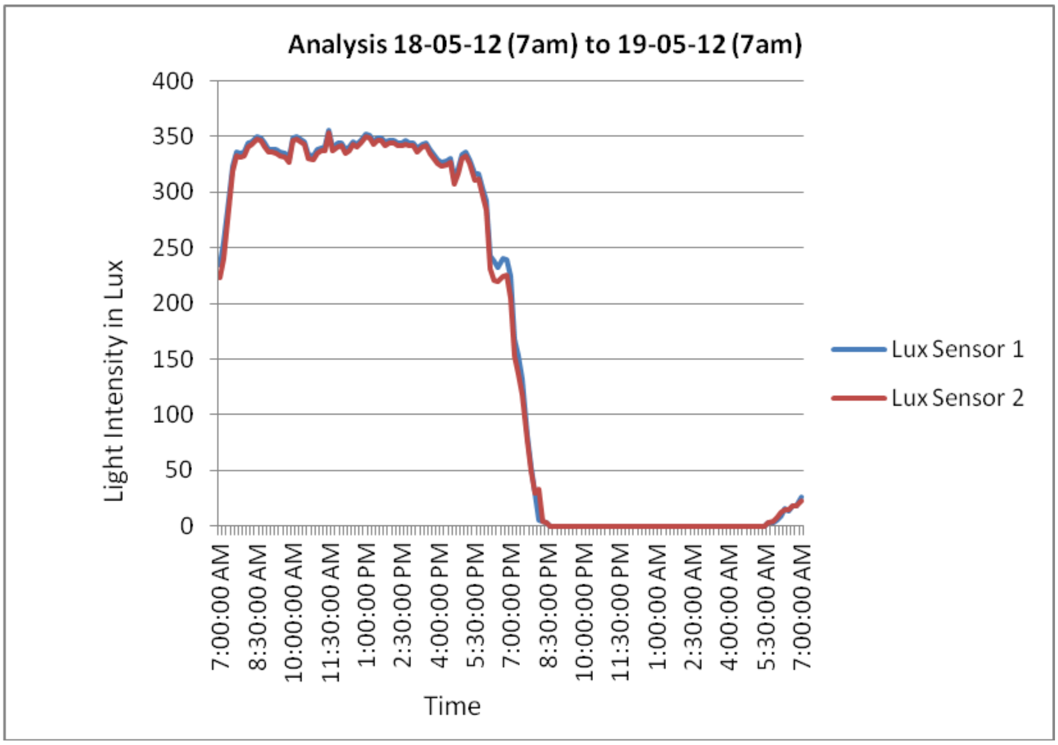



**Figure 3-10:** **Analysis of Light During the hours of 18-05-12 (7am) to 19-05-12 (7am)**

On 19-05-2012, similar patterns were recorded except for some illumination recorded of about 70lux at about 10pm. This could be attributed to moonlight or illumination from artificial sources in the adjacent rooms in the house.

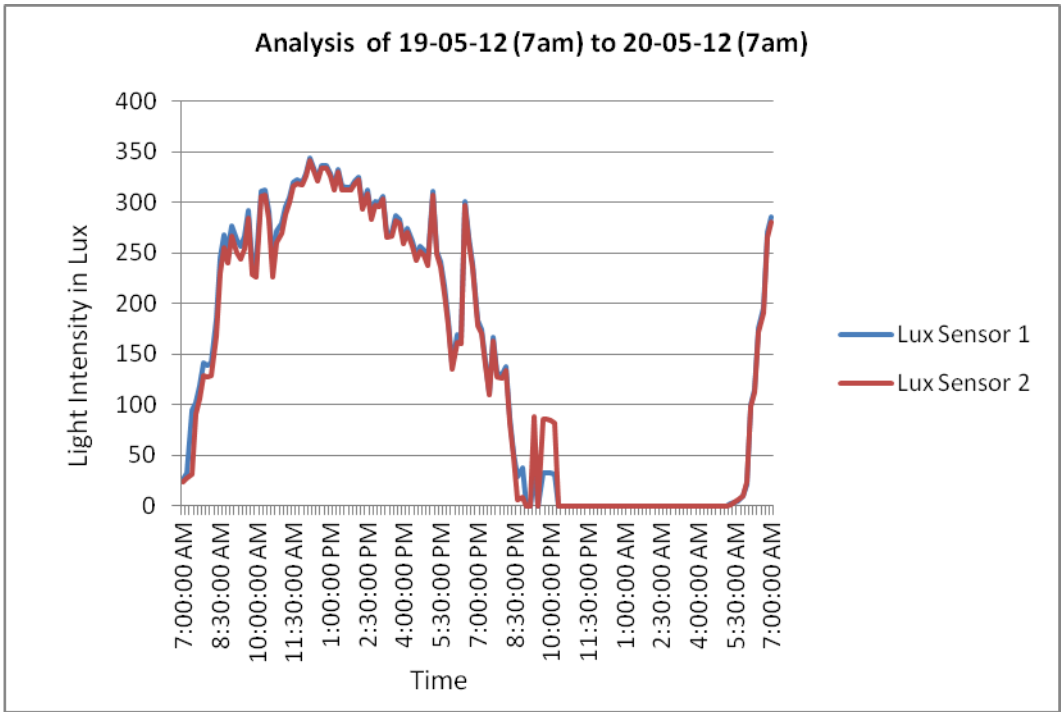



**Figure 3-11: Analysis of Light During the hours of 19-05-12 (7am) to 20-05-12 (7am)**

Data recorded on 20-05-2012 seen in Figure 3-12 and 21-05-2012 seen in Figure 3-13 also show similar patterns as in the first 3 days of testing.

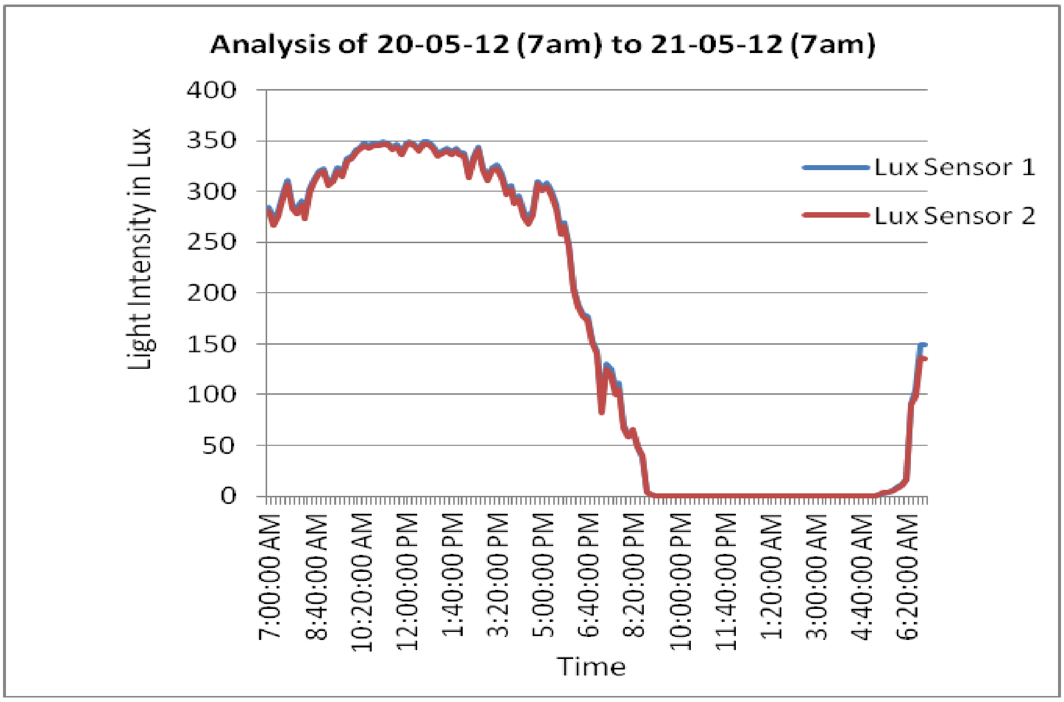



**Figure 3-12: Analysis of Light During the hours of 20-05-12 (7am) to 21-05-12 (7am)**

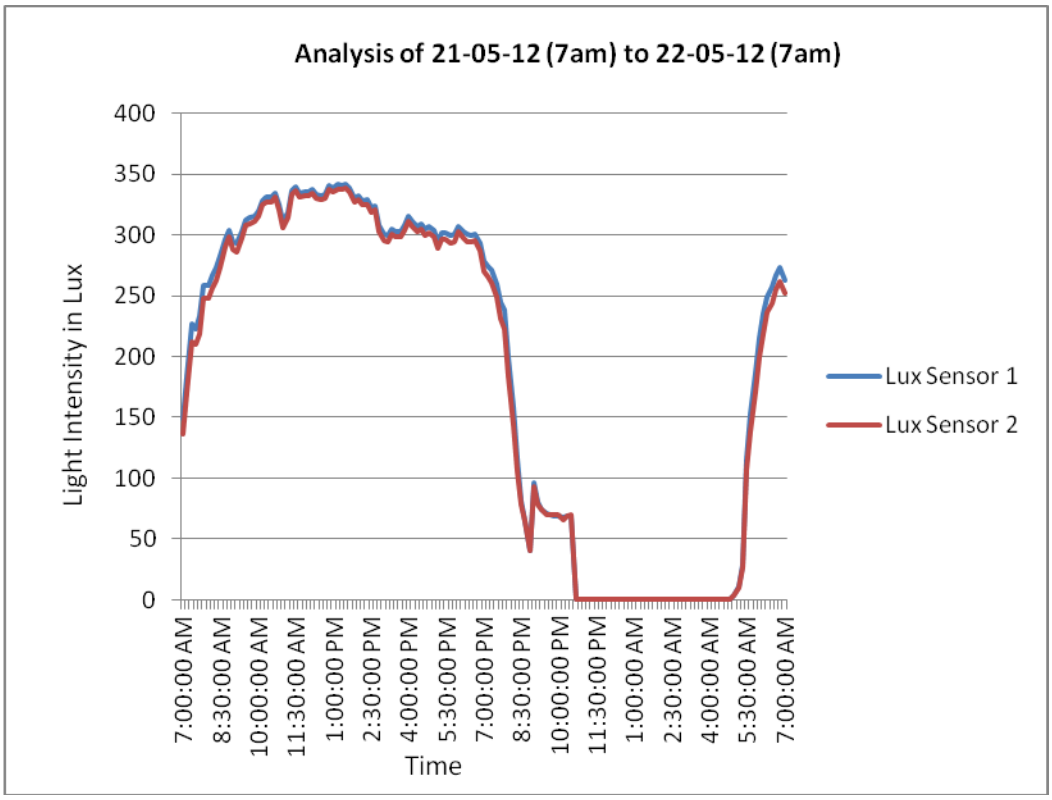



**Figure 3-13: Analysis of Light During the hours of 21-05-12 (7am) to 22-05-12 (7am)**

#### 3.2.1.2. Analysis of Covered Sunpipe

For three consecutive days and nights, the sun pipe was covered with a black plastic sheathing, so as to prevent the sunlight and moonlight from coming through, and the results collected were presented graphically in the following graphs. Figure 3-14 showed that there was no light penetrable through the sheathing except for between 8.50 a.m. and 9.40 a.m. when the occupant in the house recorded that the sheathing was temporarily displaced before it was put back in place. This is also the same as the next two days as seen in Figures 3-15 and 3-16.

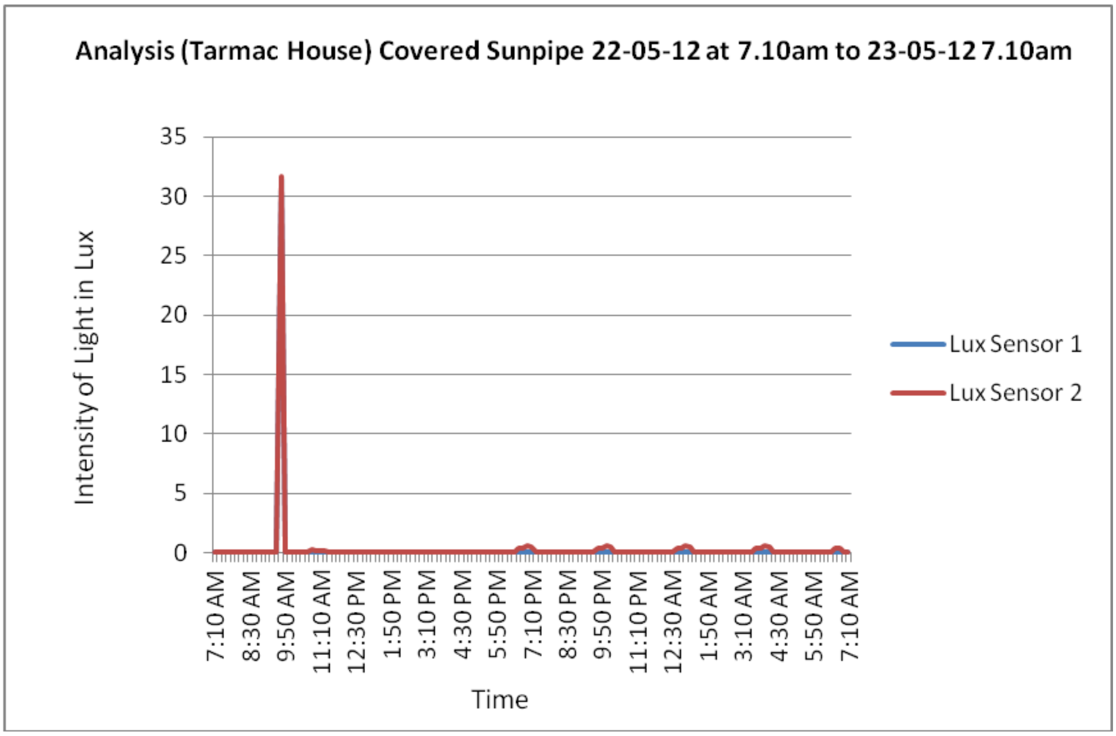



**Figure 3-14: Analysis (Tarmac House) of Covered Sunpipe 22-05-12 (7.10am) to 23-05-12 (7.10am)**

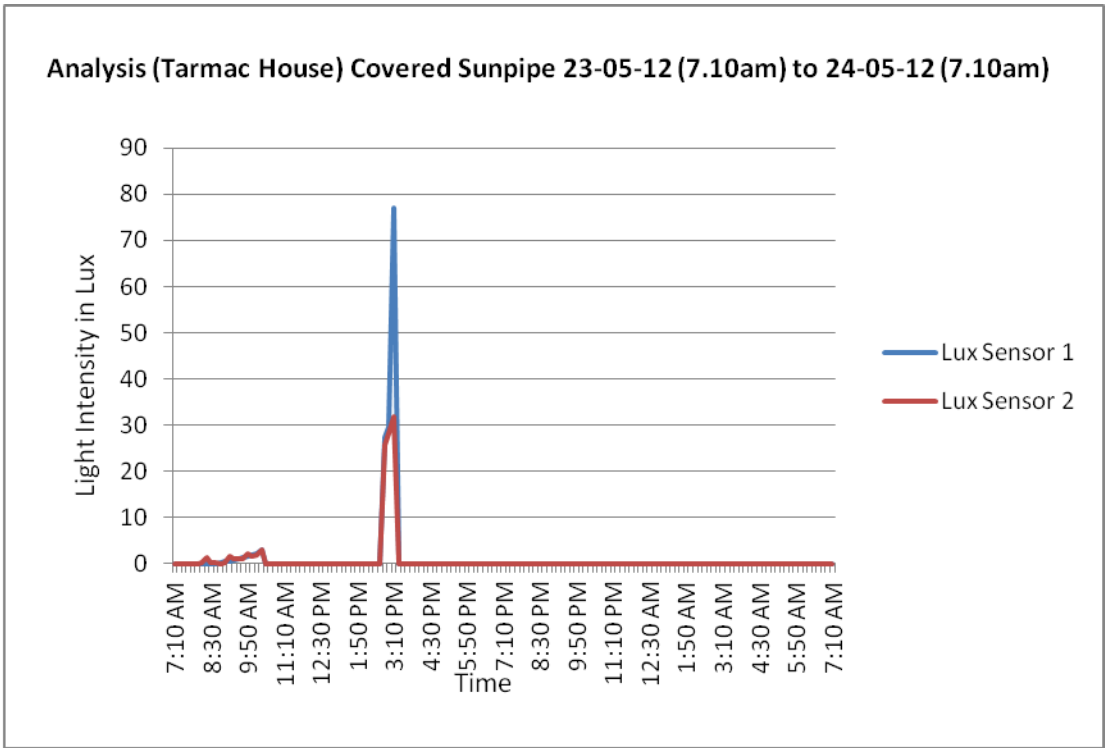



**Figure 3-15: Analysis (Tarmac House) of Covered Sunpipe 23-05-12 (7.10am) to 24-05-12 (7.10am)**

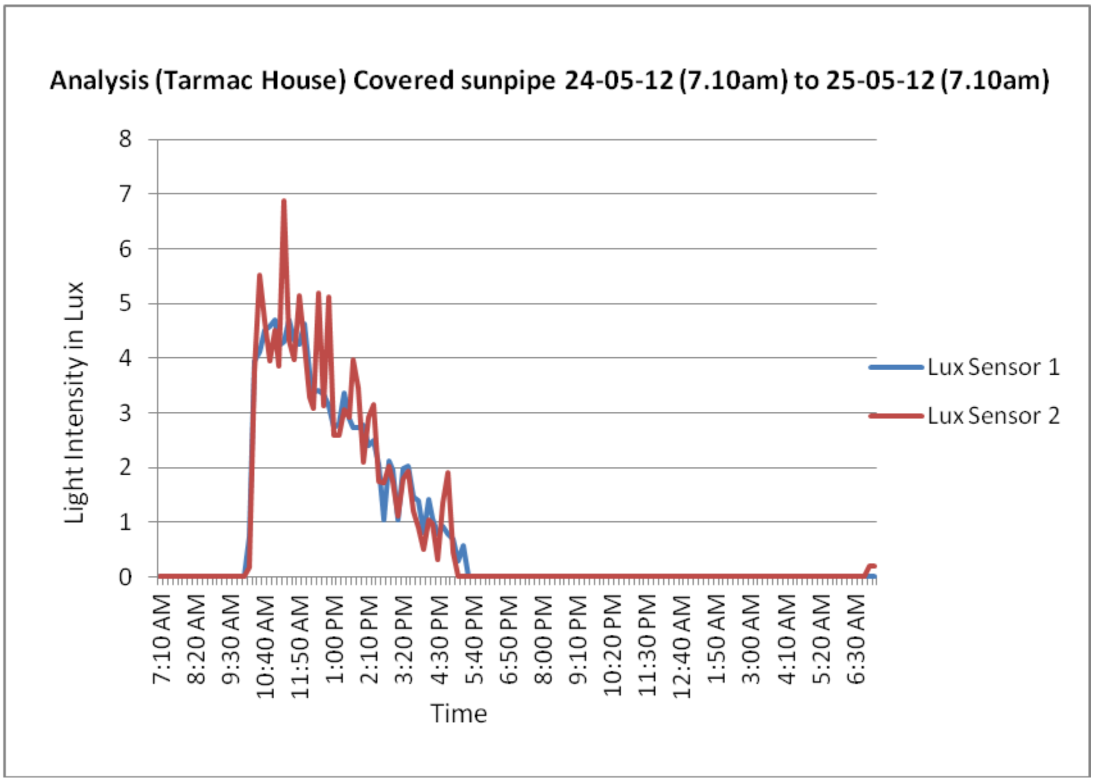



**Figure 3-16: Analysis (Tarmac House) Covered Sunpipe 24-05-12 (7.10am) to 25-05-12 (7.10am)**

#### 3.2.1.3. Results, Observations and Analysis

Results from figures 3-8 to 3-13 during the day time hours of 4.30am to 8.30pm, there is so much illumination in the room with the quantity of light peaking at 350lux on average, at between 8.30 am to 4.00pm. The immense benefit of this “free” light in an otherwise dark corridor cannot be over emphasised. There is a gradual decline in the quantity of light from about 4pm to 8.30pm when the sun is going down. There is little or no light as recorded by the sensors from between the hours of 8.30pm to 4.00am.

The Sunpipe was covered during the day and night for 3 days so as to ascertain and proof its benefits, for 3 days. On 22-05-12 (figures 3-14), there was a recording of 32lux at about 9.50am, 23-05-12 (figures 3-15) a recording of 76 lux was made at about 3.10pm and on 24-05-12 (figures 3-16) between 9.40am and 4.30pm a recording of up to 7lux was observed. These could all be attributed to the temporary removal of the black cover placed over the Sunpipe for various reasons. Apart from that there was no light from the Sunpipe which was similar to night time conditions as observed in figures 3-13.

Results obtained showed that there was remarkable gain in using the Sunpipe and brings light of nothing less than 200 lux in the early morning and late evening, and peaking at over 350 lux in the afternoons. This is especially so, as there is no means of naturally lighting the corridor apart from the employment of the Sunpipe. Observations carried out at night and during the time the Sunpipe was covered immensely show the merit of the installation of the Sunpipe.

### 3.2.2. Field Study 2: The David Wilson Home, University of Nottingham, UK

The history of the Creative Energy Homes project can be traced back to the millennium house which the Department of Built Environment built with the help of David Wilson Homes, 10 years ago. This is a four-bedroom detached property as seen in figure 3.17 uses brick and block construction. Its original purpose was to support research of domestic-sized renewable energy systems such as micro-CHP, solar thermal, micro-wind and natural ventilation devices. The House is now also used as a space for research staff offices. This eco-house is fully instrumented to allow on-going monitoring of its energy performance (Creative Energy Homes, University of Nottingam, 2013)

**Figure 3-17: West Facade of the David Wilson Eco-House**

Daylight tests were carried out in the David Wilson home for a period of one (1) week to determine the advantage or otherwise of the installation and employment of the Sunpipe in the building on the 1st floor on the landing (corridor/hallway).

#### 3.2.2.1. The Experiment Set-up

A wooden t-pole of length 1.2 was anchored above the staircase railing on the landing and two (2) Skye® Lux sensors were placed on it 300mm below the end of the diffuser of the Sunpipe similar to the test carried out in the Tarmac House.

The test was run for 6 continuous days and night and data gathered was thus processed. During that time, for approximately 3 days, the Sunpipe diffuser was covered was a black plastic material, so as to ascertain the quantity of light that will pass through the diffuser.

#### 3.2.2.2. Results, Observations and Analysis (David Wilson Home)

Due to the design of the David Wilson House, the hallway/corridor upstairs where the test was carried out is not only lit by the light pipe in the centre of the space, as is the case with the Tarmac house, but also lit from two opposite sides as can be seen from figures 3-18 and 3-19. Results obtained showed that even though there was remarkable light gain in using the Sunpipe and brings light of nothing less than 220 lux in the early morning and late evening, and peaking at over 380 lux in the early and mid afternoons, it was augmented by the steady stream of sunshine whenever available from both the northern and southern facades.

**Figure 3-18: Interior of North facade showing array of glass blocks which bring light onto the hallway/corridor**

**Figure 3-19: Interior of South facade showing window glazing which brings light onto the hallway/corridor**

However unlike in the design of the tarmac house, the David Wilson Home had a well lit corridor, as there was glazing on opposite sides of the wall which aided natural lighting and thus the Sunpipe was just an added tool for lighting, as can be seen in figures 3-18 and 3-19 above.

The graph in figure 3-20 shows the start of data collection at approximately 1.30pm on 19-06-2012 with light intensity recorded at 370lux and a steady and gradual decline to 50lux at about 9.00pm when it dark, down to zero lux when there is no sunlight outside and the only natural source of light from the outside is the moon light.

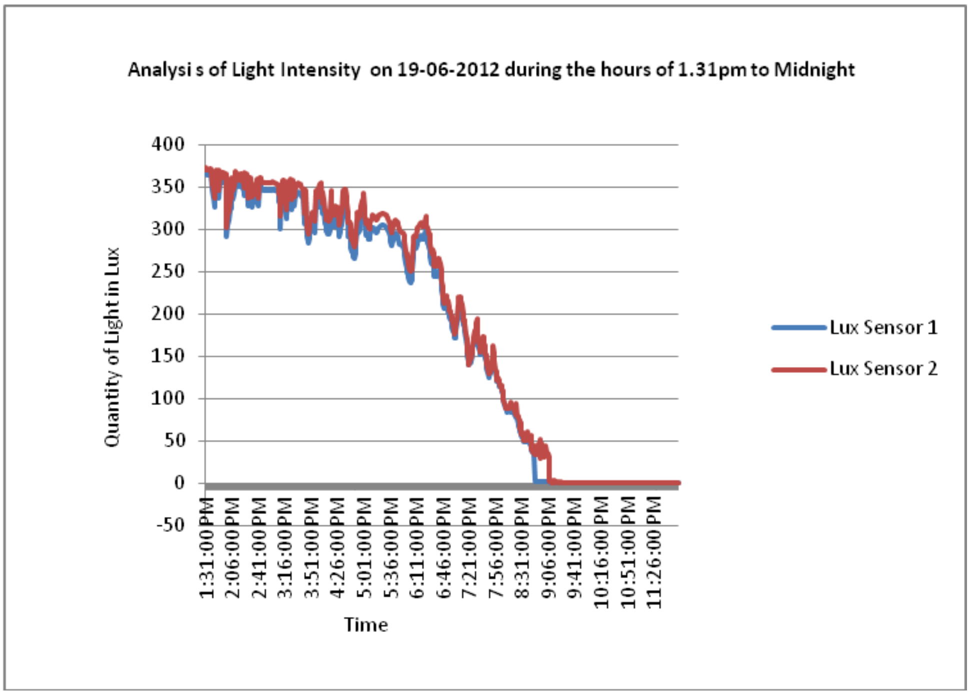



**Figure 3-20: Analysis of Light Intensity on 19-06-2012 from the hours of 1.31pm to midnight**

Figure 3-21 below shows the first ray of visible light coming from about 4am to approximatel 35 lux at 6.30am and a sharp rise to 200lux at 7am and a steady increase peaking at 370lux at 1.30pm where there was a dip to as low as 110lux due to dark cloud cover. By 5.00pm, the light again peaked to 350 lux before steeply falling to approximately 50lux at 8.00pm, and then gradual nightfall.

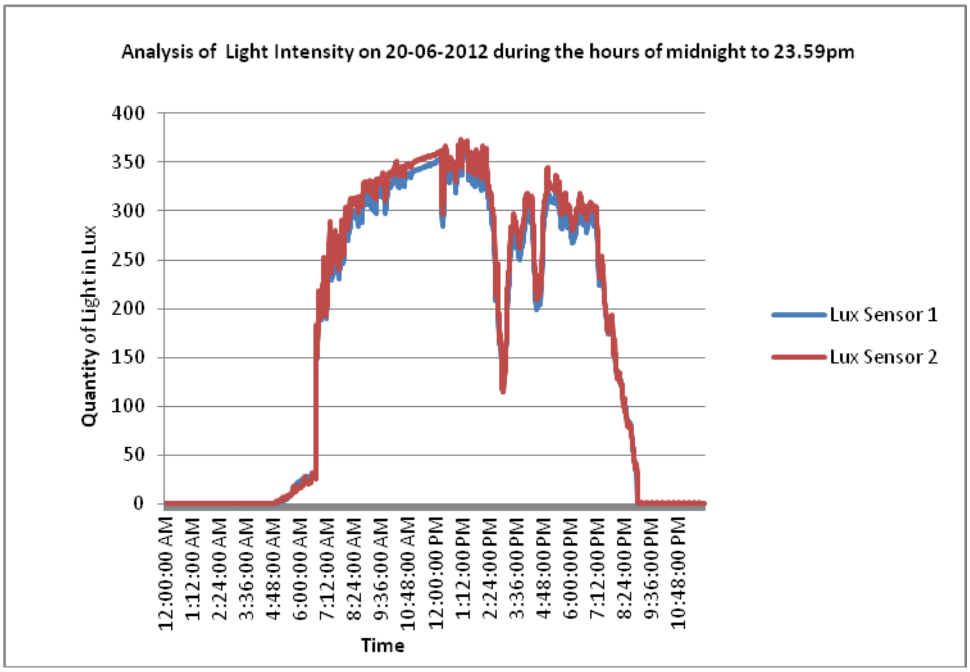



**Figure 3-21: Analysis of Light Intensity on 20-06-2012 from the hours of midnight to 23.59pm**

Figure 3-22 below showed sharp changes throughout the day from about 8am due to the overcast sky and cloud cover with rainfall. However, high intensity of light at 370 lux was recorded at about 2pm.

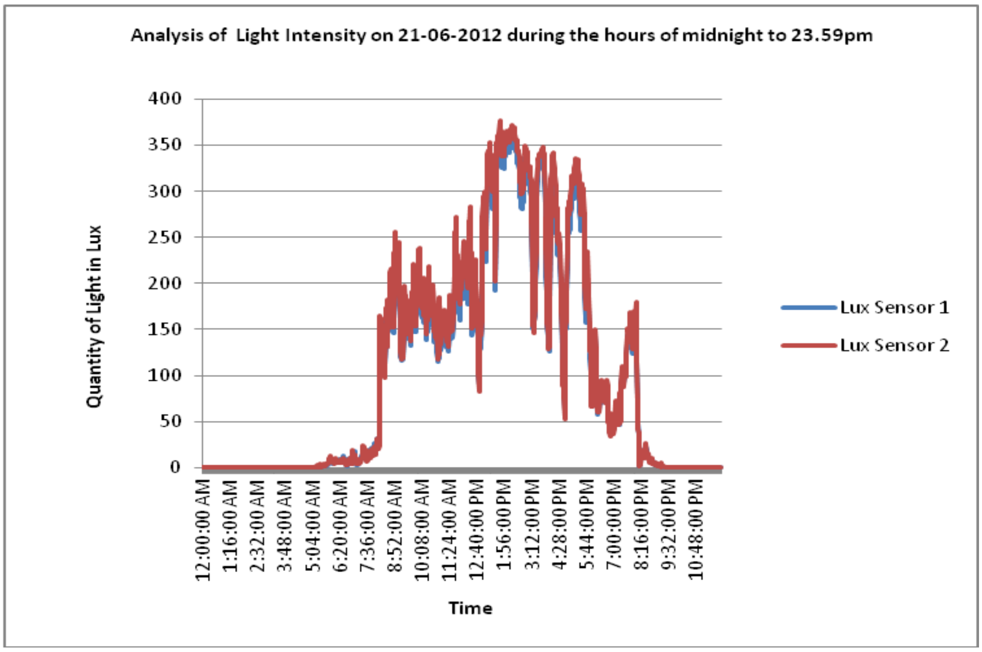



**Figure 3-22: Analysis of Light Intensity on 21-06-2012 from the hours of midnight to 23.59pm**

Figure 3-23 has similar patterns as 21-06-2012 with sharp changes due to rain and cloud cover. Howver, the sunpipe was covered at 1.30pm so as to determine the effect (or not) of the sunpipe in the space. This resulted in very little penetration of light considering the overcast nature of the sky at that time and the maximum recorded light intensity was 30 lux.

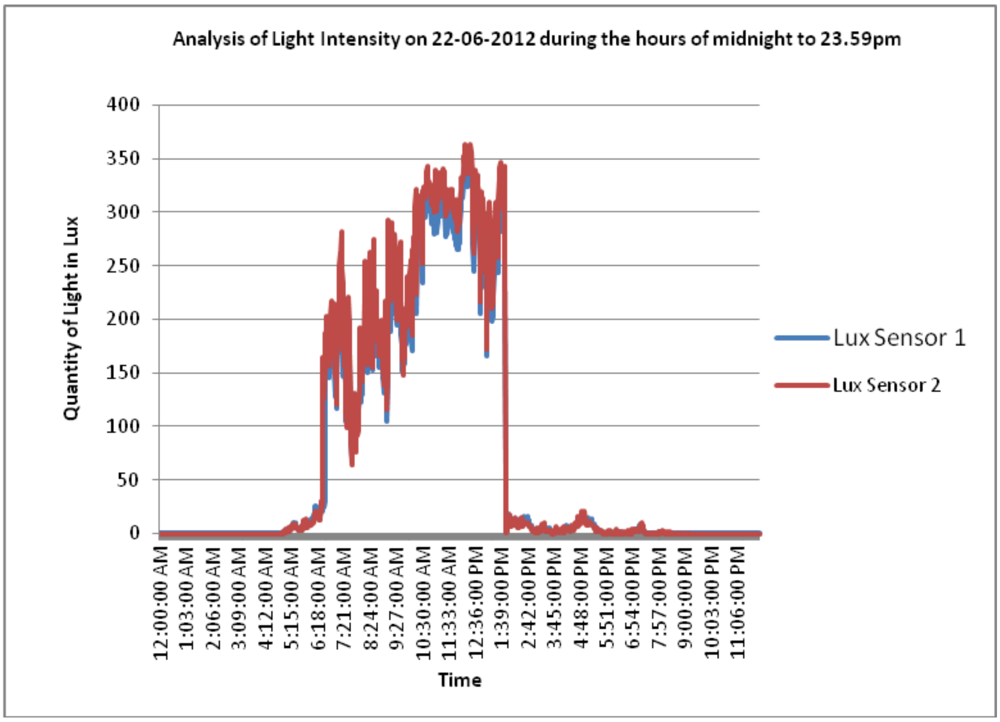



**Figure 3-23: Analysis of Light Intensity on 22-06-2012 from the hours of midnight to 23.59pm**

Figure 3-24 below has similar patterns of low penetration of light due to the cover. However when the cover became partially undone for a few hours between 1.00pm and 4.30pm, snippets of light penetrated up to a maximum of 170lux which was far below the expected reading of ≤350lux for that time of day. This proves that the cover was only partially and not wholly undone.

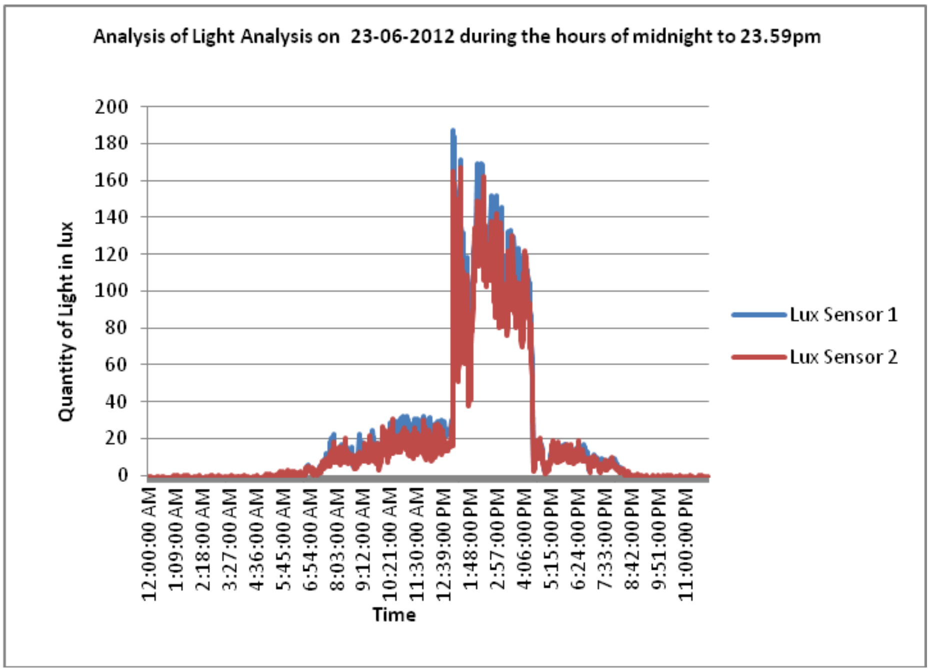



**Figure 3-24: Analysis of Light Intensity on 23-06-2012 from the hours of midnight to 23.59pm**

Figure 3-25 for 24-06-12 is a similar case as the previous day, where again the cover was partially undone, thus allowing the penetration of silmilar level of daylight, until the cover was re-installed at about 7.00pm.

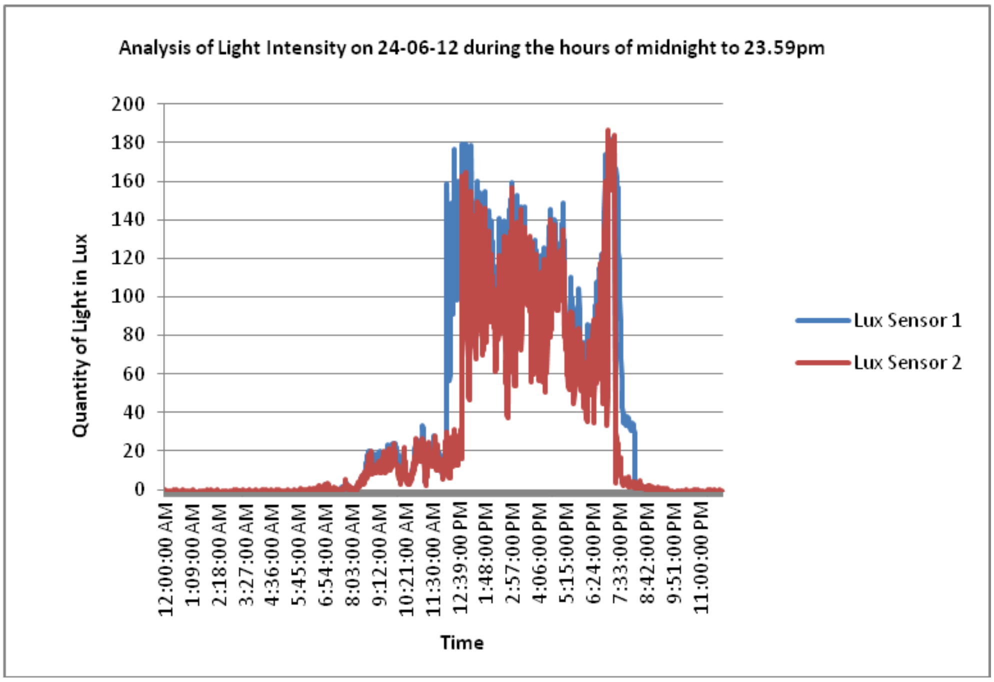



**Figure 3-25: Analysis of Light Intensity on 24-06-2012 from the hours of midnight to 23.59pm**

On the final day of the test, it shows that despite the cover there was partial penetration of sunlight as shown by sensor of up to 30lux. Sensor 1 was dispalced, thus the rogue data as can be seen in figure 3-26 below.

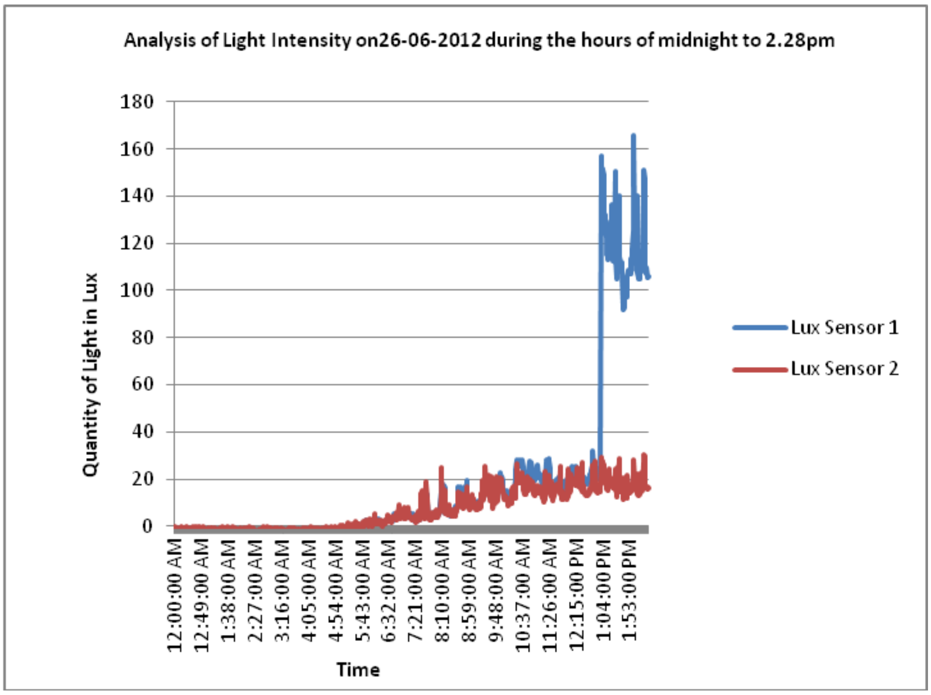



**Figure 3-26: Analysis of Light Intensity on 26-06-2012 from the hours of midnight to 2.28pm**

## 3.3. Conclusion

It can be concluded that despite the fenestration of the north and south facade, as it is a deep space, there are clearly benefits to the installation of the Sunpipe at the centre of the corridor and the combination of light ensures that the place is delightfully bright and cheery throughout the day light hours and even at night when there is a bright moon, the Sunpipe ensures that light is delivered. Without a doubt therefore one can see the clear advantage of employing the use of Sunpipes in such given spaces.

## 3.4. Outdoor Light Test with Different Light Pipes and Light Rods of Varying Diameters and Lengths

### 3.4.1. Introduction

The need to use light rods and light pipes as light guiding tools arose as an alternative to full glazing with respect to the use of windows which effectively provide high quality of light but comprise on heat loss/gain, thus compromising on thermal comfort. Ramanathan (2008) opines that daylight and thermal comfort sometimes conflict with each other i.e. the greater the window area, the greater the amount of daylight penetrating inside the space, but this leads to greater heat losses and heat gains through the glazing.

Light tubes or light pipes are used for transporting or distributing natural or artificial light. In their application today lighting, they are also often called tubular daylighting devices, sun pipes, sun scopes, or daylight pipes.

Generally speaking, a light pipe or light tube may refer to:

- a tube or pipe for transport of light to another location, minimizing the loss of light;
- a transparent tube or pipe for distribution of light over its length, either for equi-distribution along the entire length or for controlled light leakage.

Both instances mentioned above have the purpose of lighting, for example in architecture.

In terms of health effects of daylight on health, Van Bommel's research show that confirmed that light entering the eye is also responsible for certain non visual biological effects in the body which play a major role in resetting/adjusting the internal biological clock. Consequently, a lack of light can significantly affect health and well being resulting in sleep disorders, depression, Seasonal Affective Disorder, (SAD) reduced alertness and poor performance. This discovery reinforces the concept that the luminous environment should not only be designed for visual perception but also for well being (Van Bommel W.J.M, 2006)

Light tests with light pipes indoor have proven to be worth the trial and thus the test was taken outdoors so as to determine its true applicability in the real life situation. Light pipes have been tested efficiently to carry light to dark corridors and rooms as can be seen in the field studies in chapter 3.1. Figure 3-27 shows a schematic sketch of its application in buildings.

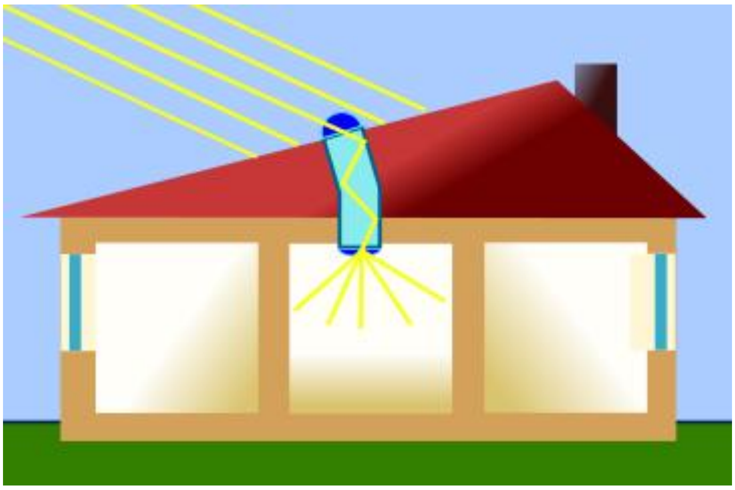


**Figure 3-27: Application of Light Pipe in Buildings (Green Edmonton, 2011)**

To study the effect of pipe diameter and length diameter on illumination, further testing was carried out with lightpipes of various of various lengths and diameters, and light rods of various lengths and diameters, as well as a novel combination of the two. The following tests further investigate the efficiency of these light pipes with decrease/increase in diameter as well as decrease and increase in length. The equipment employed in this test are:

- Insulated Wooden Box (1200 x 1200 x1200): Insulated with 50mm thickness celotex® to resist external temperature and maintain internel temperature
- DT500 Datalogger: used to record data from attached sensors at set time
- Skye® Light Sensors: used to measure light intensity in lux.
- Kipp and Zenon® Pyranometer: used to measure the radiation.
- "K" Type Thermocouples: used to measure the temperature
- 100 diameter, 1.2m/1.8m Length Light Pipe: installed devices to convey light.

### 3.4.2. Experimental Uncertainty

As with all experiments, it is expected that errors will occur due to a variety of reasons. These reasons can be attributed to both human and equipment faults, which lead to errors in results. However, these can be minimised by ensuring that equipment are well calibrated and the uncertainties are taken into consideration during result analysis. Thus, the following uncertainties as seen in Table 3-1, were taken into consideration during all the experiments undertaken. These uncertainties were obtained during self-re-calibration of the equipment used under the testing conditions.

**Table 3-1-1: Experimental Sensor Uncertainties**

| Sensor Type | Percentage Error |
|---|---|
| Light Sensors | ± 1.25 |
| Thermocouples | ± 1.75 |
| Pyranometer | ± 1.0 |
| Heat Flux | ± 1.0 |

### 3.4.3. Outdoor Test 1 – Tests with Light Pipe of Varying Lengths and Diameters

The tests were carried out using the following light pipes:

Condition 1: 100mm diameter, 1.8m length light pipe

Condition 2: 100mm diameter, 1.2m length light pipe

Condition 3: 300mm diameter, 1.2m length light pipe

#### 3.4.3.1. Test Procedure for Conditions 1 and 2

In this test, 1.8m length of light pipe with a diameter of 100mm was inserted in the middle of a box, and the tops and bottoms covered with transparent see-through material (Perspex) material so as to act as a diffuser, as well as to prevent ingress of birds and other unwanted debris as seen in Figures 3-29 and 3-30. See also, schematic diagrams in Figures 3-31

6 Lux® Sensors were used in different positions, 1 was placed at the inlet of the box to determine the quantity of light at entry level. Of the 5 placed in the box, 3 were placed on the floor of the box at the middle, near left corner and far left corner. 2 other were placed half way up the middle of the box, one at the right wall and the other at the far

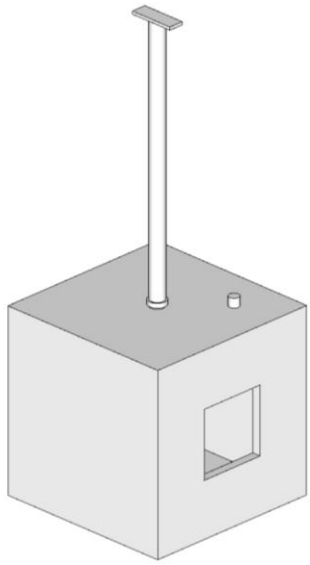
wall, and readings were taken simultaneously for approximately 5hrs spanning from morning to late afternoon.

### 3.4.4. Condition 1: 1.8m length, 100mm diameter Light Pipe in Test Box

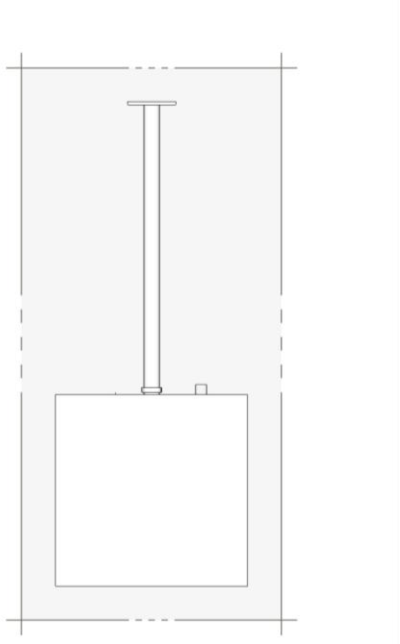
The test was set-up as described previously (see figures 3-29 & 3-30), and the irradiance level on the day the test was performed was an average of 400W/m2 with highs of over 900Ww/$m^2$ and lows of 80W/$m^2$ as can be seen in figure 3-32.

**Figure 3-28: 1.8m Length Light Pipe covered with a piece perspex material**

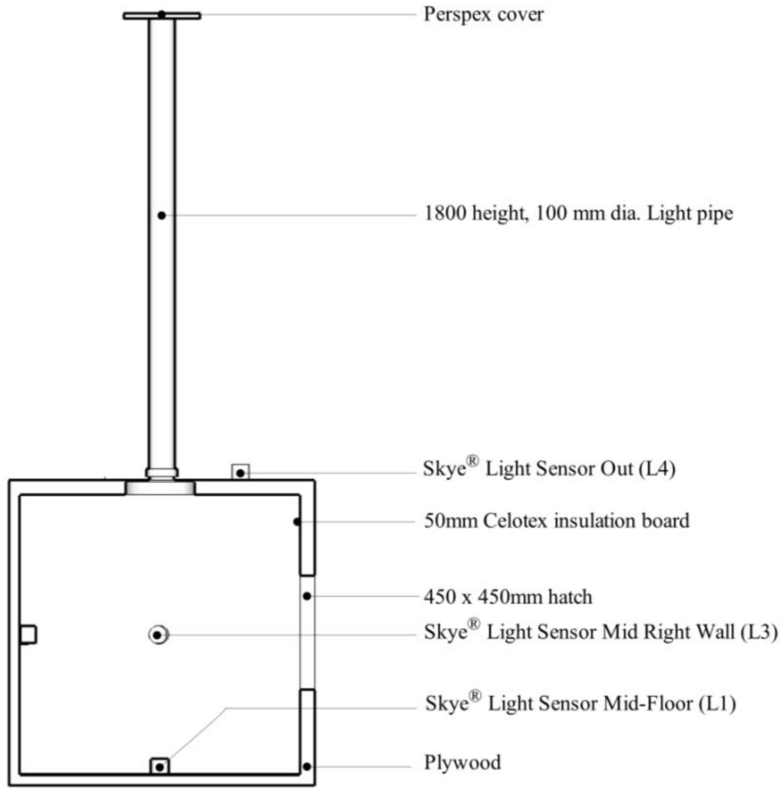
**Figure 3-29: 1.8m Length Light Pipe covered with a piece perspex material**



(a) Perspective View



(b) Typical Elevation




(c) Section

**Figure 3-30: Schematic Sketch for 1.8m Length; 100mm Diameter Light Pipe**

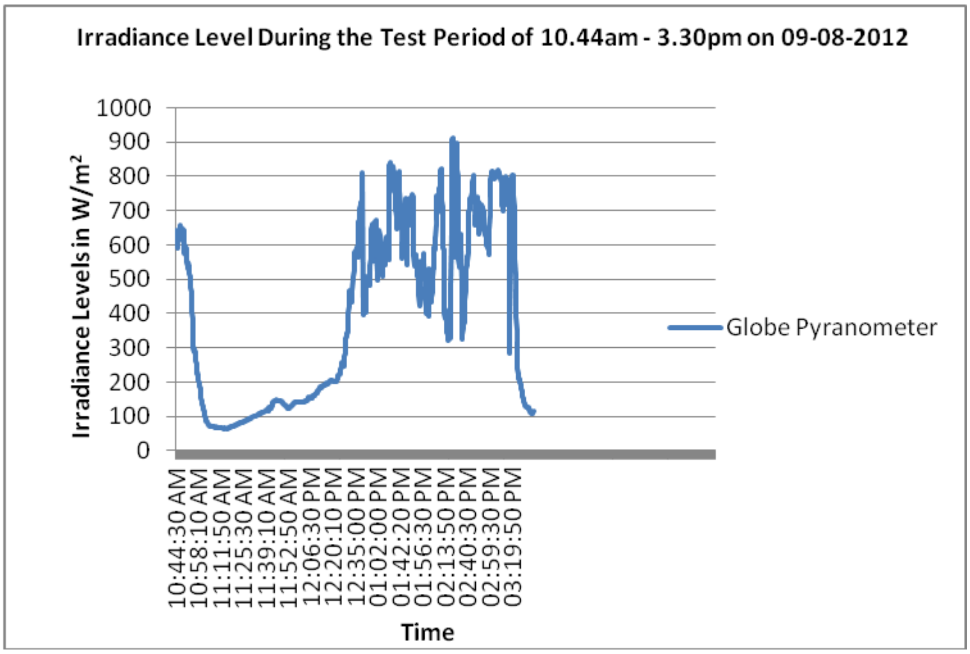



**Figure 3-31: Irradiance Level During the Test Period of 10.44am–3.30pm on 09-08-2012**

The readings from the lux sensors were taken and this is graphically represented in Figure 3-33.

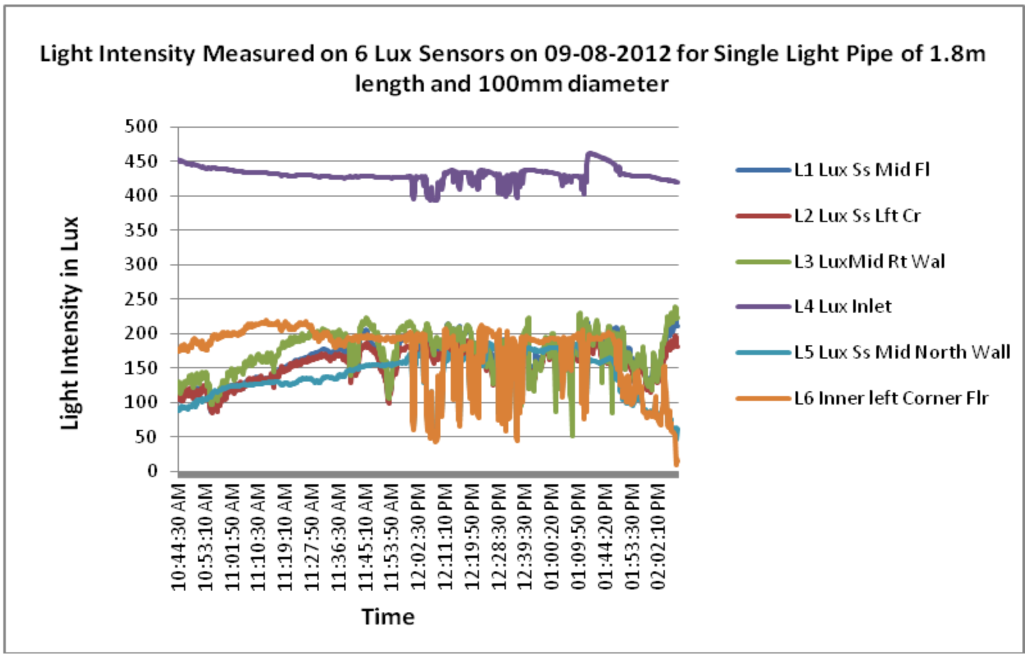



**Figure 3-32: Light Intensity Single Light Pipe of 1.8m length and 100mm diameter.**

There was a lot of fluctuation and change in the light intensity due to the nature of the UK weather with overcast skies even on a typical summer morning/afternoon. From figure 3-33 above, it can be seen that at the point of entry of the light, there is a high luminosity level of an average of 430.9lux. The highest luminosity level recorded was on the sensor on mid-right wall peaking at 235lux, and the average illuminance in the test box from all the 5 sensors was 160.9lux..

| | |
|---|---|
| Average Light At Entry | 430.9 lux |
| Average Light in the Test Box | 160.9 lux |
| Difference in Light out from in ($\Delta$L) | 430.9 – 160.9 = 270 |
| %tage of Light Loss from out to in | 270/430.9 x 100 = 62.6% |

Given the CIBSE standards for lighting in residential buildings as shown on Table 3-3, it allows that building interiors can be lit with as little as 50lux for toilets and 150 lux for corridors, bedrooms and living rooms. This goes to show that there is sufficient light in the light pipe to meet the said minimum standards. The length of the light pipe as well as the diameter was examined to see if there is any change in the quality and quantity of light thus further testing using shorter light pipe with a larger diameter.

UK light pipe manufactures Mondraught, have researched into the illumination properties of light pipe and give standard illumination properties as seen on Table 3-2 as a recommended guide for the selection and installation of light pipes.

**Table 3-2: Data for Typical a Typical Flat Roof Application Measured 1.5m below SUNPIPE® Diffuser**

| | Full Summer Sun 105klux | Overcast Summer 45klux | Overcast Winter | Area Lit |
|---|---|---|---|---|
| **530mm dia.** | 2530 lux | 1050 lux | 430 lux | $30m^2$ |
| **750mm dia.** | 4350 lux | 1975 lux | 900 lux | $50\ m^2$ |
| **1000mm dia.** | 13630 lux | 3650 lux | 1425 lux | $60\ m^2$ |

### 3.4.5. Condition 2: 1.2m length, 100mm diameter Light Pipe in Test Box

This test has exactly the same conditions as the test in condition one, with the only difference being that the length of the light pipe is 1.2m with the same nominal diameter of 100mm.

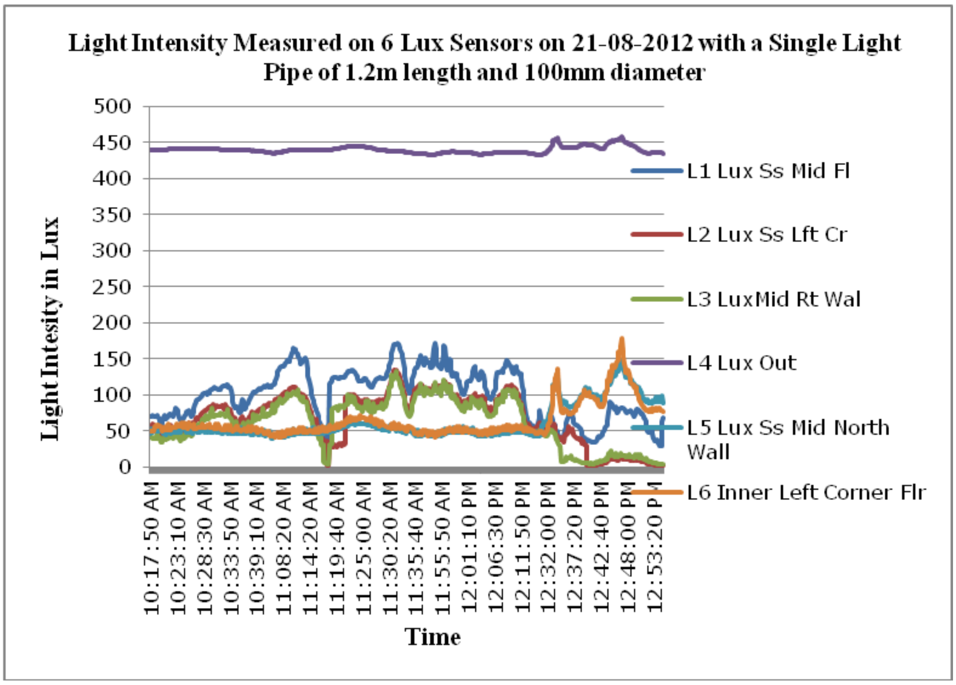



**Figure 3-33: Light Intensity for a single light pipe of of 1.2m length and 100mm diameter.**

Figure 3-30 shows the illuminosity levels at the point of entry (L4) with an average illuminance of 400 lux and at various positions in the controlled room. The fluctuatuations oncemore, can be attributed to the cloud cover at various times during the test period.

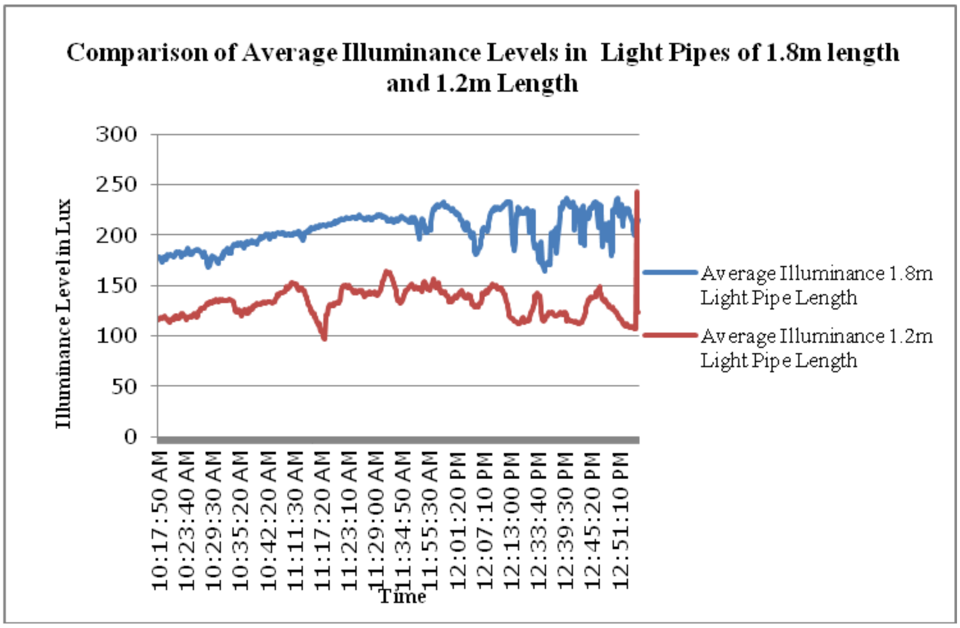



**Figure 3-34: Luminosity observed in the two Light Pipe Lengths of 1.8m and 1.2m**

Figure 3-35, shows the difference in illuminance between condition 1 and Condition 2. The tests though carried out at different times were carried out under similar conditions which were monitored using the irradiance level and lux readings from the inlet. Even though there was a difference in the luminosity in the inside of the box when the two different lengths were compared, it is not enough to say that the length is the sole determinant to this difference as opined by Callow (2008).

### 3.4.6. Condition 3: 300mm diameter, 1.2m Length Light Pipe

Sequel to the two previous tests with pipe diameters of 100mm, the test conditions remained the same, however this test was carried out with a pipe of 300mm diameter and 1.2m pipe length, with a prismatic acrylic cover, under the same typical British summer day. Subsequently, the results will be placed side-by-side and analysed

The results below in figure 3-36 show the quantity of light measured in the box by the 6 light sensors employed. With the increase in the pipe diameter, came a great increase also in the quantity of light inside the test box. The average illumunance inside the box is 278.5 lux. The outside sensor at entry recorded an average of 435.8lux. On average therefore, there was a loss of 36% form entry point to the inside of the box.

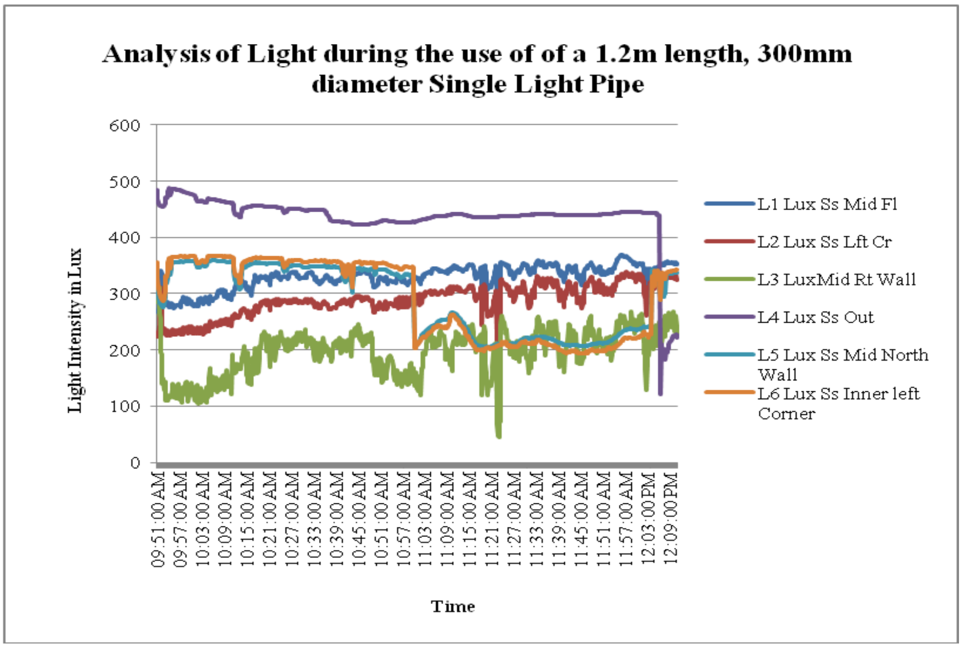



**Figure 3-35: Analysis of Light for 1.2m Length, 300mm diameter Light Pipe**

### 3.4.7. Comparison of Results for all Three Conditions and Conclusion

The average illumination in the 1.2m length light pipe with 100mm diameter test was 160.9lux, while that of 1.8m pipe length with 100mm diameter was 71.2lux. Thus, there was a 55.7% loss in luminosity with just a one third reduction in pipe length, illustrated in figure 3-37. However with the increase in the diameter of the pipe from 100mm to 300mm, there was a remarkable increase on the luminosity to an average of 278.5lux as can be further seen in figure 3-37 below. This represents a 42.2% increase from the pipe in condition 1 (1.2m length, 100mm diameter).

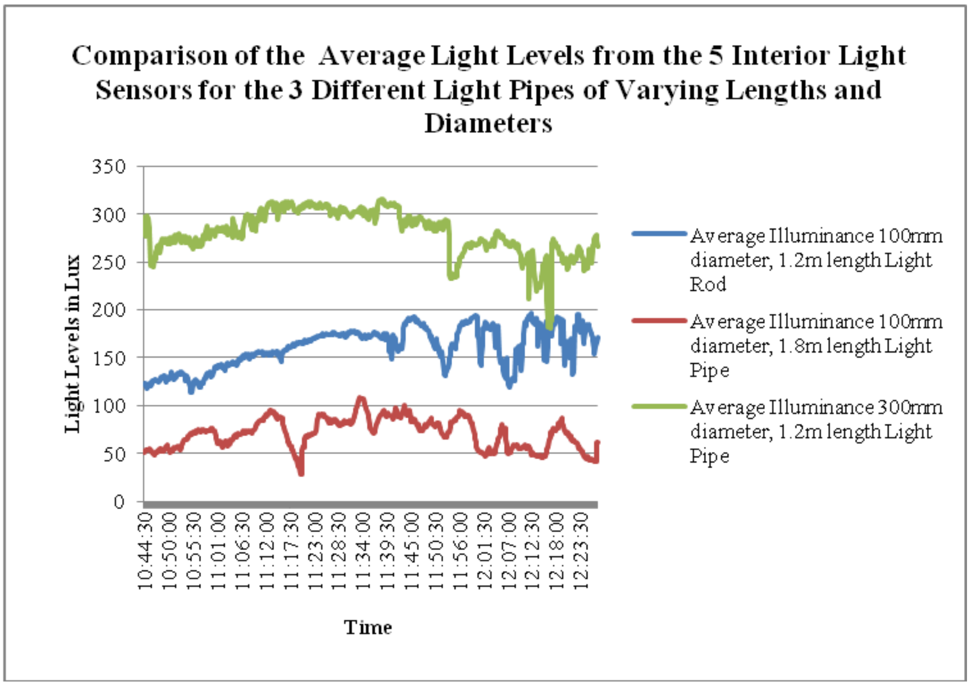



**Figure 3-36: Comparison of the Average Light Levels from the Interior Sensors for the 3 Different Light Pipes**

## 3.5. Base-line Tests with Singular Extruded Acrylic Light Rods of Similar Diameters with Varying Lengths

### 3.5.1. Introduction

Sequel to the baseline tests carried out on light pipes, similar base-line tests were carried out with the use of light rods so as to establish basic parameter before the commencement of the innovative dual technology tests which will be aimed at establishing the percentage of light gain in the system.

Two different sets of tests were carried out under the same condition; the only difference was in the variation of the light pipes lengths.

Condition 1: 100mm diameter, 1.8m length light rod

Condition 2: 100mm diameter, 1.2m length light rod

The tests were each run on typical summer days with an overcast sky and flashes of sunlight with similar irradiance readings on the pyranometer. High quality extruded acrylic glass rods of nominal diameters of 100mm were in either condition erected in the middle of the 1200mm x 1200mm x 1200mm wooden insulated box and placed in an open area within the Departmental premises. 2 thermocouples were placed inside and outside the box to monitor interior box temperature as well as external ambient temperature during the duration of the test. 6 light sensors were placed in various positions both in and outside the box (as seen in Figures 3-38 a & b and 3-42) and the end inside the box was covered with a diffuser. The light rod was placed vertically upright at angle 90° to the top horizontal surface of the box. The equipment used include:

A DT500 Datalogger

6 Skye® lux sensors in various positions

2 Temperature Thermocouples (for monitoring both outdoor and ambient temperature of the box)

A Kipp & Zonen globe pyranometer

Insulated Wooden Box (1200 x 1200 x1200)

DT500 Datalogger

Skye Light Sensors

100 diameter, 1.2m and 1.8m length light rods

### 3.5.2. Condition 1: 100mm diameter, 1.8m length Light Rod

**Figure 3-38a**

**Figure 3-38b**

**Figure 3-37a: 1.8m Length LightSingle Light Rod**
**b:Detail of Fixture, at the Foot of 1.8m Length LightSingle Light Rod**

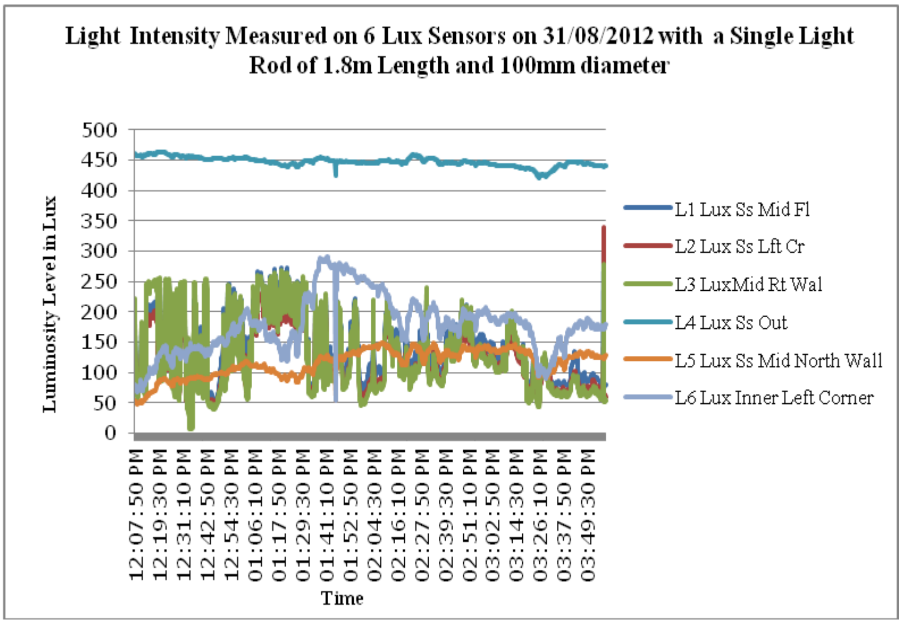



**Figure 3-38: Analysis of Light with Single Light Rod (100mm dia., 1.8m height) as base line test**

### 3.5.2.1. The Results and Analysis

From the results seen in figure 3-39 above, the light intensity on entry was at an average of 447lux throughout the testing period. The average light illumunance in the box was 137lux, however the sensor which recorded the constant highest light intensity which was the inner left corner (L6), recorded a light intensity average of 178lux, which by CIBSE standards, is sufficient for general residential illumination.

### 3.5.3. Condition 2: 100mm diameter, 1.2m length Light Rod

In this test, the 100mm diameter, 1.2m length light rod was tested outside on a typical British summer day with overcast sky, to determine the amount of light that is received in the box (see Figures 3-40 a & b and Figure 3-42). The light sensors were placed in 6 positions as with the previous tests, and the measurements were taken as seen in Figure 3-41. Subsequently the results will be placed side-by-side and analysed.

Set up is the same as that of Condition 1

(a) (b)

**Figure 3-39 a & b: Light rod in place position prior to commencement of testing**

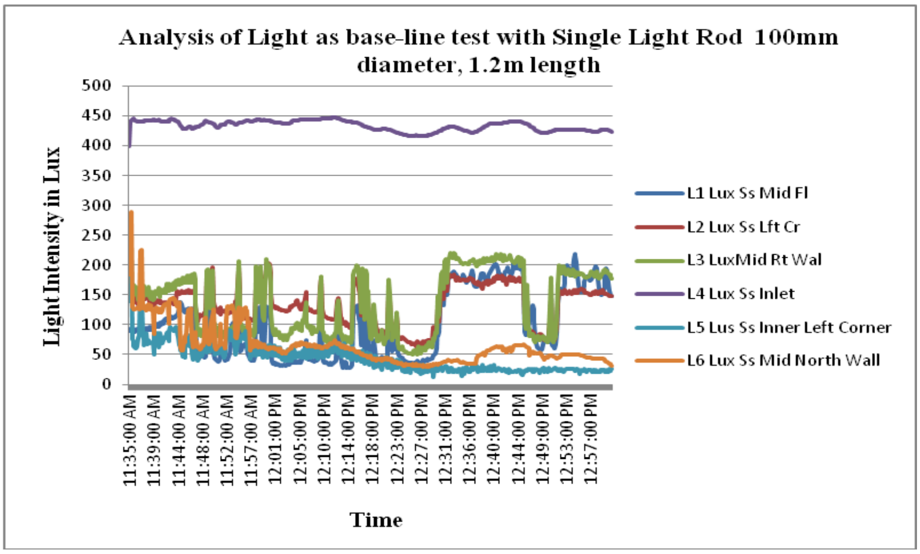
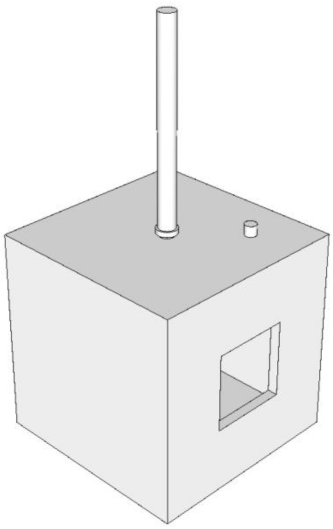
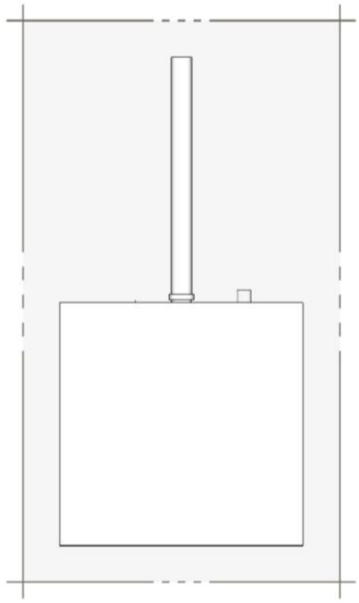


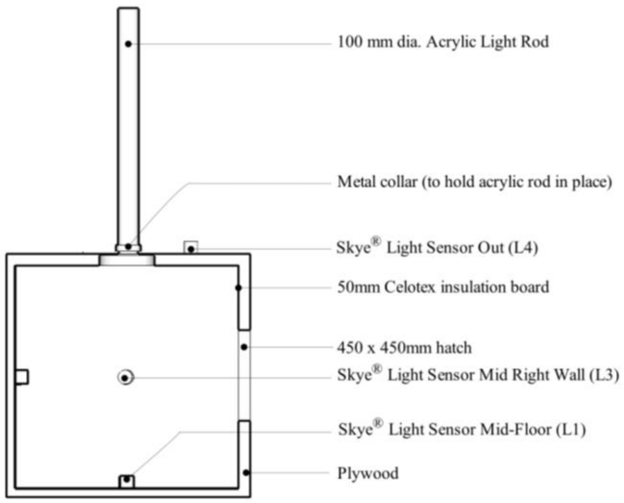

**Figure 3-40: Analysis of Light with Single Light Rod (100mm dia., 1.2m height) as base line test**



(a) Perspective View



(b) Typical Elevation




(c) Section

**Figure 3-41: Schematic Sketch for 1.2m Length; 100mm Diameter Light Rod**

#### 3.5.3.1. The Results and Analysis

The results as seen in figure 3-41 show that at inlet, there was an average of 433.5 lux. However, during transport from entry into the box, the highest light level recorded is 216 lux with sensor on the mid-right wall of the box (L3) which consistently recorded the best light intensity recorded. However the average amount of light recorded on that sensor is 136.3lux. The average of light amount of light however recorded by all 5 sensors in the box is 96.2lux. Therefore only an average of 22% of the light reaches the overall interior of the box.

### 3.5.4. Conclusion

A comparison of the two results shows that during the transport of light, there was more light transported into the box with longer length of light rod, than with the shorter light rod. This indicates that the length of the light rod affected the quantity of light reaching inside the box. From calculations there was a 40% gain in the increase of the light when the 1.2m length rod was replaced by the 1.8m length rod as illustrated in figure 3-43 below. From CIBSE guidelines which recommends illumination to fall within 100lux -300lux (depending on spatial requirement – see Table 3-3), it can be concluded that the 1.2m length light rod falls favourably within these recommendations. However, 1.8m length rod falls slightly below these recommendations at some period, but within the standard value at others. It is thus not sufficient to say that the efficiency of the 1.8m is poor.

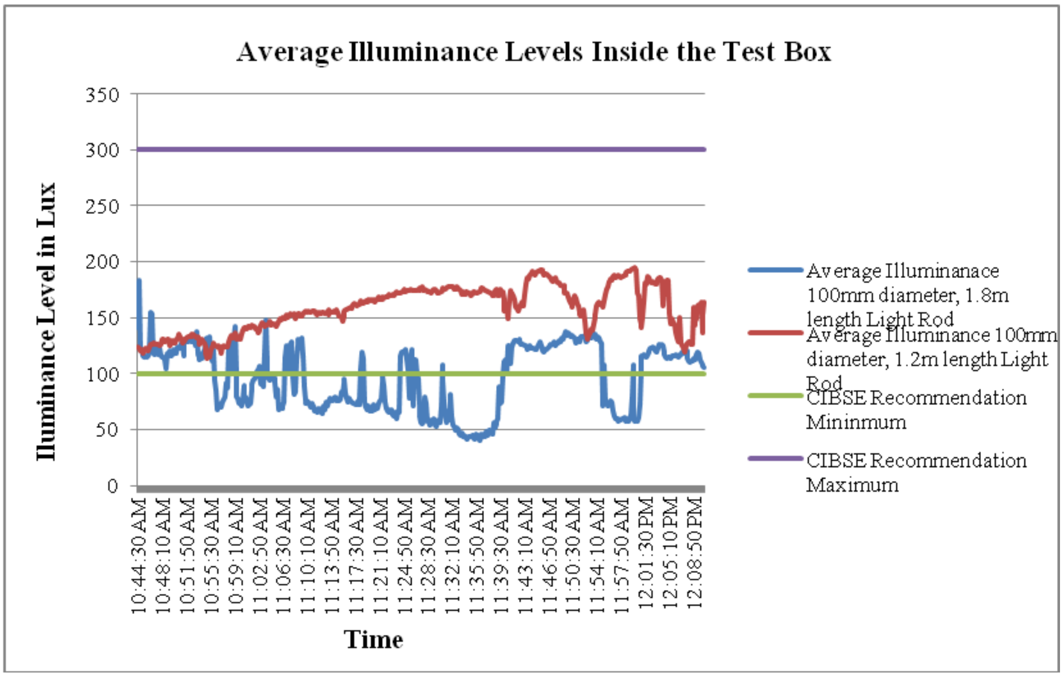



**Figure 3-42: Analysis of the Average Illuminance for the Two Different Lengths of the Light Rod**

**Table 3-3: CIBSE Illumination Levels for Residential Buildings**

| Spatial Area Description | Illumunance (lux) |
|---|---|
| Lounge | 100 - 300 |
| Kitchens | 150 - 300 |
| Bathrooms | 150 |
| Toilets | 100 |

Source: CIBSE Illumnation Level, 2005

However, despite the significant loss of light on average from 433 lux to the average of 157lux with the 1.8m length light rod, it still falls within the CIBSE average illuminance required for residential buildings, as can be seen in table 3-3 above.

## 3.6. Novel Dual Technology Outdoor Test

Tubular daylight guidance systems are linear devices that channel daylight into the core of the building, the development of which over the last decade, has increased its popularity, and led to its successful installation in many parts of the world. (Al-Marwaee and Carter, 2006). As a result of which several researches have been undertaken to explore the viability of using these tubular light guidance systems. It is on this premise that the tubular light guide was selected as a device to optimise its output and improve its efficiency. The success of the individual light guiding systems led to the crux of the investigations carried out in this section. This is to ascertain if a combination of two (or even more) of the existing technologies can further improve the transmittance of light by the said device and thereby enhancing its viability. This is what has led to the investigation and testing carried out in the following section.

This section tested the viability of incorporating the use of light rod discussed in section 3.5 with the light pipe discussed in section 3.4; and fusing the two technologies on the same platform for maximum gain of illumination. Furthermore, the following tests were therefore carried out to investigate a way to how best we can improve on the existing light guiding systems as well, given the abundance of daylight.

Figures 3-43 and 3-44 show schematic sketches of the assembled rig.

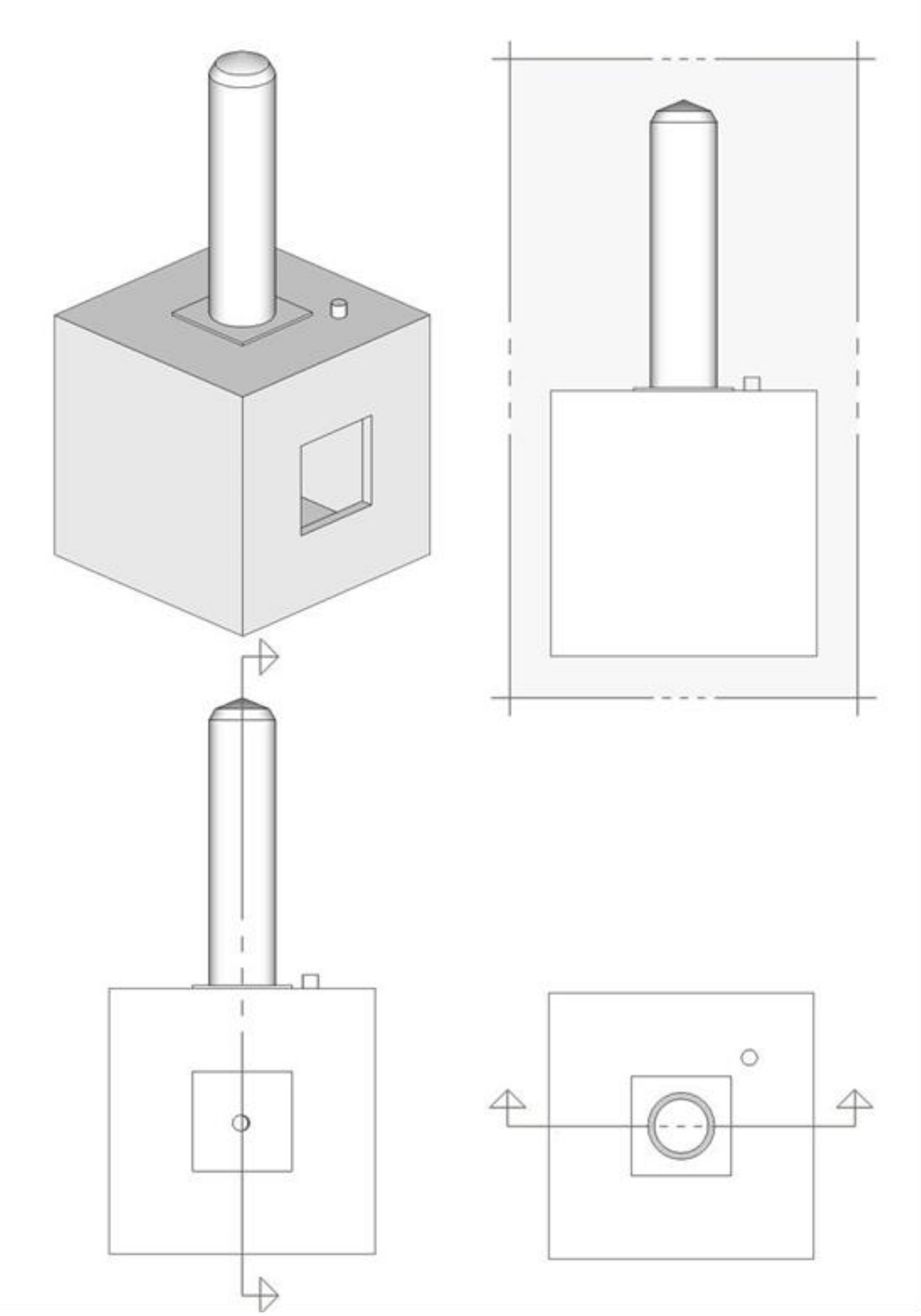


**Figure 3-43 Schematic Sketch of the Dual Technology outdoor rig (a) axonometric view (b) typical elevation (c) South Elevation showing hatch opening and section Line (d) Plan**

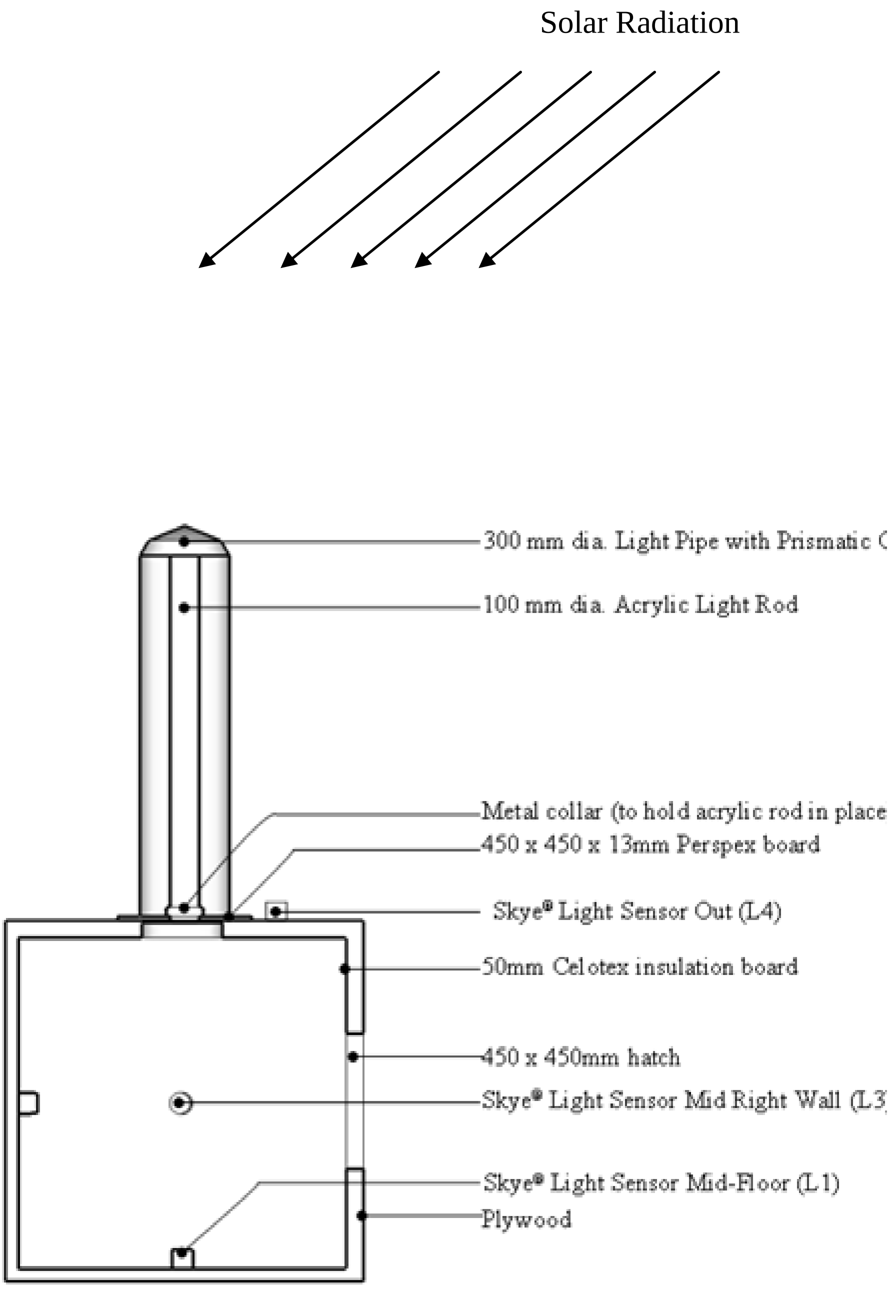



**Figure 3-44: Schematic Sketch of the Dual Technology outdoor rig Component Labellings**

The equipment used are:

Insulated Wooden Box (1200 x 1200 x1200)

DT500 Datalogger

Skye Light® Sensors

Kipp And Zenon® Pyranometer

"K" Type Thermocouples

300mm diameter Light Pipe of 1.2m length

100mm diameter Light Rod of 1.2m length

### 3.6.1. Test Set –up and Procedure

Similar procedures was carried out as in the previous tests however, intricate modifications was made to the rig, so as to be able to assemble both the light pipe and light rod symmetrically.

A hole, 300mm in diameter was cut out on the middle top surface of the box to accommodate the light pipe. A piece of clear white Perspex® 1.3cm (13mm: half an inch) thick as seen in Figure 3-45 was placed over the hole so as to act as a base to stop the light rod from slipping down as well as to act as a diffuser ( see figures 3-45, 3-46 and 3-47 as well as schematic sketches of figures 3-43 & 3-44).

**Figure 3-45: Preparation of the holes and Perspex to hold 100mm diameter light rod and 300mm diameter light pipe in place**

**Figure 3-46: 100mm diameter light rod in place**

Both the light pipe and the light rod are 1.2m long with nominal diameters of 300mm and 100mm respectively. Figures (3-47 & 3-48) show the detail of fixture of the light rod and finally the fixture of the light pipe prior to commencement of testing.

**Figure 3-47: Detail of Gasket and Perspex holding 100mm diameter light rod in place**

**Figure 3-48: Placement of Light pipe over the light rod in place**

After setting up of the rig, testing was carried for approximately 3 hrs on a typical summer day with overcast sky. Given the conditions of the weather into consideration, the results were recorded and analysed.

Average Total Light measured inside the box (from 5 light sensors):

350.6 lux + 313.3 lux + 319.5 lux + 384.8 lux + 384.4 lux = 1752.6 lux

Average Light measured inside the box: 1752.6 / 5 = 350.52 lux

Average Light measured at entry: 455.5 lux

Thus, average percentage of light delivered inside the box: 350.52/455.5 x 100 = 76.95 ≈ 77%

The efficiency of the system can be said to be 77%

### 3.6.2. The Principle Explained

As light enters through the prismatic dome on top of the light pipe, it strikes it an angle and penetrates inside, it then simultaneously strikes the interior reflective surface of the light pipe as well as the light rod. The light thus therefore has a double reflectability and thus enhances the quantity of light produced and thus improving the quantity that is beamed down. Schematic sketches in figures 3-43 and 3-44 show the positions of the light pipe, light rod, light sensors and hatch.

During the testing of this device, the efficacies of the sky conditions were considered. This calculation is based on a sunny bright day in Nottingham, UK. The efficacy was calculated thus:

$$\text{Luminous efficacy: } F = \frac{\text{illuminance}}{\text{Irradiance}} = \frac{\text{lux}}{W/m^2} = \frac{lm/m^2}{W/m^2} = \frac{lm}{W}$$

Assumed average sky illuminance on a bright sunny day = 80 000lux

On same day, average irradiance = 900W/m$^2$

$$\text{Thus } \frac{80\,000}{900} = 88.8 \text{ lm/W}$$

### 3.6.3. Conclusions

Results show that given the average illumunance provided by the 5 light sensors inside the test box, as against the light measured by the light sensor at the entry, it can be seen that there is a 77% delivery of light into the box, which shows that less than a quarter of the light is lost during delivery.

Results also show that there was 20.2% and 72.24% increase in the illumunance level in the test box when the dual technology was employed, as against the case of the single technology of 300mm diameter light pipe alone and 100mm diameter light rod alone respectively.

### 3.6.4. Comparative Analysis for the Various Sensor Positions using the Different Light Systems:

Results and analysis below show the differences in the use of the various light systems given the same conditions viz: dual technology, 300mm diameter light pipe, 100mm diameter light rod and 100mm diametre light pipe, all of 1.2m lengths.

#### 3.6.4.1. Analysis of Sensor Position L1

From the results shown on Figure 3-49, it can be seen that there was an improvement in the quantity of light that struck the sensor (L1) on mid floor of the box when dual technology was employed. Average light striking the light sensor when the dual technology was employed is 357.8 lux as against that of just the 300mm dia light pipe on its own, with 320.3lux., showing a significant improvement of over 10.5%. With a smaller diameter light pipe of 100mm diameter there was an even greater improvement of 70% thus showing that with the increase of diameter of the light pipe, quantity of light was improved under the same conditions. Still under the same conditions a singular light rod of 100mm as the one used in the dual technology was used and there was an improvement of 71.7%.

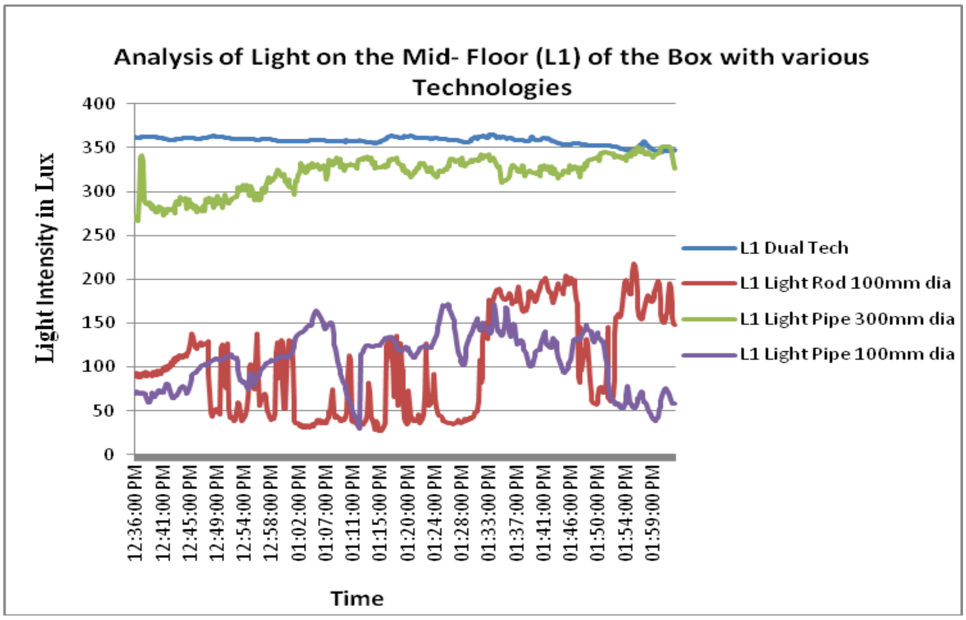


**Figure 3-49: Analysis for L1 Light Sensor: Mid-Floor**

We can thus conclude that given the same conditions, as seen in table 3-4, the best system was that of the dual tech closely followed by the 300mm dia light pipe system and then the light rod with 100mm diameter and a poor system with the small diameter of 100mm light pipe

**Table 3-4: Averages for Sensor in Position L1**

| | |
|---|---|
| Dual Technology | 357.80 lux |
| Light Rod 100mm diameter | 101.20 lux |
| Light Pipe 300mm diameter | 320.28 lux |
| Light Pipe 100mm diameter | 107.95 lux |

#### 3.6.4.2. Analysis of Sensor Position L2

Form the results shown on Figure 3-50, it can be seen that there was an improvement in the quantity of light that struck the sensor (L2) on the left hand corner of the box when dual technology was employed. Average light striking the light sensor when the dual technology was employed is 314.9 lux as against that of just the 300mm dia light pipe on its own, with 275.7lux., showing a significant improvement of over 12%. With a smaller diameter light pipe of 100mm diameter there was an even greater improvement of 75% thus showing that with the increase of diameter of the light pipe, quantity of light was improved under the same conditions. Still under the same conditions a singular light rod of 100mm as the one used in the dual technology was used and there was an improvement of 57.6%.

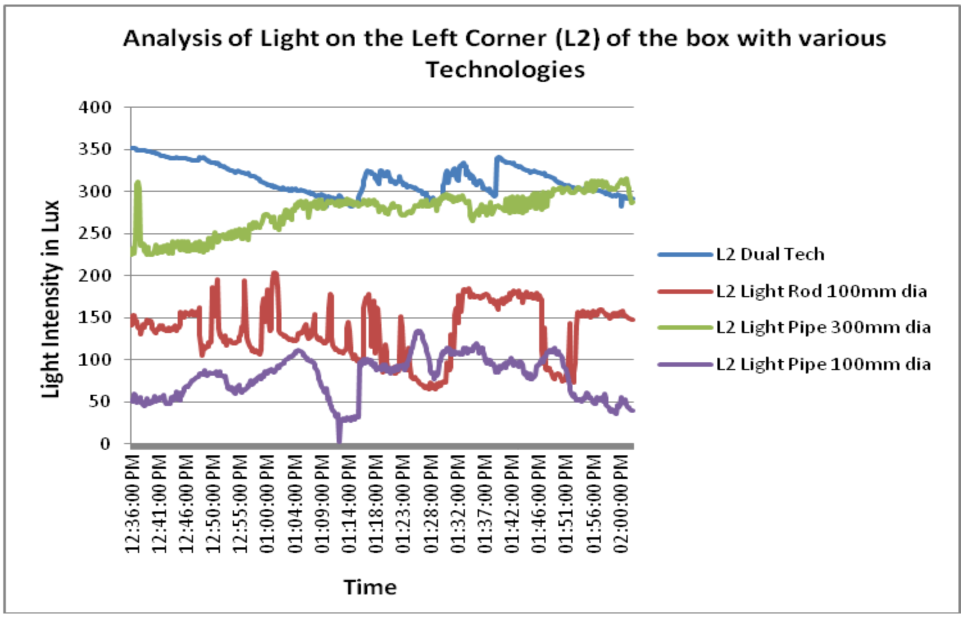



**Figure 3-50: Analysis for L2 Light Sensor: Left Corner**

From table 3-5 below, we can thus conclude that given the same conditions, the best system was that of the dual tech closely followed by the 300mm dia light pipe system and then the light rod with 100mm diameter and a poor system with the small diameter of 100mm light pipe

**Table 3-5: Averages for Sensor in Position L2**

| | |
|---|---|
| Dual Technology | 314.90 lux |
| Light Rod 100mm diameter | 133.64 lux |
| Light Pipe 300mm diameter | 275.68 lux |
| Light Pipe 100mm diameter | 79.24 lux |

### 3.6.4.3. Analysis of Sensor Position L3

Form the results shown on Figure 3-51, it can be seen that there was an improvement in the quantity of light that struck the sensor (L3) on mid floor of the box when dual technology was employed. Average light striking the light sensor when the dual technology was employed is 335.27lux as against that of 184.4lux when it was just the 300mm dia light pipe on its own, showing improvement of over 45%, which means almost twice as much light was received with the combined dual technology. With a smaller diameter light pipe of 100mm diameter there was an even greater improvement of 78% thus showing that with the increase of diameter of the light pipe, quantity of light was improved under the same conditions. Still under the same conditions a singular light rod of 100mm as the one used in the dual technology was used and there was an improvement of approximately 60%.

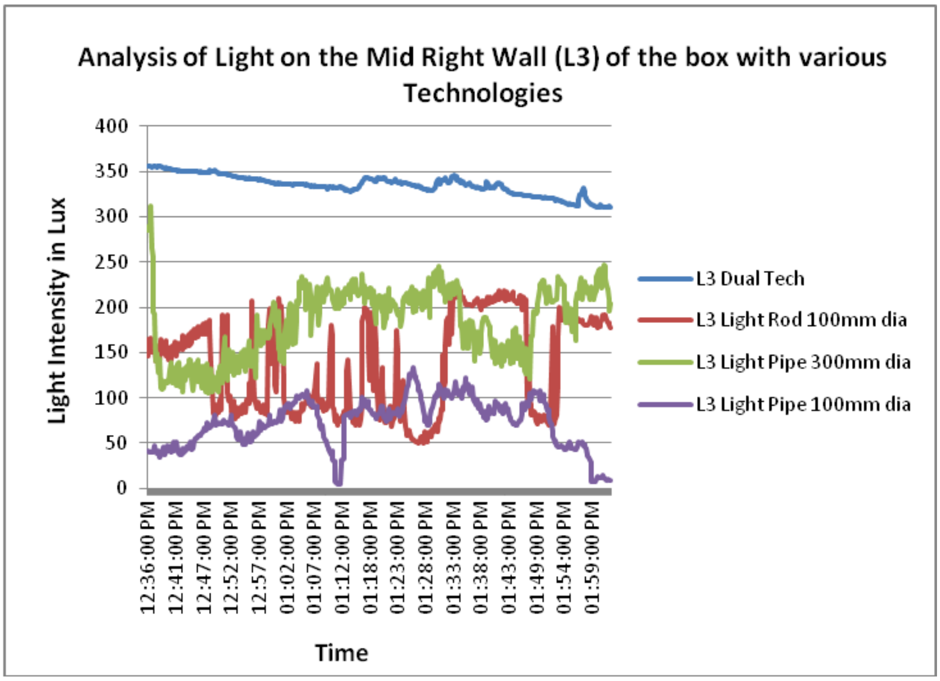



**Figure 3-51: Analysis for L3 Light Sensor: Mid Right Wall**

We can thus conclude that given the same conditions as shown in Table 3-6 below, just as the previous two conditions (L1 and L2) the best system was that of the dual tech closely followed by the 300mm dia light pipe system and then the light rod with 100mm diameter and a poor system with the small diameter of 100mm light pipe

**Table 3-6: Averages for Sensor in Position L3**

| | |
|---|---|
| Dual Technology | 335.27 lux |
| Light Rod 100mm diameter | 136.28 lux |
| Light Pipe 300mm diameter | 184.4 lux |
| Light Pipe 100mm diameter | 72.1 lux |

### 3.6.4.4. Analysis for L5 Light Sensor: Mid North Wall

With the light sensor in position 5, there was 17.2% increase of light when values for dual technology were compared with that of using the 300mm diameter light pipe on its own as shown in Figure 3-52. Similarly, when results of dual technology were against compared with that of the light rod on its own, there was again a remarkable improvement of 88.7%, (approximately 90%).

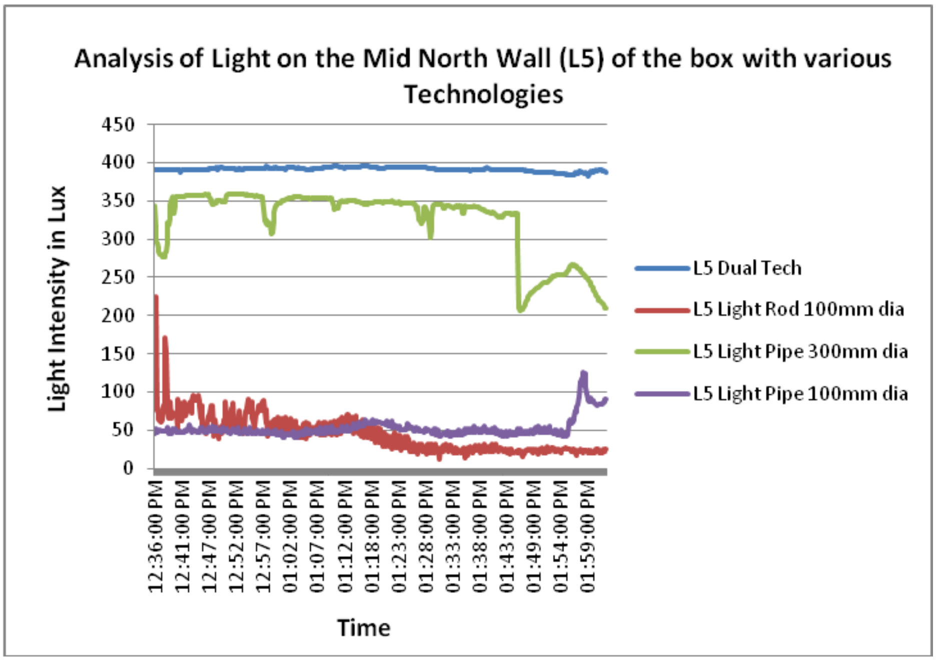



**Figure 3-52: Analysis for L5 Light Sensor: Mid North Wall**

Again, Table 3-7 below shows that the dual technology has a far better illumination capacicity than the others

**Table 3-7: Averages for Sensor in Position L5**

| | |
|---|---|
| Dual Technology | 391.41 lux |
| Light Rod 100mm diameter | 44.33 lux |
| Light Pipe 300mm diameter | 324.02 lux |
| Light Pipe 100mm diameter | 52.59 lux |

### 3.6.4.5. Analysis for L6 Light Sensor: Inner Left Corner

Furthermore under the same conditions, calculation for the L6 sensor as shown in Figure 3-53, the improvement of light with the dual technology over the 300mm diameter light pipe on its own was 15.4% and for that of the 100mm diameter light rod on its own was 83.2%

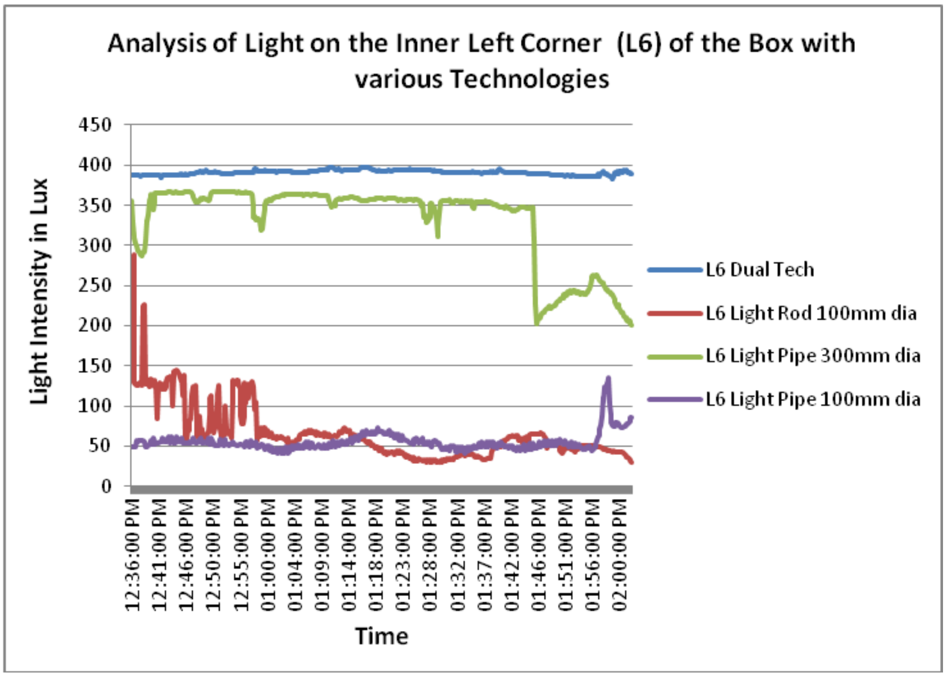



**Figure 3-53: Analysis for L6 Light Sensor: Inner Left Corner**

Analysis for L5 and L6 are not any different, given that the conditions are the same

**Table 3-8: Averages for Sensor in Position L6**

| | |
|---|---|
| Dual Technology | 390.98 lux |
| Light Rod 100mm diameter | 65.68 lux |
| Light Pipe 300mm diameter | 330.77 lux |
| Light Pipe 100mm diameter | 55.42 lux |

On analysing all the technologies, as seen in Table 3-9, in all the scenarios, the dual technology presents itself as more superior in terms of illumination followed by a 20% drop with the regular 300mm diameter light pipe.

**Table 3-9:` Tabular Analysis for all the Technologies Applied**

| | Dual Technology (lux) | Light Rod 100mm diameter (lux) | Light Pipe 300mm diameter (lux) | Light Pipe 100mm diameter (lux) |
|---|---|---|---|---|
| L1 Mid Floor | 357.8 | 101.2 | 320.28 | 107.95 |
| L2 Left Corner | 314.9 | 133.64 | 275.68 | 79.24 |
| L3 Mid Right Wall | 335.27 | 136.28 | 184.4 | 72.1 |
| L5 Mid North Wall | 391.41 | 44.33 | 324.02 | 52.59 |
| L6 Inner Left Corner | 390.98 | 65.68 | 330.77 | 55.42 |

### 3.6.5. Conclusion

From Table 3-10 below, we can conclude that the efficiency of the Dual technology from test results give an average improvement of 20.2% as against using it with the light pipe on its own, and an improvement of 72.24% when using the light rod on its own. Given that, we can conclude that it is worth combining the two technologies as against the use of a singular system. Table 3-10 below further show the percentage of improvement of quantiy of light when the dual technology is employed as against the single technology of either the light pipe and light rod each on their own.

**Table 3-10: Percentages of Improvement of Dual Technology over Singular Device Tecnology**

| Sensor Positions in Test Box | Dual Technology calculated improvement over 300mm diameter Light Pipe | Dual Tecnology calculated improvement over 100mm diameter Light Rod |
|---|---|---|
| L1 (Mid Floor) | 10.5% | 71.7% |
| L2 (Left Corner) | 12% | 57.6% |
| L3 (Mid Right Wall) | 45% | 60% |
| L5 (Mid North Wall) | 17.2% | 88.7% |
| L6 (Inner Left Corner) | 15.4% | 83.2% |
| AVERAGE | 20.2% | 72.24% |

It is important to mention here, that the transmittance of both the light pipe and the light rod were taken into consideration, especially during the time of carrying out the software simulation, as this is one of the important parameters that determine the viability (or otherwise) for the employment of these devices. The incident rays were established at 50° which is similar to that of the British Summer (in July) when the tests were simulated.

# 4. CHAPTER 4: DETERMINATION OF DEVICE TRANSMITTANCE THROUGH A COMPUTER MODEL

Using a mathematical model similar to that of Callow (2003), identification was made, of a suitable equation for calculating the transmittance of the light by the light pipe. This equation is given as

$$T = R_d^{L*\tan(\theta)}$$

Where:

T is transmittance

R is the reflectance of the inner surface of the pipe or exterior surface of the PMMA acrylic light rod

L is the length of pipe/rod

θ is the angle of incidence

d is the of the entrance aperture (nominal diameter of pipe/rod)

Consequently, for a light pipe with 98% reflectance, length of 1200mm, assumed angle of incidence of 50° and a nominal diameter of 300mm, the transmittance is thus:

$$T = \ 0.98_{300}^{1200*\tan 50}$$

$T = 0.98^{4.764}$

$T = 0.9082$

Given the same conditions, the light pipe has a nominal diameter of 100mm, the transmittance is thus:

$$T = 0.98_{100}^{1200*\tan 50}$$

$$T = 0.98^{14.292}$$

$$T = 0.3037$$

The computer model was further used to simulate with the same equation with different angles of incidences as can be found at different locations of the world globe, as can be seen in Table 4-1

**Table 4-1 Angle of Incidences and Reflectance Levels**

| Angles of Incidence (°) | 30 | 40 | 50 | 60 | 70 | 80 |
|---|---|---|---|---|---|---|
| 98% Reflectance for Light Pipe | 0.9544 | 0.9344 | 0.9082 | 0.8694 | 0.8009 | 0.6324 |
| 92% Reflectance for Light Rod | 0.5614 | 0.4319 | 0.3037 | 0.1768 | 0.0640 | 0.0034 |

The transmittance of the devices as obtained thought the mathetical model similar to that of Callow (2003) shows that with the increase in the incidence angle, the transmittance levels decrease, and the graph in Figure 4-1 shows the superiority of the light pipe over that of the light rod in terms of light transmittance.

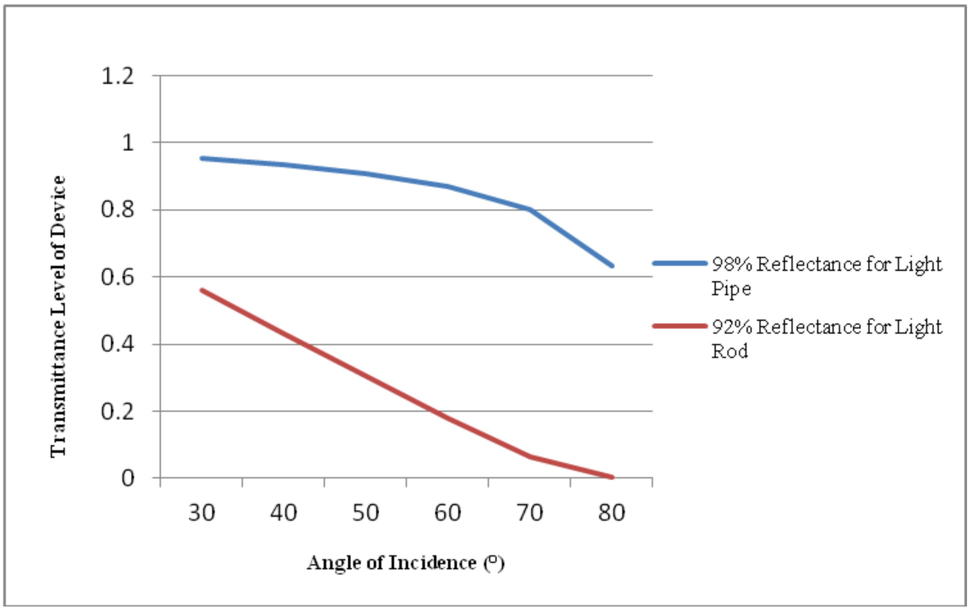



**Figure 4-1 Comparitive Reflectance Levels for Light Pipe and Light Rod at Various Angles of Incidences**

## 4.1. Software Application

Prior to the testing of the outdoor test rig, the same parameters were input into the Ecotect® and Radiance® software so as to compare and validate results. The rig was first modelled in 3ds Max Design soft ware as seen in Figure 4-2 so as to show it in wire frame mode so that internal structures can be viewed.

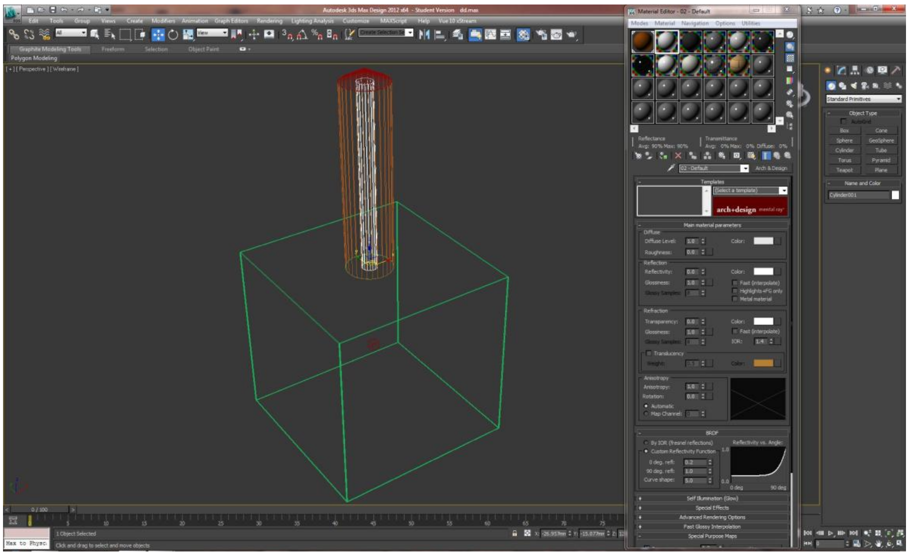


**Figure 4-2: Model in wire frame mode for internal structure to be viewed.**

The file was then exported to Ecotect® as seen in Figure 4-3

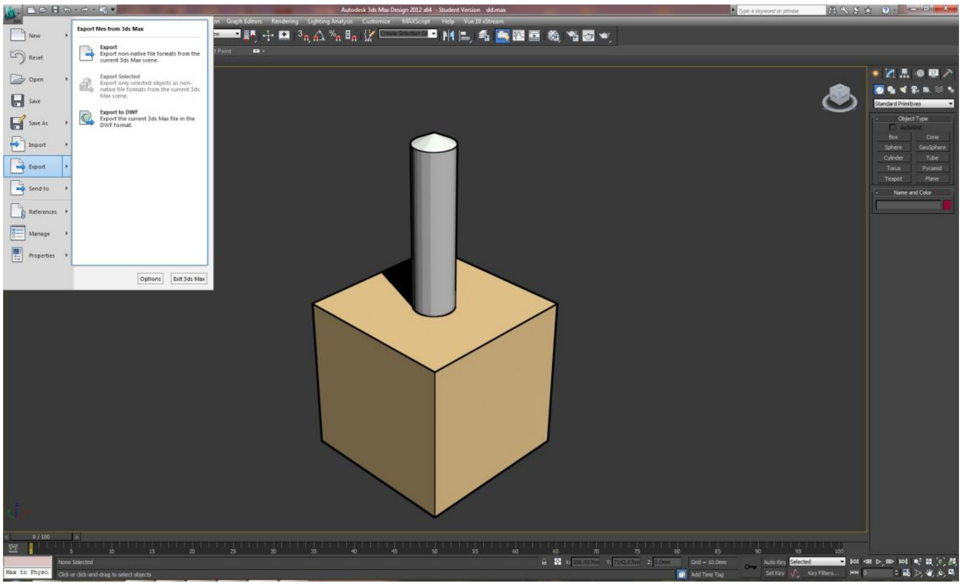


**Figure 4-3: Beginning process of exporting the model out as a 3DS file format.**

Then application of material which is crucial to proper simulation, as can be seen in Figure 4-4.

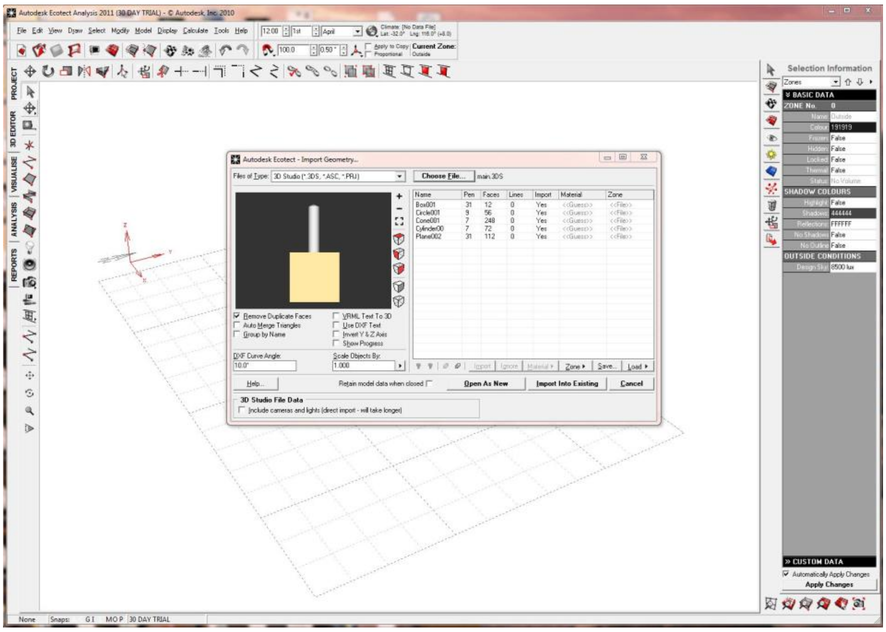


**Figure 4-4: Application of Material**

Finally, after all materials are applied a camera is placed inside the box to capture the lighting analysis within. An interactive camera was chosen as it gave the best options of manipulating the viewing angles as seen in Figure 4-5.

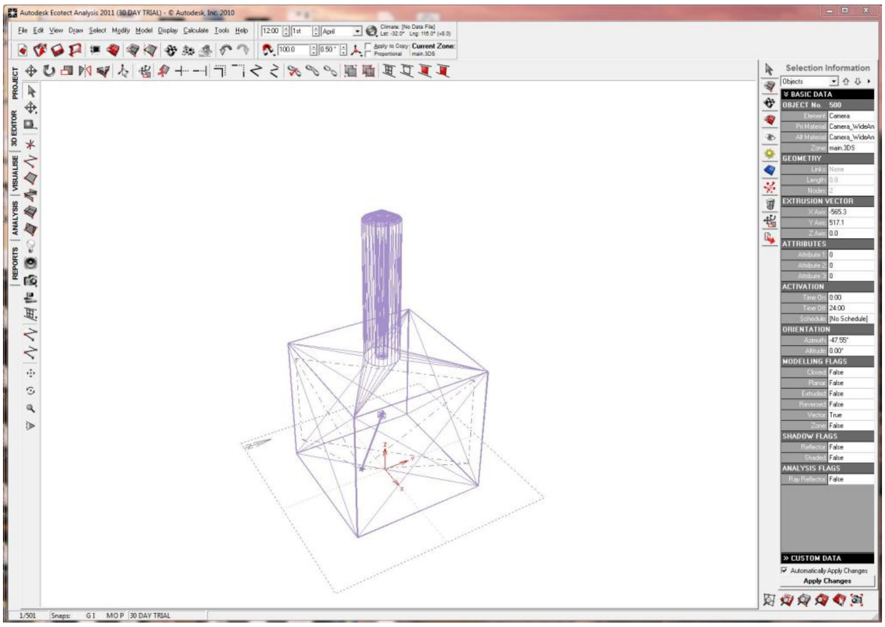


**Figure 4-5: Camera view Interior**

After placement of camera, you can select points to view the various illuminance levels as in Figure 4-6 and 4-7.

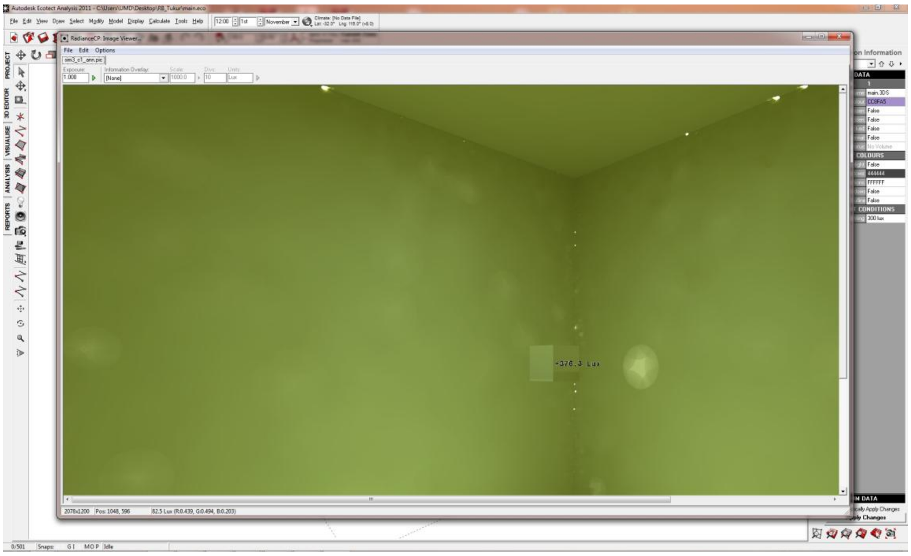


**Figure 4-6: Showing the illuminance value at the centre of the box (376.3 lux)**

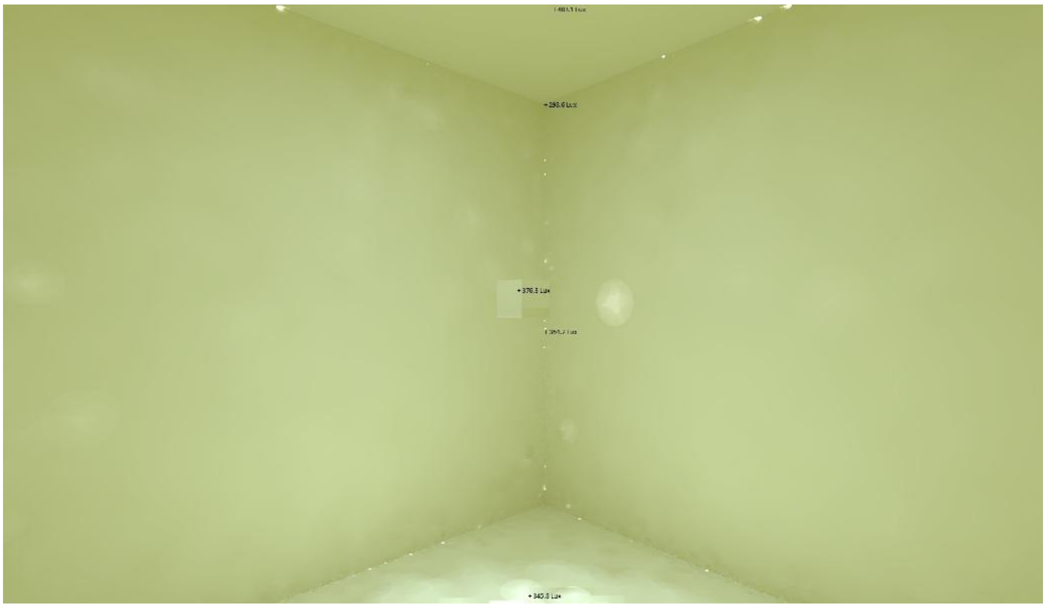



**Figure 4-7: Lux Reading at Other Sensor Positions**

Further modelling was carried through the employment of the Radiance® software under a given number of conditions as seen in Table 4-2. The sensors were kept at the same position for all the simulations carried out under conditions 1, 2, 3 and 4. The sensor positions were as follows:

**Table 4-2 Sensor Positions in Test Box**

| | Position in Test Box |
|---|---|
| Sensor 1 | Bottom mid-floor of box |
| Sensor 2 | halfway up the middle right-side of the box |
| Sensor 3 | suspended in the mid-centre of the box |
| Sensor 4 | left corner of the box |
| Sensor 5 | top entry of the box |

Table 4-3 gives the conditions under which the simulations were carried out. These conditions range from altering the diameters of the light pipe and the light rod as well as the increase of the heights of both the light rod and the light pipes, as can be seen in Table 4-4.

**Table 4-3 Conditions of Simulation**

| | **Light Pipe Diameter** | **Light Rod Diameter** | **Height** |
|---|---|---|---|
| **Condition 1a** | 450mm | 100mm | 1200mm |
| **Condition 1b** | 450mm | 150mm | 1200mm |
| **Condition 1c** | 450mm | 200mm | 1200mm |
| | | | |
| **Condition 2a** | 600mm | 100mm | 1200mm |
| **Condition 2b** | 600mm | 150mm | 1200mm |
| **Condition 2c** | 600mm | 200mm | 1200mm |
| | | | |
| **Condition 3a** | 750mm | 100mm | 1200mm |
| **Condition 3b** | 750mm | 150mm | 1200mm |
| **Condition 3c** | 750mm | 200mm | 1200mm |
| | | | |
| **Condition 4a** | 300mm | 100mm | 1800mm |
| **Condition 4b** | 300mm | 100mm | 2400mm |
| **Condition 4c** | 300mm | 100mm | 3000mm |

**Table 4-4 Illuminance Levels at Different Lux Sensor Positions for the Different conditions of Simulation**

| Conditions of Simulation | Sensor Position 1 (lux) | Sensor Position 2 (lux) | Sensor Position 3 (lux) | Sensor Position 4 (lux) | Sensor Position 5 (lux) |
|---|---|---|---|---|---|
| **Condition 1a** | 357.1 | 378.9 | 383.2 | 320.9 | 450.3 |
| **Condition 1b** | 383.2 | 411.3 | 423.8 | 373.2 | 469.3 |
| **Condition 1c** | 398.9 | 436.2 | 452.7 | 410.3 | 498.4 |
| **Condition 2a** | 383.0 | 412.2 | 421.3 | 407.4 | 506.2 |
| **Condition 2b** | 389.2 | 417.8 | 432.0 | 411.7 | 514.3 |
| **Condition 2c** | 398.4 | 427.3 | 444.1 | 418.9 | 534.6 |
| **Condition 3a** | 398.2 | 416.3 | 428.4 | 411.3 | 510.9 |
| **Condition 3b** | 415.3 | 427.7 | 439.3 | 420.4 | 547.8 |
| **Condition 3c** | 438.0 | 456.3 | 473.0 | 459.3 | 589.1 |
| **Condition 4a** | 339.6 | 358.9 | 371.2 | 291.9 | 397.6 |
| **Condition 4b** | 317.1 | 331.0 | 349.9 | 262.0 | 371.2 |
| **Condition 4c** | 291.3 | 303.0 | 319.9 | 238.9 | 346.8 |

With the above simulation results we can see that with the increase of the diameter of the light pipe, there was also a steady increase in the illumination, so the diameter does not so much affect the quality of its illumination properties. However, when the length of the pipe was increased as seen in conditions 4a, 4b and 4c, the level of illumination began to decrease steadily by 7%

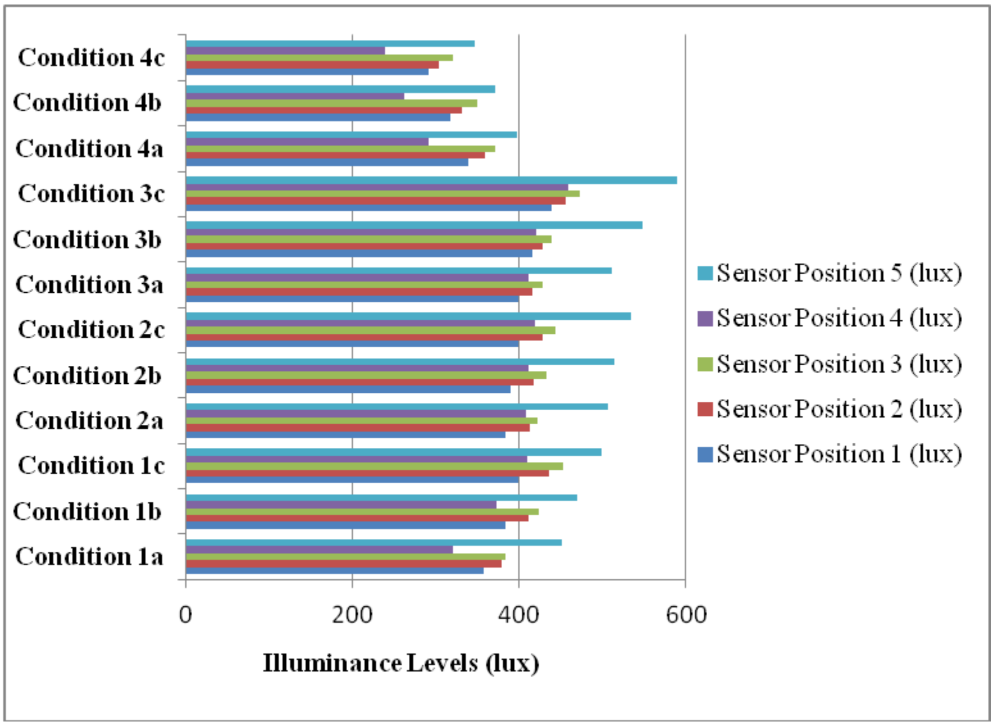



**Figure 4-8 Illumination Quality for all Conditions at all Sensor Positions**

Figure 4-8, illustrates that on average, the best condition with the best illuminance level was in condition 3c, where the heights of both the light pipe and the light rods were 1200mm, the light pipe had a nominal diameter of 750mm, and the light rod had diamter of 200mm.

The sensor that recorded the highest illuminance level was sensor always sensor position 5 which recorded the light at entry. However, within the box away from the entry, the sensor recording the best illumination was the sensor on position 3 which was suspended at the middle of the box.

Further more, analysis can be drawn from the illumination levels as can be seen from Figures 4-9 – 4-10. Figure 4-9 shows that with increase in diameter of the light pipe, there was a gradual and steady increase also, in the illumination levels at an average of 7%

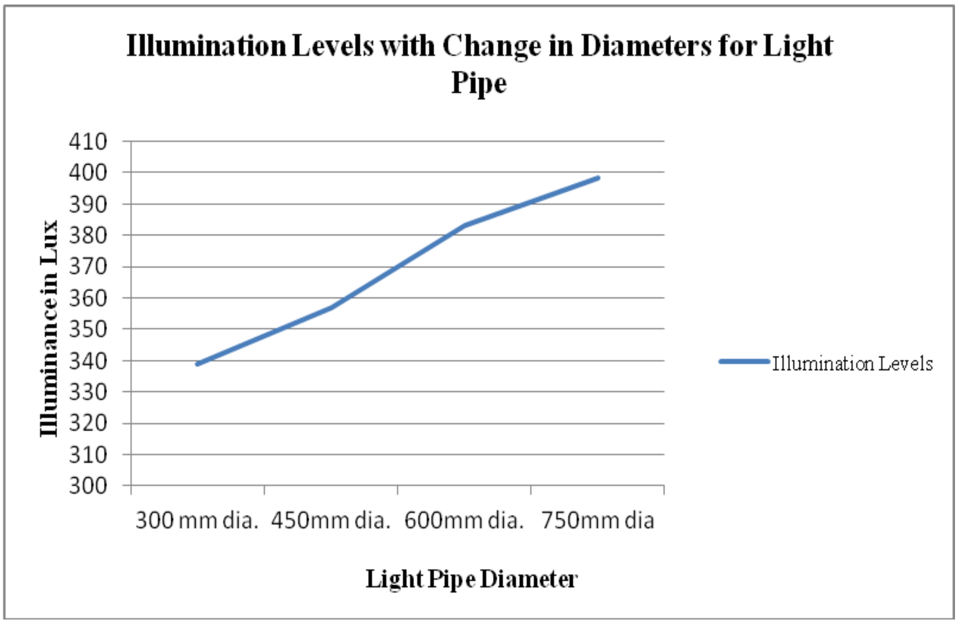



**Figure 4-9 Illumination Level with change in Diameter**

Figure 4-10 illustrates the illumination level when the the height of the light pipe and the light rod were increased - at 1200mm, 1800mm, 2400mm and 3000mm. From the figure, it can be seen that with the increase in illumination, the was a steady decline in the level of illuminace. This decline was at an average of 6.5%, which bears similar index to the increase in illumination when the diameter of the light pipe was increased. Figure 4-11 shows a typical lux reading inside the box during the time of the simulation.

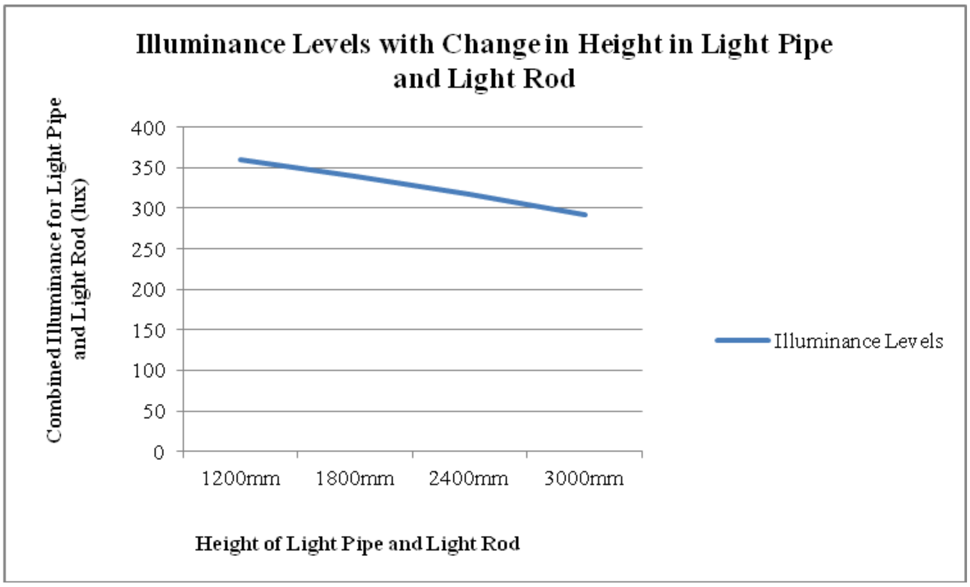



**Figure 4-10 Combined Illumination Level with change in Height for both Light ipe and Light Rod**

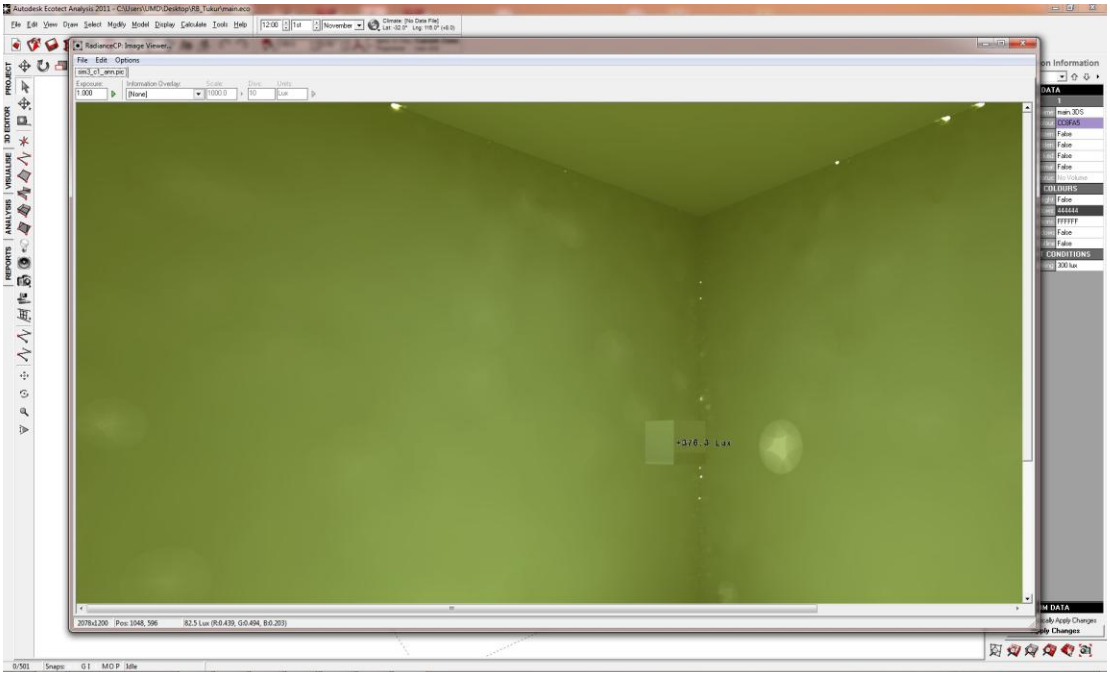


**Figure 4-11 Showing the illuminance value at the centre (376.3 Lux)**

## 4.2. Summary

The UK government's Code for Sustainable Homes (CfSH) developed to set standards for key elements of design and construction of buildings will in time become a national guide so as to standardise homes for architects, engineers and home owners. To this end, this guide was used in the design of the Tarmac and David Wilson homes which were used for field studies.

The lighting evaluated in these two building showed that there was a great maximisation of natural lighting in both building. In the tarmac house, a single light pipe as the only daylight device, was used in the hallway on the upper floor which produced averages of above 325 lux during the peak daylight hours and up to 50 lux during the night hours. In the David Wilson house, where there was a deep corridor on the upper floor, 3 daylight devices were used. These devices were windows on the south facade, light blocks on the approach facade and a light pipe at the roof level. These 3 in combination produced average illuminance of above 350 lux.

To evaluate the efficiency of the light pipes in both houses, tests were done with the light pipes covered. In the Tarmac house during this covered light pipe period, the illumunance during the day an average of 25 lux at the peak period, but it was generally at 0 lux with it falling to negative figures during the night. In the case of the David Wilson home, when the light pipe was covered there was an average illumunance of 30 lux except what could be attributed to experimental error when the cover fell out thereby producing rogue data.

This chapter further covers the novel aspect of harnessing daylight through the light pipe and light rods. Tests were done with varying lengths of light pipe and a single type of light rod. These tests showed the efficiencies of these devices. It was therefore as a result of this that testing was carried out to combine these two technologies, thus the novel dual technology device proposed which gave a 20% increase in illumunance as against the light pipe alone and a 72% increase with the light rod alone.

These results were validated when compared with the simulation done through the Ecotect and Radiance software. With the sensors at the same position by simulation there was an illuminance of 376.3lux while the actual average reading got during testing was 357.8lux, this is an error of 5%. This difference can be attributed to the changing irradiance of the sun as well as shading from surrounding buildings.

# 5. CHAPTER 5: NOVEL USE OF EVACUATED TUBES AS A MEANS OF TRANSPORT FOR VISUAL AND THERMAL AID

## 5.1. Introduction

This chapter presents an experiment conducted to investigate the potential of using the solar energy for supply of thermal comfort into the residential buildings, as well as lighting the interior. The system makes use of solar energy as a main energy provider, where dark coated evacuated tubes were used to collect and deliver both heating and light. Each evacuated tube consists of two glass tubes. The outer tube is made of extremely strong transparent borosilicate glass that is able to resist impact. The inner tube is also made of borosilicate glass. The air is evacuated from the space between the two glass tubes to form a vacuum, which eliminates conductive and convective heat loss. Unlike other types of solar collectors, evacuated tube solar collectors still provide excellent results on cloudy days. This is because the tubes are able to absorb the energy from infrared rays, which can pass through clouds (China Quality Crafts, 2011)

## 5.2. The Use of Dark Evacuated Solar Tubes as a Means of Providing Heating in a Room

The first part of this section looks at the employment of dark coated solar evacuated tubes as a conveyor of heat through this simple device into a required space. The heating properties of these tubes were further enhanced through the inclusion of kitchen-type aluminium foil, which was rolled and places in the tube, so as to increase its heating properties.

### 5.2.1. System Description and Operation

The system is a laboratory unit based on an insulated square wooden Cell made of half inch plywood measuring 1200 x 1200 x 1200.(Figure 5-1). Holes are bored on one side of the Cell, and evacuated tubes were placed in the holes. The equipment used include:

DT500 Datalogger: For recording Data

Evacuated Solar Tubes: For solar collection

Skye® Lux Sensors: To measure illuminance levels

"K" Type thermocouples: To measure temperature

Flood Lights: For solar simulation

Zenon and Kipp® Pyranometer: To measure solar irradiance

Kitchen-type Aluminium Foil: To enhance the heating properties of the evacuated tubes

Figure 5-2 shows the Cell from inside, it is well insulated so as to reduce heat loss to the minimum, there is also a hatch at the side of the Cell which is used for inspection purposes so as to make adjustments and modifications to sensors.

**Figure 5-1: Cell (room) showing evacuated tubes**

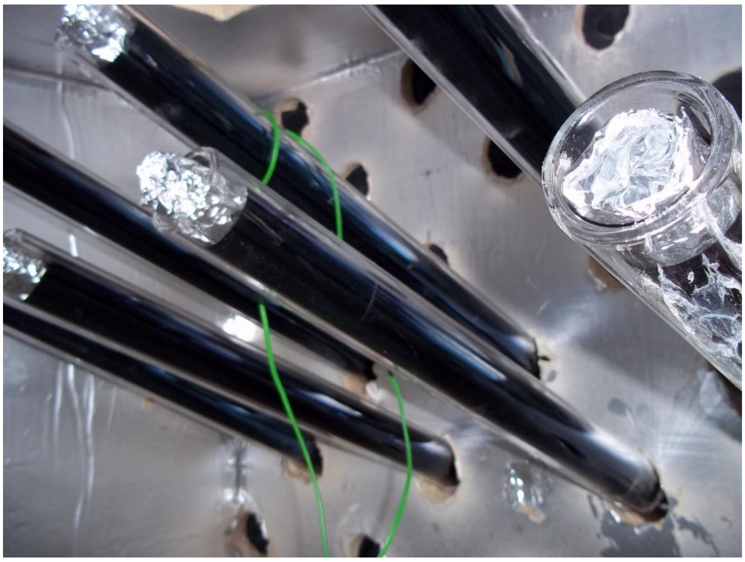


**Figure 5-2: Interior of Cell showing insulation & open end of tubes with foil infill**

### 5.2.2. Experimental Rig Set-Up

Dark coloured evacuated tubes were placed at 90° and 45° to the vertical plane of the Cell with the hollow open end of the tube in the Cell. 2 light sensors was placed (one inside and the other outside the Cell). Two temperature sensors were also placed on one of the evacuated tubes on the outside, and the other thermocouple inside the Cell at approximately the centre of the Cell. Ambient temperature was also taken.

Artificial light representing sunlight was used. This was employed at approximately 1.2m from the external end of the evacuated tubes (Figure 5-3), and giving off an average irradiance of 580W/m$^2$

**Figure 5-3: System setup**

All four sensors were connected to the data logger, and the system was allowed to warm up for about 15 minutes, while temperature and light was monitored and sensors were recording steady readings. After that, the readings were thus being saved as the testing went along.

### 5.2.3. Results and Discussion

The tests showed that the dark colour of the tubes do not allow light to penetrate into the room. However, with regards to the heat transmission, the tubes have done very well as temperatures rose to as high as 60°C on the surface of the tube. As shown in

Figure 5-4, the ambient temperature was constant at 27ºC almost throughout the duration of the test.

Room temperature however, showed a steady increase from 22ºC to about 30ºC after approximately two thirds of testing time before peaking at 31ºC.

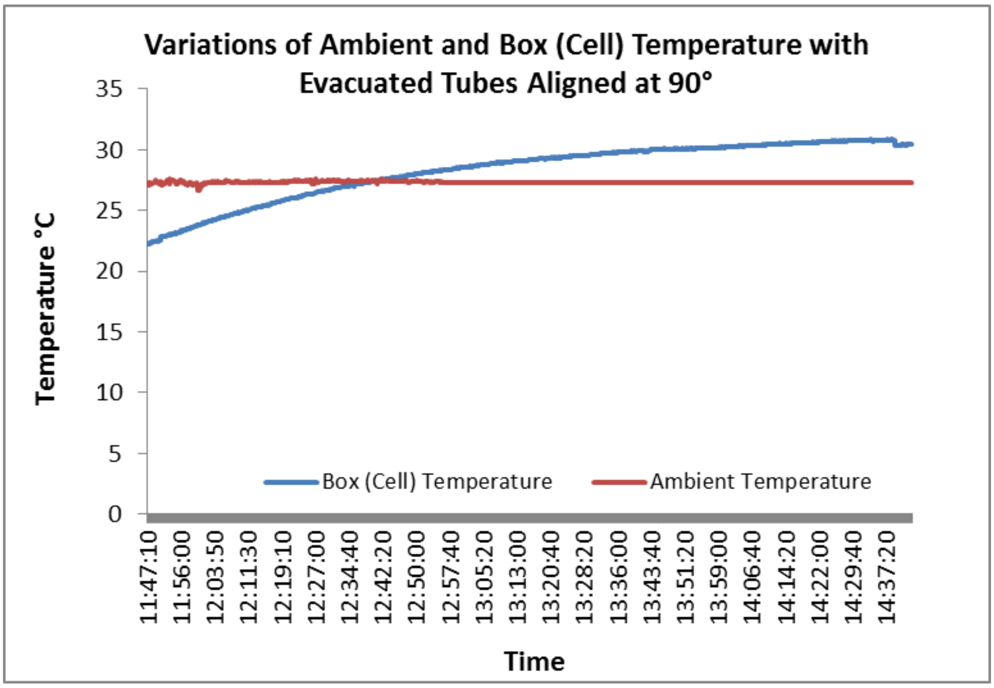



**Figure 5-4: Variations of Box (in cell) and ambient temperature when tubes were aligned at 90 degrees**

From Figure 5-5, it can be seen that light intensity outside the room (Cell) was at 34.5kLux at the start of the test, and it dropped down to 330 lux after one-fifth of the test period. The light then maintained a steady intensity of approximately 320 lux to the end of the test period.

Figure 5-5, further shows that there was little or no light going into the Cell therefore an indication for further testing.

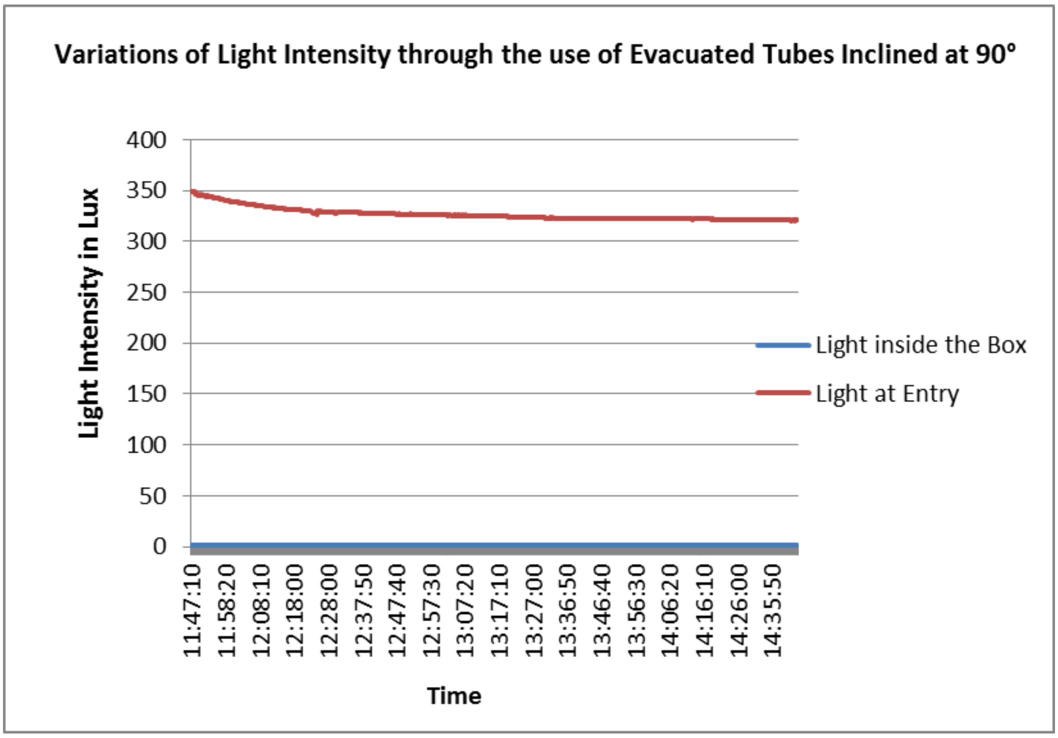



**Figure 5-5: Analysis of Light inside the Box as against light at Entry point, with tubes alignment at 90°**

Figure 5-6 shows the analysis of the data when the evacuated tubes were inclined at 45º. The ambient temperature was once again constant at 27ºC through out the duration of the test. The temperature of the room was increased in this test with a start at 32 ºC and thereon steadily rising to 34ºC and remaining constant there, till the end of the test. This shows a significant rise from the first test at 90º where the highest temperature obtained was 31ºC.

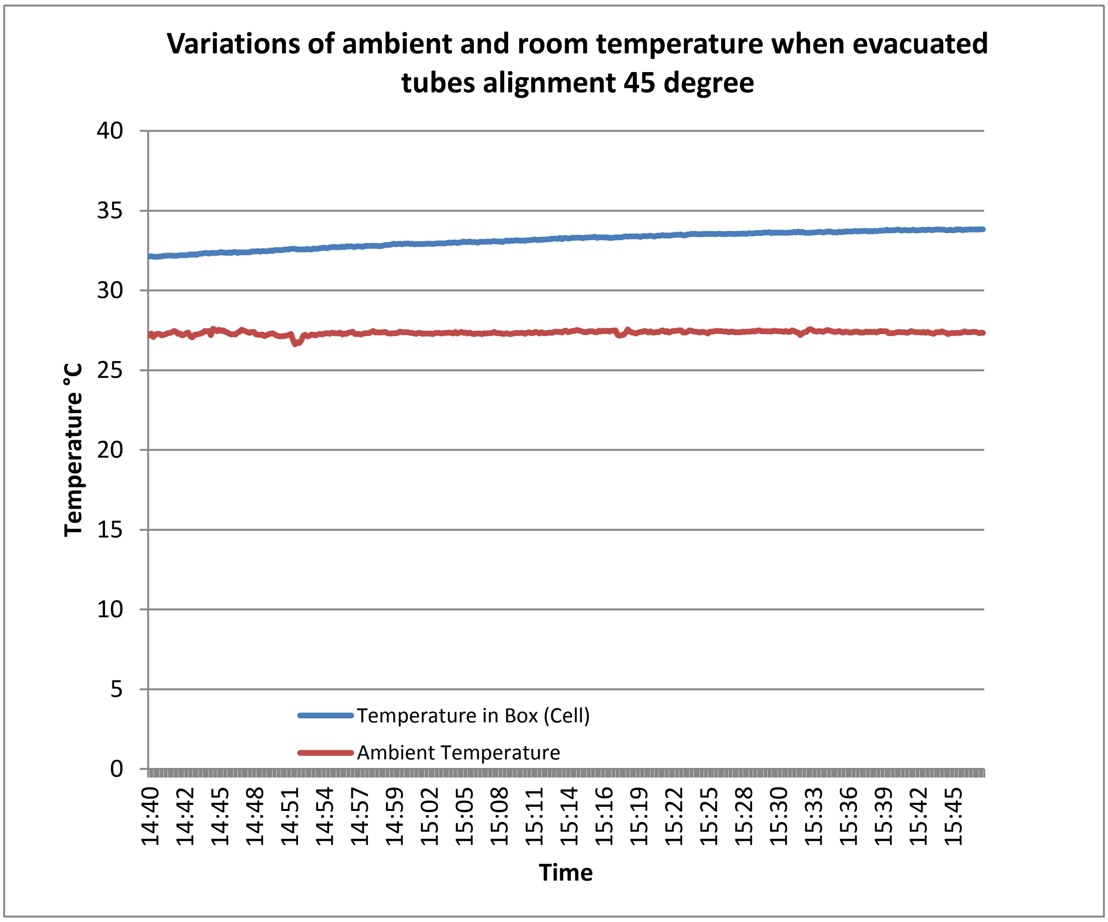



**Figure 5-6: Variation of room and ambient temperature when tubes alignment at 45 degree**

### 5.2.4. Analysis and Conclusion

From the test results above it can be seen that with the introduction of foil in to the evacuated tube, there was a considerable temperature up to 60°C on the surface of the evacuated tube as against a high of 48ºC without the aluminium foil, with ambient temperature being 27°C. Furthermore, with the tubes placed horizontally at 90°, the difference in temperature between the ambient temperature and the room temperature (ΔT) was an average of 3ºC. With the evacuated tubes inclined at angle 45°C the temperature in the room rose to 34ºC thus increasing ΔT to 7ºC.

In conclusion, it can be seen from the results that the coated evacuated tube is not good enough for the transmission of light into the room. However, the same evacuated tubes worked very well in terms of heat transmission, especially with the application of aluminium foil. Based on the results, recommendations for further testing was suggested, using clear glass evacuated tubes as well as incorporating it with light rods to further enhance its light transmittance as seen further in section 5.3.

## 5.3. Novel Clear Evacuated Tubes with Light Rods Tests for Thermal and Visual Comfort

### 5.3.1. Introduction

In these tests as reported, investigation was carried out on incorporating daylight with thermal comfort through the use of solar evacuated tubes with light rods insert. Evacuated glass tubes were used because presently, they have become the key component in solar thermal utilization as they have proven to be very useful in residential applications that require higher temperatures because of their efficiency of lower heat loss (Ma et al, 2010). These tests were done so as to harness both heat and light at the same time, as well as to adjudge its suitability for use in residential buildings. The equipment used are:

DT500 Datalogger

K-Type Thermocouples

Skye® Light Sensors

1m length Solar Evacuated Tubes

1m length, 50mm Diameter Acrylic Extruded Light Rods

Flood Lights and Solar Light Simulators

Zenon and Kipp® Pyranometer

### 5.3.2. The Test Rig: Set-up and Procedure

The system is a laboratory unit based on an insulated square wooden Cell made of half inch plywood measuring 2000 x 2000 x 2000. (Figure 1) insulated with 50mm celotex (thermal rating of 0.022 W/mK) board which is a PIR (polyisocyanurate) insulation that achieves an A+ rating when compared to the BRE Green Guide 2008, providing a lower environmental impact than typical other PIR insulation (Wickes Products, 2012).

Holes are bored on the top of the Cell, and 6 evacuated tubes were placed in the holes (see Figures 5-7 a & b as well as Figure 5-8) as in condition 2 of the test. In condition 1, the tests were carried out as baseline tests without the solar evacuated tubes, to determine the quantity of light and heat that was available in the cell, before the introduction of the evacuated tubes over the light rods. Six clear evacuated twin-glass vacuum tubes were inserted through the already prepared holes bored at the top of the box. The tubes were driven in about two thirds in and the acrylic light rods were inserted in the evacuated tubes and stood on larger acrylic rods for balance

The evacuated tubes were placed at 90° to the horizontal plane of the Cell with the hollow open end of the tube in the Cell. 2 light sensors was placed (one inside and the other outside the Cell). Three thermocouple (temperature) sensors were also placed; one on the evacuated tubes on the outside, and the other two thermocouples inside the

Cell, one at approximately the middle of the Cell and the other on the surface of the central evacuated tube. Ambient temperature was also taken.

Solar light simulators light were used to mimic. This was employed at approximately the height of 850mm from the external end of the evacuated tubes (figures 5-7 & 5-8).

The system was left to run until a steady state was achieved, which was about 20minutes after switching on of the lights. The irradiated heat from the solar simulators into the box was circulated by convective heating process


(a)


(b)

**Figure 5-7: (a) and (b) Showing Tubes and Solar Light simulators**

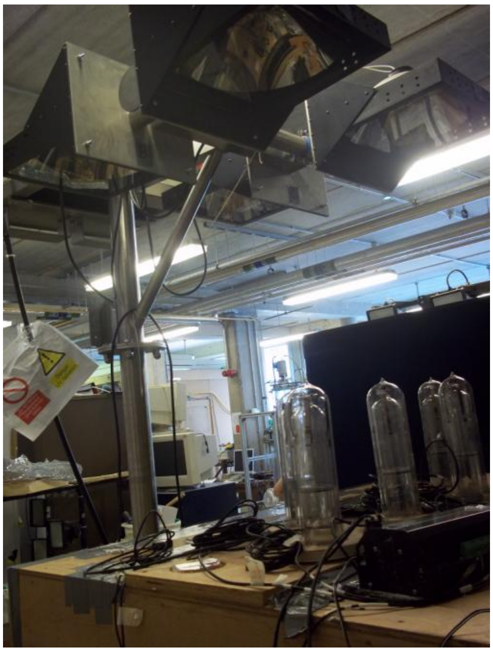


**Figure 5-8: Solar light simulator over Evacuated Tubes; Datalogger**

### 5.3.3. Results and Analysis

From the results as seen in Figure 4-9 below it can be seen that the ambient temperature in the laboratory was constant at 19°C. When the test was carried out with just the light rods, the temperature rose to an average of 24°C. When the solar evacuated tube which has high thermal conversion efficiency (Garba 2010) was placed over the light rods as seen in figure 5-8, the temperature rose, and was steady at approximately 27°C, which was an increase of 42%.

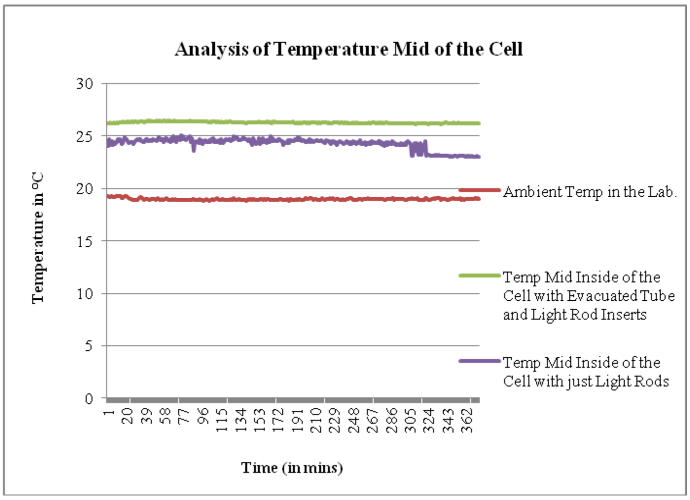



**Figure 5-9: Figure Analysis of Temperature Mid Floor of the Cell**

As the box is well insulated thermally, there was energy gain from the system, as the temperature was raised and higher than the laboratory ambient tempearature. Temperature was raised from 19°C (laboratory – ambient temperature) to 27°C which is the average temperature in the cell (box)

Given the formula for energy Q = m x C x ΔT.

Q = Quantity of Heat (Released or Absorbed) in Joules

m = Mass (grams/kilograms) of substance being heated, cooled or changing state.

C = Specific Heat Capacity (J/g/°C or kJ/kg °C).

ΔT = Difference in Temperature.(ΔT°C).

Q (Energy) = m (Mass) x C (Specific Heat Capacity) x ΔT (T2 – T1)

Volume of air = 1.2 x 1.2 x1.2 = 1.728 m3

Box temp = 26 C

Room temp = 19 C

Specific heat capacity of air = 1.006 kJ/kgC

Density of dry air =1.29 kg/m3

Therefore;

$$Q = mC\,(T2 - T1)$$

$$= (\text{density x volume of air}) \times C \times (T2 - T1)$$

$$= 1.29 \times 1.728 \times 1.006 \times 1000 \times (26-19)$$

$$= 15.7\ kJ$$

Thus we can conclude by saying that, as there was an energy gain of 15.7kJ, the cell can be said to be efficient.

With regards to illumination, at entry, there was an average of 372 lux. However during carriage to the interior of the cell, losses were recorded. The average illumination recorded in the box with just the light rods alone is 154lux as against that of 138 lux average, when the evacuated tubes were inserted. In comparison, there is only a loss of 16lux (with and without the evacuated tube), which calculated, is an 11.5% loss of light. (see figure 5-10)

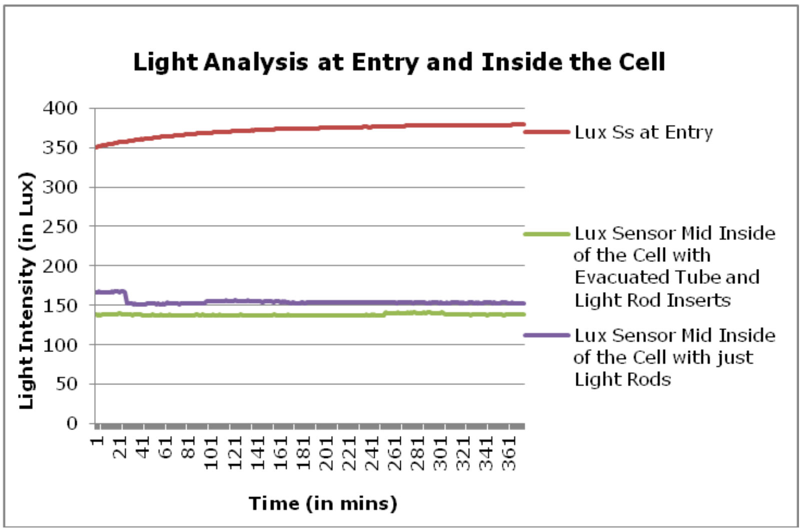



**Figure 5-10: Light Analysis at Entry and Inside the Cell**

### 5.3.4. Summary

In the first test of the use of the dark coated solar evacuated tubes, even though only a negligible amount of light was realised through this device the test was generally for the purpose of simple heat generation. Having said that, it is interesting to note that even through the dark coating of the evacuated tubes, up to 32lux of light was achieved in this system. Heat was realised with the evacuated tubes on their own, and there was a difference of 3°C between the ambient temperature in the laboratory and that of inside the test cell. More heat was further realised with the introduction of the aluminium foil into the tube, the temperature was further raised with an increase of 7°C. This shows an increase of 43% as compared to the solar tubes just on their own.

When clear evacuated tubes were used, the results as seen in figure 5-10 shows that the inclusion of the evacuated solar tubes greatly enhances the ambient temperature of the cell and raising it by 37% from the laboratory ambient temperature of an average of 19°C to 26°C. When it was just with the light rods alone, the temperature rose to 24°C, an increase of 26%. This shows that by its own merit, the light rods also transmit a very small amount of heat. The combinations of the two however give that added advantage of both heating and lighting on the same platform.

Thus, when considering the heat gain under the same conditions, it will suffice to say that there is a balance in the loss of one (heat), to the gain of the other (light). Having said that, it can be concluded that the light reaching the cell is sufficient for tasks in dwellings as seen in tables 3.1 and 6.1) and the heat dissipated within the cell will be suitable in temperate climate during the winter months when temperatures fall below

0°C and its thus undesirable for human comfort and ambience as outlined in the (ASHRAE, CIBSE handbooks)

# 6. CHAPTER 6: ROOM CHAMBER TESTS WITH LIGHT RODS AS AN ALTERNATIVE TO THE CONVENTIONAL WINDOW

## 6.1. Introduction

Windows tend to throw light onto walls (generally of high reflectance) and so there is significant reflection inside a given room (Jenkins, D. & Muneer, D, 2003), as such, windows are desirable for the lighting purposes, but may cause a problem in temperature control. Thus, these tests were carried out with the aim to ascertain the suitability of the replacement of the double glazed conventional window with acrylic light rods.

The test rig had an area of $7.5m^2$ (2.5m x 3.0m), and consisted of a well insulated single layer plywood and 100mm celotex® board closed envelope. The tests were carried out under 3 parameters

i. Window tests to act as control base line test

ii. 13 light rods insert in wall (within same area as window space)

iii. 25 light rods insert in wall (within same area as window space)

The Equipment/Instruments Used for all the 3 different parameter include

1.0m x 1.0m double glazed window/light rods)

DT500 Datataker (datalogger)

Skye® Lux Sensors

"K" type Thermocouples

Flood Lights (used for solar irradiation)

Well Insulated room measuring 2.5m x 3.0m x 2.5m (internal dimensions)

## 6.2. Control Test for Daylighting with a Double-glazed Window in a Room–Chamber in the Laboratory

Windows are the commonest forms of fenestrations in residential buildings which serve a dual purpose of providing either or lighting and ventilation. In some cases however, the windows are required only for lighting purposes especially in areas where both privacy and lighting are required. It is for this reason, that light rods are introduced to replace windows. Furthermore, heat losses and heat gains happen a lot through window opening the following tests were therefore undertaken to investigate the use of light rods in place of the conventional window so as to reduce heat gain into the room by solar radiation and well as to maintain the temperature in the room with little interference.

### 6.2.1. Method of Test

Skye® Lux Sensors were placed on the opposite far end of the interior wall parallel to the wall fitted with the light rods as seen in Figures 6-1 and 6-2.

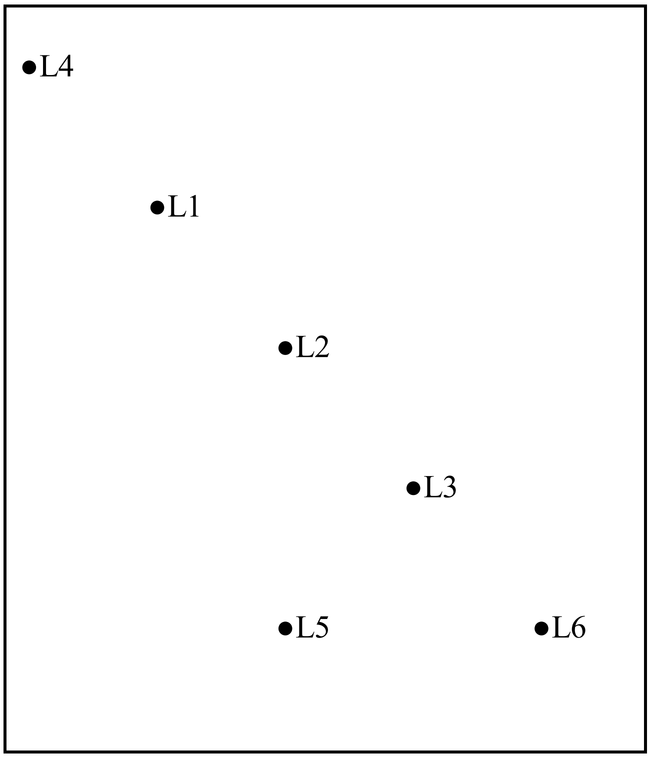



**Figure 6-1: Schematic Position of L1, L2, L3, L4 L5 and L6 lux sensor against the interior rear wall opposite the wall bearing the window.**

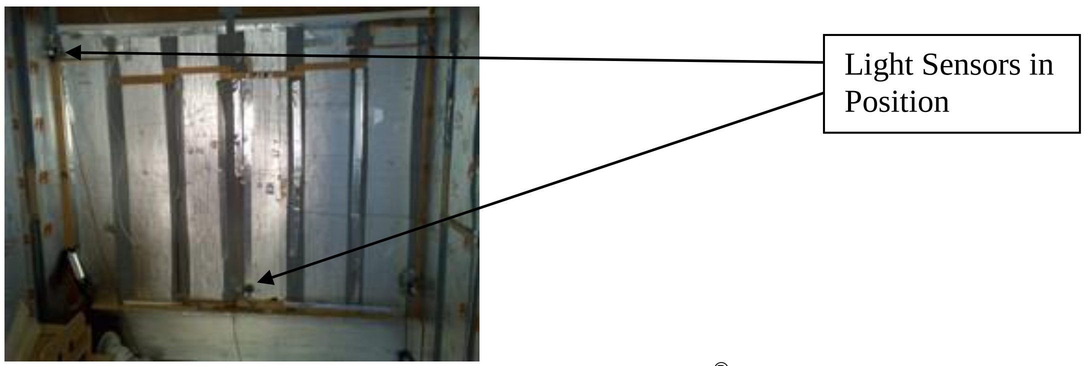



**Figure 6-2: Interior of Test Rig Showing the Skye® Lux Sensors in Position**

The Control test window had light irradiated on it with an average irradiance of 570W/m2 at a distance of 800mm away from the window surface. Temperature reading was taken inside the box, at the point of entry on the window outside the box and the ambient temperature of the laboratory was also monitored throughout the duration of the test. Lux sensor readings were taken in 6 positions (L1, L2, L3, L4 L5 and L6) simultaneously as shown in figure 6-1.

The spatial positioning of the light sensors were chosen whilst taking into cognisance the occupants in dwellings performing a variety of tasks in different locations in the home, as shown in Table 6-1. These activities include children seated on the floor level for example playing in the carpet in the living room/bedroom; there should be sufficient illumination such that they can perform their simple tasks which do not require excess illumination as taken by light sensors L5 and L6. Light sensors in positions L2 and L3 are at seated levels whilst L1 is at standing level and L4 are for tasks requiring over head lighting.

**Table 6-1: Illumination Requirement for Various Area/Activities across the Ages**

| Area or Activity | Under 25 (lux) | 25-65 (lux) | Over 65 (lux) |
|---|---|---|---|
| Passageways | 21.5 | 43 | 86 |
| Conversation | 27 | 54 | 108 |
| Grooming | 162 | 324 | 648 |
| Reading/Study | 269 | 538 | 1076 |
| Kitchen Counter | 404 | 807 | 1615 |
| Hobbies | 538 | 1076 | 2153 |

(Source: http://www.iesna.org/PDF/Education/LightInDesign.pdf)

### 6.2.2. Results and Analysis

The results obtained showed that given the various positions of the lux sensors, the light was evenly distributed ranging on the average, from 310-330 lux as shown in the graph in Figure 6-3

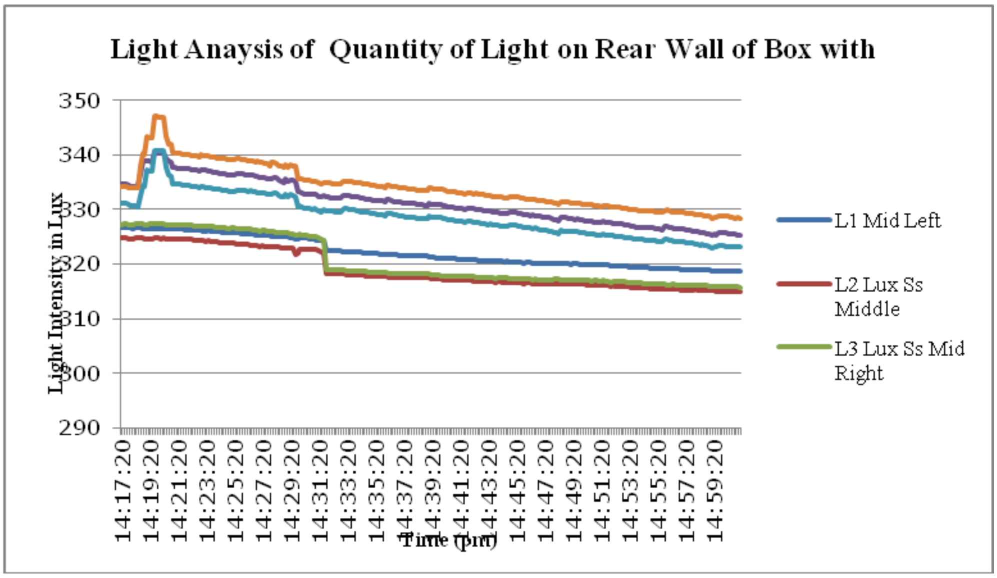



**Figure 6-3: Light Analysis with the baseline test of employing a conventional double-glazedwindow**

From figure 5-4., temperature inside the box remained constant at approximately 26°C throughout the duration of the test, so also, the laboratory ambient temperature remained constant at approximately 16°C. However, the temperature at entry rose steadily from 27°C to 37°C due to the intense solar radiation. The insulation of the box deterred the temperature of the box rising beyond the 26°C so there was a difference (ΔT) in temperature between outside (ambient) to inside of 10°C. Furthermore, there was a difference ranging between 1°C and 11°C between the temperature at entry and the temperature in the box.

This result shows that the insulation properties of the box was such that despite the level of heating from the lights the temperature of the box remained reasonable unaffected and had better thermal comfort than the ambient temperature. The temperature in the test box was found to be a bit higher at 5.69%, than the recommended ASHRAE standard of 24.6°C (Hoyt Tyler et al 2012). However, it is expected that this would be the highest that can be recorded since the irradiance level of 570w/m2 can only be recorded in the hottest of the summer months.

Figure 6.4 also shows the ambient laboratory temperature constant at 16°C, whilst the temperature in the box was at an average of 27°C. This connotes that a temperature difference (between ambient and room) ΔT being 11°C, much lower still to the temperature at entry on the surface of the window being an average of 30.9°C (peaking at a significant 37°C). Consequently, the heat dissipated into the room through the window $\Delta T_2$ less than 5°C.

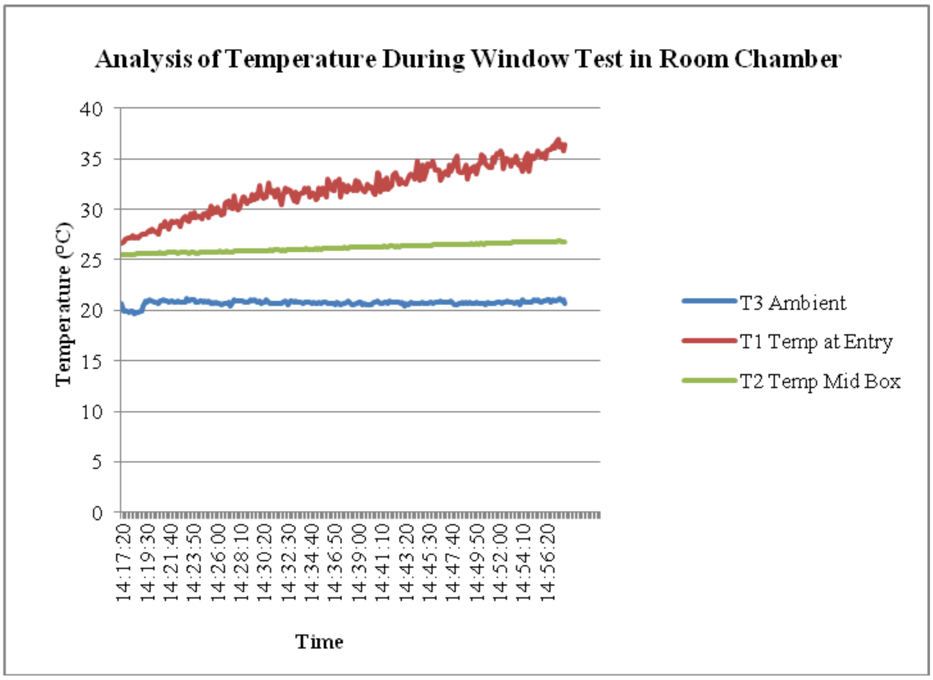



**Figure 6-4: Temperature Analysis with a Double-glazed window**

## 6.3. Daylighting Analysis with 13 Light Rods in a Room Chamber– Rig

In this test, thirteen (13) light rods as seen in figure 5-5 were fitted in the same room chamber of 7.5m$^2$ as previously used in the window chamber earlier discussed in section 5.1 to a life size control room within the laboratory. This is the same number of light rods used in the test rig with the double cavity wall as discussed in chapter 6 which by volume is in the ratio of approximately 5:1 to the smaller test box. The irradiation was also through the use 12 number 500watt flood light, as seen in Figure 6-7.

(a) (b)

**Figure 6-5: 300mm, 50mm dia. Light Rod (a) without collar; (b) with a wooden collar (gasket)**

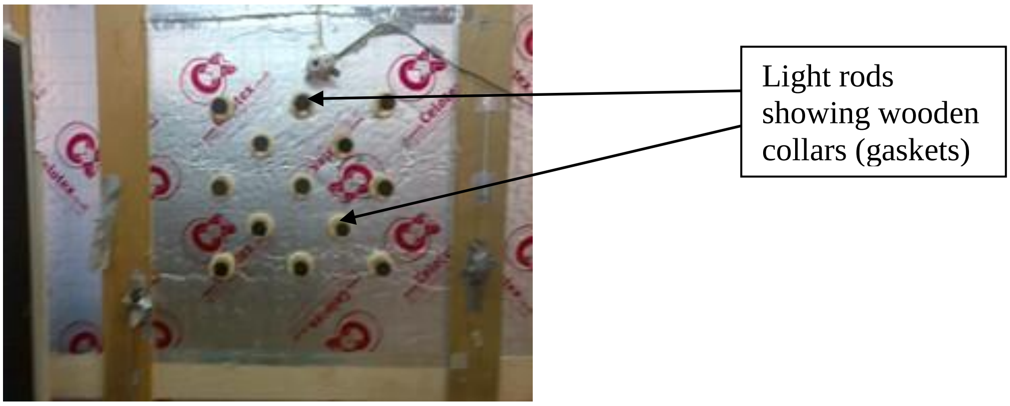
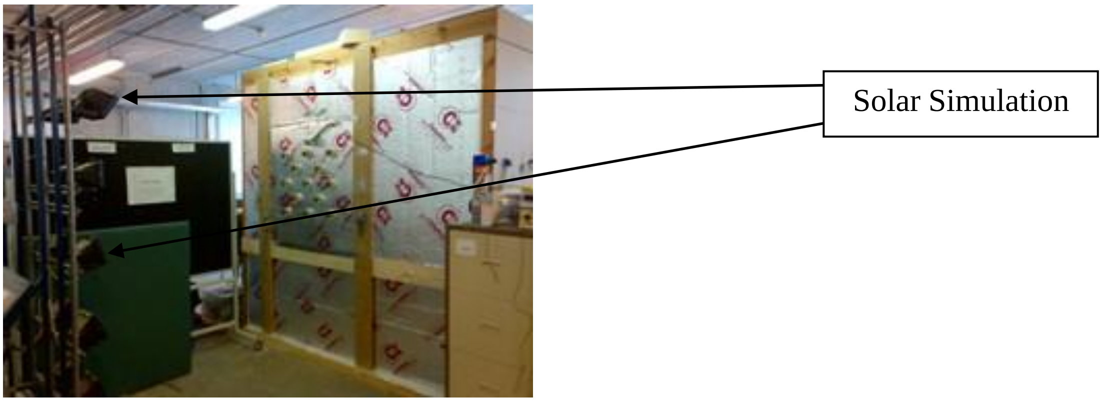



**Figure 6-6: Exterior facade of the wall showing the 13 light rod inserts**




(a) Lights Mimicking Solar Simulation

(b) 500 watts Light Array as used to simulate the sun's radiation

**Figure 6-7: Exterior facade of the wall showing the source of solar radiation and the 13 light rods inserts**

### 6.3.1. Results and Analysis

The initial test to determine the quantity of light in the box was performed with 13 light rods and subsequently, the number of light rods was increased to 25. For these tests, all light rods used were 50mm diameter by 300mm length. The light in the room was mapped out to determine the difference in the quantity of light in the room in relation to the number of light rods used.

The results on figure 5-8 show that the quantity of light in the room ranged from an average of 60 lux to 110 lux with the lowest being recorded from lux sensor L6 at the bottom. Going from table 5.1, 60 lux is still sufficient for a range of areas & activities varying from lighting passages ways or for quiet and conversational activities. The results show that the quantity of light in the room ranged from an average of 60 lux to 110 lux with the lowest being recorded from lux sensor L6 at the bottom. Going from table 5.1, 60 lux is still sufficient for a range of areas & activities varying from lighting passages ways or for quiet and conversational activities. The highest illumunance was recorded on the L1 sensor with an average of 110 lux.

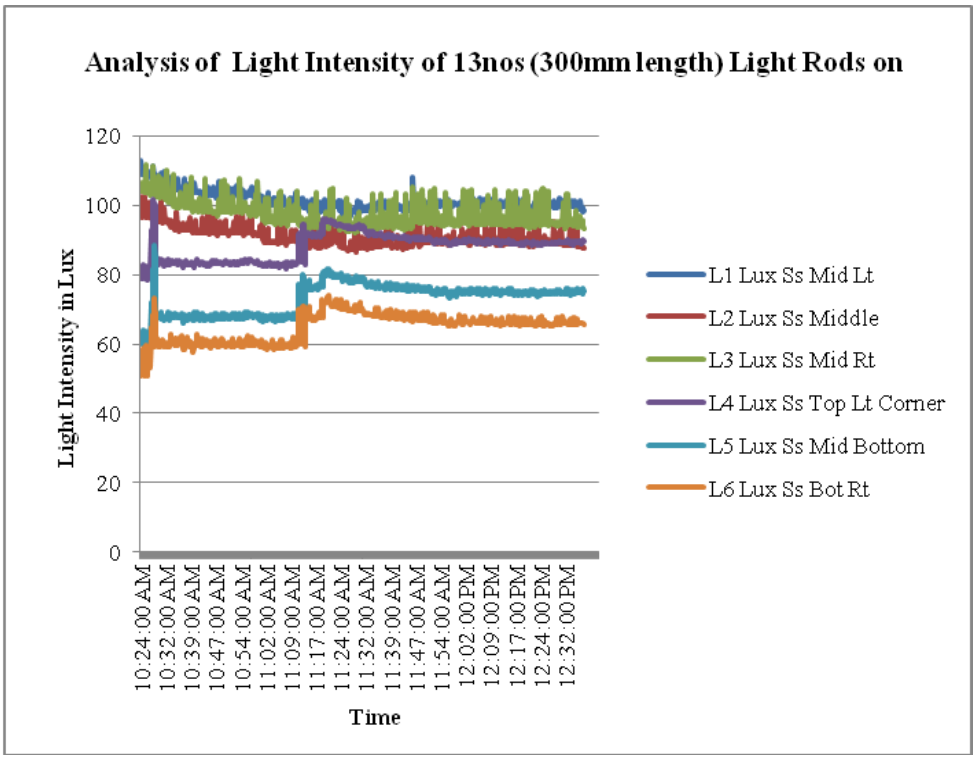



**Figure 6-8: Light Analysis with 13 Light Rods Insert**

With 13 employment of 13 light rods, the temperature (as seen in figure 5-9) at entry (T1) was at an avearge 26°C, and that of the interior middle of the box (T2) and the ambient temperature of the laboratory (T3) were 21.3°C and 21°C respectively. In this case the ambient temperature was also the same temperature mainteined inside the box and very little heat was dissipated inside the room chamber, thus leading to the assumption that the light rods are poor conductors of heat and thus do not carry heat along with them. They therefore do not cause discomfort from what would have been the heat radiated, however, they are able to carry sufficient light into the chamber.

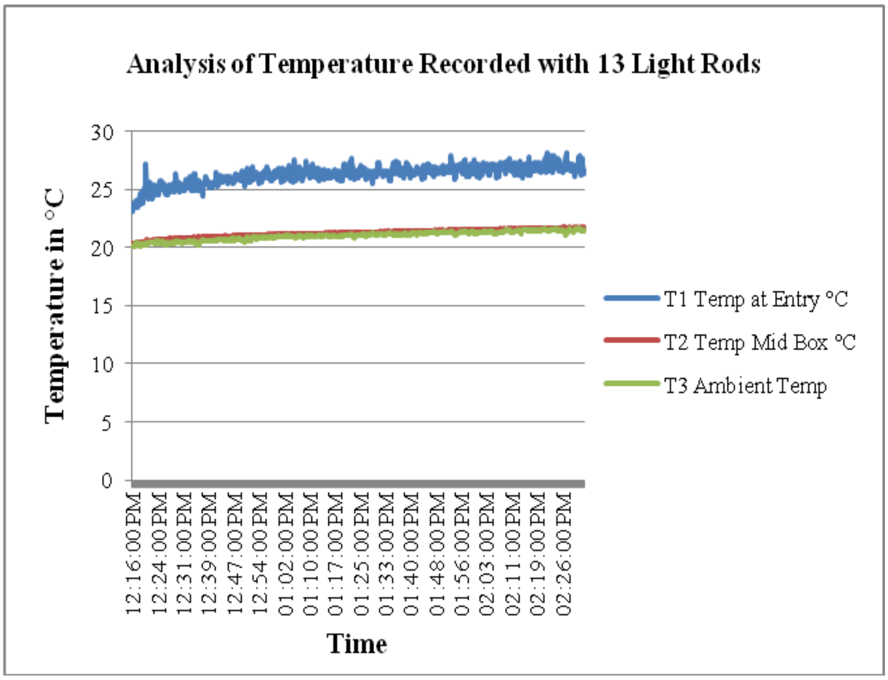



**Figure 6-9: Temperature Analysis with 13 Light Rods Insert**

### 6.3.2. Daylighting with 25 Light Rods in a Room – Rig

Under the same conditions as that of 13 light rods, in this test, 25 light rods of equal lengths of 300mm were employed within the 1m x 1m square box (same area as the window) with the same lux sensor positions L1, L2, L3, L4, L5 and L6.

### 6.3.3. Results and Analysis

The result as shown in figure 5-10 shows that the minimum light intensity observed was approximately 125lux at the L6 Position sensor (bottom right of the wall), and the highest light intensity recorded an average of 172 lux and peaking at 180 lux on L2 Position sensor being at the centre of the wall.

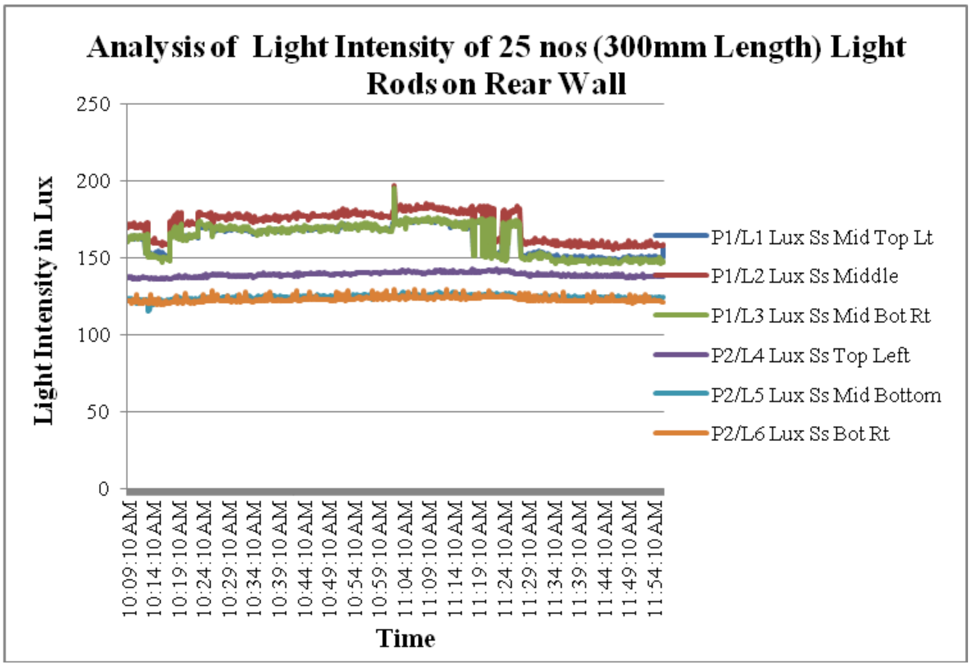



**Figure 6-10: Light Analysis with 25 Light Rods Insert**

The temperature analysis can be seen in figure 5-11. The temperature recorded at entry was an average of 27°C peaking at 30°C. The ambient temperature was at an average of 21.8°C and the temperature in the box was average of 22°C. There was significant change in temperature with the ambient temperature. However a temperature difference of up to 10°C was recoreded with the window which means the employment of light rods would be just ideal for the tropics where higher temperatures are not desired with the requirement for light.

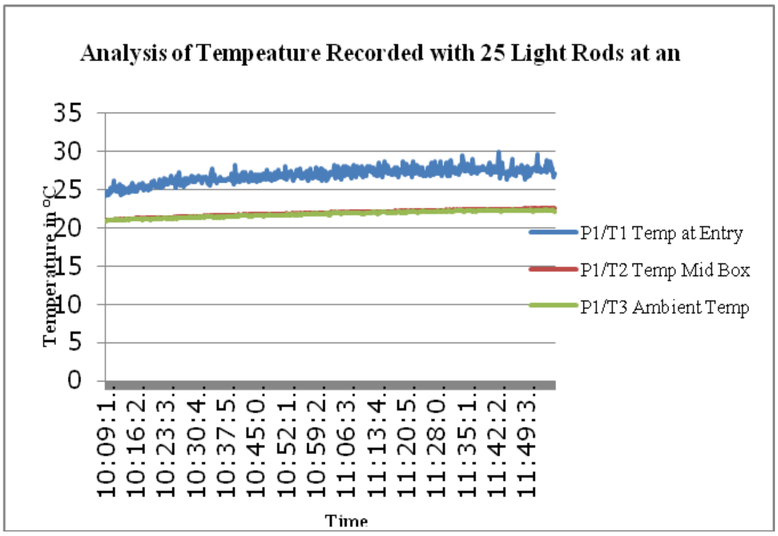



**Figure 6-11: Temperature Analysis with 25 Light Rods Insert**

## 6.4. Comparison of Light Analysis between the Window, 13 Light Rods and 25 Light Rods

The idea for the employment of light rods for the purpose of lighting was brought on initially by the need to deploy light to areas where it was construction-wise impossible to have a window or it was aesthetically unsuitable to have one. For architectural purposes also, the spaces in the residences which require light but would rather not have a window, due to the lack of privacy that comes with it, as well as the loss of heat or heat gain therein. For this reason therefore, considerations were made to come up with workable alternatives within an economical cost range, so as to proffer the best solution. Thus, the light rods were introduced into the same position as a window and the various tests as discussed above, were carried out.

Table 5-2 below shows the various room illumunance for the different applications used, i.e. light rods and window

**Table 6-2: Room Chamber Light Analysis**

| | Average Illuminance | Highest Illuminance | Lowest Illuminance |
|---|---|---|---|
| Window | 332 lux | 343 lux | 325 lux |
| 13 Light Rods (0.026m$^2$) | 85 lux | 95 lux | 82 lux |
| 25 Light Rods (0.049m$^2$) | 145 lux | 152 lux | 139 lux |

Table 6-2 shows that where high illuminance and visual contact is desired, there is no doubt that the window with 325lux offers the best alternative. However, where there is no priority for visual contact, 25 light rods will suffice, as 13 light rods will suffice for spaces where little light is desired.

## 6.5. Summary

Windows though ideal for visual contact with the ideal world given the various choices of fenestrations in buildings, have been found to be sources of heat loss and heat gain. In terms of energy efficiency, windows have been identified to have heat losses of up to ten times higher than walls (Haoyang, 2012). It was thus seen through the tests carried out that these losses can be reduced through the replacement of these windows with light rods.

From the foregoing, we can conclude that the test show that the greatest illumunance was from the window, which has a glazed area of 1m$^2$ compare to that of the 13 light rods with an area of $0.026m^2$ ($13 \times \pi D^2/4$) and 25 light rods with an area of $0.049m^2$ ($25 \times \pi D^2/4$) both spread within a square grid of $1m^2$. The average luminance by either of the light rod formation gave sufficient illumination to light a corridor/ passage and a toilet, and in the case of the 25 light rods, there was sufficient illumination to light a kitchen, living room or bedroom (see tables 2.1 and 5.1)

Whilst the window gave the greatest illumination as expected, peaking at 343 lux, it also dissipated the most heat into the room, peaking at 27°C as against that of the 13 and 25 light rods peaking at 23°C. The test also showed that even with a 48% increase in the number of light rods from 13nos to 25nos, the heat dissipated into the room did not record any significant increase. However, there was an increase of 41% in terms of illumunance, with the increase in number of light rods.

We can thus conclude that where visual contact with inter connecting spaces and in-to-out contact is not necessary, light rods can efficiently provide required lighting for specified spaces as well as the desired reduction of heat losses/gains. Light rods will also be efficient in aspects of light sharing.

# 7. CHAPTER 7: NANO-INSULATION: A CASE OF AEROGEL AS A THERMAL REGULATOR

## 7.1. Introduction

It is important to realize that daylighting is not just an energy-efficient technology, but also an architectural discipline, and a major factor in occupants' perception of how our workspaces should be in terms of visual comfort (Reinhart, 2011).

Aerogel has a high performance thermal insulation, with a thermal conductivity of 13mW/(mK). However the high cost of aerogel is what hinders its wide-spread use and over shadows its highly promising properties (Baetens et al, 2011).

The primary requirement of the building envelope is to provide adequate light and thermal comfort, so as to ease communication. The use of daylight for indoor task illumination has been widely advocated, so it is a task for the architect to balance the different environmental parameters with the design variables. Of all the available systems, light pipes and optic fibre have the greatest capacity to allow light to penetrate a considerable distance in the building envelope (Shao, 2003)

Thus, the question arises, what is thermal comfort? As defined by the Health and Safety Department of the British Government (HSE), thermal comfort is the 'that condition of mind which expresses satisfaction with the thermal environment. So the term 'thermal comfort' describes a person's psychological state of mind and is usually referred to in terms of whether someone is feeling too hot or too cold (British Standards BS EN ISO 7730 in HSE manual)

There are 6 basic factors that affect thermal comfort , broadly under environmental and personal factors (HSE Manual, 2013) as can be seen in Figures 7-1 a & b.

Environmental factors:

i. Air temperature

ii. Radiant temperature

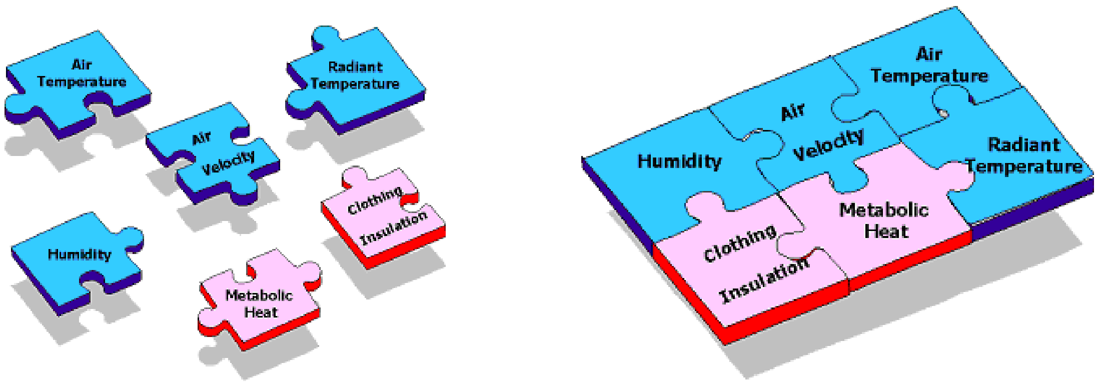
iii. Air velocity

iv. Humidity

Personal factors:

i. Clothing Insulation

ii. Metabolic heat




(a) (b)

**Figure 7-1: a & b:Factors That Affect Thermal Comfort (Source HSE Manual, British Govt.)**

Though there have been several and recent research into field of daylighting with the use of optical rods, the technology is still relatively expensive (Andre and Schade, 2002). Light pipes, are limited in their applicability due to their diameters which generally cannot more than 20 times smaller than their lengths. What obtains generally therefore, is a daylighting transmitting system which collects light by total internal reflection, with high efficiency, like fibre optic cables, allowing smaller diameters with light pipes (Callow and Shao, 2003)

The need to research and develop high performance thermal insulation materials and solutions led to the investigative use of aerogel with its renowned nano-technology capability.

Aerogels are good thermal insulators  Owing to its hygroscopic nature, aerogel feels dry and acts as a strong desiccant (Baetens et al, 2011).

Aerogel can be used in many building envelope applications with limited space as an effective remedy for intense thermal bridging. The high flexibility and good thermal insulation properties of fiber-reinforced silica aerogel composites make it a promising insulation candidate for buildings. (Kosny J., et al, 2005). Today, we can confirm that the fibre-reinforced aerogel (as produced by Spaceloft®) is available in the market and has seen wide applications in buildings. The advantages as highlighted by Spaceloft® (Spaceloft® 2010) include:

- Superior Thermal Performance: Up to five times better thermal performance than competing insulation products

- Reduced Thickness and Profile: Equal thermal resistance at a fraction of the thickness
- Less Time and Labor to Install: Easily cut and comformed to complex shapes, tight curvatures, and spaces with restricted access
- Physically Robust: Soft and flexible but with excellent springback, Spaceloft® recovers its thermal performance even after compression events as high as 50 psi
- Shipping and Warehousing Savings: Reduced material volume, high packing density, and low scrap rates can reduce logistics costs by a factor of five or more compared to rigid, preformed insulations
- Simplified Inventory: Unlike rigid pre-forms such as pipe cover or board, the same Spaceloft® blanket can be kitted to fit any shape or design
- Hydrophobic Yet Breathable: Spaceloft® repels liquid water but allows vapour to pass through
- Environmentally Safe Landfill disposable, shot-free, with no respirable fiber content

The material used in the following experiments (Figure 7-2) is the nano-porous aerogel blanket™ with extremely low thermal conductivity, superior flexibility, compression resistance, hydrophobicity, and ease of use manufactured (Spaceloft® 2010).

**Figure 7-2: Spaceloft® Aerogel Fibre Blanket (Source: Spaceloft®)**

## 7.2. Wall Tests Using Aerogel Fibre Sheets as an Infill within the Cavity Wall

Due to the thinness and versatility of the aerogel blanket, tests were carried out to ascertain its insulative properties as seen in the reported experiments below.

### 7.2.1. The Experiment Set-up

The test rig was set-up as a dual purpose rig to test both lighting and heating. For the purpose of this section however, we are focussing on only the heating component. A cavity wall was built thus (see Figure 7-3 and 7-4) using commercial aerated blocks (sample of which is seen in Figure 7-5). The blocks were laid and sealed with silicon between the joints, and two separate built up walls were placed parallel to one another with a cavity between them of 35mm, as seen in figure 7.4.

**Figure 7-3: Wall showing the drilled holes**

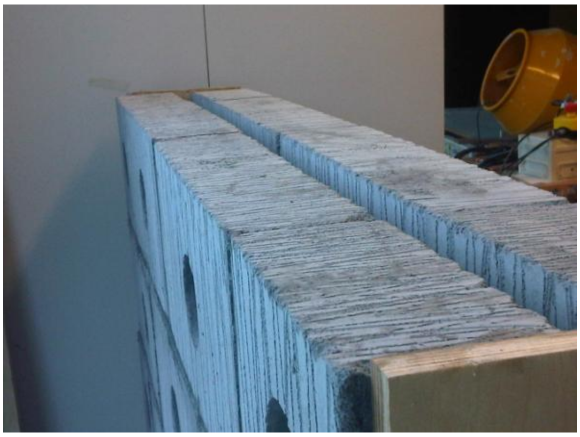


**Figure 7-4: Wall showing the cavity**

**Figure 7-5: Block Size: 440mm x 215mm x 100mm**

This wall was placed as one face of the rig cell, and the other five sides consisted of an insulated material of half inch plywood and 50mm celotex board. The internal dimensions of the cell measuring 1200 x 1200 x 1200 (Figures 7-8 and 7-9). On the panel with the block wall, holes were drilled in the middle of each block as seen in figure 7-3, through which the 50mm diameter, 300mm length light rods (as seen in Figures 7-6 a & b) will be driven through as the transporters of light into the cell.

(a) (b)

**Figure 7-6: The prepared acrylic light rods with the wooden collars in readiness to be placed through the drilled holes of the wall**

### 7.2.2. Method of Test (Procedure)

The sensors (light and temperature) are connected to the datalogger and the sensors are placed in the appropriate positions. On the inside of the cell, two heat flux sensors are placed in the inner part of the cell (see figure 6-8) in the wall to measure the heat flow. Two light sensors were placed in the cell – one on the floor, and the other on the wall opposite the block wall. A temperature sensor is also placed in the middle of the cell, just off the floor. A third temperature sensor was used to measure the ambient temperature of the laboratory. There was also a pyranometer suspended along the surface of the wall to see the irradiance level just at the point of entry into the cell.

The prepared 18 light rods were placed thru the holes with one end on the outside, and the other end in the inside of the cell with the wooden gaskets to hold them firmly in place at the two ends as can be seen in figures 6-7 a and b. A bead of silicone adhesive seal was placed around the inside and outside of the collars to ensure tight fit for proper air tightness.

The flood lights at approximately 1.5maway from the edge of the cell, giving an irradiance level of an average of 550W/m2. The lights were then turned on and allowed to run for 10minutes approximately, before the datalogger was turned on and readings began to be taken. Note the position of the heat flux sensors in figure 4.8. So also, the laying of the heat mat in the interior of the cell as seen in Figure 7-10. Each of the tests were run for between of 1-2 hours each and data gathered was thus analysed under the following conditions

The tests were carried under the following 4 conditions:

**Condition 1:** Irradiation distance of 1.5m without aerogel infill in the wall and without the use of heat mat

**Condition 2:** Irradiation distance of 1.5m without aerogel infill in the wall but with the use of heat mat

**Condition 3:** Irradiation distance of 1.5m with aerogel infill in the wall without the use of heat mat

**Condition 4:** Irradiation distance of 1.5m with aerogel infill in the wall with the use of heat mat

**Figure 7-7: Wall with light rods in Place prior to commencement of Testing**

**Figure 7-8: Lights in Position Prior to Commencement of Testing**

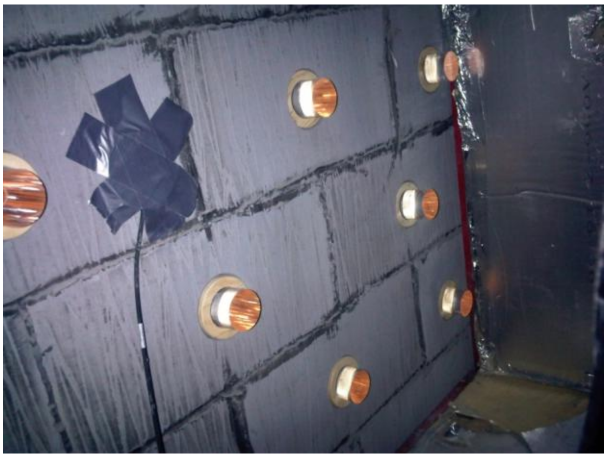


**Figure 7-9: Position 1 of Heat Flux Sensors**

**Figure 7-10: Interior of the cell showing the laid heat mat**

### 7.2.3. Analysis and Conclusion

Temperature analysis as can be seen from Figure 7-11 below show that the ambient temperature in the laboratory was constant at 22°C. When the temperature was measured in the Cell as in condition 1 (C1), without aerogel, without heat mat, temperature was constant at 20°C, a difference ΔT of 2°C between that and the ambient temperature. However when the aerogel was introduced into the cavity, the temperature rose to 25°C. This can be explained because the heat that went in stayed in and could not be dissipated by through the wall because of the aerogel buffer, but without the aerogel buffer, the air freely moved in and out through the wall, so the heat did not remain in the cell as was expected.

When the heat mat was activated in the Cell (with the thermostat set at 40°C so as to raise the internal temperature to resemble that of the tropics and thus investigate the behaviour), the temperature measured was such that the temperature was fluctuating with the heating and cooling down of the heat mat, given a sine wave with high and low peaks. Without an aerogel buffer and heat mat activated, the temperature fluctuated between 41°C and 35°C. It was constant at 41°C, then gradually dipped to 35°C, and again rose to 40°C – this could be as a result of the temperature control through the thermostat installed onto the heat mat. However, when the aerogel was introduced into the buffer, the sine curve was constant and the fluctuations could be explained due to the heating and by the heat mat and the dips in the cooling of the heat mat when the thermostat switched it off, and when back on again the heat rose, so there was less dissipation of heat into the surrounding exterior of the cell. And in both cases Conditions 2 and 4 (C2 and C4), the heat was above the heat at entry which was at an average of 32°C.

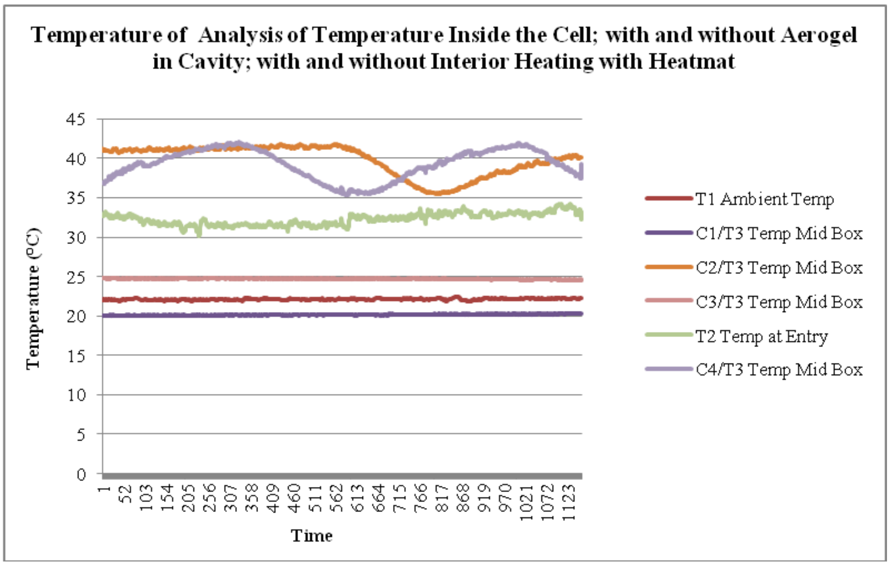



**Figure 7-11: Temperature Analysis and Effects with the Introduction of Aerogel Infill in Cavity of Wall and Heat Mat**

From Figure 7-12, the behaviour of aerogel was also put to the test. Analysis show that with the application of the heat mat, there was always a fluctuation in the pattern of the heat flow due to the regulation of the internal temperature with the thermostat set at 40°C used to simulate a tropical region such as Nigeria. The Heat flux was placed in the interior of the cell to measure the heat flow from in to out however, as there was generated heat in the interior of the cell it affected the behaviour of the heat flux sensor as can be seen in the graph below. When there was no application of the interior heat, the heat flow was constant, for both conditions C3 (with aerogel, without heat mat) and C1 (without aerogel, without heat mat). However, when there was aerogel in the cavity, the heat flow was higher, at an average of 11.5W/m$^2$ as against 4W/m$^2$ when there was no aerogel infill in the cavity.

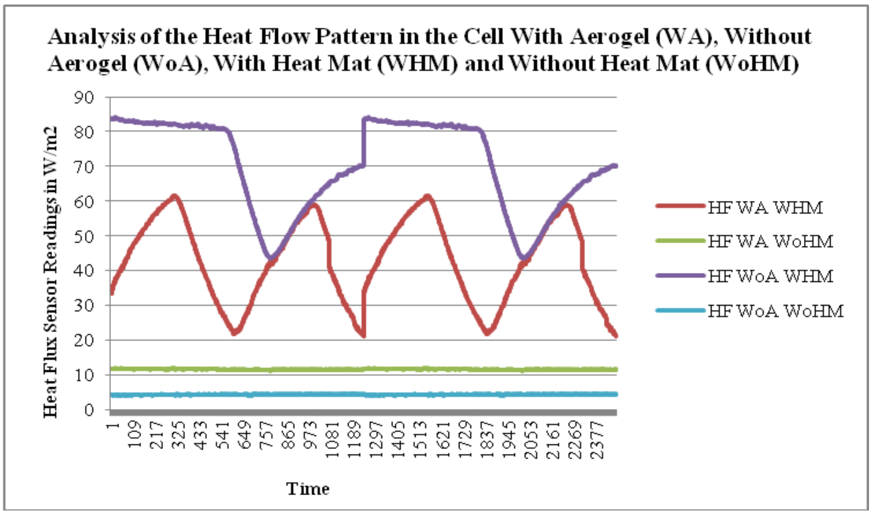



**Figure 7-12: Analysis of Heat Flow Pattern in the Cell**

### 7.2.4. Analysis and Conclusion

Given the analysis above, we can conclude that with the application of the aerogel in the cavity when there was no application of heat from the heatmat, the temperature was constant at an average of 10.5°C, but when there was heat application, the temperature was a basic sine curve peaking at 60°C and dropping to 20°C, at constant intervals, thereby giving the indication that as the heat tries to penetrate the, the aerogel barrier repels the heat and makes it to drop through a difference (ΔT) of 40°C.

However, when there is no aerogel in the cavity, when the heat is applied, the behaviour of the temperature is slightly unpredictable and more heat passes through the wall, peaking at 82°C, which is 20°C higher than when there was a buffer of aerogel. The lowest temperature recorded is 42°C which shows how effective the aerogel insulation is, as less heat is dissipated into the room when the aerogel is in the cavity.

## 7.3. Light Transmittance of Aerogel/Argon Windows

### 7.3.1. Introduction

Daylighting is recognized as an important element in architecture and a useful strategy in energy-efficient building designs, which gives a sense of cheeriness and brightness that can have a significant positive impact on the people (Li, 2010). As such, the building envelope is punctuated with windows to allow for appropriate natural lighting to be achieved. At the thermal envelope of buildings, the window area is the weakest part with respect to heat loss, but at the same time, this area also provides advantages (Jensen et al, 2004).

It is therefore as a result of this, that further to the testing of aerogel as an insulator, testing was carried out to seek the daylight transmittance potential of aerogel in windows. This was especially important where the priority of the window was for lighting (visual) rather than for insulation purposes.

Researchers have striven to find ways of maximising the quantity and quality of natural light in buildings, with the least loss of thermal comfort. As a result of this, various researches have been carried out to investigate the use of aerogel filled windows so as to be able to achieve both thermal comfort as well as natural lighting comfort. Aerogels are dry gels with a very high porosity (Hüsing et al, 1998) and were discovered in the early 1930s by Kistler (Kistler, 1931). Aerogel has a high performance thermal insulation, with a thermal conductivity of 13mW/(mK). However the high cost of aerogel is what hinders its wide-spread use and over shadows its highly promising properties (Baetens et al, 2011). Silica aerogels have very interesting optical properties with high transmittance of radiation within the range of visible light (i.e. radiation with a wavelength between 380 and 780nm) (Baetens et al, 2011). Futhermore, aerogels have a high transparency in the infrared spectrum (i.e. a $T_{IR}$ of 0.85) (Baetens et al, 2011). However, if transparency is not desired, the direct-hemispherical transmission in the visible range can be strongly reduced with up to 50% by adding only a few vol% isopropanol or other opacifiers to the aerogel (Reichenauer et al, 2004). Aerogels are reasonably transparent in the infrared spectrum below in Figure 7-13.

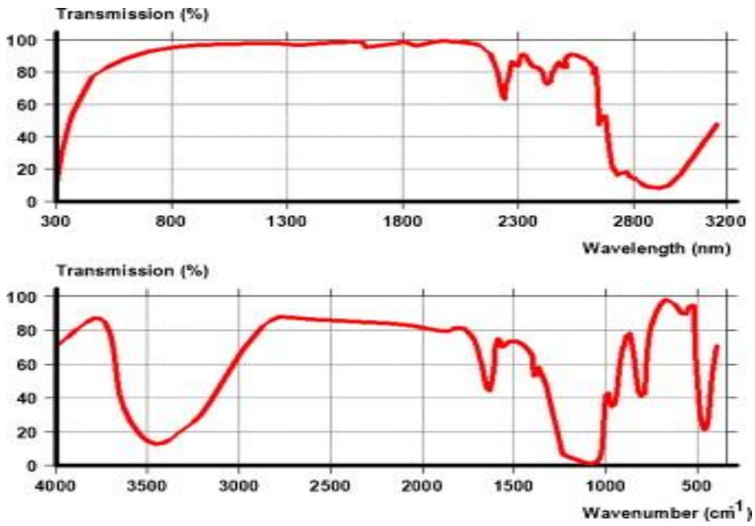



**Figure 7-13: The transmittance of a silica aerogel in the ultraviolet, visible and near infrared spectrum (top) and the infrared spectrum (bottom) (source Baetens et al, 2011)**

### 7.3.2. The Tests

The tests is carried out with the use of double-skinned windows with varying thicknesses and fillings of full silica gel or full argon gas filling or in the 3rd condition, half-silica and half argon.

Three types of windows (see Figures 7-16 and 7-17) were tested. For each window, there were 2 settings, and each of the tests was run for 1 hour (60 minutes) each. The three types of windows tested were as seen in Table 7-1

**Table 7-1: Window Sample Specification**

| WINDOW TYPE & SPECIFICATION | WINDOW SIZE | THICKNESS OF GLASS PANES (INNER & OUTER) | THICKNESS OF CAVITY |
|---|---|---|---|
| 20mm Argon-filled cavity | 300mm x 300mm | 4mm | 20mm |
| 10mm Aerogel-filled cavity | 300mm x 300mm | 4mm | 10mm |
| 6mm half filled with Aerogel & half filled with Argon Gas | 300mm x 300mm | 4mm | 6mm |

### 7.3.3. Method of Test (Procedure)

The method carried out was through the use of a solar simulator to represent natural light while recording the data with the employment of a DT500 DataTaker®.

The sample window was placed on a built in frame and mounted on a white plain raised surface.

Light sensors, energy sensors, pyranometer as well as temperature sensors (as seen in Figure 7-15) were wired on the window and solar light from the solar simulators were shone on the window, and data was relayed to the DataTaker®

The program on the datataker was set to relay information at 1 minute interval.

The data was thus collected, and processed.

### 7.3.4. The Tests

#### 7.3.4.1. Condition 1

A 6mm sample window was placed on the frame and raised to a height of 150mm off the plain white raised surface. A *Kipp and Zonen* globe type pyranometer used to measure solar radiation was placed on top to ensure that solar radiation is maintained at a constant figure so as to act as the control and constant element during the test. An energy sensor was placed above and the data was taken for approximately 1 hour.

With the same window sample, the globe pyranometer was still placed on top so as to ensure that the solar radiation was constant. Consequently, a Skye energy sensor was placed below the window, and the test was again run for approximately 1 hour and data received was recorded. As the sample was a half-aerogel and half-argon window, the test was carried out under the same condition for both sides.

#### 7.3.4.2. Condition 2

A 10mm sample window was placed on the frame and raised to a height of 150mm off the plain white raised surface. A *Kipp and Zonen* globe type pyranometer used to measure solar radiation was placed on top to ensure that solar radiation is maintained at a constant figure so as to act as the control and constant element during the test. An energy sensor was placed above and the data was taken for approximately 1 hour.

With the same window sample, the globe pyranometer was still placed on top so as to ensure that the solar radiation was constant. Consequently, a Skye energy sensor was placed below the window, and the test was again run for approximately 1 hour and data received was recorded.

### 7.3.4.3. Condition 3

A 20mm window sample was placed on the frame and raised to a height of 150mm off the plain white raised surface. A *Kipp and Zonen* globe type pyranometer used to measure solar radiation was placed on top to ensure that solar radiation is maintained at a constant figure so as to act as the control and constant element during the test. An energy sensor was placed above and the data was taken for approximately 1 hour.

With the same window sample, the globe pyranometer was still placed on top so as to ensure that the solar radiation was constant. Consequently, a Skye energy sensor was placed below the window, and the test was again run for approximately 1 hour and data received was recorded (See Figure 7-14 below).

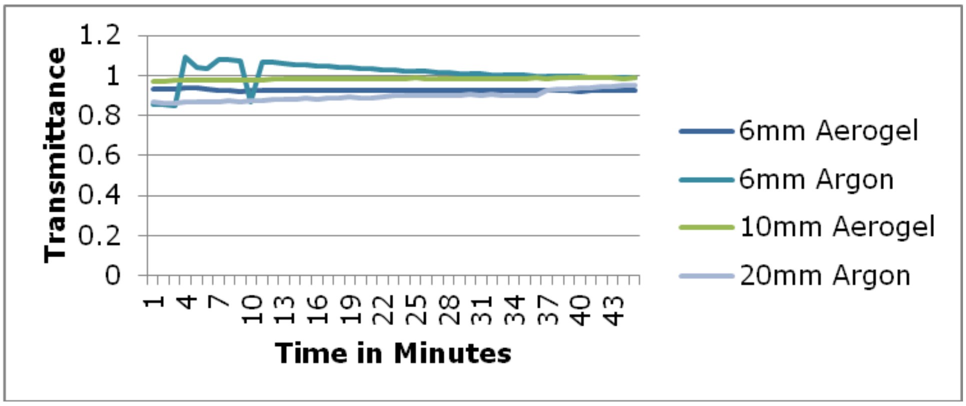



**Figure 7-14: Transmittance of Window Sample within the Visible Light Range**

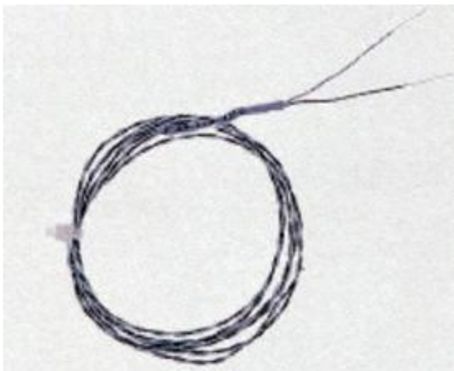
**Figure 7-15: The apparatus and equipment used in the experiments are as seen below in figures a -f**


(a) Pyranometer

(b) Lux sensor

(a) Solar Light Simulators

(d) Typical Solar Light Simulators

(f) Datalogger (DT500 Datataker)

(g) “K” Type Thermocouple

**Figure 7-16: a - c: Various Sample windows:**

(a) Aerogel/Argon 6mm window (b)Aerogel 10mm window

(c) Argon 20mm Window

**Figure 7-17 a - c: The Test Rig**



(a) Aerogel/Argon Window (b) Argon/Aerogel Window
(Argon Half covered for testing purposes)

#### 7.3.4.4. Results, Analysis and Conclusion

The solar radiation set as around 600 $W/m^2$. The surface temperature of window surface is around $50^oC$. The lab ambient temperature is around $20^oC$. The test was lasting one hour under same stable test conditions. The test results for transmittance of different window samples in the vision range have been summarized in following figures.

As shown in the Figure 7-12, the transmittances of the three window samples are close. The average transmittance of radiation within the range of visible light i.e. between a wavelength of 380nm and 780nm is 93%, 94%, 91%, 92% for 6mm Aerogel Window, 6mm Argon window, 10mm Aerogel filled double glazing window, and 20mm Argon gas filled double glazing window respectively. Going by the test data obtained, we can conclude that the average transmittance of Argon- Aerogel window is 93%. From the test results thus, it can be inferred that the Aerogel window has good transmittance, and the thickness of aerogel does not affect the transmittance to a significant value. Furthermore, In any case, aerogel glazing offers the possibility to provide diffuse natural light (Reim et al, 2011).

## 7.4. Summary of Chapter

With the ever searching quest to find thermal comfort, in the midst of hard economic times in harsh weather conditions, it has become imperative to find ways in which we can keep warm/cool as the need may be. This has necessitated the need to find better and lasting solution to make the building envelope thermally effective, as well as visually pleasing. This has therefore led to the investigative nano-properties of aerogel as both a thermal insulator as well as a light transmitter.

When aerogel was used in the wall cavity, it deterred the high exterior solar heated from penetrating into the room. The aerogel fibre blanket absorbs the heat from the outside and kept the interior temperature of the box constant. When heat was applied inside the box, and solar radiation outside the box, it was still able to absorb the heat from both sources both ways thereby making the heat fluctuate while still fighting hard to absorb the heat. It therefore was able to keep the interior room of the box close to the temperature as dissipated by the heat mat, whilst still deterring any excessive external heat from penetrating inside the box.

As the properties of aerogel have proven to be effective in terms of thermal insulation, testing for transmittance of aerogel in windows was carried out. The bench mark for the test was the use of standard argon filled windows against aerogel filled windows. The aerogel filled window proved to be effective gave a transmittance of 93%.

# 8. CHAPTER 8: CONCLUSION

Prior to this work, many works and research have been undertaken in the aspect of daylighting, and how best to utilise this under-utilised resource. This chapter provides conclusions to the works done in this entire report and give a snap shot into the work carried out, while also identifying the missing gaps and offering suggestions to into areas of further work that can be done

This research undertaken here, provides a base for industries to develop these novel components each as singular units to be assembled in-situ and even retrofitted in existing buildings. The application of using the light rods in conjunction with the light pipe can easily be manufactured in cottage industries even in less developed countries such as Nigeria with ease and without excess technical support and expensive equipment. This can be produced as a prototype and patented for use in residential buildings and even institutional buildings such as school, hospital and offices and even in industries.

## 8.1. Performance of the Devices and Systems

With the UK Government's quest to develop standards for through the Code for Sustainable Homes (CfSH), key elements of all that encompass the building envelope were looked into, and this thesis paid attention to visual and thermal comfort. The semi-detached Tarmac Houses on the University Park Campus of the University of Nottingham UK meet the Code 4 and Code 6 standards. With regards to the tarmac house, a single light pipe produced illumination of up to 325 during the day and up to

50 lux during the night which is sufficient by CIBSE standards for residential buildings.

This led to the investigation and testing of using different diameters and lengths of light pipes and light rods on a test rig and thus the invention of a novel dual-technology light pipe incorporating a light rod. This novel system brought a 20% improvement in illuminance over a light pipe and 72% improvement over that of a single light rod. It is on this premise that the dual –technology device is recommended for residential use.

Evacuated tubes have been used for several years for hot-water heating through conductive process. However in the tests carried out, its convective properties for spatial heating was investigated and further yet incorporating this simple device with light rods so that both lighting and heating are on the same platform. Room temperatures were raised by up to 37% from 19°C through to 26°C. Illumination levels ranged from 140 lux – 152lux which by CIBSE standards is sufficient for residential dwellings (see tables 2-1, 3-1 and 5-1)

The aspect of exploration of aerogel as a nano-insulator was also investigated.

An aerogel fibre blanket was used in a wall cavity of a test rig to investigate its heat insulation properties. The aerogel blanket absorbed the heat from the outside and kept the interior temperature of the box constant. When heat was applied inside the box, and solar radiation outside the box, it was still able to absorb the heat from both sources both ways thereby making the heat fluctuate while still able to absorb the heat. It therefore was able to keep the interior room of the box close to the temperature as dissipated by the heat mat, whilst still deterring any excessive external heat from penetrating inside the box.

As the properties of aerogel have proven to be effective in terms of thermal insulation, testing for transmittance of aerogel in windows was carried out. The bench mark for the test was the use of standard argon filled windows against aerogel filled windows. The aerogel filled window proved to be effective gave a transmittance of 93%.

Light rods in a well insulated room were also investigated to ascertain their light carriage properties whilst not transmitting the heat that regular double glazed windows carry/loose. During these tests, light transmitted with the light rods were sufficient to light corridors, passages, toilets as well as kitchens. Whilst the window gave the greatest illumination as expected, peaking at 343 lux, it also dissipated the most heat into the room, peaking at 27°C as against that of the 13 and 25 light rods peaking at 23°C. The test also showed that even with a 48% increase in the number of light rods from 13nos to 25nos, the heat dissipated into the room did not record any significant increase. However, there was an increase of 41% in terms of illumunance, with the increase in number of light rods.

We can thus conclude that where visual contact with inter connecting spaces and in-to-out contact is not necessary, light rods can efficiently provide required lighting for specified spaces as well as the desired reduction of heat losses/gains. Light rods will also be efficient in aspects of light sharing.

## 8.2. Contribution to Knowledge

The novelty of combining and harnessing light and heat simply from daylight both on the same platform is a new technology, and one that has not been presented before in this manner, thus the novel investigation of harnessing both light and heat on the same platform with the incorporation of light rods into evacuated solar tubes.

In the aspect of the dual technology, either technologies/devices have been used in several ways, however, the combining of the two technologies on the same platform so as to harness more get better value in terms of light is a novel idea

## 8.3. Further work

Through the novelty of the above works done, further work could be looked into in the along the various lines.

- ✓ Production of the evacuated solar tubes with in-built highly polished acrylic light rod. The sizes of the evacuated solar tubes and acrylic light rods could also be further examined, so as to determine the best fit for either of the two.

- ✓ In terms of the dual technology of the light pipe and acrylic light rod, the aspects of size can also be further investigated. So also further work can be done in terms of assessing its flexibility to suit various positions, in terms of bending both the light pipe and the acrylic light rod.

- ✓ Other work that can be done is the aspect of incorporating fibre optics and attaching to the ends of the light rod as seen in figure 7.2. and further incorporating it with LED lights which when attached to a sensor will automatically pick-up when there is insufficient daylight as seen in sample on figure 7.2. research into this aspect has commenced, but due to time pressure, it could not be completed but thus far proves to be an interesting area to continue the research on.

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Zhang, X. (2002) Daylighting Performance of Tubular Solar LightPipes:Measurement, Modelling and Validation. PhD Thesis Napier University, UK. Pp 4

# 9. Appendix 1: List of Publications

1. Tukur, R.B and Riffat S. (2012). Daylighting Systems for Visual and Thermal Comfort. In SET2012 – 10$^{th}$ International Conference on Sustainable Energy Technologies, Vancouver, Canada.

2. Elzaidabi, A., Tukur, R.B. and Riffat S. (2010). Harnesing Daylighting Potentials as a Tool for Thermal Comfort for Residential Buildings. In SET2010 – 9$^{th}$ International Conference on Sustainable Energy Technologies, Shanghai, China.

## 10. Appendix 2: Simulation and Modeling for Dual Technology; the Processes. The Rig was modeled in 3ds Max Design software

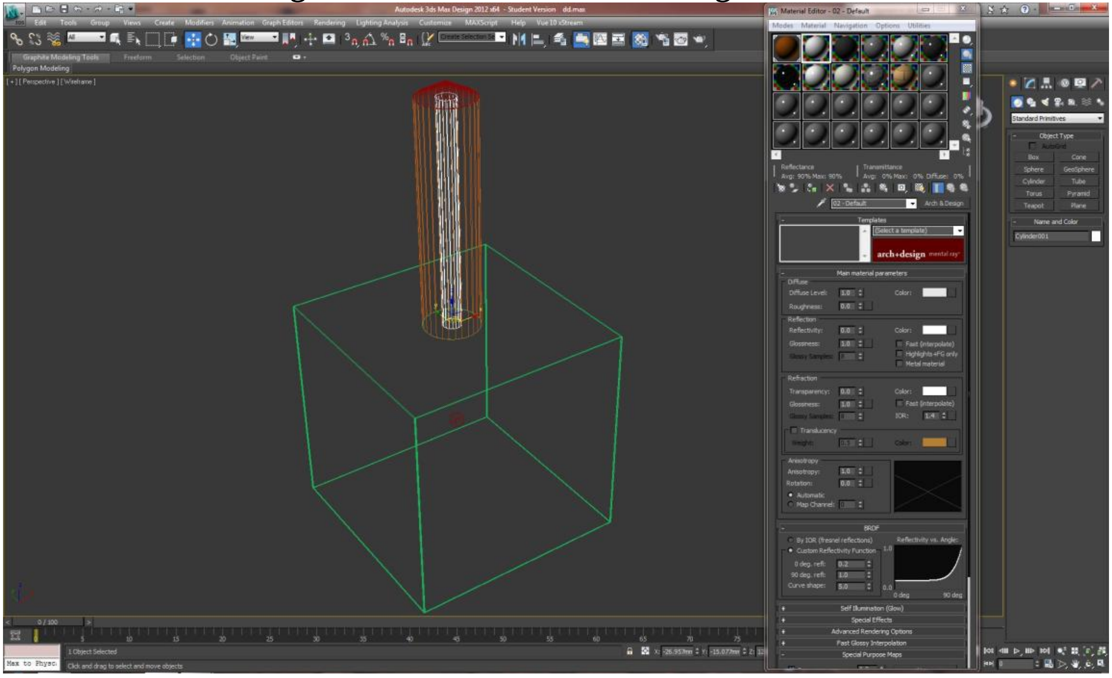

**Figure 1: Showing the model in wire frame mode so that the internal structure can be viewed.**

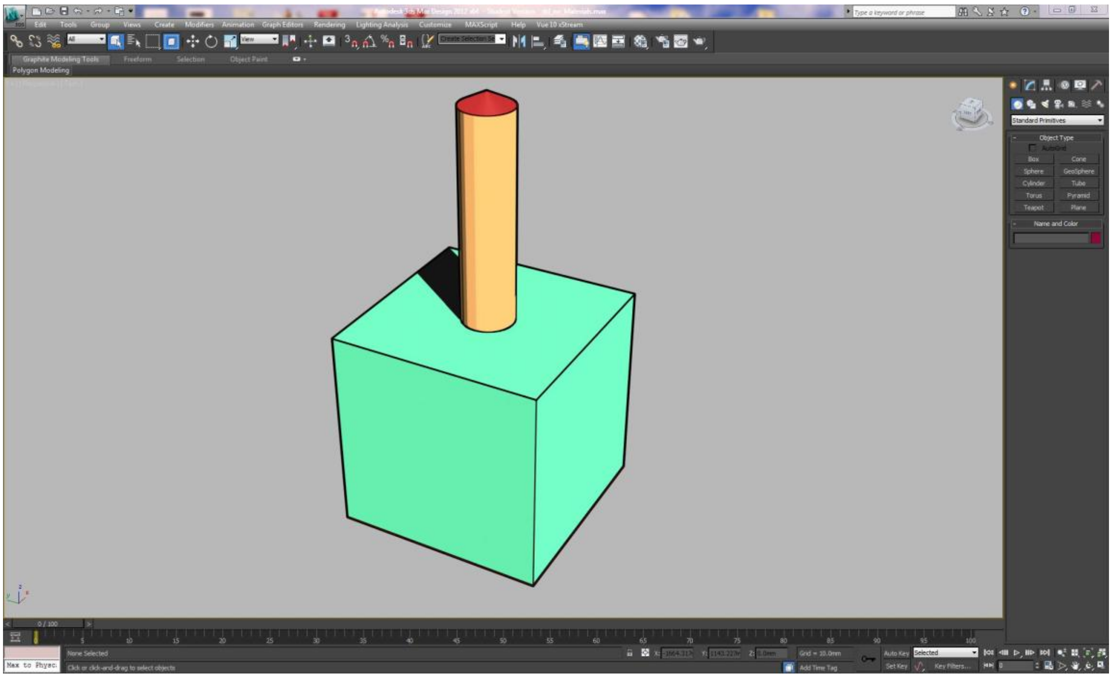

**Figure 2: Showing the model in solid shaded mode.**

The exporting process from 3ds Max to Ecotect: the file is being exported to a 3DS file format (see Pic 4) for it to be compatible with Ecotect

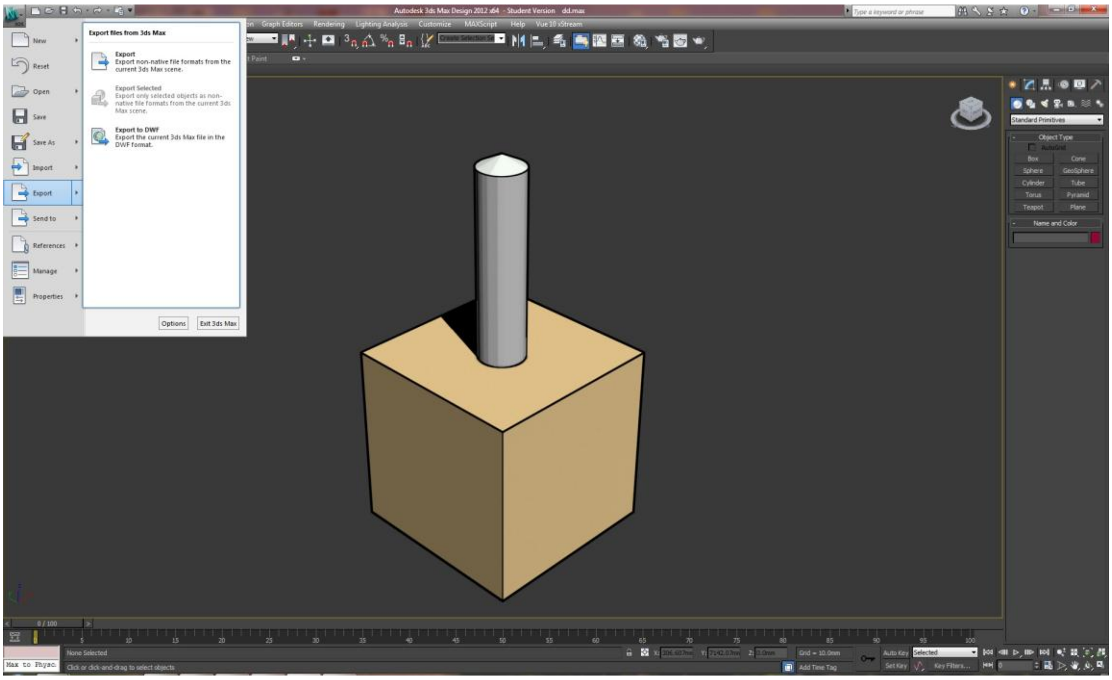

**Figure 3: Showing the beginning process of exporting the model out as a 3DS file format.**

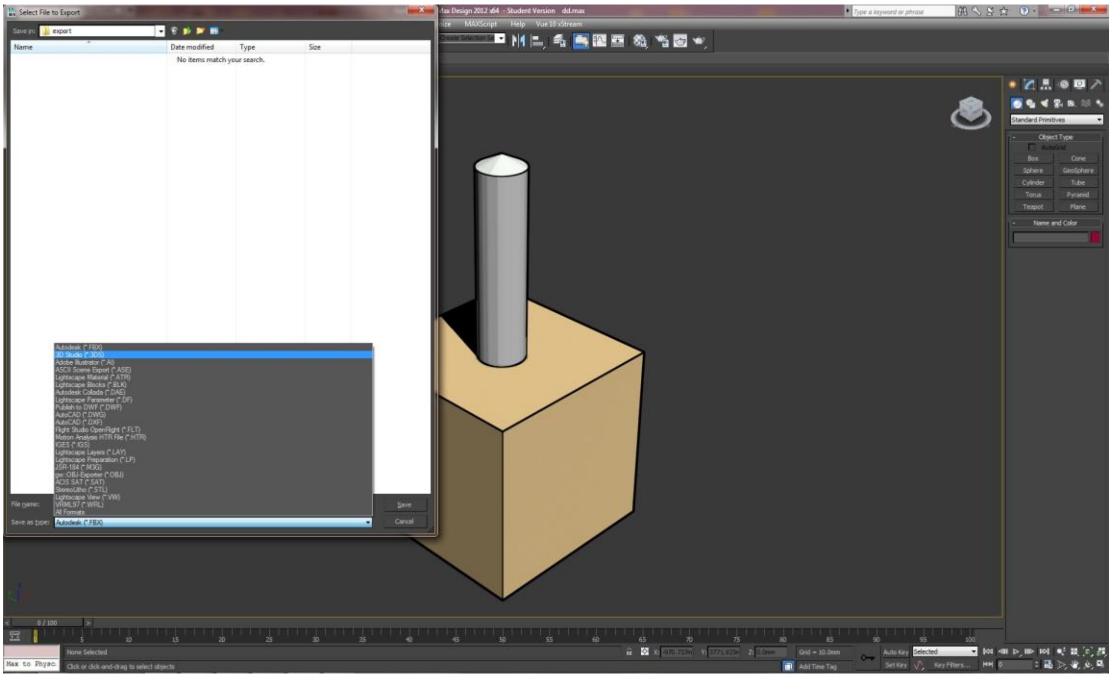

**Figure 4: Showing how the 3DS file format is being selected from a drop down list.**

The process of importing the 3DS file into Ecotect: open the Ecotect program, go to file, select import and select '3D CAD Geometry'. A dialogue box will appear then select to file and click ok.

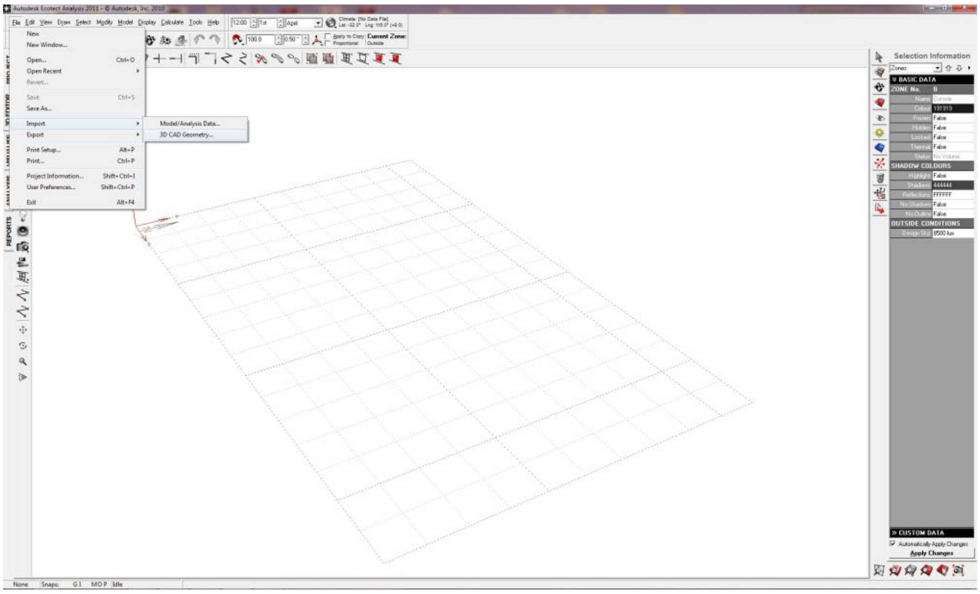

**Figure 5: Showing how the 3DS file earlier exported, is imported into Ecotect.**

After clicking ok, another dialogue box will prompt you with the list of all component objects contained in the file. This is the crucial moment where you will apply materials to the objects; the dialogue box gives you the option of applying the materials (see figures 7, 8, 9 and 10)

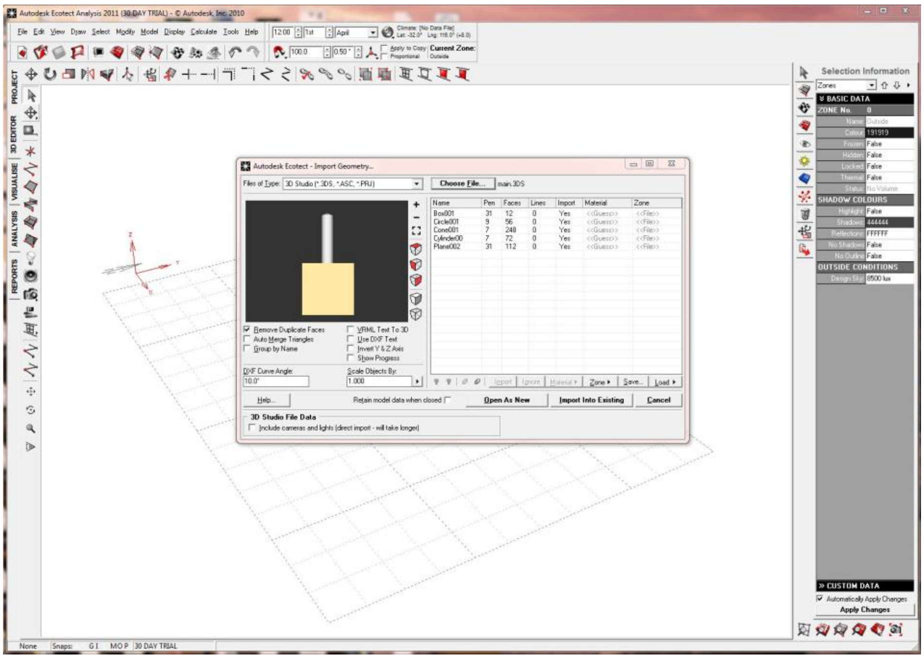

**Figure 6: Indicating the dialogue box that will appear after locating the file during the process of importing.**

The process of applying materials to the model: from the figure below, the list that appears in the dialogue box has material slot assigned to each object. By clicking the material slot, you will be able to choose which material the object should be attributed to. See figures 7-10.

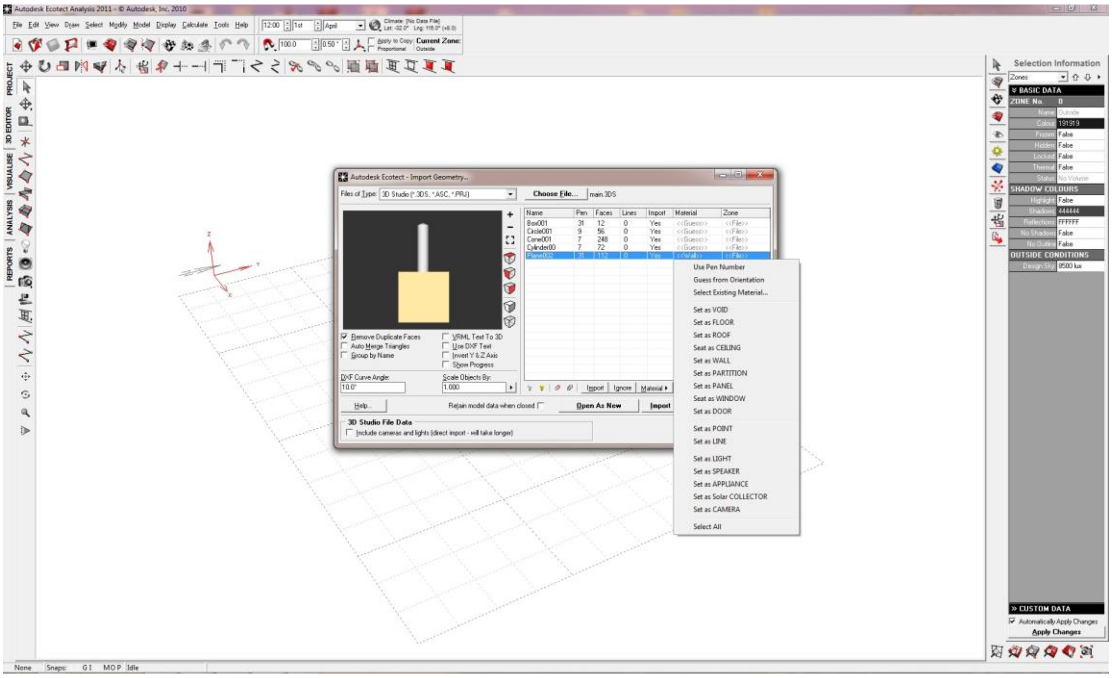

**Figure 7: Showing the options to appear when you click the material slot (The "select existing Materials" is the option to select from the menu)**

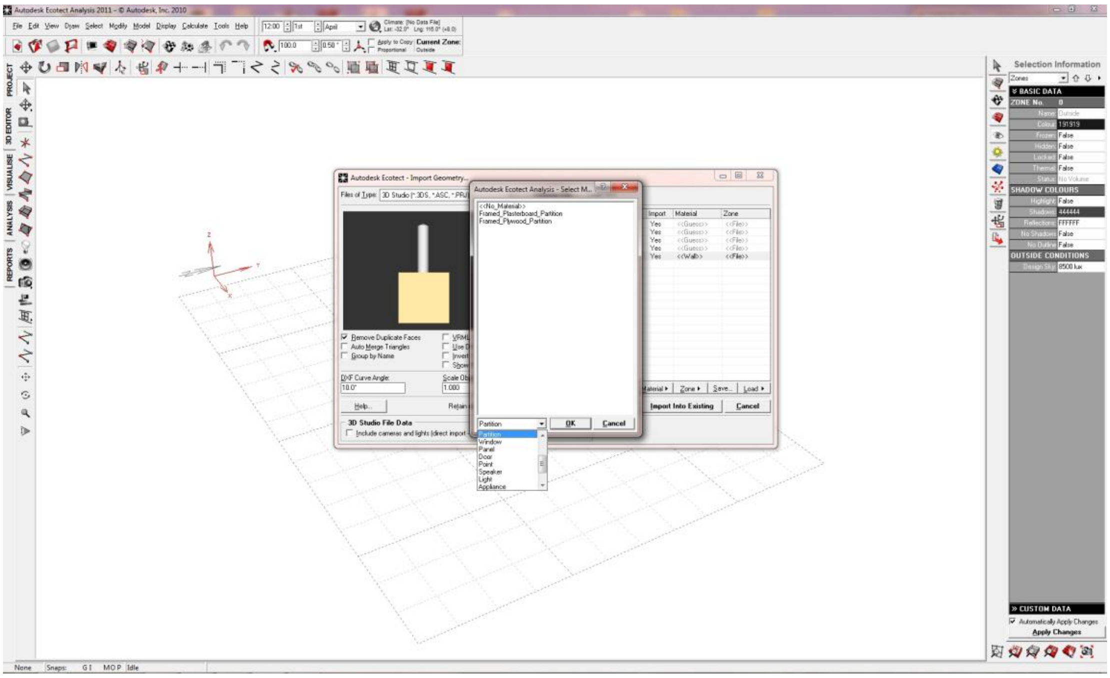

**Figure 8: Showing the process of applying materials**

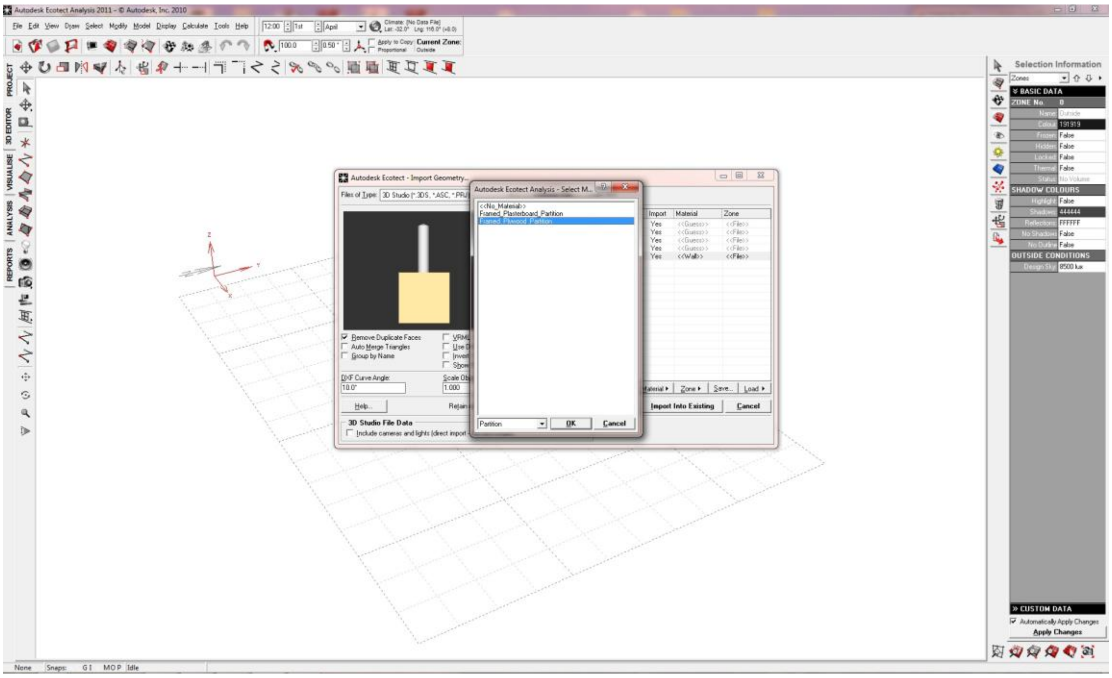

**Figure 9:** **Showing the process of applying materials (applying plywood to the box)**

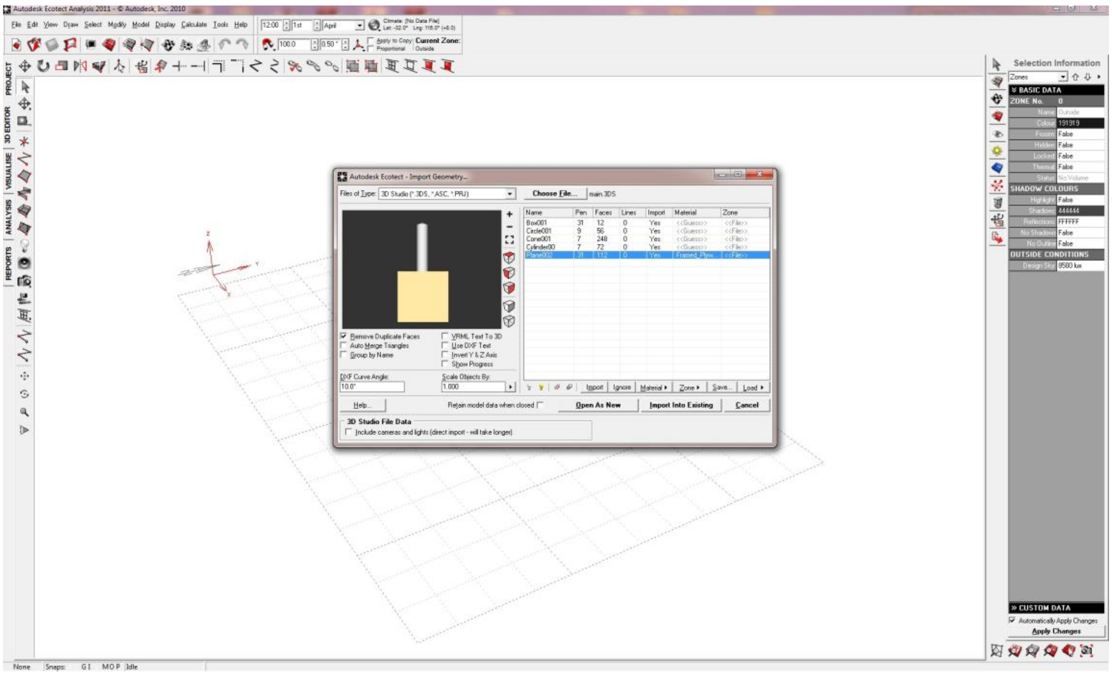

**Figure 10:** **Applying process completed for one of the objects (the box) the same process of applying materials is repeated for the remaining objects.**

Finally after all materials are applied you then finish your import by clicking the "Import Into Existing" button.

**Placing a camera**:

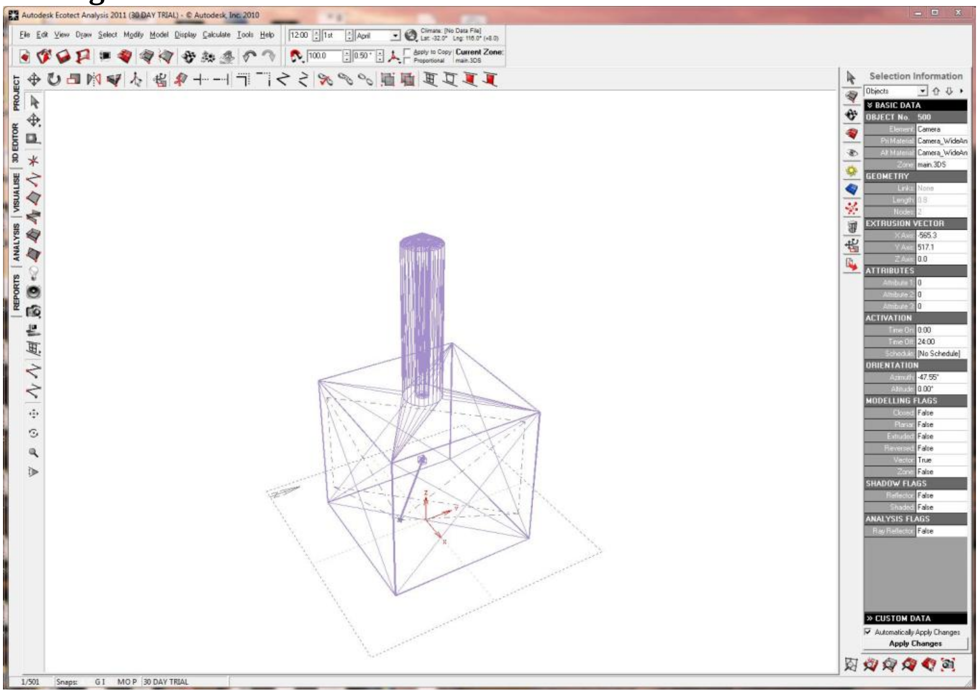

**Figure 11: Showing the Model after importing into Ecotect and all materials applied.**

The next step is to place a camera view inside the box to capture the lighting analysis within. An interactive camera is best to choose as it will allow you to manipulate the angle of view the way you want it.

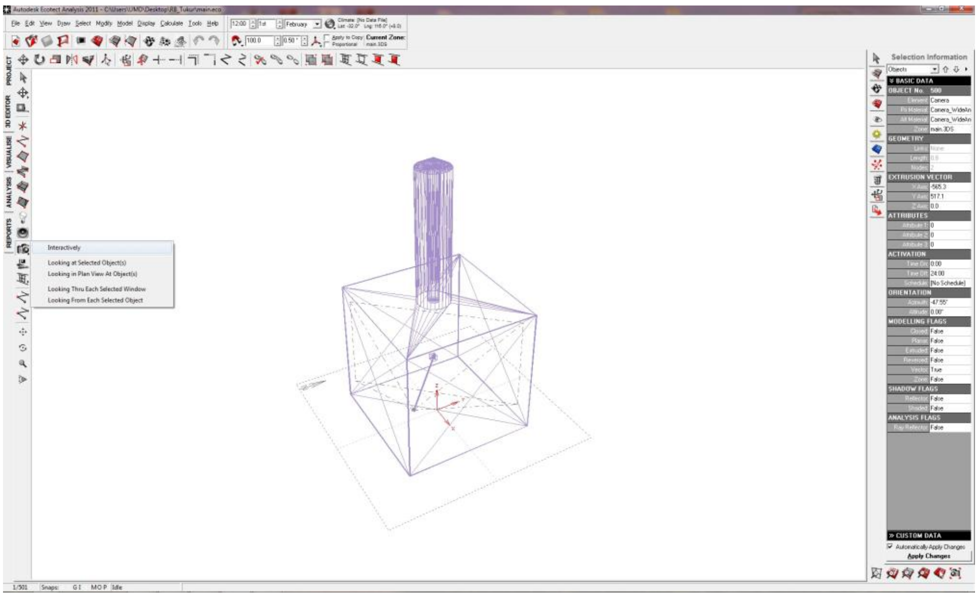

**Figure 12: Shows how to select the camera.**

After selecting the camera, just simply click inside the box and drag in the direction you want the camera to view (see figure 13)

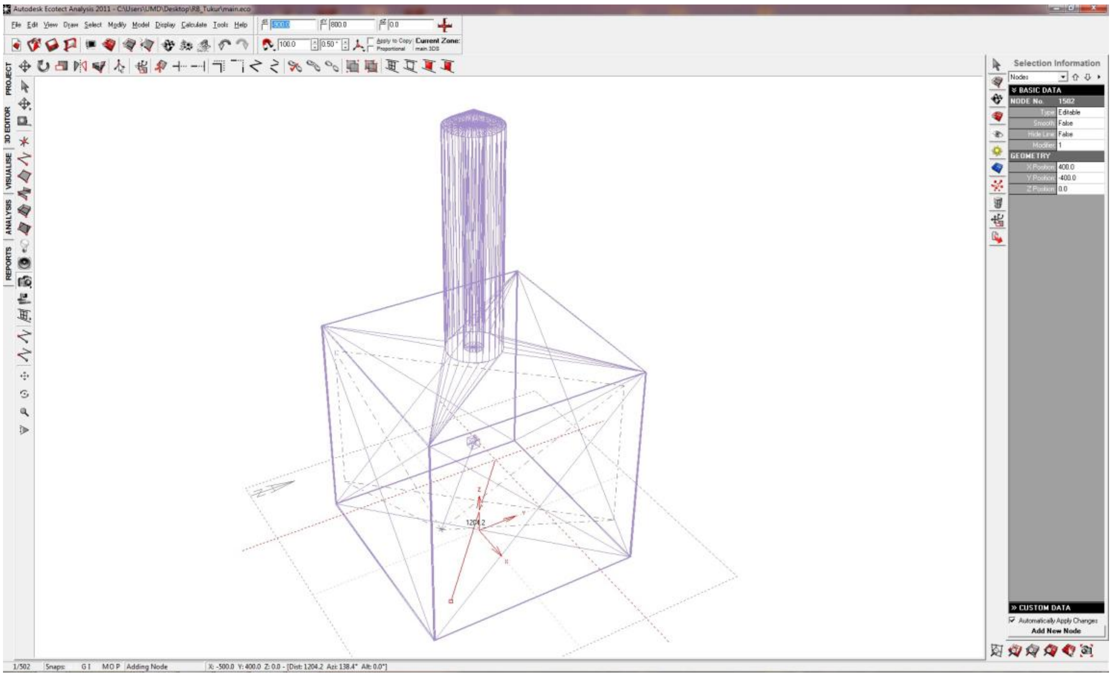

**Figure 13: Showing how to place the camera (highlighted in red lines)**

**The simulation process: after placing the camera. The simulation process begins by clicking "calculate" in the menu bar and selecting "Lighting Analysis" (see figure 14)**

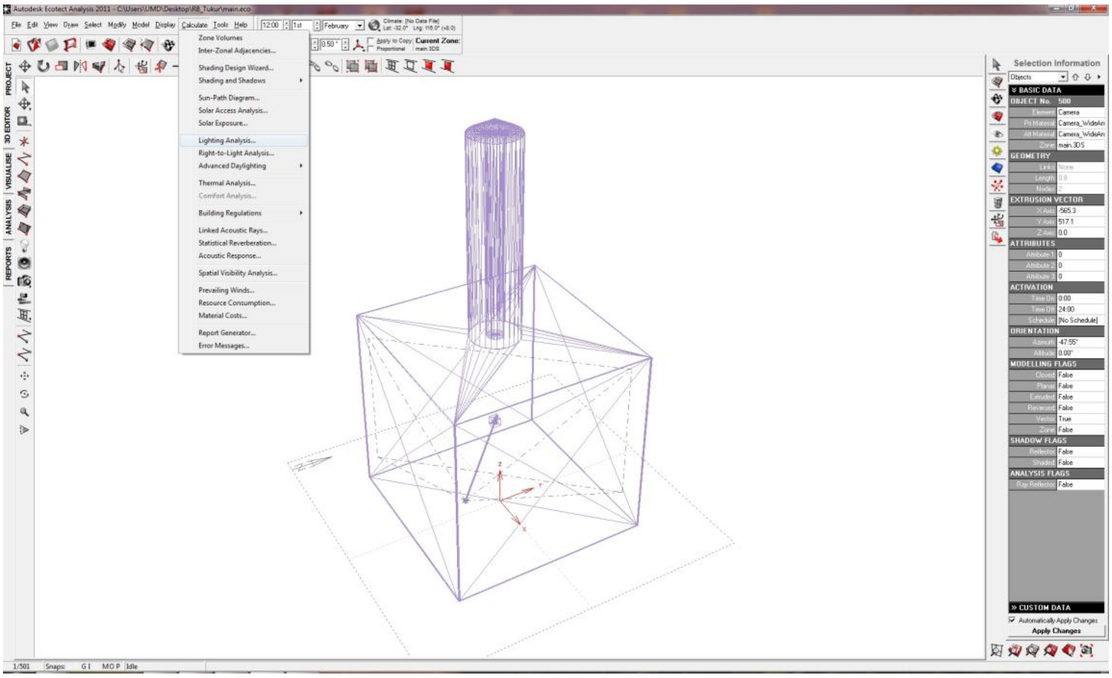

**Figure 14: Showing the beginning process of the simulation.**

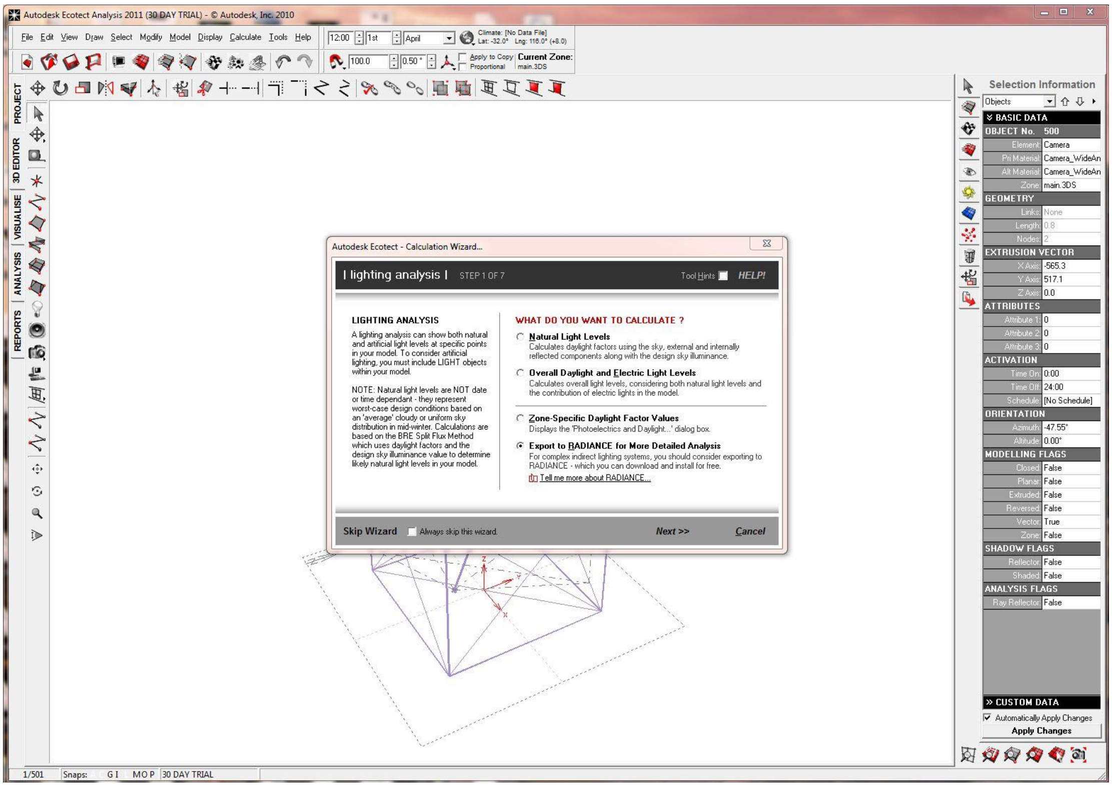

**Figure 15: Showing the first dialogue box to appear after clicking the lighting analysis. Export to radiance is the option to select.**

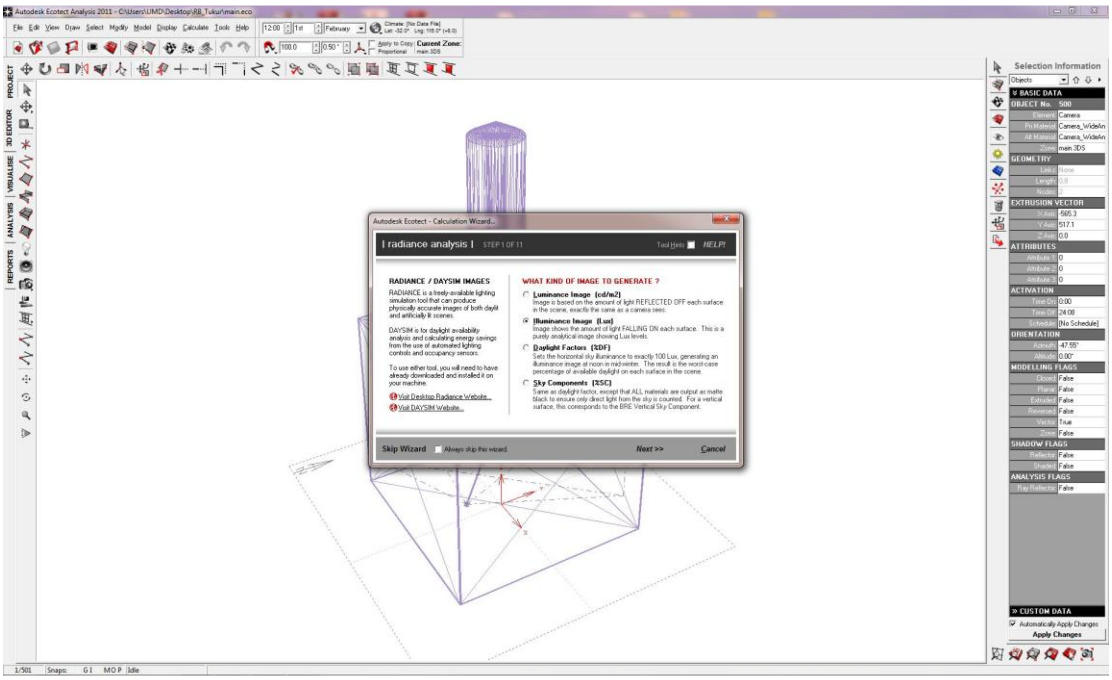

**Figure 16: Choosing the unit for analysis which is in “Lux”.**

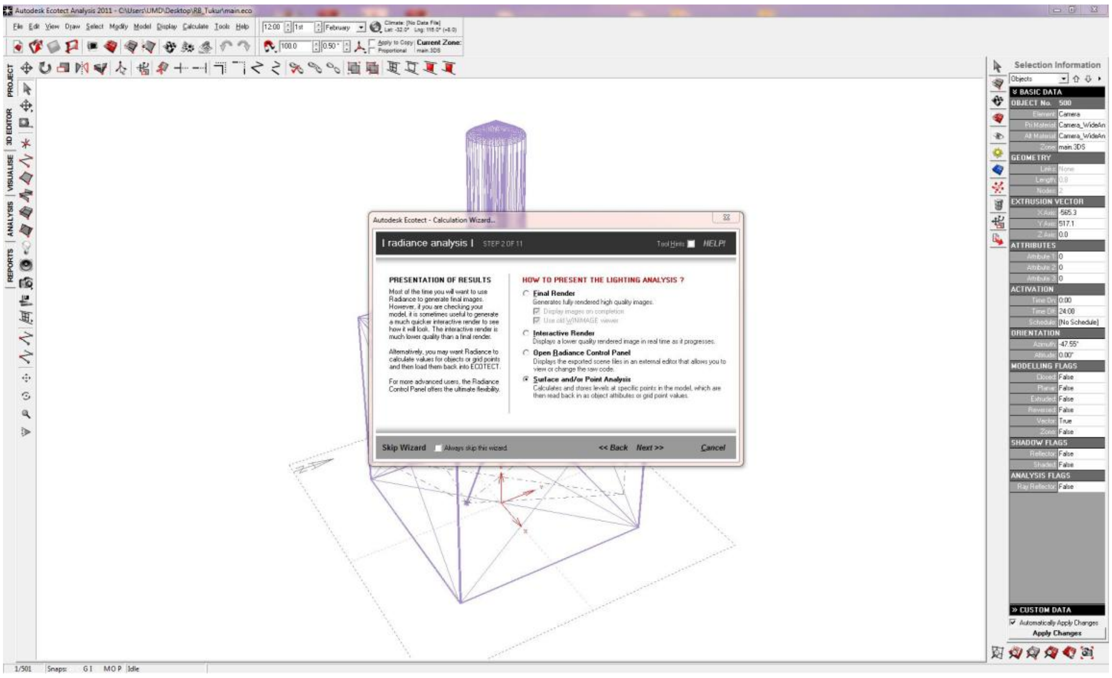

**Figure 17: Choosing the surface or point analysis option; this enables the box to store the illuminance analysed in every bit of it's surface. This can be extracted by clicking any point on the surface.**

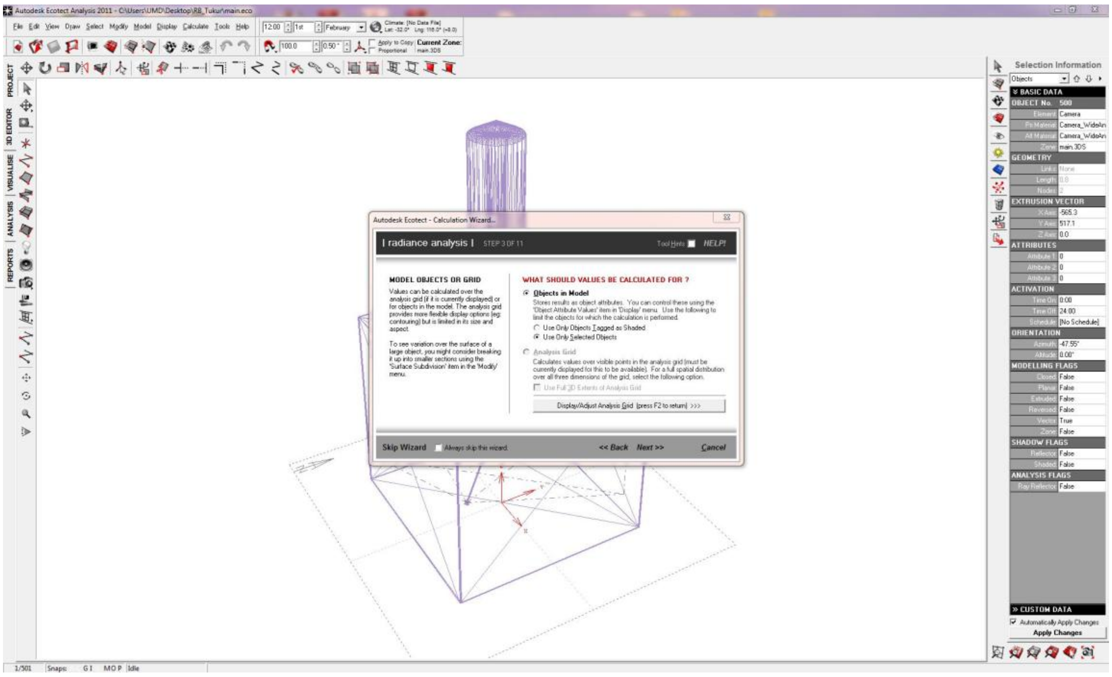

**Figure 18: Use the default (as it is) just click next**

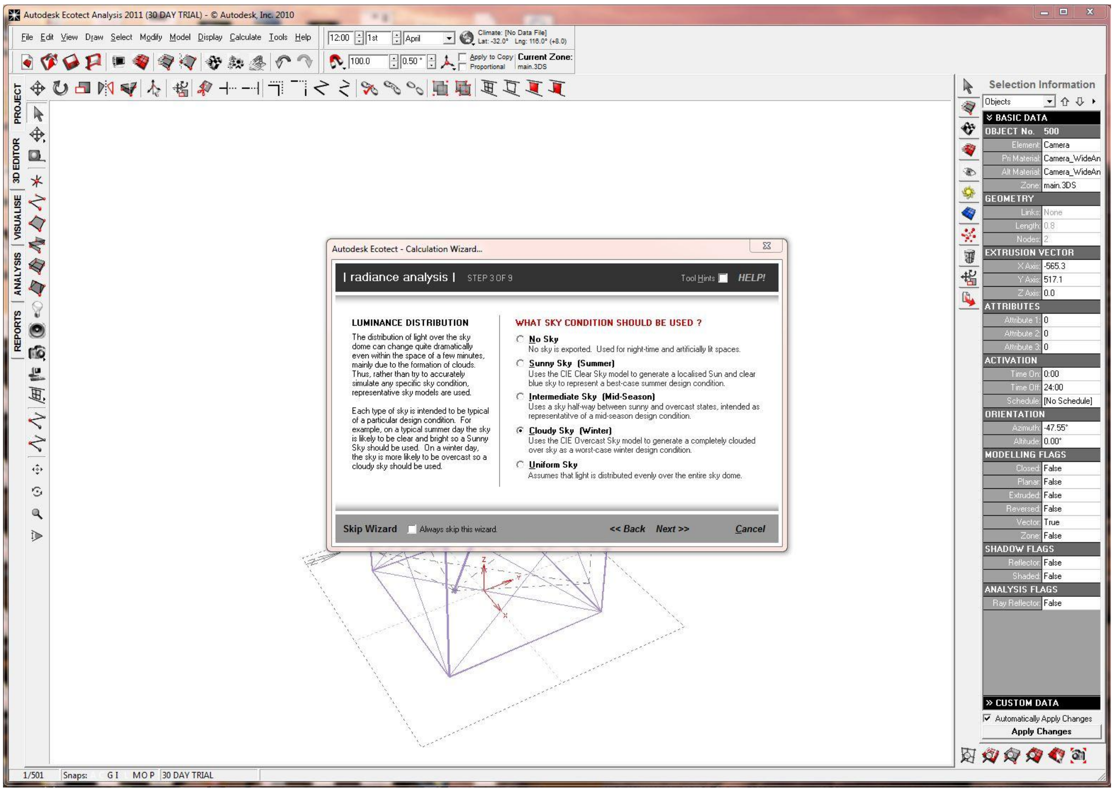


**Figure 19: Choosing the sky characteristics of you  location**

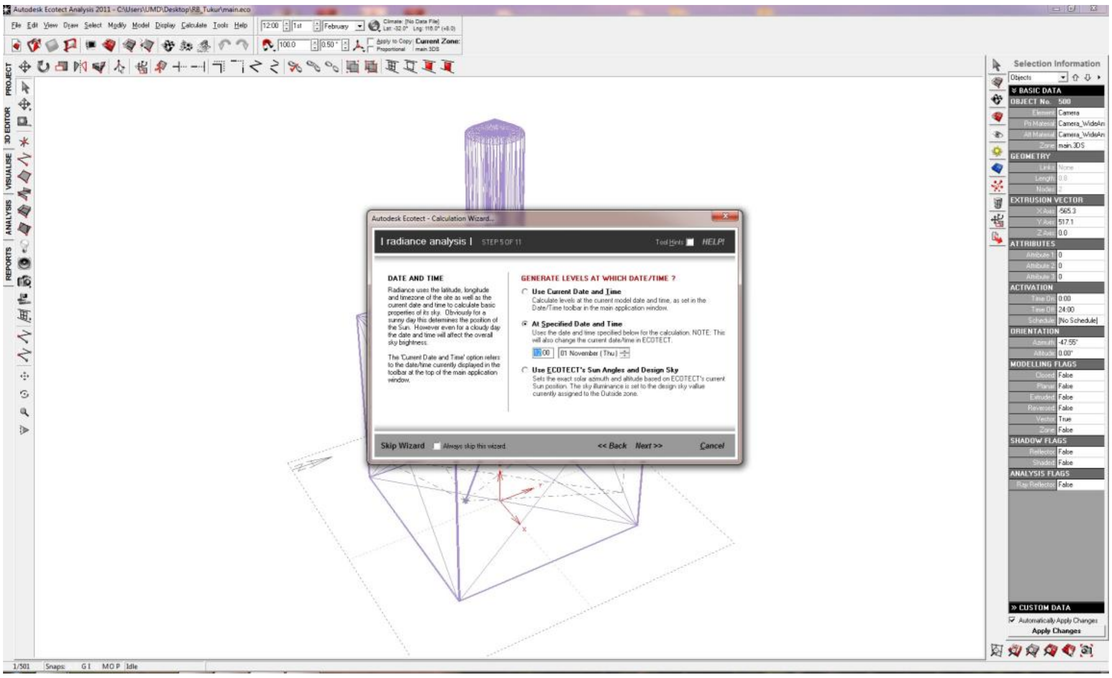


**Figure 20: Specifying the month and time of the Day.**

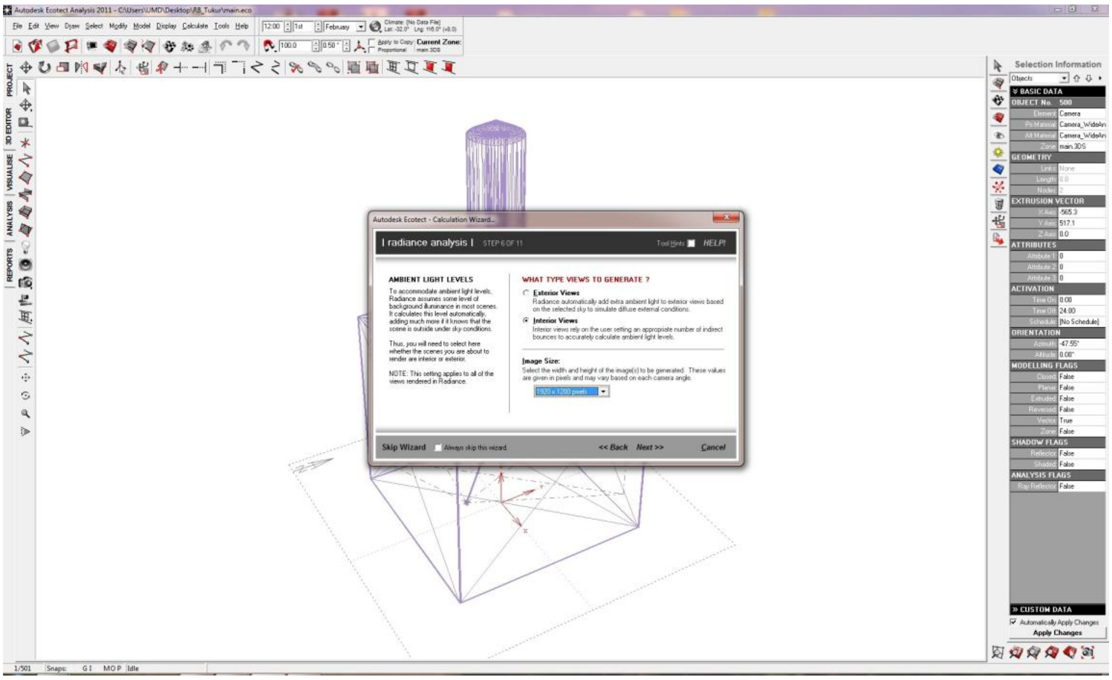

**Figure 21: Choose the interior view because the camera is viewing inside the box. And specify the image size you want.**

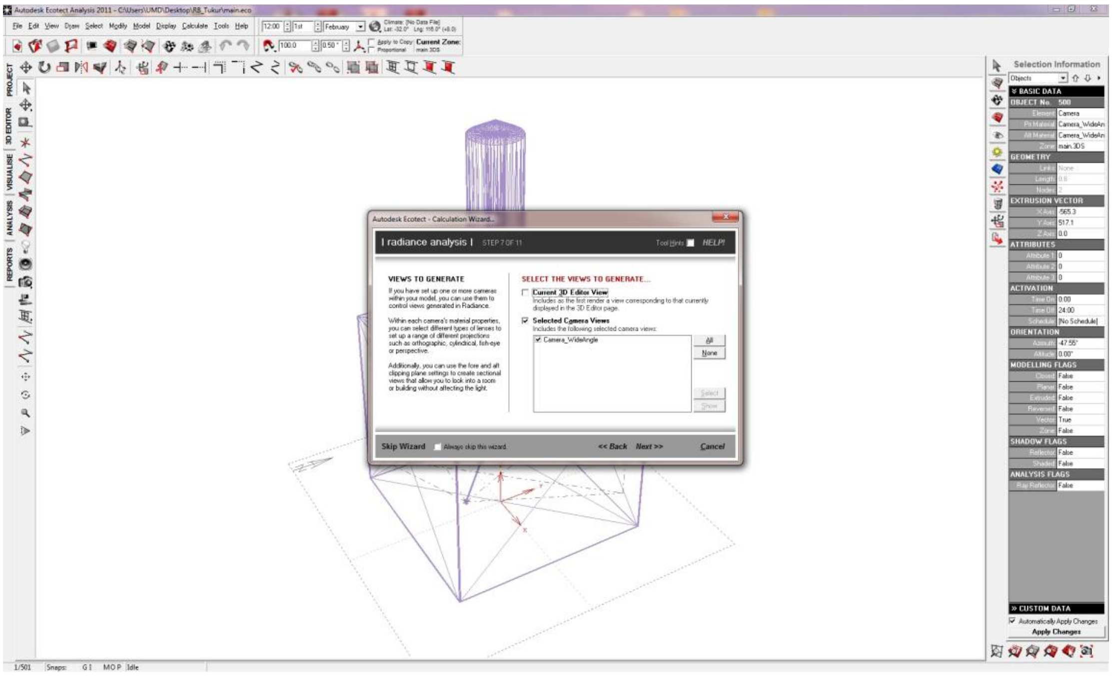

**Figure 22: Selecting the camera to render (this will be more useful if you have more than one camera in the scene so you select which one you want for the analysis)**

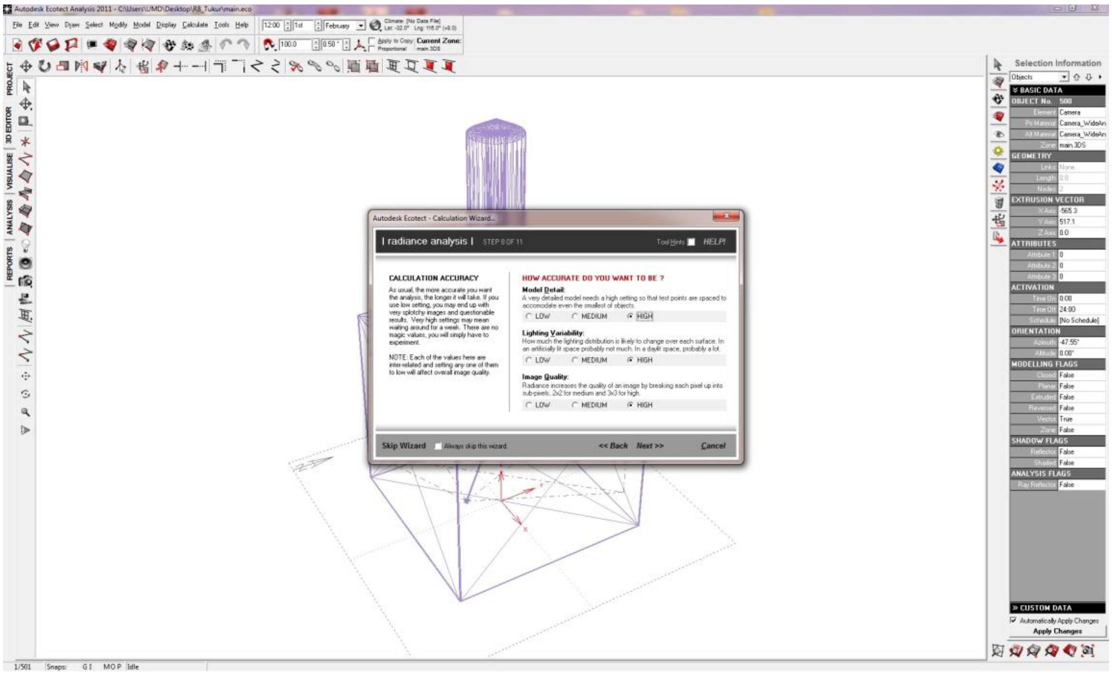

Figure 23: Choose the resolution and accuracy of the analysis. High gives more accurate result and better resolution but it takes more time to do the analysis. While vice versa for the Low

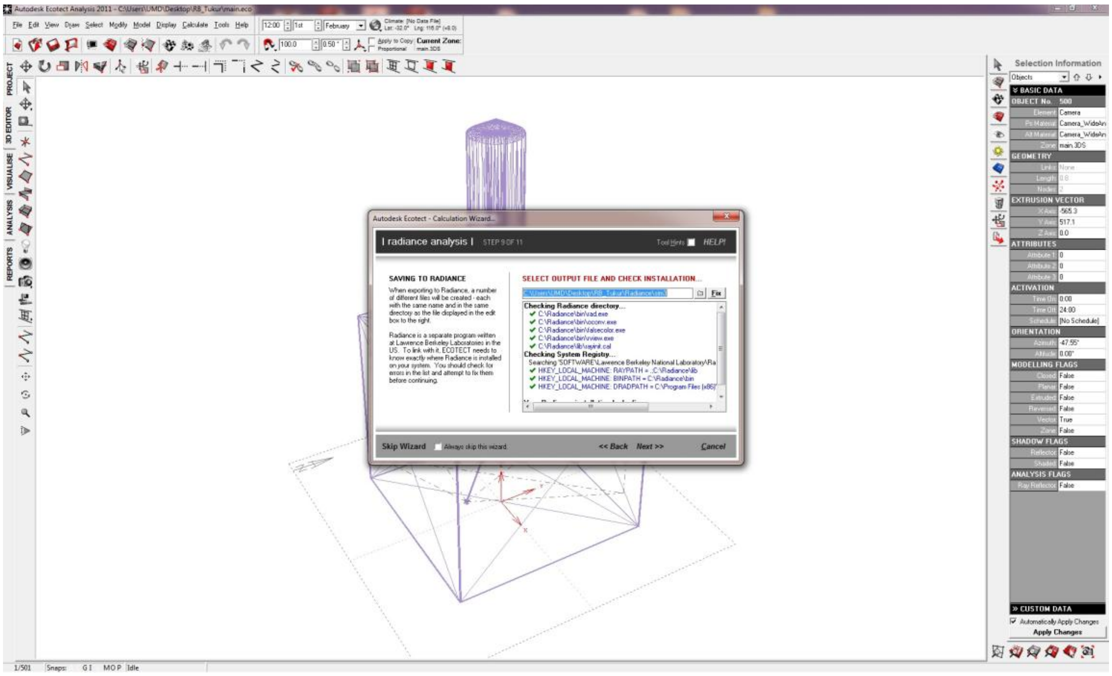

Figure 24: This is just telling you that all radiance file are set for the analysis and ready to be exported to radiance. Click next

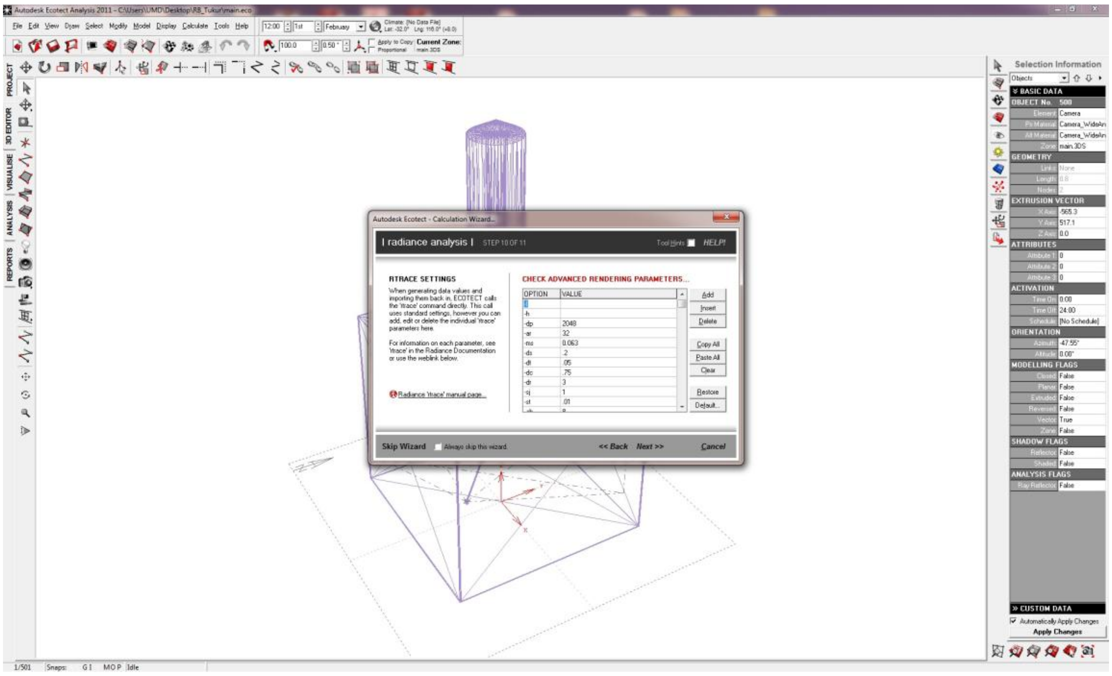

**Figure 25: Just an overview of the parameters set earlier.**

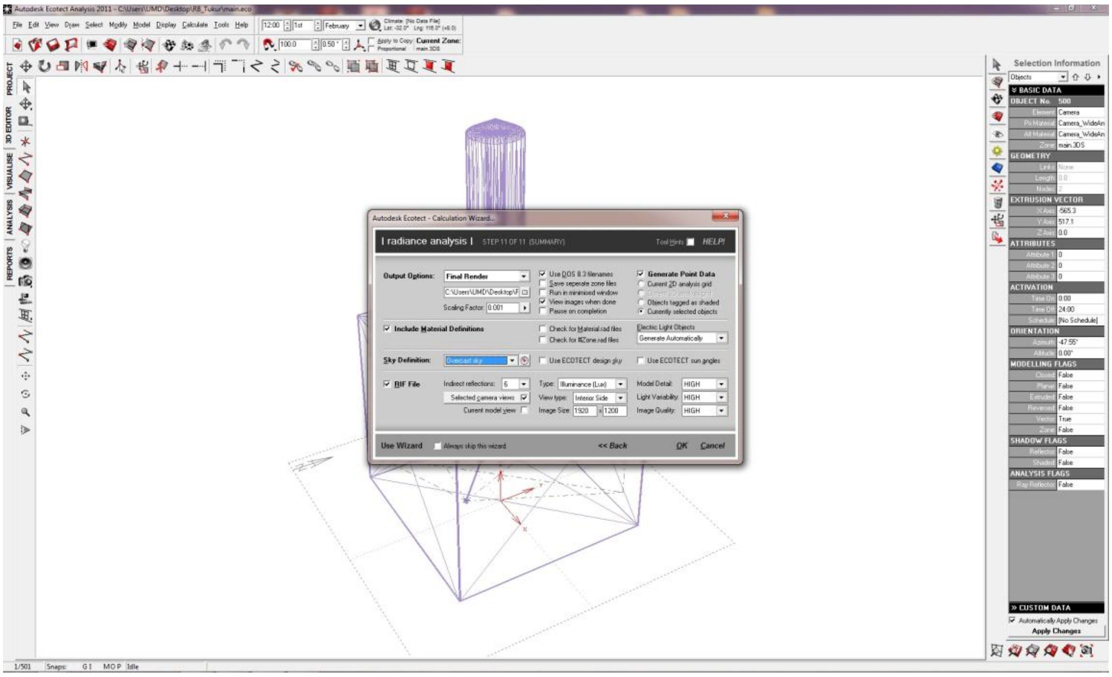

**Figure 26: A final check on the parameters. Click next to start the analysis.**

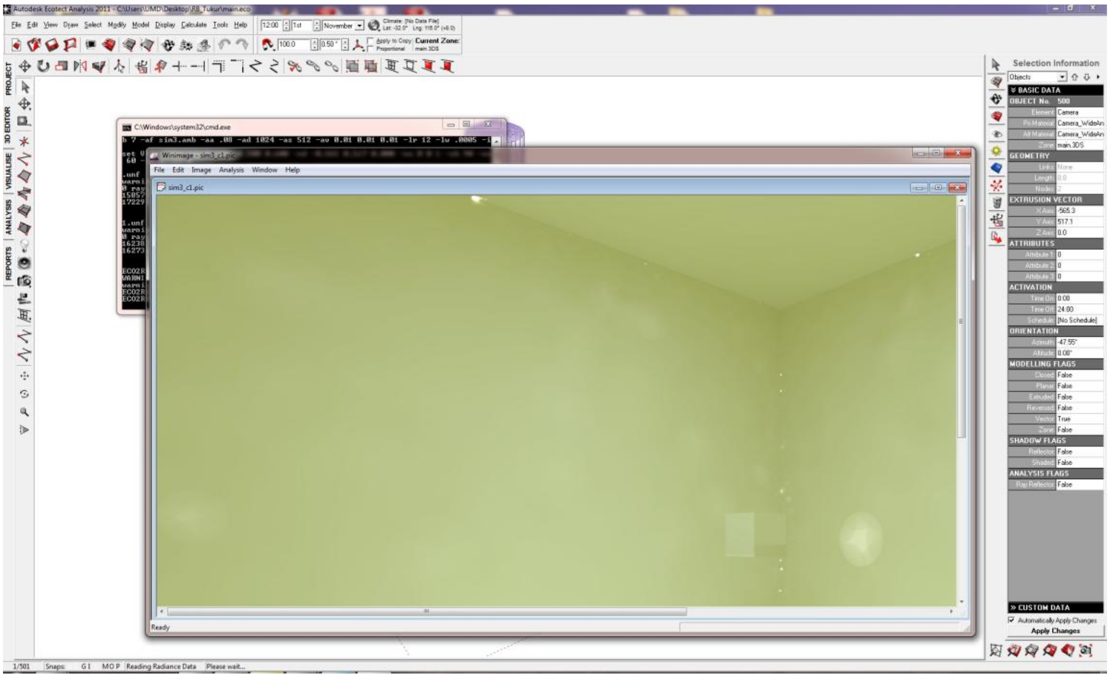

Figure 27: Analysis in progress, the image is illustrating the rendering inside the box from the camera's view.

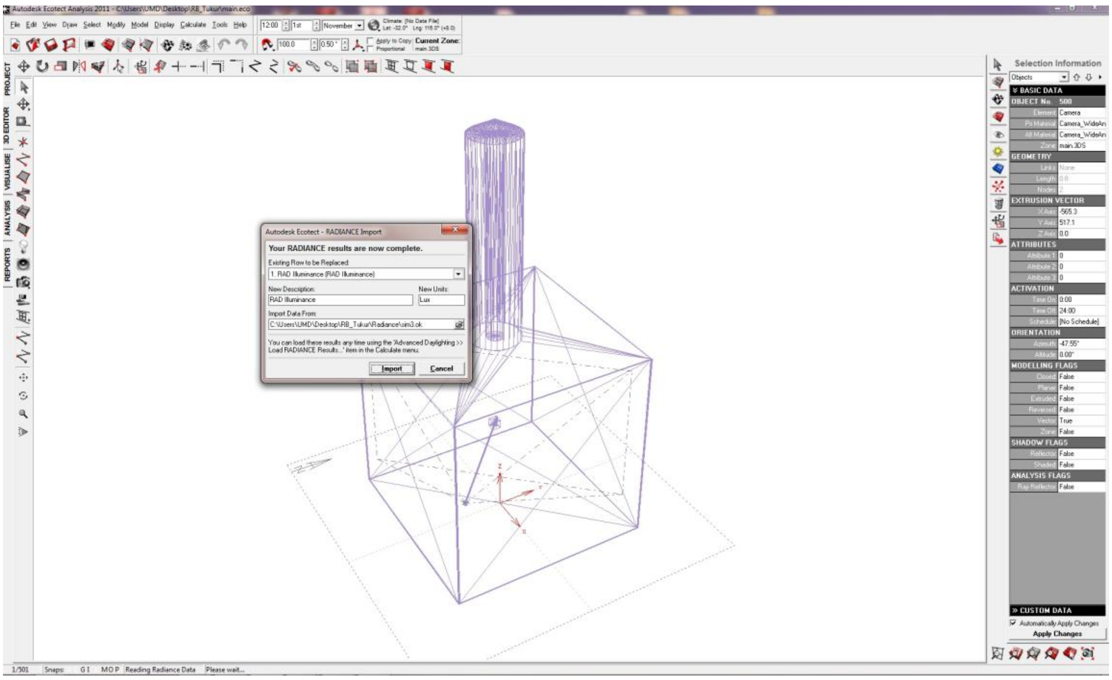

Figure 28: Analysis completed and a dialogue box will prompt you asking to import the result. Click import. The result file will be saved as an interactive pic file.

Checking the results: under "Tools" in the menu bar click the "Edit Radiance Project" to check your result. A dialogue box will appear

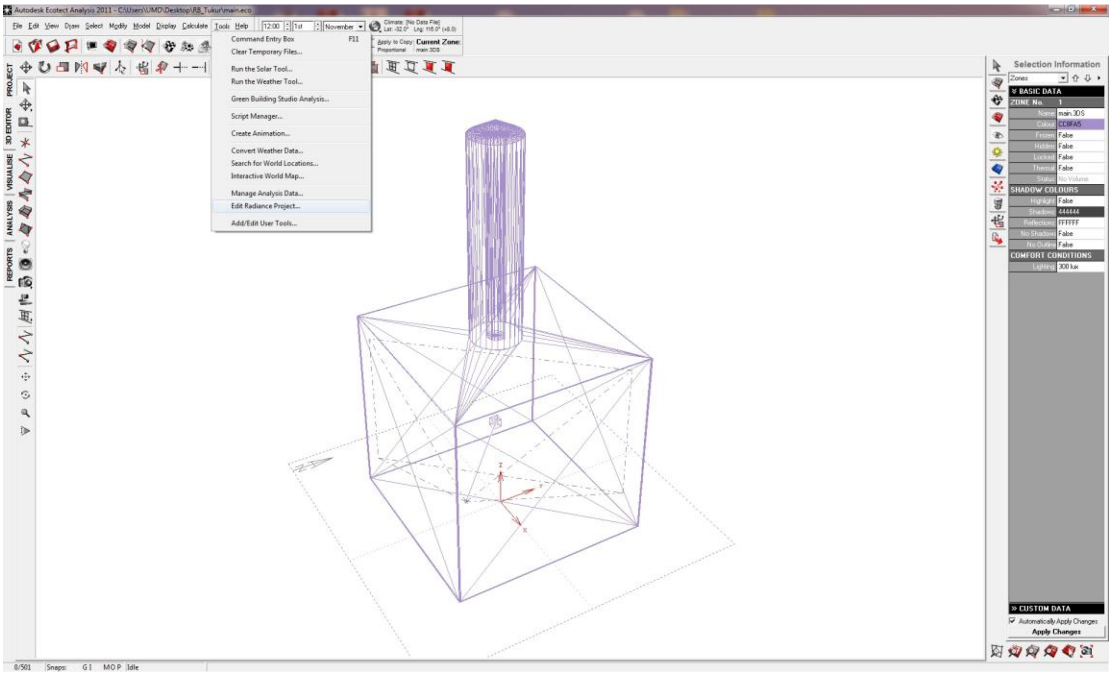

**Figure 29: Checking  your interactive result.**

Click the "Add" button in the dialogue box and locate the .pic result file you saved on completion of the lighting analysis process (see figure 31).

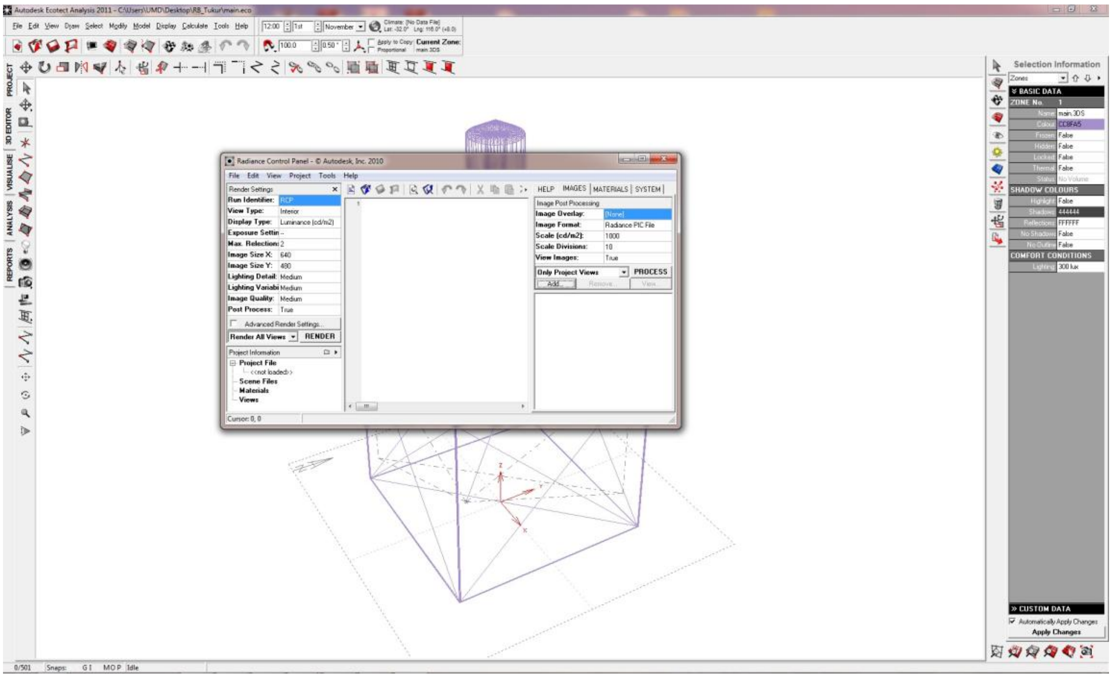

**Figure 30: Locating your "picture" result file 1**

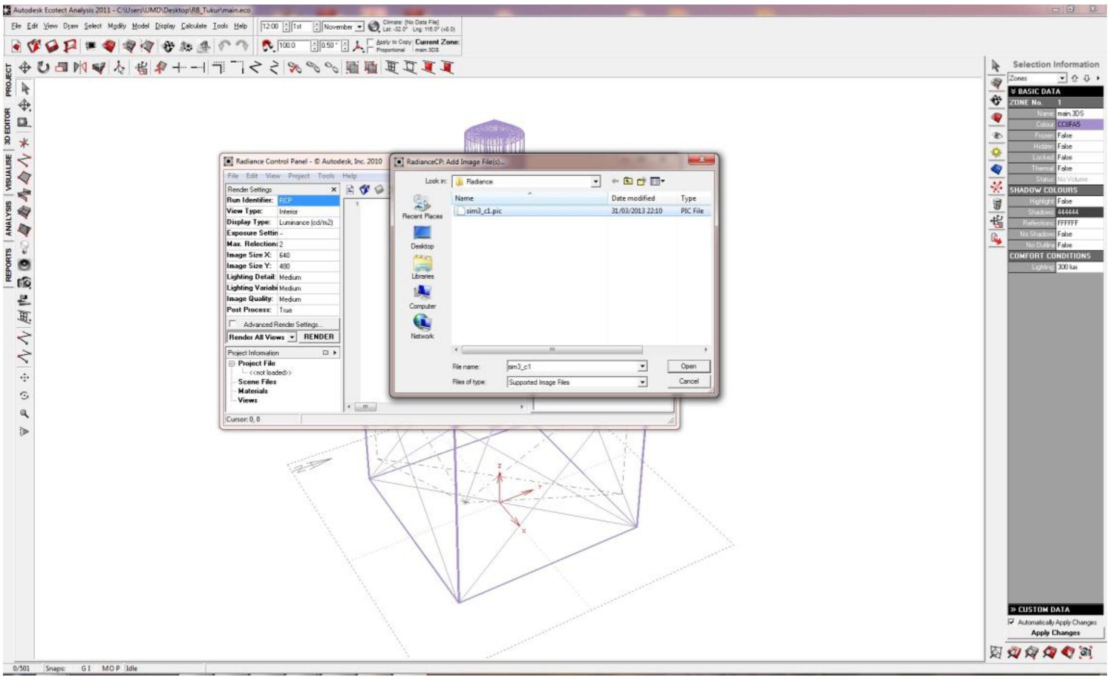

**Figure 31: Locating your "picture" result file 2**

**When the file is being located and selected. Click on it to highlight (in blue) then the "view" button will be active, go ahead to click it, a regenerated rendered image of the box will appear after some seconds or minutes. The image will look the same to that generated during the simulation. However, there is a bit of difference, the image being generated now contains the illuminance value of every spot in the box which can be extracted by just clicking inside the image. Thus the illuminance value at the center of the box is shown by clicking in figure 33.**

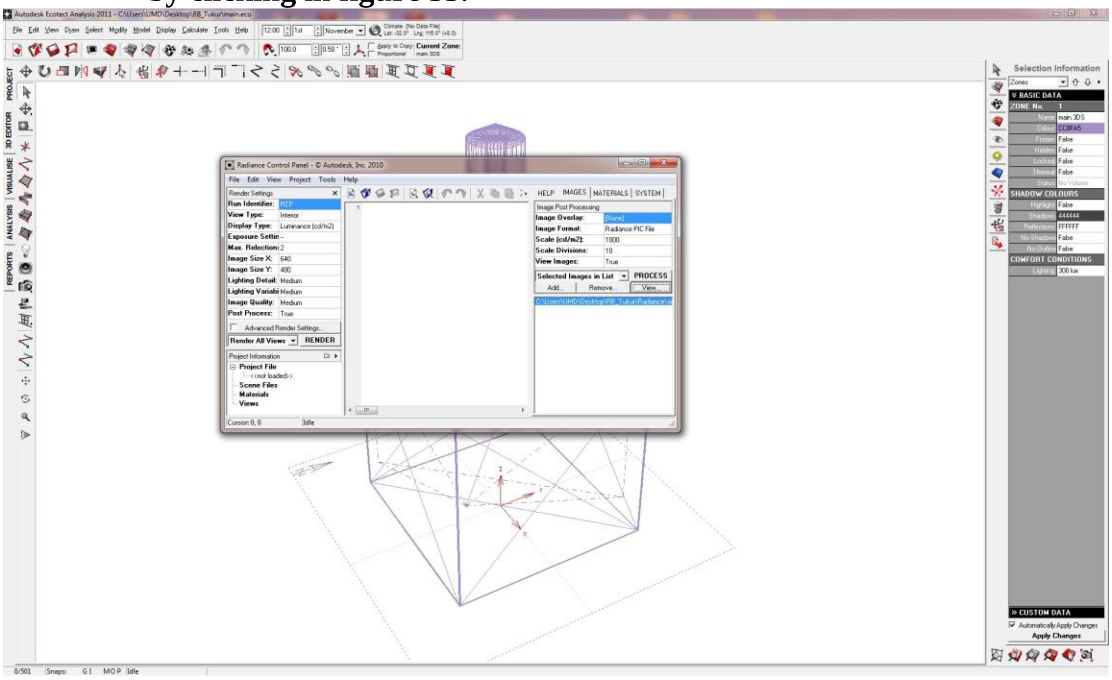

**Figure 32: Regenerating the selected "picture" result file.**

## 11. Appendix 3: Sample of Skye® Light Sensor Calibration Certificate


**SKYE INSTRUMENTS LTD.**
**21, DDOLE ENTERPRISE PARK,**
**LLANDRINDOD WELLS,**
**POWYS. LD1 6DF. U.K.**
**TEL: +44 (0) 1597 824811 FAX: +44 (0) 1597 824812**
**email: skyemail@skyeinstruments.com**
**website: www.skyeinstruments.com**


### CALIBRATION CERTIFICATE No : LUX/024/1209

| | |
|---|---|
| **UNIT TYPE :-** | PHOTOMETRIC SENSOR (LUX CALIBRATION) |
| **SERIAL NUMBER :-** | SKL 312/S 36999 |
| **OUTPUTS :-** | 0.7407 µA / klx |
| | 100.0 µV / klx |
| **DATE OF CALIBRATION :-** | 27/11/2009 |
| **LAMP REFERENCE :-** | SK3 |
| **A/D UNIT :-** | 039353 |

Calibrated against a National Physical Laboratory UK reference standard lamp.
Uncertainty ± 5% (typically < ± 3%) based on an estimated confidence of not less than 95%.

Calibrated By :- ....................................................

Checked By :- ....................................................

Issue Date :- 14-12-09

THIS UNIT IS DUE FOR RECALIBRATION WITHIN 2 YEARS OF THE ABOVE CALIBRATION DATE.

| | |
|---|---|
| Date of Last Calibration :- | N/A |
| % Change Since Last Calibration :- | N/A |