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Department of Engineering

Smart Building Envelopes

4TH Year Project Report

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TECHNICAL ABSTRACT

This project looks into the development and performance of new smart technology that helps to reduce excessive energy loads used in buildings. Building physics and the improvement of energy efficiency associated with it is a very important area of engineering research and development in the world today, with 40% of the world's carbon being consumed in maintaining a comfortable interior environment. One of the most susceptible building facades for high amounts of energy loss is glass, and with modern architectural movements in using glass to create 'honest' buildings accentuated by light and space, the use of glass facades is ever increasing.

Driven for the need for better insulated zero-carbon buildings, a new generation of actively-controlled components, are starting to replace conventional materials. These smart devices are able to respond to seasonal variations in temperature and solar radiation. Such advancements in 'smart' windows will stimulate the continued use of glass as a building facade and also reduce the energy loads associated with achieving a comfortable internal environment. The foundation of this project is to address the performance of new switchable chromogenic glass, and more specifically 'SPD SmartGlass'. SPD glass uses suspended particle device technology which gives an electronic control of light and heat transmission by altering the 'tint' of the window. When switched on the glass turns clear and allows for around 45% visible light transmission, and when no current is applied the glass holds a blue tint and allows less than 1% visible light transmission. In all states of transparency the glass rejects over 99% of UV light transmission.

SPD glass transmission properties can also control the heat flow into a room by rejecting solar heat gain. This investigation is primarily focused on the associated reduction in energy cooling required to maintain a user comfortable room environment. Experimental design was divided into three main components; laboratory testing, real-world testing, and environmental modelling. Laboratory testing took place using a small sample of SPD glass and was carried out in order to gain a better understanding of the glass's transmission properties at varying voltage level. Potentiometers were attached to the SPD circuit in order to control the variation of voltage, and the change in light intensity received through the glass was measured.

Real – world testing of the windows was carried out in an office within the department. SPD windows were installed over the existing single glazing and the room environment was measured over a month. At the same time measurements were also taken in the identical adjacent office with regular single glazing, which acted as a reference to the performance of the SPD windows. Conditions measured were room temperature, solar heat temperature, and user comfort. This aspect of the investigation was designed to give accurate knowledge into the real-world performance of the SPD glazing, and whether it would be a suitable technology to be used in everyday situations.

Environmental modelling was carried out by IESVE software, which is used to evaluate the energy and overall performance of a building. Two models were made of the test office and surrounding building, with one using SPD glazing, and the other regular single float glazing. It was desirable for the models to be an accurate representation to the test office in order to compare virtual results and real-world data. The IESVE software is able to quantify numerous values of the room's performance and conditions, and for this investigation, the air temperature, solar heat gain, and cooling loads were compared between the two different glass facades. Simulations were primarily carried out for the Cambridge location, though extra simulations were carried out in other hotter world locations to evaluate any difference in SPD performance.

Results from the laboratory experiment showed that the relationship between voltage applied to the glass and optical light transmission is not directly proportional. User feedback from the windows also suggested that the operation of the windows should come with a variable setting to increase light control and exact 'tint' of the glass. The variable change in light transmission as a function of voltage would need to be accounted for in producing an operational dial for the user.

Results from the real-world testing of the windows showed that the SPD glass was able to provide a much more uniform and comfortable internal room temperature than regular single float glazing, with fluctuations of only 2°C compared with 8°C. Temperatures recorded as a result of direct sunlight showed a difference of up to 15°C in the two offices, with temperature exceeding 40°C through the single glazing, and not rising above 30°C for the SPD office. In conclusion the SPD glass was able to reduce the heat energy gain into the room, and thus actively control the room temperature. This technology would therefore lower the energy costs of cooling interior environments during the hottest parts of the year.

Environmental modelling results showed great similarity with the trend in real-world measurements. The control of air temperature fluctuation was shown to be identical with a minimal variation while using SPD windows. Quantitative figures were able to be calculated by the software for solar heat energy reduction and subsequent cooling loads reduction. It was found that the SPD windows reduced the solar heat gain by 90% compared to single glazing, which translated to a 65% reduction in cooling loads associated with the UK location (from 0.4605 MWh to 0.1632 MWh). Worldwide simulations showed similar levels of energy saved through solar heat rejection in hotter climates, although with much larger magnitudes of energy saved. In conclusion the SPD windows were shown to be much more energy efficient than regular clear float glazing.

Overall this investigation has determined that SPD 'smart' switchable glazing technology offers a realistic and promising alternative to conventional glazing. The performance of SPD glazing helps to reduce wasteful cooling loads during the hot periods of the year, and thus will improve the energy efficiency of buildings today.

INTRODUCTION

1.1 Project Introduction

The study of building physics is becoming an ever more popular and necessary direction for engineering research and development worldwide. This includes in particular the energy conditions and efficiency surrounding the usage and maintenance of everyday buildings. For the majority of commercial and domestic buildings worldwide it is a desirable requirement to maintain a comfortable interior environment, and due to the extremes of external environmental conditions this requires energy. Energy consumption and wastage is a worldwide concern with global warming caused by excessive greenhouse gases in the atmosphere as well as rapidly diminishing non-renewable resources. There are two important directions associated with tackling these problems; to convert energy generation to renewable 'non-carbon' resources and to reduce the amount of energy consumed by society. This study focuses on the latter of these ideals and on new 'smart' technologies that aim to reduce the high energy wastage in buildings. A leading area of these new intelligent systems is the development of chromogenic switchable glazing, also none as 'smart glasses'. These 'smart glasses' have the ability to modulate optical and thermal properties, and therefore are able to adapt to prevent undesired energy flow through a glass façade.

While briefly looking at the various smart glass devices this project focuses on the performance evaluation of electrochromic switchable technology, and more specifically, suspended particle device (SPD) glass. SPD glass is able to control its optical properties by the application of an electrical current to the glass, and holds great potential in being able to reject solar heat gain into an internal environment. A reduction in solar heat gain during summer months and hotter climate could result in significant energy saving in terms of cooling and air conditioning.

This investigation hopes to gain a quantitative value and conclusion into the energy saving potential of this product in comparison to regular clear glazing. Performance data will be measured using the SPD glass in an actual real-world environment and compared with measured data using clear float glazing. In addition to this environmental modeling will be carried out using computer software to analyze the energy performance of the SPD windows. It will therefore subsequently be possible to compare the performance conclusions between a real-world and virtual environment and to comment on the accuracy of such simulation modeling. Real-world testing of this smart technology will also be able to build a better understanding into the user comfort of such a glass façade and whether it is actually a viable solution to the improve the energy efficiency of glass. In theory, chromogenic switchable glazing is a cost and energy saving technology that will improve the internal environment of a building, while still upholding the aesthetic attraction associated with glass façades in modern architecture.

1.2 A Brief History of the Glass Facade

Glass has been produced and used by mankind for thousands of years, and its use as a building facade¹ has developed significantly with technological advancements in production and the evolution of architectural design. It was during the Medieval Era that glass was first widely used as a decorative feature, and not just a means of letting light in. The architectural trend of Gothic churches encouraged the use of stain-glassed windows to illustrate biblical scenes, and set a future trend for the transparency and luminosity of glass. It was not until the industrial revolution however that there were substantial advancements in producing large sheet glass, as well as the introduction of new construction materials to hold larger glass facades in place. These developments opened up numerous possibilities of using glass in construction and it was during this time that architects experimented with the design of glass conservatories, and entire walls of glass. A famous example in such glass projects is The Crystal Palace, built in 1851, and consisting of 300,000 sheets of glass [1].

Architects use of glass during the 20th century evolved and flourished with the dominant idea of transparency and dematerialisation, in which architects created 'honest' buildings that accentuated the quality of light and space. Architect and glass enthusiast Scheerbart expressed his opinion on the importance of glass in architecture [2];

"If we want our culture to rise to a high level, we are obliged for better or for worse, to change our architecture. And this only becomes possible if we take away the 'closed' character from the rooms in which we live. We can only do that by introducing glass architecture, which lets in the light of the sun, the moon, the stars, not merely through a few windows, but through every possible wall, which can be made entirely of glass."

An important change during later parts of the century was the change in view of the structural use of glass. Instead of glass being a material for an opening in the structure, it could be used as the material for the structure itself. The development of glass skins and suspended glass techniques during the 60s enabled the construction of steel structures which literally supported skyscrapers of full glass walls [1][3]. Modern day innovations in glass technology continually open up new doors for the use of glass in architecture and have resulted in some spectacular building projects, for both corporate skyscrapers and domestic homes. The use of glass within architecture has come on a long way, and with constant technological advancements, the limitations of glass facades forever diminish.

¹ definition of facade is the face or front of a building; as well as acting as an adjective for an architectural design concerned with elegance

1.3 The Energy Cost of Glass

An important role of most buildings is to act as protective barrier against the outside environment, and daily climatic fluctuations. While buildings in general will have varying functions, purposes, and jobs so to speak, it is a fundamental requirement that the users inside have a comfortable environment to carry out whatever task that the building exists for. User comfort within buildings is seen as very important, with worldwide government guidelines and laws restricting the allowable temperature fluctuation within public buildings and working offices. User comfort is also very expensive in terms of energy consumption as well, with heating and cooling usually required for the majority of the year in most climates. The energy that is currently used worldwide to keep the internal building temperature at a comfortable level contributes to 40-50% of the world's carbon [4]. This amount is quite staggering if you imagine the current global position of climate change, and push to switch to renewable energy resources. With future predictions of energy shortages and increased cost of energy, there is currently a huge push by the government to encourage the saving of energy within all areas of day-to-day life. It's therefore not a surprise to see the energy saving potential of building physics to be on the increase of both political agenda and engineering development for the future.

Energy reduction strategies within buildings are numerous and can consist of some of the following; energy-efficient appliances, good insulation, a smart natural ventilation strategy, heat pumps, thermal storage, intelligent solar shading, etc [4]. In summary, these all act to reduce the undesirable heat flow in and out of a building, which is where the increased use of glass facades can cause a problem. Glass is a very lightweight building fabric in comparison to heavyweight structures like masonry that can absorb most of the daily temperature fluctuations. The high transmission properties of glass, and in particular, its solar radiation transmission properties can cause a thermally unstable and uncomfortable internal building environment. Buildings with even small amounts of building facades will experience overheating in the summer and high amounts of heat loss in the winter without the use of devices such as blinds (which remove one of the original purposes of having a glass facade). The historical approach to overcome this thermal in-balance was to depend entirely on heating and cooling systems, which has caused environmental awareness into the high energy waste of air conditioning systems. While glass itself is environmentally friendly in production terms and recyclability (manufactured from silica which is one of the most abundant elements on earth), and holds numerous other irreplaceable advantages - natural light improving visual comfort, reduction in artificial lighting loads, and pleasant external views etc. – its thermal transfer and solar radiation problems have to be addressed if glass is to be used as a main material for building facades. Architecturally, glass facades are not going to be dismissed and substituted by more energy efficient materials, however energy efficiency has started playing a much more influential role within building design, and has changed a previously 'aesthetically minded' discipline [3].

Driven by necessity to improve performance, the glass industry has made numerous technological advancements in producing glass with more acceptable thermal conductivity and reduced solar radiation transmission. Such advancements will stimulate the continued use of glass as a building facade and also reduce the energy loads associated with achieving a comfortable internal environment.

1.4 Energy Transmission of Glass

Solar energy is broken into a variety of light spectrums based on the wavelength of the energy. There are three main light spectrums that are transmitted by glass and which affect the internal building environment. These spectrums are Ultra Violet, Visible Light, and Infrared Energy.

Ultra Violet – UV

UV light is broken down to three categories of which two are rejected by the earth's atmosphere, and standard float glass. UVA energy however is able to pass through standard float glass and is the primary component for fading and deterioration of fabric – this is extremely important for museums and galleries which require window materials that achieve the lowest possible UV transmission. UVA energy can be blocked by glass coatings or films that reflect or absorb this light spectrum. [5]

Infrared – IR

This is the radiant heat energy emitted by the sun and determines the amount of heat that is added to an internal environment by the sun. Reducing this transmission will reduce the heat energy added and therefore prevent possible over-heating during summer months. The more infrared energy that a glass material is able to prevent results in the more energy and costs that can be saved due to reduced air conditioning and cooling loads for the building.

Visible Light

This spectrum of light is able to be seen by humans and consists of natural daylight as well as the colour spectrum. While natural light is usually desired in an internal environment compared to the use of artificial lighting it can still generate unwanted problems such as glare and eye strain. Windows are able to reduce the visible light transmission by using 'tints' and therefore control the daylight level within a room. However it is important that the visible light is controlled enough to still allow a certain level of light to enter, in order not to become reliant on artificial lighting and thus increase utility costs.

PROJECT THEORY

2.1 Aims

With the need for better insulated zero-carbon buildings, a new generation of actively-controlled components, are starting to replace the conventional materials. These smart devices can respond to seasonal variations in temperature/solar radiation. The foundation of this project is to address the performance of new switchable chromogenic glass, and more specifically 'SPD SmartGlass'. SPD glass uses suspended particle device technology which gives an electronic control of light and heat transmission by altering the 'tint' of the window. The SPD glass for this project was supplied by SmartGlass International².

2.2 Background into Switchable Technology

Research over the past decade has led to the development of numerous smart adaptive materials to regulate light and energy flows through glass facades. These smart technologies primarily employ the following behaviours; thermotropic, gasotropic, and electrochromic [6].

2.2.1 Thermotropic

This is a passive technology which responds to environmental changes in temperature and can be used to control the infrared emissivity and transmittance of glass, similar to thermochromic glass as well. Thermotropic materials also have the ability to change the thermal conductivity of the glass as well as transmittance values, which holds more energy saving potential. However the thermotropic material will only change from transmissive to reflective at a certain temperature, which needs to be set within the human comfort range for it to have realistic architectural applications. Currently most activation temperatures of thermotropic materials are not in this range and so research and development is still required to alter this transition point. A general disadvantage of passive control systems are also that the performance is only optimized according to one factor (in this case solar heat gain), and cannot be manually overrun to take into account other variables such as the visual light levels. [3]

2.2.2 Gasotropic

The change in optical properties of gasotropic materials is caused by the chemical reaction between a special layer coated on the glass, and a gas fed into the cavity between the two glass panes. Advantages of gasotropic glass is that it is able to retain high transmission

² SmartGlass International are a worldwide supplier of electronically switchable glass, www.smartglassinternational.com

properties in the clear, 'un-reacted' state, and it also experience a fast switching ability, taking 20 seconds to change from clear to coloured, and less than a minute to switch back.

Problems however arise with the complexity of the gas injection system and the build-up of water when hydrogen atoms are added for the chemical process. At this point gasotropic and gasochromic glazing is still not commercially viable but is a technology still being heavily researched in order to achieve marketability in the future. [3]

2.2.3 Electrotropic

Within electrically activated smart glass systems there are three main devices; Liquid crystal technology, electrochromic devices, and suspended particle devices.

LC Technology

Liquid crystal glazing is made up of two sheets of glass surrounding a liquid crystal film. With the application of an electric field, the orientation of these liquid crystal chains can be altered and therefore the optical transmission of the glass also. When no voltage is applied the molecules are randomly scattered and visual light is diffused in multiple directions, giving a translucent 'opal white' effect. When a voltage is applied the molecules align with the electric field and light can pass through unobstructed.

LC power consumption is low in general – less than 5 W/m^2 [7] and the transition from opaque to clear is immediate. However LC technology is not able to reduce the amount of radiation transmission from the sun very effectively. LC glass affects the way light is transferred but does not alter the quantity of radiation, and thus heat flow through glass, making it unsatisfactory for energy saving purposes. The use of LC glass is currently popular for internal architectural designs, such as privacy partitions, though due to many limitations does not have a foreseeable future as an external building façade. [7]

Electrochromic

Electrochromic devices are currently probably the most popular and complex of switchable glazing technology. The devices consist of a thin solid electrochromic film which is sandwiched between two layers of glass. On passing a low voltage across the thin coating the electrochromic layer is activated and changes colour from clear to dark. It is with this change in colour that the glass controls its optical transmission properties. Electrochromic glass is able to control solar radiation by absorbing the heat in its darkened state, though this can lead to heating of the glass. An advantage of electrochromic glazing is that the low voltage need only be applied until the desired colouration has been achieved and then the device will exhibit colour memory and maintain radiation transmission for up to 48hrs [8].

The electric current can be either activated manually or by active sensors that respond to the external light. Darkening the glass will reduce solar transmission, and when there is little sunlight the glass can brighten, reducing the need for artificial lighting. Required time for colour switching is slower than other technologies though and can take up to 30 minutes for a window size of about 2.4 m² [6]. Durability in electrochromic glazing is a current issue with having to cope with large number of switching cycles to survive a reasonable life-time of 10-15 years [3].

SPD technology

SPD is a film based technology, with a uniform response throughout the film. The film contains rod-like particles suspended in billions of liquid droplets distributed across the film. When the film has no applied voltage the particles are in random positions and block light transmission, appearing as a dark blue tint. When a voltage is then applied, the particles align and light is allowed to go through. The change in tint is instant and a user advantage to this technology is that the voltage can be varied to give a different level of tint and therefore the transmission properties can be changed to suit any particular external environment. [7]

SPD windows hold energy saving potential for the device uses solid radiation-absorbing particles in the liquid suspension. Precise optical properties depend on the thickness of the suspension film as well as the concentration of particles within [6]. Solar radiation and visible light transmittance is reduced with the application of a voltage, which in turn reduces the heat flow into the internal environment. SPD windows allow clear sight through the glass even while fully switched on and in a state of minimum transmission, which holds a visual advantage over other glazing technologies that turn the glass 'cloudy'. The current downside of this technology is the cost. As it's a very recent development, it is still in the early stages of demand, with the patent owner controlling prices. With sufficient marketing and its energy saving advantages made known then cost will come down as unit demand increases.

2.3 Comparative Analysis of Glazing Technologies

Using data carried out in previous research into switchable glazing technologies, a quantitative comparison can be made between the optical characteristics of the different glass devices. Table 1 below shows the various transmission and reflectance values of the four main switchable technologies.

	Visible Transmission	Solar Transmission	Visible Reflectance	Solar Reflectance
Thermotropic³				
Temperature of sample [°C]				
20	0.73	0.44	0.13	0.21
30	0.60	0.37	0.20	0.24
40	0.27	0.18	0.52	0.37
50	0.21	0.13	0.59	0.41
Gasotropic⁴				
Bleached	0.64	0.43	0.18	0.34
Coloured	0.15	0.09	0.07	0.08
Electrochromic⁵				
Bleached	0.50	0.35	0.12	-
Coloured	0.15	0.09	0.09	-
SPD⁶				
Clear (ON)	0.445	0.344	0.108	0.157
Tinted (OFF)	0.004	0.11	0.07	0.11

Table 1 showing optical properties of different switchable glazing devices – data from [6]

³ Optical and thermal properties of a sealed glazing unit with a thermotropic interlayer. Laminated glass consists of two 3.8mm float glass panes, argon fill, and a low-e coated inner pane. [6][9]

⁴ Optical properties of a sealed glazing unit with two airspaces and a gasotropic coating. [6][10]

⁵ Optical properties of a sealed glazing unit with an electrochromic element – system based on tungsten oxide. [6][11]

⁶ Optical properties of a sealed glazing unit with an SPD system. [6][12]

This data can more easily be represented in a graph, as shown in Figure.2a below.

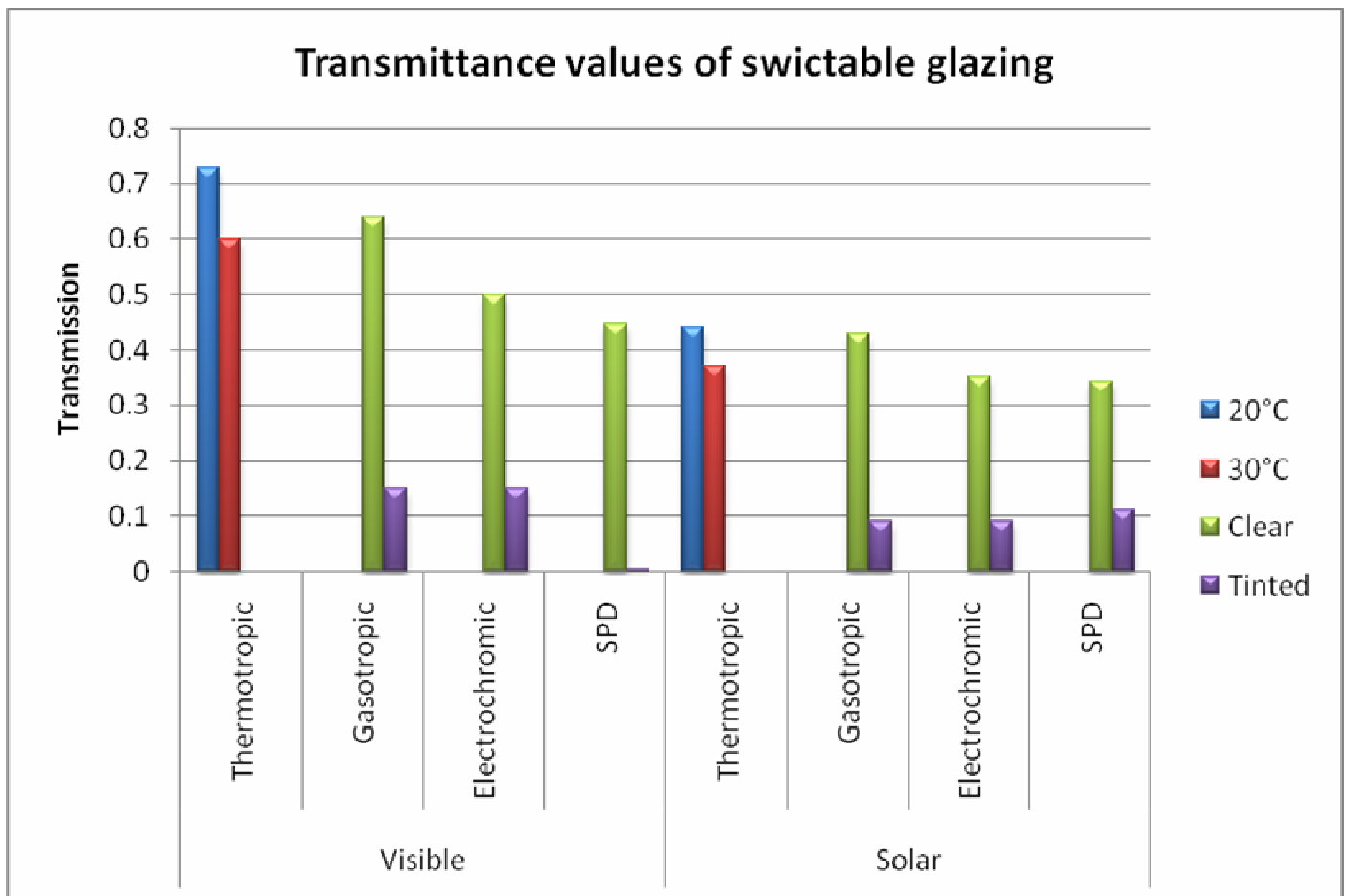


Figure.2a – comparison of visible and solar transmittance values between switchable glazing devices.

From the graph it can be seen that SPD glass has the best performance in reducing visible light transmission while only slightly behind the solar transmittance values of gasotropic and electrochromic (11% compared with 9%). It can be seen with the thermotropic data that its optimum performance is at the higher temperature band, far from the human comfort margin, and so shows that this technology is not yet sufficiently developed to be used in architectural applications

Within these numerous emerging technologies for switchable glazing, there are both self-adjusting systems, and externally activated systems. These externally activated systems are more desirable for user comfort and energy saving, for their properties can be easily controlled, and therefore can respond to daily/seasonal variations in temperature, visible light etc. As an example, it would be desired to allow solar heat into a room during winter periods to save heating loads, while reducing solar heat gain during the summer period to save on cooling loads. Out of the externally activated technologies this project will be looking into the performance of 'suspended particle device' glass (SPD) as it is a new and promising glass facade for reliability, energy performance and user comfort.

2.4 SPD Technology in Detail

As this project is investigating the performance of SPD SmartGlass the following section looks at the theory and advantages of this material in more detail. Figures and technical data are provided by SmartGlass International’s Overview of their SPD glass [13]

SPD is a film-based technology, as explained earlier, which comprises of billions of rotating particles inside a dual-layer plastic film. Figure2.b shows the mechanism that occurs as a voltage is applied to the conductive coatings surrounding the particle emulsion. This set-up is similar to a basic parallel-plate capacitor, which has a uniform electric field. This results in a uniform response throughout the SPD film when switching from clear to tinted, which is not possible with most electrochromic devices. When SPD is tinted it holds a bluish tint, which reduces to clear when switched on. This level of tint can be controlled by the magnitude of voltage applied to the glass

SPD glass requires an ac voltage to function, as a dc voltage will cause the polarized particles to migrate and cluster in the film, resulting in a gradual darkening

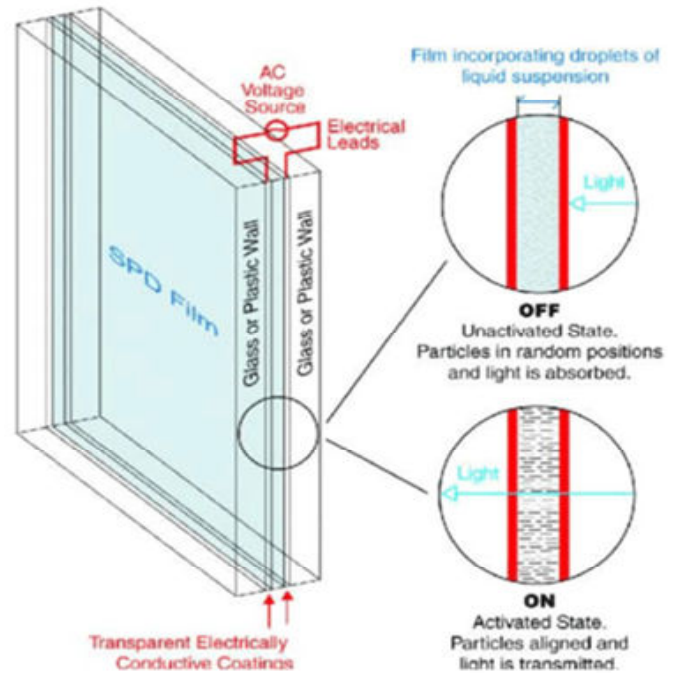


Figure.2b – diagram of SPD technology

Technical data for SPD SmartGlass supplied by SmartGlass International can be found below in Table 2

SPD SmartGlass	U-Value*	R-Value*	STC*	OITC*	UV Blocking
On (Clear)	0.24	4.17	34	26	>99.5%
Off (Dark)	0.24	4.17	34	26	>99.5%

Table 2 – technical data of SPD glass from [13]

This configuration is recommended by SmartGlass Int. to achieve the highest possible performance. This data also shows the high level of UV blocking by SPD glass, in both the ON and OFF state.

Main advantages of SPD windows;

- Accurate lighting control, while maintaining an optical view through the window. Even with the bluish tint, it is still possible to see through the glass. Figure.2c below shows the variation of window colour in the ON/OFF state
- The high durability and long life expected for smart glass technology. Testing has occurred for over 100,000 cycles without an degeneration of performance
- Reduced glare in working environments that will cause uncomfortable conditions, disruption to computer operation, and possible eye strain
- A wide working temperature from -30°C to +90°C so suitable for glass façades in numerous climates. The temperature of glass in very sunny locations can reach extremely high levels so this upper bound is very critical.
- Energy saving due to the reduced cooling and lighting costs. SPD windows are able to reduce the solar heat gain into an office and therefore create a more stable and cooler internal environment. The ability to control light levels also removes the need to have blinds and therefore the use of artificial lighting throughout the day.



Figure.2c – different tint of SPD windows

PROJECT DESIGN

3.1 Project Objectives

This project into the performance of SPD glass is to be divided up into three main components of experimental investigation, all of which cross link with one another but will aim to gain a full range of glass performance data. The components of investigation are as follows;

- 1) Laboratory experimentations on a small sample of SPD glass
- 2) Real-world testing of SPD glass
- 3) Environmental modeling of the use of SPD glass

While SPD glass is a new upcoming technology, it is still in the early stages of demand, and therefore there has been somewhat limited investigation into its performance for such a promising glass façade. My investigation will hope to bring a better understanding of the transmission properties of SPD glass, as well as its energy saving potential in the real world.

3.2 Laboratory Experimentation

The objective of laboratory experimentation of samples of SPD glass is to gain a better understanding of its transmission properties with the supply of an electrical current.

Data is already known for the UV and visible light transmission for an ON/OFF sample of SPD glass. Table 3 below shows SPD data from the SmartGlass International website.

	SPD (10.8mm) ON	SPD (10.8mm) OFF	Clear Glass (6mm)	Frosted Glass (6mm)
Visible Light Transmission	49%	0.24%	86%	76%
UV Transmission	0.5%	0.5%	55%	55%

Table 3 – SmartGlass International website [7]

This initial data shows the improved amount of visible and UV light that SPD glass is able to prevent transmitting, in comparison to regular clear and frosted glass. However this data only shows the transmission properties of SPD glass in the ON or OFF phase. The use of an electric current to control the 'tint' of SPD glass holds much more possibilities than just

using an ON/OFF switch. The use of dimmer switches, and potentiometers can control the exact 'tint' by varying the voltage from 0 – 115volts, and can gain maximum user comfort in achieving the optical clarity dependent on the outside environment.

By the use of potentiometers on the voltage supply of the SPD glass, the varying visible light transmittance values will therefore be determined, in order to understand the relationship between voltage applied, and alignment of the suspended particles.

It was also desired to gain an understanding and analysis of the exact spectrum of the SPD glass. This would involve the use of a spectrophotometer and would be able to few the visible, UV, and infrared (IR) regions of the spectrum. In order to gain this data, the SPD laminate testing would be carried out at the CAPE building (Centre for Advance Photonics and Electronics) on the West Cambridge Site. However it was soon discovered that the spectrophotometer available was not adequate in being able to test the SPD laminate due to the electrical cord attached to the SPD sample. This was a setback to the project, though other areas of investigation would still be able to produce sufficient data and conclusions on the performance of SPD windows.

3.3 Real – World Testing

A vital aspect of this project is to get real-world results into the performance of SPD glass in an office environment. There has been numerous testing and research into the performance of SPD glass in lab conditions but not in a real-world situation. It is critical to understand the performance of the windows in their actual everyday use, with the interaction of people, in order to be able to adapt to the market and ensure maximum potential. In addition simulation models using SPD glass have not been previously validated by performance data so it will also be interesting to compare and analyze how accurate these energy models are.

The SPD windows will be installed in an office and the environmental conditions will be monitored and compared against the regular glass façade in place. As well as internal environmental conditions, it is also very important to record the user comfort of the SPD windows on the office occupier. Due to the windows being externally activated, and tinted, it may or may not be desirable for the occupier to continually change the intensity of tint or work in such lighting. Such results will aid in determining the actual marketability of this style of switchable glazing.

Evaluating the real-world performance of the SPD windows in comparison to regular windows currently being used by the office of choice will give accurate knowledge into the realistic energy saving potential of this technology, the usability of switchable glazing, and a validation to computational energy performance models

3.4 Environmental Modeling

Building energy simulation software is extremely useful in the design of lower carbon buildings and gaining an understanding of a building's performance. In this project, the use of SPD glass in buildings will be modeled using IESVE software (Integrated Environmental Solutions Virtual Environment). 'IES is an innovative company at the forefront of the development and application of powerful software simulation tools and consulting services for architects, engineers and others involved in the design, development and management of truly sustainable buildings' [14]. This modeling software can simulate numerous results for the energy flow and environmental conditions within a building, and so can be used to compare the use of SPD glass against using standard double glazing. The software can be used to look at the performance of single rooms, as well as entire buildings, and uses accurate weather data for any certain world location specified.

It will also be possible to compare the results generated from a computer simulation against those gained from the real-world testing of the SPD windows. There is a strong need for the ability to model the energy performance in buildings, and an ever greater reliance on data generated to prove that new building projects are energy efficient. However there has been limited research into whether simulation models can be validated by performance data from real-world buildings. Existing models concentrate on pure theory of building physics and do not take into account random human interactions, such as manual variation in heating/cooling systems, as well as artificial light and computer use.

By the use of computer simulations the internal environment of the office chosen for real-world testing will be analyzed using SPD windows, and then compared with the internal environment of the office using the regular existing glazing. Environmental conditions that are modeled can then be compared to the environmental conditions measured by the data loggers, and thus the accuracy of energy loads calculated to maintain a user comfort level.

The main energy saving potential of SPD glass is to reduce solar heat gain during the summer and therefore reduce the energy loads associated with cooling. Simulations of the office will be carried out in the UK as this is where the real-world testing is taking place. The UK though experiences a very mild climate in relation to the rest of the world. It will therefore be important to run identical simulations in IESVE of the performance of SPD glass at varying locations around the world that experience hotter summer climates and depend much more on cooling systems during the summer. This technology will hold greater potential in the hottest of climates, such as Dubai, and Texas, where summer temperatures can become unbearable and solar radiation transmission needs to be controlled.

EXPERIMENTAL TECHNIQUES

4.1 Laboratory Testing

A small sample of the SPD laminate was supplied by SmartGlass International to use for laboratory experimentation. This sample was approximately 30cm x 20cm with 3mm glass surrounding the SPD film on both sides.

The experiment to gain visible light transmittance at varying voltages was set up by attaching a potentiometer to the switch of the SPD glass sample, to act as a varying resistance. Numerous potentiometers were used to gain a larger distribution of results; all supplied a linear resistance, with values of 1M, 100k, and 200k

Visible light was directed at the SPD glass and a light meter was positioned on the other side of the glass in order to measure light transmitted in lux. The experiment was carried out in a darkened room to prevent outside light interference, though the light intensity was measured without the glass and with the light source off to evaluate any possible background light. At the start of every set of results the light intensity of the light source was also recorded without the glass, in order to act as a reference. At no point during the experiment was the light source or lux meter moved, so the distance between them always remained the same. The voltage during each light reading was measured using a standard voltmeter with accuracy to 0.01V.

The sample of SPD glass tested is shown in Figure.4a on the right



4.2 Real – World Testing

It was decided that the real-world testing of the SPD windows would be located in the Engineering Department for matter of convenience for the maintenance department, and probable enthusiasm of the office user for the investigation. Locating the office required for testing was difficult however due to the specific conditions required. As this testing was mainly looking into the performance of the glass façade at transmitting solar radiation it was required to find an office with high levels of sunlight. The Engineering Department however is very sheltered so it was required to use an office on one of the higher floors in the Baker building, above the line of trees and Inglis building. Using the Sun Cast feature of IESVE software, it was decided to choose a south facing office to gain the most sunlight hours during the day. Figure.4b below shows the Sun Cast analysis for London, UK.

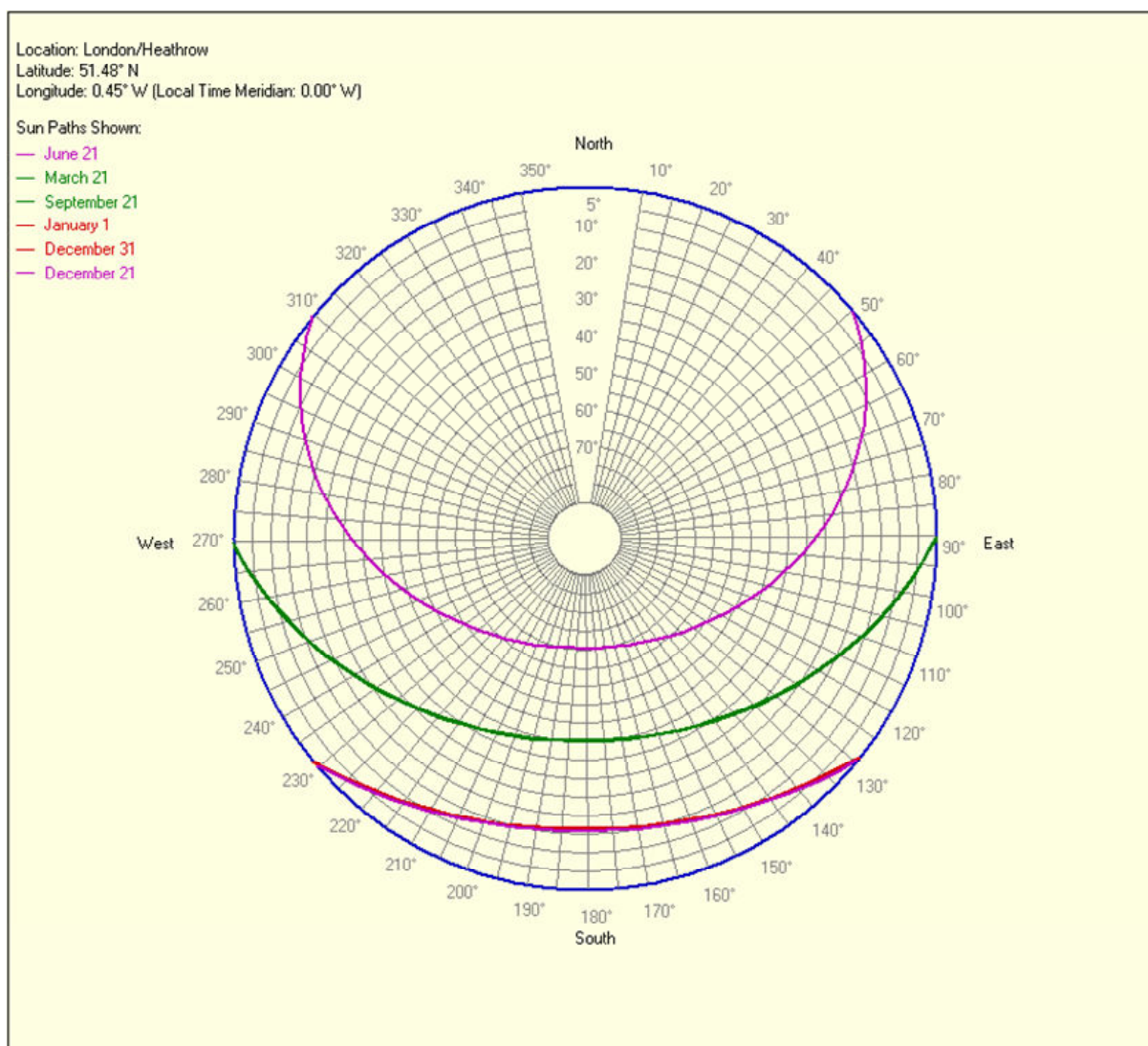


Figure.4b – shows the sun path over the UK at different times of year

It was also important to pick an office where the user will spend the majority of their working hours inside, in order to gain accurate representation of a more commercial based office environment.

Once a suitable office had been located, the SPD windows were installed as an extra layer of glazing on top of the original single glazing that existed beforehand. It was not possible to install the SPD windows instead of the single glazing due to the office being situated on the 4th floor. Nevertheless this will not be a problem for experimental results as SPD glazing will normally be provided as double glazing, so instead just a single SPD laminate was added to the existing windows.

Figures 4.c and 4.d and 4.e below show the installation of the SPD windows in the office and the difference of window tint as each of the windows were connected to an electrical current and switched on.

The dimensions of the office used for testing were; 2.5m high, 4m deep, and 3.1 m wide. The windows took up an area of approximately 3.3m² and were location 0.9m above the height of the floor.



Figure.4c shows all the SPD windows unconnected and switched off. The windows display a blue tint, and the connector wires can be seen hanging from the windows.



Figure.4d shows two of the SPD windows switched on, while the other windows are still unconnected



Figure.4e shows all the SPD windows connected and switched on. The windows display a clear state without the blue tint previously shown.

It was originally decided that the environmental conditions of the office - temperature, sunlight levels and radiation – would be first measured without the of SPD glass, and then compared to the environment with the SPD glass. However this was deemed to be too inaccurate due to the probably large variations of weather and temperature outside.

Instead the office conditions were measured with the SPD glass, and at the same time, the office conditions of the adjacent office were also measured. This office is identical in size, amount of sunlight received, and occupant usage, so will act as a reliable control to analyze against the SPD window performance.

Data Measurement

In order not to disturb the working environment of the occupier, small data logging sensors were used in the offices to measure the room environment.

Temperature – Lascar USB Temperature Loggers⁷ were used. Temperature recorded to accuracy of 0.5°C, and within a range of -35°C to +80°C.

These loggers were placed at the back of the office, out of the way of direct sunlight, to record the internal air temperature of the office.

Light – self-made light sensor logging circuits used, using an LDR and Flash memory to record light level. Note that these sensors were borrowed from the computer science department and I did not make them myself. Two light sensors were used for each office and placed on the window sill to gain maximum exposure to the sunlight.

Solar Radiation levels – it is difficult to measure the solar heat gain through windows without highly specialized equipment. However the purpose of this experiment is to gain comparative data between SPD and normal glazing so the absolute value of solar infrared radiation is not critical. Temperature loggers were once again used, and in this case with close proximity to the office windows in order to record the heat gain from direct sunlight.

The outside air temperature was not recorded as accurate data can be taken from measurements carried out at the Cambridge Weather Station⁸. Data measurement of the internal environment of the office was carried out daily from the 24th March to the 5th May. Testing the SPD windows for this length of time will provide results over multiple weather conditions and will help to provide more comprehensive results.

⁷ These data loggers can be found at <http://www.lascarelectronics.com/temperaturedatalogger.php?datalogger=378>

⁸ Weather data supplied on website - <http://www.cl.cam.ac.uk/research/dtg/weather/>

4.3 Environmental Modeling

For reliable software modeling into the performance of SPD glass it is desired that the model is an accurate representation of the office being tested in the Engineering Department. A model was drawn up using the exact dimensions of the test room, as well as the surrounding building and orientation to the sun. The surrounding building was included in the simulation in order to gain the correct height for the test room, as well as ensure the ceiling, floor, and internal walls were not treated as external by the program. This was important as the simulated heat flow into the room would be much greater if all the room's wall were treated as external. The individual environmental data and energy loads for the specific test room can be isolated when analyzing the results.

Within IESVE, the exact conditions of simulation can be controlled using the Building Template Manager. The room type was set to a standard occupied office, with default settings for air exchanges, heating/cooling profiles, and radiance surface properties. It was decided to set the human comfort range from 19°C - 23°C (recommended by the software), thus if the air temperature within the room drops below 19°C the heating system will be used, and if it rises above 23°C the cooling system commences.

The internal gains were set to regular fluorescent lighting, computers, and a personnel heat gain of 90W/person. The occupant density was given to be 14m²/person. This corresponds to the rough size of the test room so only 1 person was used for internal heat gain.

The construction materials for the room were assigned to the department's construction characteristics; internal partition – plaster/brick/plaster; floor/ ceiling – type 1 insulation; external wall – brick/block cavity wall.

These parameters were kept unchanged for all simulations, and only the external glazing was changed to analyze window performance. The first simulation was run using regular single clear float glazing, of similar dimensions to the glass within the test office. The simulation was then run using SPD glass, in which I created a separate glazing construction. This SPD glazing used emissivity, reflectance, and U-values measured during previous laboratory testing and transmittance values supplied by SmartGlass International [13]. The glazing was designed as a double glazed layer surrounding an air cavity – as used for the real-world testing.

IESVE contains detailed weather and climate data from numerous locations worldwide, however not for Cambridge, UK. The closest location was Heathrow, London which was deemed suitable as the overall year round weather would be close to identical, and the test room was orientated in the desirable direction.

Simulations first using regular single glazing, then SPD glazing were run for the whole calendar year in the locations of London, Dubai, Houston (Texas, USA), Rome (Italy), and Sydney (Australia). These locations cover a broad range of hot climates around the MEDC world, in which SPD technology could hold stronger energy saving potential.

RESULTS

5.1 Laboratory Testing

During the testing of the light transmittance of the SPD glass it was observed that even in a darkened room there was still a small amount of background light picked up by the light meter. In order to overcome this level (usually around 20 lux) of background light all further experiments were carried out during the middle of the night in order to completely eliminate any natural external light coming into the room.

The reference values of the light source and background interference were as follows;

Light source – 3140/3150 lux

Background light – 0.01/0 lux

Without the potentiometer attached the light transmittance of the SPD glass was as follows;

SPD glass OFF – 63.4/63.3 lux

SPD glass ON (115.9V) – 1488/1489 lux

Figure.5a below shows the variation of light intensity measured through the glass while the current applied to the glass was varied with a potentiometer.

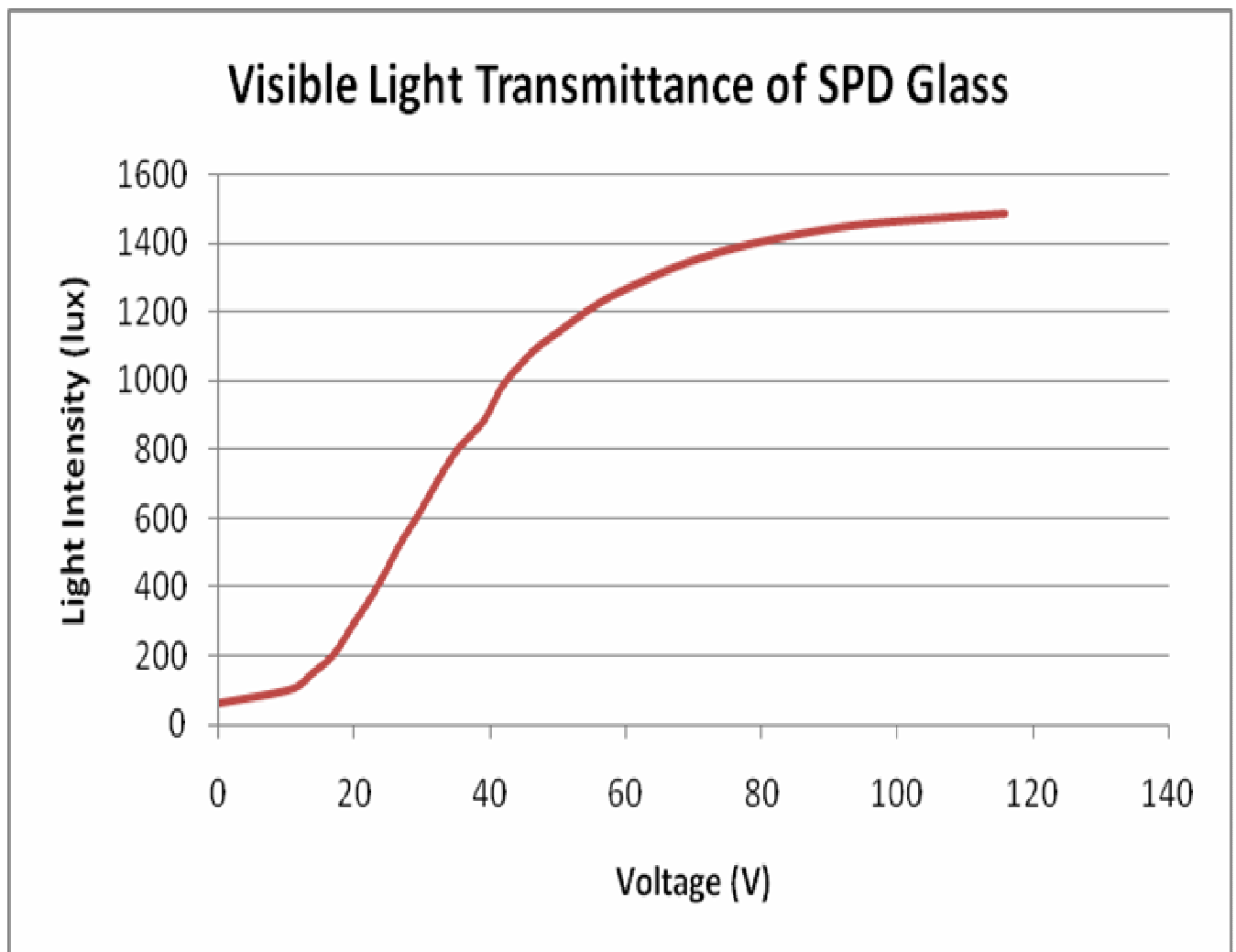


Figure.5a – shows the light intensity measured as a function of the voltage applied to the SPD glass

This figure shows that there is not a linear relationship between voltage applied and the light transmittance of the glass. The gradient of the curve between 20 and 60volts shows that the light intensity varied more per volt during these middle voltages than at the higher and lower amounts. Above 80V applied the light intensity hardly changes at all, shown by the very shallow gradient of the curve at this point. At the lower voltages the light intensity also changes minimally between 0 and 15V.

To show how this relationship would affect the user control of SPD windows the voltage was plotted against the total percentage of visible light transmittance and shown in Figure.5b below.

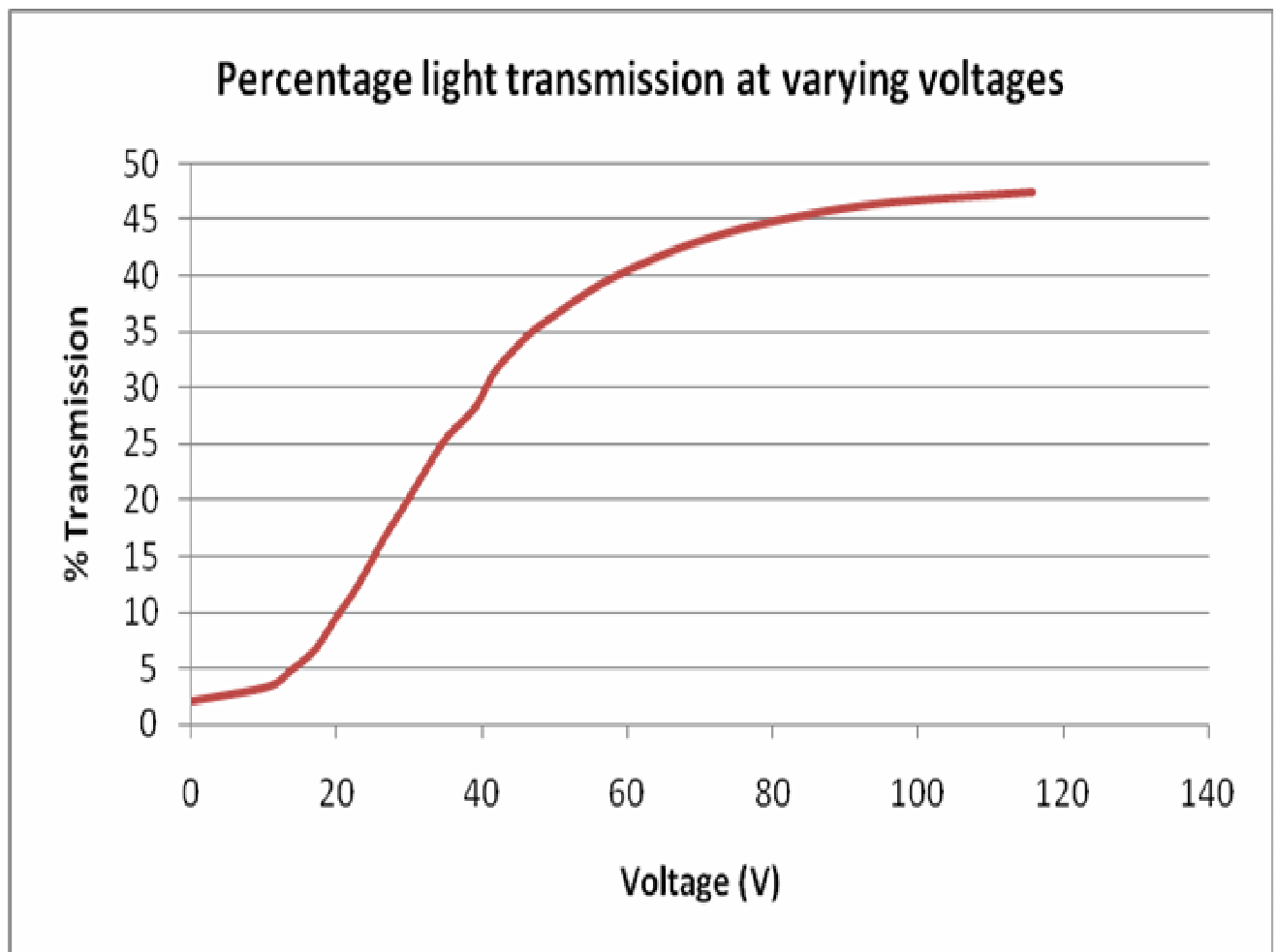


Figure.5b – shows the light transmission properties at varying voltages

The curve shown in Figure.5b is of the same exact shape to Figure.5a because the light intensity measurements were just divided by the reference light intensity of the light source. The importance of this figure is then to show the absolute levels of light transmission that can be achieved by varying voltages. It can be seen that if the user required a level of 25% visible light transmission then the voltage would have to be put at third of the maximum voltage. These results also confirm previous values of SPD light transmission shown in Figure.2a and displayed in Table 3. While variation of a couple of % it is confirmed that SPD allows between 45-50% of light transmission when clear, and less than 2% when fully tinted. For using SPD windows in the real-world it would be suggested that the voltage would have to be controlled by a non-linear potentiometer, in order to allow the user to control the light transmission as a direct proportion to whatever 'dial' is installed.

5.2 Real-world Testing

The environmental conditions of the test office in the Engineering Department were recorded between the 24th March and the 5th May.

It was found that over the period of data logging the room temperatures remained fairly constant in their fluctuations. Therefore the results shown will be taken over a period of a week during the middle of data-logging. Results shown will be from the April 11th to April 18th.

5.2.1 Room Temperatures

The room temperatures measured in the test room using SPD windows, and the reference room with single glazing can be found on Figure.5c and Figure.5d respectively.

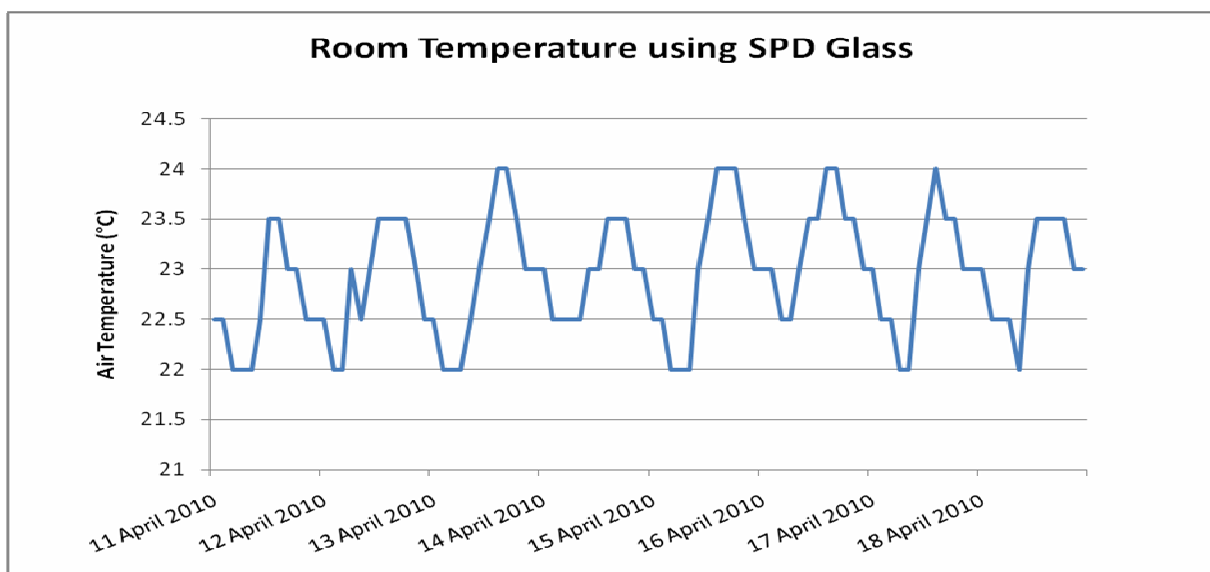


Figure.5c – shows the room temperature variation in the SPD office over one week

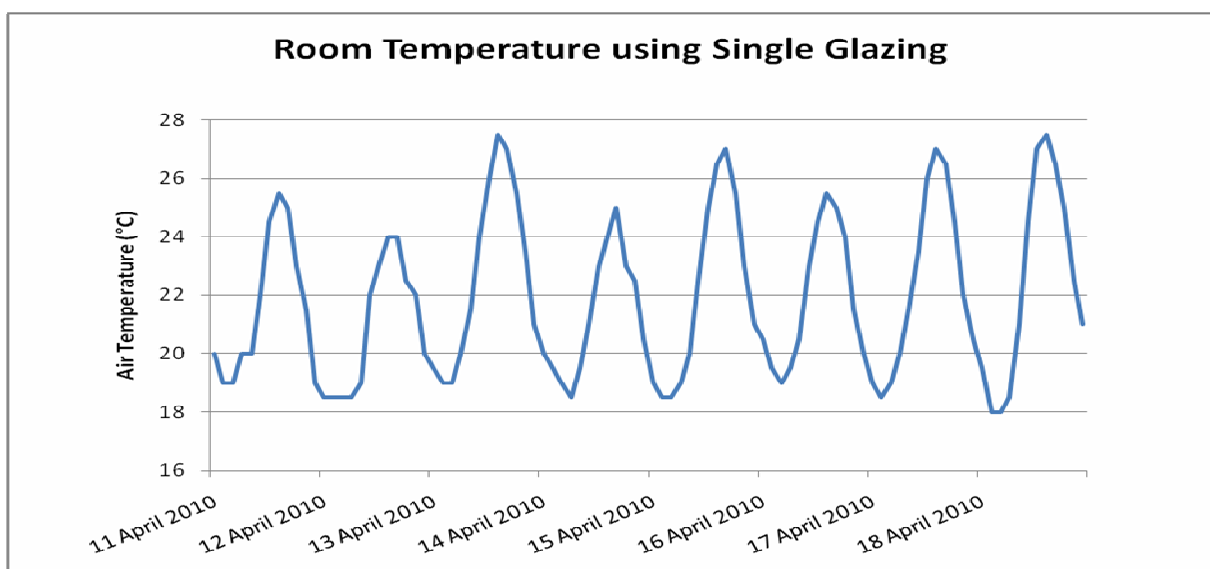


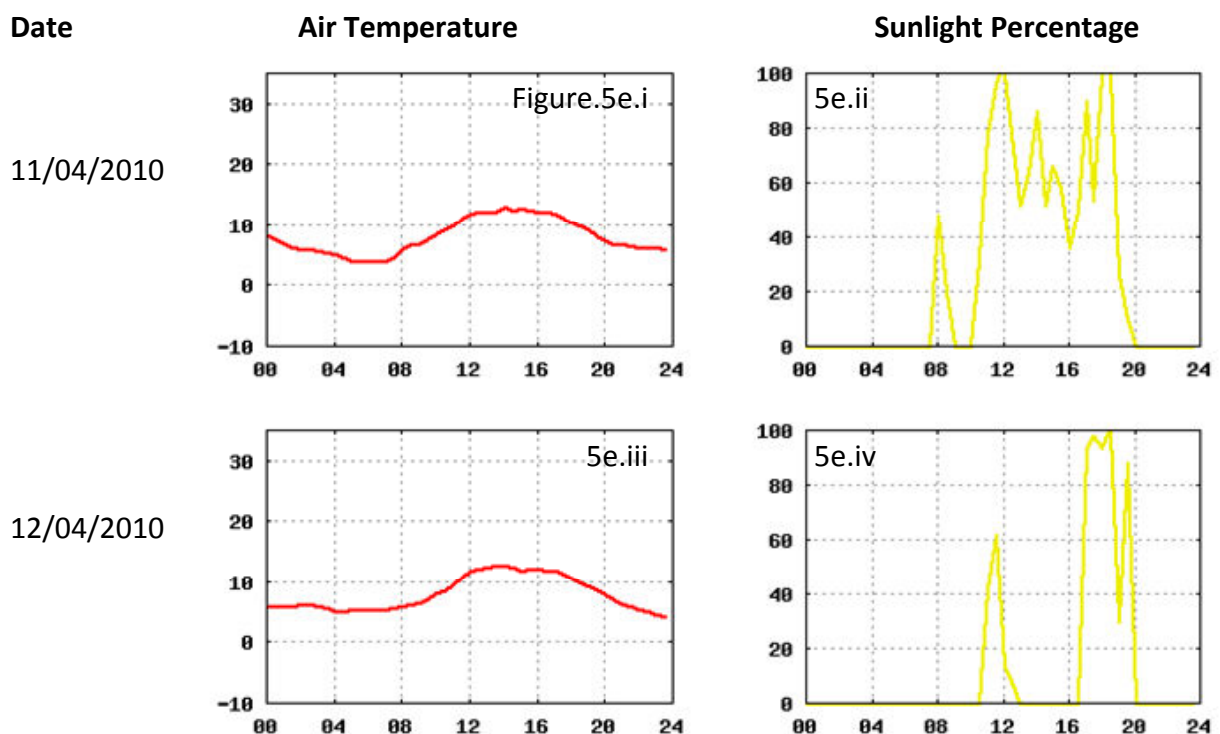
Figure.5d – shows the room temperature variation of single glazing over one week

It can be seen from these two figures that the SPD glazing has a significant effect on the internal room temperature with comparison to the regular single glazing used in the office. The temperature fluctuation throughout the day is reduced by the SPD windows, where in the week of the 11th April – 18th April the temperature did not move out of the 22°C - 24°C range. The performance of the single glazing windows however allow much larger variations in room temperature of around 7-8°C between night and day. The temperature would peak to around 26°C during the mid-afternoon, and then drop to just above 18°C during the early morning. This temperature change highlights the poor energy efficiency of single glazing units, and how energy flow through glass façade is so very vulnerable to wastage. This data remember is recorded during April, which characteristically experiences quite mild climate in the UK. Temperature changes during the winter and summer would show larger extremities in room temperature, and therefore require high heating/cooling loads to make the environment comfortable.

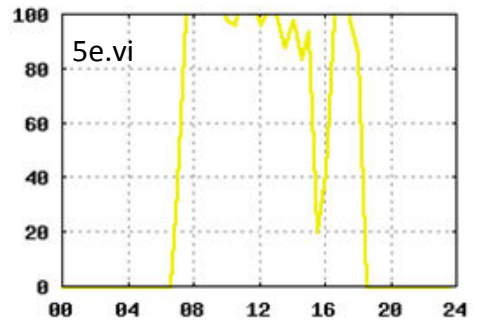
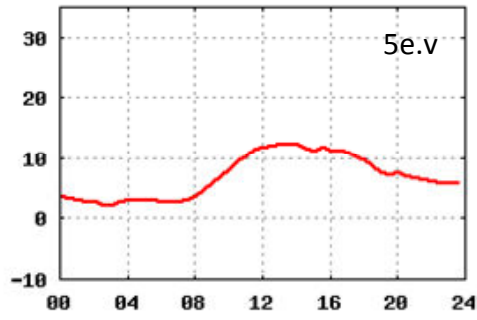
5.2.2 Weather Data

With the use of SPD windows in the test office the air temperature was controlled to a more desirable uniform temperature. Its performance shows strong potential in limiting the amount of heat gain during the hottest hours of the day, while the double glazing aspect of the windows decreased heat loss by conduction during the evening.

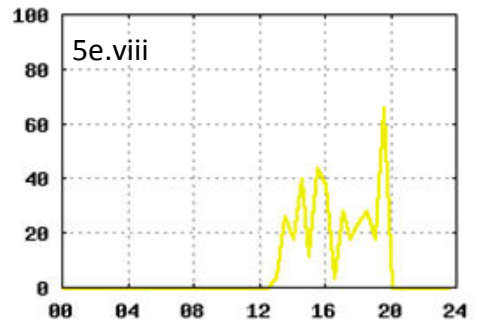
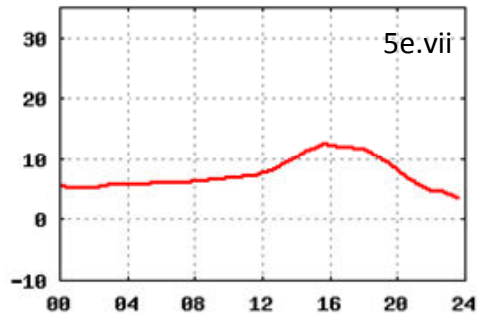
The external air temperature, and sunlight conditions for the individual days from the 11th – 18th April are shown below in Figure.5e.i to Figure.5e.xvi. The figures numbers are found in the corners of each figure. The sunlight is quantified as a percentage of the previous half-hour which was judged 'sunny' by a binary sensor which classes each 36-second interval as sunny or not sunny. This data is supplied by the Cambridge Weather Station [15]



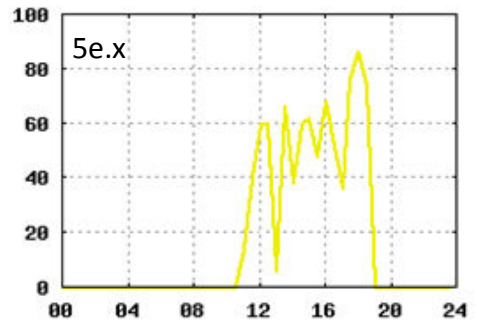
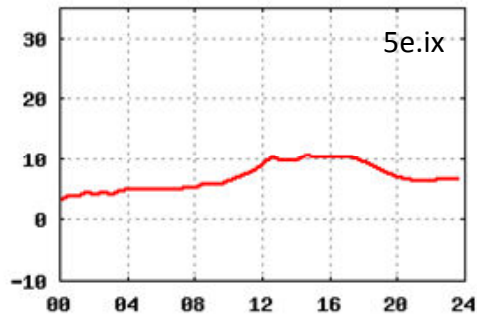
13/04/2010



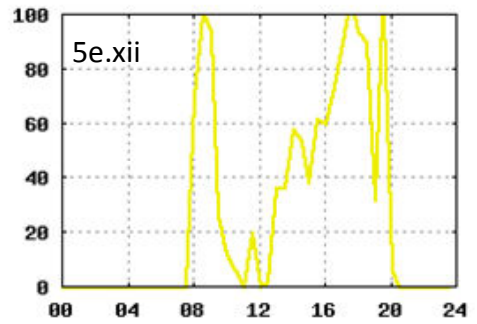
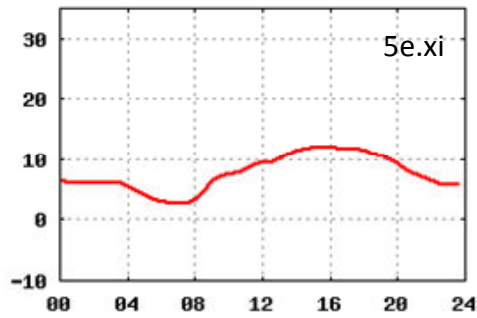
14/04/2010



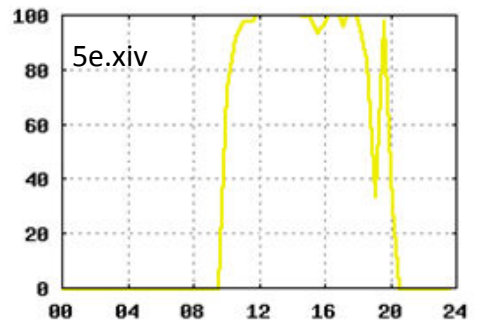
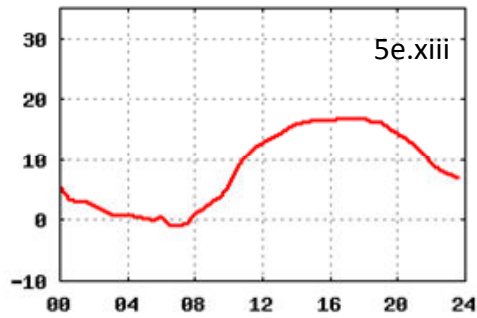
15/04/2010



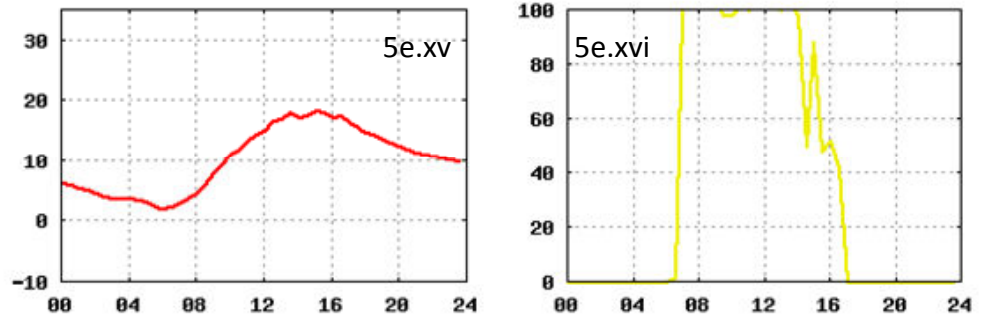
16/04/2010



17/04/2010



18/04/2010



In comparing the sunlight percentage over the week to the internal room temperatures it can be seen that even on days which had less amounts of sunshine, such as the 12th and 14th (Figure.5e.iv and Figure.5e.viii respectively), there is a slightly lower temperature within the single glazing room. This difference is only a couple of degrees Celsius however this is significant in terms of solar heat gain. With heating gains from personnel, computers and lighting it should be assumed that the internal temperature would still rise during the working day, even without any input from solar transmission. On both the 12th and the 14th there is a very slight noticeable effect on the result of the SPD glazing office, where the temperature dips by half a degree compared with the other days (seen in Figure.5c). This is a negligible change however in comparison with a reduction in 3°C, experience by the single glazing room on the 12th April (Figure.5d)

5.2.3 Solar Heat Gain

Two temperature loggers were left in the path of direct sunlight next to the windows of both SPD and single glazing.

The figures below show the variation of temperature of these loggers in both offices on each of the days from the 11th – 18th April.

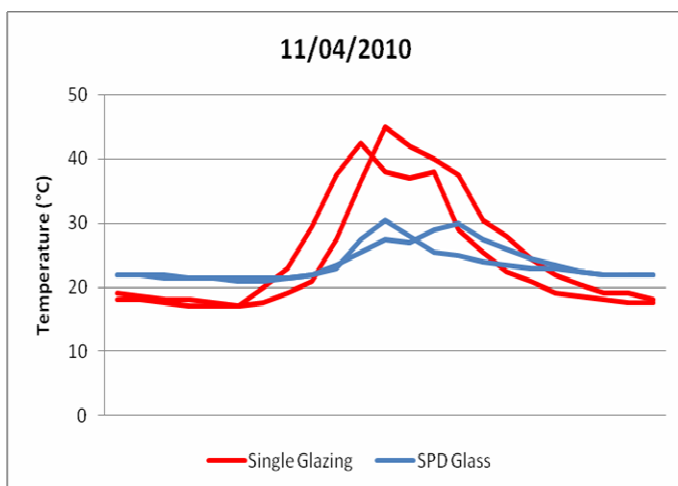


Figure.5f.i

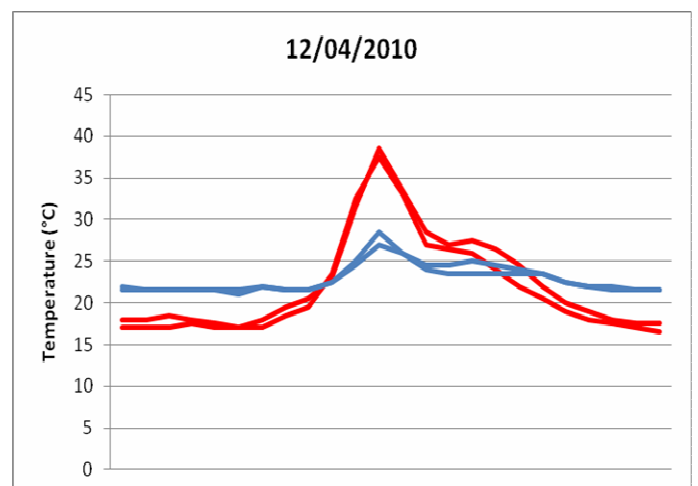
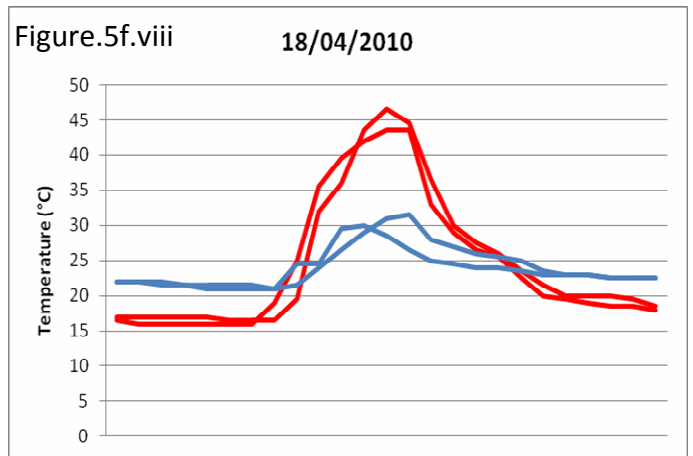
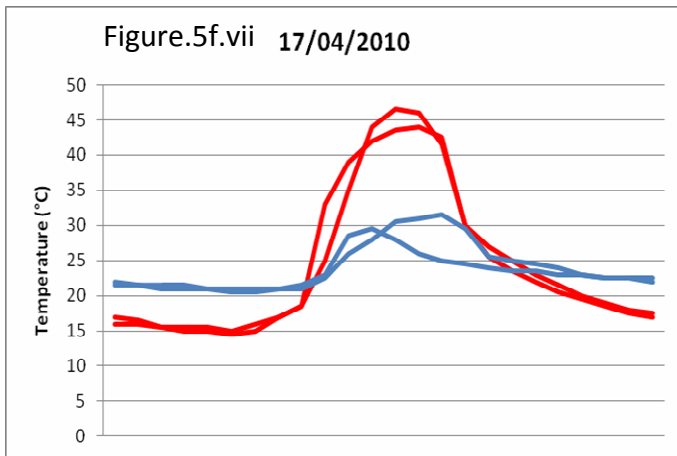
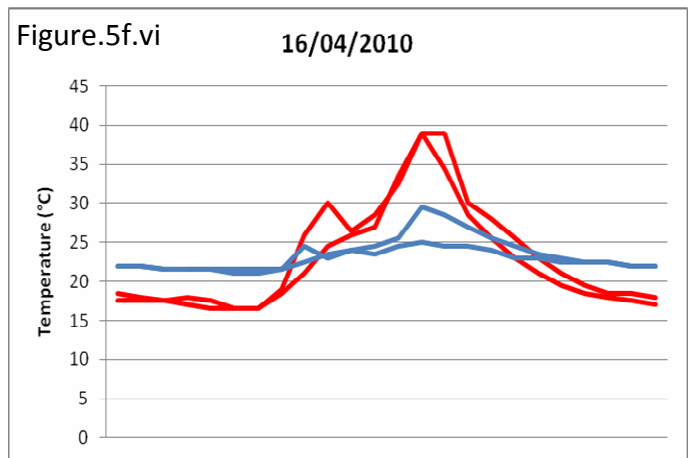
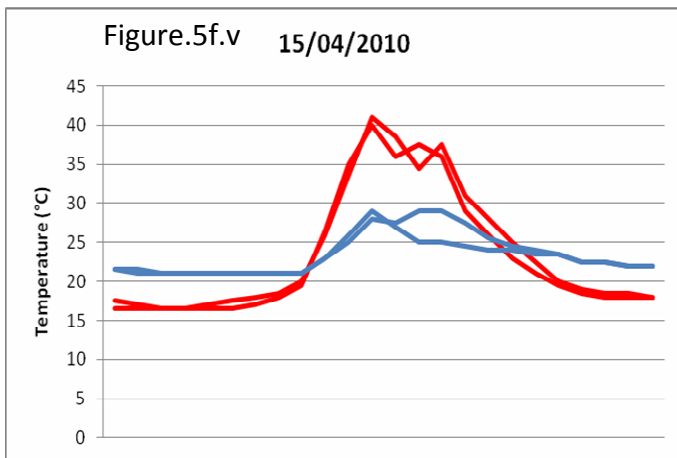
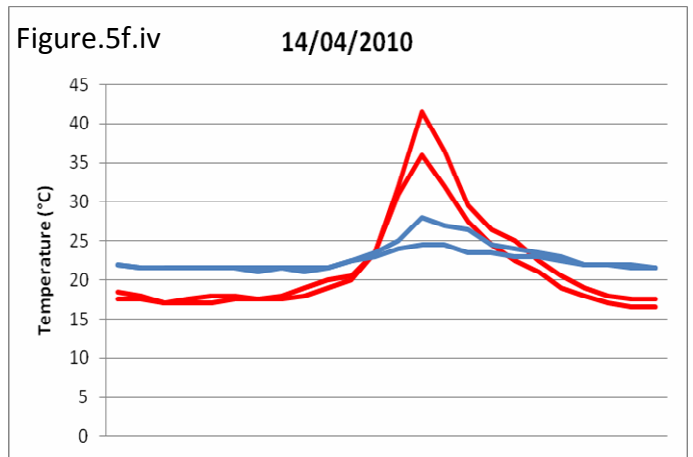
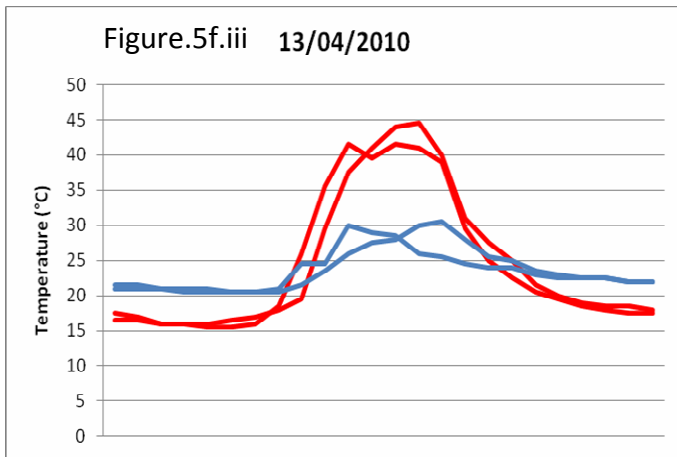


Figure.5f.ii



The Figures.5f.i to 5f.viii above shows that the temperature loggers in front of the SPD glass measured much lower values of temperature in comparison to regular glazing. Values of temperature recorded are much higher than the recorded room air temperatures due to the data loggers being left in direct sunlight and so would heat up due to direct solar heat radiation, instead of the surrounding air temperature.

The results show very large temperature variation due to transmittance through the single glazing. In general across this week period the temperature would vary from around 15°C during the night to 45°C during midday. It is quite surprising to see how high the temperature rose during sustained levels of sunlight, and shows the important of preventing solar heat gain into internal environments. If working spaces were situated in front of large windows, this temperature could be felt by the user without the aid of blinds during the day. It is also evident to see how the temperature quickly dropped off with the disappearance of solar radiation, and it must be noted that the temperature actually dropped below that of the previously recorded room temperatures in the single glazed office. This can be explained by the close proximity of the sensors to window, and probable drafts in the window unit.

For the SPD glazing, the fluctuation in temperature is much reduced, from just over 20°C during the evening to around 30°C during midday. This is a 15°C reduction compared to single glazing, which is very significant in terms of solar radiation transmittance. These results show that the SPD glass is highly capable in reducing heat energy flow into an office environment during peak sunlight hours.

This solar heat gain analysis can also be supported by the sunlight intensity represented in Figures.5.e.i to 5.e.xvi earlier in the results.

On the 12th and 14th of April the sunlight was comparatively reduced due to the lower sunlight percentages recorded in Figure.5e.iv and Figure.5e.viii. By then looking at the solar temperatures for those days on Figure.5f.ii and Figure.5f.iv it can be seen that instead of a sustained high temperature curve, there is shorter temperature peak measured.

5.2.4 Room Light Intensity

Unfortunately the data recorded by the data logging sensors was not able to be used in showing the change in visual light levels of the offices. The programming of the microprocessor was originally set to determine if the light intensity was over a certain level, and was not successfully altered to provide accurate results. This set back isn't critical in evaluating the performance of the SPD windows as there is already established knowledge into the visual light transmittance of SPD technology. In hindsight it would have also been necessary to record the ON/OFF condition of the glass and artificial lighting levels in order to decipher what light was being transmitted and what light was artificial.

5.2.5 User Comfort

The user of the SPD windows was asked about their comfort value and usability of the window as a potential replacement to regular none smart glass facades. The office belonged to Dr James Dawson, who worked primarily within the room.

It was noted that over the course of the testing he was able to notice that the glass kept the room at a fairly uniform temperature which was a positive change from the previous windows. Unfortunately due to the fact that the SPD windows were attached on top of the existing windows with temporary wooden frames it was not possible for the windows to be opened during the testing. This reduced the ability to ventilate the room and fresh air is an important input to increase user comfort during hot, stuffy days. However this was a problem only for testing in this circumstance and any SPD glass installed in reality would be fixed into a frame that could be opened.

Feedback on switching the glass was that the process was very easy, however it was noted that the tinting of the glass would be more appropriate with more than two settings. A dial system perhaps would be suited to controlling the tint and therefore transmission properties of the windows.

Due to the fact that these tests were carried out during a British spring time, the intensity of the sun would not be at such high levels that extreme cases of glare would be noticeable by the occupier. It was mentioned by the occupier that the windows were set on the clear setting for the majority of the days in order to let in maximum amounts of daylight, and any solar heat gain as a result was not uncomfortable

5.3 Environmental Modeling

Location - London UK

5.3.1 Room Temperature

Appendix 1 shows the comparison of room air temperatures between using SPD glazing and single glazing. Figure.5g and Figure.5h include the dry-bulb temperature in order to act as a reference of the variation of internal room temperature.

It can be seen that the SPD glazing reduces the fluctuation of the internal room temperature quite considerably, as well as minimizing the peak daily temperature. Even with cooling load systems operating when the temperature exceeds 23°C, the temperature still exceeds this limit with the use of single glazing in the summer months. This shows that the actual default cooling systems used for the simulation are not able to maintain the user comfort levels with single glazing. As can be seen in Figure.5h the SPD glazing only experiences this characteristic a couple of days of the year in comparison.

Figure.5i and Figure.5j below shows the room temperature fluctuation of the single peak day of the year of both normal glazing and SPD glazing respectively (peak room temperature).

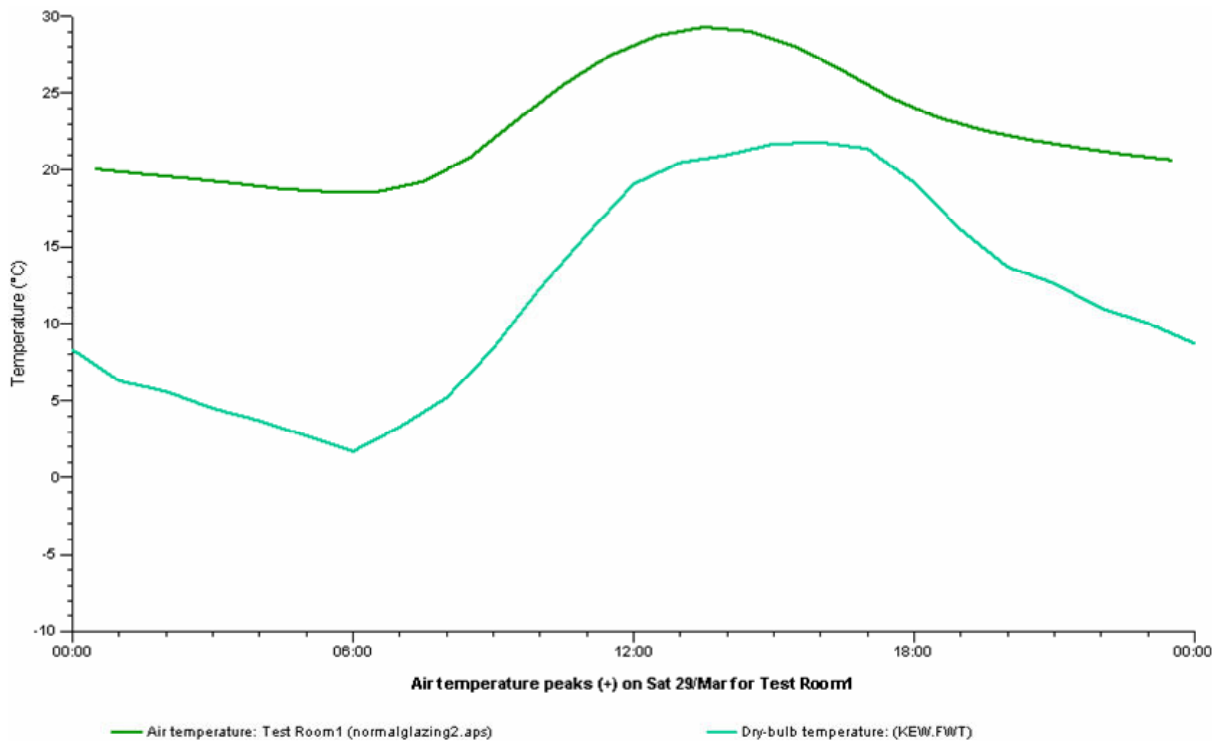


Figure.5i – shows the peak daily fluctuation in air temperature using single glazing

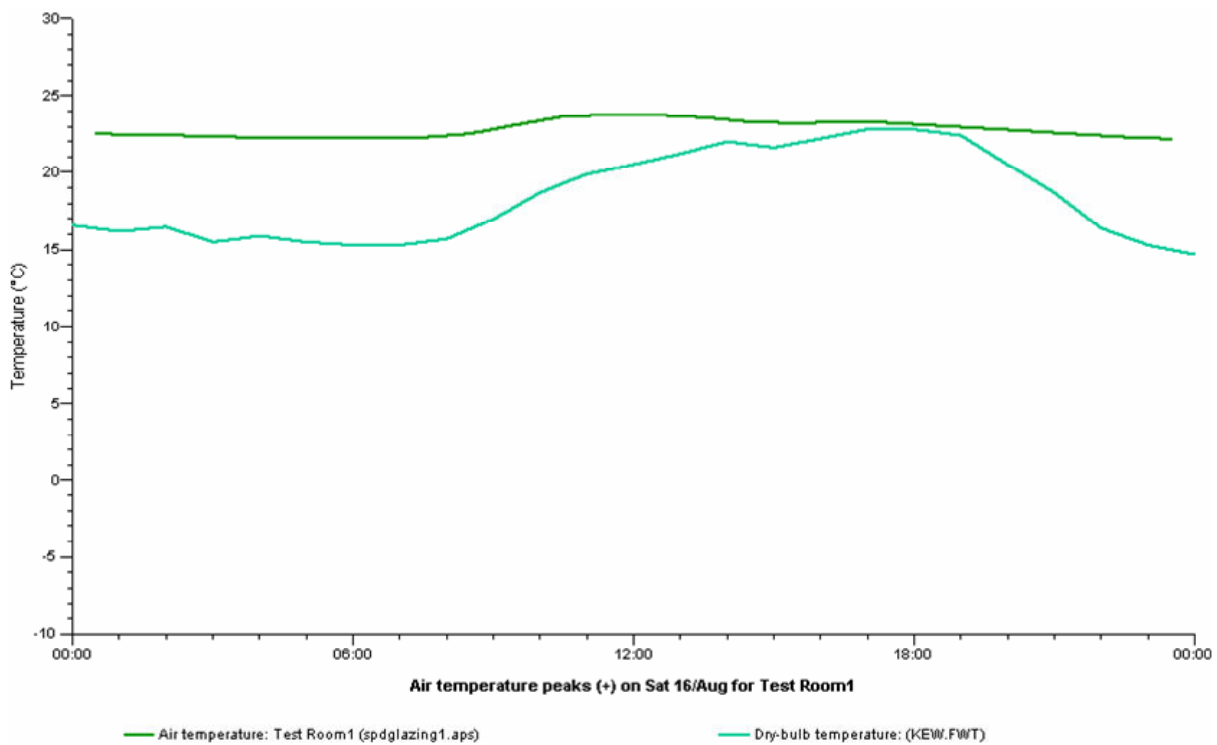


Figure.5j – shows the peak daily fluctuation in air temperature using SPD glazing

It can be seen that for the single glazing, the temperature variation within the room closely follows that of the variation in outside temperature. The temperature fluctuates by 10°C across the day and reaches a maximum of close to 30°C, a very uncomfortable office temperature. This suggests a high level of heat energy flow through the window, with an inability to retain heat during cold outside temperature, and to restrict heat radiation during hotter weather.

For the SPD glazing the air temperature remains much more constant throughout the whole day. Despite large fluctuations of around 8°C in the outside temperature, the internal room temperature varies only by approximately 2°C, and keeps the temperature within a user comfortable level. This suggests that the SPD glass has a high level of control of heat flow through the façade, being able to restrict heat gain during the hottest parts of the day.

In comparison the SPD glass performs to a much higher level than the single glazing, and is capable of maintaining a steady and comfortable internal room temperature throughout even the peak day of the year.

5.3.2 Solar Heat Gain

Appendix 2 shows the comparison of solar gain in the test office, with Figure.5k showing the use of single glazing, and Figure.5l showing the use of SPD glazing.

It can immediately be seen from these figures that SPD glazing has a significantly lower amount of solar heat gain than single glazing. It should be noted that the scales on the figures actually differ in magnitude due to the result analysis of IESVE and so the difference between the solar heat gains of the two glasses is actually much larger than initial visual comparison.

Direct comparison of monthly total figures for solar gain has been made in Table 4 below;

Date	Solar Gain (MWh)	
	Single glazing	SPD glazing
January	0.082	0.0076
February	0.0584	0.0053
March	0.1823	0.0162

April	0.1763	0.0168
May	0.1869	0.0178
June	0.1720	0.0176
July	0.1508	0.0141
August	0.1790	0.0176
September	0.1677	0.0175
October	0.1682	0.0168
November	0.0716	0.0066
December	0.0651	0.0059
Summed Total	1.6602	0.1596

Table 4 – IESVE results of solar gain

A graphical representation of these monthly totals is shown below in Figure.5m;

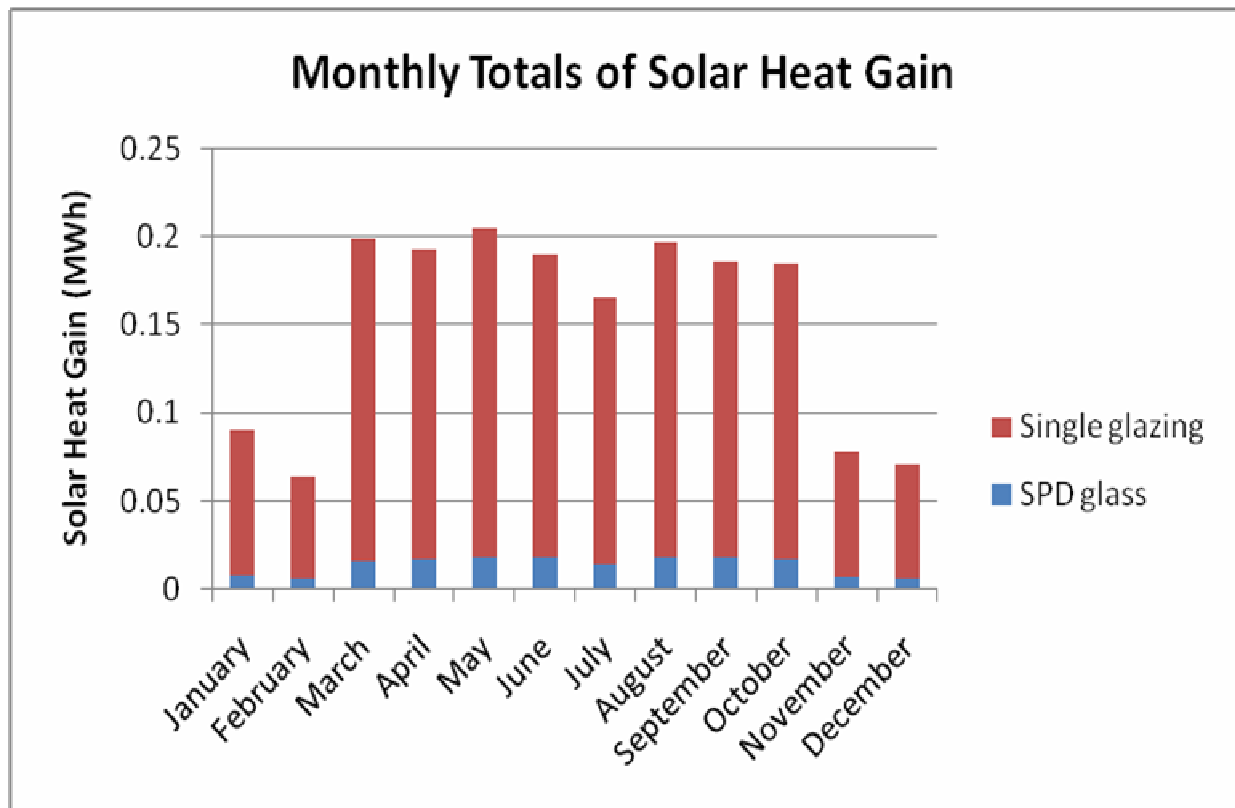


Figure.5m – shows comparative monthly totals of solar heat gain

These results show that the total solar heat gain from using SPD windows is around 10% of that from using single glazing. This shows that SPD technology is a substantial improvement to regular glazing in blocking out heat gain from sunlight, which reflected in results of the internal room temperatures, helps to maintain a more comfortable working environment.

The energy saving potential in terms of cooling loads required to maintain the room temperature at in the desirable comfort zone is also analyzed by IESVE. The simulation generates detailed cooling loads based on infiltration gains, internal gains, external gains and the sensible cooling plant load required to maintain the room temperature.

5.3.3 Cooling Loads

Appendix 3 shows the cooling loads required, with single glazing shown on Figure.5n and SPD glazing shown on Figure.5o. In comparison the cooling loads required for the room with SPD glazing is significantly lower than that of single glazing. This follows the trend seen in the previous IESVE results showing the ability of SPD glass to restrict heat flow through the glass façade. Once again the magnitude of the scales generated by IESVE is much larger for the single glazing so the monthly totals were compared and displayed in Figure.5p below;

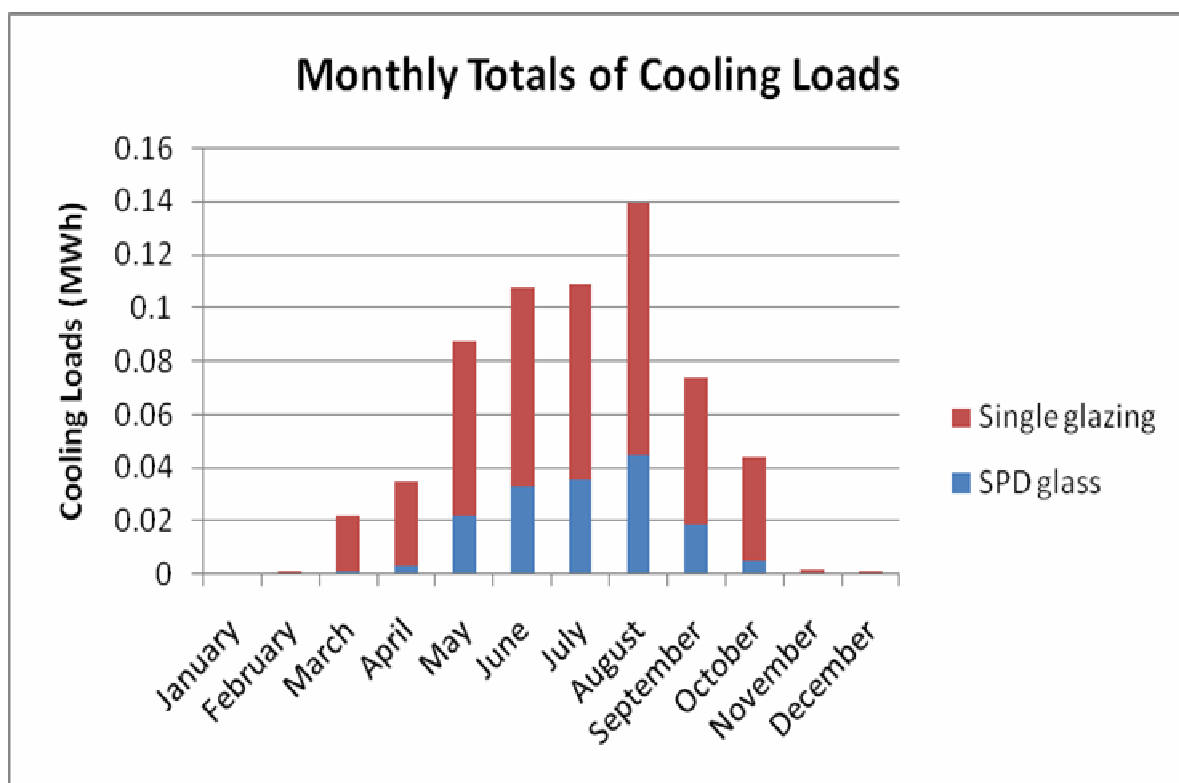


Figure.5p – shows comparative monthly totals of cooling loads

It can be seen from the figure that SPD glass uses considerably less energy for cooling throughout the year, of which the summer months have most importance. The overall summed total of cooling loads required for the test room using SPD glass is 0.1632 MWh, compared to 0.4605 MWh required for single glazing. The cooling energy used for SPD glass is 35% of that used for single glazing which is very significant energy saving. This data shows the distinct advantages of using SPD glass in improving the energy efficiency of buildings and glass facades and reducing costs associated with building maintenance.

5.3.4 Worldwide Simulations

Simulations were run to evaluate the performance of SPD glass in different, 'hotter', locations around the world. The annual solar heat gain and cooling loads were compared between using SPD glass and single glazing and are shown in Figure.5q and Figure.5r respectively

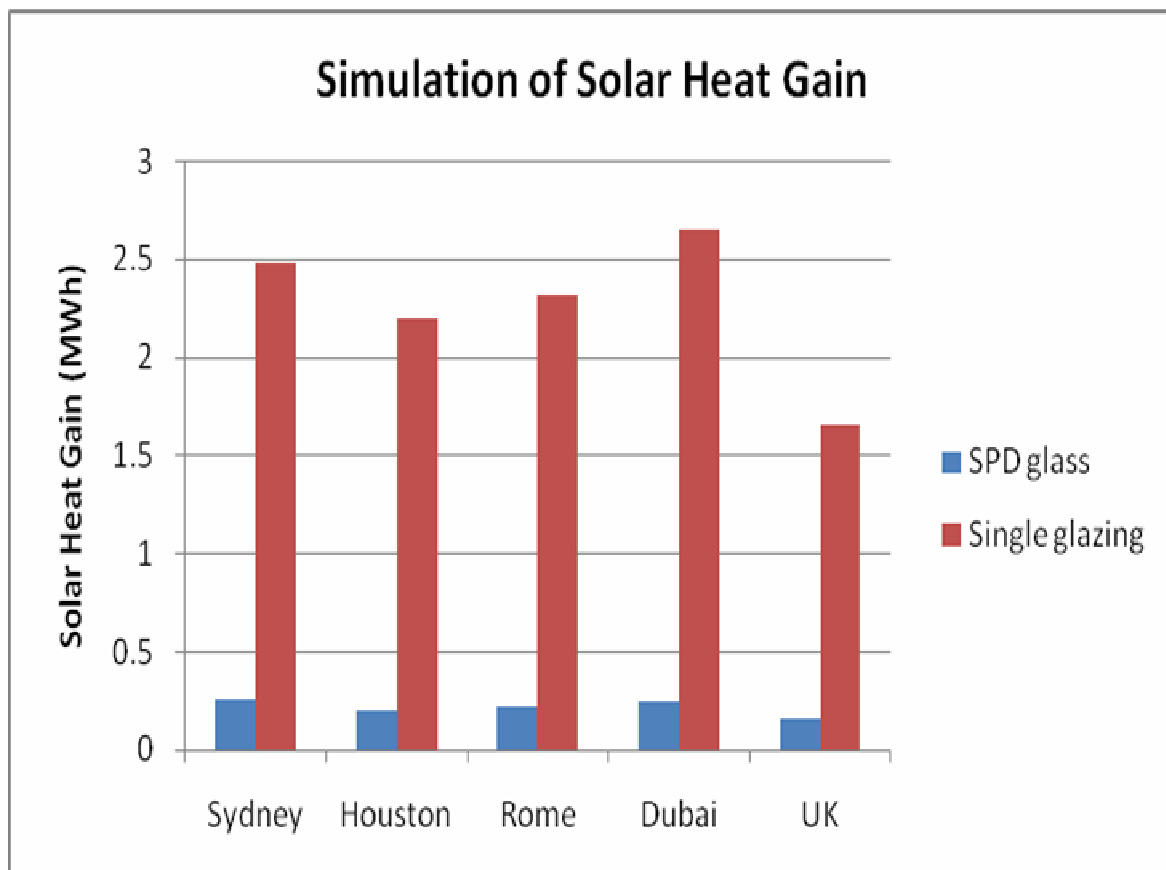


Figure.5q – annual solar heat gain of both SPD and single glazing

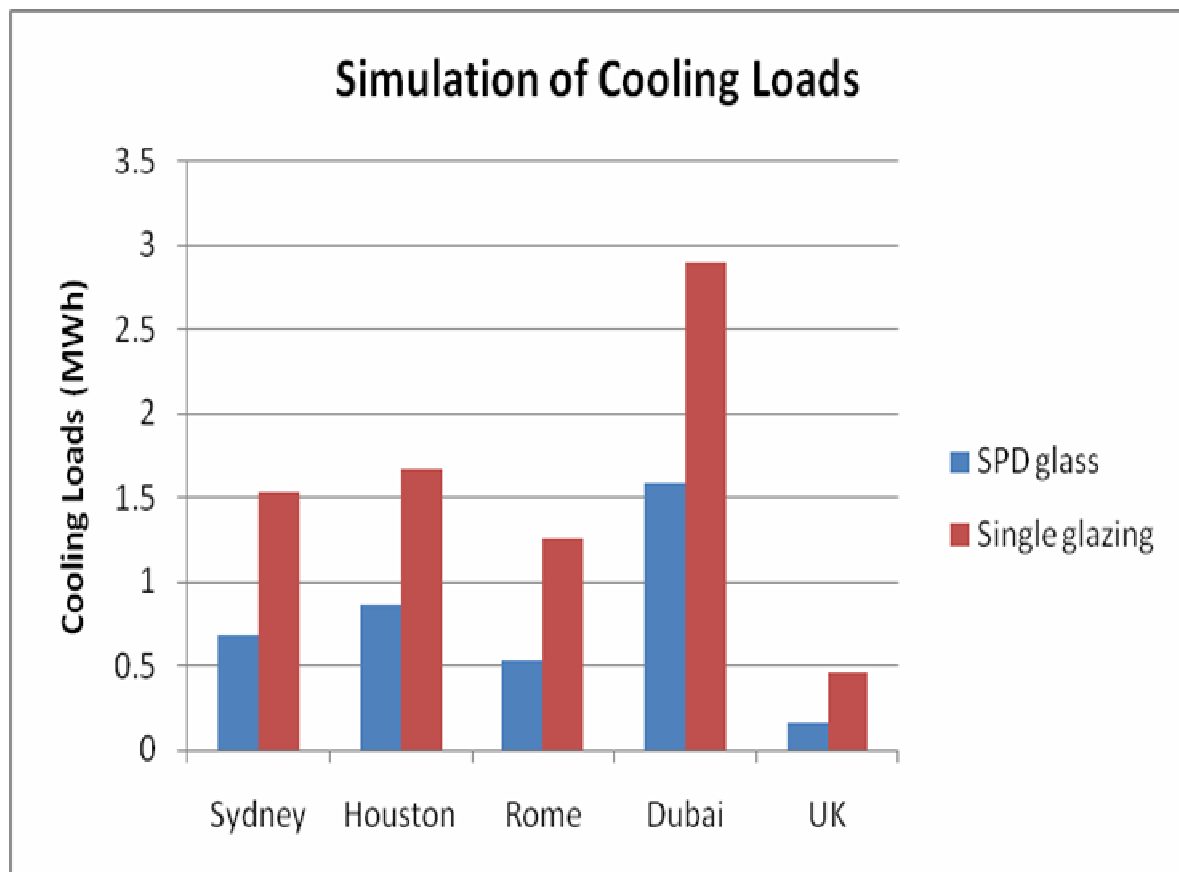


Figure.5r – annual cooling loads of both SPD and single glazing

It can be seen from these two figures that the SPD glass performs to a similar extent in hotter climates around the world compared with the UK. Figure.5q shows that there are much larger values of solar heat gain in the other four locations, with Dubai experiencing over 2.5MWh through single glazing windows. It should be noted that these simulations were run with the exact office conditions as the UK simulation, however with differing orientation depending on the solar path per location. In general the SPD windows were able to block 90% of the solar heat gain into the office, in all locations.

Figure.5r shows that the UK has very low cooling loads compared with the other locations, for which this energy saving technology could be of much greater importance. Once again Dubai had the highest cooling load required, nearly reaching 3MWh, roughly twice the loads associated with Sydney, Houston, and Rome and six times the cooling load of the UK. The performance of the SPD glass varied slightly depending on the location, with energy savings varying from 45% in Dubai, 58% in Rome, 56% in Sydney, 48% in Houston, and 65% in the UK. Note that energy savings is the percentage less cooling load that the SPD glass uses in comparison to single glazing. This reduction in energy savings is possibly comparable to the specific air temperature of the location and not just the reduction in solar heat gain experience by the office environment.

CONCLUSIONS

6.1 Conclusion of SPD Performance

This investigation into the performance of SPD glazing has shown that this switchable smart technology has significant advantages over the use of regular clear float glazing. It was identified before experimental measurements that SPD glass had a lower visible light transmission, and a similar solar heat transmission to other smart switchable glazing, such as thermotropic, gasotropic and electrochromic. These other technologies were discussed briefly and disadvantages that limited their potential noted; disadvantages which SPD technology does not experience.

From the real-world performance data of the SPD windows it can be concluded that SPD glass is able to provide a much more uniform and comfortable internal room temperature than regular single float glazing. This was shown by data measurements detailing how the room temperature only fluctuated by 2°C with SPD windows, in comparison to 8°C in the reference office. Comments from the user to the comfort of the room temperature over the course of testing also confirmed this result. A certain part of this temperature control will be down to the difference of double and single glazing of the two different offices, however further data showed the ability of the SPD windows in rejecting solar heat radiation. Temperatures recorded as a result of direct sunlight showed a difference of up to 15°C in the two offices, with temperature exceeding 40°C through the single glazing. This data confirms that SPD glazing is able to reduce the solar heat gain into an office although it is not possible to quantify the exact solar energy reduced due to this testing being carried out in an everyday office with numerous other inputs. With the SPD glass reducing the solar heat by 15°C during a UK spring it can be concluded that this technology would have a positive impact in reducing room temperatures during the summer months and hotter climates. This reduction in room temperature, to suit a more comfortable environment would subsequently lower the cooling required to maintain the interior temperature and thus save on energy and costs.

Similar conclusions can be drawn from the environmental modeling of the test office using IESVE. Simulations confirmed the improved control of internal temperature fluctuations of the office with the SPD windows, and can be closely compared with the real-world data measured. Figure.5c shows the real-world temperature variation for SPD windows, and Figure.5j shows the simulated temperature variation. Both figures show a small variation of only 2°C between 22°C - 24°C. This similarity strongly validates the accuracy of the real-world testing, and of the ability of IESVE simulations to provide accurate building performance data.

While it was not possible to quantify the solar energy and cooling energy difference between SPD and single glazing windows by real-world measurements, this analysis was

able to be undertaken using the IESVE simulations. A summary of the annual energy totals in the Cambridge office can be seen for each of the different glass facades in Table 5 below;

	Solar Heat Gain (MWh)	Cooling Loads (MWh)
SPD glass	0.1596	0.1632
Single glazing	1.6602	0.4605

Table 5 – annual energy totals for the Cambridge office using different glazing

It can easily be seen from this table that the SPD windows are significantly more energy efficient than regular clear float glazing. The solar heat gain is reduced by 90% through SPD glass, which partially results in a 65% reduction in annual cooling loads. This confirms theoretical predictions that SPD glass holds great energy saving potential and is a technology that can really help to reduce energy wastage of glass facades. The performance of SPD windows was briefly looked at in a few other hotter world locations, which are more associated with heavy cooling during the summer. While air conditioning is often a luxury in the UK, it is a necessity in locations such as Dubai and Houston, Texas. The performance of SPD windows in these locations showed identical results in solar energy gain reduction, and fairly similar results for cooling load reduction, while magnitudes of energy saved were far larger than the UK figures. The solar reduction is primarily a result of the optical transmission properties of the glass, so will not change proportionately with increased intensity. The cooling loads however are much more complicated with many more other inputs into the resultant air temperature than just solar energy, which explains the difference in energy saved in each of the locations, with Dubai saving 45% while Rome saves 58%.

It can be concluded from feedback during the real-world testing that the usability of the SPD windows is very realistic and that the task of switching the tint of the windows can easily be included in a working environment. However the switching potential of the windows should be expanded further than just an ON/OFF choice, and as laboratory testing showed, the optical transmission of the glass can be precisely controlled between 0 – 45% (approximate figures) by varying the voltage applied. This relationship was found not to be directly proportional, with light transmission changing by different amounts across the voltage scale. This could easily be accounted for however in producing an accurate 'multi-tint dial' for the user, and would provide a much improved light control of the interior environment.

Overall this investigation has looked into the performance of SPD glass in creating a more desirable room environment and on improving the energy efficiency associated with glass facades. It can be concluded from both real-world and simulation results that SPD glass is able to maintain a comfortable room temperature, and prevent unwanted fluctuation linked with the change in external temperature. It can also be concluded that SPD glass holds great energy saving potential due to its ability to reduce high levels of solar heat energy into the

room, therefore reducing in turn the energy required to cool the room to a comfortable or necessary temperature. This 'smart' switchable glazing technology has shown that it offers a realistic and promising alternative to conventional glazing, and will help to improve the energy efficiency of buildings today.

6.2 Project Evaluation

While the data of the SPD windows from real-world tests and computer modeling have given convincing conclusions into the performance of SPD windows it should be noted that there were several factors that could have possibly affected results.

For the real world testing the SPD windows were added as a secondary glazing layer to the single float glass due to installment reasons. While this would not have affected the solar heat gain results, it would act to limit the temperature variation of the room. In particular it is probably the reason why the temperature remained high during the evening compared to the single float glass, despite SPD windows not have especially high thermal rejection properties. The majority of buildings today are constructed with at least double glazing, and possibly with a heat coating, so would also reduce the room air temperature variation from reduced heat conduction. This observation shows that while many new buildings are being made with more efficient glass facades, many older buildings still need to be improved and refurbished in order to meet energy consumption standards

Another aspect of the real-world testing was that it was not recorded what state of tint the windows were at during the day. It was left to the user to switch the windows according to his comfort levels however no device was installed (e.g. a voltage logger) to actually determine the tint. It was then noted in the feedback from the user that a lot of the time the windows were kept in the clear setting to allow the most sunlight through on slightly overcast days. This would suggest that the concluded performance of the SPD glass in blocking out solar heat gain was actually recorded from the glass in its clear state, and so larger differences in temperature would have been recorded for the fully tinted glass.

For the simulation models of the test office, it was desired for the model to be an accurate representation of the real-world office in order to compare performance data from the two different methods. This was achievable in terms of size, location, and building materials however IESVE contains complicated heating and cooling simulation, which all take into accounts building natural ventilation, infiltration rates, as well as other parameters. This knowledge was not known for the test office so default values were used for a regular office profile. It was observed that in fact the test office did not have any cooling systems, and that the radiators were not on for most of the test month, so cooling loads were hypothetical predictions of those required to keep the temperature at 23°C and below.

6.3 Further Work

This project acts as a solid foundation to the performance of SPD windows, and has identified many possible directions of future work that could help verify and validate the performance of SPD windows.

In terms of laboratory testing it would be desirable to gain a full light spectrum of the SPD laminate during varying voltages. This was not possible with regular spectrophotometers however the experimental methods do exist. Such testing would show the exact wavelength of light energy that is transmitted at different degrees of tint.

More precise lab experiments and techniques could also gain values for light emittance, reflectance, and shading coefficient of the glass. The shading coefficient values are defined as the ratio of solar heat gain through a glazing system, to the solar heat gain through a single layer of double-strength reference glass. This data would give a more theoretical insight into the heat energy saving potential of the glass

In a real-world use of SPD windows, the solar angle would be continually changing in relation to the glass façade and so could potentially give different transmission values than expected. The transmission properties of the glass should therefore be measured with a light source at varying angles of incidence to the SPD laminate. This will give an insight to whether the SPD particles perform to the same standard with differing light entry angles, especially at numerous levels of tint.

It would be helpful to gain background knowledge of internal lighting levels, and human trend in using artificial lighting in rooms. Main office users have artificial lighting on during the day regardless of natural daylight levels, especially in large open office floor where a lot of desks are away from windows. This would help to understand the benefit of being able to control the particular light level in a room from tinting the glass

As well as smart switchable glazing, there is currently a lot of development into other energy efficient glass technologies, such as heat and low-e coatings. Environmental modeling can be used to compare SPD glass with not only regular single float glass but also other emerging glass coatings and switchable glazing. This would identify the best combination of glass and coatings in order to achieve the highest performance of the glass façade.

6.4 Acknowledgements

This work was supported by SmartGlass International, a worldwide manufacturer of electronically switchable glass, who provided the SPD laminates used in the real-world and laboratory testing. Acknowledgement also goes to the project supervisor, Dr Mauro Overend, who aided in the project direction and methods.

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RISK ASSESSMENT RETROSPECTIVE

The risk assessment carried out before the commencement of this project highlighted the following possible risks;

Electric wiring of the SPD could cause electric shocks and subsequent health implications if carried out without following proper safety methods, such as wiring only when electric current is switched off, using suitable fuses in voltage transformers.

Possible risks associated with the installment of the windows in the test office, and health implications of lifting, using power-tools and other methods associated with this activity.

Health implication of extending use of computer screens during IESVE simulation, necessary periodic breaks needed to prevent this.

In reality the risks associated with the wiring of the SPD were understated. Risk assessment should have been identified in having to solder connections, and the operation of a small potentiometer device while a live current is flowing.

Soldering – this creates a burning hazard as solder operates at very high temperature. Safe methods and clear working area need to be followed to prevent injury to person.

Operation of potentiometer requires careful working in order not to touch the live connections while turning the slide. This risk is reduced with sensible working ethic.

The risk assessment of installing the windows in hindsight was not necessary to carry out as the SPD windows were installed by the maintenance department and not in person. The maintenance personnel are professional workers and are qualified in this activity.

During the investigation there were no events that caused any health concerns or could be classed as a near miss. This was in general a very low risk investigation.

APPENDIX 1

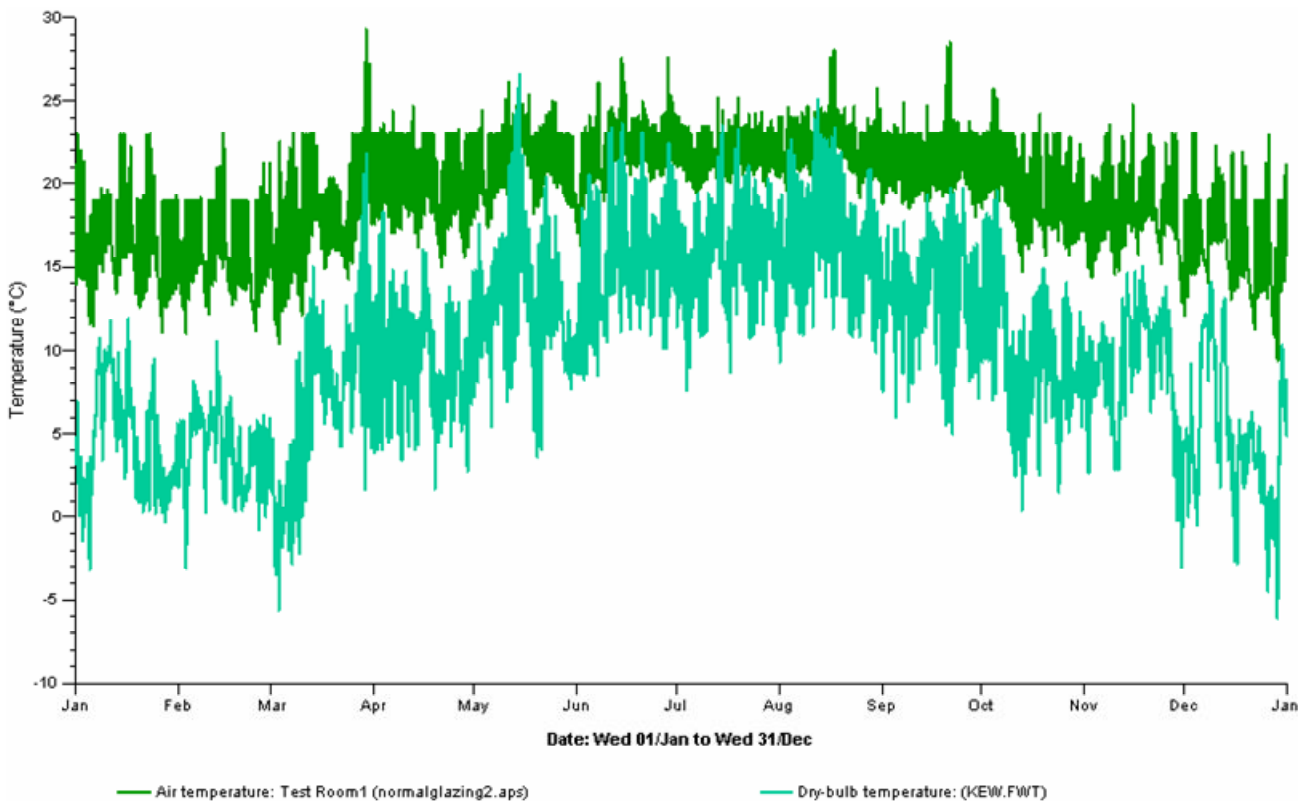


Figure.5g - shows the annual variation in air temperature within the test room and the external dry-bulb temperature while using single float windows. Data modeled by IESVE.

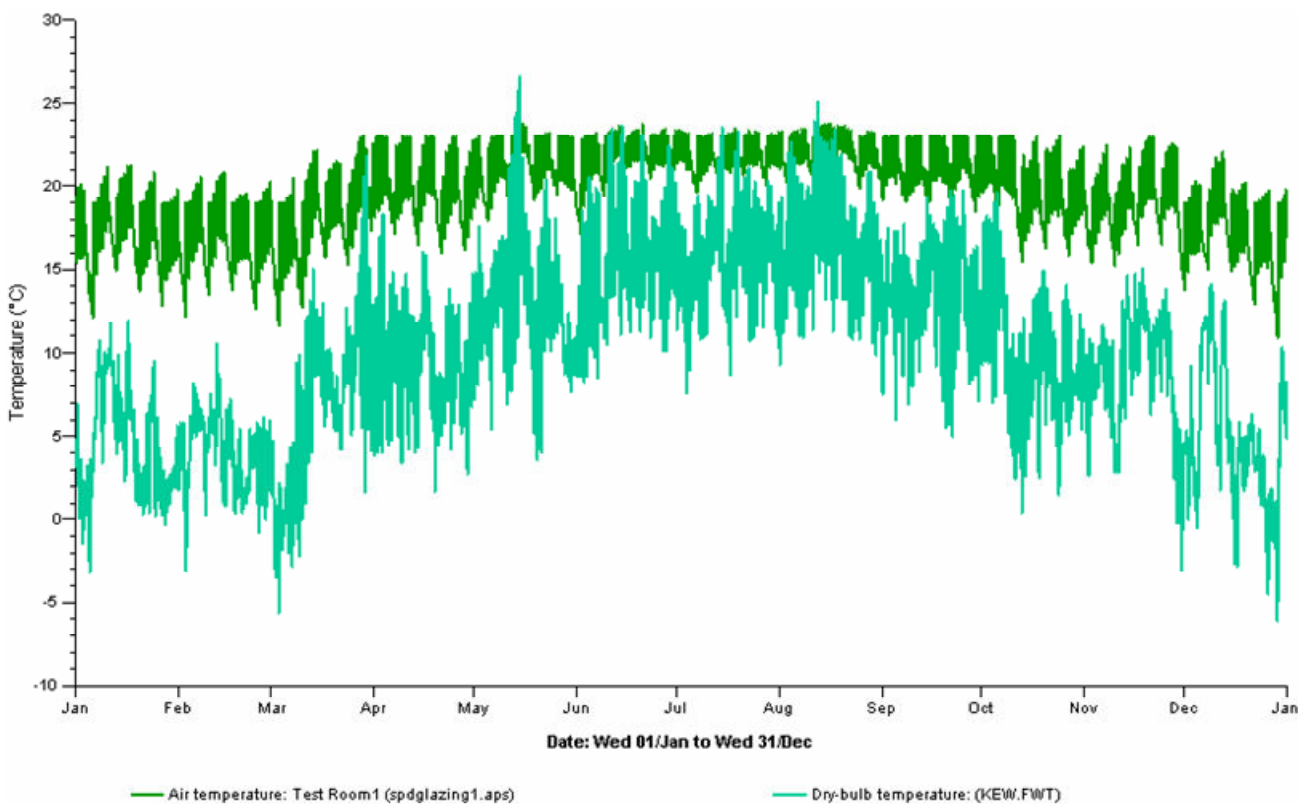


Figure.5h – shows the annual variation in air temperature within the test room and the external dry-bulb temperature while using SPD windows. Data modeled by IESVE.

APPENDIX 2

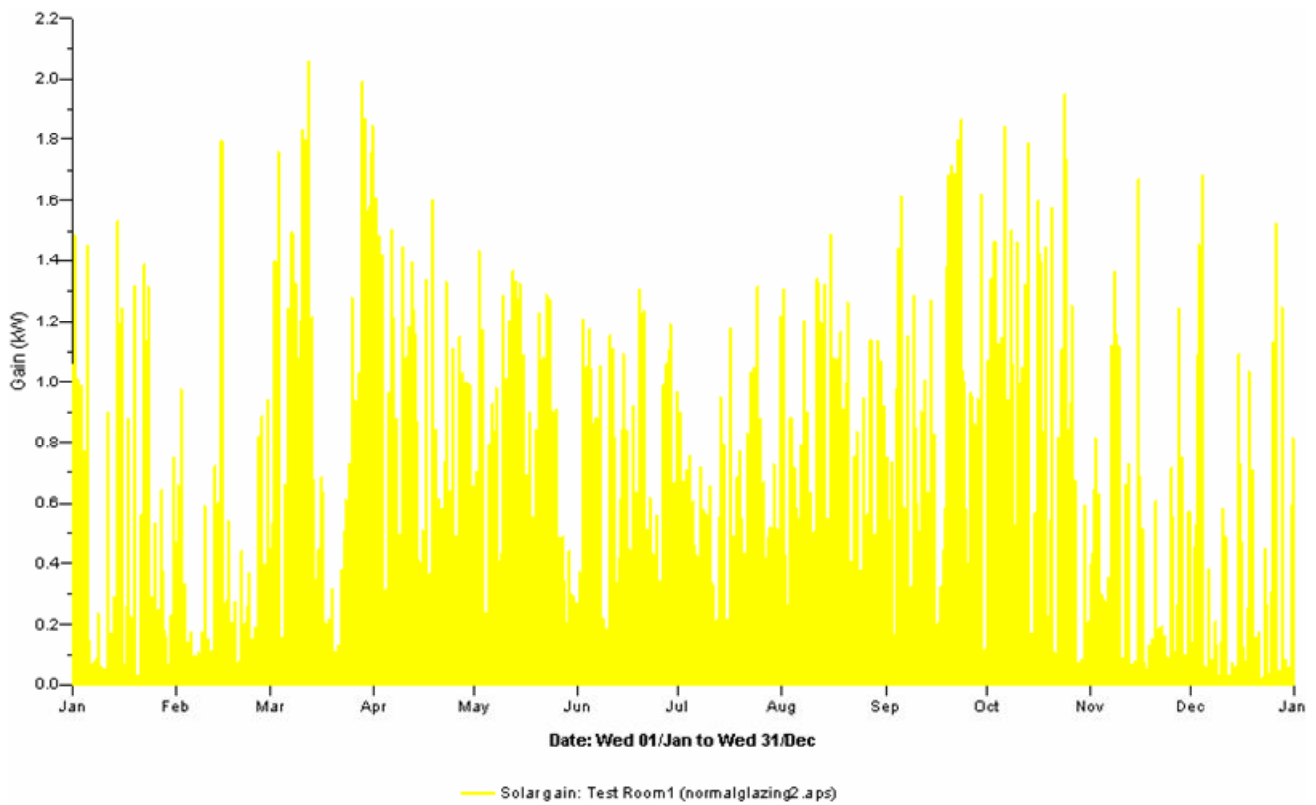


Figure.5k – shows the annual solar energy gain with the use of single float glazing. Data modeled by IESVE

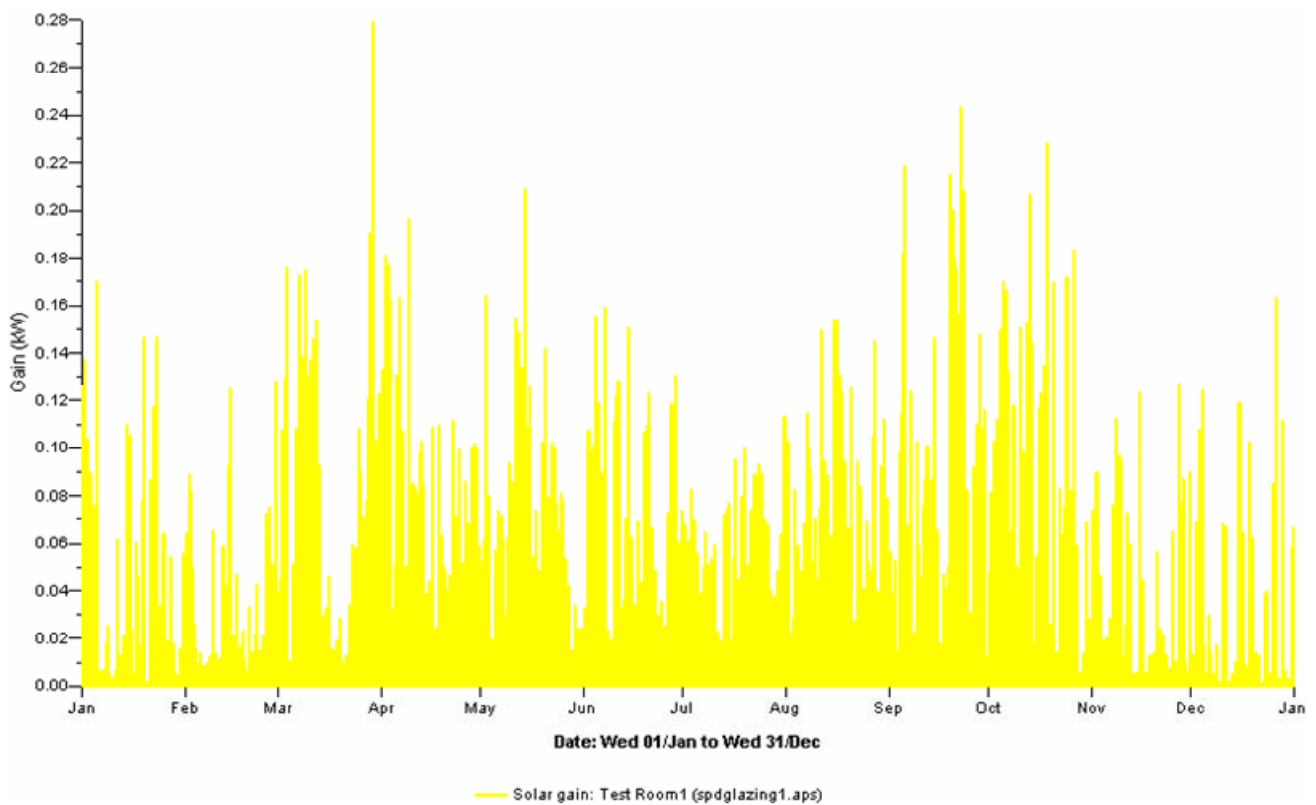


Figure.5l – shows the annual solar energy gain with the use of SPD glazing. Data modeled by IESVE. Note should be made that the scales have different magnitude to Figure.5k

APPENDIX 3

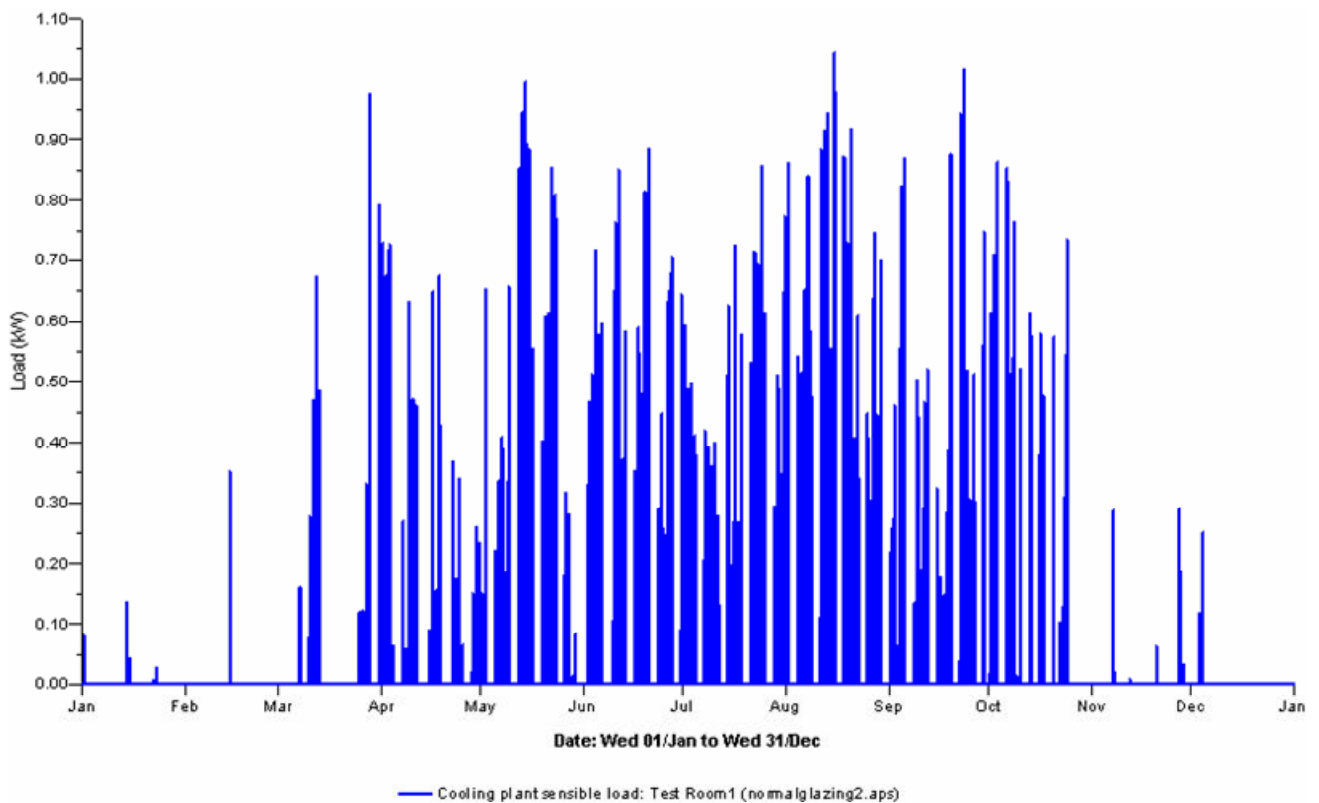


Figure.5n – shows the modeled annual cooling loads for the test room while using single float glazing.

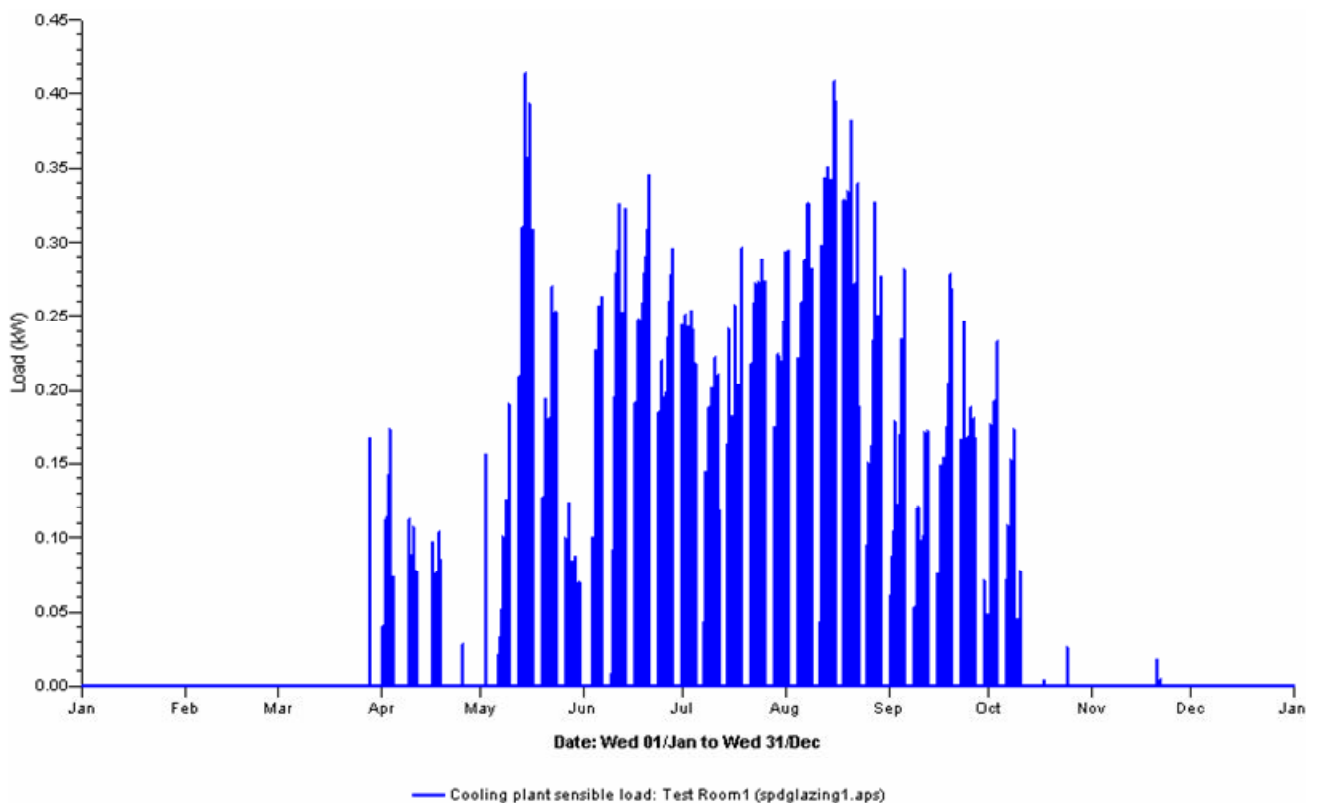


Figure.5o – shows the modeled annual cooling loads for the test room while using SPD glazing. Note should be made that the magnitude of the load scale is different to Figure.5n