Building Envelope & Lighting Systems

Reference Manual

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Preface

This Building Envelope and Lighting Systems (BELS) elective module consists of the following sub-modules:

1. Façade Systems (2 Sections): The façade of a building is an important contributor to the solar heat gain of a building. Energy managers should be well-equipped with knowledge and technical skills to minimise this load. This sub-module broadly comprises the following elements:

    a. Façade Development and Design Considerations (Chapters 1 and 2)
    b. Materials Availability and Processing (Chapters 3 to 6)
    c. Façade Construction and Applications (Chapters 7 to 9)
    d. Design Consideration and Safety aspects (Chapters 10 to 13)

2. Building Envelope And Thermal Transfer Values (3 Sections): Every energy manager is concerned with the Envelope Thermal Transfer Value (ETTV), Roof Thermal Transfer Value (RTTV) and Residential Thermal Transfer Value (RETV). There are minimum standards for these parameters when seeking building plan approval as well as for Green Mark Awards. This sub-module covers the following:
    a. Definition and components of building envelope and Thermal Transfer Values of Envelope and Roof
    b. Definition and calculation method for ETTV, RTTV and RETV
    c. Calculation examples
    d. Daylighting Design Principles, Concepts, Tools and Standards

3. Artificial Lighting Design For Energy-Efficiency and Sustainability (1 Section): Energy managers are expected to have good knowledge of electrical lighting products, systems, lighting design and methods of integrating with daylight to reduce thermal loads and energy consumption of lighting systems. This sub-module comprises the following aspects:
    a. Principles of Light, Definitions and Terminologies
    b. Eco-friendly Lighting Design Method
    c. Characteristics of Lamps, Ballasts Accessories
    d. Energy-efficiency and Life Cycle Study

The authors of this module (Kelvin Kan, Alvin Cheong and K.Seshadri) would like to record their appreciation to Mr. Andy Ong of the Institution of Engineers, Singapore (IES) for his able co-ordination of our inputs, assistance with templates and other aspects as well as co-ordination with the National Environment Agency (NEA) for the benefit of energy managers and professionals.

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Façade Systems

<u>Façade Systems</u>

Section 1:

Introduction

The 3 basic needs for human beings are; “food, clothing and shelter”

In this module, “food” will not be discussed but “clothing” in the form of “façades” will be the main topic and “shelter” in the form of “building or architecture” will be included to illustrate the different aspects of “building envelope”.

From individual houses to multi-storey towers and mega developments in any part of the world, the building “envelope” or façades (minus the “roof”) is often the largest element a building will be composed of. As such, building façades have become the most recognisable element for any building type regardless of wherever or whatever the climatic conditions it is located in.

Because of this, its significance as a “barrier” is essential to achieve the “performance” needed for a building. Similarly, “clothing” is essential to the survival or comfort for humans ranging from extreme cold weather where igloos are used to extreme hot weather where “mud walls” are used as forms of “climatic control devices” to moderate temperatures.

As the human race progressed from the roots of our forefathers to the present day, building enclosures have significantly progressed that façades are now expected to meet the essential requirements well beyond the basic needs of “food, clothing and shelter” that were once called upon. Beyond the “technical” requirements, one of the most common expectations now is the “aesthetics value” façades can provide or even “value add” in some similar ways like clothing that has often become a “fashion statement” for its owners.

However, there is a vast difference between clothing and how building façades “respond” to the environment due to the difference in size of each. Buildings are “static” whilst clothing is constantly on the move as it is worn on a live person.

The “comparison” between façades and clothing shall stop here and discussions on façade developments and its design considerations shall be illustrated in the different chapters below.

Learning Outcomes For This Section (Chapter 1 to Chapter 2):

i. To be aware of the different periods of how façades evolved and its developments
ii. To understand the impact of “in/out” relationships from views through façades
iii. To understand the “role of façades” and expectations from them
iv. To be aware of the different elements and requirements façades have to face

Chapter 1: Façade Developments: Historical To Modern Trends

1.1 Skylight

Historically, man resided in the jungle in shelters created from available materials. The materials used may be classified as “unprocessed” in the sense that they were merely cut or shaped to required lengths, etc and used as they were found, i.e. not “processed” into a more superior form of “building material” as we know it today.

Starting with the simplest building constructed using basic materials like stones, which is still commonly used as a building construction material, stones were merely stacked above one another and joined using some form of “mortar”. That is how “walls” are created. Where openings or windows are required, a “lintel[1]” is required to create the opening where an opening for a window can be formed.

The building in Figure 1 demonstrates that views out of a building bring a high value to its occupants by offering visual connections to the outside world. It is this “in-out” relationship that provides psychological comfort of being protected and yet being able to relate to the changing environment.

[1] A **lintel** is a horizontal structural member that spans the space or opening between two vertical supports.

Figure 1 Basic Openings In Stone Stacked Wall (Courtesy: Pixabay.com)

The façade is nothing more than “holes in wall” which are formed by the stone lintels spanning across the top of the openings thereby allowing the stones beneath it to be omitted to form the window openings.

In general, the windows are also of similar sizes as the span of the lintel is limited to the material’s inherent capability to span and carry the weight of the remaining walls above it. However, visually “larger” openings with curved tops can be formed using smaller stones acting upon each other in the form of a “compression arch” to transfer the loads to the sides. This early “engineering” principle has been adopted into grander buildings as shown in Figure 2 and Figure 3

Figure 2 And 3 Arched And Circular Windows Formed By Compression Arches Or A Circle

(Courtesy: Graham Lacdao, © The Chapter of St Paul’s Cathedral (Fig 2) and Pixabay.com (Fig 3))

The basic “openings” in Figure 1 have now progressed into some elaborate form of façade treatment as shown in Figures 2 and 3.

To counter the external elements, glass was incorporated as a “filter” device to provide some level of “performance” in protecting the occupants besides allowing views out of and into the building.

1.2 Early Precedents

However, limitation of the material itself has restricted the treatment of the façades although attempts have been made to improve the amount of window openings primarily to achieve more visual connections to the outside world as shown in Figures 4 - 7

Figures 4 And 5 Windows Placed Adjacent To Each Other To Give An Illusion Of A "Longer Window" (Courtesy: Pixabay.com)

Figure 6 Arched Thermal Window With Vertical Supports Enables "Larger" Window To Be Formed (Courtesy: Pixabay.com)

Figure 7 Windows Are Placed To Face And Connect To External Visual Features (Courtesy: Pixabay.com)

The desire for bigger openings in a façade has continued to the present day and the search is to achieve the ultimate "all glass box" or "all glass building" where 360 degrees of views can be achieved. Whether this is possible or not and how it can be achieved will be discussed in subsequent chapters under different topics and considerations.

1.3 Modern Architecture Precedents

In the development towards modern architecture, buildings with remarkable architectural significance due to their design, and use of materials and its applications have been built. This has led to innovative building designs which have functional and “timeless” aesthetics.

Through the use of technology, the design of “Fallingwater” (Figures 8 and 9) by American architect Frank Lloyd Wright has created a private residence in Pennsylvania, USA back in the 1930s. Dubbed a “classic” in modern architecture history, “Fallingwater” has many “firsts” in construction methods on how it deploys them and transforms it from a “traditional” to a “modern” architectural masterpiece. Its “floating balconies” and façade design are a result of understanding the materials and processing technologies. The transformation of an “ordinary material” into one that has a much “higher performance” allows for innovative designs.

Figure 8 External View Cantilever RC Decks (Courtesy: Pixabay.com)

Figure 9 View Of Metal Frame “Picture Window” (Courtesy: Pixabay.com)

In the earlier examples, we looked at “material”, i.e. mainly “stone” and its limitations in achieving long spans. At “Fallingwater”, the use of “basic” materials and their subsequent “processing” resulted in reinforced concrete (RC) and glazing, which are superior building materials.

a. Reinforced Concrete: Achieved by incorporating steel (bars) into the concrete slabs to take tensile forces. Large cantilevers of “floating decks” are possible.

b. Glazing System: Using steel frame as mullions[2] and transom[3] members enabled large glazing area with slim framing aesthetics and "frameless" glass corners to be achieved.

The above examples show the importance of understanding properties of material and how technology can be used to "process materials" transforming them into higher performance elements. Technology, if used appropriately can have a significant impact on how buildings can be designed and constructed.

With the advent of computers and software development, façade designs and construction have now gone to a stage where "any design is possible" to build. The only restriction is one's imagination and design capabilities.

It is with such "Information Technology" and software that buildings with "free-form" façades or "blob architecture" have emerged. Although "organic" designs are achievable, most free-form façades are limited due to costs and/or appropriateness for different building functions.

However, with parametric modelling, design of buildings will move further to address some of the "impracticalities" and mitigate or minimise them while making the form and space planning more efficient.

[2] A mullion is a vertical member that forms a division between units of a window or other openings.

[3] A transom is a horizontal member within a window unit usually at waist height (about 1m level) providing a horizontal "barrier" and / or at ceiling level allowing the termination of the ceiling and floor to floor separation elements known as "spandrel panel" (See figure 32).

Chapter 2: Façade Considerations – A Single "Skin" To Satisfy Many Issues

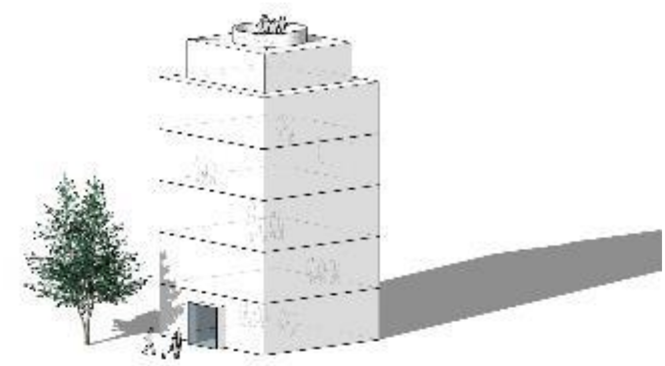


Figure 10 Façade As An Envelope Or "Skin" To A Building (Courtesy: AgFacadesign & G Facadesign Pte Ltd)

As mentioned earlier, a façade has to satisfy and perform a lot more than what is expected of "clothing" on a person.

From the most fundamental requirements like keeping water out to some not too common occurrences like explosion, other aspects a façade (Figure 10) needs to satisfy include the following considerations (Figures 11 to 22);

Figure 11 Water: Rain, Humidity, Condensation

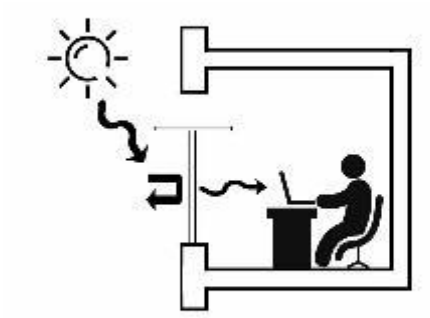


Figure 12 Heat: Solar Radiation, Air Temperature

Figure 13 Air: Wind, Ventilation

Figure 14 Pollution: Gases, Particles, Haze

Figure 15 Sound: Desired, Undesired

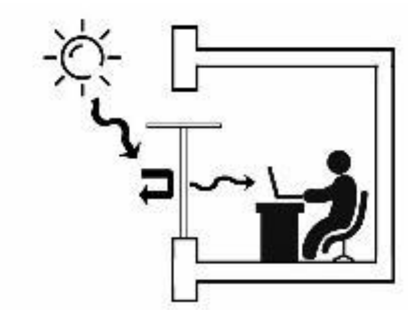


Figure 16 Light: Sunlight, Glare, Day/Artificial Light

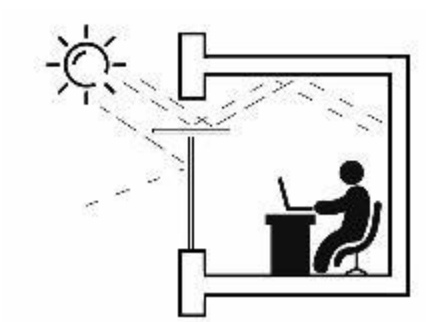


Figure 17 Views: In/Out, Private/Public

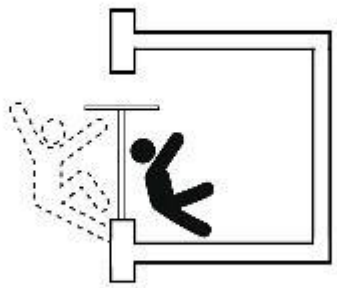


Figure 18 Safety: Falling Out

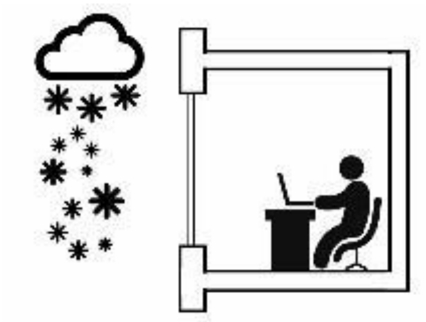


Figure 19 Snow: Condensation, Air leaks

Figure 20 Fire: In/Out, Flames, Smoke, Radiant heat

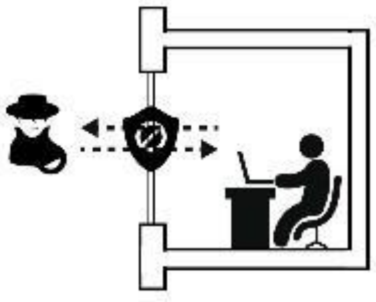


Figure 21 Security: Breaking In/Out *Figure 22 Explosion: From Outside/Inside*

(Courtesy: AgFacadesign & G Facadesign Pte Ltd)

From the above figures it can be seen that the façade “skin” on most buildings needs to overcome different aspects of the elements. However, unlike “clothing”, the façade “skin” has to withstand loads from within the building as well as external forces, which can be of a much higher magnitude.

However, through development of technologies, glass has developed significantly as a material providing high thermal and structural performance capabilities. In addition, extrusion technologies for different materials like aluminium and other rubberised form have enabled different façade systems to be developed to meet the different design, aesthetic and performance requirements of a building.

Section 2:

Introduction

From understanding the basic needs and desire of having “windows” to connect to the outside world, the next section will be investigating what makes the “skin” of a building or what is known as “façades”.

However, while façades cover the vertical surfaces of the building elevation, what is now commonly known as “the fifth elevation” is the “roof elevation” which is constructed horizontally. Together with the vertical façades, they form the “building envelope” which is the largest surface area in any building.

In order to cover the building efficiently and effectively, there are many types of “systems” that are available and with the advent of computer software, free-form or “blob” architecture is not an unusual sight today.

However, the system requirements of the basic façade systems will need to be understood before one can proceed to design and erect bespoke façade systems. We have mentioned in Section 1 that understanding materials, technology and information technology are the key ingredients for a designer to achieve any innovative outcome.

In this section, we will discuss all possible façade systems available including bespoke systems that are specifically created to meet different technical, functional or aesthetic requirements. The key considerations in the design process include fundamental aspects like planning or orientation layout and how to optimise the site features to bring out the best of the building in response to the climatic conditions that it is located in.

We will also be looking into the different components that form the bulk of the different systems namely, glass, aluminum extrusions and sealants.

The unique quality of glass as a “transparent material”, its behavior in both compression and tension, how heat treatment transforms this fragile material that breaks “spontaneously”, what can be done to minimise such occurrences and “safety” glass will be discussed.

The use of glass on its own, with coatings applied and in combination with other elements transforming it into a material that has structural and thermal qualities will be discussed.

With the advent and advancement of glass treatment and processing, one often wonders if an “all glass house” would be a possible outcome in the near future. The answer at present is that “it can be possible” but glass must be used in combination with other elements. The design considerations of the designer, site and/or weather conditions also contribute to this outcome.

Provision of external shades often provides the most effective solution. Shades in the form of “louvres” to elaborate “screens” are often used and it is up to the designer’s creativity to achieve an efficient design that provides the optimum thermal performance.

With global warming and the search for alternative or renewable energy, solar panels are being adopted. Singapore being close to the equator has a sun path that is often “overhead”. As such, solar panels are laid “flat” on the roof while building integrated photo-voltaics (BIPV) are more suitable in some European countries like Spain.

Taking into consideration all the design and technical considerations discussed, building construction will need to go through a process where design drawings are used for pricing and tender before commencement of construction.

For the building envelope, two major processes are highly recommended and will be required for most large scale projects. The Visual Mock-up (VMU) and Performance Prototype Testing (PPT) will be conducted before the full scale production of the façade – envelope panels. In special cases where the performance of the materials is critical, material testing will also be required to ensure that not only are the design criteria met but that safety is also assured.

Learning Outcomes For This Section (Chapters 3 to 13):

i. To understand what curtain wall systems are

ii. To know the various systems available and differences between them

iii. To be aware of the limitations of curtain walls

iv. To understand what are the main components used in curtain wall façades

v. To understand what are the different façade systems and key principles of the design process

vi. To understand glass production and how raw glass quality can be determined

vii. To be aware of the impact glass processing has and how it transforms the glass characteristics

viii. To be aware of the key factors in glass for thermal consideration

ix. To be aware of processes glass needs to go through to minimise chances of spontaneous breakage

x. To know what constitutes “safety glass”

xi. To understand the basic elements required in design to optimise energy efficiency

xii. To be aware of the use of artificial and natural elements to achieve better thermal performance

xiii. To be aware of the considerations for safety in design

xiv. To understand the role of shades and louvres and indirect lighting in energy efficient design

xv. To be aware of the considerations in the use of BIPV and BAPV

xvi. To understand how the project work stages tie in with the 3 main architect’s work stages

xvii. To be aware of how 3D modelling is used in the design process from conceptualisation to structural design

xviii. To be aware of the importance and values of visual mock-up, performance prototype testing and material testing

Chapter 3: Curtain Wall Systems

3.1 Modern Architecture Precedents

Curtain walls are commonly described as an external building wall which carries no roof or floor loads and comprises primarily of metal, or a combination of metal, glass and other surfacing materials like granite or any other stones supported by a metal framework.

3.2 Two Basic Types Of Curtain Wall Systems

3.2.1 Custom Design

Walls designed specifically for one project, using parts and details specially made for this purpose.

3.2.2 Standard Design

Walls made up principally of parts and details standardised by their manufacturer and assembled in accord with either the architect's design or the manufacturer's stock patterns.

3.3 The 3 Main Façade Systems Are:

3.3.1 Stick System (Figure 23)

3.3.2 Semi-Unitised System (Figure 24)

3.3.3 Unitised System (Figure 25)

Figure 23 Stick System

Figure 24 Semi-Unitised System

Figure 25 Unitised System

(Courtesy: AgFacadesign & G FACADESIGN Pte Ltd (Fig 23 & 24) and Pixabay.com(Fig 25))

One of the most commonly used terms for façade systems is “curtain wall”.

3.4 Why Is It Called: “Curtain Walls”?

The term “curtain walls” refers to the “unitised system” as the key characteristic of it is that the system resembles how curtains are installed. Their behaviour after installation enables it to move “freely from its hung (installed) position”. Hence, it is often referred to as “unitised curtain wall system”.

Figures 26 And 27 Unitised System Used On High Rise Buildings

(Courtesy: Wikimedia - Hawyih (Fig 26) and Pixabay.com (Fig 27))

3.5 Must Curtain Walls Be Used in High-Rise Buildings?

Images from around the world continuously show “glass towers” in almost every major city (Figures 26 and 27). This is because unitised curtain wall systems today have been so well developed and refined to a level that it meets the high performance requirements needed for tall buildings including “super high rise towers”. It has become a standard practice that prefabricated unitised curtain walls are used whenever a high-rise building is built.

However, low-rise buildings although not subjected to the extreme high wind loads, can also use unitised curtain wall systems. The main reasons for low-rise buildings using unitised curtain wall systems include:

a. Quality of finishes,
b. Speed of erection
c. High performance value
d. Aesthetics value

Chapter 4: Façade Design Requirements: Main Design Drivers For Unitised Curtain Walls

4.1 Unitised Curtain Wall

4.1.1 Characteristics:

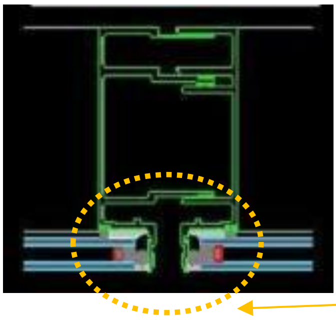
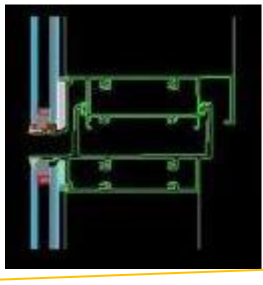
a. Prefabricated in controlled environment, glazed panels mounted directly onto slab edges (Figures 28 and 29).
b. Full height mullions and transoms erected into position between slab edges.
c. The system spans between floors of heights up to 6 metres or maximum length of extruded mullions.
d. Vertical movements between floors are accommodated in stack joints of mullions located typically at slab/floor finish level.
e. Glass glazed into mullion/transom frames provide the air/water seals.
f. Structural sealant and/or clips and fixings where mechanical fixings are required by codes secure the glass panel.

4.1.2 System Requirements:

a. Holes in mullions (concealed within horizontal transom) provide the pressure equalization (Figures 30 and 31)
b. Extruded “male and female” mullion configuration provides the movement capability under creep.
c. Stack joint allows for anticipated movements particularly those associated with the dead load loading.
d. Extruded gaskets within provide the air, water and acoustic seals while allowing for predicted movements
e. One key brackets from mullion fixed directly to structure to take the dead load of the façade panel itself

Figures 28 And 29 Unitised System Under Erection And Completion (Courtesy: Fosters + Partners Pte Ltd (Fig 28) and Pixabay.com (Fig 29))

Holes in Mullion

Figure 30 Typical Mullion *Figure 31Typical Stack-Joint*

(Courtesy: Arup Singapore Pte Ltd)

4.2 Semi Unitised System

4.2.1 Characteristics:

a. Prefabricated, glazed panels mounted on a site installed sub frame (Figures 32 and 33).

b. Sub frame consists of mullions, and perhaps transoms erected into position between slab edges.

c. The system spans between floors of heights between 5.5 metres to 12.5 metres

d. Vertical movements between floors are accommodated in sliding splice joints of mullions.

e. Glass is glazed into cassette frames that form air seals against the sub frame.

f. Cassettes are secured to the sub frame by means of clips and fixing

4.2.2 System Requirements:

a. Cavities between cassette elements that are pressure equalised as set out

b. Mullion joints are fully spliced and sealed. Seals shall allow for predicted movements

c. Cassette frames designed with sufficient strength and rigidity consistent with rear air seals and restraint positions

d. Metal brackets connected onto the mullions are then fixed onto metal frame structure

Figures 32 Semi-Unitised System Completion *Figures 33 Semi-Unitised System Detail*

(Courtesy: Wikimedia - Socksiong (Fig 32) and Arup Singapore (Fig 33))

4.3 Stick System

4.3.1 Characteristics:

a. Mullions and transoms erected into position between slab or parapet edges complete with gaskets where detailed (Figures 34 and 35)

b. Gaskets and small joint sealant between mullions and transoms as required

c. Vertical movements between floors are accommodated in sliding splice joints of mullions

d. Glass is frameless glazed on-site, with minimum use of wet seals

4.3.2 System Requirements:

a. Machined mullions and transoms delivered to site

b. Brackets to main structure supporting mullions

c. Mullion joints are fully spliced and sealed. Seals shall allow for predicted movements

d. Allowance for tolerance and thermal expansion at transom – mullion connections

e. Glazing support and back-pans with jointing consistent with the predicted movements, particularly those associated with the mullion splice

f. Covers and clips with jointing consistent with predicted movements

Figure 34 Stick System Under Installation *Figure 35 Installation Require External Access*

(Courtesy: AgFacadesign & G FACADESIGN Pte Ltd (Fig 34) and Arup Singapore Pte Ltd (Fig 35))

Chapter 5: Curtain Wall: Key Points – Fabrication And Assembly / Structural Comparison / Weather Proofing

In summary, the major differences between the 3 "basic" façade systems are tabulated in table below.

Table 1: Comparison Of 3 Main Façade Systems

	Unitised System	Semi Unitised	Stick System
Design	• Comprises aluminum extrusions • Mullions: Vertical split "male and female" profiles interlocked for side ("Left-Right") movements • Stack joint: Horizontal split "male and female" profiles for vertical ("up-down") movements • Transom: Horizontal "box" profile at waist level (as barrier) or close to ceiling	• Comprises extruded sections specifically designed for each installation • "Gutter" profile forms the base with secondary profiles to capture and secure the "cassette" where it is structurally bonded onto the glass • Dead load supports and toggle to provide support and secure the glass	• Window units made to be inserted into "openings". Lugs used for adjustments of frames • Control to achieve consistent "designed joints" widths difficult to achieve • High level of quality checks required especially for setting out • Panels alignment between different levels/floors not achievable as panels are

	level to form the spandrel panel • Panels alignment between different levels/floors achievable	• Panels alignment between different levels/floors achievable	installed on a floor by floor basis
Fabrication	• Glazed panels are fabricated and completed in factory ready for installation when delivered to site	• Glazed panel with aluminum "cassette" structurally bonded	• Glazed panels are often "site glazed" into the frame with beading to hold the glass into position
Installation	• Installed straight onto (RC) slab edge through a single fixing angle bracket to provide the "in/out" tolerance during installation	• Extruded channels secured onto steel frame structure with extruded clips and toggle designed to receive the glass panel where the "cassette" had been structurally bonded	• Glazing frames temporarily propped and plumbed on-site within the "opening" prepared. Precise accuracies are often difficult to achieve due to the different trades and materials involved
Pressure equalization	• Neatly concealed within the mullion and transom intersection	• Achieved through the different extruded frames	• Not achievable

Sun shading	• Easily accommodated with a metal bracket-plate mounted to mullion extrusions	• Difficult to integrate into the glazed system	• Unable to incorporate into the window system.

Chapter 6: Components Of Curtain Wall Façades – Glass, Aluminium Extrusion And Sealants

The main components used in a typical façade comprises the following:

6.1 Glass

a. Glass is a non-crystalline amorphous solid that is often transparent and has widespread practical, technological, and decorative usage in, for example, window panes, tableware, etc.

b. The most familiar, and historically the oldest types of glass are based on the chemical compound silica (silicon dioxide), the primary constituent of sand.

c. Many applications of silicate glasses are derived from their optical transparency. This gives rise to one of silicate glasses' primary use as window panes. Glass will transmit, reflect and refract light. Glass can be coloured by adding metallic salts, and can also be painted.

d. For building façades, glass used are typically as follows;
   i. Single or monolithic glass
   ii. Laminated glass - where 2 sheets are adhered together using Poly Vinyl Butryl (PVB), a form of inter layer that bonds the glass sheets together
   iii. Double glazing - where an air gap for thermal reasons, separates the sheet glass which is often mounted onto a frame.

Building envelope glass may also be processed to achieve a more superior quality in performance. Some of the common glasses used in buildings are;

a. Annealed glass - non heat treated glass
b. Heat strengthened glass - heat treated
c. Tempered (or toughened) glass - heat treated

Other types of glass treated to produce a different quality of glass include:

a. Low Emissivity (Low E) glass - a coating on glass to improve its thermal properties
b. Low iron glass - a reduction in iron content to provide “clearer” glass visibility
c. Non-slip glass - a coating applied onto the glass to achieve anti-slip properties
d. Laminated glass - to achieve some “safety” quality by “bonding” the glass together and prevent shards from “flying” in the event of breakage. The laminate will also add acoustic value to the glass. Coloured laminate may be used to achieve different tones and/or “patterns” inherent within the laminate. Overhead glass like canopies will require lamination to prevent glass falling in event of breakage (Figure 36).

e. Fritted glass - a paint coating “baked” onto glass to provide additional shading value.

Figure 36 Canopy Laminated Glass With Frit Coating. (Courtesy: AgFacadesign & G FACADESIGN Pte Ltd).

6.2 Aluminum Extrusion

Aluminum extrusion is a technique used to transform aluminum alloy into objects with a definitive cross-sectional profile for a wide range of uses (Figures 37 and 38). Building façades use the extrusion process to make the most of aluminum’s unique combination of physical characteristics. Its malleability allows it to be easily machined and cast. As aluminum is one third the density and stiffness of steel, the resulting products offer strength and stability, particularly when alloyed with other metals.

6.2.1 The Process Of Aluminum Extrusion

The process of aluminum extrusion consists of the following steps:

a. After designing and creating the shape of the die, a cylindrical billet of aluminum alloy is heated to 427 ^{o}C - 496 ^{o}C (800°F-925°F).
b. The aluminum billet is then transferred to a loader, where a lubricant is added to prevent it from sticking to the extrusion machine, the ram or the handle.
c. Substantial pressure is applied to a dummy block using a ram, which pushes the aluminum billet into the container, forcing it through the die.
d. To avoid the formation of oxides, nitrogen in liquid or gaseous form is introduced and allowed to flow through the sections of the die. This creates an inert atmosphere and increases the life of the die.
e. The extruded part passes onto a run-out table as an elongated piece that is now the same shape as the die opening. It is then pulled to the cooling table where

fans cool the newly created aluminum extrusion.

f. When the cooling is completed, the extruded aluminum is moved to a stretcher, for straightening and work hardening.

g. The hardened extrusions are brought to the saw table and cut to the required lengths.

h. The final step is to treat the extrusions with heat in age ovens, which hardens the aluminum by speeding the aging process.

6.2.2 The Common Finishes In Aluminum

a. Natural anodized

b. Polyester Powder Coating

c. Fluorocarbon or PVF2 Finish

Figure 37 Extruded Aluminium Glazing Frame *Figure 38 Extruded Structural Aluminium Bracket*

(Courtesy: AgFacadesign & G Facadesign Pte Ltd)

6.3 Gasket And Sealant

A gasket is a mechanical seal which fills the space between two or more mating surfaces, generally to prevent leakage from or into the joined objects while under compression.

In building façades, extruded gaskets are used to separate the aluminum from being in contact with each other and causing friction and “cracking” sounds. The gasket will also provide addition “seals” against water and noise (Figure 39).

In general, gaskets allow for *"less-than-perfect"* mating surfaces on machined parts where they can fill irregularities.

It is usually desirable that the gasket be made from a material that is to some degree yielding such that it is able to deform and tightly fill the space it is designed for, including any slight irregularities. A few gaskets require an application of sealant directly to the gasket surface to function properly.

Figure 39 Extruded Gaskets (Courtesy: AgFacadesign & G Facadesign Pte Ltd)

Sealant is a substance used to block the passage of fluids through the surface or joints or openings in materials (Figure 40).

In building construction sealant is sometimes synonymous with caulking and also serves the purposes of blocking dust, sound and heat transmission. Sealants may be strong or weak, flexible or rigid, permanent or temporary. Sealants are not adhesives but some have adhesive qualities and are called adhesive-sealants or structural sealants (Figure 41). Others are used primarily as “weather seals”.

Figure 40 Weather Sealant

Figure 41 Structural Sealant

(Courtesy: AgFacadesign & G Facadesign Pte Ltd)

However, through the advent of information technology, 3D modelling software and the desire of designers to provide “creative designs”, façade systems beyond the 3 main categories listed above have inevitably evolved to capture the imagination and desires of designers and owners alike.

For ease of reference, we shall call this “specialist designed system”. These systems look very different from the 3 basic façade systems mentioned above. However, all systems will have to incorporate the fundamental performance requirements needed for a “curtain wall”.

7.1 Monocoque Facade

An easy point of reference is to compare this to a seashell. In a seashell, the “skin” and the “structure” are fused into a homogeneous element making it impossible to separate them apart (Figures 42, 43 and 44).

In building façades, glass cladding is the “skin” and the support members are the “structure”. Attempts to mimic the seashell have resulted in a monocoque façade system where the glass and frames “act as one”. However, in construction terms this is not possible as glass cracks when subjected to forces when in contact with harder materials like metal.

Although the “skin” of a seashell contributes to direct load transfer, in a monocoque façade system, the glass is not subjected to any in-plane stress and are allowed to move “freely” but contained within its own module.



Figures 42, 43 And 44 Monocoque Structures Used On Different Sites And Support Systems

(Courtesy: Pixabay.com)

7.2 Hybrid Facades

7.2.1 Glass Fins Facade

Glass fins are integrated into aluminium panels to provide additional thermal insulation value to a distinctive façade (Figures 45, 46 and 47). Glass fins are “sandwiched” between the insulated aluminium panels, which provide a thermally efficient barrier to screen off the sun and harmful UV radiation into the building.



Figures 45, 46 And 47 Glass Fins With Aluminum Insulated Panels

(Courtesy: Arup Singapore Pte Ltd (Fig 45) and AgFacadesign & G Facadesign Pte Ltd (Fig 46 & 47))

7.2.2 Infinity Pool Integrated Facade

Infinity pool glass panels are integrated within the façade modules (Figures 48 and 49). The “spandrel” panels between the double volume glazing aligned with the pool glass form a continuous “band” around the façades.

Figures 48 Completed Building

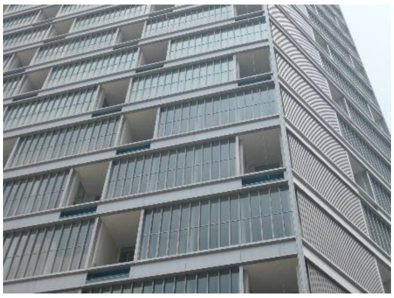


Figure 49 Façade With Infinity pool

(Courtesy: AgFacadesign & G Facadesign Pte Ltd)

7.2.3 Layered-Glass Facade

A naturally ventilated façade using glass panels that are staggered in both horizontal and vertical directions (Figures 50 and 51). Supported off a central mullion, glass panels are supported using “clips” at the outer edges. The module of these can be adjusted to suit both horizontal and/or vertical directional requirements.


Figure 50 And 51 Layered Glass Façade Allows Air And Drizzles In For The Plants

(Courtesy: AgFacadesign & G Facadesign Pte Ltd)

Although very different in appearance, all façade systems are subjected to the same criteria and must strictly comply with them. The main difference will be the different loads each façade will be subjected to. This will vary with site and building performance requirements which are set by the structural engineer before commencement of the design process.

For thermal performance, sun screens may be integrated depending on the system(s) selected and design requirement(s).

7.3 Design Process – Key Principles

The above examples show that façades can be developed to meet any design required. The key is to understand the following;

a. Materials - the limits and capabilities of different materials

b. Technology - how materials can be transformed into a much stronger form

c. Information Technogy - the capabilities of different softwares and programmes that can assist in simulation prior to fabrication

Chapter 8: Frameless Structural Glass Walls – “Spider” Clamps On Glass Fins, Steel Frame Or Cable-Net systems, Patch-Plate And Clamp-Plate

8.1 Frameless Structural Glass Walls

Another façade type is known as “frameless glass” system.

Glass panels for these are not contained within any edge frame to act as supports. The glass panels are held in place either by “point-fix” (“spider”) rotules or “clamp-plate”.

There are 2 basic systems available:

8.1.1 Point Fixed Glass

Require the glass panels to have holes at the 4 corners and additional holes at mid span of glass for longer span glass (Figure 52).

Stainless steel rotules and threaded bolt with the required separators connect the glass back to the spider-arms which are fixed onto the system.

Figure 52 Point-Fix Stainless Steel Cast Supports (Courtesy: AgFacadesign & G Facadesign Pte Ltd)

8.1.2 Clamp-Plate glass

Does not require any pre-drilled holes in the glass.

The glass panel sits on the “ledge” typically close to either end of the glass panel and relies on plates on either side of the glass to keep it in position and not falling out (Figures 53 and 54).

Figures 53 And 54 Clamp-Plate Fittings In Different Profiles

(Courtesy: AgFacadesign & G Facadesign Pte Ltd)

For better thermal performance, double glazed units with low-E coatings may be used.

Frameless glass walls are often used as “high screen glass” around “podium” levels and comprises mainly of “fixed” glass panels i.e. no window openable units.

It is also difficult to incorporate other elements like sun-shades, louvres, etc.

8.2 Four Categories Of Frameless Glass Walls

8.2.1 Glass Fin System

Laminated glass fins provide the structural support for the face glass panels.

Due to glass transparency, glass fin system is visually less obstructive and is often used where “visual transparency” is of high importance (Figures 55 and 56).

Care is needed in the design to ensure that the face glass will not collapse progressively should the supporting glass fins break.

Typical examples where glass fin frameless glass walls are commonly used include car showrooms, VIP viewing boxes, exhibition areas, etc

Glass fin system may be either:

a. Full height – from floor to ceiling; or
b. Cantilevered from the top – allows wider usage of space beneath

Figures 55 And 56 Glass Fins Allows Transparent Views In And Out Of The Building

(Courtesy: Patricia Collera (Fig 55) and Foster + Partners Pte Ltd – Nigel Young (Fig 56))

8.2.2 Steel Frame Or Steel Post

Steel member provides the structural support for the face glass. This is one of the simpler systems. The size of the steel section is determined by the total span required and can use standard off the shelf profiles (Figure 57).

The bigger the cross section, the more obstructive it is visually.

The steel frame system can be used for any building type as long as “transparent vision” is not a priority.

Steel Frame or Steel Post are available in standard profiles like;

a. Circular or rectangular sections
b. “I” or “H” profiles
c. Built-up sections to suit

Figure 57 Steel Post With Point-Fix Glass System (Courtesy: AgFacadesign & G FACADESIGN Pte Ltd)

8.2.3 Truss System

A truss system allows a large area of glass wall to be achieved.

Depending on the system, trusses can be formed using standard sections or machined rods and cables to provide an intricate network assembly (Figures 58 to 61)

Engineering of cable truss system will be more elaborate and the structure will also need to be analysed together to determine the forces.

Different truss systems are:

a. Bow truss
b. Cable truss
c. Standard truss

Figure 58 Bow Truss System

Figure 59 Truss System

Figure 60 Cable Truss

Figure 61 Hanging Truss

(Courtesy: AgFacadesign & G FACADESIGN Pte Ltd (Fig 58-60) and Arup Singapore Pte Ltd (Fig 61))

8.2.4 Cable-Net System

Often referred to as the “racket system”, cable net systems resemble how the guts are strung in rackets to provide the necessary tension to counter the forces acting on it, just like when a ball at high speed bounces off the surface of the tensioned guts of the racket (Figures 62 and 63).

Technically, this system, like the cable truss needs to be engineered with the supporting structure to ensure that the tensile forces of the cable-net (or “guts”) on the perimeter frame are able to withstand the forces acting on the perimeter frame. It can have very large spans horizontally (i.e. as a “roof element”) or vertically as a “wall”. For added safety measure, additional layer of cables may be integrated behind the cable-net supporting the glass wall to provide an added “security feature” against flying laminated glass in the event of a bomb blast.

Aesthetically, it is probably the least visible (from afar) as the tensioned cables tend to be relatively small in diameter and “disappear” from view.

Figures 62 And 63: Cable-Net System (Detail And General View)

(Courtesy: AgFacadesign & G FACADESIGN Pte Ltd (Fig 62) and W&W Glass, LLC (Fig 63))

Although glass is brittle in tension, it can be extremely strong in compression when appropriately used. It is up to the designer's understanding of how glass (or materials) is used and develop a detail that allows the glass (or other materials) to be applied "innovatively" such that it will perform at its optimum state to achieve maximum efficiency.

8.3 Examples Of Structural Glazing

8.3.1 "Glass Connector"

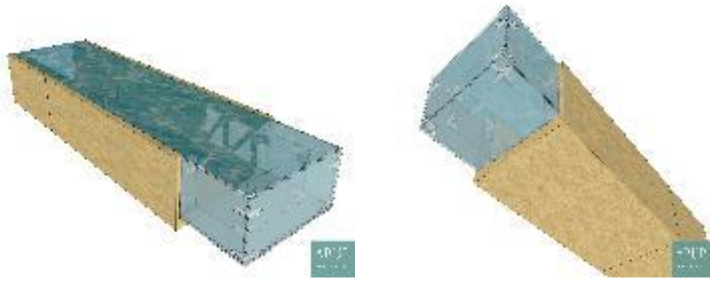
A "glass connector" is a covered link to the new wing at the Singapore National Museum (Figures 64 and 65). It consists of an all glass structure that uses laminated glass as wall panels, fin stabilizers and roof panels. All the laminated glass are connected using high strength stainless steel plates. The glass connector which measures 6m(W)x5m(H)x25m(L) is supported on a steel frame structure embedded within the century old brickwalls.

Figures 64 And 65: Glass Used In More Structural Applications As Vertical Supports And As Fin Stabilizers

(Courtesy: AgFacadesign & G FACADESIGN Pte Ltd)

8.3.2 Glass Bottom And Glass-End Pool (Unbuilt)

Figures 66 and 67 show an all glass end and glass bottom pool. It consists of the laminated glass with embedded steel plates which are connected using point-fix connections.



Figures 66 And 67: Glass End / Bottom Pool With Embedded Steel Plates Connected Using Point-Fix Connections (Courtesy: Arup Singapore Pte Ltd)

8.3.3 Glass Tubes

Figure 68 shows “glass tubes” as structural compression members to resist wind loads on a cable-net façade.

Glass tubes are tensioned via a steel rod at both ends of special castings. They are fixed onto a cable net system and the glass tubes act as compression struts transferring the live wind loads from the all glass façade onto the steel columns.

Figure 68 Glass Tubes As Compression Struts (Courtesy: Foster + Partners Pte Ltd)

Chapter 9: Glass Processing And Criteria

9.1 How Is Glass Made?

Almost all glass produced today in developed countries is done by the “float process”.

The glass composition materials, mainly silica sand, soda ash and limestone, are melted in a furnace and then flowed onto a bath of molten tin. The glass is formed and gradually cools as it moves from the tin bath to an annealing lehr, which is a controlled cooling chamber. As it moves through this process, the glass is in the form of a continuous ribbon, which is cut to size and packaged at the final stage.

9.2 Glass Processing

Ever since glass was first produced, the use of it has been widespread and the demand for use of glass on interiors and/or exteriors will keep increasing.

In building envelopes, glass forms the most area of any curtain wall façade.

Through advancement in technology, glass treatment has developed over the years to meet different building requirements.

Below are two different types of glass performance requirements that are mostly considered for buildings;

a. Thermal - through the use of coating technology

b. Structural - from heat treatment process on the glass

9.3 Thermal Performance Glass

High energy consumption is the main concern for commercial buildings as bills chalk up in terms of air-conditioning and lighting costs.

Low Emissivity (Low E) glass provides the solution to achieve both interior comfort and energy cost savings. It avoids unwanted heating of interiors while still allowing as much daylight into the building as possible.

The Low E coat provides maximum solar control with astonishing light transmittance and a low external reflection. There is also considerable freedom when designing the façade as Low E glass is available in various thickness and sizes.

Besides double glazing units (DGU), Low-E coating on glass has developed significantly to meet certain performance standards.

Originally started off in the cold climates, it is now commonly used in the tropical heat environment.

The 2 main factors concerning thermal requirements are;

a. U-value

b. Shading Coefficient (SC) value

Low E coated solar control glass, comes in various colours, solar control and light transmittance. A Low E coating applied via chemical vapour deposition is commonly referred to as a “hard coat”, whilst a Low E coating applied via magnetron sputtering is known as a “soft coat”.

Soft coat Low E Glass performs better at thermal insulation, but is prone to oxidation upon exposure to the atmosphere. Hence, soft coat Low E Glass needs to be double-glazed or laminated with edge deletion.

“Triple coat Silver Low E” is also available for an ideal balance of solar control and high visibility for all-year round comfort, making it perfect for façades, windows and building envelopes.

9.4 Structural Performance Glass

9.4.1 Glass Processing And Glass Traceability

Glass is made up of different raw materials such as sand, soda, lime, silica, etc..

The material will be cleaned and have to go through certain processes to ensure that the “right” quality is achieved before the production of float glass.

“Impurities” inherent in various raw materials will determine the quality of the raw glass. These are impossible to totally remove.

However, “impurities” in float glass can be detected by laser scanners while still on the production line. (Figures 69 and 70).

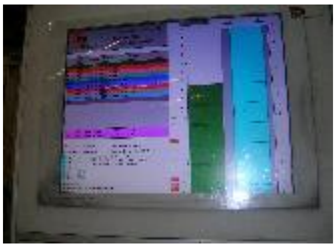
 

Figures 69 And 70: Glass On Roller Bed Production Line Being Scanned For Impurities

(Courtesy: AgFacadesign & G Facadesign Pte Ltd)

Impurities are traced and "marked" onto the glass (Figures 71 and 72) using a computer system. Depending on the proximity of the impurities, the glass will be cut and directed to different "groups" of glass production from low to high presence of impurities.

Glass with the least or low presence of "impurities" will be treated as high quality production glass and will command a higher premium.

Figures 71 And 72: Glass Impurities Check Scanning By Computer And Distributed To Different Areas For Sorting.

(Courtesy: AgFacadesign & G Facadesign Pte Ltd)

9.4.2 Heat And Quenching Process

Heat treatment is the main process that glass needs to go through in order to transform it from a normal (annealed) glass to either heat-strengthened or tempered glass.

Glass sheets flow into a heat oven to be heated up and subsequently go through quenching (by air).

The heated top and bottom surfaces of the glass sheet will be in a state of "tension" and when it goes through the sudden cool air quenching process (Figures 73, 74 and 75), the surfaces retract and go into compression .

It is through this transformation process that "surface compression" on the glass surfaces is obtained.

Two factors that determine whether the glass will be transformed into "heat strengthened" or "tempered" glass within the heat oven are:

a. Temperature

b. Speed of roller bed

Figures 73 And 74: Heat Oven And Quenching Compartment Of Tempering Line

(Courtesy: AgFacadesign & G Facadesign Pte Ltd)

Figure 75: Close Up View Of Roller Bed And Air Nozzles At Quenching Compartment

(Courtesy: AgFacadesign & G Facadesign Pte Ltd)

Heat treated glass has “surface hardness” comparable to untreated “annealed” glass. It’s the surface compressive forces that give it the “impact resistance” so that it can withstand impact unless the impact exceeds the compressive forces of the glass. When this happens, the pattern of glass breakage will reveal if the glass has been “heat strenghtened” or “tempered”.

In general the surface hardness of “tempered” glass is about twice that of “heat strengthened” glass.

At the end of the tempering line, the glass will be given a visual check on the “flatness” of the heat processed glass. The glass will be viewed against a “zebra board” (Figures. 76 and 77) where the reflections will show if the “roller waves” on the glass have visually exceeded the limits.

Figures 76 And 77: “Zebra Board” Lines Reflected For Visual Check On The Processed Glass Flatness At End Of Tempering Process (Courtesy: AgFacadesign & G Facadesign Pte Ltd)

When glass breaks “spontaneously” or “on its own”, it usually occurs in “tempered glass” because surface compression in tempered glass is almost 4 times that of annealed glass.

One of the most common causes is often due to nickel sulphide (NiS) impurities embedded within the glass which has expanded beyond the surface compressive forces of the tempered glass.

9.4.3 Heat Soak Test

NiS can be detected through the “heat soak” process.

The objective of this test is to allow any impurities embedded within the tempered glass to expand so that they penetrate through the surface of the tempered glass. This allows the glass panel to shatter “safely” within the heat soak oven (Figure 78).

Figure 78: “A”- Frame On Roller Track Where Glass Sheets Are Placed During Heat Soak Process Inside The Heat Soak Oven (Courtesy: AgFacadesign & G Facadesign Pte Ltd)

Heat soak process standards are found in different codes but in general the process involves the following steps within the heat soak oven;

- Temperature raised to 290^{o}C (+/- 5^{o}C)

- Temperature of 290^{o}C and holding time of 2-4 hours

- Temperature drops to room temperature before heat soak oven is opened

The total duration ranges between 4 to 6 hours depending on the code requirements and/or the heat soak oven capabilities.

9.5 Laminating Glass

Glass technology has progressed and laminating glass using poly vinyl butryal or “PVB” provides added “structural” strength and additional “safety”.

Laminating glass is manufactured in a cleanroom. This is to ensure that there is no dirt or particles trapped between the glass before the lamination process (Figures 79 - 81).

Figures 79, 80 And 81: Glass Is Cleaned Before Entering The Cleanroom Where PVB Sheet Is Laid

Figures 82, 83 And 84: Glass Coming Out Of Cleanroom And The Heat Machine And Lifted Off

Figure 85 Autoclave Oven

(Courtesy: AgFacadesign & G Facadesign Pte Ltd)

The final step in the glass lamination process is in the autoclave oven (Figure 85) where the opacity of the pvb and traces of bubbles trapped between the sheets of glass are cleared through heat pressure resulting in the “transparency” of the “clear” laminated glass that we see.

Chapter 10: Design Consideration and Safety in Design

10.1 “Safety Glass”

In Singapore, for single ply applications only “tempered glass” is considered as “safety glass”. This is due to the break pattern in tempered glass which breaks into small granules (Figure 88) as opposed to “shards” like break patterns (Figure 86) in annealed and heat strengthened glass (Figure 87).

Other types of “safety” glass are laminated glass (Figure 89) and bullet-proof glass (Figure 90).

10.2 Glass Break Patterns

Figure 86: Annealed Glass (Courtesy: Pixabay.com)

Figure 87: Heat Strengthened Glass (Courtesy: AgFacadesign & G Facadesign Pte Ltd)

Figure 88: Tempered Glass (Courtesy: Pixabay.com)

Figure 89: Laminated Glass (Courtesy: Pixabay.com)

Figure 90: Bullet-Proof Glass (Courtesy: Saudi American Glass Company Pte Ltd)

10.3 What Is Safety Glazing?

Glass is a breakable material, which breaks into smaller sharp pieces called shards. Shards can cause serious injury. Safety glazing material, usually tempered glass or laminated glass, reduces the risk of injury. This is accomplished in the case of tempered glass by the characteristic break pattern of breaking into many small pieces. In the case of laminated glass, it is the adhesion of the glass pieces to the inner plastic layer.

In Singapore, laminated glass with the pvb will keep the broken glass “in place” during breakage and prevent glass from “flying off”. This is seen as a “safety feature” and hence laminated glass is considered as “safety glass”

10.4 What Is Security Glazing?

Security glazing products usually involve multiple layers of glass, and in some cases acrylics which are usually laminated. This achieves maximum impact resistance from explosions, ballistic assaults and even simple forced entry. There is a wide range of such specialty glass products.

10.5 Fabrication And Design Limitations

As mentioned earlier, with the understanding of materials, technology and aid from computer software, there are literally “no limits” to the façade designs that can be achieved.

However, to achieve efficient and economical solutions, the designer must also be aware of what the industry “standard” capabilities and practices can achieve.

For building envelope or façade design, the key material is glass and it forms a large portion of the overall costs.

It is vital that glass sizes are designed optimally so that the production, fabrication, installation and replacement can be done with ease.

10.6 Glass Processing Lines

For glass production, the following processes and machines limit maximum glass sizes;

a. Low-E coating line

b. Tempering machine

c. Lamination plant

Glass sheet sizes - Glass comes in standard “stock sizes” including “Jumbo size” glass. Where possible it will be beneficial if glass modulation can be optimised to minimise wastage.

Glass thickness - Standard glass thickness commonly used in building façades range from 6mm, 8mm, 10mm, 12mm, 15mm, 20mm. Each increment has added strength as well as costs. The design should therefore consider these carefully to avoid using thicker glass than necessary.

Glass fixings - Depending on the system used, how the glass is fixed will have a significant impact on the type of glass and thickness required. Fixings as described above ranges from “frameless point-fixed, clamp-plates, structurally glazed to fully embedded glass.

Glass shapes - The modulation or shape of the glass will have direct impact on the “deflection and stress” on the glass. This will have direct impact on the glass thickness to be used.

Glass types - Thermal performance requirements will determine whether the glass needs to be single or double glazed units (IGU or DGU) or to what extent of Low-E coating the glass should have. An alternative but less popular nowadays is the use of tinted glass.

Glass coatings - Coating technology on glass is constantly improving. The main focus has been on thermal performance where the important “U” and “SC” values will have direct impact on thermal requirements and calculations.

Coatings such as “non-slip” and “anti-reflective” are also commonly produced.

“Clear glass” - Iron content in glass contributes to the “green edge” of glass. However low iron glass reduces this “green edge” and provides a “clearer” glass often used in locations where “clarity” of the objects are important, like jewellery cases where the “natural colour” of the display can be easily seen.

Curved glass - including “double curve” and as well as “free form” glass is also getting used quite often. Production of these is not cheap and not many plants have such machines and capabilities. Quality control will be essential especially where laminated curved glass is required; the alignment of glass sheets will be vital to prevent chipping and cracking.

Chapter 11: Energy And Sustainability With Building Envelopes

11.1 Orientation

In the tropics, building orientation is probably the major factor in determining how the building responds to the solar spectrum. However, not all sites are regular in shape (Figure 91) or face the “preferred” orientation (Figure 92).

Figure 91 Site Profile Can Determine Building Layouts *Figure 92 Orientation To The Desired Facing Via Design*

(Courtesy: AgFacadesign & G FACADESIGN Pte Ltd)

Passive cooling techniques and orientation (Figure 93) can be used to reduce, and in some cases eliminate, mechanical air conditioning requirements in areas where cooling is a dominant problem. It is most useful in hotter countries. The cost and energy effectiveness of these options are both worth considering by homeowners and builders. In most parts of Asia, it is wise to keep direct sun away from the interiors of the building especially during the hot months. Allowing its direct ingress and glare leads to a build-up of heat and discomfort.

For passive cooling, orientation is a major design consideration, mainly with regard to solar radiation, daylight and wind.

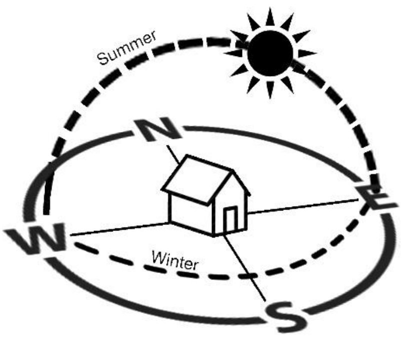


Figure 93 Passive Cooling Techniques And Orientation

(Courtesy: AgFacadesign & G FACADESIGN Pte Ltd)

In places with a tropical climate like Singapore, long façades of buildings oriented towards North—South are preferred as East and West receive maximum solar radiation throughout the year.

11.2 Insulation

The purpose of insulation is to reduce heat gain and heat loss. Insulating the roof is a good idea to reduce the heat transfer from the roof. The more insulation in a building exterior envelope, the less heat is transferred into or out of the building. Materials and easy techniques are available for insulating jobs (Figure 94). Materials like 40 mm thick expanded polystyrene insulation (thermo coal) or broken bricks are laid on top of the roof and finished with mortar. Roof tiles with less thermal conductivity are also available in the market. Painting the roof white will reduce heat absorption. Air cavities within walls or an attic space in the roof ceiling combination reduce the solar heat gain factor. Vacuum insulated glass, thermal insulating glass and heat reflective glass can be used in windows and glazing. These will reduce the heat transfer from outside to inside the building significantly.

Figure 94 Insulating Building Material (Courtesy: AgFacadesign & G FACADESIGN Pte Ltd)

11.3 Shaded Envelope

Heat gain through a window is much higher as compared to that through an opaque wall. Incorporation of shading elements with windows help in keeping out the sun‘s heat, block uncomfortable direct sun, and soften harsh daylight contrasts. Shading devices are therefore necessary to allow glare-free natural light. External shading is the most effective way of shading, as it cuts off direct sunlight during summer and allows winter sunlight to enter inside the space (Figure 95). It is preferable to design movable external shading devices on East and West façades, so that the shades can be removed after the sun faces opposite orientation. Minimum or no shading is required on North orientation. On South orientation external shades should be designed after studying the sun path.

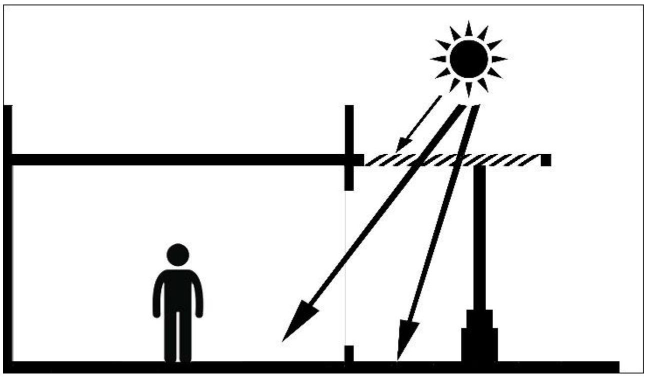


Figure 95 Trellis As A Form Of Shading (Courtesy: AgFacadesign & G Facadesign Pte Ltd)

Movable louvres can cope well with the sun's altitude and can also be adjusted as per the angle of the sun's altitude, but can be very costly.

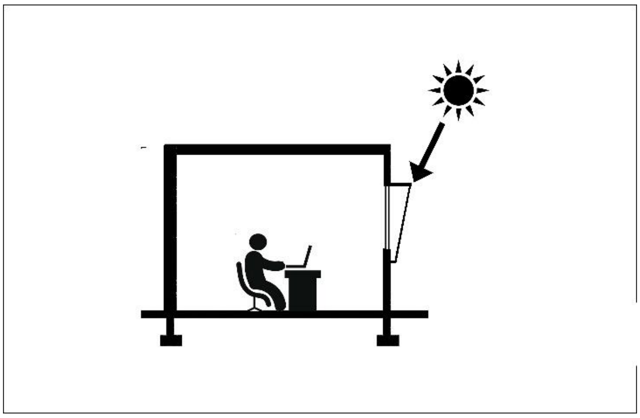


Figure 96 Use Of Sunshade Device (Courtesy: AgFacadesign & G Facadesign Pte Ltd)

Shading walls from direct sun can be one of the simplest and most effective ways of reducing the heat load on a building (Figure 96). Clever use of shade can dramatically improve the comfort conditions inside. Shading can be done by sun-proof fabric covers, light colour coated roof sheets and even by grabbing plants. Shading of roof through design features like pergolas or solar photovoltaic panels help in reducing the incident direct solar radiation on the roof surface. This in turn helps to reduce the air temperature of the roof and conduction gains in the space below.

11.4 Landscape

Landscaping is an important element in altering the micro-climate of a place. Proper landscaping reduces direct sun from striking and heating up building surfaces (Figure 97). It is the best way to provide a buffer for heat, sun, traffic noise, and airflow or for diverting airflow or exchanging heat in a solar-passive design. It prevents reflected light from carrying heat into a building from the ground or other surfaces. Additionally, the shade created by trees, reduces air temperature of the microclimate around the building through evapo-transpiration. Properly designed roof gardens help to reduce heat loads in a building.

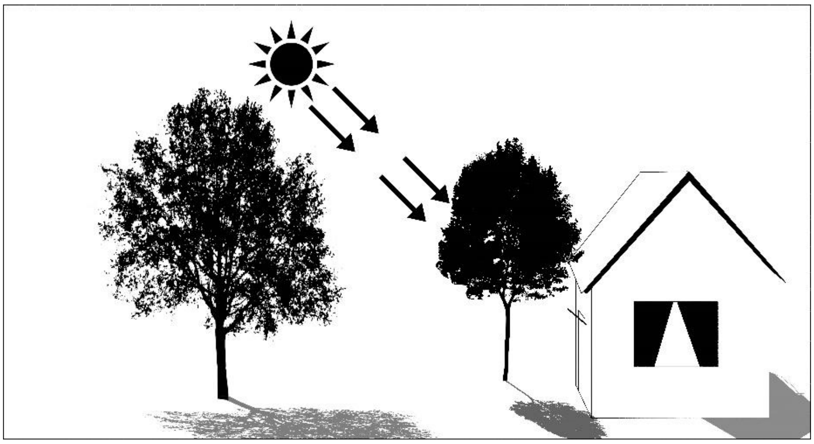


Figure 97 Use Of Landscaping To Assist In Shading (Courtesy: AgFacadesign & G Facadesign Pte Ltd)

11.5 Ventilation

In humid places like the coastal areas, having air flowing over your skin; evaporating the sweat and cooling your body achieves comfort conditions (Figure 98). For this, it is advisable to have large openings in the building's envelope. However, deep overhangs need to be used to minimise direct entry of sunlight. In addition, openings can be strategically placed to allow the heat to escape. In a single-storey house, high-level or clerestory windows allow hot air to escape and thus generate circulation even when there is very little natural breeze. Another way to set up a stack effect is to install a wind-driven roof vent. They do not require electricity to run and spin based on the difference between outside and inside temperatures – the hotter it is outside, the faster they go.

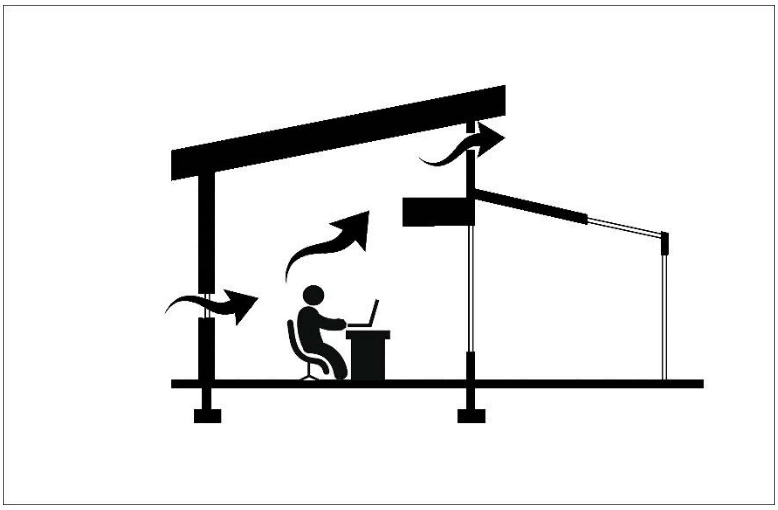


Figure 98 Cross Ventilation Across Living Spaces (Courtesy: AgFacadesign & G Facadesign Pte Ltd)

11.6 Design Considerations

11.6.1 Air-Conditioned Versus Naturally Ventilated Space

Places with tropical climate like Singapore, Malaysia, etc can be non-air conditioned (or naturally ventilated) due to its temperature all year round.

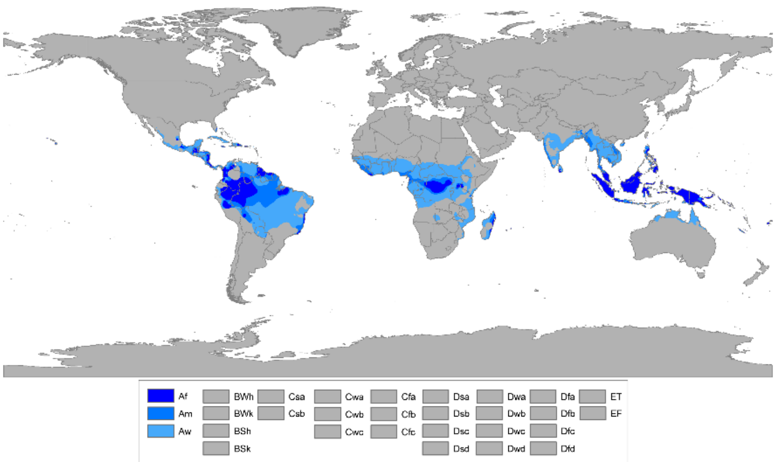


Figure 99 Areas In The Tropics (Courtesy: Wikipedia – Peel, M.C., Finlayson, B.L., and McMahaon, T.A. (University of Melbourne))

A tropical climate is a climate typically found within the Tropics (Figure 99), while a few locations outside the Tropics are considered to have a tropical climate. According to the Köppen climate classification system it is a non-arid climate in which all twelve months have mean temperatures of at least 18 °C (64 °F).

However, besides temperature, other factors that need to be considered in the design of naturally ventilated spaces include:

a. Relative humidity

b. Wind conditions

c. Security

d. Weather conditions like haze

e. Smells

Other factors are dependent on the needs and requirements of the owners/users and/or function of the spaces that include:

a. Image
b. Consistent comfort
c. Merchandise
d. Safety

Naturally ventilated spaces are more sustainable (Figure 101) compared to air-conditioned spaces (Figure 100) but may not be possible due to different conditions

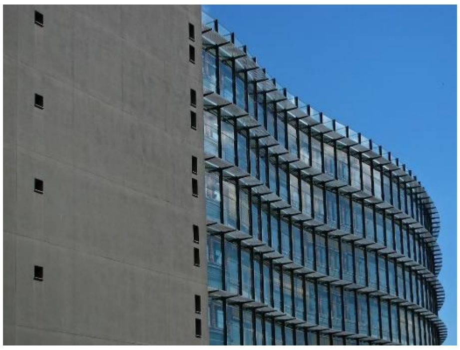


Figure 100 Air Conditioned Office Spaces

Figure 101 Naturally Cross Ventilated Spaces

(Courtesy: Pixabay.com (Fig 100) and Foster + Partners Pte Ltd – Nigel Young (Fig 101))

For high rise buildings, natural ventilation with open windows may not be practical as wind pressure can be extremely high and unpredictable. Hence, curtain walls are mostly not openable and cooling of the building is by air conditioning.

In most advanced countries, sustainability and energy design will need to be incorporated to meet the relevant energy ratings. In Singapore, “There are different “Green Mark” ratings which are regulated by the Building and Construction Authority (BCA).

Buildings with “glass box” aesthetics will have double glazed units (DGU) for its thermal properties with Low-E coated glass used to enhance its thermal performance. Due to the high percentage of glass façade to solid “wall” surface area, the use of Low-E and DGU glass may satisfy the relevant “Green Mark” rating but heat is often felt within the internal spaces. Such conditions will have a greater psychological impact on the thermal “performance” of the glazed units.

A louvre (American English) or louvre (British English) is a window blind or shutter with horizontal slats that are angled to admit light and air, but to keep out rain, direct sunshine, and noise. The angle of the slats may be adjustable, usually in blinds and windows, or fixed.

An efficient way to achieve effective thermal shading is to use external sun-shades. Louvre sometimes also known as “Brise soleil” (Figure 102) is an architectural feature of a building that reduces heat gain within that building by deflecting sunlight.

Figure 102: A Basic Brise Soleil As Shading Device For Vehicles At The Outdoor Carpark Of CENTRAL Mall In Singapore. (Courtesy: Patricia Collera)

Brise-soleils comprises a variety of permanent sun-shading structures, ranging from the simple horizontal shades (Figure 103) to elaborate patterned devices (Figure 104)

Figure 103: Bentini S.P.A, Italia

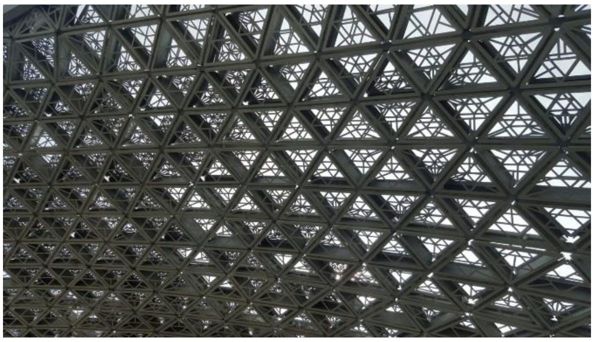


Figure 104: Triangulated Screens

(Courtesy: PiuArchitects – Andrea Martiradonna (Fig 103) and Patricia Collera (Fig 104))

Brise soleil can also be in an elaborate form like the wing-like mechanism for the Milwaukee Art Museum (Figures 105-108)




Figures 105-108: The Movable Burke Brise Soleil On The Quadracci Pavilion Of The Milwaukee Art Museum Closes At Sunset

(Courtesy: Pixabay.com)

In the typical form, brise soleil is a horizontal projection that extends from the sun side façade of a building. This is most commonly used to prevent façades with a large amount of glass from overheating during the summer. Often louvres are incorporated into the shade to prevent the high-angle summer sun from falling on the façade, and to allow the low-angle winter sun to provide some passive solar heating.

Other examples of brise soleil with different materials are shown in Figures 109 to 111;

Figure 109 : Concrete

Figure 110 : Metal Louvre

Figure 111 : Concrete

(Courtesy: Pixabay.com)

11.6.2 Safety In Design

The guide, “Guidelines on Design for Safety in Buildings and Structures” was published in July 2011 by the Workplace Safety and Health Council in collaboration with the Ministry of Manpower.

Design and planning is an essential component of every construction work. In line with the Workplace Safety and Health Act (WSH Act), reducing risk at source is one of the components to improving site safety.

To address risk at source, there is a need to look at who creates the risk and address the issue from there. While the WSH Act imposes a duty on the occupiers, employers and principals, the risks inherent in the design also needs to be addressed and means to mitigate the risks identified. In addition, accidents are often a result of either poor planning or lack of communication between the designer and occupier, resulting in loss of information.

Safety within buildings is expected but safety on the exterior of a building differs between buildings. Careful considerations will be required right from the design stage through to implementation of the works

Factors to be considered include; height, form, usage and even materials selection for a building (Figure 112). However, other factors such as design, views, orientation, access and even costs may alter the final outcome.

All buildings need to be maintained and safe access is of paramount importance (Figure 113). Despite this, maintenance access is often a "low consideration" in the early design stages of a building.

Often left to the "specialists" at the latter part of the design or even construction stages, changes to equipment or parts of a building may be required to achieve the safety standards required. Such changes can be costly and disruptive especially during construction stage.

Safety in design at heights and accessibility

Figure 112 Curved Feature

Figure 113 Use Of "Spider Man" For Maintenance

(Courtesy: AgFacadesign & G FACADESIGN Pte Ltd (Fig 112) and Pixabay.com (Fig 113))

Curved surfaces are difficult to access and require special equipment and specially built work platforms.

Façades of buildings with no building maintenance unit (BMU) will need to be maintained by abseilers. Maintenance at these locations will be very cumbersome and can be expensive if equipment needs to be replaced.

Chapter 12: Shades And Louvres For Building Envelopes

12.1 Orientation

In the tropical climate, the orientation of a building plays a significant part in the exposure of solar heat into the building. In Singapore, it is a well-known fact that the late afternoon sun from the West direction should be avoided as much as possible.

In most cases, sites are usually different in size, shape and orientation. However, in “terraces”, similar size plots are aligned side-by-side facing the same orientation.

Understanding the site and its surroundings in relation to the sun path movements, angles and prevailing wind directions will minimise energy consumed by air-conditioners to cool the building.

Sun-shading elements like brise soleil and other architectural features effectively integrated into the building design will significantly reduce the energy demand of the building.

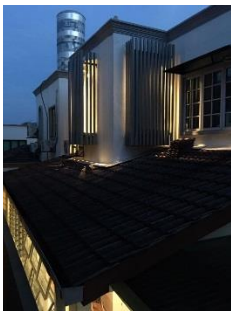
In addition, using environmental sustainable design (ESD) software such as ECOTEC, etc will enable the building to be designed to optimise the environmental conditions for the site.

12.2 Shade And Louvres

Direct sun can generate the same heat as a single bar radiator over each square metre of a surface, but effective shading can block up to 90% of this heat. By shading a building and its outdoor spaces we can reduce summer temperatures, improve comfort and save energy.

A variety of shading techniques from fixed or adjustable shades to trees and vegetation can help depending on the building’s orientation as well as climate and latitude.

In the tropical climate, shades and louvres installed vertically onto building façades (Figures 114 and 115) are very effective as they allow breeze to pass through allowing cross ventilation and help to deflect rainwater outwards.

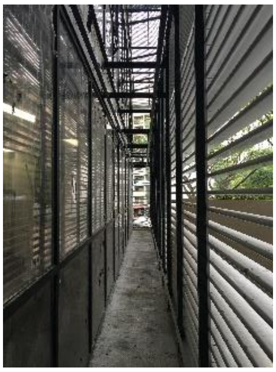
Figures 114, 115 And 116: Metal Louvres Providing Shade And Glass Louvres Providing Visibility. Both Allowing For Ventilation

(Courtesy: AgFacadesign & G FACADESIGN Pte Ltd (Fig 114&115) and Pixabay.com (Fig 116))

Glass shades (Figure 116) allow views through making it ideal for use in non-air-conditioned spaces where mass crowds gather like entrances to MRT stations.

Louvres are also commonly used in a horizontal position. Usually installed on the roof level, it provides shade but is unable to keep the rainwater out. A good example of this application is in outdoor car parking areas.

For building applications, louvres are used to provide additional shade to protect the façade from being exposed directly to the sun thus keeping the surfaces and building “cooler”.

Figures 117, 118 And 119: Overhead Louvres Used Internally And Externally

(Courtesy: AgFacadesign & G FACADESIGN Pte Ltd (Fig 117&119) and Pixabay.com (Fig 118))

With air conditioned spaces, louvres may be installed either on the internal or external side of the glass enclosure.

External sunshades provide better thermal shading performance. However, easy and safe access to maintain the external louvres will be a major consideration and often impacts the design (Figures 117 to 119).

12.3 Performance Louvres

The specification of performance louvres always involves compromises and requires some judgement to take into account the particular needs of each application. At one end of the scale, for example a car park may require maximum ventilation but little protection from rain penetration. Alternatively, a plant room containing special machinery or electrical equipment may still need high levels of ventilation but with maximum protection from water entry.

The ideal design solution is to produce a louvre system that offers the best rain defence and aerodynamic performance. Unfortunately, this seems to be unachievable.

Considerations to be taken into account are:

a. Site location and exposure

b. Severity of local (site) weather conditions

c. Location and exposure of louvres on building

d. Airflow rate and direction through louvre

e. Maximum acceptable pressure drop

f. Acceptable degree and depth of water penetration

g. Special solutions for sloping applications

12.3.1 Water-Tight Louvres

In areas where water tightness is required, “weather-proof” louvres can be used (Figure 120). To achieve water tightness, “double” or triple banks” louvres will be required. These “performance louvres” are laboratory tested and provide a “water proof” effect of close to 100% depending on the wind and rainfall conditions. Typical examples of weatherproof louvres are found in sub-stations, which require good air ventilation as well as a dry environment.

Figure 120: Water-Tight Louvres (Courtesy: Patricia Collera)

12.3.2 Acoustic Louvres

In areas where noise will be a problem such as plant rooms, acoustic louvre panels can be installed.

Plant room openings, cooling towers, substations, etc. typically produce noise levels which may exceed existing or required noise control levels at prescribed distances from the building. Acoustic louvres are mounted behind standard louvre panels and can help to reduce noise egress (Figure 121).

For flexibility, the louvre panels can either be supplied partly pre-assembled, with the louvres pre-cut to size and fitted with insulation and the frames supplied separately, or be supplied in its component parts.

Figure 121: Acoustic Louvres (Courtesy: AgFacadesign & G FACADESIGN Pte Ltd)

12.3.3 Sand Trap Louvres

Although not an issue in tropical countries like Singapore, in arid areas, the provision of natural inlet ventilation is essential in commercial and industrial premises if a satisfactory environment is to be maintained. Yet providing this ventilation invariably allows sand to penetrate into the building causing discomfort to personnel and possible damage to machinery (Figures 122 and 123).

How do sand trap louvres work?

Airborne particles pass through a series of deflector louvres arranged such that the sand hits the louvres. The sand's forward momentum is arrested and the particles fall out of the airstream. The sand falls out of the bottom of the louvre panel. Due to the panel's configuration, additional filters are not required and since it has no moving parts, it is virtually maintenance free.

12.3.4 Optional Accessories

Depending on the location and its environment, bird and insect guards can be integrated where required. Usually fitted to the panels in the factory, slight modifications to the basic design and profiles can be incorporated to suit specific aesthetic requirements i.e. extended cills, flashings, etc.

Figures 122 And 123: Sand Trap Louvres

(Courtesy: AgFacadesign & G FACADESIGN Pte Ltd)

12.3.4.1 Shades

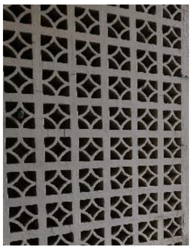
Another form of protection from the sun is the use of screens.

“Breeze blocks”, usually made from precast concrete can be stacked up easily to provide an effective screen against the harsh sunlight (Figures 124 to 126).

The “perforations” in the block allow air to flow through making it an “ideal” building block for buildings in the tropics with natural ventilation and shades. Breeze blocks were very popular in the 70’s and due to the interesting “patterns” that can be achieved, this has become a favourite amongst some architects especially in passive energy design (Figures 127 to 129).

Figures 124, 125 And 126: Use Of Air Block In PJ Trade Centre

(Courtesy: AgFacadesign & G FACADESIGN Pte Ltd (Fig 124-126)


Figures 127, 128 And 129: Air Blocks With Different Profiles As Shades

(Courtesy: AgFacadesign & G FACADESIGN Pte Ltd)

Another form of shade is more for “shading” against rain rather than sunlight.

Ethylene tetrafluoroethylene (ETFE), an extremely lightweight plastic material can be formed into “pillows” filled with air. This enables large areas to be easily covered with minimal structural provision (Figures 130 and 131).

However, for thermal performance, such “ETFE pillows” are not very effective and is often used in an open-air area. In tropical regions, such applications will be suitabe for night time use but will have restricted use in the day.


Figures 130 And 131 ETFE Roof Canopy At Clarke Quay, Singapore

(Courtesy: Patricia Collera)

12.3.4.2 Indirect Lighting

There are 2 types of indirect light;

a. Natural Daylight

In architecture, a clerestory is a high section of wall that contains windows above eye level. The purpose is to admit light, fresh air, or both.

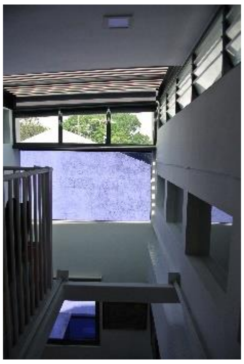
Historically, *clerestory* (Figures 132 and 133) denoted an upper level of a Roman basilica or of the nave of a Romanesque or Gothic church, the walls of which rise above the rooflines of the lower aisles and are pierced with windows.



Figures 132 And 133: Clerestory Lights

Figure 134: Skylight To Staircase

(Courtesy: AgFacadesign & G Facadesign Pte Ltd)




Figures 135, 136, 137, 138: Clerestory Lights

(Courtesy: AgFacadesign & G FACADESIGN Pte Ltd (Fig 135-137) and Pixabay.com (Fig 138))


Figures 139 And 140: Skylights And Natural Day-Lighting

(Courtesy: Dr Joseph Lim - Architect)

b. Artificial Lighting

Benefits of Indirect Lighting

Indirect linear fluorescent lighting directs light upwards towards the ceiling and, depending upon placement within the space, may also provide light to upper walls (Figure 141).

Favorable attributes include, but are not limited to:

- Soft and even illumination – from light bouncing off surfaces instead of direct lighting
- Computer friendly – minimal or no glare problems created to the computer screens
- No visible lamp image – light fittings are designed to be concealed within ceiling profiles
- Increased perception of comfort within the space
- Light is applied to ceilings (and often, to upper walls)

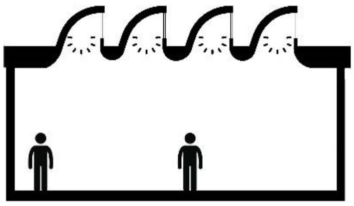


Figure 141 Indirect Artificial Lighting (Courtesy: AgFacadesign & G Facadesign.com Pte Ltd)

12.3.5 Building-Integrated Photovoltaics (BIPV)

BIPV are photovoltaic materials that are used to replace conventional building materials in parts of the building envelope such as the roof, skylights, or façades.

Since Singapore is located close to the equator, the sun path is generally in an "overhead" position. The potential gain for the solar panels is maximised if they are placed on the roof as the roof surface is most exposed along the sun path. However, due to limited land, buildings in Singapore tend to be "high" rather than "low rise" in nature. This gives the buildings a much higher façade area compared to roof surface areas.

Photovoltaics are more commonly found on low rise slab blocks like factories and individual houses where the ratio of roof to façade areas is much higher compared to high rise buildings.

BIPV on façades in Singapore is in general not suitable due to the overhead sun angle along the Equator. However, in some European countries like Spain, BIPV on façades is possible due to the amount of sun exposure on their façades (Figures 142 and 143).

BIPVs are incorporated into the construction of new buildings as a principal or ancillary source of electrical power, although existing buildings may be retrofitted with similar technology.

In certain countries, where a "power grid" system is available, excess energy generated from solar panels can be sold to the national grid. However, this is not common in Singapore yet.

The advantage of integrated photovoltaics over more common non-integrated systems is that the initial cost can be offset by reducing the amount spent on building materials and labor that would normally be used to construct the part of the building that the BIPV modules replaces. These advantages make BIPV one of the fastest growing segments of the photovoltaic industry and is popular with owners.

The term building-applied photovoltaics (BAPV) is sometimes used to refer to photovoltaics that are retrofit – integrated into the building after construction is complete. Most building-integrated installations are actually BAPV.

Some manufacturers and builders differentiate new construction BIPV from BAPV

Figure 142: Photovoltaic Wall (Courtesy: Pixabay.com)

Figure 143: BIPV Façade With CIGS Film Solar Modules (Courtesy: Mansz-AG, www.manz.com)

After learning about façade evolvement, various types of façade systems and glass technologies, we now move onto the practical aspects of the building process.

Chapter 13: Project Work Stages

It is important to understand the key phases involved in the architectural process and what the key elements of the phases are.

The 3 key phases are:

a. Design Stage

b. Tender Process

c. On-site construction

The main activities are briefly summarised for each of the key phases as follows:

13.1 Architect Work Stages

The following will illustrate the main elements involved in the different stages:

13.1.1 Design Concept / Scheme Design

- Sketches, Building Forms and Massing [4], Planning / Authority Requirements, etc.

a. Design Development

- Building layouts, building service core[5] efficiency and spatial planning designs, building elevation design and aesthetics, etc.

a. Detail Design

- Space efficiency design and Gross Floor Area (GFA) calculations, window fenestrations and elevations treatments, materials selection, etc.

13.1.2 Tender Preparation Stage

- Preparation of Working Drawings and Performance Specifications

[4] Building forms and massing refer to the building shape seen three-dimensionally.

[5] A building service core refers to the vertical space used by pedestrians for circulation in-between floors. This includes elevators, staircase, and M&E (Mechanical & Electrical) services.

a. Tender Calling / Award

- Administering the tender process and conducting interviews, making recommendations and award to contractors, etc

13.1.3 Site Commencement And Installation Stage

- Conduct and chair meetings, review and attend to design clarifications, conduct inspections, etc

a. Completion Stage – preparation of handover documentations and review of "As-built" drawings and compile operations manuals for maintenance

b. Authority Applications / Inspections – conduct on-site inspections with officers on building compliances

c. Defects Period – establish works to be rectified within the defects period.

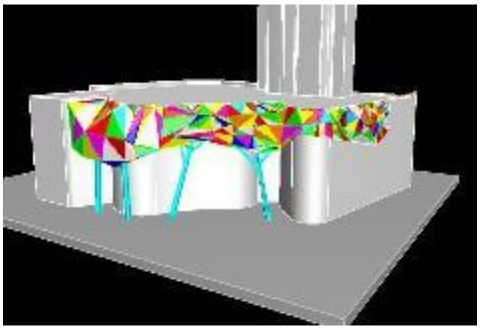
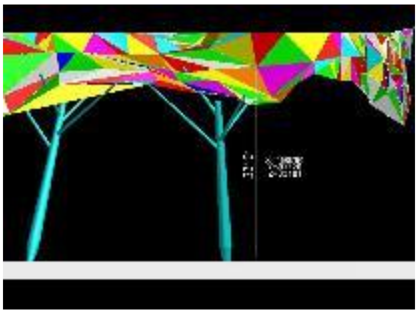
13.2 Design Stage

Building envelope design especially façades has progressed from the basic plaster and paint to cladding, curtain wall and beyond. "Free form façades have also led to a new term called "blob architecture" which used to be associated with "expensive", "difficult to build", etc.

However, such preconceived notions are no longer the case with the advent of computers and drawing software. With the aid of information technology (IT), literally any form of façade "skins" is possible not only in terms of constructing complex geometries on the computer but its ability to transform the information into fabricated components and eventually onto site for assembly.

One such example is the free form "monocoque skin" found in the ION Orchard shopping complex building in Singapore.

The completed façade skin was first modelled on the computer to optimise the curvature for the different façades. Where the curvature was too much, the panels were required to be triangulated in order to achieve the required "bends" while identifying the maximum twist permitted for the "flat" panels. Together with the steel structure members, glass panels were identified and itemised individually in drawings, then fabricated in the fabrication yard before being delivered to site. All members were assembled on-site with almost zero wastage.

Figures 144 And 145 Computer Simulation Of Canopy And Façade Elements

(Courtesy: Arup Singapore Pte Ltd)

13.2.1 3D Modelling

An example is the duty-free shop in Bangkok where 3D modelling was used in the design stages to on-site installation (Figures 146 to 149).

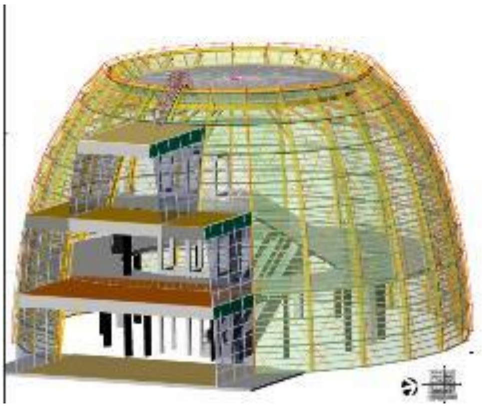


Figure 146: 3D Modelling

Figure 147: Structural Analysis

Figure 148: On-Site Construction

Figure 149: Completion

(Courtesy : Arup Singapore Pte Ltd)

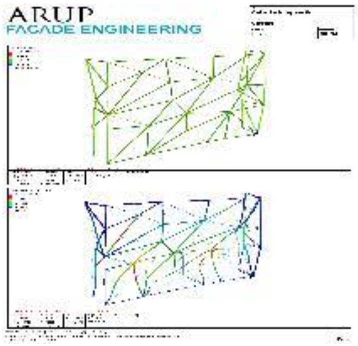
13.2.2 Structural Analysis

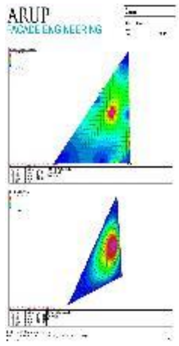
To support the modelling of the building, software for structural analysis is required to analyse the behaviour of the elements (Figures 150 to 153). Checks are done mainly for deflection and stress in the key components such as;

a. Structural frames

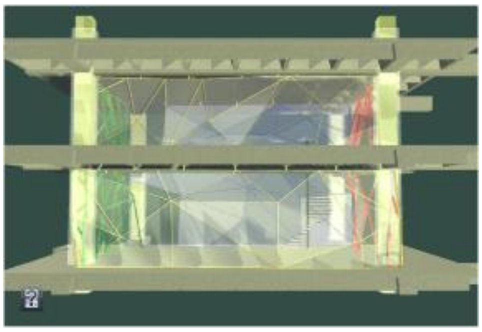
b. Connections

c. Glass and/or cladding panels





Figures 150 And 151: Structural Analysis Of Structural Frame And Glass



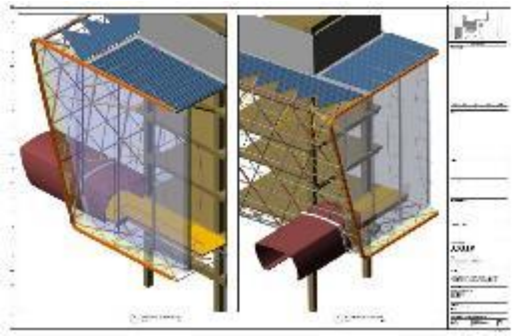
Figures 152 Steel Frame

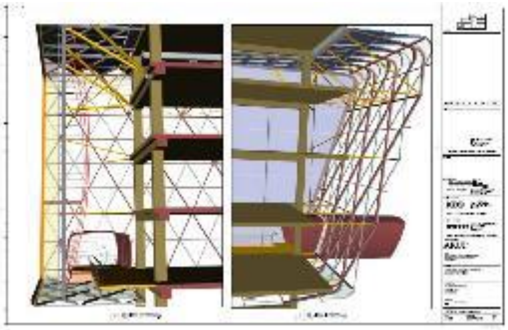
Figure 153: 3D Documentation

(Courtesy : Arup Singapore Pte Ltd)

From concept to detailed design, the information and drawings will be collated and together with the performance specifications, these will form the tender documents (Figures 154 and 155).

Specialist façade contractors will price according to the tender documentation. Project consultants assess their bids in terms of compliances, track record and experience before making their recommendations to owners for award.





Figures 154 And 155: 3D Tender Documentation

(Courtesy: Arup Singapore Pte Ltd)

For façade works upon award, the critical activities are as follows:

13.2.3 Shop Drawings Preparation – for comments and approval by Consultant
Preparation for this can almost be instantaneous as the design intent has already been established. It is also common to expect that any major technical issues would have been addressed during the tender interview rounds of Question and Answer sessions.

13.2.4 Visual Mock-up (VMU) – to be erected, reviewed and approved by Client/Consultants
After award of the façade package, one of the critical and often most urgent items is to have the VMU set up (Figures 156 to 162).

Usually erected on a full size scale of 1:1, the key objectives of the VMU are to review the major and typical components of the façade assembly in terms of:

a. the overall size(s) of the members

b. colour and finishes of the components

c. visible connections and interfacing of different members and components

d. assembly sequence of erection

e. glass - internal and external impact

It is important to know which critical components to review and approve for works to proceed. Due to urgency, most items in VMUs are often "simulated to look like what they should be" i.e. they need not be the actual components if unavailable. However, glass will have to be the actual component specified in the tender because it will need to be approved before the order for glass fabrication can be made. Often the long procurement time is attributed to the time required for glass processing.

One of the important objectives of VMU is also to obtain approval for items by having them “signed off” as minimum benchmarks to follow. This minimises disputes during on-site installation (Figures 163 and 164).



Figures 156, 157 And 158: VMU Of Glass Tonality In Day And Night Conditions


Figures 159 And 160: Close Up Of Glass Tonality In VMUs


Figure 161: VMU Of Monocoque Frame And Glass Condition

Figure 162: LED Lights In Façade

(Courtesy : AgFacadesign & G FACADESIGN Pte Ltd (Fig 156-162))

Figure 163 And 164: Record Of Approvals Documented

(Courtesy: AgFacadesign & G FACADESIGN Pte Ltd)

13.2.5 Performance Prototype Test (PPT) – to establish if the system and its components as designed meet the performance requirements (Figures 165 to 167)

This is one of the most critical stages where actual components are assembled in full scale for testing against the elements in simulated real life conditions. Typically the tests are done to 1.5 times the design requirements.

Typical tests cover:

a. Structural performance on the framing system and glass

b. Leakage tests - for air and water

c. Destructive testing (to failure)

Most of the tests pertain to structural and leakage requirements.

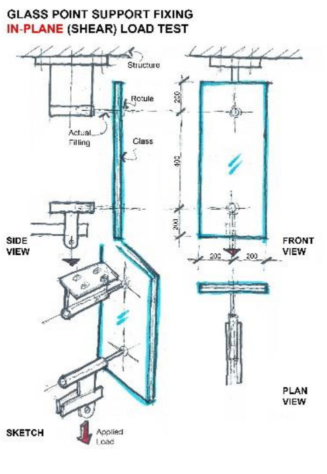
Destructive tests are usually for items where safety is of utmost importance so the user knows what the limits are before failure occurs which can be catastrophic in nature.

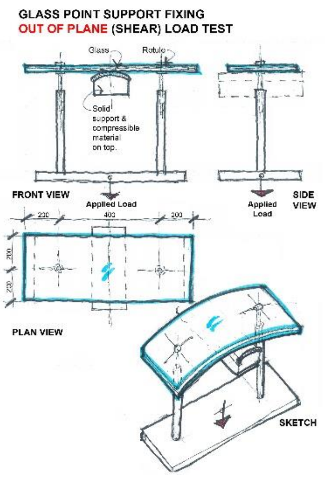
Figures 165, 166 And 167 Performance Test Assembly (Courtesy: Arup Singapore Pte Ltd)

13.2.6 Material Testing

In certain instances, only certain critical components and materials are required to be tested.

Typically, these are connections and materials where the performance requirements are of a specific nature.





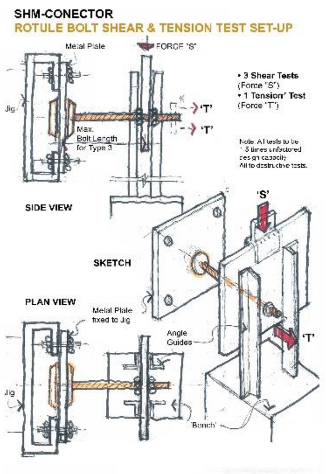


Figure 168, 169 And 170: Material Testing Diagrams For Glass And Bolts

(Courtesy: AgFacadesign & G Facadesign Pte Ltd)



Figures 171, 172 And 173: Material Testing Of Bolts

(Courtesy: AgFacadesign & G Facadesign Pte Ltd)

Building Envelope And Thermal Transfer Values

Section 3:

Introduction

Since early days, the primary aim of a shelter was to provide protection against the natural elements and to provide thermal comfort. While design has evolved through the times, the primary objective remains the same. It is thus necessary to understand the fundamentals of heat transfer to ensure the most effective and suitable design.

The building envelope is the interface between the interior of the building and the outdoor environment, including the walls, roof and foundation. By acting as a thermal barrier, the building envelope plays an important role in regulating interior temperatures and helps to determine the amount of energy required to maintain thermal comfort. Minimising heat transfer through the building envelope is crucial for reducing the need for space heating and cooling. In cold climates, the building envelope can reduce the amount of energy required for heating; in hot climates, the building envelope can reduce the amount of energy required for cooling. It is thus important that the building envelope should respond to the local climate.

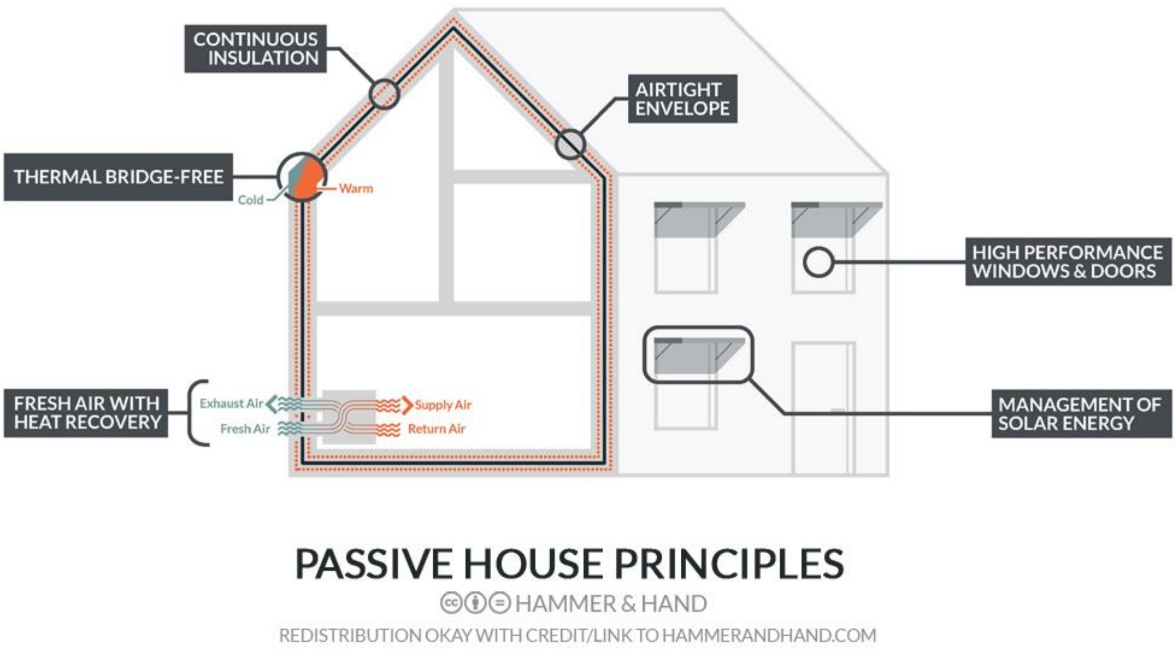


Figure 174: Building Envelope (Credit: Hammerandhand.com)

Learning Outcomes For This Section (Chapter 14 And Chapter 15):

i. To understand the various methods of heat transfer
ii. To analyse key parameters that affect building envelope
iii. To calculate the performance of the different thermo-physical properties
iv. To analyse how different components of a building's façade affect the thermal transfer value
v. To determine the various ways to improve a building's envelope performance

Chapter 14: Building Envelope

14.1 Roofs

Roof design and materials play an integral part in reducing the amount of air-conditioning required in hot climates. Such design considerations and materials selection will increase the amount of solar heat reflected, which coupled with proper insulation will result in reduced amount of heat absorbed by the roof. Roofs serve as ready platforms for installing on-site energy generation systems such as solar photovoltaic (PV) systems. Such systems can either be installed as a rooftop array on the top of a building or integrated into building roofing tiles or finishes as a building-integrated photovoltaic system (BIPV).

14.2 Walls

Similarly, the amount of energy lost or retained through walls is also dependent on both design and materials. Design considerations such as placement of windows and doors, their sizes and locations are instrumental and should be optimised to reduce energy losses. Materials selection, including wall construction and insulation, can affect the building's thermal properties. Thermal mass buildings absorb energy slowly, have longer heat-retention capability and thus effectively reduce fluctuations in indoor temperatures and overall heating and cooling requirements.

14.3 Windows, Doors And Skylights

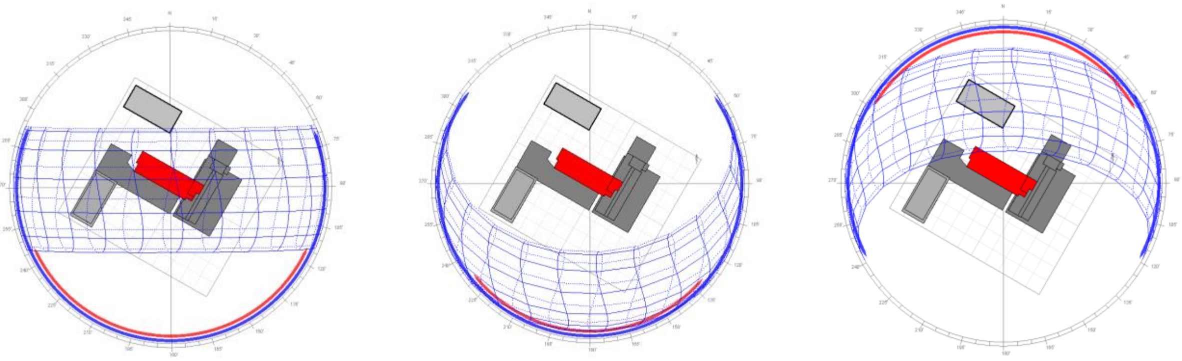
Collectively known as fenestrations, windows, exterior doors and skylights affect both the lighting and HVAC requirements of a building. While design influences the amount of available natural lighting transmitted through fenestrations, material and installation influence the amount of energy transmitted and air leakages through the fenestrations. Emerging materials, coatings and designs have all contributed to the improved energy efficiency of high-performing windows, doors and buildings. Recent technology for windows include multiple glazing, which is the use of two or more panes of glass, layered with insulating films, or air gap filled with low-conductivity gas such as argon, or coated with low-emissivity (low-E) coatings, which functions to reduce the flow of heat energy between the building and the environment.

Chapter 15: Key Parameters Affecting Building Envelope

15.1 Massing And Building Orientation

It is important to consider building geometry as part of passive design strategy, to ensure that exposure to the sun at different times of the day, building height and width can be optimised for passive comfort.

Strategies for a passive massing and orientation depends on climate. It is important to note that the sun path depends largely on the geographical location. Figure 175 below shows the different sun path diagrams for a similar development in (a) Singapore, (b) Canada and (c) Australia.



(a) (b) (c)

Figure 175: Comparison Of Annual Sun Path Diagram

The strategies for passive building envelope design should not be confused with those for daylighting. Some important points to note:

a) The amount of sunlight required for daylighting is not optimal for solar heat gain.
b) While daylight comes from all directions, the heat from the sun is dependent on its solar orientation. Façades facing away from the sun's path can still get sufficient amount of diffused light required for daylighting and will not get significant heat gain.
c) The heat from the sun can be stored by thermal mass while the sun's light cannot. This is an important consideration when designing the window and wall fabric for the west-facing façade.

The orientation of the building can affect the choice of material and glazing to be used.

Taller buildings with a lower roof area per unit volume are able to reduce unwanted heat gain in hot climates like Singapore.

As mentioned, walls facing the sun's path get the most light as well as heat. Windows and walls on the east façade are warmed in the morning, while those in the west façade are heated in the afternoon. To even out the temperature gain, the façades on the west should be designed with better insulation and low thermal mass to reduce the amount of heat absorbed.

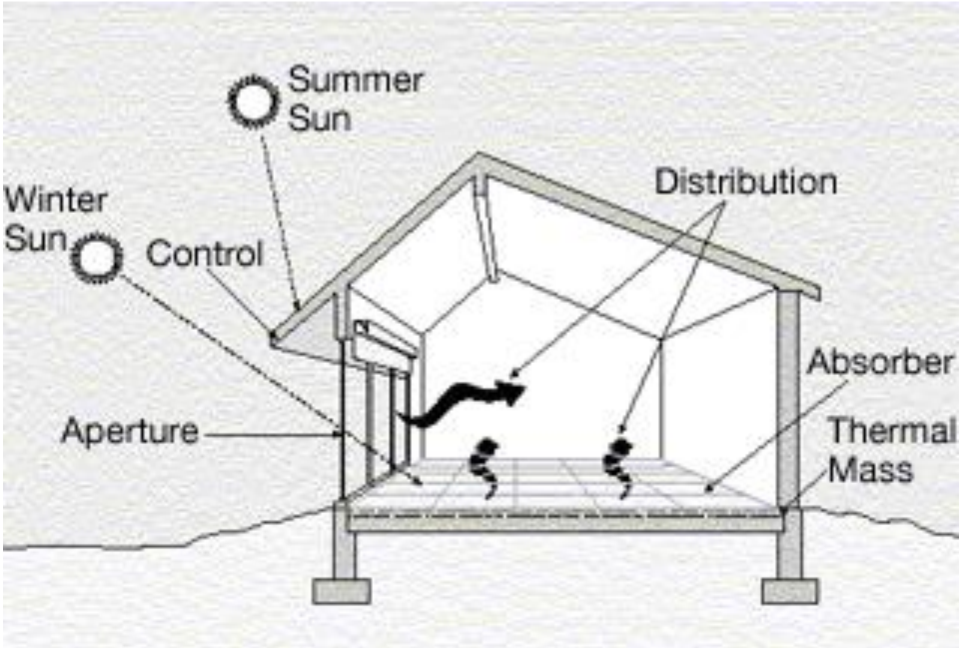
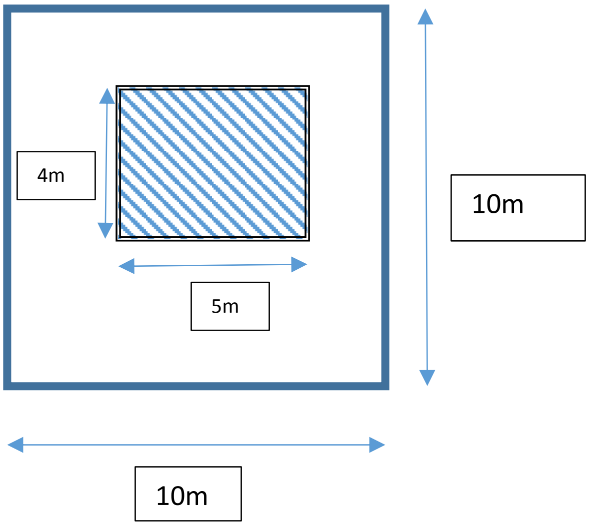


Figure 176: Orientation Of Building (Credit: Wikipedia.org)

15.2 Window To Wall Ratio

The window to wall ratio (WWR) is the percentage that results from dividing the total glazed area of the building by the total exterior wall area. The following examples below provide a better understanding of WWR.

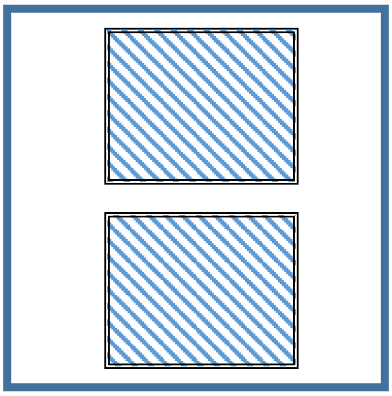


Total Wall area = $100m^2$

Window Area = $20m^2$

Window to Wall Ratio (WWR) = $\left(\frac{20}{100}\right)$ **= 0.2**

Should the wall area remain the same, and the number of windows doubled,



the WWR would thus be $\left(\frac{40}{100}\right)$ = **0.4**

15.3 Wall Fabric

The wall fabric forms the interface between the inside and outside of a building. It has a tremendous impact on the climatic regulation, energy consumption as well as the building's overall carbon intensity. The thermal performance of a wall fabric is thus dependent on the heat transfer across the materials of the wall fabric.

There are three basic methods of heat transfer; conduction, convection and radiation. It is important to understand heat transfer in order to determine the allowances for thermal movement in terms of contraction and expansion, as well as to calculate the energy efficiency of the wall design.

Conduction: The transfer of heat across a temperature gradient through direct molecular contact. This can occur either through a single material or through multiple materials. For solid building materials, this is the method by which most heat is transferred. Exterior walls made for highly conductive heat flow can thus result in significant heat gain if not thermally isolated.

Convection: The transfer of heat across a temperature gradient through fluids (liquids, gases). Convective heat and mass transfer take place both by diffusion and advection.

Radiation: The transfer of heat by electromagnetic waves through a vacuum or transparent medium (solid or fluid). This is a result of random movements of atoms and molecules in matter.

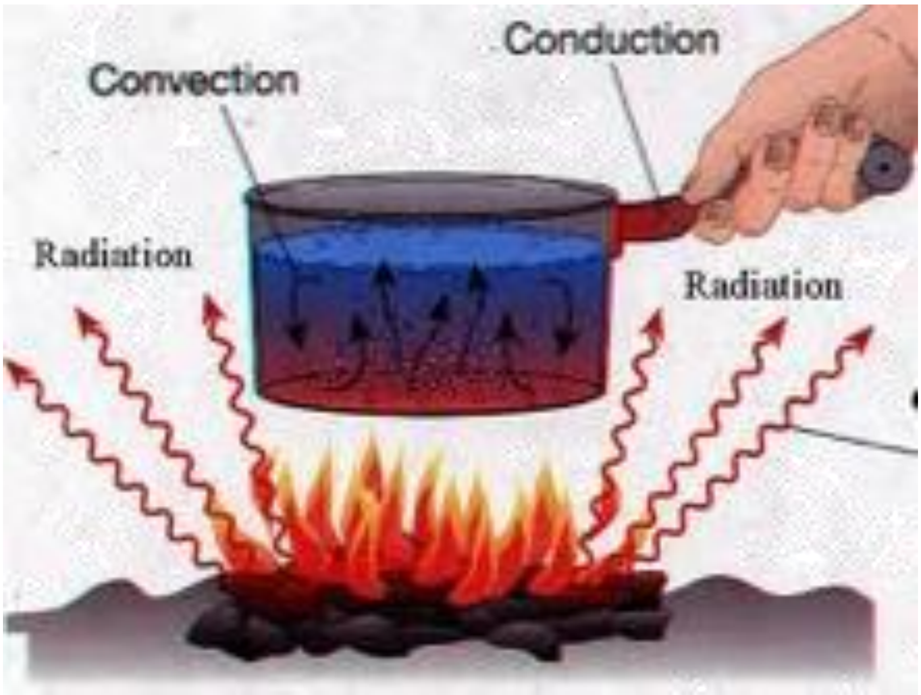


Figure 177: Modes Of Heat Transfer (Credit: chem1.com)

15.4 Thermo-Physical Properties

The different thermo-physical properties of building materials are discussed below:

15.4.1 Thermal Conductivity (K-Value)

Thermal conductivity is the quantity of heat transmitted under steady state conditions through unit area of material of unit thickness in unit time when unit temperature difference exists between the opposite sides. Thermal conductivity describes the ability of a material to conduct heat and the unit is W/mK.

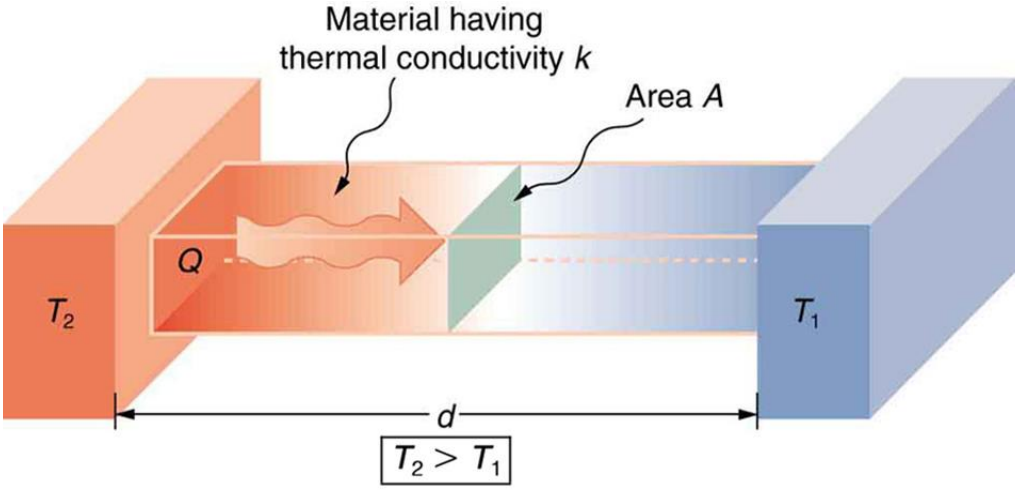


Figure 178: Heat Conduction Across Material (Image Credit: Openstax College Physics)

The thermal conductivity of some typical materials is given in Table 2 below:

Table 2: Thermal Conductivity Of Typical Materials. (Table extracted from BCA "Guidelines on Envelope Thermal Transfer Value for Buildings)

S/No	Material	Density (kg/m^3)	k-value (W/m K)
1	Asphalt, roofing	2240	1.226
2	Bitumen	-	1.298
3	Brick		
	(a) dry (covered by plaster or tiles outside)	1760	0.807
	(b) common brickwall (brickwall directly exposed to weather outside).	-	1.154
4	Concrete	2400	1.442
		64	0.144
5	Concrete, lightweight	960	0.303
		1120	0.346
		1280	0.476
6	Cork board	144	0.042
7	Fibre board	264	0.052

15.4.2 Thermal Resistivity (r)

Thermal resistivity is the reciprocal of thermal conductivity. It is expressed in mK/W and is given by:

$$r = \frac{1}{k}$$

It can be defined as the time required for one unit of heat to pass through unit area of a material of unit thickness when unit temperature difference exists between opposite faces. Thermal resistance is the ability of a material to resist heat flow.

15.4.3 Thermal Conductance (c)

Thermal conductance refers to specific thickness of a material or construction. It is the thermal transmission through unit area of a material per unit temperature difference between the hot and cold faces. It is expressed in W/m^2K and is given by:

$$c = \frac{k}{b}$$

where b is the thickness of the material (m)

15.4.4 Surface Air Film Resistance

The presence of a thin layer of air above the surface of a material adds to the insulating properties of a construction. These static layers of air on both sides of a wall provide additional resistance and results in a temperature drop across the layer of air.

The air resistance results from convention currents at the surface of a material and is affected by wind velocity. The outside and inside air films would therefore have different resistance values. These are defined as:

R_o : air film resistance of external surface (moving air)

R_i : air film resistance of internal surface (still air)

Table 3: Surface Film Resistance For Walls And Roofs (Table Extracted From BCA "Guidelines On Envelope Thermal Transfer Value For Buildings)

Type of Surface	Thermal Resistance (m^2K/W)
A. Surface Film Resistance for Walls	
1. Inside Surface (R_i)	
(a) High Emissivity	0.120
(b) Low Emissivity	0.299
2. Outside surface (R_o) – High emissivity	0.044
B. Surface Film Resistance for Roof	
1. Inside Surface (R_i)	
(a) High Emissivity	
(i) Flat roof	0.162
(ii) Sloped roof 22½ ^{o}	0.148
(iii) Sloped roof 45^o	0.133
(b) Low Emissivity	
(i) Flat roof	0.801
(ii) Sloped roof 22½ ^{o}	0.595
(iii) Sloped roof 45^o	0.391
2. Outside surface (R_o) – High emissivity Flat or sloped	0.055

15.5 Thermal Transmittance (U-Value)

The thermal transmittance of a construction is defined as the quantity of heat that flows through a unit area of a building section under steady-state conditions in unit time per unit temperature difference of the air on either side of the section.

The thermal transmittance of a construction takes into account losses due to thermal radiation, thermal convection and thermal conduction. Well insulated walls have a low thermal transmittance while poorly insulated walls have a high transmittance. The lower the U-value, the lower the heat flow and this results in greater energy savings as a lower amount of energy is required to maintain a constant room temperature.

Thermal transmittance of wall depends on the following factors:

a) Material layers
b) Thickness of materials
c) Thermal conductivity of material
d) Air resistance

It is expressed in W/m^2K and is given by:

$$U = \frac{\mathbf{1}}{\boldsymbol{R_T}}$$

Where R_T is the total thermal resistance and is given by:

$$R_T = R_o + \frac{b_1}{k_1} + \frac{b_2}{k_2} + \cdots + \frac{b_n}{k_n} + R_i$$

Where

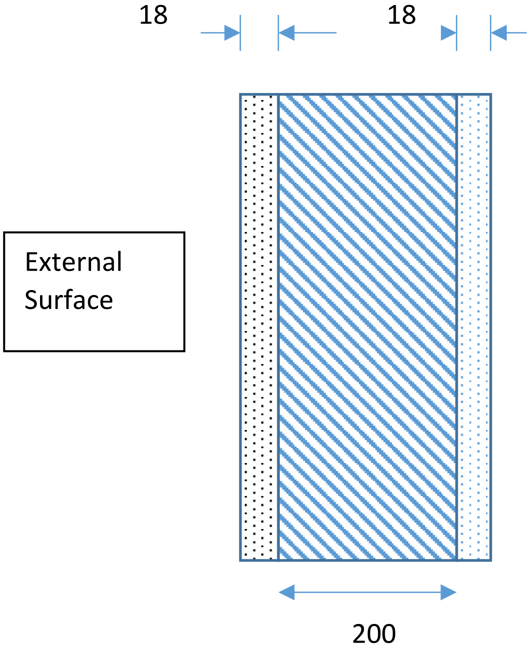
R_o : air film resistance of external surface (m^2K/W)

R_i : air film resistance of internal surface (m^2K/W)

k_1, k_2, k_n : thermal conductivity of basic material (W/mK)

b_1, b_2, b_n : thickness of basic material (m)

Example:



Layer	Thickness (mm)	Thermal Conductivity (W/mk)	Thermal Resistance (m^2k/W)
External air film			0.040
External wall plaster	18	0.533	0.034
Brickwall	200	0.807	0.248
Internal wall plaster	18	0.533	0.034
Internal surface			0.120
Total R			0.475

U-Value = (1/R) = 2.104 W/m^2k

15.6 Thermal Transmittance (U-Value) Of Fenestration

The U-value of a fenestration system measures the rate of non-solar heat gain or loss through the assembly, which includes the effect of the frame, glass, seal and spacers if any. Again, the lower the U-value, the greater is the window's resistance to heat flow across the assembly.

The U-Value of the glass depends on:

a) Glass Thickness
b) Air Gap
c) Low Emissivity Coating

Typical U-values of various glass types can be found in table 4 below:

Table 4: U values of different glazing

Glazing Type	U-Value (W/m^2K)
Single Pane	4.8
Double pane, air filled	2.5
Double pane, low-E	2.1
Triple pane	2.1
Triple pane, low-E	1.4

15.7 Air Space Resistance

Air is a poor conductor of heat. If there is an air space between 2 layers of wall or roof construction, the air trapped between the 2 layers acts as a barrier to heat transfer due to the poor conduction of heat.

Heat is transferred across the air space by conduction, convection and radiation. The effectiveness of the air space as an insulation layer is thus dependent on the thickness of the air gap. Typical values of thermal resistance for air cavities are provided in table 5:

Table 5: Air Space Resistances For Walls And Roofs (*Table Extracted From BCA "Guidelines on Envelope Thermal Transfer Value for Buildings)*

	Type of Air Space	Thermal Resistances (m^2K/W) 5mm	20mm	100mm
A	Air Space Resistances (R_a) for walls Vertical air space (Heat flows horizontally)			
	(a) High emissivity	0.110	0.148	0.160
	(b) Low emissivity	0.250	0.578	0.606
B	Air Space Resistances (R_a) for Roofs Horizontal or sloping air space (Heat flows horizontally)			
	(a) High emissivity			
	(i) horizontal air space	0.110	0.148	0.174
	(ii) sloped air space 22.5^o	0.110	0.148	0.165
	(iii) sloped air space 45^o	0.110	0.148	0.158
	(b) Low emissivity			
	(i) horizontal air space	0.250	0.572	1.423
	(ii) sloped air space 22.5^o	0.250	0.571	1.095
	(iii) sloped air space 45^o	0.250	0.570	0.768
C	Attic space resistance (R attic)			
	(a) High emissivity		0.458	
	(b) Low emissivity		1.356	

15.8 Window And Glazing

Windows and glazing are important elements in a building. In addition, windows are a major contributing factor of heat gain/loss, visual and thermal comfort. While windows played an aesthetic role in early times, the increase in use of windows and glass for façade has led to significant technological advancement of windows. Energy efficient windows and glazing systems are able to improve indoor thermal comfort and in the process reduce the energy consumption of the building. High performance window features include multiple glazing, insulating gas between panes, coatings as well as improved frames.

Selection of the windows and glazing depend on factors such as local climate, orientation and space usage to achieve indoor thermal comfort. Table 6 below details some typical glazing types:

Table 6: Glazing Selection

Characteristic	Tinted Single Glazing	Tinted Double Glazing	Double Glazing with Low Emission Coating
Properties	One layer of glass	Two layers of glass separated by an air gap	Two layers of glass separated by an air gap. Invisible metallic coating on glass that allows visible light to enter but blocks out radian heat.
Thermal transfer value ($W/m^2\,°K$)	4.88 – 5.96	2.4 – 3.29	1.6 – 1.87
Shading coefficient (SC)	0.23 – 0.47	0.4 – 0.89	0.12 – 0.45
Solar Load	Medium	Medium	Low
Heat Transmission Load	High	Medium	Low
Glare pollution	High	Medium	Low
Reflectance	High	Slightly High	Low
Visibility	Low	Low	High

A brief description of the commonly used architectural glass is given below:

Annealed glass is one of the most commonly used architectural glass as it has good surface flatness. The glass is not heat treated and will therefore not be distorted which typically happens during a tempering process. The disadvantage is that annealed glass breaks into sharp shards which is potentially dangerous.

Heat-strengthened glass is heated and quenched to create residual surface compression in the glass. It has a mechanical strength of about twice that of annealed glass and breaks into large pieces from edge to edge. Heat–strengthened glass is usually specified when additional strength is required to resist wind pressure, thermal stress or both.

Tempered glass is treated to put the outer surfaces into compression and inner surfaces into tension. Tempered glass is about 4 times stronger than annealed glass and when it breaks, tempered glass breaks into many small fragments.

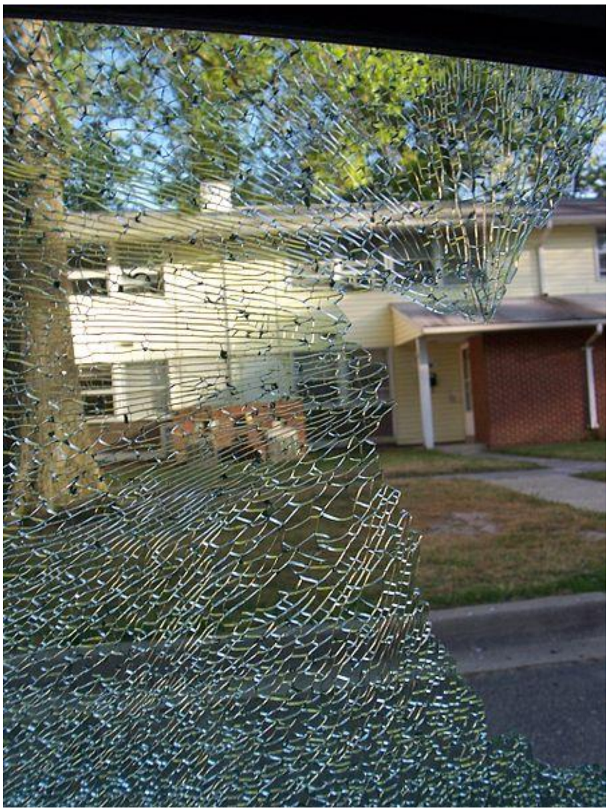


Figure 179: Breakage Pattern Of Toughened Glass (Image credit: User Markjurrens Wikipedia)

Laminated glass consists of 2 or more sheets of glass held together by an interlayer, typically of polyvinyl butyral (PVB) or ethylene-vinyl acetate (EVA). The interlayer ensures that the glass is held together even when broken. Its high strength enables it to be used as a safety glazing and often in skylights. In addition, the interlayer provides protection from ultraviolet rays as well as good acoustical characteristics due to its ability to absorb vibration.

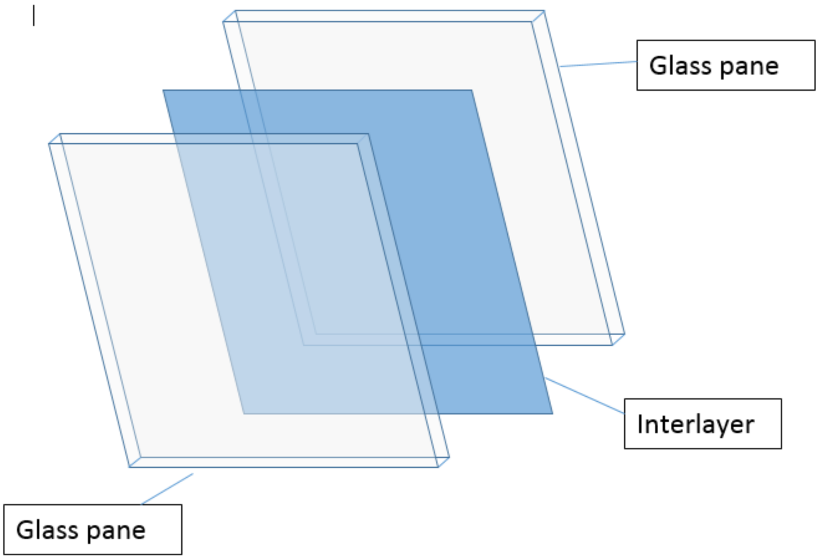


Figure 180: Laminated Glass

Tinted glass with heat absorbing properties is made by adding colour pigments to the raw materials in the float process. The colour density is dependent on the thickness. As the glass gets thicker, the density of the colour increases and the amount of light transmittance decreases. In reducing the transmittance of visible light, tinted glass also reduces the amount of infrared radiation passing through.

Coated glass is often covered with a reflective or low-emissivity (low-E) coating. This coating improves the thermal performance of the glass by reflecting visible light and infrared radiation, while still maintaining a clear look. The low-E glass has a microscopically thin, transparent coating that reflects long wave infrared energy as well as UV transmission.

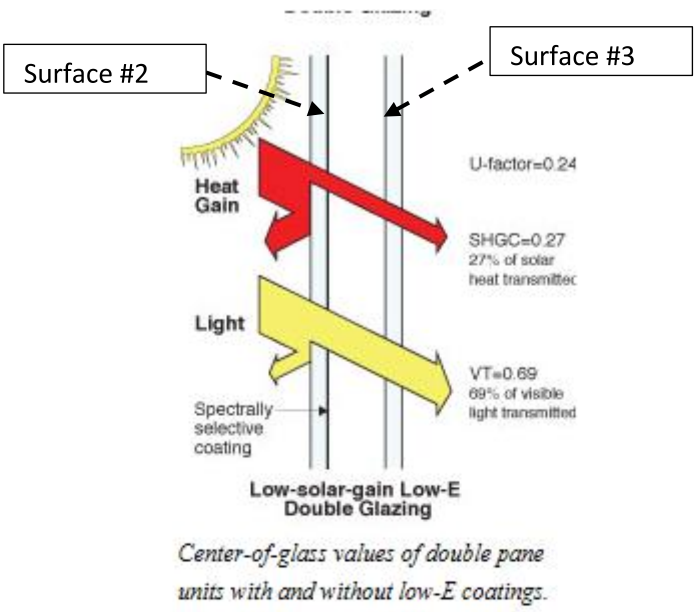


Figure 181: Low- E Glass (Photo Credit: Efficient Windows Collaborative)

The coating is typically coated on one glass surface facing into the air gap. The surface to be treated with low-E coating depends on the climate.

For climates dominated by the need for cooling, a low U-value and low SC is required. The coating is usually coated on outer glazing (Surface #2), where it rejects most of the solar heat gain.

For climates dominated by the need for heating, the need would be to block radiation from the inside, thus the low- E coating would be coated on the interior glazing (Surface #3) for effective passive solar heating applications where low U-value and high SC is required.

Insulating glass units consist of 2 or more panes of glass separated by a spacer material and sealed together. The insulating airspace can be filled with air or other inert gases such as argon or krypton, thereby improving the overall U-value of the window. In addition, when the 2 panes of glass have different thickness, the acoustical performance of the insulating glass units is also greatly improved.

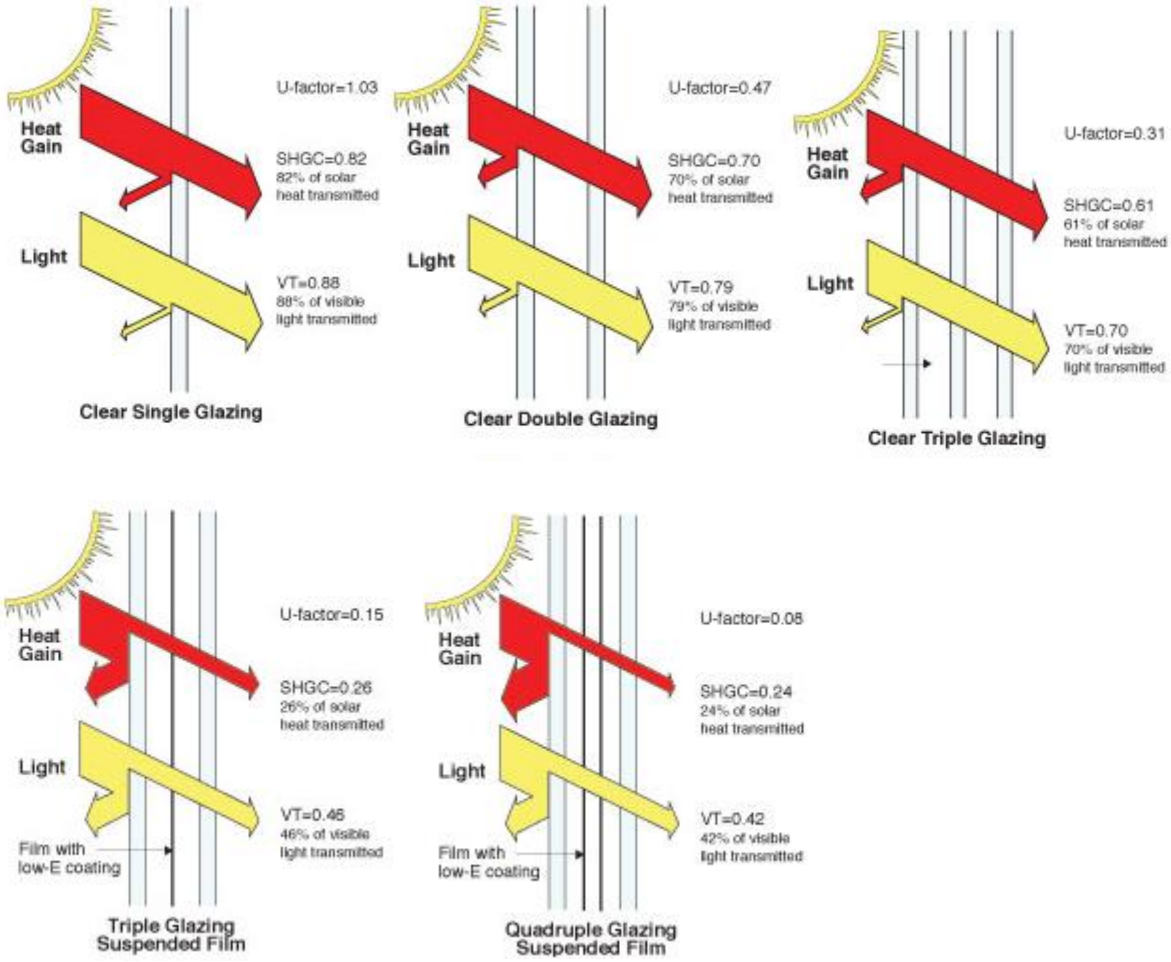


Figure 182: Types Of Insulating Glass (Photo Credit: Efficient Windows Collaborative)

15.9 Shading Devices

In tropical climates, external shading devices are very useful in keeping solar radiation off the external façade of the building envelope. Special design consideration should be taken to shade windows and transparent surfaces. External shading devices are often preferred to internal ones as they are more effective.

The type of shading devices depends on building orientation and geographical location. For locations with seasonal variation, the solar position is an important characteristic. For the southern-hemisphere, the sun rises slightly south-east and sets slightly south west. In winter, the sun rises slightly north-east and sets slightly north-west. The sun also rises earlier and sets later in summer than in winter.

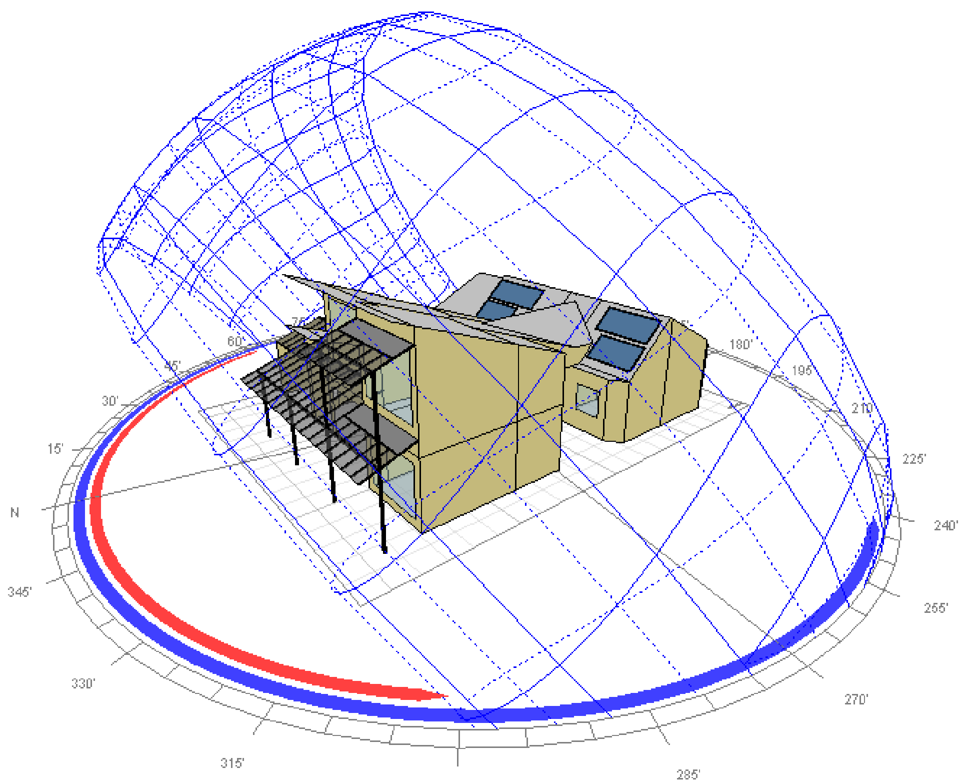


Figure 183: Sun Path Of A House In Southern Hemisphere

For a building in the southern hemisphere, the following guidelines would apply:

Orientation	Effective Shading
North (Facing equator)	Fixed horizontal device
East or West	Vertical louvres
South (Facing Pole)	Not required

The reverse would apply for a building in the northern hemisphere

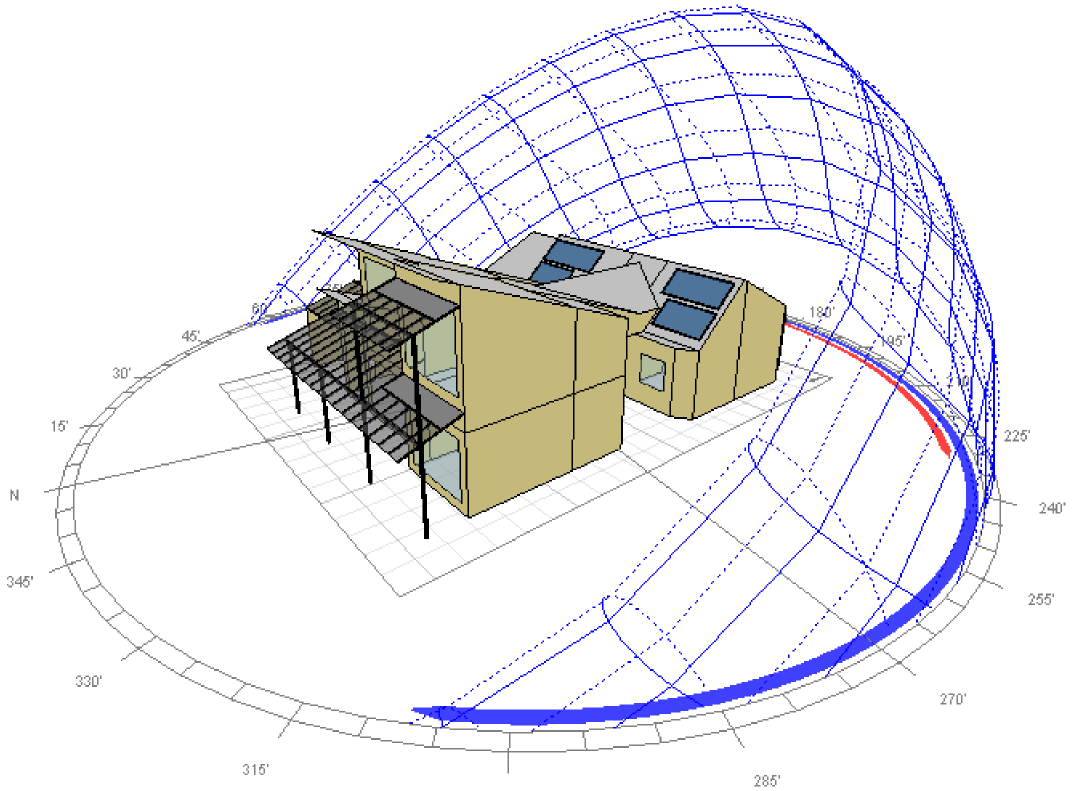


Figure 184: Sun Path Of A House In Northern Hemisphere

Orientation	Effective Shading
North (Facing equator)	Not Required
East or West	Vertical louvres
South (Facing Pole)	Fixed horizontal device

For a building in the tropics, the sun path remains relatively the same throughout the year.

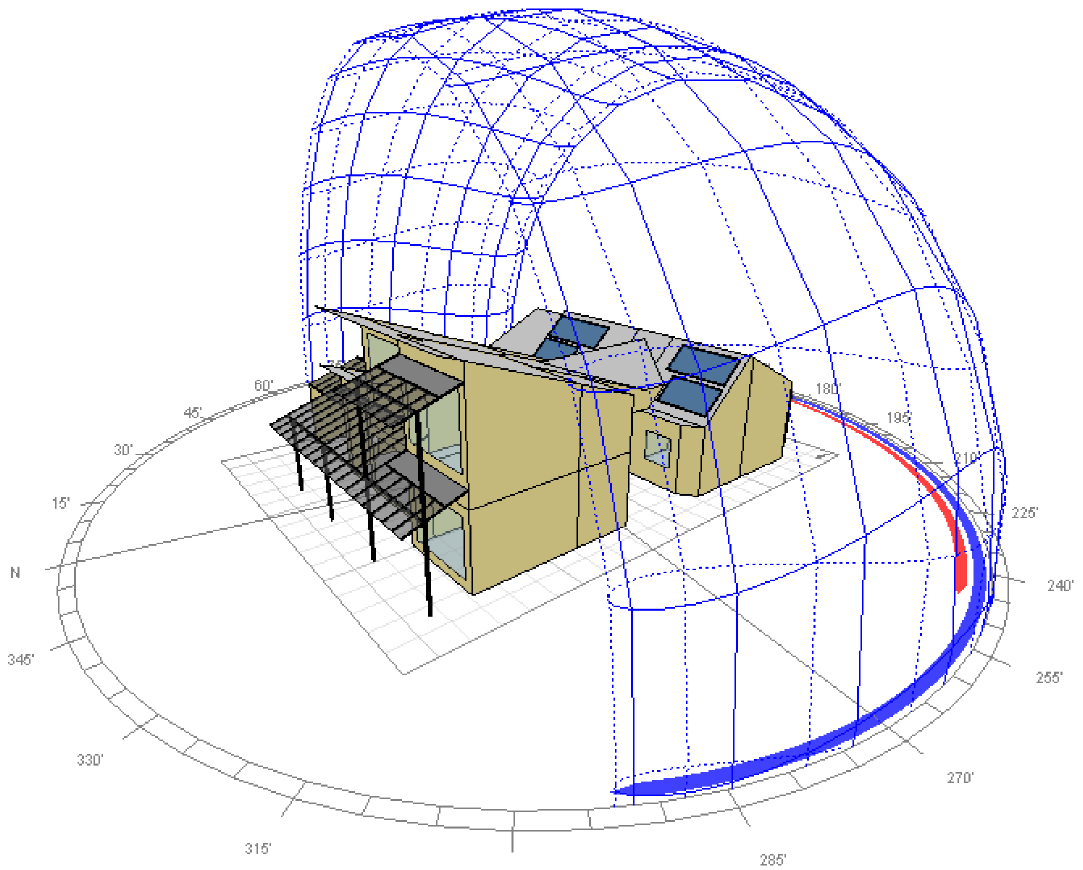


Figure 185: Sun Path Of A House In The Tropics

Orientation	Effective Shading
North or South	Fixed horizontal device
East or West	Vertical louvres

When designing shading systems, fixed overhangs should be used to control direct beam solar radiation. Indirect (diffuse) radiation should be controlled by the use of high performance glazing.

Section 4:

Introduction

Envelope Thermal Transfer Value (ETTV) is a result of a review of the Overall Thermal Transfer Value (OTTV) previously used to regulate the design of air-conditioned buildings. Buildings must be designed to have an OTTV of not more than 45W/m^2. It was however found that OTTV did not accurately reflect the relative performance of the different elements in an envelope system. It was found that OTTV underestimated the solar radiation gain component through the fenestration system and hence did not represent the full extent of heat gain through the envelope.

The OTTV was thus reviewed and a new formula that more accurately measures the thermal performance of building envelope was derived and given the name ETTV.

ETTV formula consists of 3 basic components:

a) Heat conduction through opaque walls
b) Heat conduction through fenestration
c) Solar radiation through glass windows

These three components of heat input are averaged over the whole envelope area of the building to give an ETTV that represents more accurately the thermal performance of the envelope. For the purpose of energy conservation, the maximum permissible ETTV has been set at 50W/m^2. The baseline has been tightened to 45W/m^2 with the launch of BCA Green Mark for New Buildings (Non-Residential) 2015.

Learning Outcomes for Chapter 16 to Chapter 18:

i. To understand the importance of the development of ETTV
ii. To determine the 3 basic components of ETTV
iii. To identify the various components in the ETTV formula
iv. To extract the necessary data from the various tables provided in the BCA “Code on Envelope Thermal Transfer Value for Buildings.”
v. To analyse the effectiveness of the different types of shading devices
vi. To calculate the ETTV of different types of building façade

Chapter 16: Envelope Thermal Transfer Value (ETTV)

16.1 Formula

$$\boldsymbol{ETTV} = \mathbf{12}(\mathbf{1} - \boldsymbol{WWR})\boldsymbol{U_w} + \mathbf{3.4}(\mathbf{WWR})\boldsymbol{U_f} + \mathbf{211}(\mathbf{WWR})(\mathbf{CF})(\mathbf{SC})$$

Where

ETTV : envelope thermal transfer value (W/m^2)

WWR : window-to-wall ratio (fenestration area / gross area of external wall)

U_w : thermal transmittance of opaque wall (W/m^2K)

U_f : thermal transmittance of fenestration (W/m^2K)

CF : correction factor for solar heat gain through fenestration

SC : shading coefficients of fenestration

Where more than one type of material and/or fenestration is used, the respective term or terms shall be expanded into sub-elements as shown:

$$ETTV = \frac{12(A_{w1} \times U_{w1} + A_{w2} \times U_{w2} + \ldots + A_{wn} \times U_{wn})}{A_o} + \frac{3.4(A_{f1} \times U_{f1} + A_{f2} \times U_{f2} + \ldots + A_{fn} \times U_{fn})}{A_o} + \frac{211(A_{f1} \times SC_{f1} + A_{f2} \times SC_{f2} + \ldots + A_{fn} \times SC_{fn})(CF)}{A_o}$$

Where

A_{w1}, A_{w2}, A_{wn}	:	areas of different opaque wall (m^2)
A_{f1}, A_{f2}, A_{fn}	:	areas of different fenestration (m^2)
A_0	:	gross area
U_{w1}, U_{w2}, U_{wn}	:	thermal transmittances of opaque walls (W/m^2K)
U_{f1}, U_{f2}, U_{fn}	:	thermal transmittances of fenestrations (W/m^2K)
SC_{f1}, SC_{f2}, SC_{fn}	:	shading coefficients of fenestrations

16.2 Solar Correction Factor (CF)

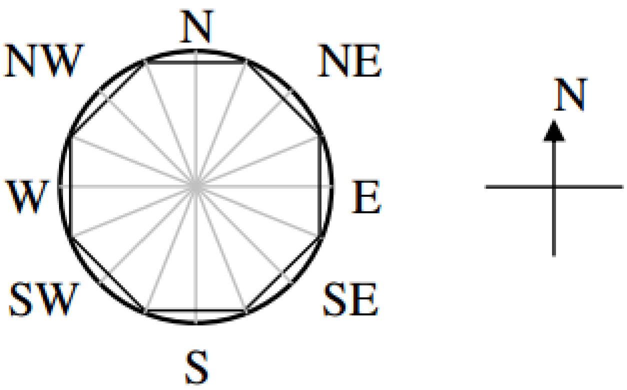
The solar correction factors for the eight primary orientations of the walls have been determined for the Singapore climate. These can be found in Table 7 below:

Table 7: Solar Correction Factors (CF) For Walls (ETTV) (Table Extracted From BCA "Code On Envelope Thermal Transfer Value for Buildings" Table C1)

Pitch Angle	Orientation							
	N	NE	E	SE	S	SW	W	NW
70°	1.17	1.33	1.47	1.35	1.21	1.41	1.56	1.38
75°	1.07	1.23	1.37	1.25	1.11	1.32	1.47	1.28
80°	0.98	1.14	1.30	1.16	1.01	1.23	1.39	1.20
85°	0.89	1.05	1.21	1.07	0.92	1.14	1.31	1.11
90°	0.80	0.97	1.13	0.98	0.83	1.06	1.23	1.03
95°	0.73	0.90	1.05	0.91	0.76	0.99	1.15	0.96
100°	0.67	0.83	0.97	0.84	0.70	0.92	1.08	0.89
105°	0.62	0.77	0.90	0.78	0.65	0.86	1.01	0.83
110°	0.59	0.72	0.83	0.72	0.61	0.80	0.94	0.78
115°	0.57	0.67	0.77	0.67	0.58	0.75	0.87	0.73
120°	0.55	0.63	0.72	0.63	0.56	0.71	0.81	0.69

Note: 1. The correction factors for other orientations and other pitch angles may be obtained by interpolation.

For curved walls, the eight primary orientations are segmented as follows:



16.3 Roof Thermal Transfer Value (RTTV)

The concept of ETTV would apply to an air-conditioned roof with a skylight opening. The term RTTV is used to differentiate between the walls and roof of a building.

RTTV formula consists of 3 basic components:

d) Heat conduction through opaque roof
e) Heat conduction through skylight
f) Solar radiation through skylight

The maximum permissible RTTV is $50W/m^2$

16.3.1 Formula For RTTV

$$\boldsymbol{RTTV = 12.5(1 - SKR)U_r + 4.8(\mathrm{SKR})U_s + 485(\mathrm{SKR})(\mathrm{CF})(\mathrm{SC})}$$

Where

RTTV : roof thermal transfer value (W/m^2)

SKR : skylight ratio of roof (skylight area / gross area of roof)

U_r : thermal transmittance of opaque roof (W/m^2K)

U_s : thermal transmittance of skylight area (W/m^2K)

CF : correction factor for roof

SC : shading coefficients of skylight portion of the roof

Chapter 17: Residential Thermal Transfer Value

17.1 Residential Thermal Transfer Value (RETV)

The RETV calculation is largely similar to the ETTV calculation and applies to residential buildings. The RETV formula consists of 3 basic components:

a) Heat conduction through opaque walls
b) Heat conduction through glass windows
c) Solar radiation through glass windows

The maximum permissible RETV has been set at 25W/m^2

17.1.1 Formula For RETV

$$\boldsymbol{RETV = 3.4(1 - WWR)U_w + 1.3(\mathrm{WWR})U_f + 58.6(\mathrm{WWR})(\mathrm{CF})(\mathrm{SC})}$$

Where

RETV : envelope thermal transfer value (W/m^2)

WWR : window-to-wall ratio (fenestration area / gross area of external wall)

U_w : thermal transmittance of opaque wall (W/m^{2}K)

U_f : thermal transmittance of fenestration (W/m^{2}K)

CF : correction factor for solar heat gain through fenestration

SC : shading coefficients of fenestration

17.1.2 Deem-To-Satisfy Criteria For RETV

Should the building's WWR and SC fall within any of the following sets of criteria, the building is deemed to have complied with RETV and hence exempted from computing RETV

WWR_{Bldg}	$SC_{façade}$
< 0.3	< 0.7
< 0.4	< 0.5
< 0.5	< 0.43

Where

WWR : Window to wall ratio

SC : Shading coefficient of fenestration = SC_{Glass} X $SC_{shading\ device}$

17.2 Shading Coefficient

The rate of solar heat gain through a fenestration system is altered by the shading coefficient, which is defined as the ratio of heat gain through the fenestration system having combination of glazing and shading device to the solar heat gain through an unshaded 3mm clear glass.

$$SC = \frac{\text{Solar heat gain of any glass and shading combination}}{Solar\ heat\ gain\ through\ a\ 3mm\ unshaded\ clear\ glass}$$

The shading coefficient of any fenestration system can be obtained as follows:

$SC = SC_1 \times SC_2$

Where

SC: shading coefficient of the fenestration system

SC_1: shading coefficient of glass or effective shading coefficient of glass with solar control film where a solar control film is used on the glass

SC_2: effective shading coefficient of external shading devices

It should be noted that the shading coefficient of the glass (SC_1) should be based on the manufacturer's recommended value.

The effective shading coefficient (SC_2) of external device can be obtained in Tables C12 to C23 of the BCA "Code on Envelope Thermal Performance for Buildings" and will be discussed briefly below. In cases where the type of shading device is not included in the table, the effective shading coefficient shall be calculated from the basic solar data based on first principles, in accordance with the method specified in the guideline.

Alternatively, the shading coefficient can be obtained by the use of software to obtain solar insolation data.

17.3 Types Of External Shading Devices

17.3.1 Horizontal Projections

Key 1 Horizontal Projections [Tables C12 to C15]

$R_1 = \frac{P}{H}$

ϕ_1 = Angle of inclination

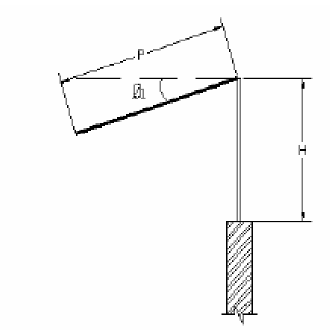


Figure 186: Horizontal Projections (Extracted From BCA Code On Envelope Thermal Performance For Buildings, Section B4.1)

Table C15: Effective Shading Coefficients of Horizontal Projection at Various Angles of Inclination

Orientation: South-East & South-West

R_1	0°	10°	20°	30°	40°	50°
0.1	0.9253	0.9167	0.9107	0.9072	0.9065	0.9086
0.2	0.8574	0.8405	0.8280	0.8203	0.8177	0.8204
0.3	0.7964	0.7715	0.7527	0.7406	0.7355	0.7377
0.4	0.7413	0.7100	0.6862	0.6692	0.6601	0.6597
0.5	0.6981	0.6615	0.6321	0.6109	0.5985	0.5951
0.6	0.6578	0.6179	0.5890	0.5663	0.5503	0.5417
0.7	0.6289	0.5891	0.5555	0.5289	0.5107	0.5004
0.8	0.6059	0.5604	0.5251	0.5044	0.4880	0.4765
0.9	0.5828	0.5372	0.5096	0.4863	0.4702	0.4592
1.0	0.5619	0.5248	0.4942	0.4727	0.4573	0.4493

Figure 187: Effective Shading Coefficients Of Horizontal Projection (Extracted From BCA Code On Envelope Thermal Performance For Buildings, Section B4.1)

Example (Extracted from BCA Code On Envelope Thermal Performance For Buildings, Section B5.1)

Given : Window on South-West facing wall with a 0.3m horizontal overhang.

Find : The effective shading coefficient if (a) height of window is 0.6m; (b) height of window is 0.75m with the overhang inclined at 30° to the horizontal.

Solution: Refer to Table C15

a) $R_1 = 0.5$ SC = 0.698

b) $R_1 = 0.4$ SC = 0.669

17.3.2 Vertical Projections

Key 2 Vertical Projections [Tables C16 to C19]

$$R_2 = \frac{P}{W}$$

ϕ_2 = Angle of inclination

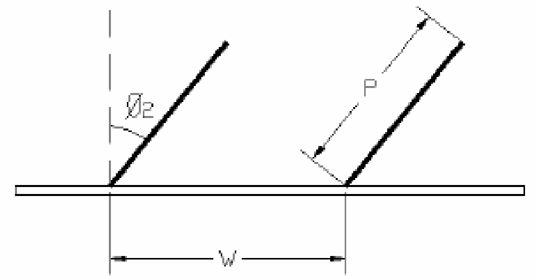


Figure 188: Vertical Projections (Extracted From BCA Code On Envelope Thermal Performance For Buildings, Section B4.2)

Table C16: Effective Shading Coefficients of Vertical Projection at Various Angles of Inclination

Orientation: North & South

R_2	0°	10°	20°	30°	40°	50°
0.1	0.9526	0.9534	0.9549	0.9571	0.9606	0.9638
0.2	0.9066	0.9082	0.9110	0.9155	0.9225	0.9289
0.3	0.8605	0.8630	0.8672	0.8739	0.8844	0.8940
0.4	0.8144	0.8177	0.8236	0.8325	0.8463	0.8591
0.5	0.7752	0.7800	0.7892	0.8005	0.8159	0.8277
0.6	0.7540	0.7563	0.7632	0.7768	0.7950	0.8078
0.7	0.7379	0.7434	0.7464	0.7560	0.7771	0.7920
0.8	0.7290	0.7306	0.7348	0.7423	0.7637	0.7807
0.9	0.7202	0.7230	0.7269	0.7319	0.7507	0.7699
1.0	0.7114	0.7183	0.7190	0.7246	0.7388	0.7595
1.1	0.7060	0.7137	0.7144	0.7173	0.7308	0.7523
1.2	0.7022	0.7091	0.7098	0.7099	0.7251	0.7451
1.3	0.7000	0.7045	0.7053	0.7055	0.7206	0.7379
1.4	0.6977	0.6999	0.7007	0.7022	0.7173	0.7307

Figure 189: Effective Shading Coefficients Of Vertical Projection For North And South (Extracted From BCA Code On Envelope Thermal Performance For Buildings, Table C16)

17.3.3 Egg-Crate Louvres

Key 3 Egg-crate Louvers [Tables C20 to C23]

$$R_1 = \frac{P}{H}$$

$$R_2 = \frac{P}{W}$$

$\phi 1$ = Angle of inclination

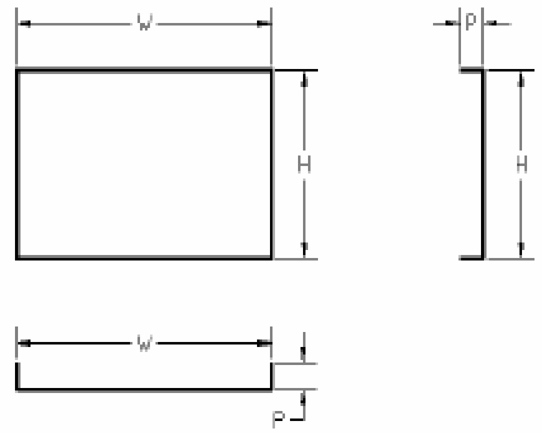


Figure 190: Egg-Crate Louvres (Extracted From BCA Code On Envelope Thermal Performance For Buildings, Section B4.3)

Table C20: Effective Shading Coefficients of Egg-Crate Louvers with Inclined Horizontal Fins

Orientation: North & South

R_1	R_2	0°	10°	20°	30°	40°
0.2	0.2	0.8125	0.8053	0.8011	0.8002	0.8025
0.2	0.4	0.7476	0.7432	0.7409	0.7409	0.7431
0.2	0.6	0.7086	0.7059	0.7047	0.7050	0.7068
0.2	0.8	0.6945	0.6926	0.6917	0.6920	0.6934
0.2	1.0	0.6850	0.6836	0.6829	0.6832	0.6843
0.2	1.2	0.6802	0.6790	0.6785	0.6787	0.6796
0.2	1.4	0.6779	0.6768	0.6764	0.6766	0.6774
0.2	1.6	0.6756	0.6747	0.6743	0.6744	0.6752
0.2	1.8	0.6733	0.6725	0.6722	0.6723	0.6729
0.4	0.2	0.7184	0.7070	0.7002	0.6977	0.6995
0.4	0.4	0.6808	0.6747	0.6716	0.6709	0.6727
0.4	0.6	0.6631	0.6604	0.6593	0.6594	0.6605
0.4	0.8	0.6601	0.6586	0.6581	0.6581	0.6587
0.4	1.0	0.6587	0.6580	0.6578	0.6578	0.6580

Figure 191: Effective Shading Coefficients Of Vertical Projection For North And South (Extracted From BCA Code On Envelope Thermal Performance For Buildings, Table C20)

Chapter 18: BCA Green Mark ETTV Requirements

18.1 BCA Green Mark For New Buildings (Non-Residential)

The Criteria for the BCA Green Mark for New Buildings (Non-Residential) 2015 (GMNR v5) was launched in September 2015 with the aim to create more streamlined and robust criteria.

18.1.1 Change In Baseline

The calculation of ETTV remains a pre-requisite requirement for all projects with GFA ≥ 2000 m^2 and air-conditioned areas ≥ 500 m^2.

The requirements for ETTV have however been tightened with the baseline at 45W/m^2 instead of 50W/m^2. Table 8 below shows the maximum allowable ETTV for the various rating levels:

Table 8: Maximum ETTV (GMNR Ver5)

Level of Award	Maximum ETTV
Certified	45W/m^2
Gold	45W/m^2
Gold^{Plus}	40W/m^2
Platinum	38W/m^2

18.1.2 Tropical Façade Performance

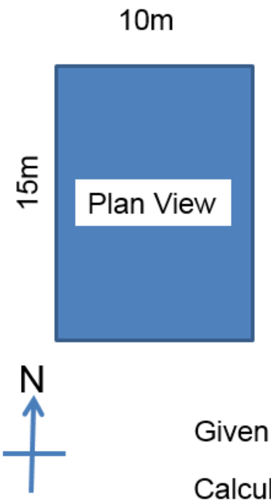
Under the section on Climatic Response Design; Topicality (Section 1.03a), the criteria recognises efforts made in improving the building's façade performance in the tropics by reducing heat gain into the building. Up to 4 points shall be awarded for improving the façade performance of the building. There are 2 scoring options provided.

Example

Part 1

Given:

$$ETTV = 12(1 - WWR)U_w + 3.4(\mathbf{WWR})U_f + 211(\mathbf{WWR})(\mathbf{CF})(\mathbf{SC})$$



Height of Building : **4m**

	N	S	E	W
U_w	2.7 W/m²K	2.7 W/m²K	2.7 W/m²K	2.7 W/m²K
U_f	5.82W/m²K	5.82 W/m²K	5.82 W/m²K	5.82 W/m²K
CF	0.57	0.58	0.77	0.97
SC	0.47	0.68	0.58	0.47

Given WWR = **0.2**

Calculate the ETTV

Proposed Solution:

$ETTV_N$ = 12(1- 0.2) (2.7) + 3.4 (0.2)(5.82) + 211 (0.2)(0.57)(0.47) = 41.18W/m^2

$ETTV_S$ = 46.52W/m^2

$ETTV_E$ = 48.72W/m^2

$ETTV_W$ = 49.11W/m^2

Area of each facade

Direction	Area	%
North	40	0.2
South	40	0.2
East	60	0.3
West	60	0.3

$ETTV_T$ = 0.2 ($ETTV_N$) + 0.2 ($ETTV_S$) + 0.3 ($ETTV_E$) + 0.3 ($ETTV_W$)

= 46.89 W/m^2

Part 2

From Part 1;

Given ETTV = 46.89 W/m^2

What is the highest WWR possible to achieve ETTV of 50W/m^2?

Proposed Solution:

$$\boldsymbol{ETTV = 12(1 - WWR)U_w + 3.4(\mathrm{WWR})U_f + 211(\mathrm{WWR})(\mathrm{CF})(\mathrm{SC})}$$

$ETTV_N$ = 12 (1-WWR) (2.7) + 3.4 (WWR) (5.82) + 211 (WWR) (0.57)(0.47)

= 32.4 (1-WWR) + 19.788 (WWR) + 56.527 (WWR)

= 32.4 – 32.4 WWR + 19.788 WWR + 56.527 WWR

= 32.4 + 43.915 WWR

$ETTV_S$ = 12 (1-WWR) (2.7) + 3.4 (WWR) (5.82) + 211 (WWR) (0.58)(0.68)

= 32.4 (1-WWR) + 19.788 (WWR) + 83.218 (WWR)

= 32.4 – 32.4 WWR + 19.788 WWR + 83.218 WWR

= 32.4 + 70.606 WWR

$ETTV_E$ = 12 (1-WWR) (2.7) + 3.4 (WWR) (5.82) + 211 (WWR) (0.77) (0.58)

= 32.4 (1-WWR) + 19.788 (WWR) + 94.233 (WWR)

= 32.4 – 32.4 WWR + 19.788 WWR + 94.233 WWR

= 32.4 + 81.621 WWR

$ETTV_E$ = 12 (1-WWR) (2.7) + 3.4 (WWR) (5.82) + 211 (WWR) (0.97) (0.47)

= 32.4 (1-WWR) + 19.788 (WWR) + 96.194 (WWR)

= 32.4 – 32.4 WWR + 19.788 WWR + 96.194 WWR

= 32.4 + 83.582 WWR

$ETTV_T = 0.2\ (ETTV_N) + 0.2\ (ETTVs) + 0.3\ (ETTV_E) + 0.3\ (ETTV_W)$

$50 = 0.2\ (32.4 + 43.915\ WWR) + 0.2\ (32.4 + 70.606\ WWR) + 0.3\ (32.4 + 81.621\ WWR) + 0.3\ (32.4 + 83.582\ WWR)$

$50 = 6.48 + 8.783\ WWR + 6.48 + 14.121\ WWR + 9.72 + 24.486\ WWR + 9.72 + 25.075\ WWR$

$50 = 32.4 + 72.465\ WWR$

$17.7 = 72.465\ WWR$

$WWR = 17.7/72.465 = 0.244$

Section 5:

Introduction

Daylighting is the controlled admission of natural light into a given space to reduce the dependency on artificial lighting and in the process result in energy savings. Daylight is a natural resource that is readily available and not expected to run out in the near future. It has the ability to illuminate and visually stimulate a space, as well as provide a positive environment for the occupants. Studies have shown that proper use of daylighting increases productivity, improves general health and has a positive physiological effect.

Daylight varies in intensity as well as quality and the desirable tolerance is very much dependent on the usage of a particular space. The three factors that should be considered when providing lighting: quantity, quality and distribution. Excessive direct sunlight when admitted can cause severe glare which can be irritating and debilitating for the occupant's task. It is thus important that careful consideration be taken when integrating daylighting into the design of a space.

Since the early days of civilization, cave men have depended on daylight to differentiate between night and day. As dwellings developed, openings were integrated to allow daylight to enter.

Figure 192: Cave Monastery, Erusheli.
(Image Credit: https://commons.wikimedia.org/wiki/File:Panorama_Wardzia.jpg)

From such crude openings, windows were later developed to control the flow of air, heat and cold into a space. The primary function of a window was still the introduction of daylight into a given space. While glass had been discovered as early as 3000BC in Egypt, it was used mostly for decorative objects. During the Roman period, small pieces of hand –blown glass set in bronze frames were used as infill for window openings.

While the mediaeval cathedrals had illustrious stained glass designs for daylighting, it was only in the seventeenth century that advancement in manufacturing process allowed large panes of glass to be used as window infills. This led to the wondrous interiors of the Baroque churches.

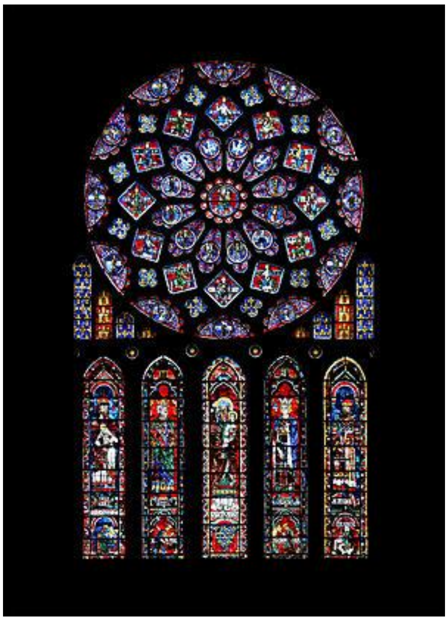


Figure 193: Stained Glass (Image Credit: User Eusebius_Wikipedia)

Figure 194: Sunlight Shining Through Stained Glass (Image: User Ayyoubsabawiki-Wikipedia)

Daylighting remained the primary means of lighting for all types of buildings until the light bulb was made commercially available in 1880 by Thomas Edison. In the early twentieth century, with the development of electric sources, the design for daylighting began to decline. With reduction in floor to floor height due to economics of structure, daylight penetration into buildings was reduced.

It was not until the recent energy crisis that people realised the need to reduce the reliance on fossil fuels. The approach to reduce the electrical load in the buildings led to the return to an understanding of the natural resource of daylight.

Learning Outcomes For This Section (Chapter 19 To Chapter 26):

i. To appreciate the importance of daylighting
ii. To analyse the advantages and disadvantages of daylighting
iii. To evaluate the different parameters that determine the effectiveness of daylighting design
iv. To describe the various design tools used for daylighting design
v. To develop different design concepts for maximising daylighting

Chapter 19: Daylighting

19.1 Principles

Daylighting needs to be considered from the initial design stage of a building and requires a holistic approach to design. Part of sustainable architecture is associated with minimising the energy consumption in the operating of the building throughout its life. Daylighting does not only reduce the dependency on artificial lighting and reduce electricity consumption of lighting, it also reduces the cooling load of a space.

Daylighting design takes into account the following factors which will be discussed further in the following chapters:

a. The siting of the building, taking into account its orientation, sun path and surrounding buildings and landscape;
b. The function and purpose of the building as these will determine the floor height and floor division. These have an impact on the daylight penetration as well as the building costs;
c. The location and size of the windows, as these have a bearing on the control of heat gain and loss, glare as well as provision of views. This will depend on the glass selection and will be discussed in some detail later.

Chapter 20: The Sun

The Sun is our singular source of renewable energy and sits at the center of our solar system. It emits energy in the form of electromagnetic radiation at a very large and relatively constant rate. The sun produces 63MW/m^2 of energy and has a brightness of about 6000 million lumens. It is about 150 million km away and light from the sun takes about 8 minutes to reach the earth.

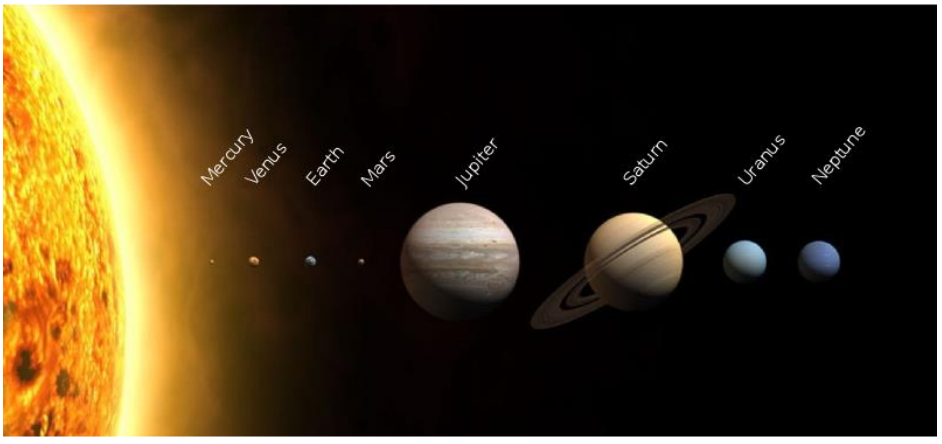


Figure 195: Planets In The Solar System (Image Credit: User PlanetUser_Wikipedia)

The rate at which solar energy reaches a unit area on the earth is known as the solar irradiance or insolation and the unit is W/m^2. The earth absorbs about 70 percent of the total solar irradiance (TSI) that falls on the outermost atmosphere of the Earth, the rest is reflected into space. The TSI does not remain constant and varies with sunspots and solar weather activities.

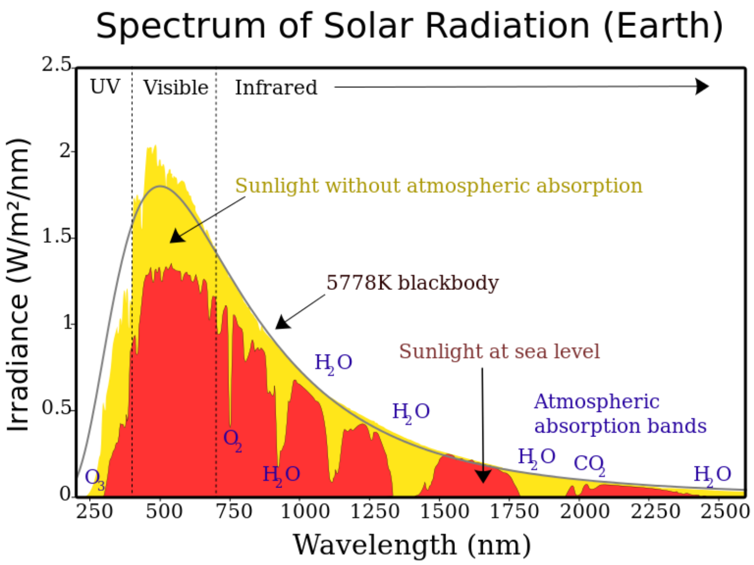


Figure196: Solar Irradiance Spectrum Above Atmosphere And At Surface (Image Credit: User BenRG_Wikipedia)

20.1 Visible Light

Sunlight might appear white, but it actually consists of electromagnetic waves with a wide range of wavelengths. This broad range of wavelengths is known as the electromagnetic spectrum.

This spectrum is subdivided into regions in order of decreasing wavelength and increasing energy and frequency. These regions as shown in Figure 197 below are radio waves, microwaves, infrared (IR), visible light, ultraviolet (UV), X-rays and gamma-rays.

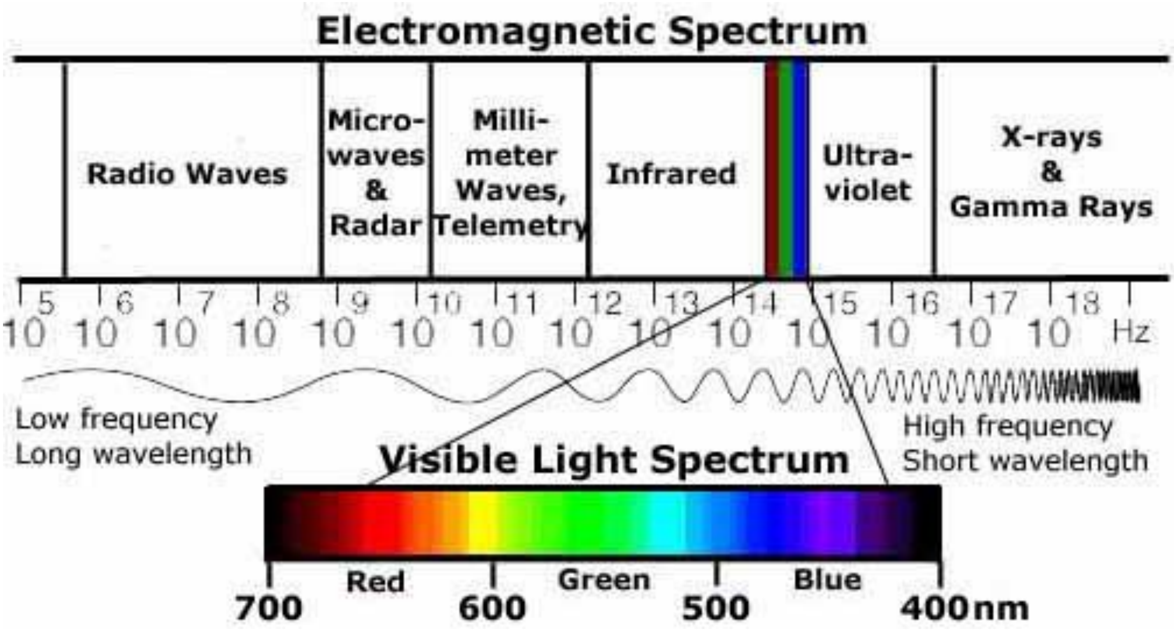


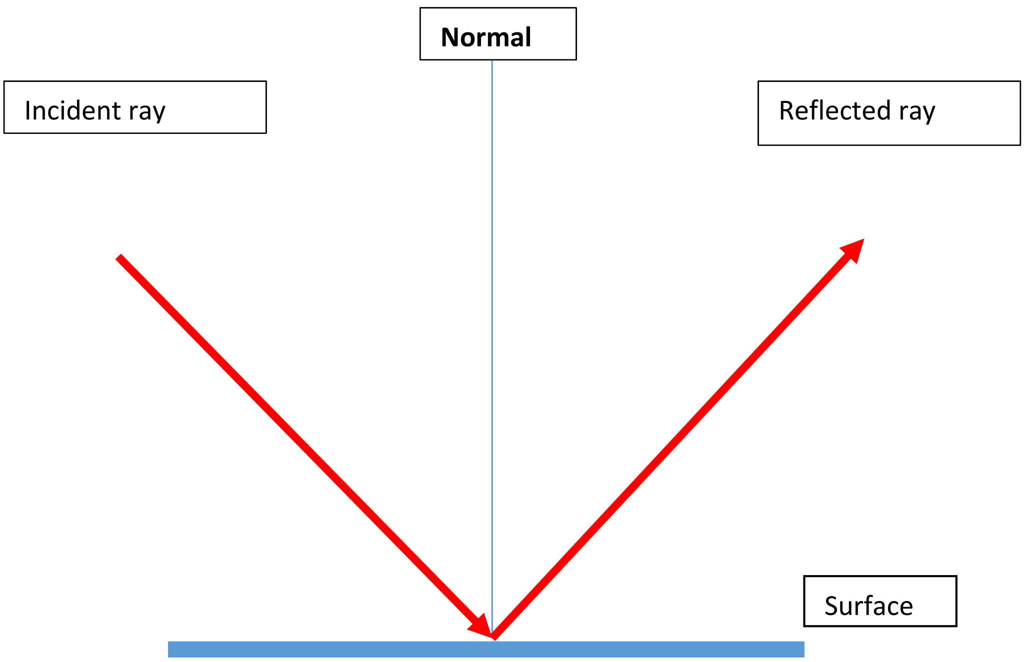
Figure197: Electromagnetic Spectrum

All electromagnetic radiation is light, however only a small portion of this radiation, called visible light can be seen. The wavelengths in the visible light spectrum range from about 400 nanometres to 700 nanometres

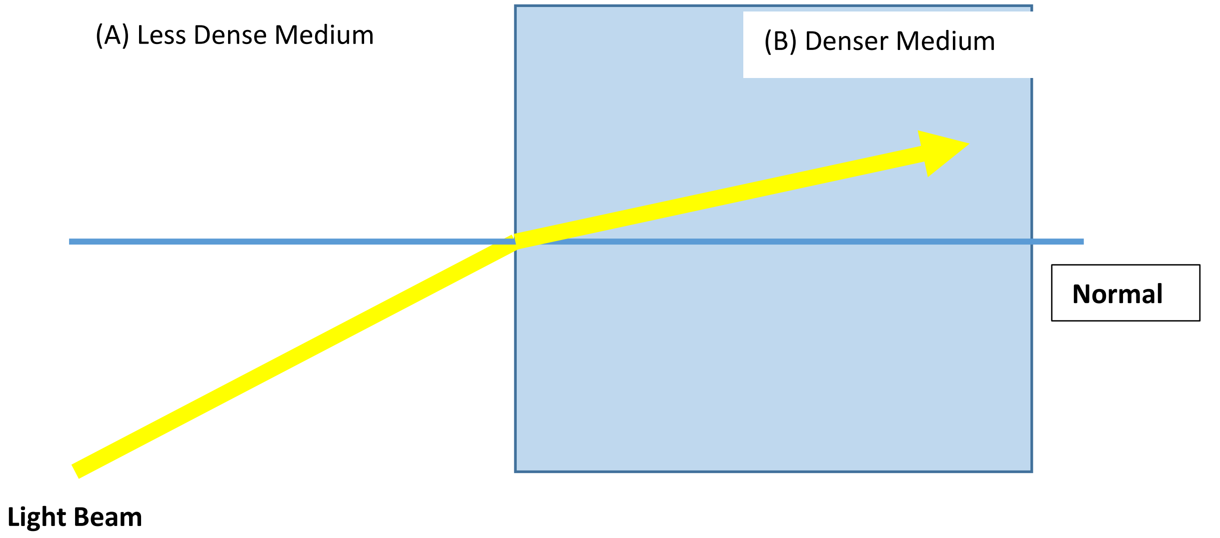
Approximately 45% of the radiation energy from the sun is within the visible light range.

Light can be reflected and refracted.

Reflection occurs when the angle of reflection equals the angle of incidence.



Refraction is the bending of a wave when it enters a medium where its speed is different. When light passes from a less dense to a denser medium, the light is refracted towards the normal.



The bending occurs because light travels more slowly in a denser medium.

White light is actually made of a whole range of colours mixed together. When visible light travels through a prism, it is separated into its different wavelengths and shows the various colours that make up visible light.

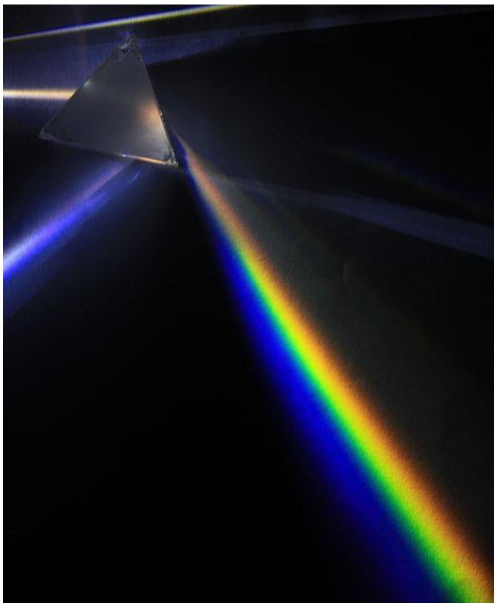


Figure 198: Separation Of Light By A Prism According To Wavelength (Image Credit: D-Kuru/Wikipedia Commons)

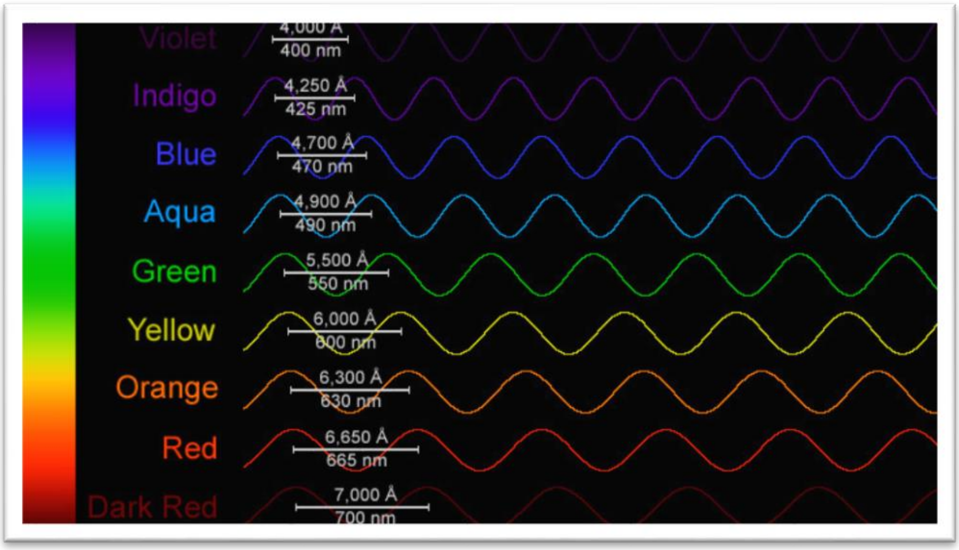


Figure 199: Waves Of Light With Different Wavelengths (Image Courtesy Of Windows To The Universe)

When light of that particular wavelength strikes the retina of our eye, we perceive that specific colour sensation.

When all the wavelengths of the visible light spectrum strike our eyes at the same time, we perceive the colour white, which is a combination of all the colours of the visible light spectrum.

Similarly, if none of the wavelengths reach our eyes, we perceive the colour black, which is merely the absence of the wavelengths within the visible light spectrum.

Chapter 21 Advantages And Disadvantages

21.1 Advantages

a. Its free

Solar energy is the most abundant natural resource available and most importantly it is completely free. No electricity is required when designing for daylighting and this energy is not likely to run out in the near future.

b. It minimises the use of artificial lighting, reduces electricity cost and lowers HVAC cost.

The main objective of daylighting is to minimise the dependency on artificial lighting. Electrical lighting accounts for 20% of the total electrical energy consumption in a commercial building. The waste heat generated by electrical lighting imposes additional heat loads on the building's mechanical cooling system. The energy savings from reduced electrical lighting through daylighting design is about 10% to 30%. Actual savings depend on several factors such as efficiency of the HVAC system, usage of building as well as the building footprint.

c. Impact on occupant comfort

Daylight regulates circadian rhythms and psychological mood. The human circadian system consists of the biological process that regulates our sleep-wake cycle. It was found that without exposure to normal 24-hour light –dark cycles, a person's sleep- wake cycle can deviate by as much as two hours a day.

The production of neurohormones regulates our patterns of alertness and sleepiness. Exposure to sunlight increases the brain's release of a hormone, serotonin, which boosts mood and helps a person stay calm and focused. At night, darker light triggers the release of melatonin, which causes drowsiness. Without sufficient exposure to daylight, a person's serotonin levels can dip and the levels of melatonin increase. This leads to a higher risk of 'Seasonal Affected Disorder' or SAD which affects a large number of people at certain times of the year due to lack of sunlight.

Exposure to sunlight has been found to increase the production of Vitamin D, which has a significant impact on bone health.

d. Humans have a natural attraction to sunlight

Studies have shown that humans have a natural attraction to sunlight as it increases occupant satisfaction and productivity. Daylight also gives the occupant a psychological value of space and a sense of security. It has been observed that a view of a natural scene through a window can relieve stress.

From the commercial aspect, studies have been conducted on malls with skylights and those without (Heschong-Mahone, 1999a; Heschong et al., 2002a). The most obvious difference apart from the skylights, was that malls with skylights had generally higher ceilings and had photo sensor control of the artificial lighting under the skylights. The higher ceiling created a general sense of space within the mall.

After dark, the appearance of all the malls were found to be similar. By day however, the illuminances under the skylights were often much higher than those provided by artificial lighting in malls without skylights. It was found that malls with skylights had a higher sales index over the duration of the opening hours than malls designed without the skylights.

Figure 200: Mall With Skylight (Image Credit: User VictoriaDFong_Wikipedia)

e. Colour rendering

Daylight is often considered the best source of light for good colour rendering as it matches human visual response most closely. Daylight will almost always have a good light spectrum, in the sense that it has a high CIE (The International Commission on Illumination) General Colour Rendering Index.

21.2 Disadvantages

a. Fluctuation In Illumination

One major disadvantage of daylighting is the large fluctuation in illumination intensity caused by movement of clouds across the sky as well as reflection from terrain and surrounding buildings. Since we are unable to control or predict the movement of clouds and the natural elements, careful consideration has to be taken to determine if a particular space is suitable for daylighting.

Spaces where light intensity is not critical are suitable for daylighting. These include staircases, corridors, toilets and lift lobbies. Such spaces are usually also equipped with photo sensors so that the artificial light can be turned on or adjusted should the lux level fall below a required level.

Figure 201: Fluctuation In Illumination Intensity

b. Undesirable Heat Gain

If not designed properly, direct sunlight falling directly incident on occupants near the window can cause thermal discomfort. It is thus important that the glazing designed for daylighting does not contribute to undesirable heat gain. If so, the added cooling load may offset any savings from the decreased lighting cost.

The following chapters will discuss how to maximise daylighting designs to ensure that energy savings achieved from reduced artificial lighting are not lost through increased cooling needs.

c. Glare

The purpose of daylighting is not only to provide sufficient illuminance levels for good performance, but also to maintain a comfortable and pleasing atmosphere. Direct sunlight penetration into a space can result if not designed properly and results in unpleasant glare.

Glare often refers to an area of intense brightness within the visual field and the difficulty in seeing in the presence of bright light. The Illuminating Engineering Society (IES) defines glare as one of two conditions: too much light, or excessive contrast, where the range of luminance in the visual field is too great.

Glare can be experienced as discomfort glare or disability glare.

Discomfort glare is glare which is distracting or uncomfortable, and can interfere with the visual perception but does not reduce the ability to see.

Disability glare is glare which reduces the ability to see and is usually caused by light scattered within the eye, decreasing contrast and reducing visibility.

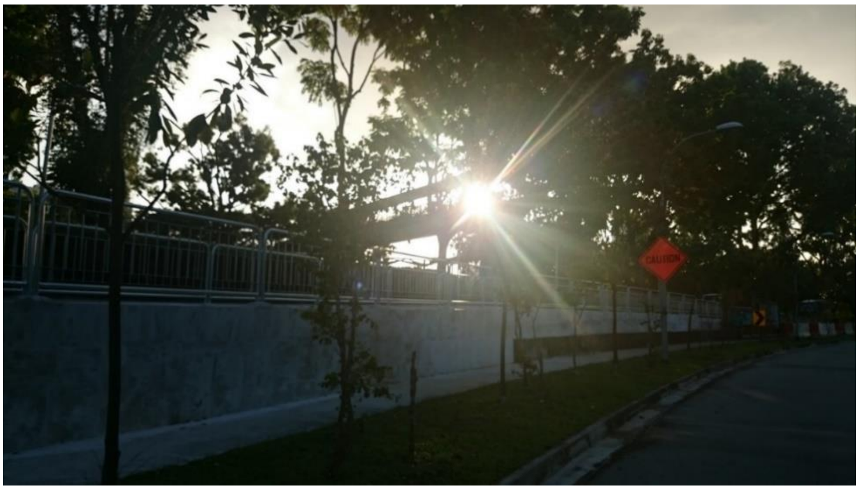


Figure 202: Example Of Glare: Excessive Contrast

The human eye is able to perceive light levels of less than 1 lux (equivalent to starlight) to more than 100,000 lux (equivalent to a sunny day). The eye can however only adapt to a small part of this range at one time and takes a few moments to adapt whenever the range changes. This is apparent when you enter a dark tunnel on a sunny day and you are temporarily blinded as your eyes are already adapted to the daylight. As you leave the tunnel, the external daylight is temporarily glaring.

The susceptibility to glare is thus dependent on the ability of the eye to adapt. The darker the surroundings that you have adapted to, the more likely you are to experience glare from a light source.

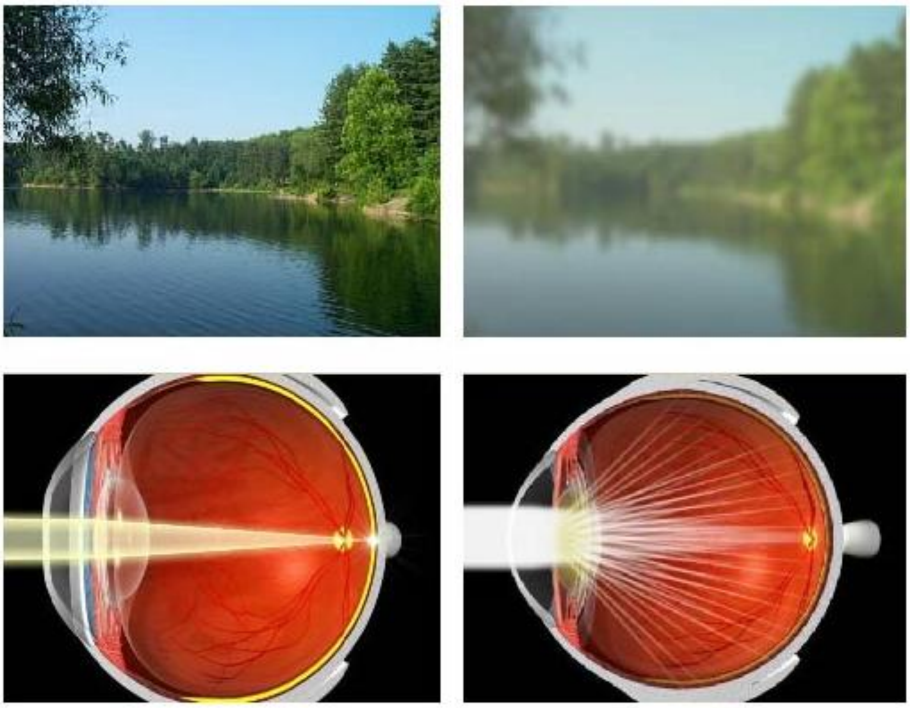


Figure 203: Human Eye, Glare (Image Credit: http://kaushalgrade10optics.wikispaces.com/Cataracts#cite_note-2)

From Figure 203 above, when light ray is able to focus through the lens onto the retina, a sharp image is formed. In the instance of glare, too much light enters the lens instantaneously and the image on the retina appears blurry until the eye is able to adjust the lens or the iris to adapt to the new environment.

Glare is hard to measure as perceived light is subjective and dependent on many factors, including the age of a person. The baseline used to assess glare is the luminance within the individual's field of vision measured at a specific vantage point (cd/m^2). This is the amount of light reflected off a surface into the viewer's eye.

Good daylighting design is thus required to reduce discomfort glare from windows. This often involves considering the overall form and orientation of the building, or the use of external shading devices.

The Unified Glare Rating (UGR) is widely used as a general assessment of glare. The formula is given below:

$$UGR = 8\log\left[\frac{0.25}{L_b}\sum\left(\frac{L^2\omega}{p^2}\right)\right]$$

Where

L_b is the background luminance

L is the luminance of the luminaire

P is the Guth index, which increases the further the luminaire is from the viewer's line of sight

ω is the Solid angle of the light-emitting surface of each light relative to the observer's eye

Thus, from the formula, it can be seen that glare increases with a stronger light source and lower background light. Similarly, as the source moves further from the line of sight, glare as measured by the UGR decreases.

Some points to note:

- UGR < 10 is considered insignificant and can be ignored
- UGR > 30 is considered excessive and might cause discomfort

Chapter 22: Design Parameters

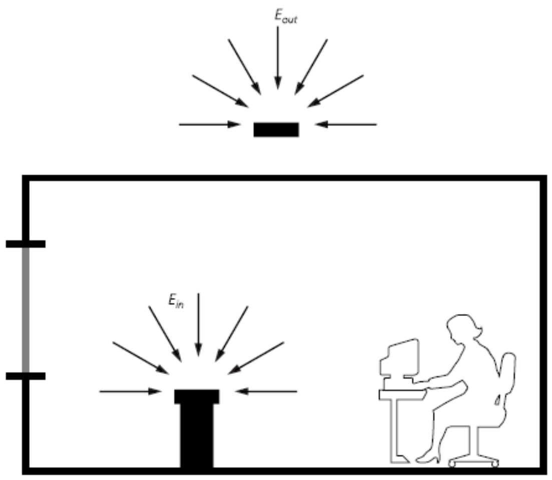
Design parameters vary with the building applications and can be used to determine the most suitable system to be used to achieve the design objective. Parameters include visual performance and comfort, usage of the building and the integration with the building system. The primary objective of daylighting design should be to provide usable daylight for the specific building type, which allows natural daylight to offset the dependence on artificial lighting.

Design solutions should aim to maximise the usage of usable daylight in climates with predominately overcast skies; reduce exterior obstructions to increase usable daylight and transport usable daylight deeper into a given space or into windowless spaces.

22.1 Daylight Factor

Daylight factor (DF) is a measure of the amount of natural light in a space. It quantifies the amount of light at a particular point relative to the instantaneous amount of daylight available outside.

Daylight factor is defined as the ratio of the interior illuminance to the horizontal illuminance under a standard overcast sky condition. It is expressed as a percentage; the higher the daylight factor, the more natural light is available in the space.



Daylight factor can be expressed as:

$$DF = \frac{E_i}{E_0} X100 \ (\%)$$

Where

- E_i = illuminance due to daylight at a point on the indoors working plane
- E_0 = simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky

Therefore, a DF of 4 % means that the indoor light is 4% of the available outside daylight.

SS531: Part 1

Below is an extract from SS531: Part 1 on Daylighting requirements:

Daylight may provide all or part of the lighting for visual tasks.

Daylight varies in level and spectral composition with time and therefore provides variability within an interior. Daylight may create a specific modelling and luminance distribution due to its nearly horizontal flow from side windows. Daylight can also be provided by roof lights and other fenestration elements.

Windows can also provide a visual contact with the outside world, which is preferred by most people. Avoid excessive contrast and thermal discomfort caused by direct sunlight in work areas. Provide adequate sun control such as blinds and shades, so that direct sunlight does not hit workers and/or surfaces within their field of view.

In interiors with side windows, the available daylight decreases rapidly with distance from the window. In these interiors, the daylight factor should not fall below 1% on the working plane 3m from the window wall and 1m from side walls. Supplementary lighting should be provided to achieve the required illuminance at the work place and to balance the luminance distribution within the room. Automatic or manual switching and/or dimming can be used to ensure appropriate integration between artificial lighting and daylight.

22.2 Green Mark

Extracts of the Daylighting requirements from the BCA Green Mark Residential and Non-Residential criteria can be found below

22.2.1 BCA Green Mark –Residential Criteria Version 4.1

<table>
<tr>
<td>

<u>**RB 1-3 Daylighting**</u>

Encourage design that optimises the use of effective daylighting to reduce energy use for artificial lighting.

(a) Use of daylight and glare simulation analysis to verify the adequacy of ambient lighting levels in all dwelling unit's living and dining areas. The ambient lighting levels should meet the illuminance level and Unified Glare Rating (UGR) stated in SS CP 38 – Code of Practice for Artificial lighting in Buildings and SS 531:Part 1:2006 – Code of Practice for Lighting of Work Places.

</td>
<td>

Extent of coverage: At least 80% of the units with daylighting provisions meet the minimum illuminance level and are within the acceptable glare exposure.

Points scored based on the extent of perimeter daylight zones

Distance from the Façade Perimeters (m)	Points Allocation
≥ 3.0	1
4.0 – 5.0	2
> 5.0	3

(Up to 3 points)

</td>
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<td>

(b) Daylighting in the following common areas :

(i) Lift lobbies and corridors
(ii) Staircases
(iii) Car parks

</td>
<td>

Extent of Coverage : At least 80% of the applicable areas
1 point
1 point
1 point

</td>
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</table>

22.2.2 BCA Green Mark – Non- Residential Criteria Version 4.1

<table>
<tr>
<td>

<u>**NRB 1-5 Daylighting**</u>

Encourage design that optimises the use of effective daylighting to reduce energy use for artificial lighting.

(a) Use of daylighting and glare simulation analysis to verify the adequacy of ambient lighting levels in meeting the illuminance level and Unified Glare Rating (UGR) stated in SS 531:Part 1:2006 – Code of Practice for Lighting of Work Places.

</td>
<td>

Extent of coverage: At least 75% of the units with daylighting provisions meet the minimum illuminance level and are within the acceptable glare exposure.

Points scored based on the extent of perimeter daylight zones

Distance from the Façade Perimeters (m)	Points Allocation
≥ 3.0	1
4.0 – 5.0	2
> 5.0	3

(Up to 3 points)

</td>
</tr>
<tr>
<td>

(b) Daylighting for the following common areas:

(i) Toilets
(ii) Staircases
(iii) Corridors
(iv) Lift Lobbies
(v) Atriums
(vi) Carparks

Note (5) : All daylit areas must be integrated with automatic electric lighting control system.

</td>
<td>

Extent of Coverage : At least 80 % of each applicable area

0.5 point each

(Up to 3 points)

</td>
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</table>

*It should be noted that the various Green Mark criteria mentioned are the prevailing criteria at the time of writing

22.3 LEED

Below are extracts of daylighting from the LEED Green Building Rating system Version 2.1

Credit 8.1

EQ Credit 8.1: Daylight & Views: Daylight 75% of Spaces
1 Point

Intent

Provide for the building occupants a connection between indoor spaces and the outdoors through the introduction of daylight and views into the regularly occupied areas of the building.

Achieve a minimum Daylight factor of 2% in 75% of all space occupied for critical visual tasks. Spaces such as storage areas, mechanical plant rooms, laundry and other low occupancy support areas are excluded from this requirement

EQ Credit 8.2: Daylight & Views: Views for 90% of Spaces
1 Point

Chapter 23: Design Principles

23.1 Types Of Skies

a. Uniform Sky

   Characterised by a uniform luminance that does not change with altitude or azimuth. Used from days when calculations were done by hand or tables and of Right of Light cases.

b. Overcast Sky

   Changes with altitude. Three times as bright in the zenith as it is near the horizon. Used when measuring daylight factors.

b. Clear Sky

   Luminance varies over both altitude and azimuth. Brightest around the sun and dimmest opposite. Brightness of the horizon lies in between these extremes.

c. Intermediate Sky

   Somewhat hazy variant of clear sky. Sky is not as bright as the clear sky and the brightness changes are not as drastic.

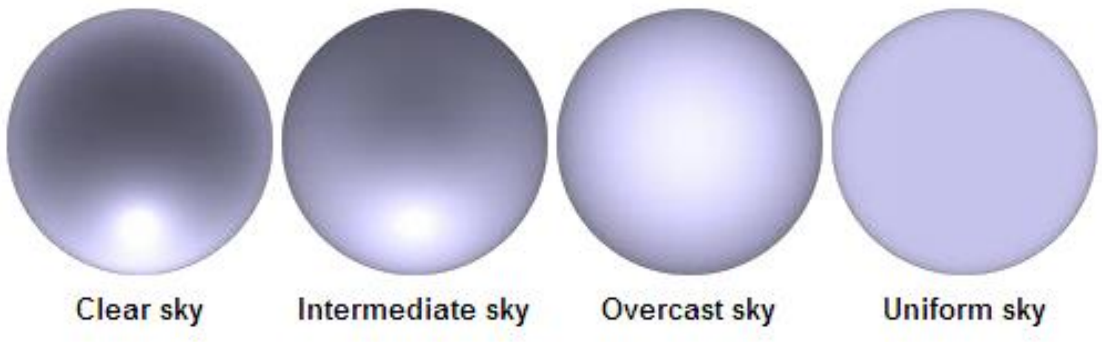


Figure 204: Types Of Sky (CIE) (Credit: Comfortable Low Energy Architecture)

The CIE standard Overcast Sky is used to assume the luminance distribution of the sky when determining the minimum contribution of daylight to an interior. This assumption does not take into account sunlight.

23.2 Components Of Daylight

Daylight consists of the following components:

a) Direct Sun
b) Direct Sky
c) Externally Reflected
d) Internally Reflected

The Direct Sun and Direct Sky are light that reaches the measurement point directly from the sky. The externally reflected component is daylight that reaches the measurement point after reflection outside the room, either from natural or man-made structures. The internally reflected component is daylight that arrives at the measurement point after reflection inside the room.

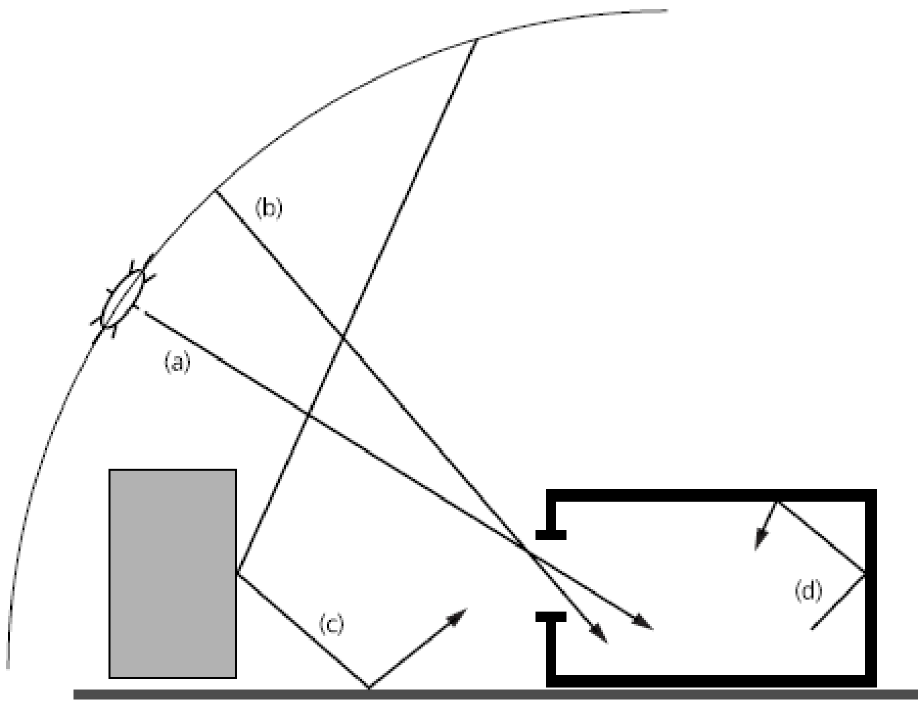


Figure 205: Components Of Daylight

Chapter 24. Design Tools

24.1 Heliodon

The Heliodon is a sun simulator that imitates the sun passing across a sky-dome, with the model being fixed on a horizontal ground plane. The larger the Heliodon, the more accurate the simulation will be as the light rays reaching the model will be parallel.

The Heliodon's size is also its greatest disadvantage, since a larger space is required for a larger Heliodon.

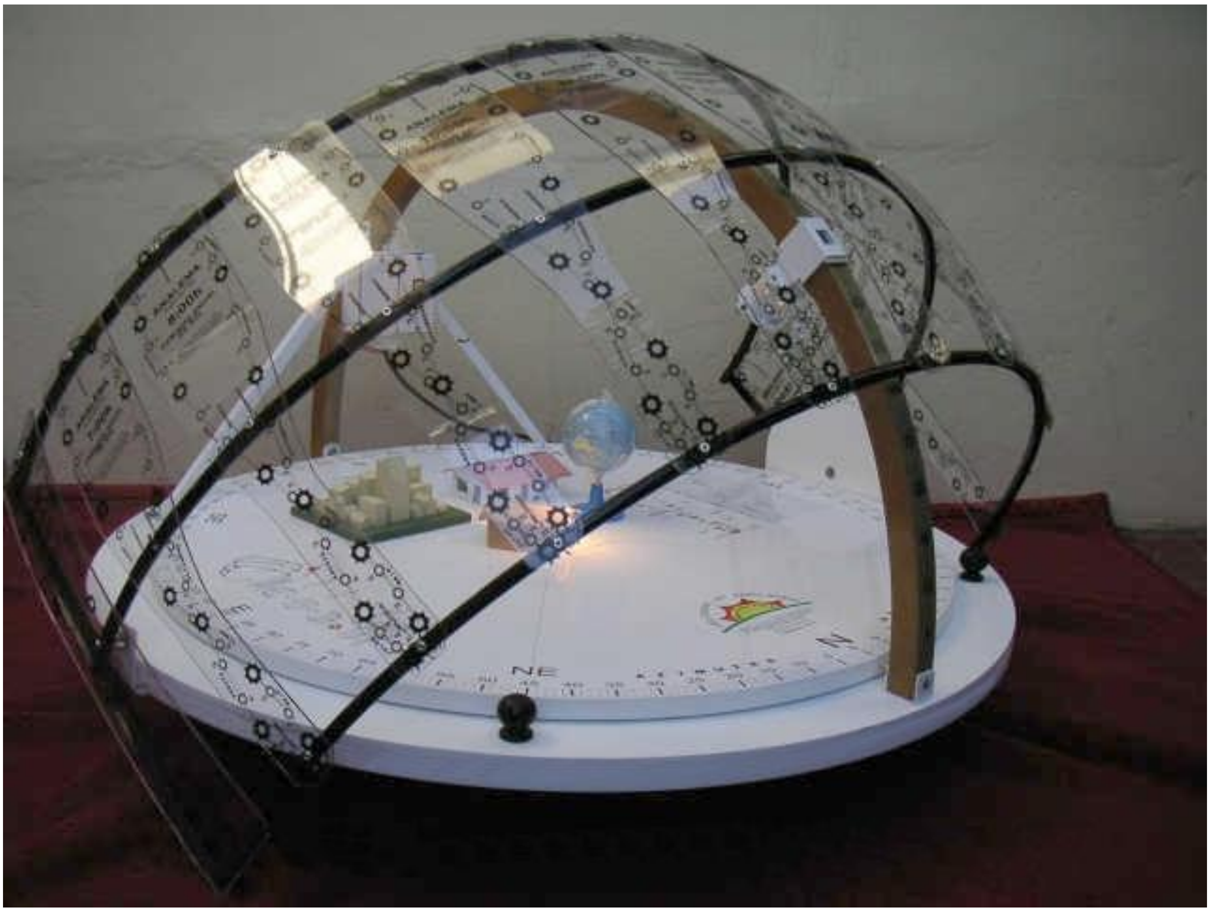


Figure 206: Heliodon (Image Credit: Jbarta _Wikipedia)

24.2 Artificial Sky

An artificial sky allows the testing of scaled models under simulated standard CIE overcast sky conditions. The daylighting performance of the proposed model can then be determined and fine-tuned. The daylight factors can be measured with special multiple lux meters for optimisation of daylighting. These are however expensive to set up and maintain and are being replaced by computer models.

Figure 207: Box Shaped Artificial Sky (Image Credit Vashon Baker)

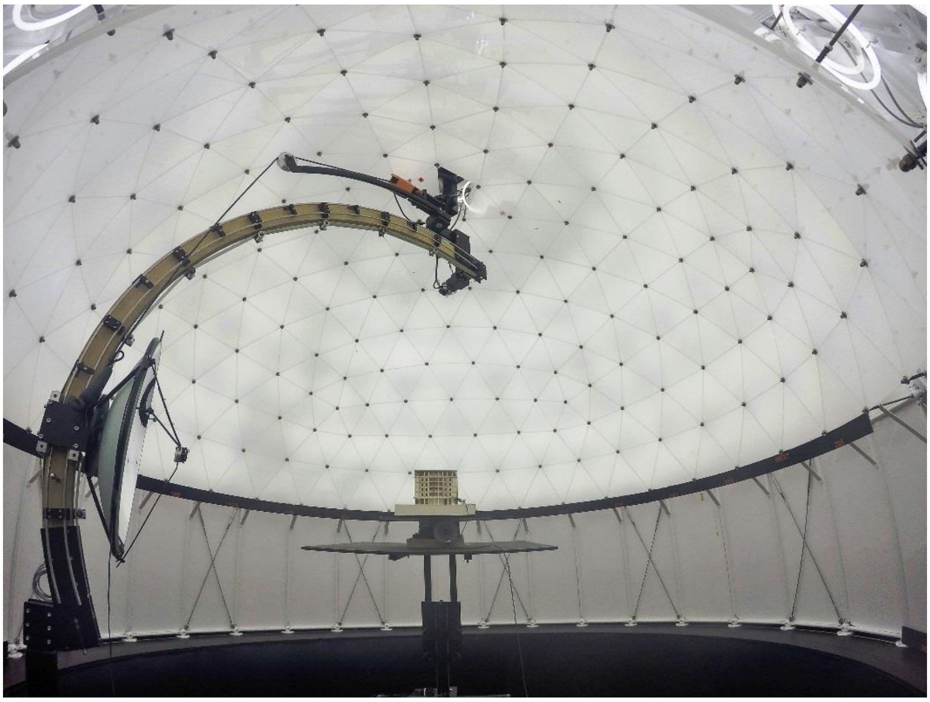


Figure 208: Artificial Sky Lab (Image Credit: User Vu K Hoang_Wikipedia)

24.3 Computer Modelling

With the advancement in technology and graphics techniques, computer simulations are more commonly used to predict daylighting levels as well as solar insolation. The software allows the accurate modelling of interiors to produce realistic images and quantified photometric output.

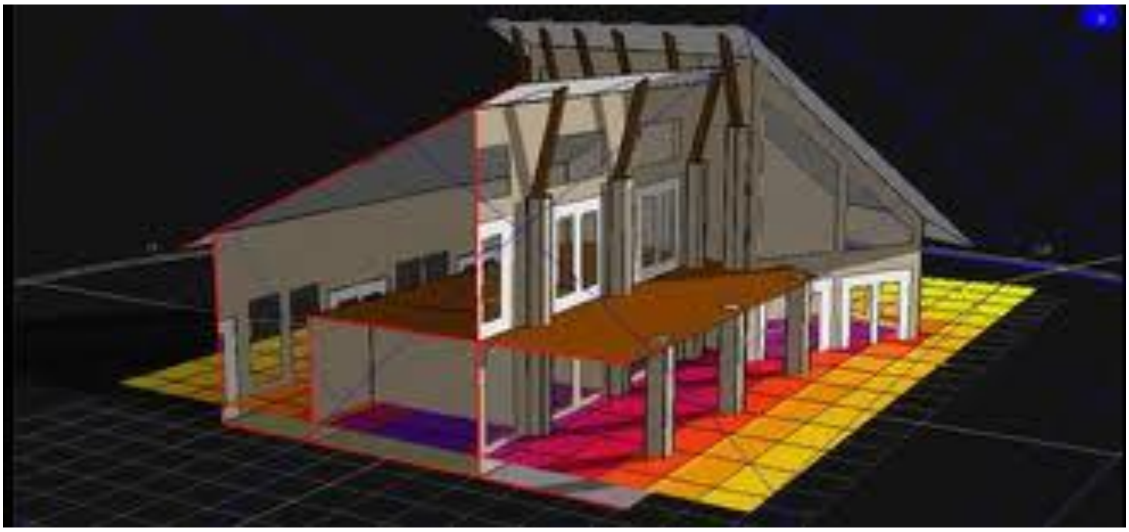


Figure 209: Daylight Simulation Of House In Ecotect

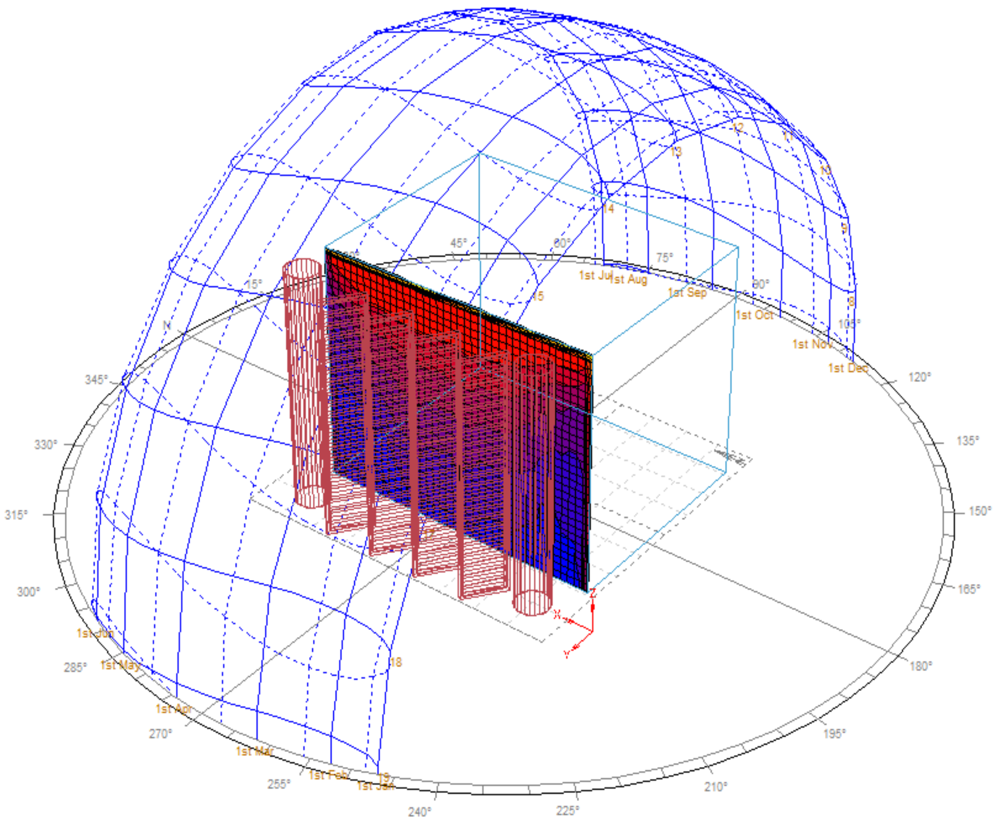


Figure 210: Image Showing Solar Insolation Simulation

Chapter 25: Design Concept

25.1 Overview

Daylighting concepts involve the integration of the different disciplines of design. Daylighting design should be integrated early in the design process to ensure that concepts and ideas are carried out throughout the project.

The amount of daylight that penetrates a space depends on the window orientation, size and glazing characteristics.

25.2 Daylight Penetration

The two factors that quantify daylight penetration are the amount and distance of daylight.

The amount of daylight that penetrates a space depends on the window orientation, size and glazing properties. The distance that adequate daylight penetrates a room depends on the window location and interior surfaces.

Typical adequate daylight should penetrate about one and a half times the height of the window head.

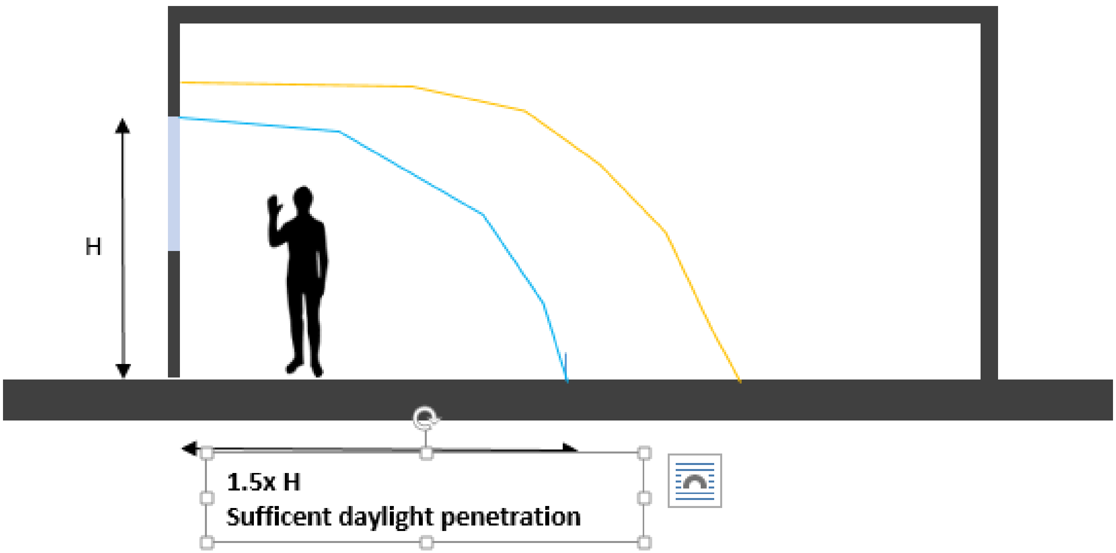


Figure 211: Adequate Daylight Penetration

22.3.1 Light Shelves

The use of light shelves can increase the depth of penetration into a given space and are most suitable for spaces with higher than average floor-to-ceiling height.

A light shelf is a horizontal element designed to shade and reflect light on its top surface and shield direct glare from the sky. It is usually mounted horizontally on either side of the window above eye height. The lower the height of the window, the greater amount of light is reflected onto the internal ceiling.

Depending on the length of the light shelf, the depth of penetration can be increased to about two and a half times the window height.

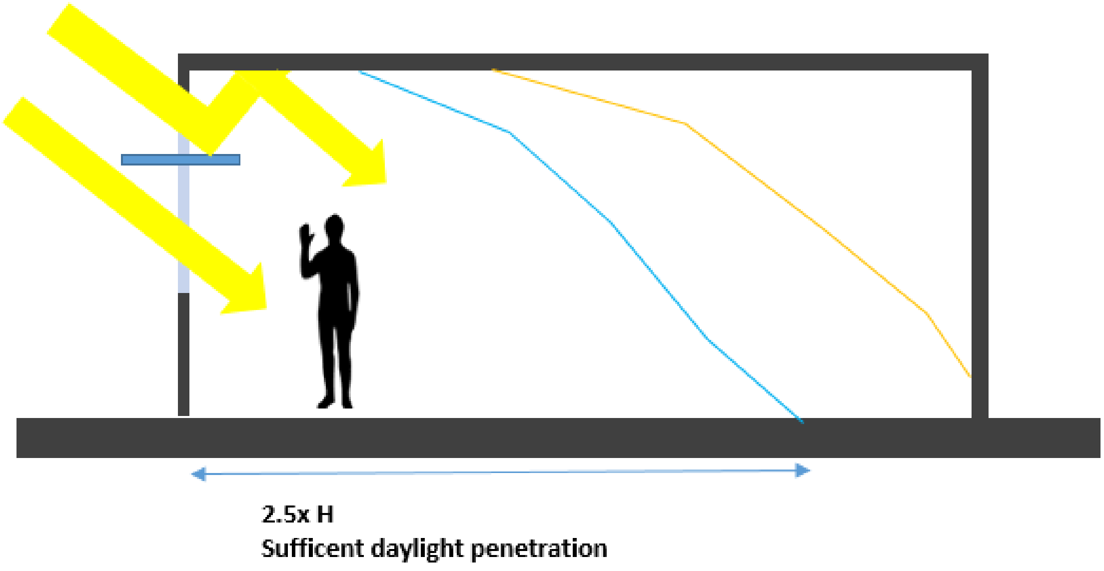


Figure 212: Increase Depth Of Penetration From Light Shelves

Light shelves can be mounted on the interior or exterior. Compared to those installed at the exterior, light shelves on the interior reduce the amount of light brought into the space; however the light distribution is more even.

For best results, light shelves should be mounted horizontally and the surface of the shelf should be highly reflective. The surface can also be painted with a rougher, less mirror-like finish to diffuse the spread of the incoming sunlight. Similarly, the ceiling should also be painted with a light coloured reflective paint to allow the light to reflect further into the internal space.

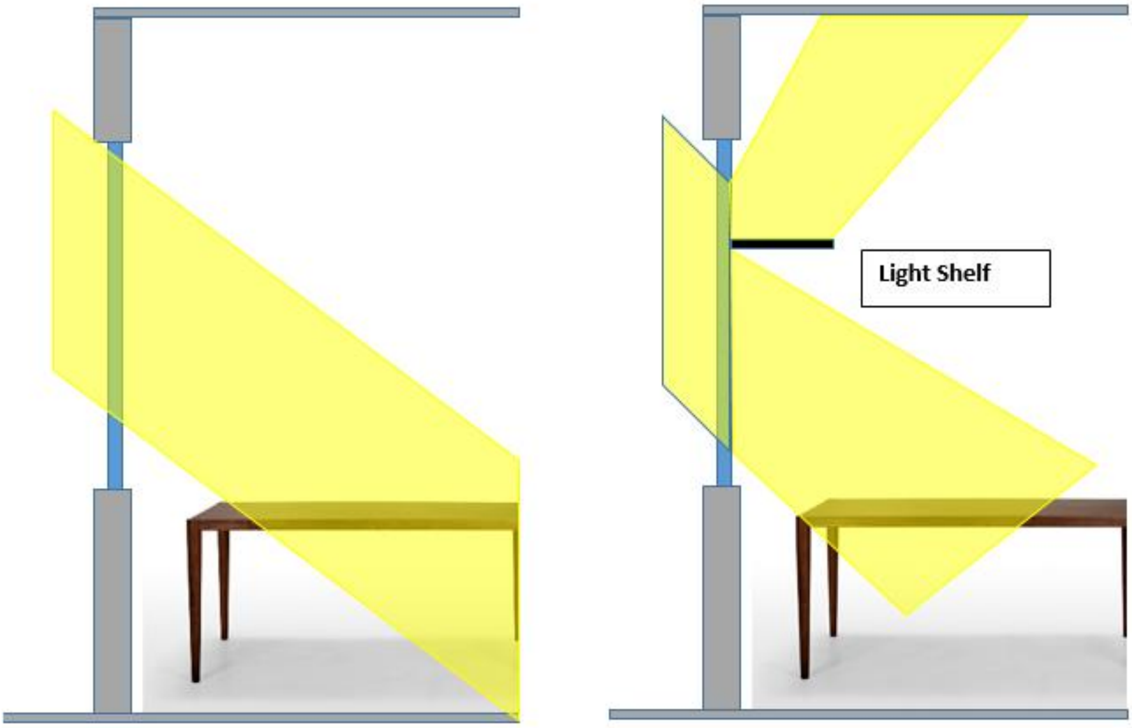


Figure 213: Reduction Of Glare

For workspaces along the building perimeter, light shelves are able to reduce the effect of glare by directing the incoming light upwards towards the ceiling.

Light shelves can be constructed of any material, not necessarily metallic. Factors such as construction cost, structural strength, ease of maintenance and aesthetics should be taken into account when designing light shelves.

25.3 Building Orientation

To maximise the advantage from daylighting design, buildings should be orientated to take advantage of the sun's path throughout the day, and seasonal variations if any. A sun path diagram allows the designers to strategically place openings to admit usable daylighting and at the same time minimise low angle direct sunlight entering a space.

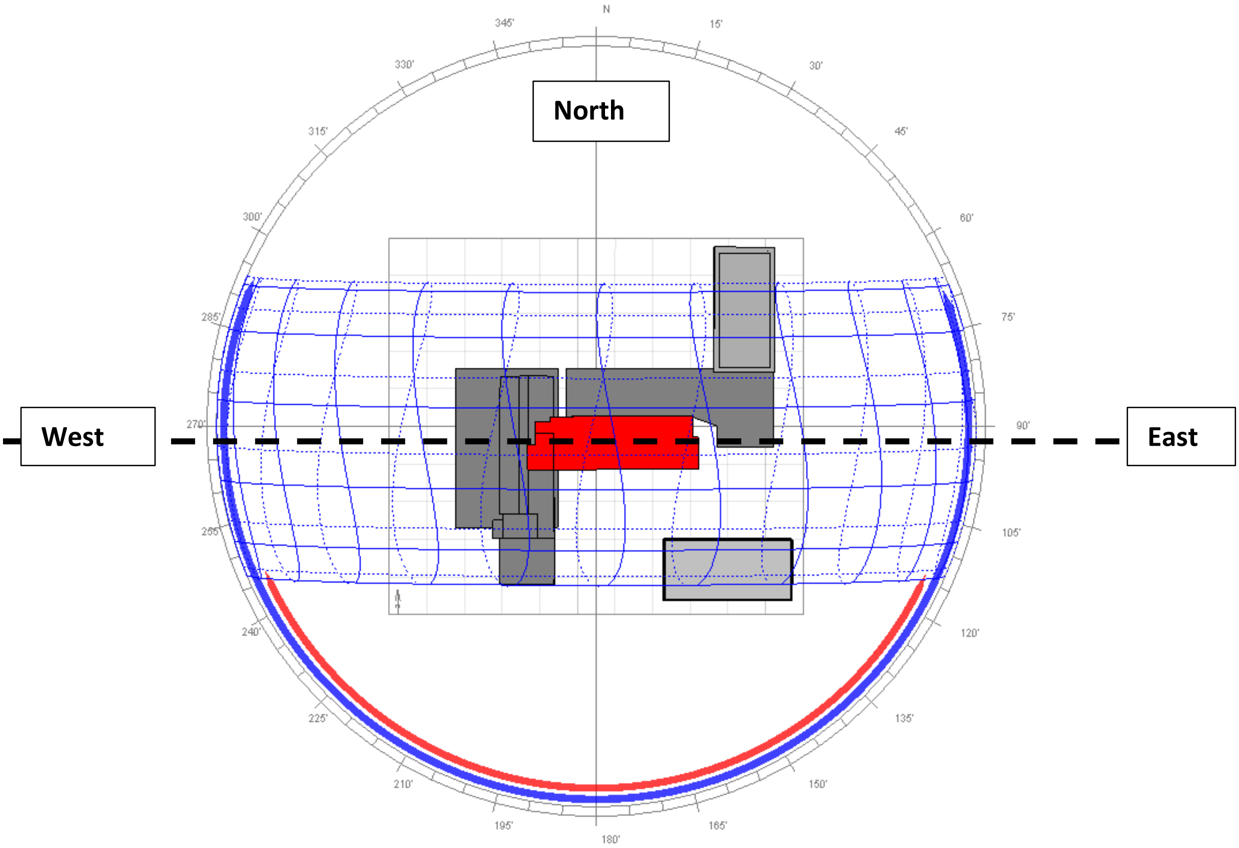


Figure 214: Annual Sun Path Diagram Of Singapore

For optimum daylight potential, the building should have their long axes running east and west, instead of north-south. This orientation allows daylight to be harnessed consistently and control glare along the long faces of the building. The glare from the rising and setting sun is also minimised.

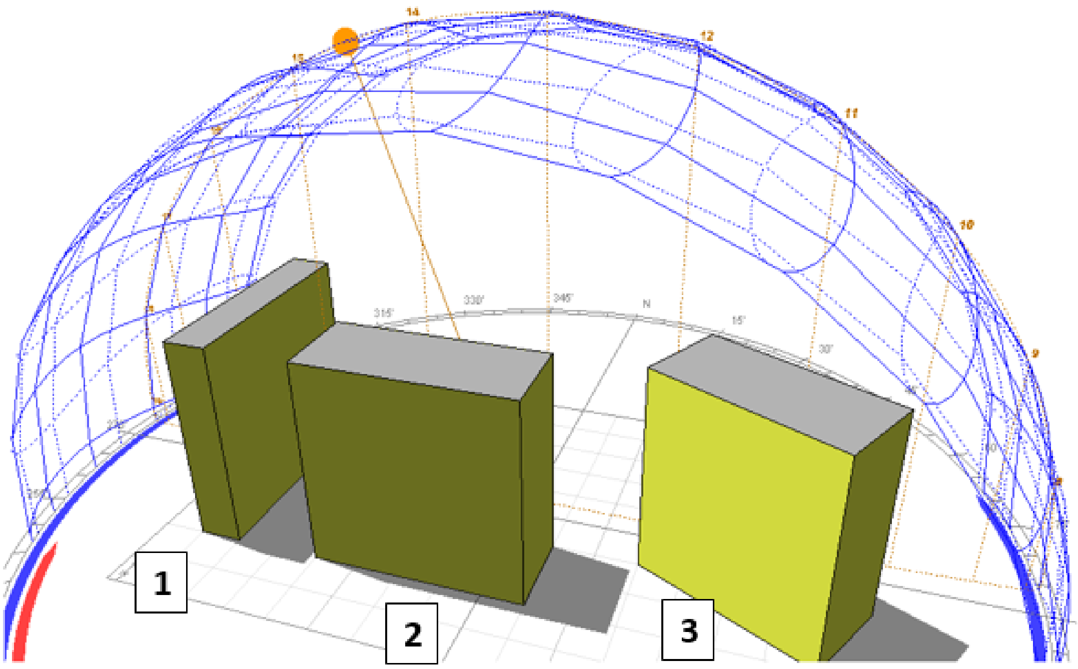


Figure 215: Massing For Visual Comfort

From Figure 215 above, it can be seen that orientation #1 is the worst for daylighting, followed by orientation #3, with orientation #2 having the best orientation.

While single storey buildings can easily achieve good daylighting by maximising window openings and by the use of skylights, these buildings are not the best use of land. For larger and taller buildings, good daylighting design can be a challenge. These buildings can optimise their daylighting potential from side windows by having thinner profiles. Large buildings can also increase daylighting into more spaces by having central courtyards or atria, or having building forms that increase the perimeter footprint.

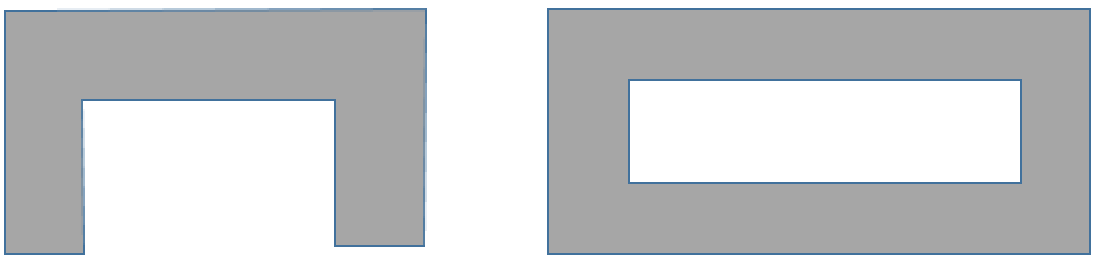


Figure 216: Building Footprints With Good Daylighting

25.4 Window Orientation

Window orientation is largely dependent on the building orientation and Sun path. The greatest amount of solar energy received through a window is when the sun is perpendicular to the window and about 30 to 35 degrees above the horizon.

In Singapore's context, our Sun path deviates little along the east and west axis. It is thus advantageous to maximise window openings along the north and south façades. The diffused light from the north and south façade will provide sufficient illuminance for interior lighting needs while reducing solar heat gain.

Windows at the eastern and western façade should be minimised as these are where the sun angle is the lowest and most likely to cause glare and excessive solar heat gain. Sunshades can be added at these directions to minimise discomfort.

25.5 Window Performance

25.5.1 Solar Heat Gain

The Solar Heat Gain Coefficient (SHGC) measures the amount of solar energy through a window. The SHGC can be measured for the entire window unit, including the frames, or for just the glazed area. The higher the SHGC, the more solar energy is collected by the window. Windows should have a lower SHGC to reduce heat gain from solar energy.

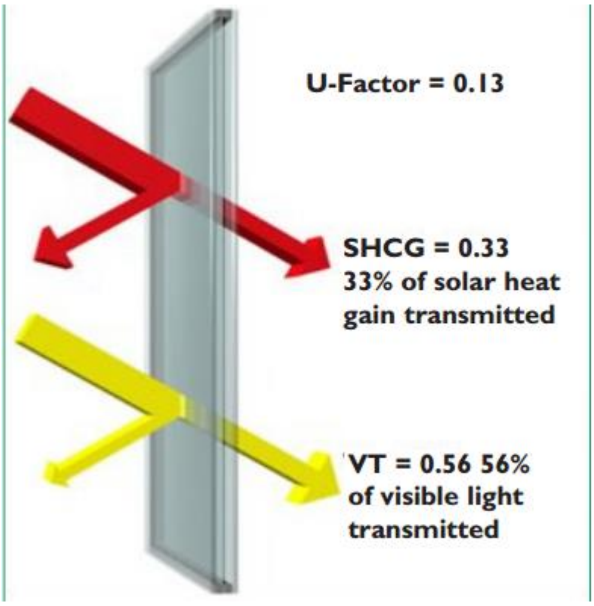


Figure 217: Solar Heat Gain (Source: Efficient Windows Collaborative)

25.5.2 Glazing

Glazing is an important element for daylighting and the simplest method to maximise daylight within a space is to increase the glazing area. However, three characteristics of glass need to be understood in order to optimise a fenestration system:

a) U-Value: represents the rate of heat transfer due to temperature difference through a particular glazing material. The lower the U-value, the greater a glazing’s resistance to heat flow and the better its insulating property.

b) Shading Coefficient (SC): a ratio of solar heat gain of a given glazing assembly compared to double-strength, single glazing. It is a measure of how well a glazing lowers solar heat gain from the sun. The shading coefficient is the percentage of the incident solar radiation (both directly transmitted and absorbed) admitted through a window, and subsequently released to the interior. It is expressed as a number between 0 and 1. A lower value represents less solar heat transmitted and thus better performance.

c) Visible Transmittance (VT): a measure of how much visible light is transmitted through a given glazing material. It is expressed as a number between 0 and 1; the higher the number, the more light is transmitted.

A high-performance glazing system will admit more light and less heat than a typical system.

The performance of a glazing material is often compared against a single pane of clear glass, which will admit the most visible solar radiation, some infrared radiation and little ultraviolet radiation.

Glazing materials can be altered to increase both thermal and optical performance. Glazing manufacturers have a wide variety of tints, metallic and low-emissivity coatings, and fittings available in their range of products. Other options include multi-paned glass panels filled with air or other inert gases such as argon or krypton to improve U-values.

For effective daylighting in large buildings, the use of glass with moderate-to-low shading coefficient and relatively high visible transmittance should be considered.

25.5.3 Switchable Glazing

Recent developments in glazing technology include glazing materials that can vary their optical or solar properties according to the external stimuli such as light (photochromic), heat (thermochromic) or electric current (electrochromic)

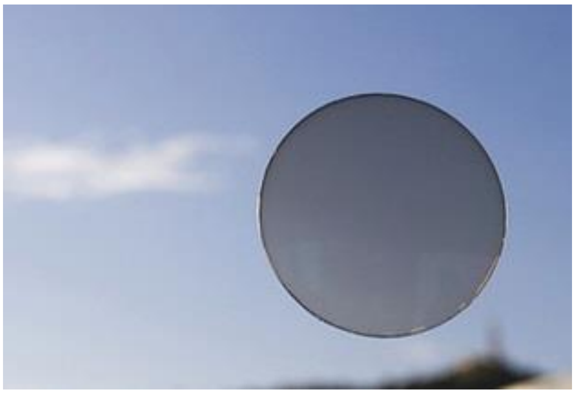


Figure 218: Photochromic Glass

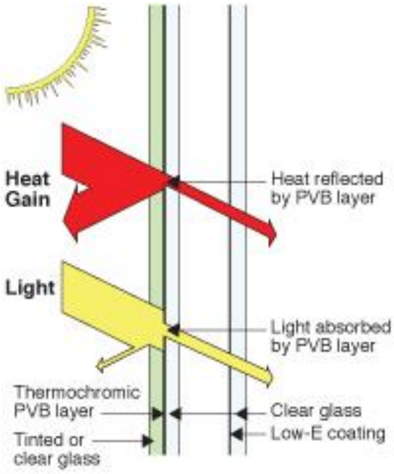


Figure 219: Diagram Of Thermochromic Film (Image Credit Commercial Windows)

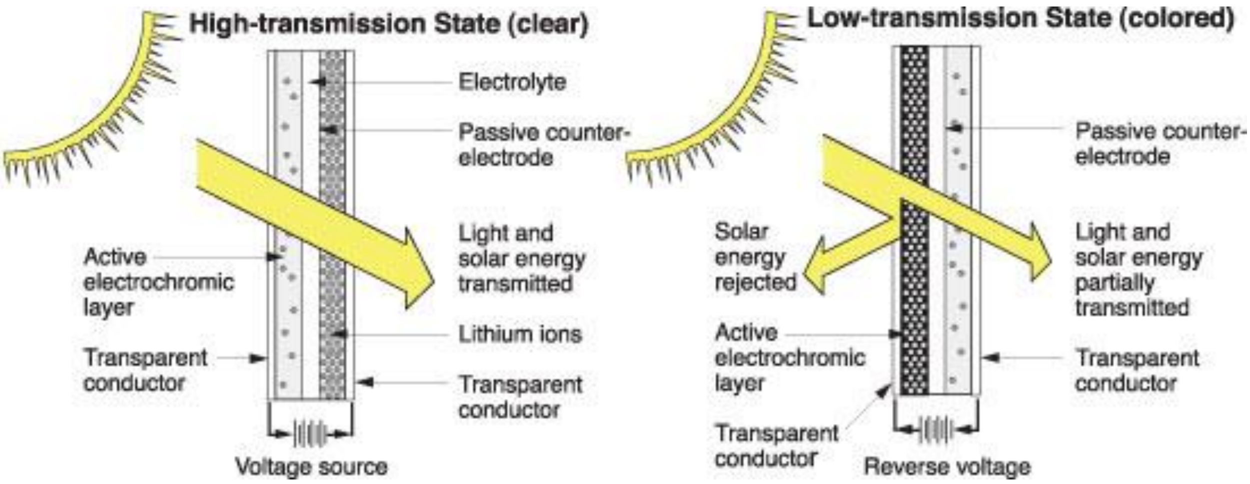


Figure 220: Diagram Of Electrochromic Coating (Image Credit: Commercial Windows)

25.6 Skylight

Skylights can provide satisfactory lighting for spaces that can tolerate large variations in illumination levels. The major advantage of skylights is the ideal colour rendition of daylight. Skylights have a positive effect on retailing, restaurants and public areas, providing a sense of natural ambience. The major disadvantage is the large fluctuation in illumination intensity that cannot be controlled, and this often results in annoyance. Spaces such as offices, classrooms are thus not suitable for skylight applications.

Skylights should be installed at a high place to allow for daylight penetration and reduce the likelihood of excessive brightness. It is better to have a large number of smaller skylights as this would allow better distribution of light, less modification to the roof structure as well as avoiding leakage problems.

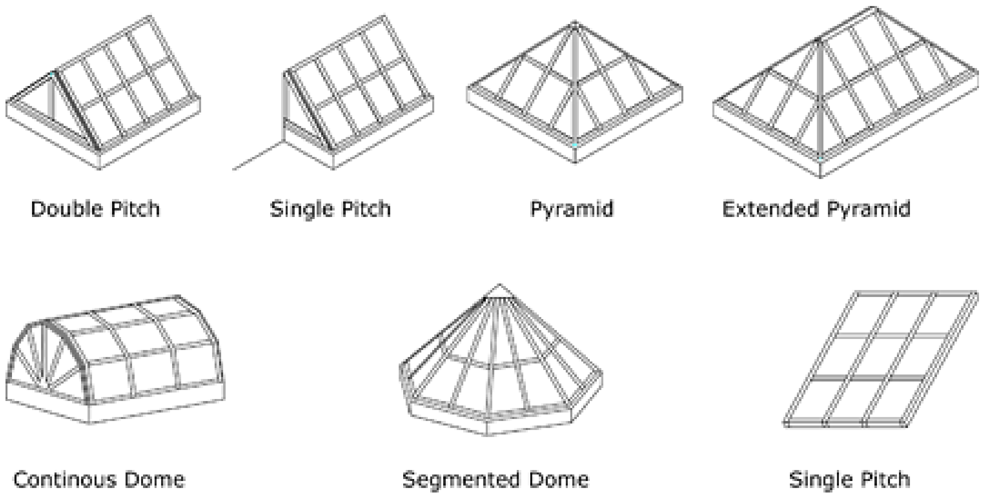


Figure 221: Skylight Designs (Image Credit: Unicel Architectural)

25.7 Diffusion

Direct sunlight is usually not suitable for daylighting as it results in localised bright spots. Diffusion of the direct sunlight minimises the changes in illumination intensity caused by the motion of the sun.

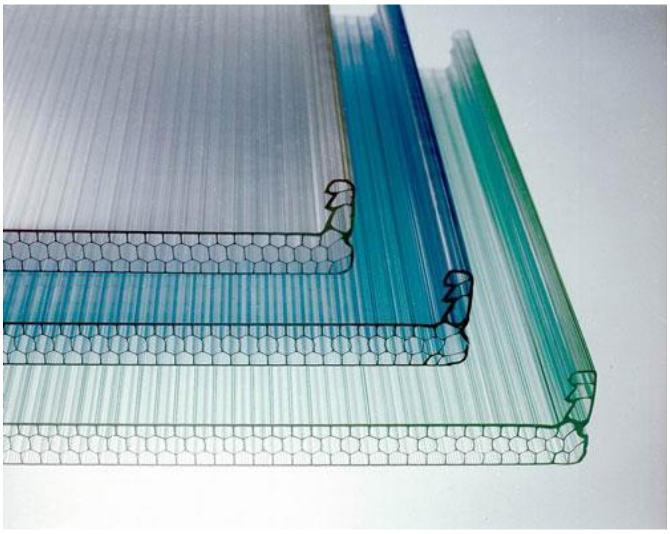


Figure 222: Materials To Diffuse Direct Sunlight

25.8 Skylight Material

Skylights are commonly made from glass, glass composites, plastics and plastic composites. All these materials can be treated to reduce light transmission and heat load.

The advantages and disadvantages of glass and plastic are summarised in the tables below:

Table 9: Glass As Skylight Material

Advantages	Disadvantages
Unlimited life	Vulnerability to breakage
High light transmission	Weight
Hard, rigid	
Can be coated to reduce UV	

Table 10: Plastic As Skylight Material

Advantages	Disadvantages
Light weight	Buckling with age
Resistant to shattering	Strength deteriorates with age
Easily moulded to reduce water leakage	Reduction in light transmission due to UV light, heat , oxidation
Can be reinforced with fibres to diffuse light	

25.9 External Shading Devices

A good shading system will permit lower levels of artificial illumination to be specified, because the eye can accommodate itself without strain to function within a wide illumination range.

External shading devices are effective at controlling solar gain. Interior window shading will allow much of the solar energy into the building and will allow more heat to enter the building. Light –coloured interior shading will reflect some of this energy back through the window.

Interior shading is most effective at controlling glare. It has the ability to be controlled to suit the tolerances of the occupants.

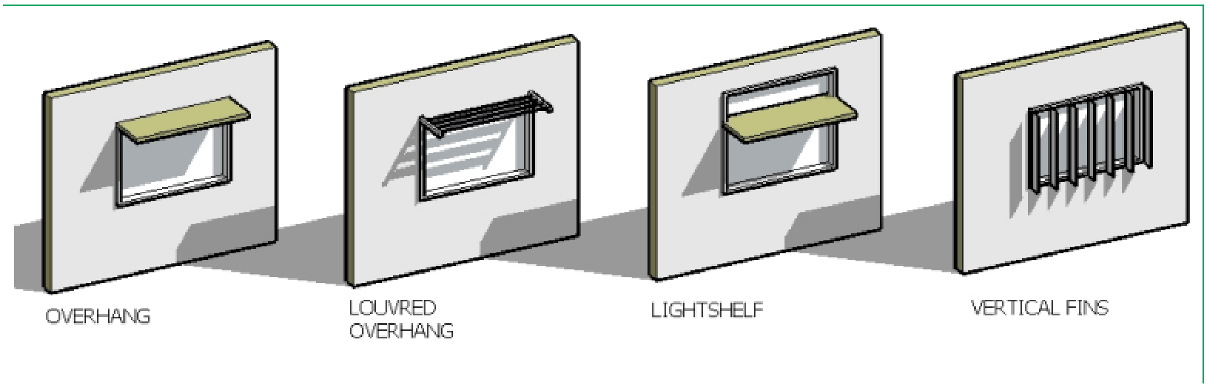


Figure 223: External Shading Devices

25.10 Light Transport Systems

These light transport systems collect and transport sunlight over long distances to the core of the building via light pipes or fibre –optics

25.10.1 Light Pipes

Light pipes allow the transport of daylight through thick roof structures and attics. They are also easier to retrofit as compared to a skylight. The collection area is however smaller for practical reasons

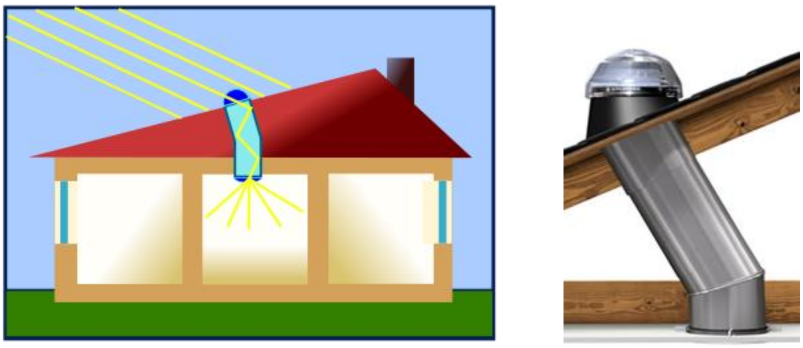


Figure 224: Light Pipes (Image Credit: https://commons.wikimedia.org/wiki/File:Sonnenrohr.svg)

Chapter 26: Controlling Lighting

It is desirable to control both artificial lighting within a space as well as the daylight entering it. This allows the user to minimise the usage of electricity for artificial lighting, benefit from the usage of daylight while maintaining the required level of illuminance.

26.1 Controlling Daylighting

The primary control of daylighting should be made by choice of window size and position. The daylight transmittance of the glazing then determines the maximum light that can be received in the room.

26.1.1 Manual Control

Manual control over the quantity and quality of daylight in the rooms can be provided either by simple diffusing curtains or venetian blinds, or by more sophisticated light redirecting systems. The latter aims to optimise the quantity and quality of the incident natural light and thus the avoidance of glare.

26.1.2 Automatic Systems

Automatic systems can perform a wide range of control actions. They can tilt or turn horizontal / vertical lamellae, lower or raise curtains and rotate sun-tracking systems. Many of these systems do not respond to overall daylight availability, but respond only to the direct sunlight or solar position. The heliostat shown in figure 225 is based on solar position.

Figure 225: Mirror Heliostat (Image Credit: Comfortable Low Energy Architecture, Bartenbach Lichtlabor, Austria)

Daylight responsive daylighting control systems consist of a sensor to measure incident flux, and a control system acting according to the sensor's signal. An example of such system is the fibre optics system

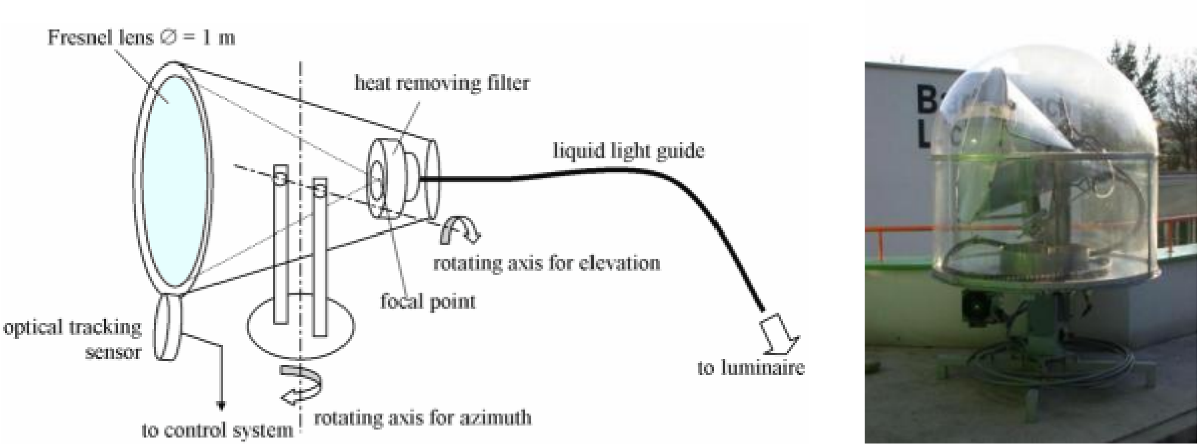


Figure 226: Fibre-Optic System

26.1.3 Case Study: Changi Airport Terminal 3

The Singapore Changi Airport Terminal 3 has a roof consisting of 919 skylights which allow daylight into the terminal building. Direct sunlight is limited by the louvres suspended below the skylight, thus flooding the terminal with diffused, ambient light.

Figure 227: Daylighting System In Changi Airport Terminal 3

Each skylight has its own shading system comprising 2 aluminium panels aligned like butterfly wings. The aluminum reflectors ensure that maximum daylight is reflected to the terminal below.

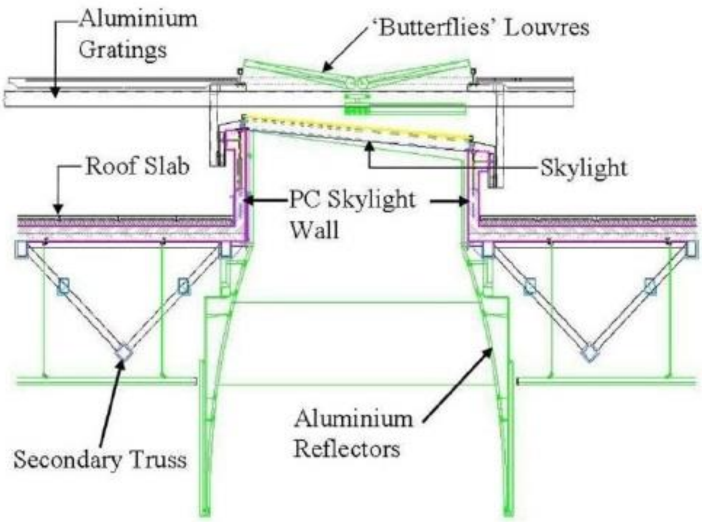


Figure 228: Cross Section Of Skylight At T3

Figure 229: Rooftop Installation Of Daylighting System In Changi Airport Terminal 3

The main terminal is aligned in an east-west orientation to maximise the daylight harvesting potential. The computer controlled system, together with strategically placed sensors results in an intelligent and efficient daylight system.

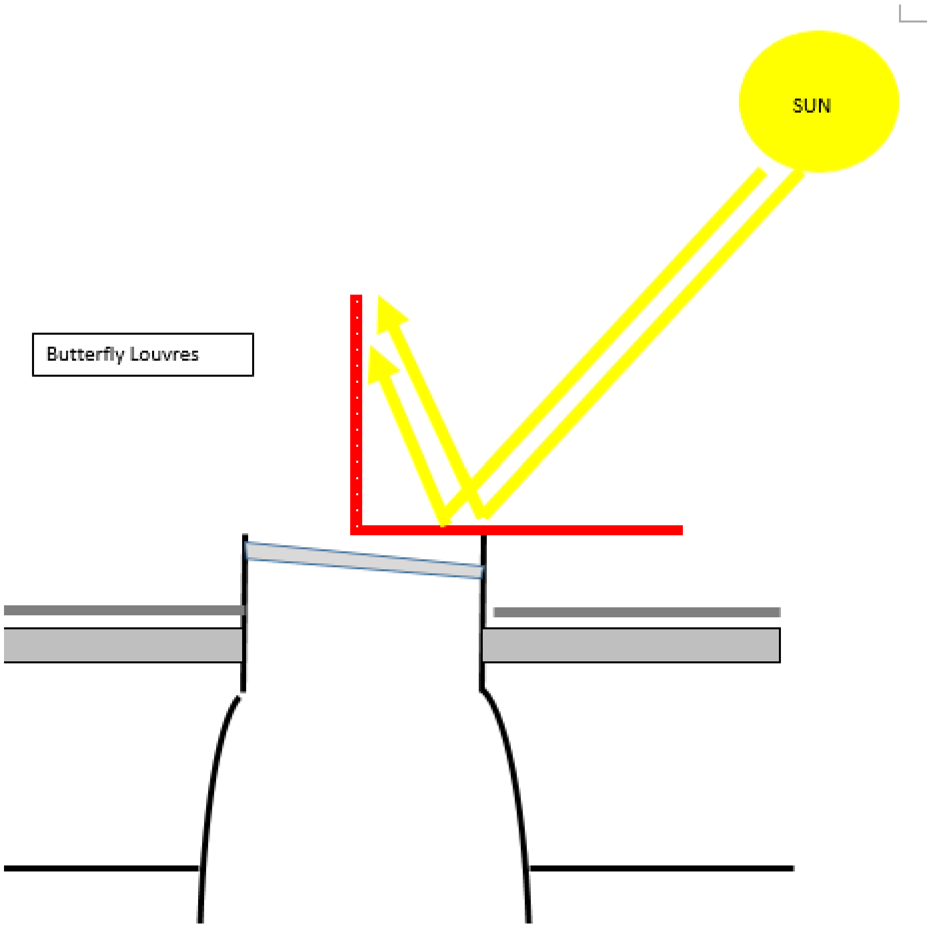


Figure 230: Daylighting System In Changi Airport Terminal 3

In the morning, the eastern wing of the skylight will be closed to reduce the direct sunlight entering the shaft. The western wing will remain open to allow diffused daylight to enter. When the sun is directly overhead at mid-day, both the wings will be folded half-way, allowing diffused light to enter from both sides, but at the same time preventing direct sunlight from entering the shaft. In the afternoon, the west wing will be closed while the east wing will be opened. The skylight consists of insulated laminated glass to further reduce solar heat gain.

In addition to the skylights, artificial lamps were also integrated into the skylight. These lamps are switched on and off depending on weather conditions as well as the time of the day. The lamps ensure that the illumination provided is uniform throughout the terminal. The system also ensures that with decreasing amount of daylight towards the evening, the illumination is supplemented seamlessly by artificial lighting.

Section 6:

Introduction

Lighting As A Building Utility

Electric lighting has become indispensable for our work, home-life, travel, entertainment, and recreation, etc. It has extended the day into night for commercial establishments, industries, hotels, airports, seaports, hospitals and innumerable other facilities round the clock. Our sense of vision (i.e. the ability to see things with clarity and comfort) is recognized as the most important link with our surroundings. Over 80 per cent of all information reaches our brain through the eyes and strongly influences the way we understand, function and act.

From the time Thomas Alva Edison invented the incandescent bulb in 1879, lighting technology has developed substantially. The functional, physiological and psychological aspects of light are increasingly recognized. The stringent requirements being placed on lighting parameters, the growing ‘appreciation’ of light by building occupants and the need to achieve energy-saving without compromising the end-results, are positive stimulants for the development of lighting products and application techniques.

SS 531:2006 (with its parts 1-2-3) is the Singapore lighting code of practice for indoor and outdoor work places. It is an approved code of the Building and Construction Authority for Green Mark award. Its recommendations are compulsory under the Workplace, Safety and Health Act. Thus, we now fully appreciate that electric light is no longer just a substitute for daylight but has its own leading position in building services.

Learning Outcomes Of This Section (Chapter 27 to Chapter 30)

i. To survey the existing lighting of a building with the use of a pre-designed template
ii. To analyse current lighting components and devise possible changes and retrofits with state-of-the-art lighting products for greater energy-efficiency and use of sustainable products
iii. To evaluate the most appropriate new or retrofit solution based on initial cost as well as life-cycle economics; and
iv. To integrate the above management practice into the business practices of clients and their own organisations

Chapter 27: Principles of Light, Definitions and Terminologies

27.1 Light, Infrared And Ultraviolet

Light is part of the electromagnetic spectrum together with X-Rays, Radio waves, Microwaves, etc. These forms of energy are each propagated and grouped at certain range of frequencies with corresponding wavelengths (Figure 231).

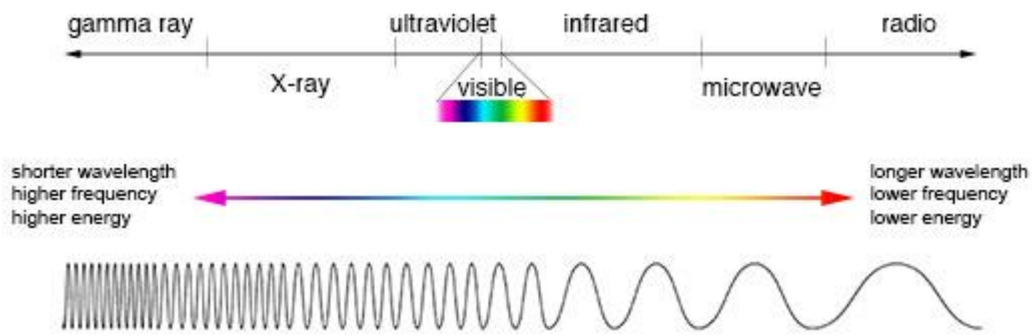


Figure 231: The Electromagnetic Spectrum (Image Credit: NASA Free Use Guidelines)

When the spectrum range is 400-700 Nanometer (nm) in wavelength, it makes an impression on our eye and is called visible light. There are two other bands of energy on either side of light i.e. infrared and ultraviolet that are supposed to be invisible. But at certain close wavelengths to light, they make a small impression of light in the eye (Figure 232).

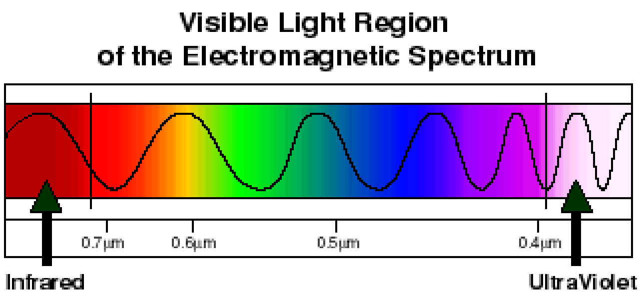


Figure 232: Light, Infrared And Ultraviolet
(Image Credit: NASA Free Use Guidelines)

Infrared (when it is emitted as part of a lamp's output) becomes radiated heat that contributes to the cooling load of an interior. E.g. the incandescent lamp gives out about 90% of its output as infrared heat and the rest as light. *That is one of the reasons why the incandescent bulb is being phased out in many countries*.

27.2 Definition of Lighting Units

27.2.1 Light Output:

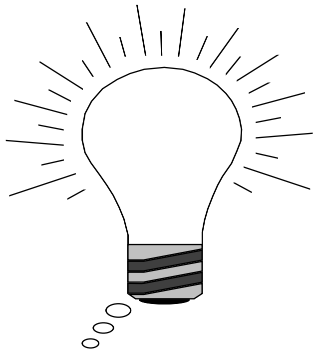


Figure 233: Light Output (Image Credit: Author)

Light output (also called Luminous flux – Figure 233) is the quantum of energy radiated per second by a light source in the 'visible' waveband of 400-700 nm. The unit of light output is Lumens. Every light source has certain light output in Lumens published by lamp makers in their catalogue as per examples below.

- Incandescent bulb 75W = 900 Lumens
- LED Torch bulb 1W = 40 Lumens
- Compact Fluorescent Lamp 15W = 900 Lumens
- 36W Fluorescent Daylight type = 2400 Lumens
- High Pressure Sodium 400W = 56000 Lumens

27.2.2 Efficacy

Efficacy is the light output of a lamp divided by its input wattage (without taking into consideration the possible losses in ballast, driver, etc). In the above example, the following efficacies can be derived:

- Incandescent bulb 75W = 900 / 75W = **12** Lumens/W
- LED Torch bulb 1W = 40 / 1W = **40** Lumens/W
- Compact Fluorescent Lamp 15W = 900 / 15W = **60** Lumens/W
- 36W Fluorescent Daylight = 2400 Lumens / 36W = **67** Lumens/W
- High Pressure Sodium 400W = 56000 Lumens / 400W = **140** Lumens/W

Efficacy (at a glance) shows to what extent a lamp can be an energy-saving type provided other aspects like electrical, mechanical and optical characteristics suit the installation.

27.2.3 Light Intensity

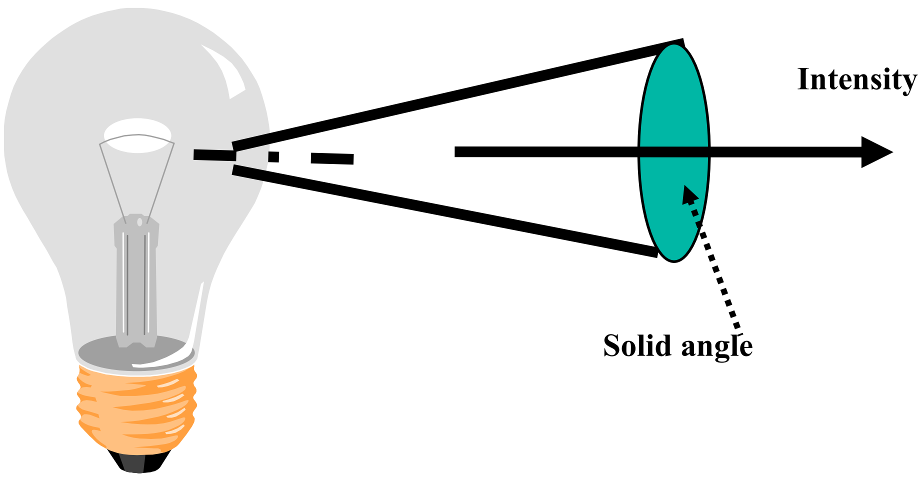


Figure 234A: Light Intensity (Image Credit: Author)

Light intensity (unit = Candela **Cd**) Figure 234A is defined as the light output of a source per solid angle. The solid angle's unit is a Steradian (see Figure 234B) and it is the angle submitted by an area of radius^2 at the centre of a sphere where the light source is deemed to be positioned.

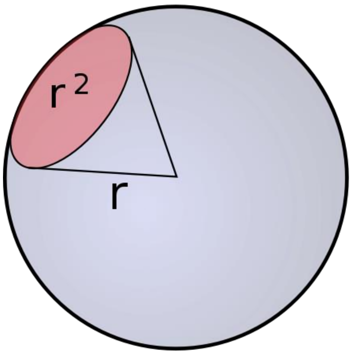


Figure 234B: Solid Angle (Steradian)
(Image Credit: Wikipedia Free Use Guidelines)

A few examples of lighting intensity are as follows:

- Bicycle lamp with no reflector = 2.5 Cd
- Bicycle lamp with reflector = 250 Cd
- Halogen 50W lamp at centre of beam = 10,000 Cd

27.2.4 Lighting Level (Or Illuminance)

Illuminance (Figure 235A) = Total lumens effectively falling on a surface divided by the area of that surface (also called Lighting Level)

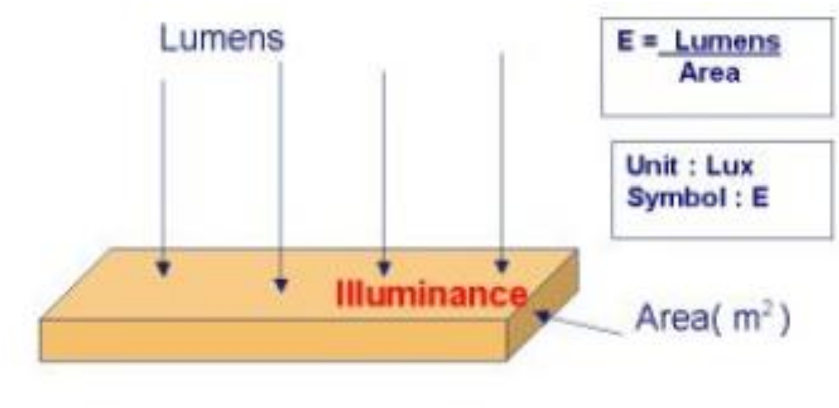


Figure 235A: Lighting Level Definition (Image Credit: Author)

Figure 235B: Lighting Levels in Nature ***(Lux)*** *(Image Credit: Wikipedia Free Use Guidelines))*

A few examples of nature's prevailing illuminance are shown in Figure 235B. For thousands of years, humans have been experiencing daytime lighting levels of about 10,000 Lux in the shade and 100,000 Lux in the open. On the other hand, the light of a full moon produces just about 0.25 Lux and yet we can see the landscape fairly clearly. However, neither colours are visible nor can we read or write under moonlight. If the human eye can handle 100,000 Lux down to 0.25 Lux, what is the basis of indoor work place lighting? Who formulates them?

27.3 Basis of Singapore Standard Lighting Recommendations

27.3.1 Ophthalmologic Investigations

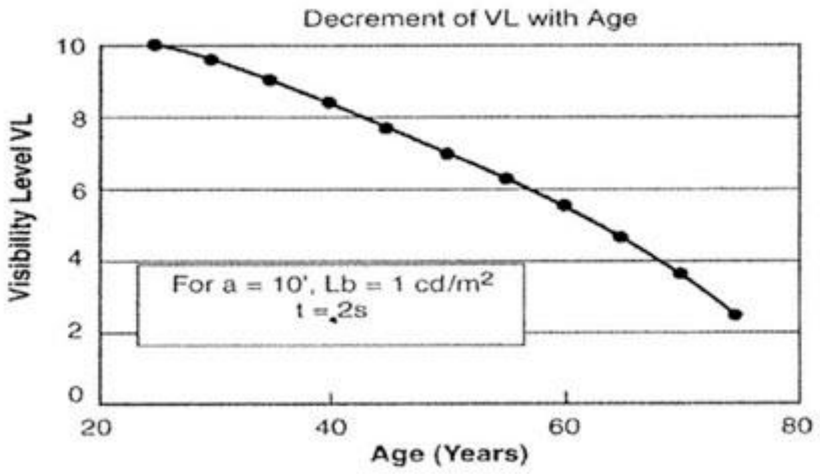


Figure 236: Age Vs Lighting Level

(Image Credit: Federal Highway Handbook 2012 Free Use Guidelines)

Like many other biological functions like hearing, walking, talking or comprehending, our ability to 'see' things will also get impaired as we grow old. So the lighting requirement of a 40-year-old worker in an office will be much higher than a younger worker of 20. This ophthalmologic research finding is shown in Figure 236. Because the retirement age in many countries is expected to increase beyond 60 years, it is possible that the average working illuminance in future may have to be raised further. At the same time, there is a limit to the lighting level that we can provide due to energy considerations.

27.3.2 Lighting-Productivity-Errors And Eye Fatigue

Research on the impact of lighting on productivity and errors, etc. has been ongoing in different forms by the Illuminating Engineering Societies of Europe and USA as well as the International Commission on Lighting (CIE in French). This continued research has been on how the human eye works, how we see, and what role lighting plays with respect to productivity, safety, errors and visual comfort. A summary of these research findings were published by Dr. Dietrich Fischer (in Philips International Lighting Review 1985 /Vol 2). In these investigations, productivity (Figure 237) was found to be highest under 10,000 Lux. That is the same as noon time-illuminance under the shade of a tree. Such a high level is obviously impossible to realise in an office or industry. Progressive reduction of illuminance to 2,000 Lux, 1,000 Lux and 500 Lux (in the experiments) still showed no great fall in productivity up to 500 Lux. But, going below 500 resulted in a steep drop in productivity.

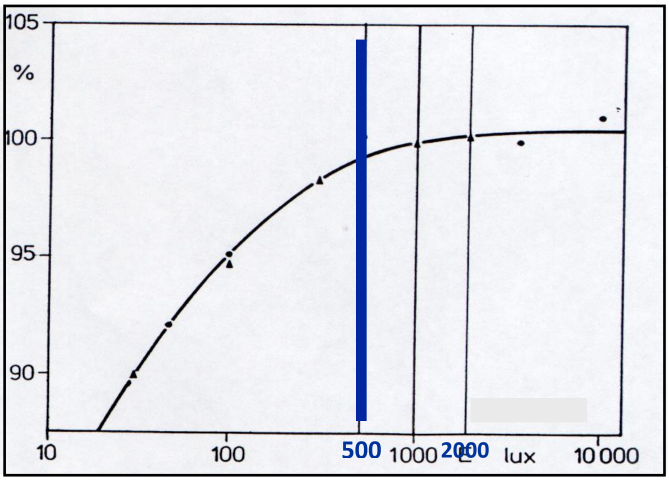


Figure 237: Lighting and Productivity

Errors were likewise minimum under 10,000 Lux but gradually increased as the illuminance decreased to 500 Lux. Below this level, errors (rejects and accidents) increased exponentially (Figure 238)

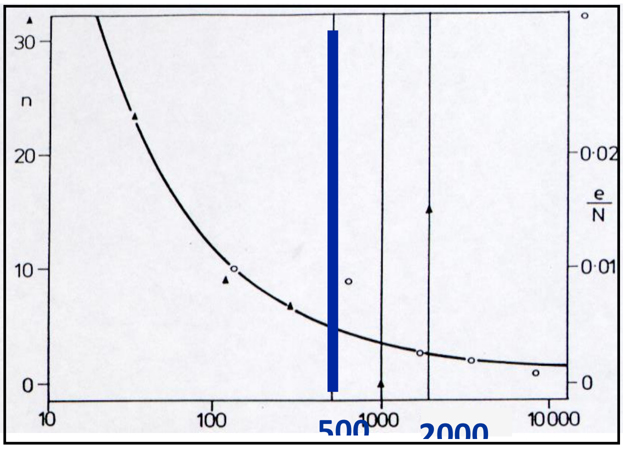


Figure 238: Lighting and Errors

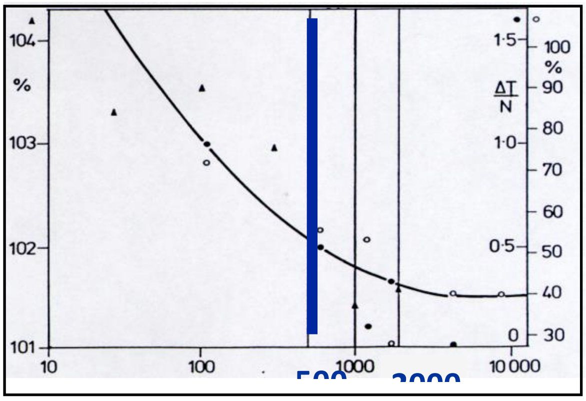


Figure 239: Lighting And Eye Fatigue

(Figure237, 238, 239 Image Credit: Philips International Lighting Review Vol 2 1985)

Eye-Fatigue likewise (Figure 239), increased drastically when the average illuminance decreased below 500 Lux. So there are consistent indicators to the desirability of having 500 Lux in working interiors. This is the basis for SS 531-1 (Lighting of indoor work places) to specify 500 Lux for many applications (see Table 11)

Table 11: Lighting Levels Specified In SS 531-1:2013

	Interior Application area	**Lighting level (Lux)**
1.	Filing, Copying	300
2.	Reading, Writing, Data processing	500
3.	Technical Drawings	750
4.	CAD work stations	500
5.	Conference and Meeting rooms	500
6.	Reception desk	300
7.	Archives	200

27.4 Colour Temperature And Colour Rendering Index

27.4.1 Correlated Colour Temperature (CCT)

The CCT of a light source has important applications for lighting of indoor and outdoor work places, videography and photography. Colour temperature is conventionally stated in the unit of Absolute temperature (Kelvin), with symbol K.

An easy way to understand Colour temperature is to look at the gas-flame in a gas cooker (Figure 240). The blue flame is obviously hotter than the yellow flame of match stick. But blue is a 'cool' colour and so we can draw an analogy that if a lamp looks blue or bluish white, its "Correlated Colour Temperature' will be high. For the same reason, a yellow light (like Sodium) has low Colour temperature because it resembles the less hot yellow flame.

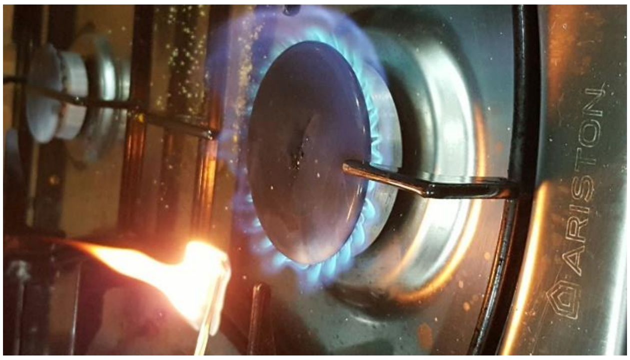


Figure 240: Correlation Of Colour Temperatures (Image Credit: Author)

The 'Colour Temperature' of light is not the actual temperature of the lamp. The standard incandescent lamp and the Halogen lamp are thermal radiators and so their colour temperature is also their filament temperature. All other light sources like fluorescent lamp or LED (light emitting diodes) give out light primarily by processes other than thermal radiation. Their light output is in bands rather than continuous. It means that the emitted radiation does not follow the form of a black-body as it is heated up. These sources are assigned what is known as Correlated Colour Temperature (CCT). CCT is the colour temperature of a corresponding black-body radiator which most closely matches the light from that lamp.

In the morning as the sun crosses the sky from the horizon, it first appears to be reddish and the sky gradually changes to blue at noon. This mid-day sky corresponds to a black body with colour temperature of 6000 K. So a fluorescent tube that gives bluish-white light is called 'Daylight' tube. Figure 241 shows two impressions of 'Cool or 'Warm' interiors that have the same 'physical temperature' otherwise!

Figure 241 Illustration Of Colour Temperatures In An Interior (Image Credit: Philips Lighting)

In Figure 242 is an illustration of Colour Temperatures in nature

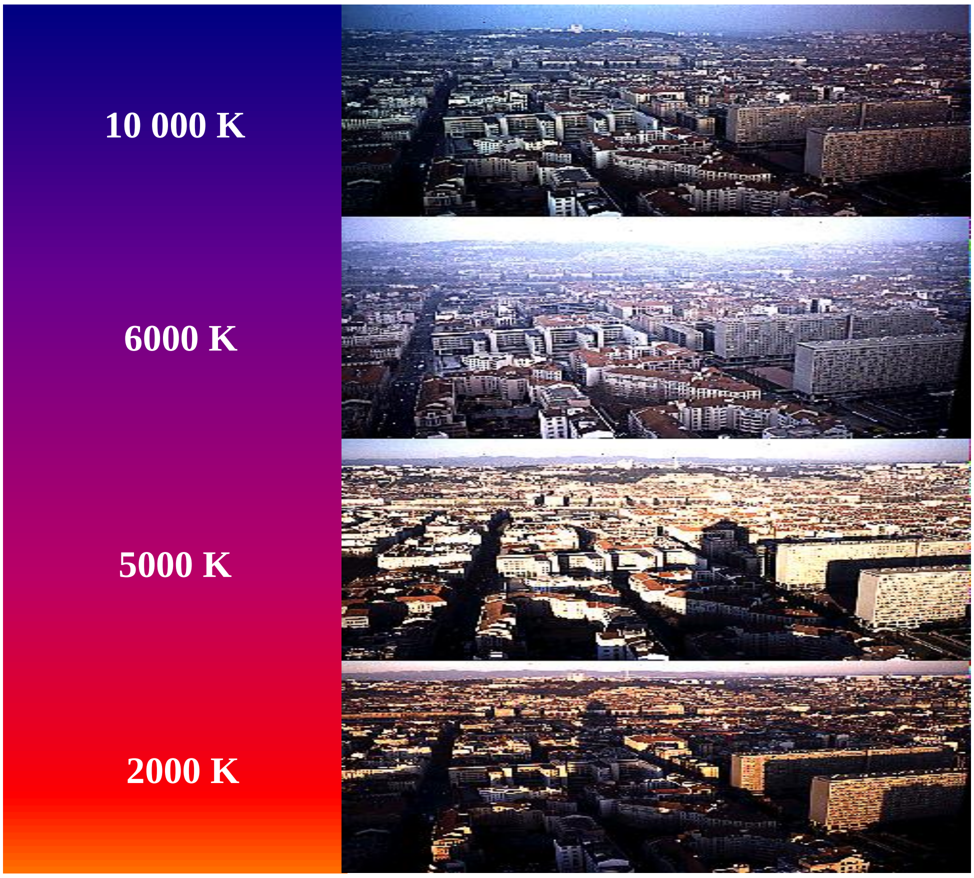


Figure 242: Colour Temperatures In Nature (Image Credit: Philips Lighting)

SS 531-1 shows a division of three groups according to their CCT (Table 12).

Table 12: Colour Temperature Groups.

Colour appearance	Correlated colour temperature
warm	below 3300 K
intermediate	3300 K to 5300 K
cool	above 5300 K

The choice of colour appearance is a matter of psychology, aesthetics and what is considered to be natural by the user or owner of a premises. The choice depends on illuminance, colours of the room and furniture, dominant external climate, etc. In warm climates, generally a cooler light colour appearance is preferred, and in cold climates a warmer light colour appearance is preferred. This is borne out by the fact that until now, fluorescent tubes of 6000K were hardly ever marketed in Europe while Asians hardly bought any tubes below 4000K for homes or offices. Different manufacturers used to call the same CCT by fancy-names such as 'warm', warm white', 'white', 'cool white' that are confusing. The present practice in professional lighting is to specify lamp colour in Kelvin.

27.4.2 Colour Rendering Index (CRI)

A simple definition of Colour Rendering Index is - it is a measure of the ability of a light source to accurately render all colours of an object or scene so that there is true colour perception. This is very important for 'Visual Satisfaction' of users. CRI is rated on a scale from 1-100. The lower the CRI rating, the less accurately colours will be reproduced. Of all the light sources, only the Sun, and incandescent and Halogen lamps have a CRI of 100 because they are thermal emitters with a continuous spectrum with all the colours present them (Figure 243).

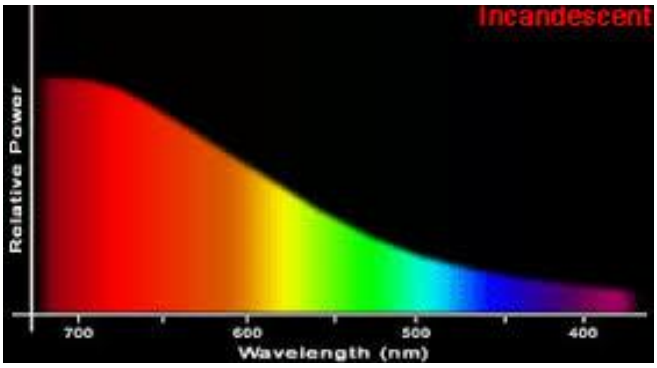


Figure 243: Full Spectrum Of An Incandescent / Halogen Lamp With CRI=100

(Image Credit: neonlighting.com)

SS 531 stipulates that for most of working interiors (Commercial and Industrial), the CRI should be more than 80. It is because 80 is the threshold at which our eyes can discern colours reasonably well. Occupants should have visual satisfaction of their own skin tone, objects, ladies' cosmetics and surrounds. Figure 244 illustrates the effect of different CRIs on the same bunch of flowers.

Figure. 244. Different CRI At Same Lighting Level

(Image Credit: Philips Lighting)

27.5 Essentials Of Visual Perception And Visual Comfort

27.5.1 Important Elements

Apart from illuminance, there has to be restriction on Glare as it will produce discomfort to make things less visible in spite of proper lighting levels. Also, the colours of objects, humans and surroundings should come out reasonably well to produce visual satisfaction. So the following criteria are important for indoor lighting.

- Illuminance (in Lux)
- Discomfort glare (Numerical rating)
- Colour Rendering Index (Numerical rating)

There are other criteria which are less critical but nevertheless that contribute to visual perception and satisfaction. They are:

- Colour Temperature
- Brightness or luminance in the field of view
- Directionality and shadows

The above criteria, together with the aesthetics of an installation, define what is loosely termed as the 'lighting quality'. It is important that these criteria should not be seen in isolation but more as inter-dependent factors.

27.6 Measurement Method And Worked Example

27.6.1 Measurement Method And Grid

The lighting measurement (for illuminance) is done at a height of 0.85 to 1.0 m above the working plane. To have a uniform method of calculation, the following formula can be used to calculate the maximum grid size to measure the average illuminance.

$$P = 0.2 \times 5^{\log_{10}(d)}$$

Where:

'd' is normally the longer dimension of the calculation area (m). However, if the ratio of the longer to the shorter side is 2 or more, d becomes the shorter dimension of the area.

'P' is the maximum grid cell size (m) when length of area is less than 10m. That will result in the following grid sizes for a number of example dimensions (Table 13):

Table 13: Measurement Grid For Indoor Illuminance

(Source: EN 12464-1:2014 Lighting Of Work Places Appendix 1)

Length of Area	Maximum distance between Grid points	Minimum no. of Grid points
0.40	0.15	3
0.60	0.20	3
1.00	0.20	5
2.00	0.30	6
5.00	0.60	8
10.00	1.00	10
15.00	2.00	12
50.00	3.00	17
100.00	5.00	20

27.6.2 Worked Example:

As the principles of indoor lighting design have to be understood first, the worked example to calculate number of luminaires and their layout to achieve recommended illuminance is moved to Chapter 28.

Chapter 28: Eco-Friendly Lighting Design

Figure 245A: A Modern Office Interior (Image Credit Philips Lighting)

28.1 Singapore Standard SS 531-1:2006

28.1.1 Maintained Lighting Level

SS 531-1 is based on an international standard ISO 8995-1: 2003 whose recommendations cover commercial, industrial and other work places. The right choice of lighting level (illuminance) is the first important consideration when designing a lighting installation. It is specified in terms of 'average illuminance' and measured on the 'working plane' which is taken at 1.00 meter above the floor-level for offices and industries (Figure 245B). Asia work tables tend to have a lower height of 0.85m but the lighting design is deemed to make little difference by taking 1.0 meter for the working plane.

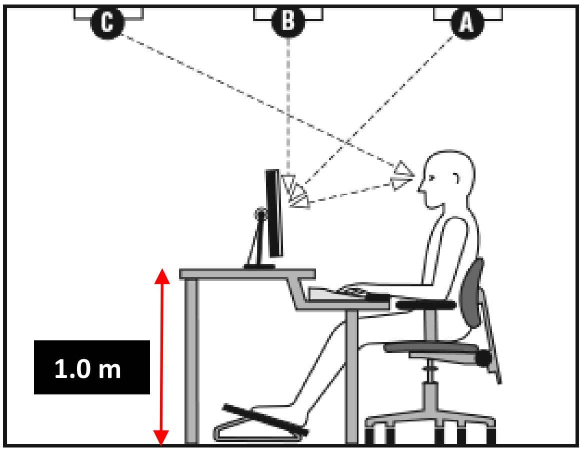


Figure 245B: Measuring Plane For Indoor Work Place Illuminance
(Image Credit: OSH Fact Sheet- Canadian Center For Occupational Health And Safety)

Our visual acuity (or sharpness of vision) is directly dependent upon the illuminance – the higher it is, smaller are the objects that can be discerned and less is the eye-strain. So lighting that is suited to the nature of the task being performed improves visual perception for that task. The choice of lighting level also depends on other factors like:

a. Work duration;
b. Contrast of the task;
c. The risk of making mistakes;
d. Age of the worker; and
e. Amount of daylight present

SS 531 (with Part 1-2 and 3) stipulates what is called the 'maintained illuminance' over the task area or a reference surface which may be horizontal, vertical or inclined. Maintained illuminance is the depreciated level of lighting taking into consideration the lamp lumen depreciation, luminaire output depreciation and room surface depreciation (Figure 246). When the combined impact of these reaches 70% of the initial lighting level, it will signal the replacement of the lamp or luminaire. That is called 'maintained illuminance' which should not fall below the values given in the code regardless of the age and condition of the installation.

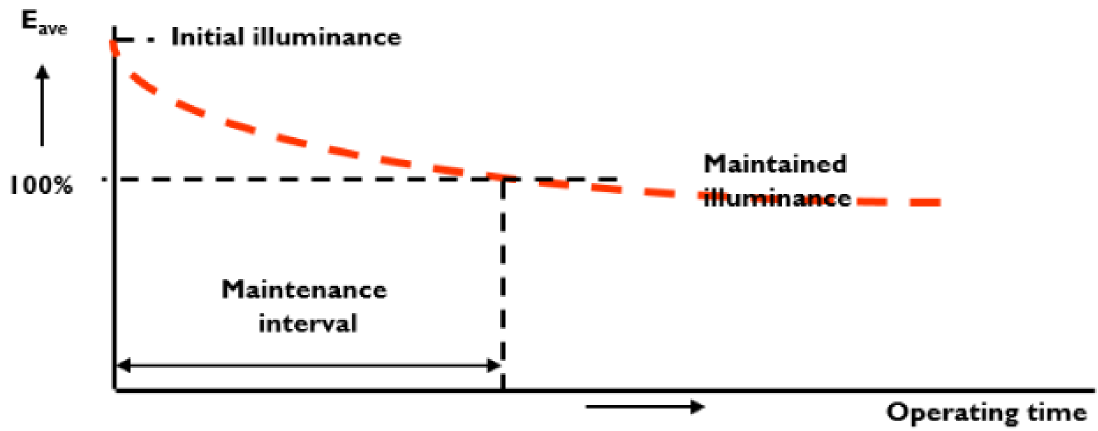


Figure 246: Maintained Lighting Level (Image Credit: Author)

If the visual conditions are poorer than based on normal assumptions, the value of illuminance may be increased by at least one step on the scale of illuminance. This can happen when:

a. Contrasts are poor in the working area;
b. Work is critical;
c. Errors are costly to rectify; and
d. Accuracy and higher productivity are important

28.1.2 Scale Of Illuminance

A factor of approximately 1.5 represents the smallest significant difference in subjective effect of illuminance. In normal lighting conditions, about 20 lux of horizontal illuminance is required to just discern features of the human face and is the lowest value taken for the scale of illuminances. The recommended scale of illuminance is:

20 - 30 - 50 - 75 - 100 - 150 - 200 - 300 - 500 - 750 - 1000 - 1500 - 2000 - 3000 - 5000 lux.

Likewise, the maintained illuminance may be reduced when:

a. Details are of large size or with high contrast; and
b. Task is undertaken for an unusually short time.

As a default, in any area where continuous work is carried out, the maintained illuminance shall not be less than 200 lux.

28.1.3 Illuminance Of Immediate Surroundings

The illuminance of immediate surroundings shall be related to the illuminance of the task area and should provide a well-balanced distribution of luminance (brightness) in the field of view.

Rapid spatial changes in illuminance around the task area may lead to visual stress and discomfort. The maintained illuminance of immediate surrounding areas may be lower than the task illuminance but shall not be less than the values given in the Table 14.

Table 14: Ratio Of Task To Surrounding Illuminance.

(Source: SS 531-1:2006)

Task illuminance lux	**Illuminance of immediate surroundings lux**
≥ 750	500
500	300
300	200
≤ 200	Same as task illuminance

28.1.4 Discomfort Glare And Unified Glare Rating (UGR)

Glare from the lighting system impairs vision and produces discomfort to occupants in working interiors. An empirical formula is used to determine Glare. Because there are many occupants in a working interior, their directions of view and luminaire-brightness that comes into their view, cannot be controlled. That will again vary due to the constant multi-directional viewing of occupants. Also glare is a 'subjective' feeling. *So UGR cannot be physically measured.* It can only be derived from software programs like Dialux that take into account the above factors automatically while computing Glare.

$$UGR=8\log\left(\frac{0.25}{L_b}\cdot\sum\frac{L^2\cdot\omega}{p^2}\right)$$

In the Formula above, the number 8 gives a multiplying factor to get a UGR range of 10-40.

The Log function is because our eye has a logarithmic way of registering brightness.

The Summation sign is to take into account all the luminaires in the field of view of an occupant.

L is the luminance of the luminaire

The sign Omega is the angle between the line of sight of occupant and the luminaire

p is the so-called Guth index and it is based on the distance of a group of luminaires from the observer. P being in the denominator of above equation, it would mean that the further away a luminaire, the less glare it will produce.

L_b is the background luminance in Cd/m^2, while L is the luminance of an individual luminaire. Looking at L (which gets squared) and L_b that is linear, it is clear that glare increases for those lamps with high luminance (like LED) at normal ceiling heights. With more diffused sources like fluorescent, UGR tends to be less. That is one of the reasons LED luminaires are equipped with prismatic or opal diffusors to limit the glare.

Some limits:

- UGR < 13: Hardly any glare experienced
- UGR < 19: Tolerable for normal office interiors
- UGR > 28: High glare tolerated only in non-working areas

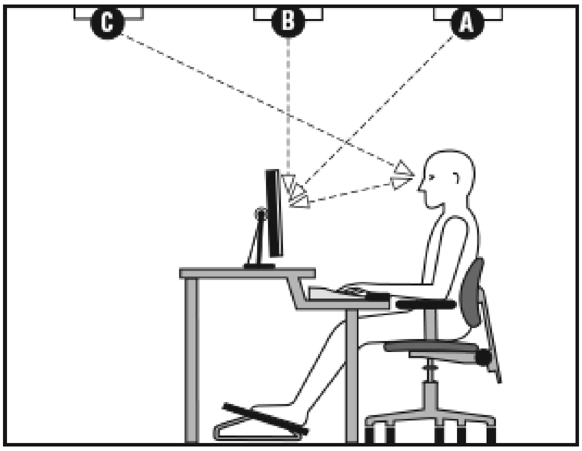


Figure 247: Contribution To Glare By Luminaires

(Image Credit: OSH Fact Sheet- Canadian Center For Occupational Health And Safety)

Figure 247 shows which rows of luminaires can produce direct discomfort glare at a work station. Details of the UGR method are given in document CIE 117 - 1995. We have already seen that factors like frequently-changing viewing directions of occupants, layout of work-stations as well as office equipment or industrial machines in an interior will affect glare. Glare is also 'subjective' and hence it is not possible to calculate UGR manually. It is done by the computer using lighting design software and based on various interior parameters, luminaire optics and layout. For accuracy of result on Glare, the most important parameter is the integrity of the Photometric characteristics of the luminaire. This is called the Illuminating Engineering Society 'IES file' of a luminaire-Photometrics. The IES file contains digital plot of the light output and intensities in all the planes surrounding a luminaire.

The *UGR* value of a lighting installation shall not exceed the value given in SS 531. The values of *UGR* limits in clause 5 of the Code are taken from the so-called *UGR* scale - where each step in the scale represents one significant change in glare and No.13 represents the least glare and it increases in steps of 3 as below.

The *UGR* scale is: 13 - 16 - 19 - 22 - 25 – 28

28.2 Green Mark Guidelines Of BCA Singapore

The Building and Construction Authority (BCA) of Singapore administers the Green Mark scheme for buildings. It is a rating system to evaluate a building for its environmental impact and performance. It is endorsed and supported by National Environment Agency and provides a comprehensive framework for assessing the overall environmental performance of new and existing buildings to promote sustainable design, construction and operation practices in buildings.

Under the assessment framework for new buildings, developers and design teams are encouraged to design and construct green, sustainable buildings which can promote energy savings, water savings, healthier indoor environment as well as the adoption of more extensive greenery for their projects. For existing buildings, the building owners and operators are encouraged to meet their sustainable-operation goals and to reduce adverse impacts of their buildings on the environment and occupant health over the entire building life cycle.

The assessment criteria cover the following key areas: -

- Energy Efficiency
- Water Efficiency
- Environmental Protection
- Indoor Environmental Quality
- Other Green Features and Innovation

Lighting finds a place under Energy Efficiency and Indoor Environmental Quality, the latter (at present) preferring the use of Electronic High Frequency ballast for fluorescent luminaires. The major Green Mark criteria are the lighting power density (in Watts/m^2) as per SS 530:2014.

The Green Mark assessment identifies the specific energy-efficient and environment-friendly features and practices incorporated in the projects. Points are awarded for incorporating environment-friendly features which are better than normal or approved practice. The total number of points obtained will provide an indication of the environmental friendliness of the building design and operation. Depending on the overall assessment and points scoring, the building will be certified to have met the BCA Green Mark Platinum, Gold ^{Plus}, or Gold rating. Certified Green Mark buildings are required to be re-assessed every three years to maintain the Green Mark status. Table 15 shows the Points that can be scored for lighting as per BCA' brochure "Green Mark Non-Residential Buildings NRB:2015 Technical Guide and Requirements"

Table 15: BCA NRB:2015 Green Mark Rating For Lighting

Energy Efficiency	Green Mark Points
<u>Non-Residential Building Clause 1-6</u> Encourage the use of energy efficient lighting to minimise energy consumption from lighting usage while maintaining proper lighting level <u>Baseline</u> Maximum lighting power budget stated in SS 530:2014	0.3 point for every percentage improvement in lighting power budget Points scored = 0.3 (% improvement) (including Tenant lighting provision) (up to 12 points) (Excluding tenant lighting provision) (up to 5 points)

28.3 Luminaire Types And Modern Developments

T8-T5 fluorescent luminaires have been the dominant light source for commercial offices and flatted factories with ceilings up to a maximum of 7 metres in height. Currently, there are millions of fluorescent luminaires used in Singapore and the ASEAN region. Their replacement with more modern luminaires (using Light Emitting Diode) calls for understanding of the existing lighting system and characteristics.

Figure 248

Figure 249

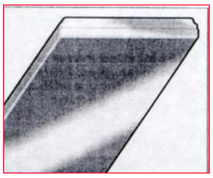


Figure 250

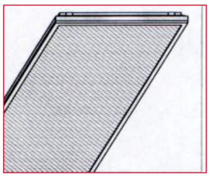


Figure 251

(Image Credit Philips Lighting)

Of these, the bare-tube fluorescent luminaire (Figure 248) is the least expensive. Because of its basic look and glare, it is limited to usage in corridors, passages, small shops, food courts, toilets, etc.

Figure 249: This luminaire with a trapezoidal metal reflector directs the tube's output mainly downward and a small amount of light upwards. Downward efficiency is higher but glare is still a problem due to bare lamp.

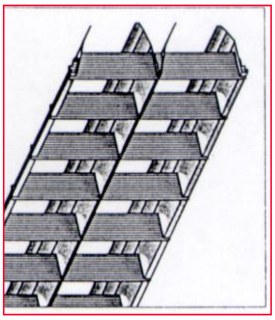
Figure 250 and 251: These are luminaires with opal (milky) or prismatic diffusor. The diffusor helps to conceal the lamp from direct view, reduces glare and helps to distribute the light wider. However, absorption of light in the diffusor could be up to 30% and hence efficiency is not that good. (In a strange twist of technology, LED indoor luminaires have got to make use of these diffusors again)

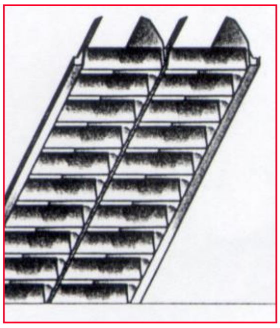
The so-called mirror optic fluorescent luminaires (Figure 252) are installed in most Singapore office interiors.

Figure 252: A Typical Mirror Optic Luminaire

(Image Credit Philips Lighting)

Mirror optic luminaires have a pair of glossy or semi-glossy reflectors surrounding the tube to provide optic control, beam spread and glare-control at certain viewing angles. The cross-blades or laminations shield the lamp from direct view along the length of the lamp. Such a luminaire (with no blockage of light like a diffusor) can direct the light better where needed. Different mirror louvres are used to provide different beam spreads depending on the interior and the choice of specifier. (Figures 253-254-255).





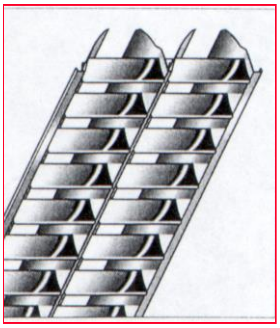


Figure 253 *Figure 254* *Figure 255*

Typical Mirror-Optic Fluorescent Luminaires

(Image Credit: Philips Lighting)

LED Luminaires are getting increasingly specified and used for indoor lighting. They do not use mirror-optics because LED itself has a directional output and mirrors cannot contribute further. Instead, such luminaires use opal or prismatic diffusors because LED can otherwise cause glare (Figure 256). Because LED's efficacy is increasing, the limitation of the diffusor absorbing some light, will not be a hindrance and may be overcome soon.

Figure 256: LED Luminaire With Prismatic Diffusor

(Image Credit: Philips Lighting)

For more than 7-8 meters mounting height, the so-called High Intensity Discharge (HID) lamps were preferred until now. HID lamp family consists of High Pressure Mercury, Standard Metal Halide, Ceramic Metal Halide, Sodium and Induction lamps. Typical HID high bay luminaires are shown in Figure 257 and 258**.** In the last few years, LED high bay luminaires are also entering this field. Cost-benefit analysis should be done while making a choice between HID and LED High bay luminaires. Figure 259 shows a typical LED high bay luminaire.

Figure 257

Figure 258

Figure 259

HID And LED High Bay Luminaires (Image Credit: Philips Lighting)

28.4 Uniformity And Glare

28.4.1 Uniformity

Regarding uniformity of lighting, Singapore standard SS 531-1 stipulates the following.
“The uniformity of the illuminance is the ratio of the minimum to average value. The illuminance shall change gradually. The task area shall be illuminated as uniformly as possible. The uniformity of the task illuminance shall not be less than 0.7. The uniformity of the illuminance of the immediate surrounding areas shall be not less than 0.5.

28.4.2 Glare

On glare, SS 531-1 has the following stipulations

“Glare is the visual sensation produced by bright areas within the field of view and may be experienced either as discomfort glare or disability glare. Glare may also be caused by reflections in specular surfaces usually known as veiling reflections or reflected glare. It is important to limit the glare to avoid errors, fatigue and accidents”.

A typical recommendation including Glare (in terms of Unified Glare Rating-UGR) is shown in Table 16 below.

Table 16: Glare (UGR) Limits By SS 531-1

Clause	Application area	Maintained lighting level Lux	**UGR**	CRI
3.1	Filing, Copying	300	**19**	80
3.2	Writing, Reading and Data processing	500	**19**	80
3.3	Technical Drawings	750	**16**	80
3.4	CAD Work stations	500	**19**	80
3.6	Reception	300	**22**	80

28.5 Photometric Data, Room Reflectance And Room Index

28.5.1 Photometric Data

What are photometric data of a lamp or luminaire? The total luminous flux of a lamp and how it manifests in various directions with different intensities are captured in the photometric data of a lamp or luminaire. The intensities can be upward, downward and sideward and in infinite number of planes as in Figure 260.

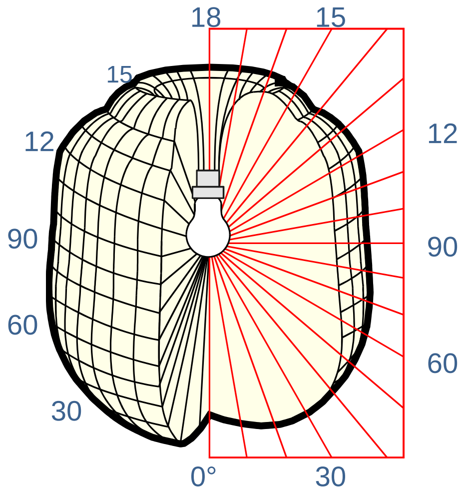


Figure 260: Light Intensity Diagram On Multiple Planes

(Image credit: Philips Lighting)

While the multi-directional output of bulb is in Figure 260, the controlled downward light intensity of a luminaire is shown in Figure 261.

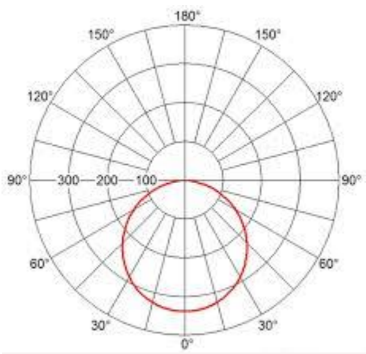


Figure 261: Downward Light Intensity (In Red)

(Image Credit: Zumtobel Lighting)

These intensity diagrams are plotted using the so-called Gonio Photometer. It is a mechanical device to support and optionally position the light source (a luminaire or lamp) and a photo-sensor which measures luminous intensity at each angle, at a set distance. In this case, the luminaire is mounted on an automatic turning frame, which rotates the device under test through two axes. A measurement of luminous intensity is taken at each angle as shown in further figures.

If it is a rectangular luminaire – Figure 262 (as is often used in office lighting), its light distribution in two cardinal planes as below will be practical.

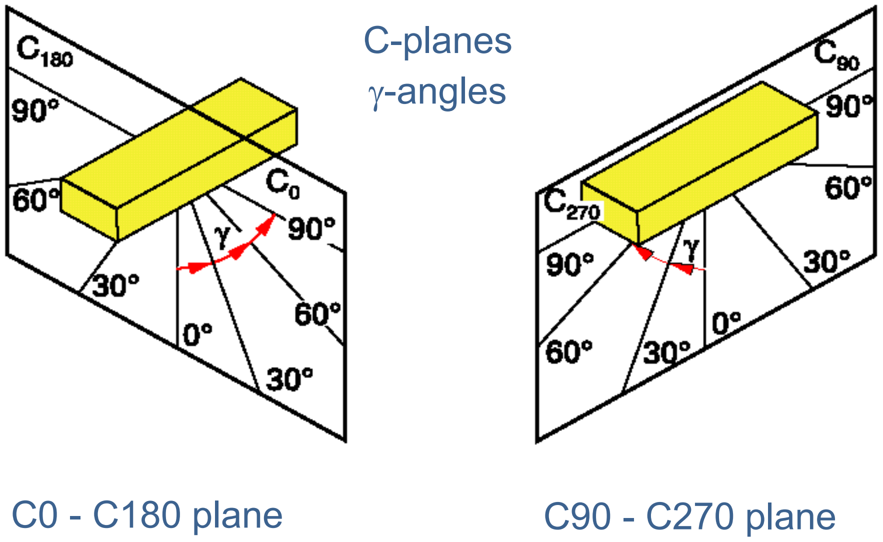


Figure 262: Light Intensity Diagram Of A Rectangular Luminaire (Image Credit: Author)

However, to calculate the lighting level that will be produced at several points of the working plane of an office, it will be too cumbersome to calculate each point manually. So to enable a lighting design software to use luminaire Photometrics, it is necessary to make the data electronically transferable.

The Illuminating Engineering Society of North America (IES), created the standard document LM-63-86, “IES Recommended Standard File Format for Electronic Transfer of Photometric Data.” This is called the IES file of given luminaire and the most common method used globally to do lighting design is with software like Dialux.

28.5.2 Room Reflectances

When room surfaces reflect more of the available light, they contribute towards higher utilisation of the lighting system. Hence for commercial and industrial interiors, light-colour or pastel colour finishes are suggested to increase the surface reflectance of the Ceiling, Walls, Working plane and Floor as shown in Figure 263.

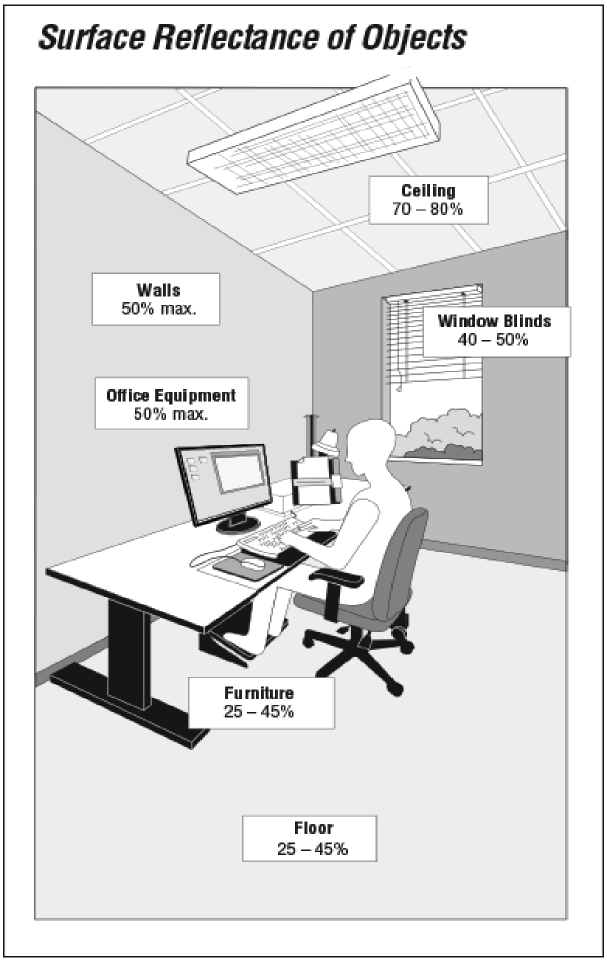


Figure 263: Surface Reflectance In A Room

(Image Credit: OSH Fact Sheet- Canadian Center for Occupational Health and Safety)

28.5.3 Room Index (with K as abbreviation)

K (the Room Index) is the ratio of the vertical reflecting surfaces of an interior to its horizontal reflecting surfaces as shown in Figure 264.

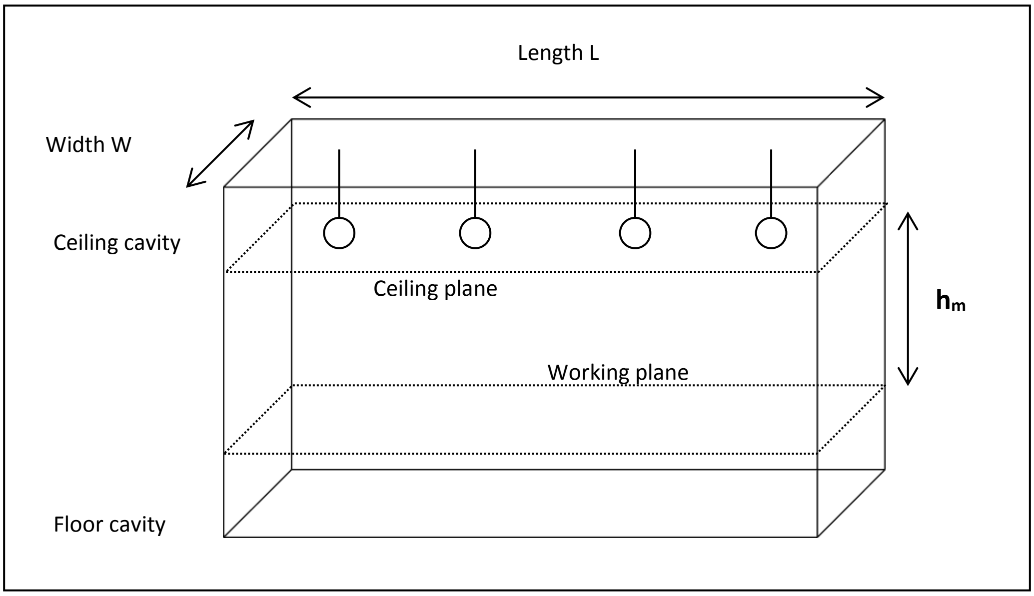


Figure 264: Room Dimensions Of An Interior (Image Credit: Author)

$$K = \frac{\text{Length (L) X Width (W)}}{H_m\ (L+W)}$$

Where H_m is the height of Luminaire above the Working plane

28.6 Utilisation Factor, Maintenance Factor and Spacing-to- Height Ratio

28.6.1 Utilisation Factor

Utilisation factor (UF) is the proportion of the luminous flux emitted by the lamps to what is utilized to produce the illuminance on the working plane. Factors that affect the value of UF are:

- Room Index (based on room proportions)
- Room Reflectances
- Photometrics of the luminaire

Room Reflectances and Room Index have been explained earlier. We have to consider the reflectance of the Ceiling (Rc) (False or hard ceiling), Walls (Rw) and working plane (Rp). Typical reflectances in a modern office interior are:

- Ceiling = 0.70
- Wall = 0.50
- Working plane = 0.30

Together with the Room Reflectances and Room Index, we can get the Utilisation Factor of a selected luminaire as in Table 17:

Table 17: Typical Utilisation Factor Table Of A Luminaire (Source: CIE, 1995)

room index K	reflectances (%) for ceiling, walls and working plane										
	80 50 30	80 50 10	70 50 30	70 50 20	70 50 10	70 30 10	50 30 10	50 10 10	30 30 10	30 10 10	0 0 0
0.60	0.44	0.42	0.43	0.42	0.41	0.37	0.37	0.34	0.37	0.34	0.33
0.80	0.52	0.49	0.51	0.50	0.48	0.44	0.44	0.41	0.43	0.41	0.40
1.00	0.58	0.54	0.57	0.55	0.54	0.50	0.49	0.47	0.49	0.47	0.45
1.25	0.64	0.59	0.63	0.60	0.58	0.55	0.54	0.52	0.54	0.52	0.50
1.50	0.68	0.62	0.67	0.64	0.61	0.58	0.58	0.55	0.57	0.55	0.54
2.00	0.74	0.66	0.72	0.69	0.66	0.63	0.62	0.61	0.62	0.60	0.59
2.50	0.78	0.69	0.76	0.72	0.68	0.66	0.65	0.64	0.64	0.63	0.61
3.00	0.80	0.70	0.78	0.74	0.70	0.68	0.67	0.66	0.66	0.65	0.63
4.00	0.83	0.72	0.81	0.76	0.71	0.70	0.69	0.68	0.68	0.67	0.65
5.00	0.85	0.73	0.82	0.77	0.72	0.71	0.70	0.69	0.69	0.68	0.66
	suspension ratio: 0 calculated acc. to CIE publication 40 and 52 LVW1076900-00										

For example, if the room index K is 2.5 and room reflectances are 70/50/30, the UF of the particular luminaire in this situation will be 0.76.

28.6.2 Maintenance Factor (MF)

MF is the overall ratio of the lighting level produced by an installation at a specified time, compared to the lighting level it produced when it is new. The gradual decline in lighting level is caused by the following sub-factors:

Lamp lumen maintenance factor (LLMF). This is the ratio of a lamp's light output after a set time to its output when the lamp was new. This factor allows for the depreciation of lumen output with age. For example, in the graph of Figure 265, the lamp lumens will depreciate to 70% of initial output when the lamp reaches 12,500 hours of burning. In this case, LLMF = 0.70

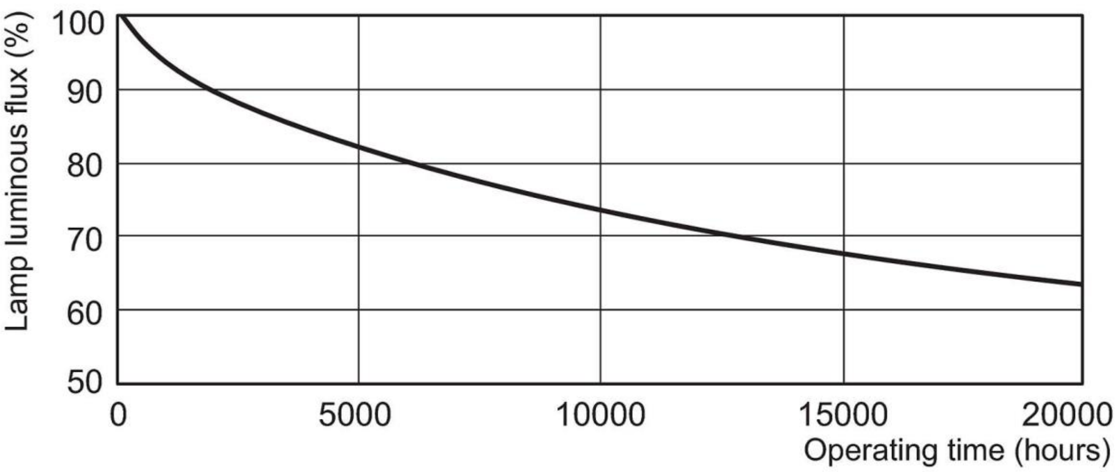


Figure 265: Typical Lamp Lumen Depreciation (Image Credit: Author)

Luminaire maintenance factor (LMF) is the proportion of the light output from a luminaire after a set time to the initial light output from the luminaire. It is mainly due to the accumulation of dust and dirt on the luminaire. The factors to consider here are the type of luminaire, indoor atmospheric conditions and maintenance interval.

Room surface maintenance factor (RSMF) is the proportion of the illuminance provided by a lighting installation in a room after a set time compared with what occurred when the room was clean. It takes into account possible dust and dirt that accumulate on room surfaces and reduce surface reflectance.

Combining the 3 above elements, the Maintenance Factor of a lighting installation is the product of above three elements:

MF = LLMF x LMF x RSMF

The following overall MF is generally taken based on experience for all conventional luminaires (except LED).

- Air Conditioned interiors 0.85
- Non Air-conditioned interiors 0.80
- Industrial Areas (normal) 0.7 - 0.75
- Industrial Areas (dusty) 0.65- 0.7

For LED luminaires, light depreciation will be lower because LED tends to maintain its output longer. Hence the MF can be taken as .05 more for each of the above cases. E.g. for an air-conditioned interior, the MF can be taken as 0.90 with LED (instead of 0.85).

28.6.3 Spacing To Height Ratio (SHR)

Figure 266: Spacing To Height Ratio Of Luminaires (Image Credit: Philips Lighting)

SHR is Spacing distance **(S)** / Mounting height **(H)** as in Figure 266. Here **H** is the height above the work plane. If the spacing between rows of luminaires is high, then the uniformity can suffer because the light beams will not spread enough. That will also depend on the photometric characteristics of the luminaire. The manufacturer usually specifies the maximum SHR for each luminaire in two perpendicular directions. For rectangular fluorescent luminaires, the maximum SHR can go up to 2.2 (perpendicular to lamp length) and just 1.0 (along lamp length).

28.7 Indoor Lighting Design And Calculating Power Density

28.7.1 Design Steps For Indoor Lighting

a. Identify the lighting requirements for the application. This is taken from SS 531-1 for the specific application. Examples can be seen in Table 1 earlier.
b. Select the lamp type and luminaire. This selection is based on the familiarity and knowledge of the designer about a specific luminaire, previous experience, in-house preference for a particular brand, the marketing and sales efforts of the lighting company, etc. The selected lamps and luminaires will influence lighting level, Correlated colour temperature, CRI and efficiency of the lighting system.
c. Use the Lumen method of calculation

The *lumen method* of lighting design is a well-established method. It gives good insight into what a lighting design software does. It is good for practitioners to know the Lumen method in order to understand the choices they have while giving inputs to computer programs. A software called Dialux is freely available to make lighting design easier and elegant. Most lighting companies seem to support Dialux by providing details of their luminaire range and IES files to be easily exported to Dialux. The lumen method of lighting design involves a few easy steps as below:

a. Determine, length, width and height of working space
b. Calculate Room Index (K)
c. Select the reflectance factors of ceiling/wall /working plane
   Rc / Rw/ Rp (For offices, 0.7, 0.5, 0.3 are common default values)
d. Look at the Utilisation Factor table of the selected luminaire
e. Choose Utilisation factor (UF) from the Luminaire's UF table
f. Select Maintenance factor (MF)
g. Calculate no. of luminaires with the formula

$$N = \frac{E \times L \times W}{C \times T \times UF \times MF}$$

Where,

E = Average Illuminance (lux)
L = Length of room in 'm'
W = Width of Room in 'm'
C = Light output / lamp (lumens)

T = No. of lamps per luminaire
UF = Utilisation Factor
MF = Maintenance Factor

- Make a layout of the luminaires
- When applied to a square or rectangular interior, the general layout can be as in Figure 267.

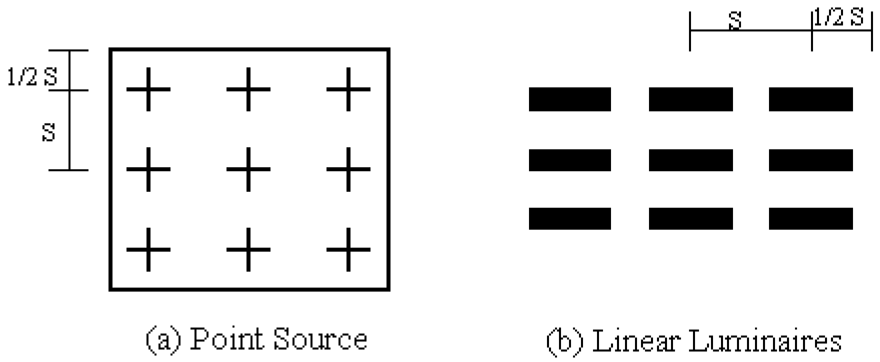


Figure 267: Luminaire Spacing Arrangements (Image Credit: Author)

28.7.2 Calculating Power Density (Watts / m^2)

a. The first step is to calculate the load (in Watts) per luminaire. That will include (lamp load + ballast loss per lamp) x the no. of lamps per luminaire. That is the load per luminaire.
b. The next step is to multiply the above by the no. of luminaires installed.
c. Calculate the area of interior in m^2
d. Power Density = Total Watts / m^2

28.7.3 Case Study

Kapco Motor Traders Pte Ltd (KMT) is renovating their office with following parameters:

- Area = 48m x 20m x 2.8m
- Design illuminance = 500 lux
- Luminaire = Type ABC with 2 x 36W with Mirror louvre
- Lamp = T-8 36W with 2 lamps in each fitting
- Maintenance Factor = 0.85

- Room Reflectance = 70, 30 and 10
- Light output per lamp = 3275 lm
- Ballast used = Electronic ballast with 4 Watts loss per lamp
- Usage time = 12 hrs / day

Question

A. Calculate the no. of luminaires required to provide 500 Lux average

B. Calculate the Power Density in W/m^2

Luminaire : Fluorescent with Mirror optic louvre

Lamp : 2 Nos. of T8-36W tubes in each luminaire

Measurement code (in Lab) : LVK0148500-00 (Related to Table 18)

Table 18: UF Table of Specific Luminaire In Case Study

Room index K	Reflectance (%) for Ceiling, Walls and Working plane										
	80	80	70	70	70	70	50	50	30	30	0
	50	50	50	50	50	30	30	10	30	10	0
	30	10	30	20	10	10	10	10	10	10	0
0.60	0.43	0.41	0.43	0.42	0.41	0.37	0.37	0.34	0.37	0.34	0.33
0.80	0.51	0.48	0.50	0.49	0.47	0.44	0.43	0.41	0.43	0.41	0.39
1.00	0.56	0.52	0.56	0.54	0.52	0.49	0.48	0.46	0.48	0.46	0.45
1.25	0.62	0.57	0.61	0.58	0.56	0.53	0.53	0.50	0.52	0.50	0.49
1.50	0.65	0.59	0.64	0.61	0.59	0.56	0.55	0.54	0.55	0.53	0.52
2.00	0.71	0.63	0.69	0.66	0.63	0.61	0.60	0.58	0.59	0.58	0.56
2.50	0.74	0.65	0.72	0.68	0.65	0.63	0.62	0.61	0.61	0.60	0.59
3.00	0.76	0.67	0.74	0.70	0.66	0.65	0.64	0.63	0.63	0.62	0.61
4.00	0.79	0.68	0.77	0.72	0.68	0.67	0.65	0.65	0.64	0.64	0.62
5.00	0.81	0.69	0.78	0.73	0.68	0.67	0.66	0.66	0.65	0.65	0.63
	calculated acc. to CIE publication 40 and 52 LVK0148500-00										

ANSWER (in steps)

A. No. of Luminaires

Room Index K =

$$\frac{\text{(Length 48m x Width 20m)}}{\text{(Height 2.8m—1) (48+20)}} = 7.8$$

1.When K = 7.8., take the maximum of 5.00 from the UF table
2. From the Table, for K = 5.00 and Room Reflectances of 70-30-10, the UF=0.67
3. Use the formula

$$N = \frac{E \times L \times W}{C \times T \times UF \times MF}$$

$$= \frac{48 \times 20 \times 500}{3275 \times 2 \times 0.67 \times 0.85}$$

i. *Luminaires*

1. Power Density

1. A 36W tube dissipates only 32W when operated with an Electronic ballast
2. Load per lamp = 32W (lamp) + 4W (ballast loss) = 36W
3. Load for 125 x Twin-lamp Luminaires = 125 x 36W x 2 = 9.00 kW
4. Area served = 48 x 20 metres

Power density = 9000W / 960 Sq. Meters = *9.40 W/ m^2*

Chapter 29: Characteristics of Lamps-Ballasts And Accessories

29.1 Introduction

Buildings and projects now have a vast choice of lamps and LEDs to suit their applications. The history of electric lighting has been one of continuous development with major innovations in the last few decades.

When the incandescent lamp was invented in 1879 by Thomas Alva Edison, its “efficacy* was just 3 lm/W. That has now improved to about 12 lm/W for commonly used wattages 25-100W. In 1930s and 40s, the invention and commercialisation of Fluorescent and Gas discharge lamps offered efficacies around 30 to 35 lm/W. Now they have reached beyond 100 lm/W. In fact, the T5 fluorescent lamp seems to be still one of the most suitable light sources for interiors up to 8 Metres in height in terms of Total Cost of Ownership. A fast-progressing innovation in lighting is the use of Solid State Lighting i.e. Light Emitting Diode (LED). An overall look at the Lamp family is in Figure 268.

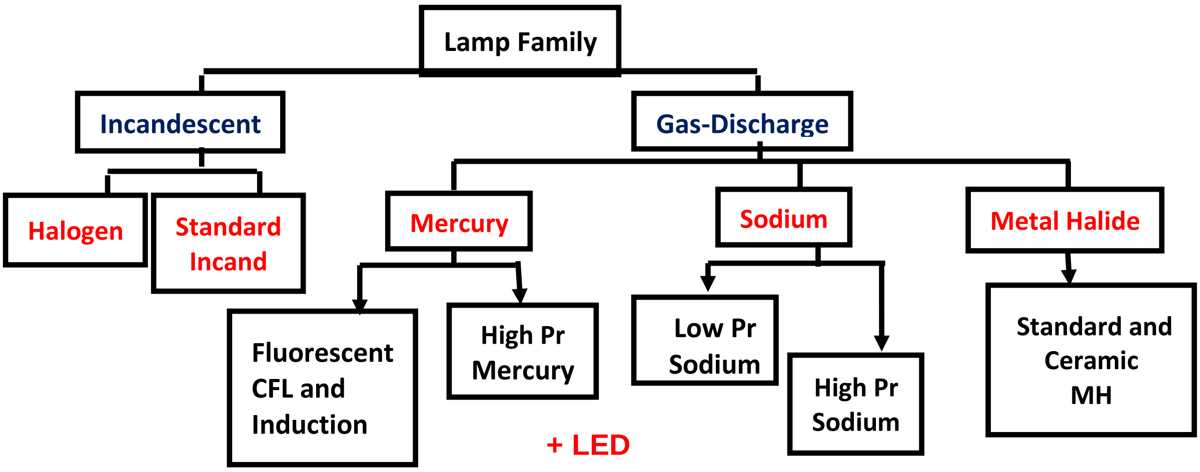


Figure 268: The Lamp Family (Image Credit: Author)

29.2 Lamps And Ballast Characteristics

29.2.1 Incandescent Lamp

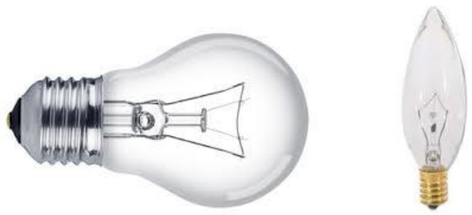


Figure 269: Typical Incandescent Lamps

(Image Credit: Philips Lighting)

In a typical incandescent lamp (Figure 269), an electric current passes through a tungsten filament which is a high-resistance wire and heats it to incandescence (= light emitted through heat). To prevent oxidation of the filament, the bulb contains some inert gases like Argon and Nitrogen. Over time, the evaporation of tungsten from the filament blackens the inside of the bulb and depletes the filament until it eventually breaks at its thinnest point. So the life of the incandescent bulb is just about 1,000 hours. Because of its low efficacy, this lamp is gradually being banned in many countries including Singapore (from mid-2015). Still this family of lamps is expected to be used for a long time in future by many under-electrified countries of Asia, Africa, and Latin America because of its affordability, ability to glow at any low voltage and freedom from accessories like ballast, starter, capacitor etc.

29.2.2. Halogen Lamp

The halogen lamp family (Figure 270) is also incandescent lamp with a tiny filament. To minimise its evaporation, some 'halogen' compounds are introduced in a quartz or hard-glass bulb. This lamp comes in a few shapes and wattages to suit different applications, mainly in social (and non-working) areas and car headlights. Its efficacy is about 25 lm/W but it is still deemed as an energy-guzzler and a source that heats up the interior.

Figure 270: The Halogen Lamp Family

(Image credit: Philips Lighting)

The spectrum of both incandescent bulb and halogen lamp contains all wavelengths of the visible spectrum (from violet to red) as shown in Figure 271.

Figure 271: The Rich Spectrum Of Halogen Lamp Used Mainly In Shop Lighting (Image Credit: Philips Lighting)

Because of this rich spectrum, these lamps are deemed to have the highest Colour Rendering Index of 100. Especially it is more popular in lighting up shops and shopping centres, hotels, homes, restaurants, etc because of its CRI and the sparkling light appearance. With the small size of its filament and easy optical control of light beam, the halogen lamp is also a preferred light source for car head-lights.

29.2.3 Energy Saving Alternatives

Both the standard bulb and Halogen are thermal emitters of light and hence not so energy-efficient. They add to the air-conditioning load to cool the interior. While the incandescent bulb is getting banned in Singapore and some other countries, Halogen lamps are very much in use. There are energy-saving alternatives to Halogen lamps such as Compact Fluorescent Lamp, Ceramic Metal Halide Lamp and Light Emitting Diode. These lamps are covered later.

29.2.4 T8-T5 Fluorescent Tubes

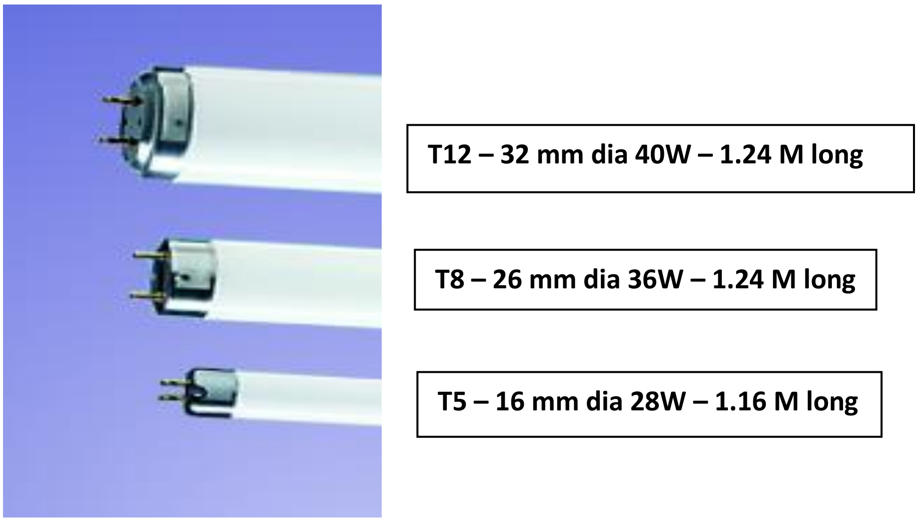


Figure 272: The Fluorescent Lamp Family
(Image Credit: Philips Lighting)

The Fluorescent lamps (Figure 272) come in 3 diameters. The oldest is T12 (1.5” diameter). Though it is not so energy-efficient, it is used in many developing countries because of its ability to start at low voltage at night. The T8 (1.0” diameter) provides the same output as 40W but with 10% less power. T5 is the most efficient in this family. But its diameter is lower (5/8”) and its length shorter than the T12-T8 tubes. It is highly recommended to avoid the use of T5-Adapter tubes or LED tubes in an old luminaire that is pre-wired for T8 tube. That is because the reflector of the old luminaire was designed for T8’s bigger diameter that does not suit T5. The old accessories (like magnetic or electronic ballast, starter, capacitor, etc for T8) will still remain inside the fitting. Hence, there is a possibility that those existing accessories may get in series with the built-in driver of a LED tube. The result could be overheating or short-circuit of some of the components that could cause fire hazard or electrical faults.

A fluorescent tube is basically a low pressure mercury vapour Lamp with a small dose of noble gases like Argon and Krypton (Figure 273). Initially, free accelerated electrons from the heated electrodes tend to excite the noble gas and then the mercury atoms via impact ionisation. This creates UV emission which is converted by the fluorescent powder to visible light.

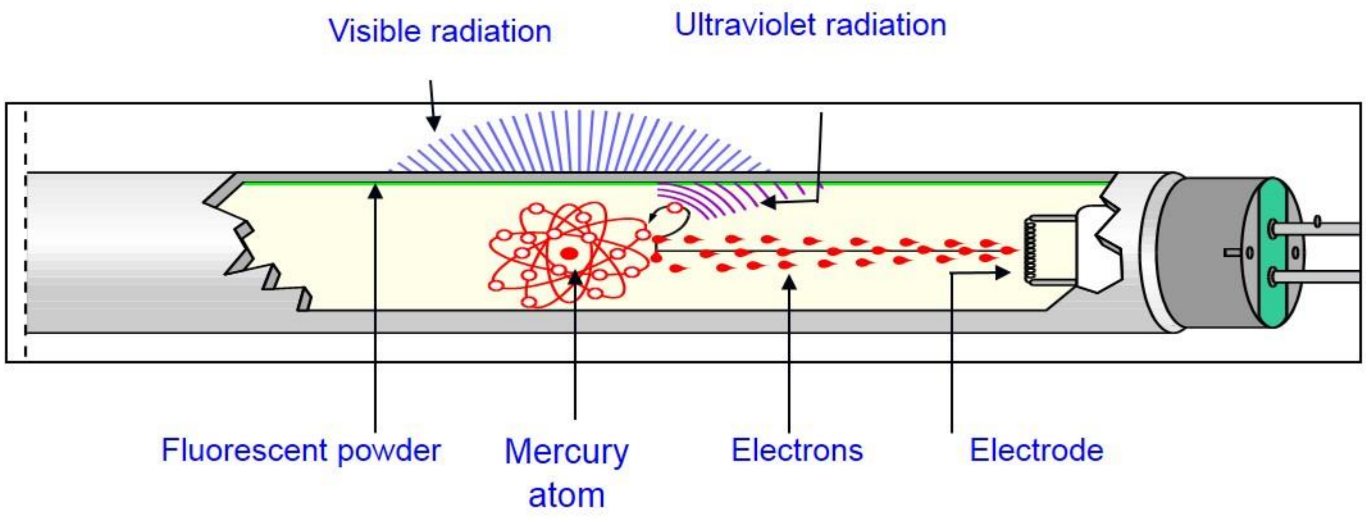


Figure 273: The Fluorescent Lamp Operation
(Image Credit: Philips Lighting)

The composition of the fluorescent powder determines the desired light spectrum and colour temperature. The tubes that are preferred for offices and industries are the 'Tri-Phosphor' type that give out 30% more light than the common Daylight tube. The latter has also a lower Colour Rendering Index of 70 and hence not recommended for working interiors as per SS 531-1. Figure 274 shows the fluorescent lamp spectrum of 4000K and CRI of 85.

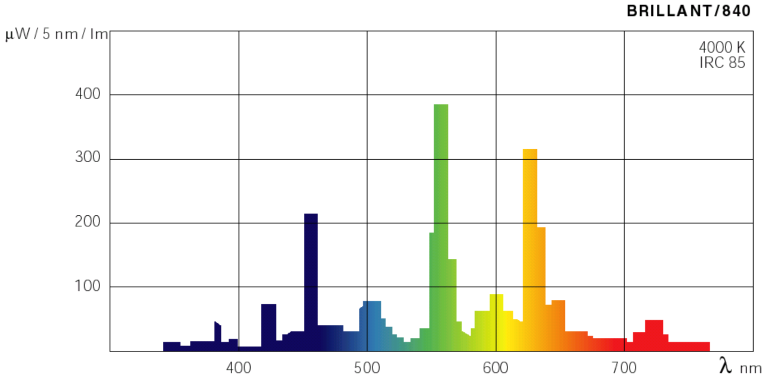


Figure 274: Spectrum of Daylight Tube
(Image Credit: Philips Lighting)

29.2.5 Ballasts for Fluorescent lamp

29.2.5.1 The Electro Magnetic (EM) Ballast

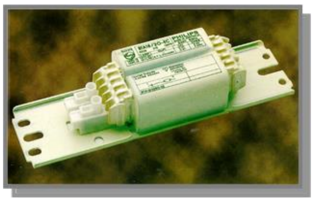


Figure 275: The Electro Magnetic Ballast
(Image Credit: Philips Lighting)

The fluorescent lamp (until 1990s) was generally operated with the so-called Electro-Magnetic (EM) ballast (Figure 275). The EM ballast had two versions, one with about 9W standard loss and the other with about 6W loss (called the Low loss ballast).

29.2.5.2 The Electronic (EL) Ballast

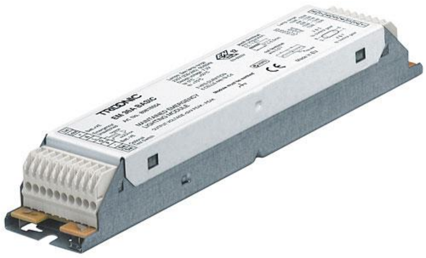


Figure 276: The Electronic Ballast (Image Credit: Zumtobel -Tridonic)

Many projects in Singapore changed to the Electronic (EL) ballast (Figure 276) 25 years ago while there are still many installations with the old EM ballast. Marketing of EM ballasts has however stopped. However, there is still marketing and presence of EM ballasts in many Asia Pacific countries. The advantage of EL ballast is a 20% reduction of electrical load and corresponding energy savings as shown in Table 19.

Table 19: Energy Saving Due To EL Ballast

Same Lamp	Ballast Type	Lamp Watts*	Ballast loss	Total Watts/lamp
T8-36W	EM	36W	9W	45W
T8-36W	EL	32W*	4W	36W

*Note***:** *The T8-36W tube when operated with the EL ballast will dissipate* only 32W in the tube. With a ballast loss of 4W, the total input-power per lamp will be 36W.

So the load-reduction with an EL ballast in a twin tube fitting will be 18W (= 2 x 9W). Besides, the EL ballast provides more visual comfort due to avoidance of the so-called stroboscopic effect that is possible at 50 Hz. The EL ballast is also cooler in temperature and enables longer life of the fluorescent lamp due to less stress on the lamp electrodes.

29.2.6 Compact Fluorescent Lamp

This miniaturized fluorescent lamp (called Compact Fluorescent Lamp or CFL Figure 277) became commercially available from the eighties. They are now extensively used in homes, commercial centres, hotels, restaurants, public housing, etc because of its compact size and higher efficacy at about 55 lm/W compared to incandescent's 12 lm/W. The latter comes in 2 versions i.e. "Integrated" (with the ballast inside) and Non-Integrated (with ballast outside in the luminaire)

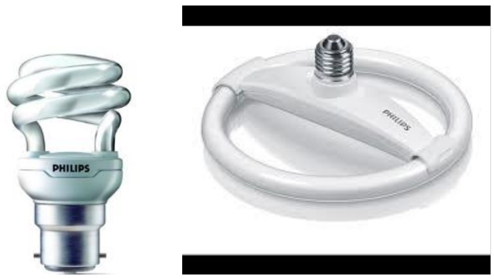


Figure 277: Compact Fluorescent Lamp (Image Credit Philips Lighting)

29.2.7 High Pressure Mercury (HPM) Lamp

While the fluorescent tube produces low light intensities and suitable for ceilings up to 8 metres (for T5), there is another group of lamps with higher intensities suitable for mounting heights greater than 8 metres. These applications are in high bay industries, warehouse and street lighting. These lamps are collectively called HID lamps as follows:

Figure 278: High Pressure Mercury (HPM) Lamp
(Image Credit: Philips Lighting)

The HPM lamp (Figure 278) contains mercury vapour in a quartz discharge tube (called a burner) which is inside a pear-shaped bulb. It emits a large proportion of its energy in bluish-white light. The inner surface of its pear-shaped bulb is coated with a fluorescent powder that produces about 10 % additional light from the UV content of the burner. The HPM lamp has rather low efficacy of about 60 lm/W and hence it is gradually being phased out by the lighting industry with higher efficacy lamps like LED, Induction, etc.

The HPM spectrum and an application example are in Figure 279

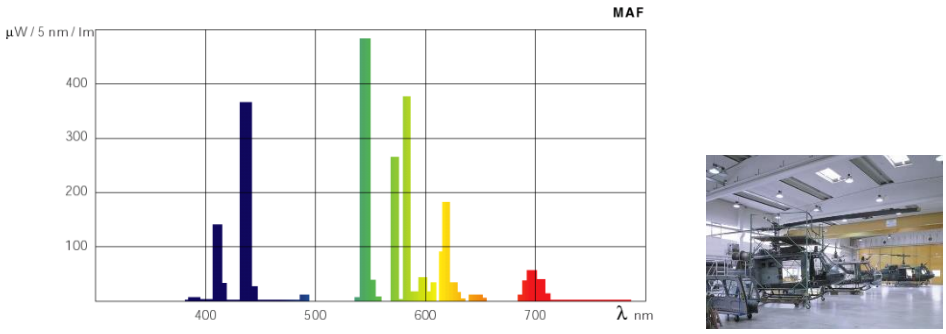


Figure 279: HPM Lamp Spectrum And Typical Application
(Image Credit: Philips Lighting)

29.2.8 High Pressure Metal Halide (MH) Lamp

Figure 280: The Metal Halide Lamp (Image Credit: Philips Lighting)

The High Pressure Metal halide simply called as Metal Halide (MH) (Figure 280) is basically also a Mercury lamp with Quartz tube. But additional 'Halide' compounds (i.e. salts of Iodine and Bromine) are introduced to serve as a catalyst that produces higher light output and better CRI. This lamp is mainly used for sports lighting like swimming pools, sports stadium, tennis and basketball courts and also for high bay lighting of some industries. The limitation is the colour-shift during lamp-life and rather short life of about 8000 hours. (Note: There is another version of Metal Halide with more refinements to increase its Colour Rendering Index to >90 for colour telecast from professional sports facilities like Olympic stadiums, F-1, World cup soccer. Its spectrum is as shown in Figure 281.

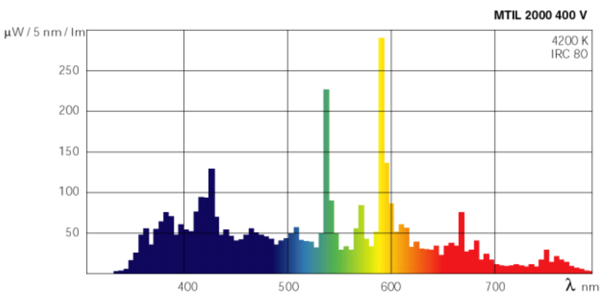


Figure 281: Spectrum of Sports Lighting MH lamp
(Image Credit: Philips Lighting)

29.2.9 High Pressure Sodium (HPS) Lamp

Figure 282: High Pressure Sodium Lamp (Image Credit: Philips Lighting)

The HPS (High-Pressure Sodium) lamp (Figure 282), gives a very high efficacy of 140 lm/W due to the nature of sodium and gases inside. But the spectrum is not rich enough that it only gives predominantly yellow light output and its CRI is low at 25. Because of these reasons, sodium is not preferred for indoor applications but more or less exclusively used in road lighting (Figure 283).

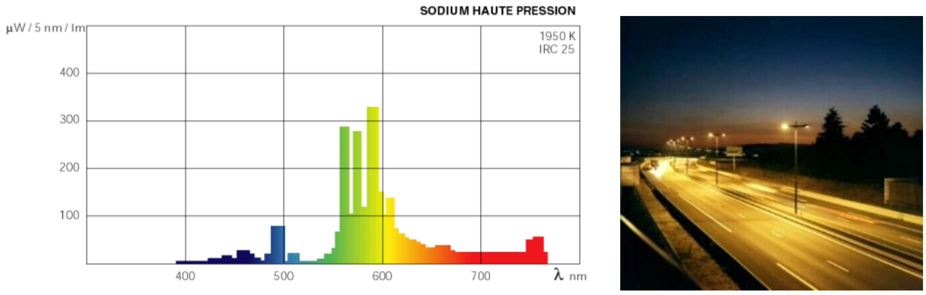


Figure 283: High Pressure Sodium Spectrum and Road Lighting Application (Image Credit: Philips Lighting)

29.2.10 Low Pressure Sodium (LPS) Lamp

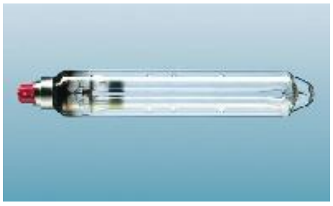


Figure 284: Low Pressure Sodium Lamp (Image Credit: Philips Lighting)

Low Pressure Sodium (Figure 284) has the highest efficacy of about 200 lm/W in the lighting industry (higher than LED at this point of time). Despite such high efficacy and energy-saving possibility, the LPS lamp is not accepted in working or social areas due to its 'mono-chromatic' yellow colour with practically zero Colour Rendering. The only place where it is still useful is in tunnels (Figure 285) where very high lighting levels are required at the entrance zone to help adapt the vision of drivers from high daylight illumination outside to the 'black hole' nature of the tunnel opening. Here the Colour Rendering is not known to be critical.

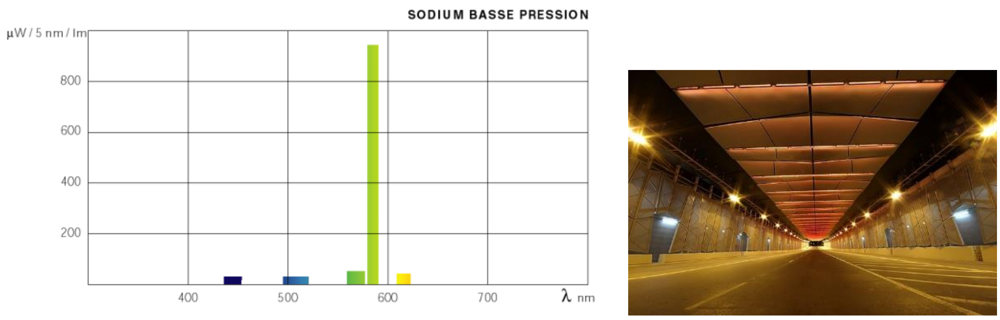


Figure 285: LPS Lamp Mono-Chromatic Spectrum And Tunnel Application (Image Credit: Philips Lighting)

29.2.11 Ceramic Metal Halide (CMH) lamp

Figure 286: Ceramic Metal Halide (CMH) Lamps (Image Credit: Philips Lighting)

The standard Metal Halide lamp uses a ‘Quartz’ tube and Metal Halide vapour. But the Ceramic Metal Halide (CMH) Figure 286 uses a ‘Ceramic’ tube instead. The discharge of metal halide in a ceramic tube produces entirely different light spectrum suitable for many indoor and outdoor applications. The efficacy increases to about 90 lm/W and CRI ranges to 80-90. So this lamp is preferred for shop and show-window lighting. It is an ideal replacement for Halogen lamps because of about 4 times more light output/W and much longer life-span. But the existing Halogen luminaire has to be changed because CMH is a gas-discharge lamp requiring a ballast, while halogen is incandescent with a step-down transformer. The rich spectral light distribution of CMH lamp (called “Mastercolor” by one Brand with 4000K Colour Temperature) is shown in Figure 287. For the past several years, CMH has become one of the best shop-lighting lamps and energy-saving substitute for Halogen.

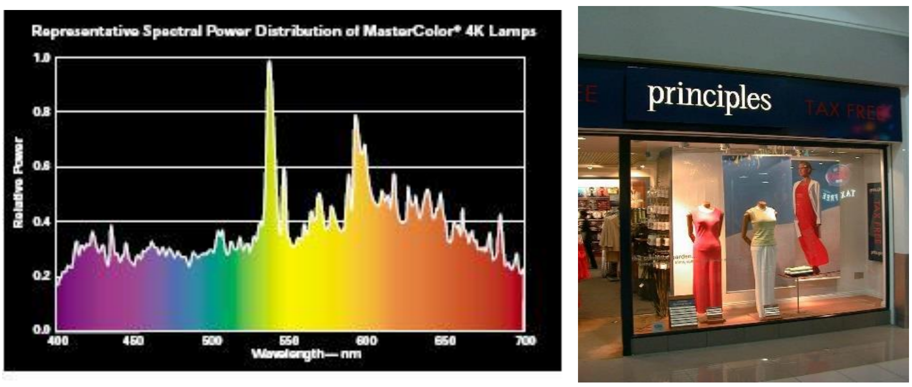


Figure 287: The Rich Spectrum Of CMH For Shop Lighting
(Image Credit: Philips Lighting)

29.2.12 Common Characteristics Of HID Lamps

From the time of switching, HID lamps can take up to 4 minutes to reach full brightness and stabilised electrical state as seen in the Figure 288. They also have another limitation. When there is power interruption and after it is restored quickly, the lamp will not re-strike immediately but take some time. This can take up to 8 minutes during which there could be total darkness and safety issues. Hence it is advisable to use a few Halogen, LED or fluorescent lamps that will re-strike immediately after power restoration.

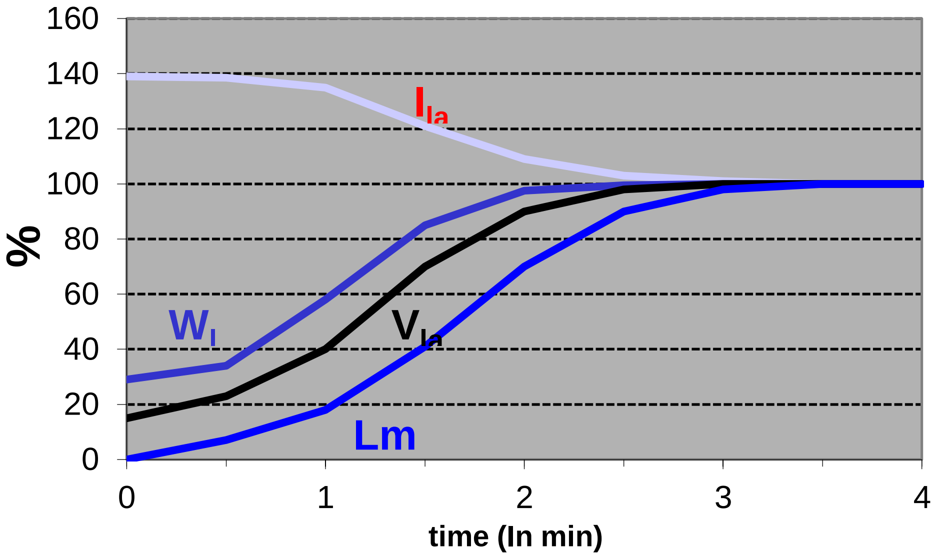


Figure 288: The Start-Up Characteristics Of HID Lamps (Image Credit: Philips Lighting)

29.3 Electrode-Free Lamps

All the lamps described so far have electrodes at both ends of the discharge tube or burner. The gradual evaporation of the emission-coating on this electrode signals the end of lamp life. What, if there is a lamp with no electrodes? Theoretically such a lamp could have decades of maintenance-free life. There are 3 such light sources:

1. Light Emitting Diode (LED)
2. Induction Lamp (IL)
3. Light Emitting Plasma (LEP) (Not covered in this manual as it is less suitable for Building interiors)

29.3.1 Light Emitting Diode

LED has been an 'indicator' lamp in our TV sets and appliances for almost 40 years now. So the LED technology has been around for a long time without our paying much attention. Electrical control panels and traffic lights started to make LED more visible. From that position of 'indicator', LED has now become a big time 'illuminator' in many applications (Figure 289) with clear advantages of 'white' light, long life, high efficacy, and small size and little maintenance.

Figure 289: Some Applications Of LED (Image Credit: Philips Lighting)

29.3.2 Principles Of LED Operation

LED's light generation principle is similar to what happens in a gas discharge lamp except the discharge happens in a solid state material. Hence LED is also called Solid State Lighting (SSL). As the name implies, LED is a Diode belonging to the Semi-conductor field. Photon-emitting p-n junctions are typically based on a mixture of elements like Gallium, Arsenic, Phosphorous, Indium, and Aluminum. The recent addition of Silicon Carbide and Gallium Nitride has yielded Blue-emitting diodes. The p and n junction is the meeting point of two different semiconductor materials (Figure 290).

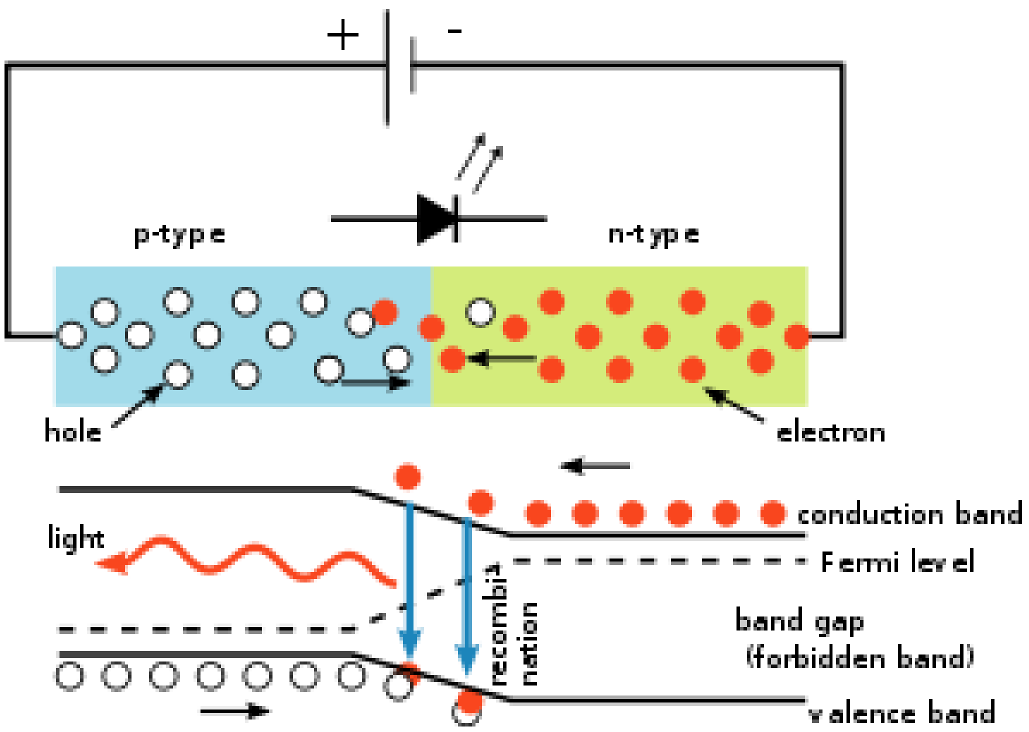


Figure 290: LED Light Generation Method

(Image credit: Wikipedia, The Free Encyclopedia)

When dissimilar semiconductor materials are fused, the flow of current into the junction and the wavelength of light are determined by the electronic character of each material. Electrons from the **n**-type region and holes from the **p**-type region recombine in the vicinity of the junction that inhibits current flow and creates heat. So to make the current flow, an external DC voltage is necessary. This DC voltage is provided by an electronic driver that converts AC to low voltage DC (usually 12V or 24V). A typical LED cross section is shown in Figure 291.

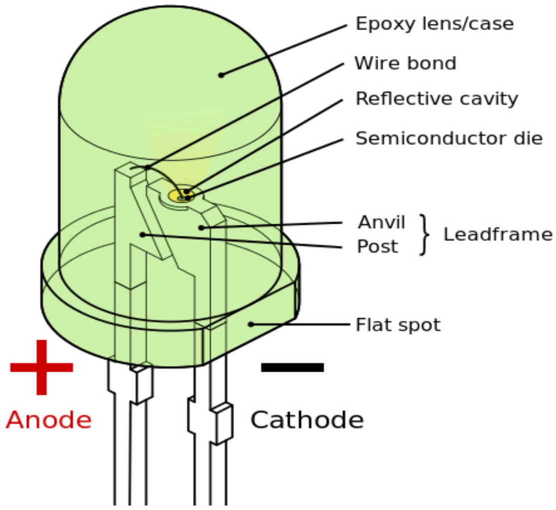


Figure 291: Cross Section of A LED

(Image Credit: Wikipedia, The Free Encyclopedia)

29.3.3. Heat From LED

At the p-n junction, substantial heat is developed and it needs to be conducted away through a heat sink (as shown below) or other dissipation methods. So heat sinks with cooling fins (Figure 292) are common features of many LED luminaires and lamps.

Figure 292: Cooling Fins On LED Luminaire Ad Lamps

(Image Credit: Philips Lighting)

The heatsink is important part of LED luminaires because it can affect both light output and lifespan.

29.3.4 Making White Light From LED

By nature, LED generates monochromatic light. To create white light, two or more colours need to be combined. One solution is to mix the output of LEDs in Red, Green and Blue (RGB colours) in a single window and get white light. This is as per the well-known Physics principle of adding Red, Green and Blue to produce White light as in Figure 293.

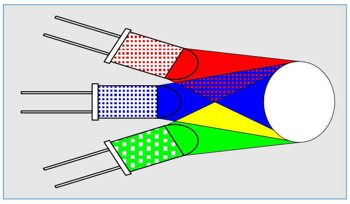


Figure 293: RGB Producing White Light

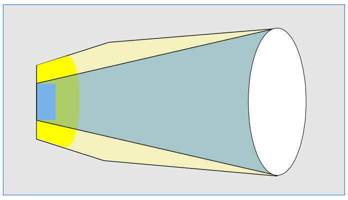


Figure 294: Blue LED With Yellow Phosphor

(Image Credit: Philips Lighting)

Another and more common approach is to use LED that emits blue light and coat it with yellow phosphor that converts part of the blue to yellow light (Figure 294). In the additive colour-mixing process, Blue + Yellow = White. If the yellow coating is less, the LED looks bluer (like 6000K). If the yellow coating is more, then it looks more yellow (like 3000K). By applying multiple phosphor coatings, blue light can be converted into more colours to improve the CRI to a level of >80 recommended for working interiors and shop lighting. But heat-resisting phosphor can be expensive. So a bluish white (6000K) LED will cost less than a white (4000K) LED because of additional phosphor layer for the latter. For the same reason, the light output of blue LED is higher than white LED as the phosphor tends to absorb part of the light.

29.3.5 LED Efficacy (Lumens/W)

Right now, the LED industry claims an operational efficacy of about 140 lm/Watt. This is the so-called ‘performance efficacy’ delivered after taking care of heat dissipation in the total system. Further increase is predicted in the coming years taking LED to unique high levels. The nearest established competitor to LED in office lighting is T5 Tube and for street lighting, the HPS lamp both having >100 Lumens/W and lifespans exceeding 20,000 hrs. Just for this group of applications, a comparison of Sodium and T5 with LED and Induction are in Table 20. The Induction lamp is described further on.

Table 20: Comparison Of High Efficacy Lamps

Lamp	Efficacy Lumens/ W	Life time Hrs	CRI	Applications and Remarks
Induction	85	50,000	80-90	Industries, Warehouses and Street lighting. No temperature issues and hence known to be durable where maintenance-freedom is important.
T5	104	20,000	>80	Offices, industries and supermarkets. Well-established and trouble-free product
HPS	140	24,000	25	Street lighting. Well-established, most common and durable product
LED	140	50,000	70-90	Offices, industries, Supermarkets, shops, Streets, Tunnels, etc. 140 lm/W is the ‘delivered efficacy” under practical conditions.

It can be seen that T5 and Sodium are still good competitors of LED in similar applications but the former are at lower cost. This may change more in favour of LED in the coming years due to fast technological improvements by many brands, the huge installed manufacturing capacities and decreasing prices.

29.3.6 Induction Lamp

The induction lamp is a well-established technology which features reasonably good efficiency and very long life. It creates light by using high-frequency (>250 KHz) in an electromagnetic field to excite mercury atoms (Figure 295). The ionized mercury creates UV radiation which is converted to visible light via a fluorescent coating.

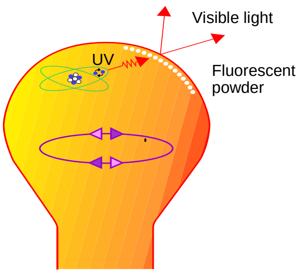


Figure 295: Principle Of Induction Lamp

(Image Credit: Philips Lighting)

The difference of Induction lamp is – there is no electrode and hence theoretically this lamp can last longer than any known lamp. However, the High Frequency generator (at >250 KHz) in Figure 296 is like any other electronic ballast with a lifespan of 50K-60K hours (about 15 years in an office or industry use).

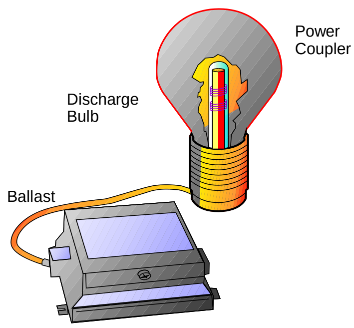


Figure 296: Electronic Ballast Of Induction Lamp

(Image Credit: Philips Lighting)

Induction lamps use a small dose of mercury amalgam i.e. mercury combined with other metals. This amalgam is in a chemically stable state, more like a solid paste and not harmful in the way pure mercury is. It can be recovered at the end of lamp-life more safely than pure mercury which is in liquid form and more difficult to gather without spillage.

29.4 Comparison Of Different Lamps For Same Interior

A comparison of the characteristics of lamps used from similar heights are shown in Table 21.

Table 21: Comparison Of Lamps And Mounting Heights

Mounting Height	Suitable lamps	Comments
3-5 m	LED, T8-T5, CFL and CMH	Offices, Industries, shopping centres
5-7 m	LED, T5 (High output type), CMH	Offices, Industries, Shopping Centres
7-16 m	LED and Induction	Heavy Industries, Warehouses, Atriums

29.5 Selection Criteria Of Different Lighting Systems

Table 22 shows the selection criteria and the technical boundaries that are relevant to the different lamps and their cost-benefit for the various light sources.

Table 22: Technical And Application Comparison Of Light Sources In Professional Applications

	Technical Boundary	T8-T5 with Electronic ballast	Sodium	Metal Halide	LED	Induction	Remarks
1	Life span	20K hrs	24K hrs	8K hrs	50K hrs	60-80K hrs	As of now, many LED systems seem to have shorter life due to the acute competition and consequent quality-compromise. The technology itself is sound.
2	Colour Rendering Index	80-90	25	70	70-90	80-90	Working areas must have CRI of minimum 80
3	Mercury content (If it is Amalgam, only weight of pure Mercury is taken)	10mg	10-50mg	20-60mg	Nil	10-15mg	

4	Photopic lumens / Watt	90-104	100-140	70	40-140	75-85	Photopic lumen is applicable during daytime and generally lighting levels >20 Lux.
5	Time to full brightness	1-5 Sec	3-5 Minutes	3-5 Minutes	1-5 Sec	10-30 Sec	
6	Colour temperature range	2700-6500K	1950K	3500-5400K	2700-6000K	2000-6000K	
7	Flicker	No	Yes	Yes	No	No	
8	Application areas	Offices and industries up to 8 metres in height	Roads, Open areas and tunnels	Mostly for Sports (Flicker control for professional applications necessary	Retail, Office, industries, Roads, Façades and dynamic effects	Industries and warehouse with >10 meters' height, Roads and tunnels	

Chapter 30: Energy Efficiency And Life-Cycle Study

30.1 Factors Affecting Lighting Energy

30.1.1 Ratio Of Lighting Energy Cost To Product Cost

Lighting (together with other building services like air-conditioning or lifts), consumes certain amount of energy. For an air-conditioned commercial building in the tropical climate, this is estimated at 20% of the total energy consumption of the building. So every effort must of course be made to minimise this energy. But the surprising part is – when we do the Total Cost of Ownership (TCO) / year, the energy-part constitutes a very high percentage of the TCO in a lighting installation unlike other services. Table 23 shows this.

Table 23: Typical Lamps And Energy Consumption

Lamp Type	Ballast loss	Total W	Lamp life	Energy consumed in life time	Energy cost @S$ 0.20/kWh	Product cost
75W bulb	Nil	75W	1000 hrs	75 kWh	S$ 15.00	S$ 0.80
36W tube	9W	45W	10,000 hrs	450 kWh	S$ 90.00	S$ 3.50

For a product like incandescent bulb, the energy cost is 18.75 times the product price (=15.00 / 0.80). For a fluorescent tube, it is 90.00 / 3.50 = 25.71 times the product price.

For other services like air-conditioning or lifts, the capital cost of equipment (and annual depreciation) will form a much bigger part of TCO. But lighting equipment are relatively inexpensive but its annual energy-consumption is substantial. Hence careful choice of luminaires (even with higher investment on reputable and dependable brands) can provide both economy and peace of mind to building professionals.

30.2 High Efficiency Light Sources And Gears

Table 22 of Chapter 29 has covered many light sources for indoor and outdoor use. Of them, the following are deemed to be high efficiency types with the option to use with electronic gear (i.e. Ballast or Driver):

a. LED (for Offices, Industries, shops and Commercial premises)
b. T8-T5 (for Offices, Industries, shops and Commercial premises)
c. Ceramic Metal Halide (Shops, shopping centres)

30.2.1 LED As Leading Light Source

From an old indicator lamp on our TV sets and appliances, LED has grown to be a highly useful light source for many applications. The principles, operating characteristics and applications of LED are listed in Chapter 29. Unlike most other lamps, LED has no mercury content and hence is a truly sustainable light source. With its low energy requirement, it can also operate on direct DC supply of solar power. Thus, the advantage of LED can be summed up as follows:

a. Ultra-long life (>50K hours including the Driver)
b. Low power consumption
c. Low maintenance
d. No moving parts
e. No UV radiation
f. Cool beam of light
g. Digitally controllable
h. Environment-friendly

30.3 Selection Of Luminaires With High Utilisation Factor (UF)

30.3.1 Luminaire Light Distribution

In selecting luminaires with high Utilisation Factor (UF), we have to reckon with the specific interior and what type of lighting distribution will provide maximum impact suited to that interior. In other words, simply directing all the available light downwards is not always the solution.

The distribution of light from luminaires is broadly classified in Figure 297.

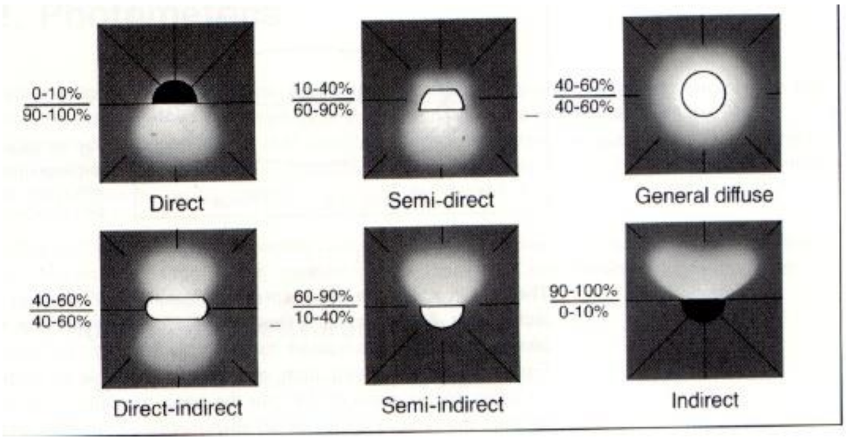


Figure 297: Luminaire Light Distribution Types

(Image Credit: Philips Lighting)

<u>Direct</u> lighting (Figure 298) applies to offices and industries with heights of up to 7-8 metres. Coupled with walls, ceiling and work surfaces being 'light or pastel' colour in finish, it will lead to high Utilisation Factor. Glare control of the luminaire is important through the use of appropriate diffusors or mirror-reflectors.

<u>Semi-direct</u> (Figure 299) may give the impression of sending some light upwards and wasting it thereby decreasing Utilisation Factor. But in high-ceiling interiors like heavy engineering workshops and warehouses, the throw of all the light downwards may render the ceiling dark and occupants may get visually tired with the dark contrast of ceiling. To have a sense of well-being, they ought to know the finite space in which they work. For this, high bay luminaires often come with slots or gaps on the upper part of the reflector so that some light is deliberately sent upwards to the ceiling. That provides a view of the ceiling and an assurance that occupants are not in a 'tunnel' like situation. So, achieving the highest Utilisation Factor is not always the aim in lighting practice. Avoiding severe contrast in the work interior is equally important to reduce eye-fatigue.

<u>General diffuse</u> lighting (Figure 300) is used where some 'vertical' illumination is important to reveal the walls, pillars and other possible obstructions in basements, in multi-storey car parks, corridors and passages of public housing apartments. Revealing of the human face from a distance is important to some extent for reasons of public safety.

Figure 298: Direct Lighting (Image Credit: Zumtobel -Tridonic)

Figure 299: Semi-Direct Lighting (Image Credit: Zumtobel -Tridonic)

Figure 300: General Diffuse Lighting

(Image Credit: Zumtobel -Tridonic)

Other light distributions (like Direct-indirect, Semi-indirect and Indirect) are not preferred in work spaces. They are somewhat wasteful of light but they are important to create 'impact' in social spaces like the Main lobby and Lift lobbies of prestigious hotels, atriums, conference and exhibition centres etc. Here the finish of the luminaire (like gold-plating and use of use of crystal glass, high-grade plastics, light-diffusing marble, etc) can emphasise the prestige of the building more)

30.3.2 Reflection Of Room Surfaces

Room Reflectances have been covered under chapter 28. They play a very useful part to give a higher UF of the installed light. Other than direct light from the system, what is diffused and reflected back from these surfaces contribute to better utilisation. For working interiors, it is highly recommended to use 'light or pastel' colour finish of the ceiling, walls and work surfaces. Restaurants, Clubs, theatres, etc are known to use dark colour finish for their interior as their aim is to create the so-called 'cozy' atmosphere and such premises are not governed by SS 531-1 requirements.

30.4 Lamp And Ballast Retro-Fit And Luminaire Upgrades

30.4.1 Lamp Retrofits

There are many situations where the change of an entire lighting system is not affordable or practical. Also, Luminaires in offices and industries often continue to be used for > 25 years without renewal, though their life class is about 10 years. In such cases, the changing over to retrofit lamps that save energy is logical. The following retrofits are common in existing luminaires:

a. CFL replacing the Incandescent lamp
b. LED bulbs replacing incandescent and Halogen lamps
c. LED tube to replace T8 Fluorescent tube

Most hotels and commercial establishments in Singapore have more or less retrofitted their incandescent downlights with CFLs. In a typical example, the 11W CFL with 8000 hrs lifespan replaces a 60W bulb with 1000 hrs lifespan.

- Load reduction (60-11) W = 49W
- Energy saved in 8000 hrs life (49x8000/1000) = 392 kWh
- @S$ 0.20/Unit, the monetary savings (392 x 0.20) = S$ 78.40
- Avoidance of 8 incandescent Bulbs @ S$ 0.80 each = S$ 6.40
- Total benefit of CFL = S$ 84.80
- Price of one CFL = S$ 8.00!

Similarly, the economics of LED bulbs and Retro-fit tubes can be calculated. While selecting the LED Retrofit tube, it should conform to the most recent standard IEC 62776: 2014 (Double-capped LED Retrofit Lamps). Non-conforming tubes have the potential to create Fire and Electrical safety incidents.

30.4.2 Ballast Retrofits

In Table 19 (chapter 29), we saw that the load-reduction due to a 'twin tube' EL ballast for 4' lamp is 18W. The extra cost of a twin-lamp EL ballast (over 2 x EM ballasts) can be recovered in a matter of less than 2 years. However, ballast retrofit is a very cumbersome process in existing fittings. The old luminaires have to be taken down to a workshop where the EM ballast, Capacitor, etc have to be taken out and re-wiring done with EL ballast. Luminaires have to be tested again and transported back to site and installed. During this time, the office or industry will have many dark areas and constant site work leading to employee discontent and complaints. So it is more elegant to procure new luminaires with EL ballast or totally new LED luminaires rather than retrofitting existing luminaires with so many site problems.

30.5 Depreciation, Product Mortality and Maintenance Issues

30.5.1 Lamp Lumen Depreciation, Mortality and Group Replacement

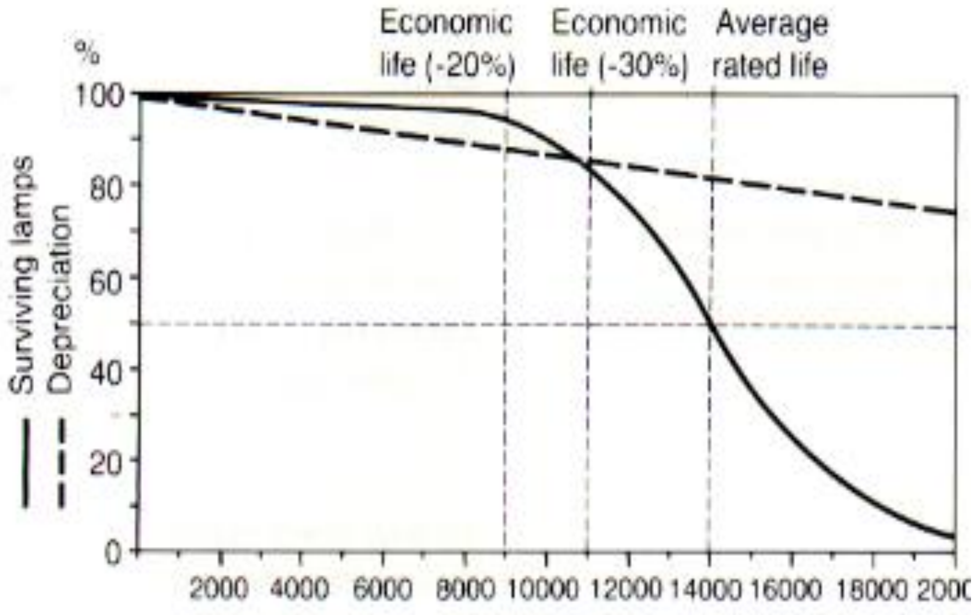


Figure 301: Lamp Depreciation And Mortality Graph (Image Credit: Author)

The declared life of a lamp by the manufacturer is the time when 50% of lamps will fail (Figure 301). Obviously, no building can afford to wait till half the lighting has failed. When a lamp burns out, the maintenance person first ascertains the lamp type (by visiting the site), gets a replacement lamp from the store, carries a ladder to the site, opens the fixture, replaces the lamp and then arranges for disposal of the failed lamp. The entire process may well distract employees in the vicinity. And without close supervision, the tendency is to drop the failed lamp into the nearest dust bin where they are quickly covered or probably smashed by other trash, releasing a small dose of mercury.

So, most lamp manufacturers and lighting maintenance firms recommend "Group replacement of lamps" at some point before they burn out. It greatly reduces labour wasted on spot re-lamping, reduces workplace disruption and better controls the lamp disposal process.

Group re-lamping is often done by professional contractors who have focus and training in this field. The other advantages of group replacement are:

a. Reduce inventory of replacement lamp and ballast. Lighting maintenance contractors maintain their own stock of lamps and ballasts, obviating the need for a customer to do the same.
b. Recycle lamps: Many facilities seeking LEED points or other green status may wish to hand this task over to a firm that knows the most economical and acceptable ways to meet requirements.
c. Secure incentives. Some lamp manufacturers occasionally offer rebates or discounts for bulk purchase of lamps. Some countries (like USA) offer incentives for reducing the load demand that is possible when switching to low-power lamps during group re-lamping.
d. Handle difficult locations. Professionals are better equipped for high bay or inaccessible situations.

How Often?

With increased lamp life of T8-T5 tubes, re-lamping cycles are spaced 3 to 4 years apart.
The average T5 lamp life is typically 20,000 hours when (by definition) 50 percent of lamps will have burned out. At 70 percent of that time (about 14,000 hours) and 4,000 hours' usage per year, the group replacement time will come to about 3.5 years.
With LED luminaires, it is common to take a 10-year life span as the time when the initial light output will depreciate to 70% of the initial value and it is called **L_{70}** life.

30.6 Dimming Controls, Occupancy Sensor And Daylight Link

30.6.1 Switching, Timer And Dimmer Control For Luminaires

Figure 302: Switch, Timer And Dimmer Controls

(Image Credit: Zumtobel Lighting)

The purpose of Indoor Lighting Controls is to provide the right light at the right time and place, saving as much energy as possible and providing the comfort expected for any application like offices and industries. The easiest way is of course, to use a wall-switch as we mostly do now. In bigger premises, it is possible to use Timers so that at a given time, the lights will come on. For example, a certain percentage of luminaires will switch off (say) at lunch time and switch on again when people resume work, etc.

Dimmer controls provide variable lighting. When lightbulbs are dimmed, it reduces their wattage and output which helps save energy. Dimmers are inexpensive and provide some energy savings when lights are used at a reduced level. They also increase the service life of lightbulbs significantly. However, dimming reduces an incandescent bulb's lumen output more than its wattage. This makes the bulbs less efficient as they are dimmed. For many reasons (mainly due to low efficacy, the incandescent bulb is progressively banned in many countries.

Dimmers-CFLs and Fluorescent tubes

Unlike incandescent bulbs, not all Compact Fluorescent Lamps (CFLs) are compatible with standard dimmers. This will be indicated on their package. Others require special dimming ballasts and bulb holders. Fluorescent dimmers can control dedicated fixtures to provide greater energy savings than a regular fluorescent lamp. Dimming type EL ballasts are required for this.

Dimmers and LEDs

Some light-emitting diode (LED) lightbulbs can be used with dimmers. LED bulbs and fixtures must be specifically designed for dimming, and you may need to replace existing dimmer switches with ones that are compatible with LED. The packaging or accompanying instructions will indicate if the product is dimmable and which dimmers are compatible. Fully compatible LED dimmers are expected to become more common as the LED industry expands.

30.6.2 Occupancy Sensing

Occupancy sensors work on the principle of sensing the natural heat emitted from humans or scanning for microwaves due to any interruption by moving objects (i.e. occupants). Occupancy sensors detect indoor activity within a certain area. They provide convenience by turning lights on automatically when someone enters a room, and save energy by turning lights off soon after the last occupant has left the room. Occupancy sensors must be located where they will detect occupants in all parts of the room.

There are two types of occupancy sensors: Microwaves and Infrared. The former sensor detects reflected waves (with Doppler Effect), while infrared sensors detect heat given out by humans. In addition to controlling ambient lighting in a room, they are useful for task lighting applications such as kitchen counters. In such applications, task lights are turned on by the motion of a person washing dishes and automatically turn off a few minutes after the person leaves the area.

Figure 303: Functioning Of The Occupancy Sensor

(Image Credit: Philips Lighting)

30.6.3 Daylight Linking

Lighting (whether natural or artificial) has a big influence on the appearance of a space and the moods and productivity of its occupants (Chapter 29). Daylighting is the controlled admission of natural light into a space to reduce or eliminate the need for electric lighting. It offers environmental, economic and social benefits when applied successfully. There is a great variation between sky conditions in tropical climates like ASEAN and those in Europe and USA. Most daylighting research is conducted in Europe and daylighting technologies, lighting calculations and simulations have been developed for those climates. Such welcome admission of daylight can bring in a lot of solar heat, thereby increasing the Envelope Thermal Transfer Value (ETTV) of the building. ETTV is the main component for the cooling load of a building. In general, bright skies and hot climates mean that daylighting cannot be a great advantage to reduce the electrical lighting load. In order to develop effective daylighting practices, it is necessary to have a thorough understanding of how particular daylighting devices will affect a space and its occupants by admitting more solar heat.

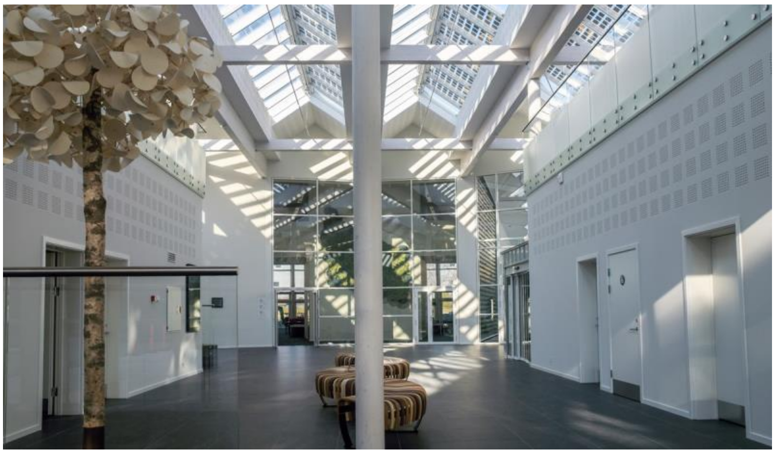


Figure 304: Daylight Penetration Through Skylight And Windows Image

Credit:(D/A Magazine By VELUX And Photo Credit To Adam Mørk/ Daniel Blaufuks)

Shading devices and small window openings are employed as the main features of building design to control excessive penetration of direct sunlight so that heat-gain and glare can be reduced. Daylighting techniques are explained in the Building Envelope sub-module and not in the realm of this electric lighting section.

30.7 TCO And Case Study

30.7.1 What Constitutes The Total Cost Of Ownership (TCO)?

The Total Cost of Ownership (TCO) is a financial estimate intended to help buyers and owners determine the direct and indirect long-term costs of a product or system. It is a management accounting concept that can be used in full cost accounting or even ecological economics including social costs.

Methods include:

a. Return on investment
b. Time to recover the extra price (Delta) of a chosen system over a cheaper alternative
c. Economic value added by a system

30.7.2 TCO Of Lighting Systems

A Customer's decision when based only on the initial price of a lighting system, can lead to:

a. Long term high energy expenditure;
b. Frequent lamp replacements; and
c. Defective accessories and maintenance problems; and
d. Poor impression about Facilities Department in the eyes of occupants

Financial Decision-makers often prefer to know the long term cost of owning a system rather than just the initial investment at the lowest price. They are increasingly calling for the TCO approach for procurement decisions. Put in a simple way,

TCO = THE 'ANNUALISED' COST OF (INVESTMENT + MAINTENANCE).

Generally, a lighting installation is supposed to have a life of 10 years and during this life span, we can calculate the cost of owning it each year.

Annualized cost of investment = Taken at 10% of the cost of luminaires (on a 10 year life span).

The initial lamps' cost is excluded in the investment cost because a lamp is more a 'consumable' item and cannot be depreciated over 10 years. So they are taken under annual maintenance cost as a replaceable item.

Annualized cost of maintenance = Energy cost + Replacement lamp cost + Labour cost

- Energy cost / yr. = (Load kW x Burning hrs per year) x Tariff charge per kWh
- Lamp cost (Pro-rated for each yr.) =

$$\frac{\text{(No. of lamps x price per lamp x Burning hrs per year)}}{\text{Lamp life in hours}}$$

- cleaning charges

Usually, cleaning charges are not taken into account in most Asian countries because it is done whenever the lamp is replaced.

30.7.3 TCO Worked Example

Question: A factory decides to procure 100 Nos of 2 x 36W fluorescent luminaires with Electro Magnetic (EM) ballast. A supplier offers the specified luminaire at S$ 80.00 each (excluding lamps). The vendor has also made an alternative offer for that luminaire but with a twin-lamp Electronic (EL) ballast. The cost of the latter is S$ 20 more. Given the following data, compare the TCO of both luminaires

- EM Ballast loss for each lamp = 9W
- EL Ballast loss for each lamp = 4W
- No. of burning hours per year = 4,000 hrs
- Electricity tariff = S$ 0.20/kWh
- Lamp price (each) = S$ 4.00
- Lamp life with EM ballast = 8,000 hrs
- Lamp; life with EL ballast = 12,000 hrs

Table 24: Answer To Worked Example

	Description	Luminaire with 2 x 36W EM ballasts	Luminaire with 1 x Twin 36W EL ballast
1	No of luminaires	100	100
2	Price of each luminaire	S$ 80.00	S$ 100.00
3	Investment on 100 luminaires	S$ 8,000.00	S$ 10,000.00
4	10% Depreciation per year	S$ 800.00	S$ 1,000.00
5	2 lamps' load	2 x 36W=72W	2 x 32W=64W
6	2 EM ballast or 1 Twin EL ballast loss	2 x 9W=18W	2 x 4W=8W
7	Total load per luminaire	90W	72W
8	Load for 100 luminaires	9.0 kW	7.2 kW
9	Energy for 4000 hrs per year	36,000 kWh	28,800 kWh
10	Energy cost @S$ 0.20 per kWh /	S$ 7,200.00	S$ 5760.00
11	Lamp life	8,000 hrs	12,000 hrs
12	No. of Pro-rated Lamp replacements per year	100	67
13	Price of each spare lamp	S$ 4.00	S$ 4.00
14	Lamp replacement cost / yr	S$ 400.00	S$ 268.00

15	Total Cost of Ownership / year (= S/N 4 + 10 + 14)	S$ 8400.00	S$ 7028.00
16	Annual savings with EL ballast luminaire (= 8200-7532)	--------	S$ 1372.00
17	Additional investment on EL ballast luminaire (Row 3 = 10,000 – 8000)	--------	S$ 2000.00
18	Time to recover this additional investment = 2000 / 1372	---------	1.45 years!

The 3 elements of TCO (for a luminaire with EM ballast in the above Table), are:

- Investment Depreciation cost = $ 800 (9.5%)
- Energy cost = $ 7200 (85.7%)
- Lamp replacement cost = $ 400 (4.8%)
- Total Cost of Ownership = $ 8400 (100%)

From the above, it is clear that energy is the biggest annual expense in a lighting system. Any additional investment to reduce the electric load can be well-justified and recoverable through savings within 1-3 years.

30.8 Selection Criteria Of Lighting Systems

When investing in a lighting system, the following criteria should receive attention:

a. Electrical
b. Mechanical
c. Optical
d. Ease of installation and maintenance

30.8.1 Electrical Criteria

The following will come under this:

a. Load (Watts) of the system
b. Power Factor: this has to be >0.85 in Singapore
c. Electro Magnetic Compatibility: Products must conform to IEC 61000-3-2 Immunity requirements of electrical systems
d. Radio interference

30.8.2 Mechanical Criteria

The most important mechanical criteria will be:

a. Adequate strength to withstand the conditions of use for the luminaire and its fixing arrangements
b. Heat dissipation: Enough mass (by way of casting, cooling fins, etc to dissipate the heat generated by the light source and driver). This is particularly important for LED luminaires
c. Ingress Protection (IP) Rating for outdoor applications

30.8.3 Optical Criteria

Here, the criteria will be:

a. Energy efficiency through maximum Downward Light Output Ratio (DLOR) and high Utilisation Factor
b. Use of reflectors and diffusers to spread the light in an appropriate way to increase the spacing and thereby reduce the no. of luminaires without affecting uniformity
c. Glare control

30.8.4 Ease Of Installation And Maintenance

The maintenance person will have to access the luminaire at certain intervals to replace the lamp, trouble-shoot any malfunction and clean its light-contributing surfaces (reflectors, LED lens etc). So the luminaire should allow easy access to human hands and tools. Diffusors must be able to hinge open with a retaining mechanism so that the diffusor does not fall down when the maintenance person is trying to replace the lamp. Ballast, capacitor etc should be mounted on a gear tray a male-female socket connection so that a defective tray could be disconnected smoothly at site and replaced with a good gear-tray. The defective one can then be brought back to the repair-facility and handled. Hardware like screws, clips etc should preferably be of stainless steel so that they are rust-free and maintenance-free for a long time.

30.9 Survey Of Existing Lighting In A Building

In order to survey the existing lighting of a building and its energy performance, a well-regarded Survey-tool and Template is contained in Technical Report NREL/TP-550-38602 of October 2005 by the Department of Energy (DOE-USA). Energy managers are well-advised to use this report for their lighting survey and the model therein for improvement suggestion and action. (See details under Reference).

30.10 Summing Up

Illumination is obviously an important building service because all our understanding and impressions in life, work, learning, interactions and success are attributed to good and comfortable eye-sight. The investment on luminaires in a commercial building is known to be just about 1.0% of the total cost of construction and furnishing of the building. But lighting's impact on productivity, safety and morale is substantial. So it is hoped that the contents of this sub-module will bring the right perspective on lighting to energy managers.

References and Links

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2. Building and Construction Authority "Guidelines on Envelope Thermal Transfer Value for Buildings"
3. Building and Construction Authority "Code on Envelope Thermal Transfer Value for Buildings"
4. Daylighting guide for buildings. Keith Robertson, Solterre Design
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6. BCA Green Mark for NEW Buildings (Non-Residential); 2015
7. SS530: 2014 Code of Practice for Energy Efficiency Standard for Building Services and Equipment, SPRING Singapore
8. SS531-1: 2006 Code of Practice for Lighting of Work Places (Indoor), SPRING Singapore
9. LM3-13 IES Guidelines for Upgrading Lighting Systems in Commercial and Institutional Spaces (Illuminating Engineering Society of North America 2013 edition)
10. IES Lighting Handbook, Tenth Edition (Illuminating Engineering Society of North America 2011 edition)
11. Susan M. Winchip, Fundamentals of lighting Second Edition 2011(Fairchild Books US)
12. Philips Lighting Manual, NV Philips Gloeilampenfabriekien, Nederland 2002
13. M.Deru, N. Blair and P. Torcellini. Procedure to measure Indoor Lighting Energy Performance, Department Of Energy-US document Technical Report NREL/TP-550-38602, October 2005

Suggested Reading Materials (For Lighting)

1. The Physics of Light, Lighting Research Centre, Rensselaer Polytechnic Institute http://www.lrc.rpi.edu/education/graduateeducation/courses.asp
2. Lamp and control gear http://www.gelighting.com/LightingWeb/apac/products/technologies/asia-control-gear/
3. GREEN BUILDING 101: Environmentally Friendly Lighting for Health and Well-Being http://inhabitat.com/green-building-101-environmentally-friendly-lighting/
4. Lighting Maintenance – Group Relamping (Industrial Lighting and Power) http://www.industriallightandpower.com/lighting_grouprelamp.php
5. The LEED view: Sustainable lighting http://www.ecmag.com/section/lighting/leed-view-sustainable-lighting